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An Overview of Surface Conditions in Numerical Simulations of Dust Devils and the Consequent Near-surface Air Flow Fields

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ABSTRACT

Dust devils are generally attributed to the near-surface conditions, usually the composite actions of the surface parameters, such as heat flux, wind shear and surface friction. Dust devil scale (DD-scale) numerical modeling has been developed to simulate the air flow of dust devils (Gu *et al.*, 2006, 2008). In the DD-scale model, local vorticity is imposed on the boundary domain (the outer dust devil), as described by Lewellen *et al.* (2000). The computational domain is close to the size of convective plumes. The predicted physical parameters of Arizona-type dust devil, such as the maximum tangential velocity, the updraft velocity, the pressure drop in the inner core region and even the inverse flow at the top of the core region, approach the observation results, testifying the validity of the DD-scale modeling. The effects of buoyancy (ground temperature) and surface friction (surface momentum impact height) on the fine scale structure of dust devils are further examined in this paper. The results indicate that even with small temperature difference (weak buoyancy), severe dust devils may be formed by strong local vorticity, and that different surface momentum impact heights may result in different conic angles of corner flow.

***Keywords**:* Dust devil; Convection; Large eddy simulation (LES); Vortices; Surface friction.

INTRODUCTION

Atmospheric dust particles have important impacts on global and regional climates. These small particles are difficult to move by simple boundary-layer wind shear. Some specific convective wind systems in the convective boundary layer (CBL), such as dust storms and dust devils, can carry dust into the atmosphere. Among these wind systems, the dust devil is the most common small-scale dust transmitting system (Gu *et al.*, 2008a). It is a special case of convective vortices occurring in the atmospheric boundary layer. It belongs to a family of concentrated vortices that are present on different earth's surfaces in events, such as tornadoes and waterspouts (Vatistas *et al.*, 1991). The dust devil is usually of short duration with low pressure and warm-core, which swirls dust, debris, and sand to heights above the CBL. The dust devil can be regarded as a strong, dynamically forced columnar vortex above a rigid lower boundary.

The main driving force for the dust devil is buoyancy created by the solar heating of the ground surface and the main vorticity source is the local wind shear. Many investigators have studied the principle of dust devil formation and most of them think that dust devils occur within rising plumes in the CBL (Battan, 1958; Ryan and Carroll, 1970; Cortese and Balachandar, 1993; Shapiro and Kogan, 1994), or within swirling rising plumes (SRP) (Zhao *et al.*, 2004). The air near the ground of the SRP region is characterized by a superadiabatic lapse rate (Sinclair, 1976; Oke *et al.*, 2007). If there exist ambient vorticity sources, the air parcels near the surface spiral toward the center of SRP while absorbing heat from the surface. The radial inflow of the warm air into the rising plume results in the concentration of ambient vorticity. As the convective plume rises to higher altitudes, the pressure depression increases at its base. The low-pressure center near the surface reinforces the spiral inflow of warm air into the incipient dust devil. The swirling energy is strengthened gradually and finally a dust devil arises at the center of SRP. Once formed, some intense dust devils can be extended to a height of several kilometers, enabling particles to be carried aloft and transported laterally or vertically (Hess and Spillane, 1990). When the surface is composed of loose materials, dust particles might become airborne, making the dust devil vortex visible, that is to say

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that the vortices may not be visible if loose materials and dust particles are not present. Besides, the field measurement have shown that charge separation within terrestrial dust devils produces electric fields that might play a significant role in dust sourcing (Renno *et al.*, 2004).

The surface-atmosphere interface in terrestrial deserts contains small loose grains that can be lifted into saltation and suspension by both horizontal and vertical winds (Renno *et al.*, 1998). Since dust grains in the air are different in size and shape, the airflow with dust grains is extremely complex. As is described in the typical case in the review literature (Balme and Greeley, 2006), the vortex in the core and upper part of the dust devil contains loose fine dust, whereas the bottom of the core is surrounded by a 'skirt' of large heavy particles. The observations of a large vertical electric field have confirmed the presence of separate charge centers in the dust devil, which is associated with the dust stratification within the dust devil (Farrell *et al.*, 2004). Recently, the integration of electrostatic dynamics and fluid dynamics within a dust devil (Farrell *et al.*, 2006) and the interactions between the aloft dust particles and the air flow field (Gu *et al.*, 2006) have been investigated. The aloft dust may expedite the energy dissipation of the air flow and shorten the life span of dust devils. Nevertheless, considering that the swirl in the developing stage might not be strong enough to levitate the dust and that the complication of particle impact and the effect of electric field (Renno *et al.*, 2004; Huang *et al.*, 2008) on particle movements make difficult the numerical study of the gas-solid two-phase flow of the dust devil in terrestrial deserts, most studies only focus on the atmosphere flow fields.

The evolution of dust devil and its characteristics have been investigated with observation (Schofield *et al.*, 1997; Renno *et al.*, 2004), experiment (Greeley *et al.*, 2003) and numerical simulation (Zhao *et al.*, 2004). Computer simulations are regarded as an important tool for interpreting laboratory and field observations of dust devils (Balme and Greeley, 2006) and for study of several coherent structures (CSs) on different spatial scales ranging from the microscale at the ground-air interface to the mesoscale (Zurn-Birkhimer and Agee, 2005). Many researchers have introduced different simulations of dust devils on Earth (Smith and Leslie, 1976; Kanak *et al.*, 2000; Kanak, 2005) or Mars (Rafkin *et al.*, 2001; Toigo *et al.*, 2003; Michaels and Rafkin, 2004) to reveal the similar evolutionary mechanism of dust devils on Earth or Mars. Since the simulation of dust devils on Earth can be verified by field observations, the simulation of terrestrial dust devils on Earth has been mainly concerned. Willis and Deardorff (1979), Moeng and Sullivan (1994), Kanak (2005), and Zhao *et al.* (2004) have demonstrated in their simulations that 'microfronts' on convective boundary layer (CBL) scale are analogous to the evolving branches of the cellular convective patterns, which can provide local vorticity for the dust devil. Zhao *et al.*'s simulation of terrestrial dust devil have revealed that the air flow on free-slip surface is different from the flow on no-slip surface, which means that the ground surface has an impact on the air flow structure of dust devils. It follows that the small coherent structures of dust devils may be dominated by the surface properties, such as surface heat flux, wind shear and surface friction (Gu *et al.*, 2006).

Like many pioneer researchers, Kanak *et al.* (2000) explored the dust devil model using large eddy simulation (LES). However, their early model is based on CBL-scale simulation using 35 m horizontal grid spacing. This model simulates vertical vortices of greater diameter than most observed dust devils. It has been observed that typical diameters and near-surface shapes of dust devils may depend strongly on geography (Balme and Greeley, 2006). However, the vertical vortices they have simulated are larger than those of the actual dust devils. That is, the vertical vortices they have simulated are larger than those of the actual dust devils. This larger scale simulation cannot present the fine structures and characteristics of dust devils. Recent researchers have tried to improve the simulation resolution, such that the high resolution simulation, together with the numerical model, can give better pictures of dust devils (Zhao *et al.*, 2004; Kanak, 2005). Kanak (2005) used 2 m spacing in her model, while in Zhao *et al.*'s work (2004), a three-dimensional, unsteady, high resolution simulation model of dust devil is utilized to depict the air flow evolution of dust devil. In Zhao *et al.*'s simulation using Smagorinsky's SGS scheme and fine grids, the radial grid spacing smoothly stretches from 0.1 m at the center to 4 m at outer domain and the vertical grid spacing stretches from 0.1 m on the surface to about 10 m at the top. Zhao *et al.*'s model is a dust devil scale (DD–scale) simulation.

In general, the CBL–scale simulation is carried out to investigate the genesis of dust devils, that is, to investigate how the air flow of dust devils gives rise to and maintains the swirling, converging plume on the hundreds-of-meter scale. The DD-scale simulation is used to get the fine coherent structure of dust devil flow and the properties of velocity and pressure fields. Due to the limitation of computer capacity, it is difficult to carry out the simulation using the CBL-scale model embedded in the DD-scale model and vice versa.

Instead of considering the larger scale, Lewellen *et al.* (2000) takes into account a larger domain than might seem necessary in their simulation of the air flow of tornados. In this way, a physically reasonable range of flow fields immediately bounding the corner flow domain is obtained by imposing a variety of flows on the outer tornado scale as the far-field boundary conditions. Similarly, in the DD-scale simulation, the computational domain is usually confined to or little larger than the size of a convection cell, giving local vorticity as boundary conditions (Willis and Deardorff, 1979; Moeng and Sullivan, 1994; Zhao *et al.*, 2004; Kanak, 2005). Zhao *et al.* (2004) compares the CBL-scale simulation for the convection cells with the DD-scale simulation for the air flow of dust devils. They find that given the appropriate initial conditions on the boundary of the computational domain, such as the heat flux and the initial temperature field, the convection cell can be initiated, thus easily allowing for the development of the air flow of dust devils. Considering the three parameters of initial local vorticity, the ground temperature and the surface momentum impact height (SMIH), Gu *et al.* (2008b) predicts the physical characteristics of the dust devil, such as the maximum tangential velocity, the updraft velocity, the pressure drop in the inner core region, and even the inverse flow at the top of the core region. The different modeled dust devils are also reproduced. However, the different scales of coherent structures (CSs) with differing spatial and temporal dimensions (Zurn-Birkhimer and Agee, 2005), particularly the details of fine flow field structure near ground surface, is not well identified for dust devils in Gu *et al.*'s study.

The motivation of this work is to further discuss the mathematic formulation of DD-scale modeling and to examine the physical characteristics of dust devil by virtue of the grid refinement in the core region above the surface. The general relationship of buoyancy, horizontal vorticity and surface friction and the LES modeling are discussed in Section 2. In section 3, quasi-steady dust devil-scale numerical simulation of terrestrial dust devils is carried out. The simulation results are compared with the observation results by Sinclair (1973) to show the influence of buoyancy (ground temperature) and surface friction (surface momentum impact height) on the flow structures of dust devils. Section 4 is the summary and the discussion of future work.

MATHEMATIC FORMULATION AND LES MODELING

Studies have shown that on a small scale, dust sourcing is sensitive to factors such as soil cover, physical characteristics, composition, topographical features and weather (Renno *et al.*, 2004). There would be no dust devil formation without some shear in light of inviscid fluid dynamics. In fact, for viscous air flow, the horizontal shear on the surface can produce vorticity, in the form of either horizontal vorticity or vertical vorticity. This vorticity is the source of spinning momentum of dust devils in a CBL. Dust devils occur under light wind conditions, for example, 1.5–7.5 m/s in Oke *et al.*'s observation (2007), which indicates that the coherent structures (CSs) of dust devils grow with buoyancy as the dominating physical mechanism for organizing the convection (even in the presence of substantial wind shear) (Zurn-Birkhimer and Agee, 2005). The buoyant plume tilts and stretches the horizontal vorticity. It is also observed that typically, some weak, local microscale "gust" of wind starts the vortex formation. Even a series of vortices can be observed along the boundary of this "microscale gust front" as it moves across the farm or desert of dry, loose dusty soil. Besides, surface friction shows its effects on the buoyancy and vorticity, which are the different profiles of dust devils on different ground surfaces such as bushes, desert and airfield.

For Arizona dust devils, an average diameter is likely on the order of tens of meters (Sinclair, 1973). In contrast, Hess and Spillane (1990) have reported mean diameters for dust devils in Australia ranging from 32 to 141 m. The heights of dust columns in dust devils are usually less than 600 m; however, under desert conditions typical of deep mixed layers, the thermal updraft associated with deep mixed layers have been observed to extend as high as 4500 m (Sinclair, 1966). The dust or grass is lifted by dust devils to a height ranging from 1500 m to 2400 m (Hess and Spillane, 1990), while the dust columns themselves reach heights of about 300–660 m. Kanak (2005) can be referred to for more information of the observed typical physical characteristics of terrestrial dust devils.

Computational Domain

The results of the CBL-scale simulation of dust devils indicate that the diameters of convective plumes are hundreds of meters (Zhao *et al.*, 2004). The warm updraft extends to the level of about 1000m. According to the CBL-scale simulation results (Kanak, 2005) and the observed data (Sinclair, 1973), the computational domain of the DD-scale simulation of Arizona-type dust devil in this work is set to be 1200 m high with a radius of 200 m, as is adopted by Gu *et al.* (2008b). The radial dimension is an order of magnitude of convective plumes, at the bottom of which dust devils might be formed (Battan, 1958; Ryan and Carroll, 1970). Accordingly, the CSs of dust devils are analysed based on this DD-scale simulation.

As mentioned in the introduction, the boundary and initial conditions on the computational boundary for the DD-scale simulation are set based on the parameterization of the CBL-scale investigation and/or the field observation. In the following, the role of the surface properties and the consideration of physical conditions will be examined as the boundary condition parameters to determine the shape and intensity of the dust devil in the present DD-scale LES simulation. Since the Arizona-type dust devils are simulated in this paper, Sinclair's observation data in Arizona desert are used to validate the DD-scale LES simulations in this work.

Heating

The intensity of a dust devil depends on the surface air temperature differences between the local environment and the center of the dust devil). The daytime surface air temperature over a desert is regulated by the sensible heat flux from the ground into the surface air. An air temperature lapse rate of 0.9 °C/m, measured between 12 and 252 cm away from the ground, is required for the initiation of the dust devils, whose frequencies increase with the decreasing of the lapse rate (Oke *et al.*, 2007).

The sensible heat flux, in turn, is proportional to the difference between the ground temperature and the surface air temperature. Therefore, the ground temperature provides an upper bound (Renno *et al.*, 1998). Generally, a constant heat flux is specified at the lower boundary (Moeng and Sullivan, 1994; Zhao *et al.*, 2004; Kanak, 2005) in simulation models to allow for super-adiabatic lapse rate near the ground surface, or the buoyancy. The temperature difference between the near-surface ambient air and the ground surface is used as a parameter in the present study, as is done in Gu *et al.*'s work (2008b), to show the effect of different ground temperatures when the constant temperature of the converging ambient air parcels is maintained. The heat flux can be specified by the temperature difference (Renno *et al.*, 2004).

Horizontal Vorticity and Surface Friction

There is a substantial difference in the surface roughness between the bare areas, and the chenopod shrub lands and bushy areas. The vegetation provides a considerably rougher surface than the bare areas, placing an increased drag on the air flowing over it, resulting in slower airflow over the vegetated areas than that over the bare patches. This difference in wind speeds over the different surfaces can result in shear in the airflow (Oke *et al.*, 2007). Vegetation may also absorb part of the momentum of the wind, thereby degrading the columns and reducing the erosion efficiency of the dust devils (Scott, 1995).

Typically, some weak, local microscale "gust" of wind can start the vortex formation. Through the CBL-scale simulations, a number of investigators have also indicated or provided evidence that larger-scale convective circulation, which is not initially rotational, can provide vertical and/or tilted horizontal vorticity (Carroll and Ryan, 1970; Willis and Deardorff, 1979; Cortese and Balachandar, 1993; Shapiro and Kanak, 2002). The vortex size is proportional to the value of the background vorticity (Renno and Bluestein, 2001). However, in the DD-scale simulation the background vorticity is parameterized as the lateral boundary condition of the computational domain, and expressed in terms of the tangential velocity. It is difficult to choose an appropriate swirling flow condition at $r = R$ since there are a number of possibilities (Leslie and Smith, 1977). Smith and Leslie (1976) have indicated one of the two swirling flow conditions can be used, the tangential velocity v_t or the vertical component of vorticity ζ, and that the choice between them can be made according to the information deduced from observations of the air flow in the vicinity of a dust devil.

In this work, the tangential velocity on the lateral boundary is specified as the parameter of the background vorticity in the DD-scale simulation. The tangential velocity drops to zero at the surface due to surface friction (Lewellen *et al.*, 2000). The surface friction effect results in the vertical distribution of the near-surface tangential velocity on the domain boundary (Leslie and Smith, 1977; Vatistas, Kozel and Mih, 1991). The tangential velocities at different heights show different values due to the reduction of the angular momentum caused by surface friction (resulting from grass, sand, bush, etc.). In the following, the surface momentum impact height (SMIH) is defined as a parameter to account for the surface friction effect. Therefore, the tangential velocity on the lateral boundary is a function of SMIH.

The profile of temperature, pressure and the three cylindrical components of the velocity of wind through the base of a dust devil are obtained from Sinclair's measurements near Tucson, Arizona (Sinclair, 1973). In light of Sinclair's recorded profiles of tangential velocity beyond the center of the dust devil (Sinclair, 1966), a tangential velocity profile $v_t(z) = C_1(1 - e^{-z/C_2})$ is adopted in this paper for the swirling flow condition at the lateral boundary, $r = R$ (Gu *et al.*, 2008b). C_1 is the initial tangential velocity (rotating speed), representative of the background vorticity, and C_2 reflects the vertical distribution of the rotating speed, accounting for the effect of the surface roughness on the near-ground flow. Different from the geometric surface roughness, C_2 is defined as SMIH, which is sensitive and directly proportional to the surface roughness.

It deserves to be mentioned that SMIH in this work is not the aerodynamic roughness Z_0 although a better profile equation for the surface friction effect may be the simple aerodynamic rough-surface. SMIH is just a parameter derived from Sinclair's observation. The profile in the present simulation does not differ greatly from the horizontal boundary layer profile with coefficients based upon the height (of 10 m, for example); however, with the profile used here, the arbitrary coefficients will be much easier to justify.

Pressure Inlet Conditions

The computational domain is bounded by the no-slip flow bottom boundary and the pressure inlet condition lateral boundary. Neumann boundary conditions for the pressure inlet condition on lateral boundary of dust devils (Smith and Leslie, 1976; Leslie and Smith, 1977) means that the air is allowed to flow in or flow out of the computational domain through the lateral boundary and that the direction of the air flow must be determined dynamically. Accordingly, in this paper the pressure is specified on the lateral boundary, $r = R$, under Neumann condition for the velocity on the lateral boundary $\partial u_i/\partial n = 0$. The pressure gradient is zero if $z < 800$ m. If $z \geq 800$ m, the field pressure above 800 m is determined by the temperature distribution of the inversion layer (Gu *et al.* 2008b).

LES Modeling

In LES method, the large-scale turbulence is resolved using fine grid resolution by the filtering procedure while the unresolved small-scale turbulence (sub-grid scale turbulence) is parameterized. Large-scale turbulence, geometry-dependent and anisotropic, contains most of the turbulent kinetic energy. Small-scale turbulence, by contrast, contains only a small fraction of the turbulent energy and can be considered to be isotropic and geometry-independent. Therefore, small-scale turbulence is much easier to be parameterized by sub-grid scale model, whose governing equations, sub-grid schemes and grid spacing have been described by Gu *et al*. (2006, 2008b).

The treatment of wall shear stress near the solid boundaries by the SGS model requires special considerations. Generally, the dynamic SGS scheme can deal with wall shear stress without the need to involve ad hoc near-wall damping functions because the Smagorinsky constant (Smagorinsky, 1963) decreases automatically in the boundary vicinity. However, for wall-bounded high Reynolds number flows such as dust devils, there is little prospect of directly resolving the viscous sub-layer due to the limited computing resources. Therefore, wall functions are still necessary to be adopted (Ciofalo, 1996; Walton *et al.*, 2002).

Agee and Gluhovsky (1999) have found that LES models show high sensitivity to parameters such as domain size, grid resolution, and the number of large-eddy turnover times of integration. They have also indicated that these parameters play their respective effects on the characteristic turbulence statistics computed from the simulation of convective flows in planetary boundary layers (PBLs). Lewellen *et al.* (1997) have done the LES simulation of turbulent transport in the tornado vortex for one set of physical boundary conditions, showing that for sufficiently fine grid resolution, the simulation results are relatively independent of grid resolution and subgrid model modifications. Since the duration of dust devils is about 10–20 minutes, the non-uniform grids (Kanak, 2005) and small time step are employed for large eddy simulation of dust devils in this work. The dense grids are adopted for the solution of the most important turbulence in the near-surface region. The simulation starts from the static state and continues over a great number of time steps. Since time averaging plays an important role in the attainment of a quasi-steady state of air flow, the time-averaged air flow field within 30 s is used to generate the LES model turbulence statistics (Gu *et al.*, 2006).

The commercial software code CFX from AEA Technology, together with supplementary User FORTRAN, is utilized as a solver in this paper. This approach has the advantage that many numerical schemes are available in CFX and that many boundary conditions can be adaptable. Pre-processors in CFX can construct complex geometries and multi-block finite-volume grids. Post-processors in CFX also allow easy treatment of results. This CFX-LES approach has been validated by the simulation of the channel flow (Zhao and Voke, 1996). Since then, the approach has been extensively studied and sufficient experimental data are available to validate it.

CASE SIMULATIONS AND ANALYSES

Using different combinations of the ground temperature, initial tangential velocity (background vorticity) and SMIH as parameters, the simulations of three cases of Arizona-type dust devils are carried out to show their influences on the fine structure of near-surface air flow of dust devils in the following. Against the observations by Sinclair (1973), the initial tangential velocity (background vorticity), $C_1 = 2.5$ m/s, and SMIH, $C_2 = 4.0$ m, are selected for the boundary condition parameters in this study, as is done in the early work (Gu *et al.*, 2008b). The temperature difference is the main driving force for convection in dust devils. Li (2002) measures the distribution of air temperature over deserts and reports that the temperature difference between the ground and the air at the level 1 m is over 20–30 K at sunny mid-day. The super-adiabatic lapse rate near the surface is thus evaluated by the temperature difference in this study. In the present simulations, the average atmospheric temperature at midday in deserts is assumed to be 313 K. The ground surface temperature and the surface temperature are obtained from Gu *et al.*'s study (2008b).

The evolution of dust devils is divided into three stages (developing, developed and decaying stage) and the characteristics of each stage have been described in detail by Zhao *et al.* (2004). The mature phase (the transition period from the developed stage to the decaying stage), which lasts several minutes to tens of minutes, is therefore focused in this paper. By virtue of the grid refinement in the core region above the surface, the fine structure of the airflow in the modeled dust devil is extracted from Fig. 1 in Gu *et al.*'s study (2008b), as shown in Fig. 2. Fig. 2 shows the detailed vertical profiles of the flow in the bottom domain, 100 × 100 m, under the same surface conditions.

In the following, the above modeled dust devil is used as the first case to further discuss the characteristics of the air flow. As shown in Fig. 1(b), the flow of a fully developed dust devil vortex is divided into four regions: the outer flow region, the core region, the corner, and the near-surface layer. The 'core region' is the central core of the vortex. It is the mainstream of dust devils, where low pressure updraft occurs in the inner core zone of the core region. The outer flow region is beyond the core region, where the air flow swirls slowly in response to the background vorticity and the positive buoyancy force in the convective plume. The inflow spirals into the center in near-surface layer or inflow layer, and then deflects upward into the corner region. The maximum tangential velocity in the corner region is about 12 m/s. This maximum tangential velocity contours consist of the core ring (C in Fig. 1 (b)). The swirling velocity at a certain level in the corner is much greater than that in the 'core region' above the corner. The highest swirling velocity and the strongest turbulence of an actual dust devil generally located at the corner region have been observed by Sinclair (1973) and Hess and Spillane (1990), showing high promise of the present simulation.

The pressure gradient and centripetal forces are balanced in a swirling flow in light of aerodynamic theory (Balme and Greeley, 2006). The pressure gradient is relevant to the pressure drop field. It is demonstrated in Fig. 2 that stronger swirling updraft results in higher pressure drops in the inner core of dust devil, with the maximum drop reaching 2 hPa. The maximum pressure drop in Fig. 1 is slightly lower than that of Sinclair's observations (1973). This pressure deficit, providing the driving force for 'lift', is thus suggested as one of the possible mechanisms for dust lifting in dust devils. Another possible mechanism for particle lift is the enhanced local wind speeds in the vortex, which creates large wind shear forces (Balme *et al.*, 2003; Greeley *et al.*, 2003; Ringrose *et al.*, 2003). However, the effect of the above pressure deficit and large wind shear forces are not available in the explanation of the dust stratification in dust devils. In actual dust devils, the dust stratification occurs, that is, most of the small size grains swirl to the top of dust devil while most of large size grains swirl near the surface. Therefore, the interaction between

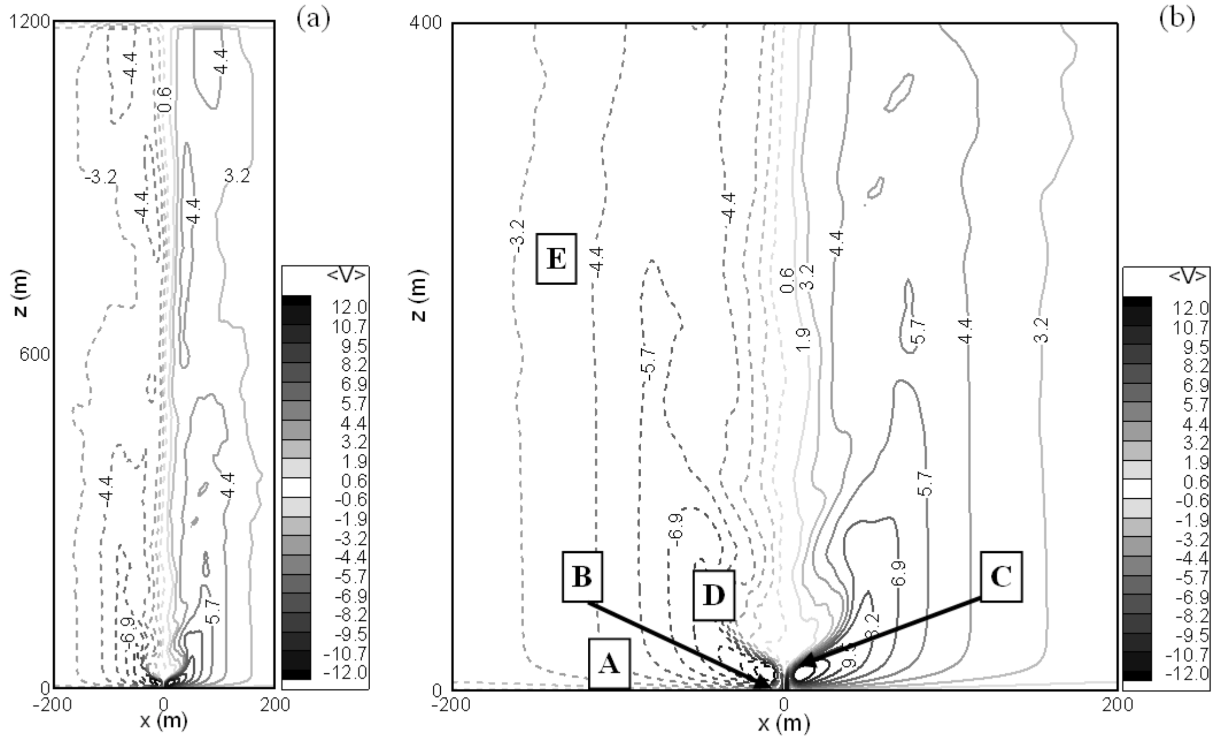

Fig. 1. Tangential velocity contours of the modeled dust devil with T_{wall} = 343 K, C_1 =2.5 m/s, and C_2 = 4.0 m (Gu *et al*., 2008). (a) The whole field. (b) The enlarged near-surface region. The velocity is the time-averaging value, m/s. Dashed line represents negative value. As shown in Fig. 2 (b), in the near surface layer (A), the ambient air flows inwards into the center and then deflects upward into the corner region (B). C shows the core ring. In the core region (D), especially the inner core, there is low pressure updraft with high velocity. In the outer flow region (E), air parcels spiral slowly owing to the background vorticity.

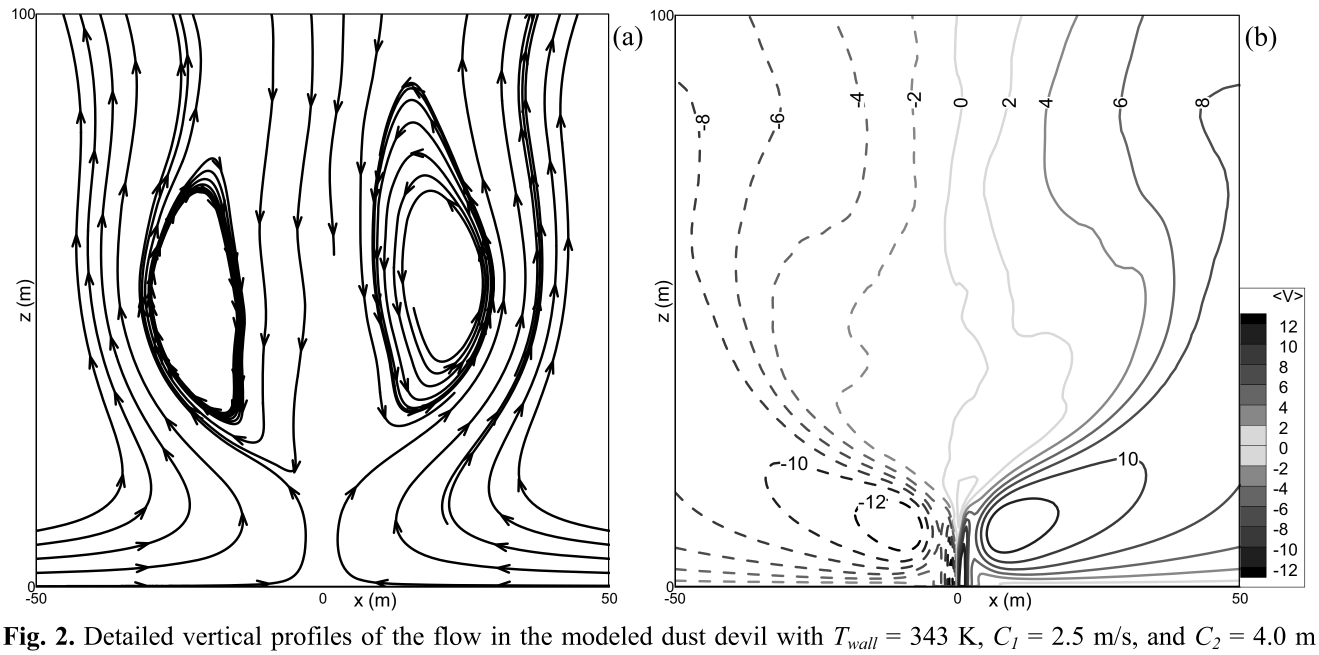

Fig. 2. Detailed vertical profiles of the flow in the modeled dust devil with T_{wall} = 343 K, C_1 = 2.5 m/s, and C_2 = 4.0 m (100 × 100m region). (a) Streamtrace of radial and vertical velocity components. (b) Contours of the tangential velocity component, m/s. Dashed line represents negative value.

the aloft dust particles of different sizes and the interaction between particle and the air flow field of dust devils should be considered for the mechanisms for the lifting of dust particles entrained in dust devils (Gu *et al.* 2006). The effect of dust saltation, dust loading and static field on the air flow in dust devils might be important and should be investigated in the future (Huang *et al.*, 2008).

The streamtrace of the radial and vertical velocity components (Fig. 2(a)) shows the two dimensional directions of the airflow. The overall vertical flow structure in Fig. 2(a) is quite similar to the sketch of the possible vertical flow in a dust devil given by Balme and Greeley (2006). The stagnation point near the surface represents the center of the spot where air shifts from inward to upward direction. The upper stagnation point, the intersection of the upward hot air and the vortex breakdown (downward flow), is occupied by turbulences. The central downdraft reverses near the upper stagnation point and surrounds a low-speed stagnation region. The contours of tangential velocity component in the 100 × 100 m region (Fig. 2(b)) show the detailed rotating velocity field in the core of the dust devil. According to Fig. 2(b), the core ring region, where the maximum rotating velocity occurs, has a diameter of about 20 m and locates at a height of about 10m. The detailed structure of the dust devil is important for the future research into the evaluation of the scalar transport, such as the dust lifting capability.

Fig. 3 shows the tangential velocity contours of the modeled dust devil in the near-surface region under the conditions of weaker convection (at a surface temperature of 323 K), constant surface momentum impact height and initial rotating speed. In this case, the surface temperature is 20 K lower than that in the first case, and thus the driving force of the vertical vortex is relatively weaker. Compared with the first case shown in Fig. 1(b) and Fig. 2(b), the second case depicted in Fig. 3 shows similar overall shape but obviously small updraft velocity. The predicted near-surface rotating speed and updraft velocity are of the same value, 10 m/s, which is accompanied by a reduction of 1 hPa in pressure drop in the inner core. This case shows a weaker convection plume and lower pressure drop and updraft velocity in comparison with the first case; whereas the maximum tangential velocity slightly slows down. According to the first case and the second case, the maximum tangential velocity is relevant to the background vorticity, which agrees with Lewellen *et al.*'s finding (2000) that the swirl ratio is the most important variable in determination of vortex structure. The maximum horizontal centrifugal velocity is 6 m/s in the corner flow region. The maximum centripetal velocity in the near-surface layer is 7 m/s.

The profile of the tangential contours in the upper-corner flow resembles a cone. It is observed that the surface friction significantly affects the conic angle, or the near-surface shape of dust devils. In the third case, in order to evaluate the effect of SMIH on the near-surface shape, SMIH is reduced to from 4.0 m in the first case to 2.0 m (C_2 = 2.0 m) while the initial tangential velocity C_1 = 2.5 m/s and the ground surface temperature 343K are maintained. The tangential velocity contours of the modeled dust devil in the enlarged near-surface region are shown in Fig. 4. The conic angle of this case is lager than that of the first case. The near-surface shape of this kind of dust devil looks like a bowl. According to Fig. 4(b), the core ring locates at a height of around 5 m and has a diameter of about 30 m, which means that the corner flow region in the third case is closer to the surface than that in the first case. This phenomenon can be interpreted as a result of the reduction of SMIH. The maximum updraft velocity is low down to 9.5 m/s while the maximum rotating velocity in the corner region keeps the same value, 12 m/s. The pressure drop in the inner core is up to 3 hPa. Different near-surface shapes of dust devil occur on different roughness surfaces, varying from a column on a very smooth surface (Zhao *et al.*, 2004), a bowl shape on a moderate rough surface, to an upside-down thin cone shape on a rougher surface whilst the intensity of dust devil increases with the decrease in the conic angle of the corner flow.

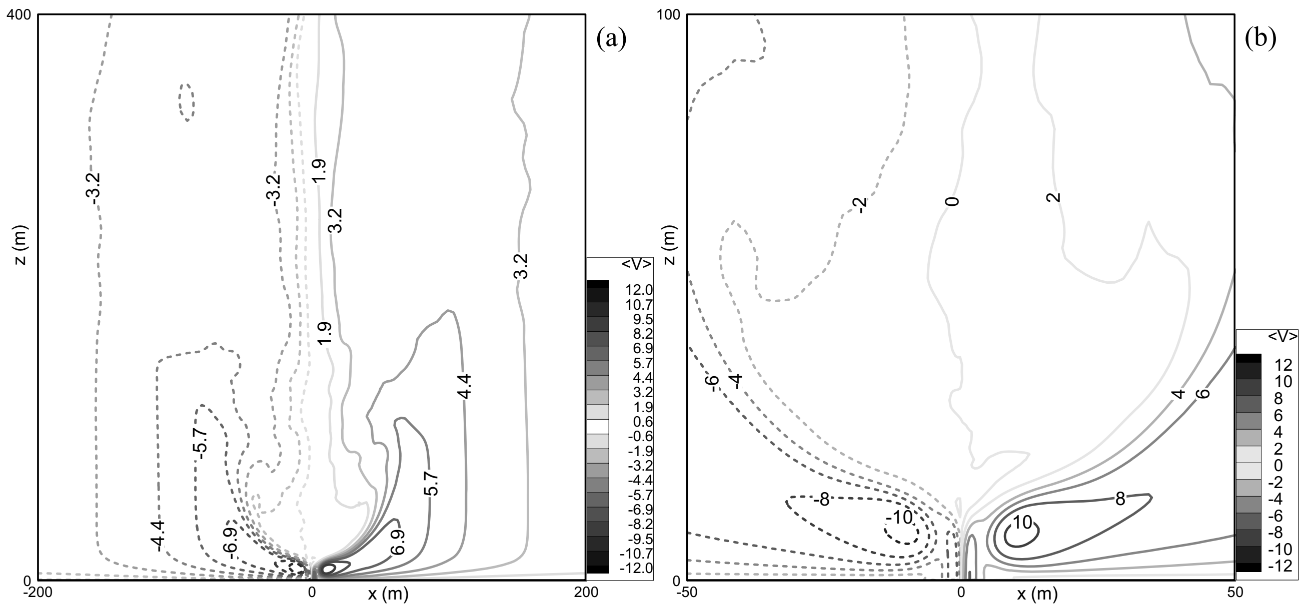

Fig. 3. Tangential velocity contours of the modeled dust devil with T_{wall} = 323 K, C_1 = 2.5 m/s, and C_2 = 4.0 m in the near-surface region. (a) 400 × 400 m region. (b) 100 × 100 m region. Dashed line represents negative value.

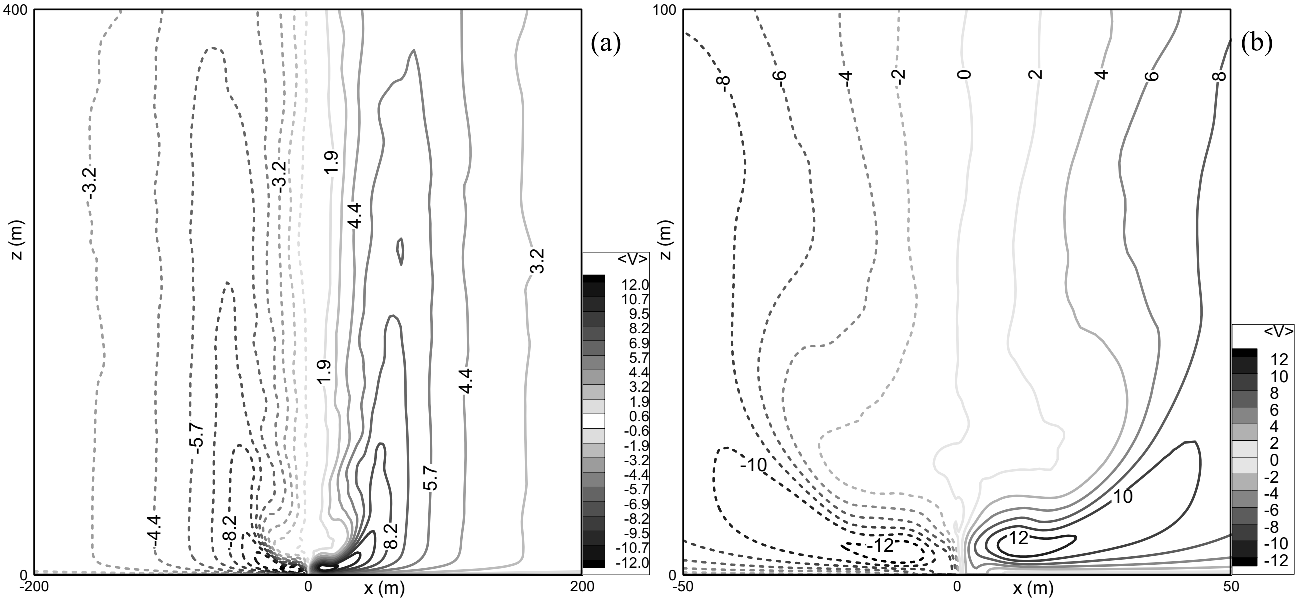

Fig. 4. Tangential velocity contours of the modeled dust devil with T_{wall} = 343 K, C_1 = 2.5 m/s, and C_2 = 2.0 m in the near-surface region. (a) 400 × 400m region. (b) 100 × 100 m region. Dashed line represents negative value.

SUMMARY

In principle, the moving air can not rotate itself without background vorticity if the air flow is inviscid. For actual flow, the maximum tangential velocity is under the control of the ambient vorticity (Lewellen *et al.*, 2000). The existence and the size of a convective vortex depend on the presence of vorticity and its magnitude (Renno and Bluestein, 2001). As air parcels move toward the center of the updraft in the presence of vorticity, they spin while attempting to conserve angular momentum. As shown in the dust devil simulation cases, the heat flux from the surface strongly affects the updraft velocity due to buoyancy. The surface momentum impact height mainly influences the near-surface vertical distribution of the tangential velocity and then the near-surface shape of dust devils. Generally, dust devils can be only attributed to the near-surface conditions, usually the composite actions of the surface parameters, such as heat flux, wind shear and surface friction. Therefore, in this paper, the effects of two parameters, buoyancy (ground temperature) and surface friction (surface momentum impact height), on the fine scale structure of dust devils are examined and demonstrated by the DD-scale modeling. In the DD-scale model, local vorticity is imposed on the boundary (the outer dust devil), as illustrated by Lewellen *et al.* (2000).

The different scales of coherent structures (CSs) with differing spatial dimensions are primarily identified for the developed stage of dust devils in this work, using the dust devil-scale large eddy simulation (LES) method. The computational domain is close to the dimension of convective plumes. Three parameters, local (background) vorticity, surface momentum impact height and surface temperature, are justified as the boundary conditions. The commercial software code CFX from AEA Technology is utilized as a solver based on Cartesian coordinate system. Similar to the tornado vortex structure (Lewellen *et al.*, 2000), the near-surface air flow structure of dust devils can be identified as four distinct regions: an outer region with a constant (or slowly varying) vorticity, a near-surface layer with sharp vertical vorticity gradients and near-to-zero vertical velocity, a core region with near-to-zero radial velocity, and a corner flow region where the horizontal flow transits to vertical flow and all velocity components vary significantly. The predicted physical characteristics of Arizona-type dust devil, such as the maximum tangential velocity, the updraft velocity, the pressure drop in the inner core region, and even the inverse flow at the top of the core region, approach the observation results, showing the promise of our simulation method.

The maximum rotating speed, the maximum updraft speed, and the pressure drop in the inner core of dust devils in the developed stage are generally used to indicate the intensity of dust devils. By using different combinations of the background vorticity, SMIH and surface temperature for different surfaces, a variety of the air flows of dust devils can be calculated. The simulations of the three cases show that even for smaller temperature difference – weaker buoyancy, severe dust devils may be formed by strong background vorticity. Our simulation result suggests that the radius of the dust devil must be determined by the initial angular momentum of air parcels, which can be explained by Renno *et al.*'s finding that dust devils receive their vorticity from ambient wind shears (1998). It is indicated that SMIH substantially affects the near-surface shape of terrestrial dust devils, changing from a column on a very smooth surface (Zhao *et al.*, 2004) to an upside-down cone-like dust devil near the ground. Different SMIH might result in different conic angles of corner flows. The tangential velocity and intensity of dust devil increase with the decrease of conic angle. Further work should focus on the composite effects of these surface parameters on the air flow of dust devils to unveil the different shapes and intensities of dust devils in nature.

The coherent structures of the air flows in the evolution of dust devils help us to understand the grain lifting in the air flow field and the interaction of particle collision and tribocharging mechanism. Recent efforts in the integration of electrostatic and fluid dynamics within a dust devil (Farrell *et al.*, 2006), and the numerical simulation of dust lifting within dust devils (Gu *et al.*, 2006) have been made for the first time. However, the simulation of the gas-solid two-phase flow with electrostatic field for dust devils is extremely difficult and should be developed in the future.

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