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LARGE EDDY SIMULATION OF VERTICAL VORTICES IN HIGHLY CONVECTIVE MARTIAN BOUNDARY LAYER

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1. Abstract

The Phoenix lander, a NASA scout mission, is scheduled to arrive on Mars near 70 degrees North in May 2008 and operate during the northern summer (2008). Among other experiments, it will make continuous meteorological measurements of pressure and temperature, plus some wind and humidity measurements. Phoenix will use a vertically pointing lidar provided by the Canadian Space Agency (CSA) to observe profiles of dust and water ice particles. It is hoped to use the lidar data to determine boundary-layer depths assuming a detectable drop in aerosol level at the top of the daytime convective boundary layer. Suspended atmospheric dust is an important driver of the boundary-layer circulation and climate system of Mars. It is also an important factor in Earth's atmosphere. Convective Boundary Layers (CBLs) generate a variety of dynamical structures including vertical vortices which provide a mechanism for dust lifting into the atmosphere. Dust devil tracks have been observed at the 65-72 latitude band of Mars' North Polar Region by the Mars Global Surveyor (MGS) Mars Orbiter Camera Narrow-Angle (MOC-NA). These satellite images indicate evidence of dust devils and strong winds in the Phoenix landing site environment. In this study, Large Eddy Simulations (LES) of planetary boundary layers are performed to compare the physical characteristics of simulated vertical vortices to those of observed dust devils. LES allows time-evolving simulations of turbulence and convection in a three-dimensional computational box and has been successfully used for a wide range of terrestrial atmospheric problems. Our LES model is based on the NCAR LES, developed by Peter Sullivan and others, adapted and developed for Martian applications. As a necessary part of preparation for the analyses of data from the mission, this study examines the possible formation and maintenance mechanisms for vertical vortices in the highly convective Martian and terrestrial boundary layers. The simulations performed include both terrestrial and Martian atmospheric CBLs to compare characteristics of dust devil-like vortices of each planet, in situations with and without ambient wind.

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2. Introduction

Vertical vortices can form when extremely hot air near the surface rises quickly through a small pocket of cooler low pressure air above it. On Mars, dust devils were first photographed by the Viking orbiters in the 1970s. In 1997, the Mars Pathfinder lander detected a dust devil passing over it. On April 20, 2008, the Mars Reconnaissance Orbiter's (MRO) Context Camera captured Images showing two active dust devils within the Phoenix landing ellipse. The 6m/pixel image shows two dust devils and their shadows. Based on measurement of the shadows cast by the dust devils, one of the vortices towered about 590m with a dust plume extending 920m above the surface. The other reached about 390m high, with a dust plume extending to 790m [11]. As spring gives way to summer, dust devils are likely to occur more frequently, as local temperatures rise.

The focus of this study is simulations of convective vortex formation over the homogeneous surface of Phoenix lander site, in situations with and without ambient wind. For this purpose, a comparison of convective vertical vortices formation in quiescent environments on Earth and Mars has been performed in order to verify our simulation results by comparing characteristics of dust devil-like vortices of each planet with other researches and observations. Also further progresses can provide us valuable information such as quantity of possible vertical vortices per unit of area and their physical specifications. These investigations will later address the vertical distribution of dust particles on Mars due to local storm events in lifting dust from surface and also possible critical issues regarding landing and operation of the future landers or rovers on Mars.

3. The model

In this study an investigation of the fundamental nature of the Planetary Boundary Layer (PBL) has been made by employing and developing the NCAR LES, developed by Sullivan and others [1]. The numerical method of this model solves momentum and thermodynamic equations in a computational box with external forcing and boundary conditions representative of an atmospheric PBL. The equations are cast on a staggered Arakawa C-grid. The grid spacing is set to be stretched in the vertical direction, so that the highest resolution is concentrated near the lower boundary. A two-part eddy viscosity turbulence model parameterizes subgrid turbulent stresses [1]. A third-order Runge-Kutta scheme is used for integration over time. The code uses mixed pseudospectral (along horizontal planes) and second order finite-difference (in the vertical direction) spatial discretization. Boundary conditions of the computational domain box consist of no slip conditions with M-O similarity theory at the bottom. A sponge boundary condition is used at the top and periodic conditions along lateral boundaries. The NCAR LES code is written to run on massively parallel computer architectures using the Message-Passing Interface (MPI) and OpenMP programming models.

Procedures have been developed to calculate the time series of vertical vorticity extrema and its horizontal location. This is used to guide the detection of vertical vorticies. Additionally, specific algorithms have been performed based on connecting regions of opposite velocity directions at the first vertical grid points. These algorithms provide the approximate locations of the vortices' center and some of their specifications such as maximum diameter, vorticity, horizontal and vertical velocities, and temperature increment at every time step. Knowing the locations of vorticies at every time step can also help us to estimate their lifespan and traveling speed.

4. Results and conclusions

4.1. Comparison Exercise

As the first step, verification of our implementation of the model was performed based on studies of Fedorovich *et al.* [2] for an application on Earth. All participating LES codes in the Fedorovich comparison and our implementation used the same simulation domain, boundary conditions and simulated flow properties. Figure 1 compares some of the results in terms of statistical vertical profiles at 10000s (2.78 hr) simulated time. These instantaneous profiles are averages over all horizontal grid points at each level. From the comparison data, including data which were not presented here, it can be concluded that our implementation of the NCAR LES model has shown very good agreement with other codes for all the predictions of CBL turbulence structure features [3].

4.2. Experimental designs on Earth and Mars

The current simulations examine the possible formation and maintenance mechanisms for vertical vortices in the highly convective boundary layer on Earth and Mars. Simulation properties for Earth and Mars are based on our former investigations [3] and have been listed in Table 1. From the physical characteristics of vertical vortices on Earth and Mars, listed in Table 2, it can be concluded that the Martian vorticity column extends six times higher and ten times wider than Earth's. The height of the Martian dust devil agrees very well with the observation of MRO on April 20th, 2008, as the simulation properties somehow are similar to the observation situations.

4.3. Dust devil formation at Phoenix landing site

As a necessary part of preparation for future upcoming data from the Phoenix Lander we have conducted several simulations at phoenix lander environment around noon in a sunny summer day. Simulation properties are same as Table 3 and the only changes are surface heat flux and location which respectively have been set as 25wm^{-2} and 70^{o} N. Figure 2 gives a perspective idea about formation of a dust devil like vortex around 2000s simulated time.

4.3.1 Effect of ambient wind on dust devil formation

In order to improve the detailed analysis of vertical vortices, effect of ambient wind in structure and formation of vertical vortices has been investigated at Phoenix lander site. For this six simulations have been performed for 6 different geostrophic winds including zero. Figure 3 shows vertical velocity contour plot and stream lines at vertical cross sections of the selected dust devil like vorticies around 2500s simulated time, and Table 3 lists an over view of the simulation results at this time. Over all the increase of geosrophic wind destructs vertical vortices or dust devils and dust devils almost take place in absence of winds.

4.3.2 Total vertical vortices within the computational domain

It might be critical to know how many vortices represented earlier are active at a same time around Phoenix lander or per unit of area on Mars. Some of these vortices may be visible and detectable by the lander's camera because of dusty condition, but some may not. In order to know this, procedures have been developed by performing an algorithm based on connecting regions of opposite velocity directions at the first vertical grid points. In Figure 4 we can see the application of our algorithm in detection of 84 vorticies at t=2351s. By using this algorithm we can specify properties of each vortex such as location, maximum diameter, horizontal velocity, vertical velocity, and vorticity. Having the location of each vortex can also help us to calculate its lifespan. For example, In Figure 5 we can see number of vortices around one hour simulated time is not more than 60 in the 5x5km^2 computational domain size (less that 3/km^2). Figure 6 shows whirlpools' vorticity in average is about 0.15s^{-1} which is higher by a factor of 10 from ensemble average of vorticity.

Some optimizations are under gone to improve the accuracy of our method. Further investigations also may be done by using the recent method in order to check the properties of vortices in situations with ambient winds

For more information please visit:

http://www.yorku.ca/pat/research/Phoenix.html

Acknowledgments

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Figures and tables:

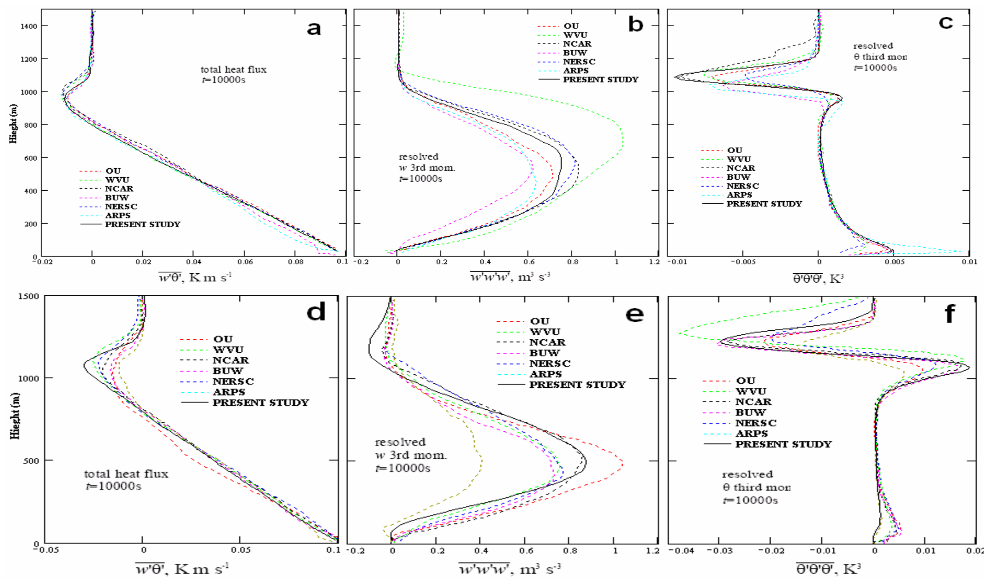


Figure 1 (a) Total heat flux, (b) Third-order resolved vertical velocity, (c) Third-order resolved virtual potential temperature, at t=2.8hr and zero geostrophic wind,
(d) Total heat flux, (e) Third-order resolved vertical velocity, (f) Third-order resolved virtual potential temperature, at t=2.8hr and 20m/s geostrophic wind.

Parameter	Mars	Earth	Unit
Height-constant Geostrophic wind,	0, 0	0,0	$m\ s^{-1}$
Surface heat flux,	1.65 (18)	0.2 (242)	$K\ ms^{-1}$ (Wm^{-2})
Surface roughness length,	0.01	0.01	m
Surface initial temperature	242	300	K
Domain size,	(5, 5, 10)	(0.5, 0.5, 1.25)	km
Grid points	(200,200,106)	(250,250, 120)	
Virtual potential temperature gradient,	3	3	$K\ km^{-1}$
Horizontal grid size	25	2	m
Vertical grid size (stretch)	25 - 265	3 - 25	m

Table 1 Simulation Properties of Highly Convective Boundary Layers on Earth & Mars

Characteristic	Mars	Earth	Unit
Simulated Time (~2000s)	2298	1850	s
Height (~)	600 (587)	100 (98.7)	m
Rotation Sense at 1/10 of Height	0.28ccw	2.02cw	s^{-1}
Horizontal Velocity at 1/10 of Height	5.3max,-4.6min	2.7max,-2.6min	ms^{-1}
Vertical Velocity at 1/10 of Height	3.4 max	1.5max	ms^{-1}
Diameter at 1/10 of Height	125	12	m
Temperature Increment at 1/10 of Height	8	3	K

Table 2 Physical Characteristics of Vertical Vortices on Earth & Mars

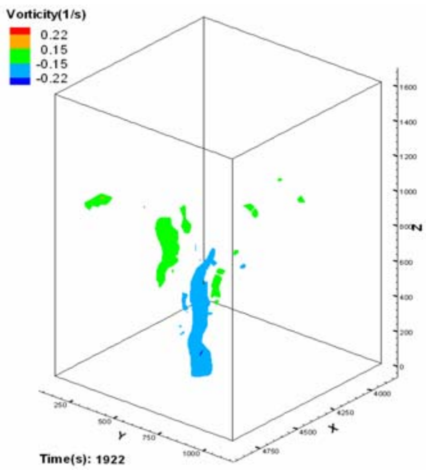


Figure 2a Volume vorticity contour plot.

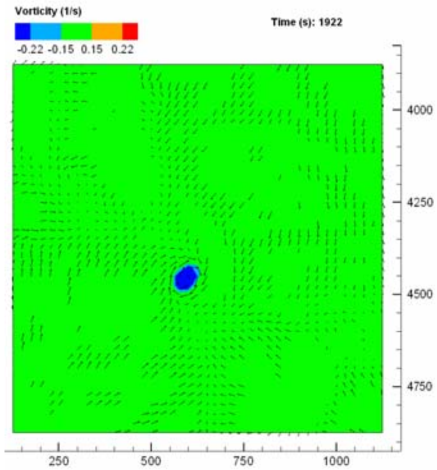


Figure 2b Vorticity contour plot and velocity vector field, z=20m

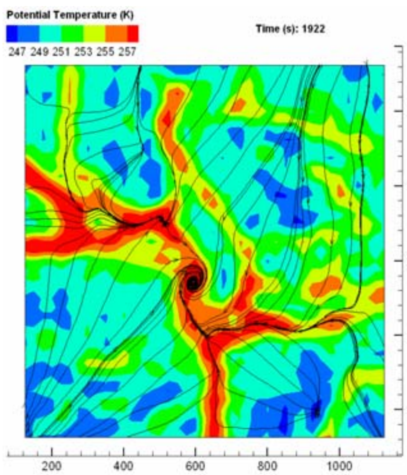


Figure 2c Potential temperature contour plot and streamlines at z=20m.

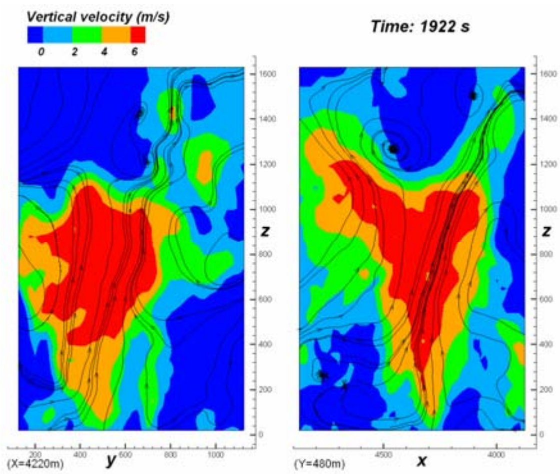
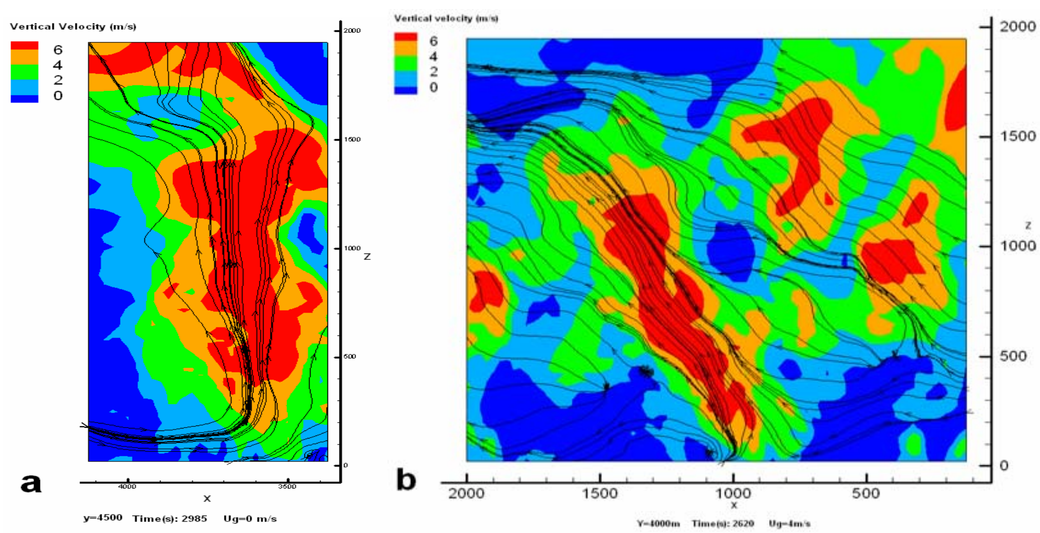


Figure 2d Vertical velocity couture plot and stream lines at the cross sections of the vertical vortex.



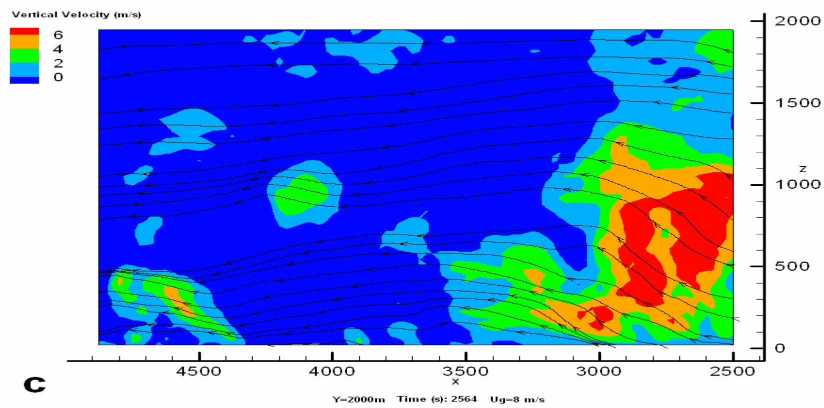


Figure 3 Vertical velocity contour plot at the vertical cross section of the dust devils in situations with a) no, b) 4m/s, and c) 8m/s geostrophic wind, around 2500s simulated time.

Characteristic at 20m above surface					*Unit*
Geostrophic wind	**0**	**1**	**4**	**8**	**ms-1**
Simulated Time (~2700s)	**2770**	**2755**	**2700**	**2650**	**s**
Height (~)	**2000<**	**700**	**450**	**<120**	**m**
Rotation Sense	**0.47cw**	**0.482cw**	**0.55ccw**	**0.7ccw**	**s-1**
Horizontal Velocity (max/min)	**6.5/-5.6**	**5/-4.8**	**7.6/-7.2**	**15/-14.2**	**ms-1**
Vertical Velocity (max)	**2.1**	**2.8**	**3.1**	**5.3**	**ms-1**
Diameter (~)	**175**	**150**	**100**	**80**	**m**
Temperature Increment (~)	**8**	**8**	**6.5**	**5**	**K**
Movement speed	**0.4 xy**	**0.5 xy**	**2.5-x**	**6.4-x**	**m/s**
Orientation (angle)	**88**	**82**	**73**	**68**	**Deg**

Table 3 Simulation results of the selected dust devil like vortices in different geostrophic winds

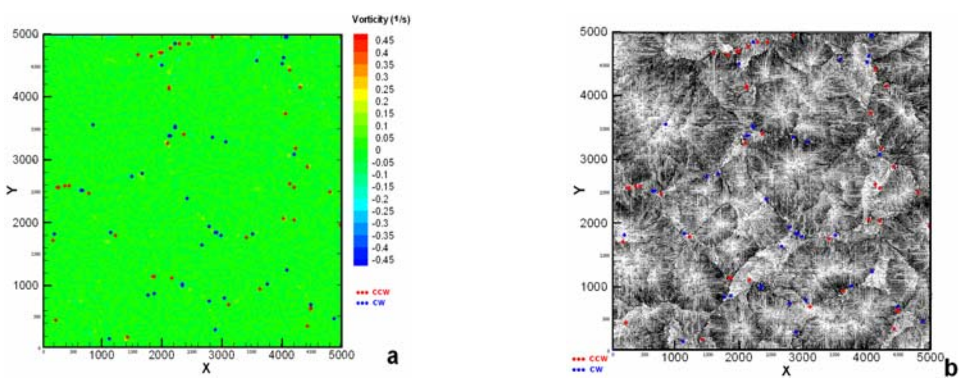


Figure 4 a) Vorticity contour plot and the locations of vortices, b) Velocity vector field and the locations of vortices, at z=20m and t=2351s.

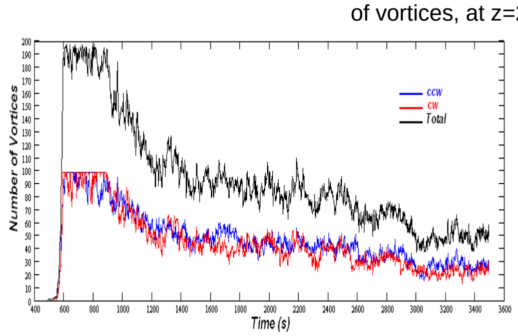


Figure 5 Evolution of the vorticies quantity by time in the 5x5 km^2 domain size.

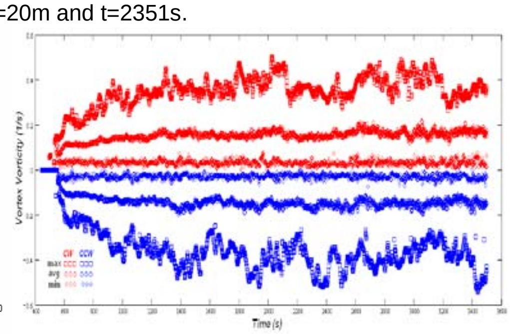


Figure 6 Changes of maximum vorticity by time for the most intense vortex (box), the weakest vortex (diamond), and average of the whirlpools' vorticity (circle) at each time step in the 5x5 km^2 domain size.