NUMERICAL MODELING OF MARTIAN DUST DEVILS.

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Introduction

We present large eddy simulations of vertical convective vortices and dust devils in the Martian convective boundary layer, employing a version of the Mars MM5 mesoscale model, adapted to use periodic boundary conditions and run at resolutions of 10 to 100 m. The effect of background wind speed and shear on dust devil development are studied in four simulations, each extending over the daytime portion of one Martian day. The general vorticity development in all cases is similar, with roughly equal positive and negative vorticity extrema. Two dust devils were found to develop in the highest wind speed case and in a case run without background wind. The dust devil structures were found to agree well qualitatively with terrestrial dust devil observations, including the prediction of greatly diminished upward velocities in the vortex core. Thermodynamic scaling theory of dust devils was found to provide good prediction of the relationship between central pressure and temperature in the modeled vortices. Examination of the turbulent kinetic energy budgets suggests balance between buoyancy generation and loss through dissipation and transport. The vorticity for the dust devils is provided by twisting of horizontal vorticity into the vertical. The horizontal vorticity originates from horizontal variations in temperature at the lower boundary (thermal buoyancy).

Background

Convective boundary layers generate a variety of dynamical structures. Dust devils provide a dramatic example of these structures due to the entrainment of dust within the walls of convective vortices. The lifting of dust does not actually appear to be of major dynamical importance for the development of these vertical vortices [*Sinclair*, 1969, 1973]. Instead, only a fraction of convective vortices develop into visible "dust devils", and even then, only a fraction of the vortex is populated with dust and becomes visible.

Dust devils and convective vortices are commonly observed in desert areas on the Earth, and have also been observed in the Martian atmosphere from orbiting and landed spacecraft [*Ryan and Lucich*, 1983; *Thomas and Gierasch*, 1985; *Schofield et al.*, 1997; *Metzger et al.*, 1999; *Malin and Edgett*, 2001; *Cantor et al.*, 2002; *Fisher et al.*, 2002]. They are of significant interest in studies of the Martian atmosphere for two main reasons. First, vertical vortices form as a part of the convective boundary layer, which is a poorly understood component of the Martian atmosphere. Their observed development provides an observational test for resolved models of the planetary boundary layer (PBL). Second, the injection of dust into the Martian atmosphere remains a major problem for studies of the Martian atmosphere and climate. Dust devils provide an observable form of dust lifting, and as such, study of their dynamics is of broader significance for study of global feedbacks between climate, circulation, and the dust on Mars.

Suspended atmospheric dust is a major driver of the Martian circulation and climate [*Zurek et al.*, 1992]. While it is tempting to ascribe the seasonal cycle of dustiness to fallout from large (regional and global scale) dust storms, the observed year-to-year repeatability of Martian atmospheric temperatures and dust opacities in northern spring and summer *Liu et al.* [2002] suggests that it cannot be explained by large storms alone. Instead, a steady source of atmospheric dust is needed that generates a seasonal supply pattern that is essentially repeatable. Dust devils have been widely suggested to operate in this role [*Greeley et al.*, 1992].

Model Description

This study uses an adapted version of the Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) Community Mesoscale Model (MM5). MM5 is a non-hydrostatic model that includes treatment of the full, three-dimensional Coriolis torque [*Dudhia*, 1993]. It has been adapted to Mars to study lander meteorology data records [*Toigo and Richardson*, 2002] and dust lifting by polar cap edge wind systems [*Toigo et al.*, 2002b]. The Martian model (the Mars MM5) includes treatment of heating due to the solar and thermal infrared radiative interactions with atmospheric dust and CO_2, injection and transport of dust and water vapor, and surface energy balance and subsurface heat diffusion [*Toigo and Richardson*, 2002]. All physical constants have been adjusted to appropriate Martian conditions.

Two adaptations of the Mars MM5 were necessary for this study. First, in order to most efficiently resolve the Martian PBL, we have implemented periodic boundary conditions (i.e. the model domain is coupled to itself across the domain walls). This modification removes the need to specify boundary conditions that cannot be directly generated from the much lower resolution GFDL

Mars General Circulation Model (GCM) output (as used in earlier Mars MM5 studies) [*Toigo and Richardson*, 2002], and would require excessive downward nesting within the Mars MM5. The second adaptation involved the sub-grid scale treatment of turbulent eddies. We use a modified version of the Medium Range Forecast model PBL scheme (MRFPBL) [*Hong and Pan*, 1996]. Since the goal of this study is to explicitly model eddies down to the limiting scale of resolution, we have sought to minimize sub-grid scale heat and momentum mixing in the convective PBL. Thus, the MRFPBL scheme was modified to produce minimum diffusion by forcing it to remain permanently in the stable mode. The treatment of heat and momentum exchange in the lowest model layer, which includes the surface layer, was unmodified. Above the lowest level, the diffusivities generated by the modified MRFPBL scheme are small and transports are dominated by the explicitly resolved flow.

Results

Four large eddy simulations (LESs), at 100 m horizontal resolution, were undertaken with differing initial wind fields. Dust devils have been found to develop in two of these cases: with no initial wind, and with maximum initial wind and shear. Based on this admittedly limited statistical sampling, we propose that dust devil development is not strongly sensitive to background wind speed or shear. The development of a dust devil in the no wind case also suggests that vorticity need not be present in the mean wind field. This result likely reflects the ability of the planetary boundary to rapidly develop horizontal vorticity as a result of free convection, followed by the generation of vertical vorticity by turbulent twisting of the vorticity field. The proximate development of dust devils, however, does appear to result primarily from the convergence of environmental vertical vorticity into the plume. The role of vorticity tilting seems to be in providing the environment with the necessary population of vertical vorticity extrema, rather than in the direct generation of the dust devil vortices. Consideration of the turbulence kinetic energy equation terms suggests that turbulence and convection in the planetary boundary layer is driven predominantly by buoyancy, and that the dust devils developed in the simulations can be considered rotating, free-convective plumes.

The two dust devils that develop in the LES simulations are clearly distinct from other rotating and non-rotating plumes. The time trend of maximum and minimum domain vorticity shows vorticity peaks associated with the dust devils that are a factor of 2 to 3 greater than observed in the absence of dust devils. When map projected, the vorticity field shows the development of sharp, nearly circular structures. Winds in the vortex walls and the central pressure drop confirm that the vortices are in cyclostrophic balance. The tangential velocity distribution is close to that of a Rankine vortex, which has been shown to explain the velocity distribution in terrestrial dust devils and laboratory fluid vortices. Vertical cross sections through the vortices show a structure with strong upward motion in the vortex walls with much decreased vertical motion in the core. Within the lowest few tens of meters, the central motion is actually downwards, providing a first numerical simulation of this aspect of field observations by *Sinclair* [1973]. These detailed aspects of the modeled dust devil structure are very clearly illustrated in a nested 10 m-resolution domain, centered on the “no wind” case dust devil. While the high-resolution simulation allowed more detail to emerge in the vortex, it did not yield major differences in vortex radius, central pressure drop, or peak tangential winds. This is in accordance with a cyclostrophically-balanced vortex and with the thermodynamic scaling relationships for dust devils developed by *Renno et al.* [1998].

Although we use the term “dust devil” in this paper, the convective vortices likely would not have lifted dust. We feel confident in using the term as the structures developed in this paper agree very well with theory (quantitatively) and observations (qualitatively) of dust devils, and they are clearly distinct from other structures developed in the model PBL (they are not simply the largest of a continuum of similar structures). Comparison of the central pressure drop with those observed for Martian dust devils by the Mars Pathfinder (tabulated by *Renno et al.* [2000]), suggests the simulated dust devils are of a similar size to the smallest of the observed structures.

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