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A numerical study of the effects of orography on supercells

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ABSTRACT

The effects of idealized two- and three-dimensional terrain on a cyclonically rotating supercell thunderstorm are studied with a numerical model. The airflow over the terrain produces horizontal heterogeneity in the characteristics of the soundings and hodographs, which, in horizontally homogeneous environments, are the primarily factors that influence storm structure and evolution. Indeed, many of the differences between control simulations that feature storms over flat terrain and simulations in which terrain variations are introduced (e.g., a hill, escarpment, and valley) can be ascribed to differences in the storm environments, especially the thermodynamic conditions (variations in convective inhibition and relative humidity have the biggest effect on the simulated storms), caused by the airflow over and/or around the terrain. Regions of downsloping winds tend to be regions of enhanced convective inhibition and reduced relative humidity. Accordingly, there is a tendency for the simulated supercells to weaken (in terms of the intensities of their updrafts and mesocyclones) in the lee of terrain features where downsloping is present. Though most aspects of convective storm dynamics are independent of the ground-relative winds and only depend on the storm-relative winds, the ground-relative wind profile is of leading-order importance in determining the impact of the underlying terrain on the storms that cross it; the ground-relative wind profile dictates where winds will blow upslope or downslope, which controls to a large extent the manner in which the environment is modified.

When three-dimensional terrain is introduced (e.g., an isolated hill, a gap incised into a ridge), the resulting horizontal heterogeneity in the thermodynamic and vertical wind shear fields is considerably more complex than in the case of two-dimensional terrain (e.g., an infinitely long hill, valley, or escarpment). The effect of three-dimensional terrain on the storm environment can be further complicated by the generation of mesoscale vertical vorticity anomalies. In some cases, the interaction of supercells with preexisting lee vorticity anomalies can briefly enhance low-level rotation within the storm; however, the dominant role of three-dimensional terrain generally is its modification of soundings and hodographs, as is the case for two-dimensional terrain.

1. Introduction

Despite decades of observing and simulating deep moist convection, our understanding of how the underlying orography influences convective storms remains extremely limited. Little is known about the sensitivity of convective storms to the lower boundary condition, in general. Historically, most numerical simulations have used a flat, free-slip, non-conducting lower boundary. In this article we report on our recent investigation of the effects of idealized orography on supercell storms. Additional ongoing research is examining the sensitivities of convective storms to other aspects of

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the lower boundary, for example, the influence of cloud shading and associated modifications of the surface energy budget (Markowski and Harrington, 2005; Frame et al., 2008, 2009; Frame and Markowski, 2010), and the possible effects of environmental heterogeneity associated with a convective boundary layer driven by a surface heat flux (Knopfmeier et al., 2008; Nowotarski et al., 2010).

Although many investigators, at least anecdotally, express little doubt that terrain can have an appreciable effect on convective storms, there are few formal papers on the influence of terrain on convective storms. The primary difficulty with observational studies (e.g., Hannesen et al., 1998, 2000; LaPenta et al., 2005; Bosart et al., 2006) is that it is never possible to know how the storms would have evolved in the absence of terrain. Thus, observational work tends to remain fairly speculative about the impact of terrain on the observed structure and evolution of convection. A numerical modeling approach ought to be better suited for this line of work, for models allow the user to compare a simulation with terrain against a simulation without terrain (e.g., Frame and Markowski, 2006; Ćurić et al., 2007).

Frame and Markowski (2006) and Reeves and Lin (2007) previously have studied the effects of mountain ridges on mesoscale convective systems (MCSs). It was found that the forward speed and depth of the outflow are affected by its passage over a terrain barrier, with the outflow slowing and thinning as the mountain crest is approached, and then accelerating and deepening rapidly in the lee of the barrier, often forming a hydraulic jump. Because the evolution of an MCS is critically tied to the behavior of the cold pool—the MCS is maintained by the continuous triggering of new cells by the cold pool—terrain-induced modifications of cold pool evolution and structure unavoidably affect the evolution and structure of the MCS. Frame and Markowski (2006) found that many MCSs weaken as they approach a mountain crest and then reintensify in the lee of the mountain where a hydraulic jump develops in the outflow (i.e., where the outflow depth rapidly deepens).

Ćurić et al. (2007) simulated an isolated cumulonimbus cloud in an environment containing relatively strong vertical wind shear, with and without underlying terrain. The underlying terrain was that of the mountainous part of the Western Morava basin of Serbia. A number of differences were found between simulations with and without terrain, for example, storm-splitting occurred later and the counter-rotating vortices were weaker in the simulation with terrain. No dynamical explanation was offered for how the terrain led to the differences in storm evolution and structure.

The present study on the influence of terrain on supercells uses idealized terrain rather than actual terrain. It is much easier for us to develop a dynamical understanding of the cause-and-effect relationship of the storm–terrain interactions if the terrain configuration is kept simple. In the next section, we elaborate on our methodology, and in Sections 3–5, we present the results. Control simulations (i.e., those with flat terrain) are described briefly (Section 3), followed by the results of simulations with two-dimensional terrain features (an isolated ridge, an escarpment, and a valley, all oriented in the north–south direction; Section 4) and three-dimensional terrain features (an isolated hill and channeled flow through a gap in a north–south-oriented ridge; Section 5). A summary and closing remarks appear in Section 6.

2. Methodology

The simulations were performed using the Bryan Cloud Model 1 (CM1 version 1, release 13) described by Bryan and Fritsch (2002) and Bryan (2002). The terrain-following coordinate of Gal-Chen and Somerville (1975) is used, and the governing equations are integrated using the Runge–Kutta technique described by Wicker and Skamarock (2002). The advection terms are discretized using fifth-order spatial discretization; no artificial diffusion is applied. The subgrid turbulence parameterization is similar to the parameterization of Deardorff (1980). The microphysics parameterization includes ice and is the NASA-Goddard version of the Lin–Farley–Orville (Lin et al., 1983) scheme.

The horizontal grid spacing is 500 m; the vertical grid spacing varies from 100 m in the lowest 1 km, to 500 m at the top of the domain. The domain is 100 km $\times$ 250 km $\times$ 18 km in the x, y, and z directions, respectively. The grid is stationary, that is, the grid does not move with the storms (we were uncertain what unintended effects might arise with the introduction of terrain undulations if grid translation was employed). The large (small) time step is 3 (0.3) s. Simulations were carried out for 4 h.

The lower and upper boundaries are free-slip (the results reported herein were qualitatively unaffected when surface drag was imposed at the lower boundary). A Rayleigh damping layer (Durran and Klemp, 1983) occupies the uppermost 4 km of the model domain in order to damp gravity waves that propagate upward from the terrain and convection. An open-radiative boundary condition is applied along the lateral boundaries, where the speed of gravity wave propagation is estimated by vertically averaging outward-directed gravity wave phase speeds along the lateral boundaries, with the inward-directed phase speed set to zero before averaging (Durran and Klemp, 1983).

There are no surface heat fluxes; although it is well-known that circulations generated by the heating of sloping or elevated terrain are often important in the initiation of convective storms, the focus of this study is on the interaction of mature storms with terrain rather than the role of terrain in convection initiation. No atmospheric radiative heating is considered either, and there is no Coriolis force. The absence of surface heat fluxes, radiative forcing, and the Coriolis force allows the model environment to remain steady during the simulations, at least far from the influence of the terrain (the model fields unavoidably evolve in the vicinity of the terrain in the early stages of the simulations owing to the airflow over the terrain).

The environments of the simulated storms are initialized with a sounding very similar to that used by Weisman and Klemp (1982) (Fig. 1a). The analytic function used to define the vertical profile of relative humidity has the same form as that used by Weisman & Klemp, but it has an exponent of 0.75 rather than 1.25. This results in our sounding being drier than the Weisman & Klemp sounding in the layer that is immediately above the constant-mixing ratio layer in contact with the surface. In our initial experiments using the original Weisman & Klemp sounding, the orographic ascent over even a small hill commonly resulted in the formation of a moist absolutely unstable layer (Bryan and Fritsch, 2000); we did not want the interpretation of our results to be complicated