Numerical simulations of supercells over idealized orography

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I. INTRODUCTION

Despite decades of observing and simulating deep moist convection, we know little about how the underlying orography influences convective storms. At the 5th ECSS we report on our recent investigation of the effects of idealized orography on supercell storms.

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. 2000; LaPenta et al. 2005; Bosart et al. 2006; these and other references are available upon request) 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 et al. 2006; Ćurić et al. 2007).

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. Below we briefly summarize the simulations with a two-dimensional hill parallel to the y axis. At the ECSS we will present the results of additional simulations with two-dimensional terrain [e.g., we also investigated the effects of a storm passing over an idealized valley, similar to the case observed by Bosart et al. (2006)], as well as simulations with three-dimensional terrain (e.g., an isolated hill, channeled flow through a mountain gap). In the case of three-dimensional terrain, there is also the possibility of the storms interacting with preexisting terrain-induced vortices (Smolarkiewicz and Rotunno 1989; Epifanio and Durran 2002).

II. METHODOLOGY

The simulations were performed using the Bryan Cloud Model 1 (Bryan and Fritsch 2002) with a terrain-following vertical coordinate. 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 lower and upper boundaries are free-slip (sensitivity tests were performed with surface drag at the lower boundary); a Rayleigh sponge occupies the uppermost 4 km of the model domain.

The model was initialized with a sounding similar to that used by Weisman and Klemp (1982). The environmental wind profile is defined by the quarter-circle hodograph used by Rotunno and Klemp (1982). The hodograph was shifted in three different ways in order to vary the terrain-relative winds. One wind profile has 4 m s^{-1} surface easterlies (in the far field, away from the hill), one has calm surface winds, and the other has 4 m s^{-1} surface westerlies. The problem we are studying is not Galilean invariant, which adds extra dimensions to the parameter space (this is generally the case when one wishes to include the effects of the lower boundary, whether surface fluxes and/or sloping terrain are included).

Storms are initiated with a warm bubble, and an eastward-moving supercell results in every case. The ground-relative motion of the supercell, as well as the upslope and downslope side of the terrain, varies depending on the location of the hodograph trace relative to the origin of the hodograph. A north-south oriented hill having a height of 500 m and zonal half-width of 10 km was centered at different longitudes (ranging from $x = 85$–145 km), depending on the storm motion, so that the storm would cross the ridge at approximately the same time in each of the simulations. Herein we present the results for the experiments in which the supercells crossed the hills at approximately $t = 2$ h. Other hill locations/hill passage times were tested—we report only the results that are robust and do not depend on the exact timing of the hill-crossing.

III. RESULTS

In general, the simulated supercells weaken (in terms of both low-level and midlevel updraft strength and vertical vorticity) on the lee slopes of the hills (Figs. 1 and 2), where the lee and windward slopes are defined relative to the direction of the surface wind, not the storm motion [e.g., in the case of the hodograph trace that is shifted to the left of the origin, there is easterly low-level flow; thus, the eastern (western) slope of the hill is the windward (lee) slope]. The results turn out to be fairly intuitive in that the supercells simply appear to be responding to changes in environmental convective inhibition (CIN) and relative humidity that are induced by the airflow over the terrain. For example, in the lee of a hill, isentropic surfaces are depressed (a hydraulic jump may be observed if the flow is very strong, depending on the ambient stratification) and relative humidity is anomalously low. Both effects contribute to anomalously large CIN on the lee slope. In some of the cases, some modest intensification of the storms occurs on the windward slope (e.g., Fig. 1; notice the lifting of the isentropes on the windward slope—the lifting was associ-

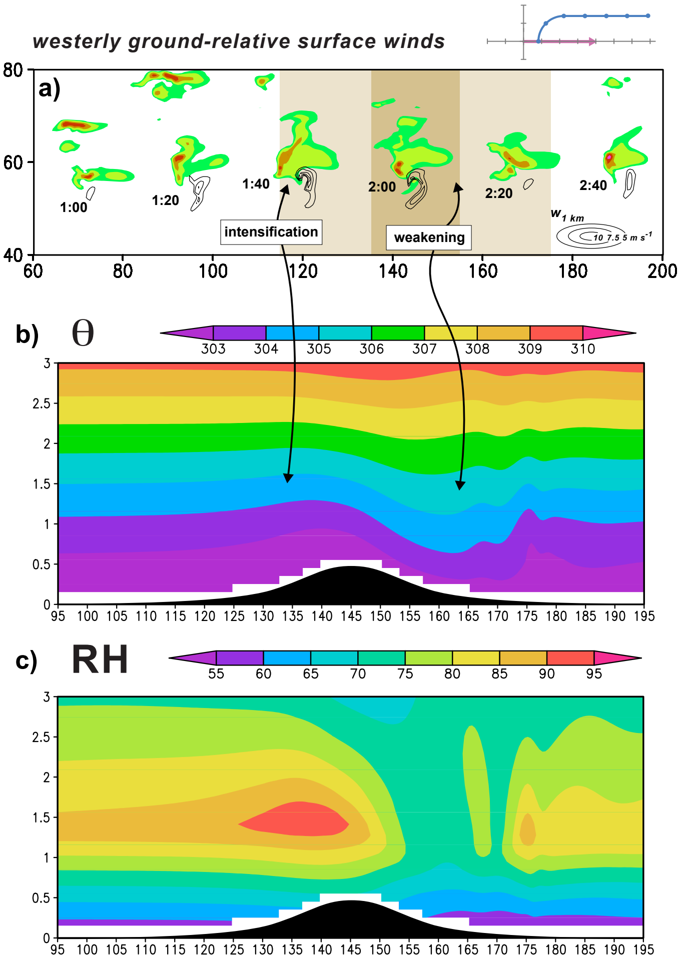

FIG. 1: Model output from a simulation with westerly low-level, ground-relative winds and a hill centered at $x = 145$ km (the hodograph is shown schematically at the top). (a) Rainwater fields at 1 km at 20-min intervals (color shading), with vertical velocity at 1 km overlaid (contours). The light (dark) brown shading indicates the region where the terrain elevation is ≥90% (≥50%) of the height of the hilltop. (b) Vertical cross-section of steady-state potential temperature in a simulation with the same terrain configuration but without a storm. (c) As in (b), but relative humidity (%) is displayed.

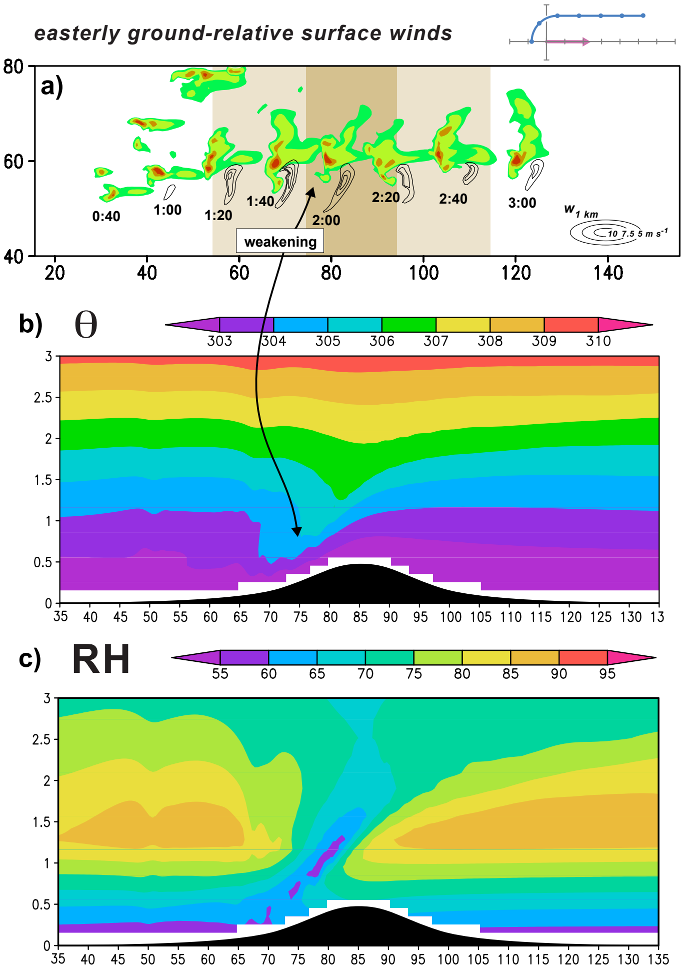

FIG. 2: As in Fig. 1, but for a simulation with easterly low-level, ground-relative winds and a hill centered at $x = 85$ km.

ated with humidification and CIN reduction). In the case of calm ground-relative winds at the surface (not shown here)—the case in which the hill perturbs the isentropic surfaces the least—the hill has the smallest effect on the supercell.

IV. CONCLUSIONS

Regardless of the set-up of the numerical simulation, *changes in storm evolution relative to the control can be attributed to changes in the environment that are associated with airflow over hill*, with the environment on the lee slope being more hostile to the storms than the far-field environment and windward-slope environment in terms of CIN and relative humidity. Predicting the details of how a hill influences the airflow over it is itself a very difficult problem outside of a limited number of idealized situations, as many have devoted a significant fraction of their careers to studying this problem alone (e.g., Smith 1979, 1989; Durran 2003). (Most studies looking at terrain-induced waves only consider relatively simple upstream wind and temperature profiles; supercell hodographs not only have shear but may have large variations of shear direction and magnitude with height, and soundings often have large vertical variations in static stability.) But if one knows how a hill affects the isentropic surfaces, then it seems fairly straightforward to determine the effects on environmental CIN and relative humidity, and ultimately the effects of the hill on the overlying storm.

V. ACKNOWLEDGMENTS

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