3.2

CONVECTIVE INITIATION AHEAD OF SQUALL LINES INVOLVING SMALL HILLS

Seung-Hee Kim, and R. G. Fovell*
University of California, Los Angeles, California

1. Introduction

On 21 June 2003, Squall line was propagating toward Oklahoma from the west to the east and new convective cells were developed in upstream region of the convective system. Interestingly, Doppler radar imagery in Oklahoma revealed the new cells were aligned with acute angle to the oncoming storm. Comparing the radar imagery and terrain map indicated a strong correlation between new convective cells forming in advance of a squall line and small-scale terrain features such as river valleys lined by small hills (Fig. 1).

A number of previous observational and modeling studies have shown that terrain can play an important role in triggering convection and distribution of precipitation. These studies have mostly focused on large-scale terrain features or were concerned with radiative heating during daytime. However very little number of studies has been done on interaction between convective initiation and small-scale terrain. This case was associated with small-scale orographic features (Note that maximum height of the ridge lines are about 500m in Fig. 1) and occurred at night, so the processes involved are probably rather subtle.

In this study, effects of the small-scale terrain on convective initiation under the upstream environment of Mesoscale convective systems (MCSs) were examined. To explore this, idealized numerical simulations were used with simple orographic features.

2. Model setup

For numerical simulations, we employed Advanced Regional Prediction System (ARPS), version 5.2.8, cloud-resolving model to test our hypothesis. In three-dimensional (3D) simulation, domain size was 800km by 150km and 21km in vertical direction with 1km by 1.5km horizontal grid spacing. Stretching grid space using cubic function was employed in vertical direction. We adapted open radiation boundary condition cross-line direction but periodic boundary condition was used along-line (north to south) direction. Therefore we did not have line-end effects on squall line simulation and could have relatively smaller domain size on y-direction. We also employed two-dimensional (2D) simulations with same size as 3D simulation.

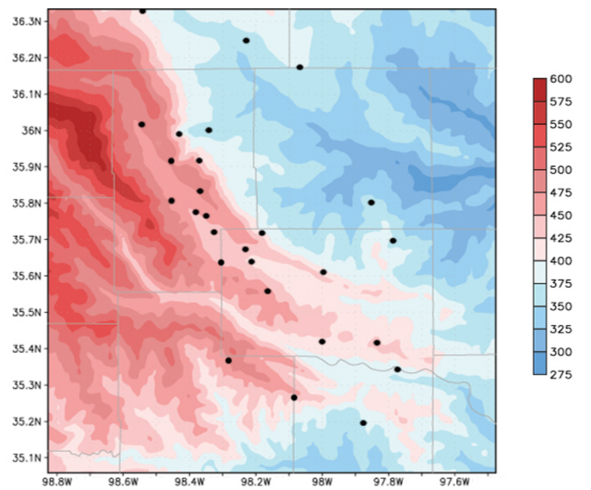

Figure 1. Shaded region indicates terrain height with 25m interval in Oklahoma and black dots shows location of new convective cells based on radar imagery on 21 June 2003.

For the initial environmental conditions, horizontally uniform with 300K surface temperature and 13.5 gkg^{-1} surface mixing ratio was used. Model employed analytic thermodynamic sounding and wind profile by Weismann and Klemp, 1982. The convection was initiated by line thermal (4K warmer than environment) and 5% of random perturbation was superposed. Unidirectional vertical wind profile, which is perpendicular to the squall line, was used for maintaining squall line propagation. Initial wind speed increases from zero at surface to 7.5ms^{-1} at 2500m above ground level. We also use vertical wind profile with non-zero wind speed at the surface with same amount of vertical wind shear (0.003 s^{-1}). With this

* *Corresponding author address:* Prof. Robert Fovell, UCLA, Dept of Atmospheric and Oceanic Sciences, Los Angeles, CA 90095-1565; e-mail: rfovell@ucla.edu

modification system scale circulation will not be affected.

Before testing complex terrain in numerical simulations, first step was using simple terrain feature. Bell-shaped mountain or hill was employed for terrain features and these will present clear view of mechanism involved in convective initiation near complex terrain. In 3D simulation, we put double mountain ridges and it has angle to the oncoming squall line, similar with terrain features in western side of Oklahoma where the convective initiation occurred (Fig. 1). Maximum height of the ridge was 200m and the length of ridges was about 190km. The height of the ridges was decreasing as it is approaching to northern and southern boundary to avoid boundary problems. We also conducted numerical simulations with various mountain ridge configurations in 2D simulations to investigate interaction between orographic features and upstream region of squall line.

3. Results

3.1 Numerical simulation

At 0825 UTC, squall line was located near 460km in the domain and mid-level moist layer in upstream of the convective line was well developed both control run and simulation with mountain ridges (Fig. 2). The moist tongue was a result of ‘n=2’ mode on low frequency gravity wave produced by persistent heating and cooling in main convective region of squall line (Nicholls et al., 1991). Control simulation with flat terrain indicates that new convective cells did not develop in upstream of squall line even though moist layer was well developed (Fig. 2(a)). Mountain ridge simulation, however, shows a different result. As the convective system is approaching to the terrain features, new convective cells were developing in upstream region of the squall line (Fig. 2(b)). The new convective cells were located along the ridgelines, northwest to southeast direction and developing cells were located about 20km to 40km a head of leading edge of the squall line. Therefore the results suggest that mechanical uplifting near surface by cold pool can be excluded as a possible mechanism and small-scale terrain was involved in convective initiation event.

The 3D simulation results show new convection appeared only when the moist tongue reached orographic feature. To examine role of upstream environment of convective systems, we conducted set of 2-D simulations since property of cells and system scale circulation features are similar along the squall line. The upstream environment is continuously changing with time since it is under the influence of rapidly varying convective system. To investigate influence of environment in upstream region of squall line, first of all, we varied location of the hill (500m height) in the domain from 400km to 650km with 50km intervals. As a result of that, the squall line will have various time spans to reach the mountain ridge in each simulation. Thus, interaction between orographic features and various stage of squall line can be examined.

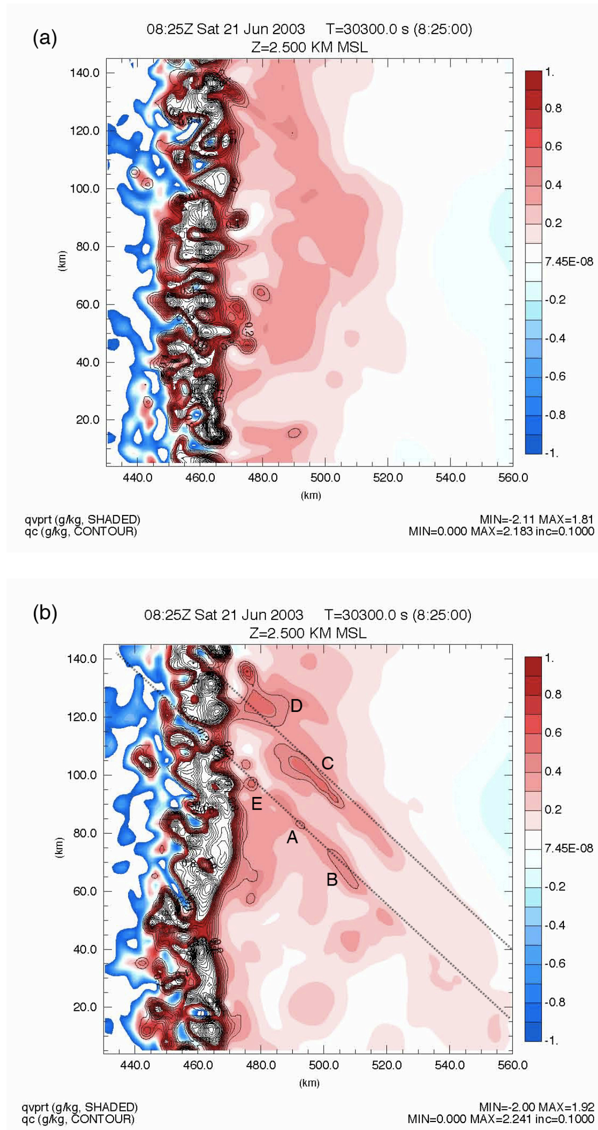

Figure 2. Horizontal cross section of squall line simulation at 2.5 km MSL on 0825UTC. (a) indicates control run without terrain and (b) shows with mountain ridges. Black contures indicate cloud fields and colored shaded region shows water vapor mixing ratio. Dotted lines present location of the mountain ridges and each character shows cloud will become a deep convective cell later.

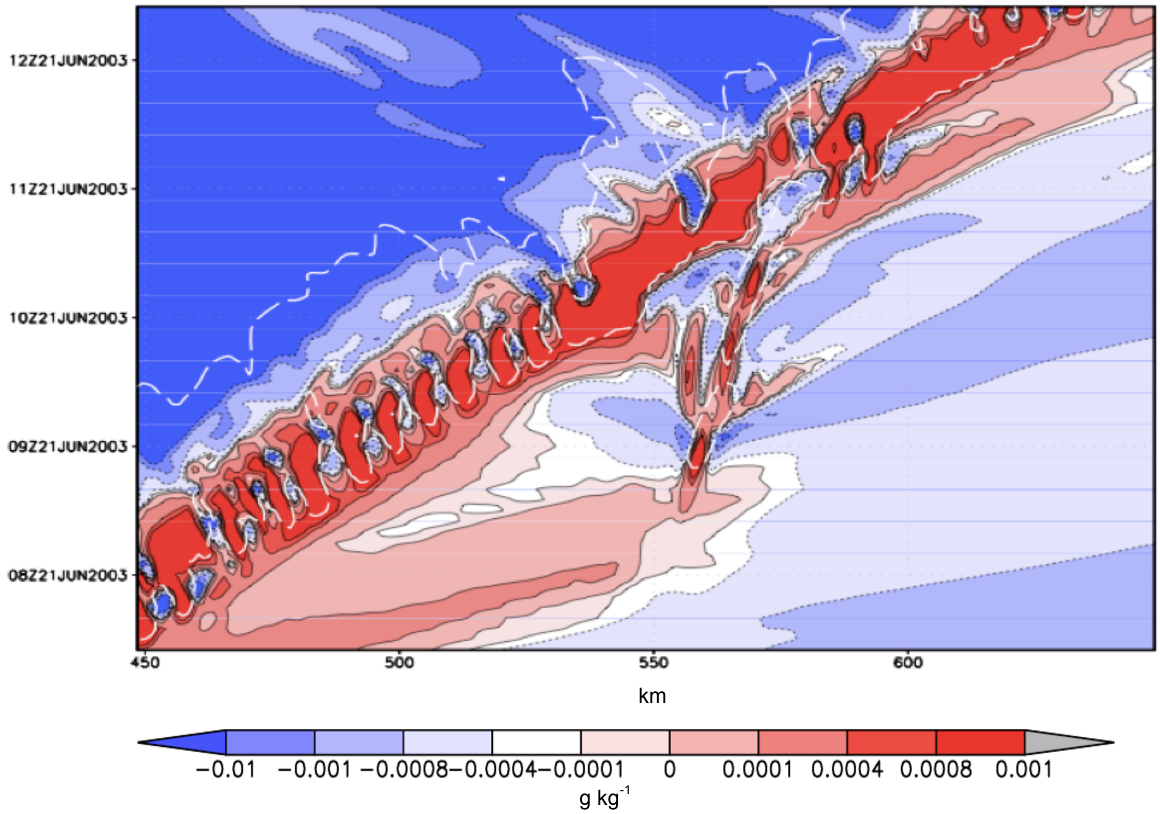

Figure 3. Hovmoller diagram of squall line simulation at 2800m AGL with mountain at 550km in the domain Color shaded region shows water vapor mixing ratio at 2.5km AGL and white dashed line presents outline of rain water. Note that new covection was developed around 0830UTC when moist tongue reached at 550km where the mountain was located.

2D simulation with mountain location at 550km indicates that new cells were initiated near the hill and the timing of the new cell developing was when positive moisture perturbation reached to the hill (Fig. 3). The model runs with different location of the hill also denote similar results as hill at 550km case. These results, thus, apparently show that new convection was associated with moist tongue and terrain features. Our previous study also confirmed the moist layer does key roles on initiating convection (Fovell et al. 2006)

The distance between squall line and new cells are proportional to distance between initial location of squall line and the hill. For examples, new cell developed about 55km ahead of main storm when hill located 550km in domain, but 70km ahead in case of hill located at 600km (not shown here). This is mainly due to the squall line developing with time from the initial warm bubble and becoming a mature stage later so that stronger moist region was provoked and developed to the further ahead from its origin. Also the moist tongue propagates faster than squall line so once strong moist tongue is developed, the distance from the main storm increases with time until downdraft from high frequency gravity waves disturbing moisture perturbation.

3.2 Critical level

To find how small-scale terrain features trigger convection under the favorable condition such as moist tongue in upstream region of squall line, 2D dry simulation was performed to investigate storm scale circulations with the initial “top-heavy” heating profile. The heating profile, resulting from convective latent heat release, excites low-frequency gravity waves that can more than temporarily but beneficially modify the lower tropospheric inflow environment, by cooling and moistening as well as inducing flow towards the storm (Figure 11 in Fovell 2002). In the dry run, convective region of squall line does not produce cold pool near the surface because of absence of evaporation cooling. To mimic squall line propagation, the warm bubble was shifted to the east with 17.5m/s, same speed as squall

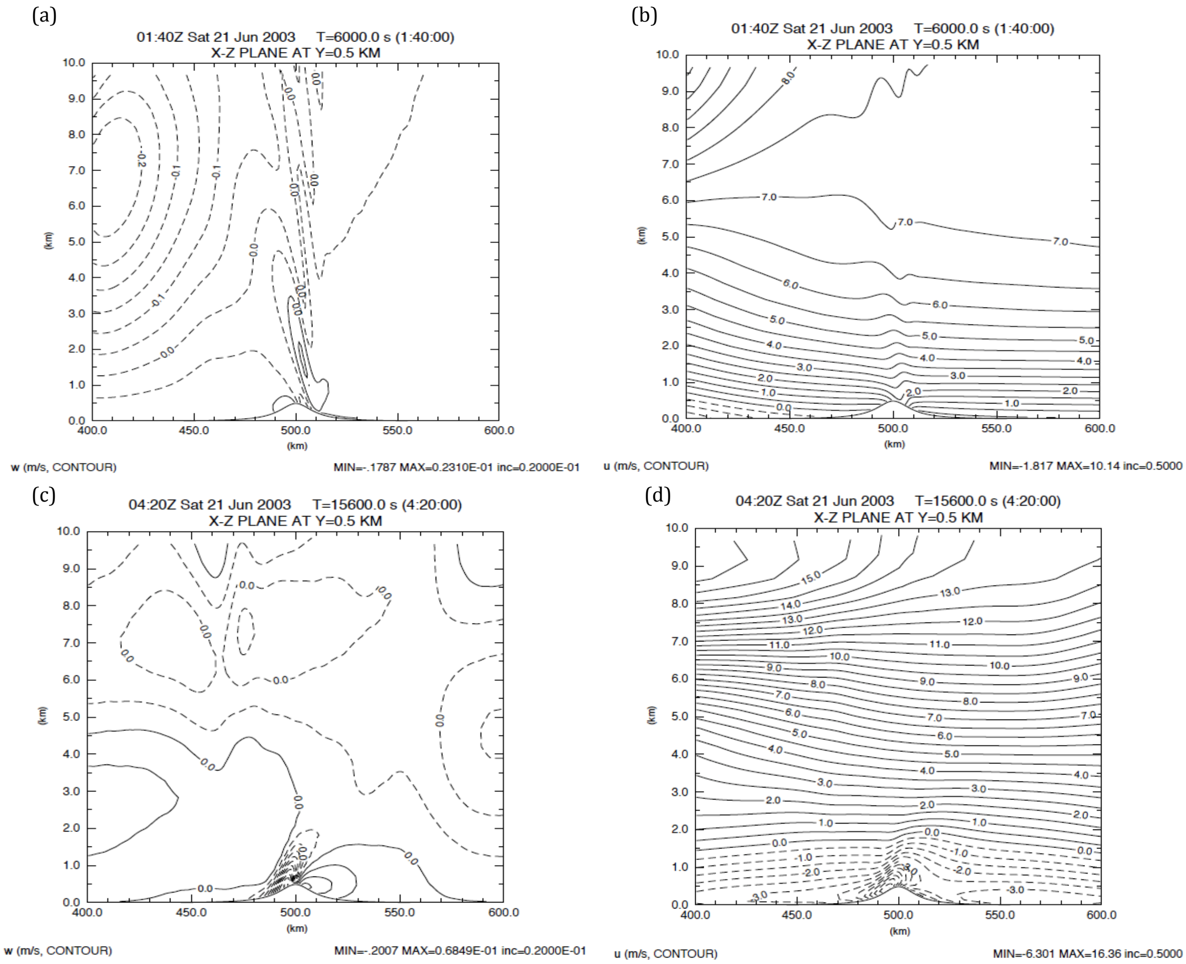

Figure 4. Vertical cross section of moving heat source simulation near mountain in the domain. (a) shows vertical wind speed but (b) is horizontal wind speed at 0140UTC. (c) is same as (a) but at 0420UTC. (d) is same as (b) but 0420UTC.

line. System scale circulation of the heat source run and squall line simulation was almost identical but trapped high frequency gravity wave was missing. The high frequency gravity waves generated by storm unsteadiness can propagate through the storm's inflow environment when trapped from above by the forward anvil. Eliminating both updraft and downdraft by the high frequency gravity wave is helpful to analyze interaction between system scale circulation and terrain.

Figure 4 shows horizontal and vertical wind near the mountain when heat source was approaching to the terrain feature from left-hand side of the domain. After 0140 UTC, compensating subsidence (n=1 mode) was approaching to the mountain and located on western side of mountain. Also there was vertically propagating mountain wave on top of the mountain (Fig. 4(a)). After 3 hour later, as n=2 mode reached near the mountain, strong outflow higher level and storm relative inflow at lower level was apparent. As the result of the low-level inflow increasing, wind reversal was created in 1500 m above ground level (Fig 4 (d)). At this point, no more vertically propagating wave exists and instead of that, there was relatively stronger downslope wind in western side of mountain. The terrain induced gravity waves transport energy and momentum to the upper atmosphere. However, when critical level exists, the vertically propagating energy is confined below the level and flow acceleration is produced on downslope

Small scale hill (500m height and 10km half-width) and weak surface wind speed (3 ms^{-1}) produce very small amount of downslope wind. (-0.2 ms^{-1}) (Fig. 4 (c)) Also maximum of the downslope wind was confined near the surface thus the wind itself did not provide enough forcing for the convective initiation. However gravity wave trapping under critical level generates moisture convergence near top of the hill about 1.5 km AGL. The location of convergence is well matched to the place of new cell development. In addition to the moisture convergence on top of the ridge line, the wind reversal influences to approaching cool and moist layer.

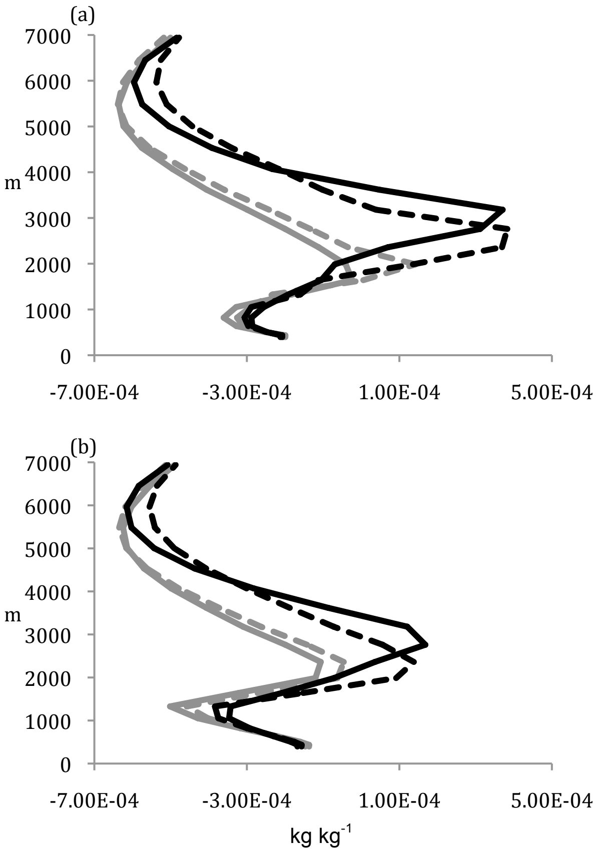

Figure 5. The plots show that vertical profile of water vapor mixing ratio perturbation at (a) storm side and (b) lee side from 0820 to 0920UTC with 20 minutes interval; Solid Gray line indicate profile at 0820 UTC, dashed gray line is 0840 UTC, black dashed line is at 0900 UTC and solid black line is 0920 UTC.

Figure 5 shows the moisture perturbation changes both side of the mountain with time. Around 0900 UTC just before convection developing, positive moisture perturbations in storm side of the mountain were larger than lee side. This implies moisture blocking occurs near top of the hill. As a result of that moist layer near top of the hill became stronger and deeper since approaching squall line continuously provided positive moisture perturbation.

Another set of numerical experiment was designed to investigate effects of the critical level. We put additional westerly wind entire level in initial wind profile to eliminate critical level. It has same amount of vertical wind shear thus this modification did not affect to squall line dynamics. Due to the stronger westerly wind, the easterly wind component near surface, produced by squall line circulation was disappeared or very shallow. As a result of that both wind reversal above the mountain and trapping mountain wave was disappeared. Although well-developed moist layer was placed in upstream of the squall line, new convective cloud did not develop near the mountain in simulation without critical level (Fig. 6). The results suggest that wind reversal above the mountain did important roles in generating deep moist convection.

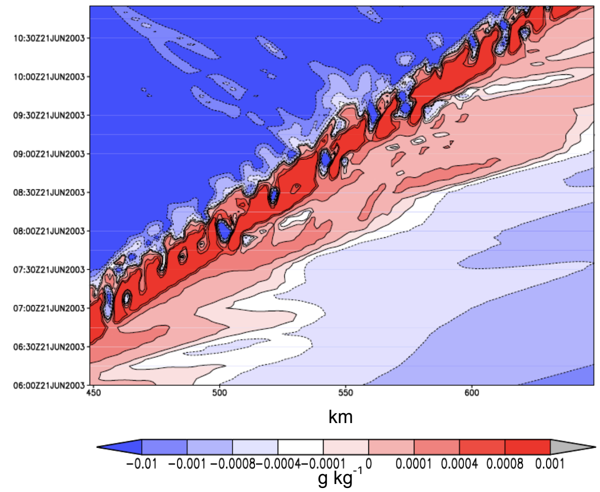

Figure 6. Same as Fig. 3 but modified initial vertical wind profile. Note that no convective initiation occurs near mountain at 550km.

3.3 Role of High Frequency gravity wave

The experiments with various mountain sizes show that large-scale mountain such as 1500m high and over 20km half width can trigger deep convection by providing mechanical uplifting without oncoming squall line. Some of the case in smaller size of the mountain simulation indicates that convective initiation was not always occurred near the orographic feature. For examples, results from 500m-height and 10km half-width of mountain at 500km did not show new convective cloud but simulation using same size of mountain at 600km in the domain indicated new convection in near mountain, even though both of the case has mature stage of squall line produce both moist tongue and strong inflow near the surface.

Comparing two simulations reveals that downdraft, which is produced by high frequency gravity, suppressed the developing convection in case of no convective initiation. ‘A’ in Figure 7 shows new cell started to develop at 500km where the mountain was located when moist tongue arrived (0700 UTC). The cell was drifted by ambient wind speed of 2m/s and it experienced strong downdraft of trapped high frequency gravity wave around 0740 UTC (‘B’ in Fig. 7). The subsidence seems to interrupt development of the convective cell. Around 0820 UTC the cell encountered updraft component of gravity wave and the upward motion provokes the cell to the deep convective cloud (‘C’ in Fig. 7). Before the cell was fully developed, however, it was merged onto convective region of the squall line.

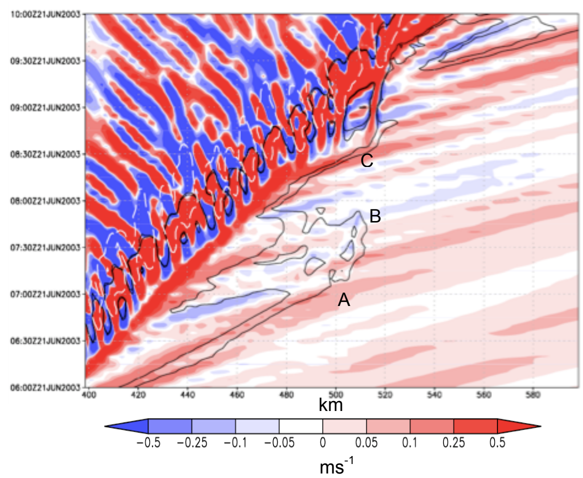

Figure 7. Same as Fig.3 but color shaded region indicate vertical wind and black contour shows positive water vapor mixing ratio. The mountain is located at 500km.

4. Summary

Our goal was to understand how mesoscale convective systems can alter its environment over complex terrain and also how the evolution of MCSs themselves can be influenced by even small-scale topographic features. This was accomplished using a variety of idealized numerical simulations involving two- and three-dimensional models and hills of various shapes and sizes, along with both explicitly simulated squall lines and specified heat sources.

Our analysis suggests that the new convection in this case results from a combination of gravity waves excited by the squall line and by flow over the small hills. When the initial environmental winds near the surface are weak, the induced inflow can produce a critical level. Below the critical level gravity wave energy is confined instead of upward propagating; this can result in downdrafts on the hill’s upwind side moisture convergence above the hill.

5. References

Fovell, R. G., G. L. Mullendore and S-H. Kim, 2006: Discrete Propagation in Numerically Simulated Nocturnal Squall Lines *Monthly Weather Review*, **134**, 3735–3752

Fovell, R. G**.**, 2002: Upstream Influence of Numerically Simulated Squall-line Storms. *Quart. J. Roy. Meteor. Soc.*, **128**, 893-912

Nicholls, M. E., R. A. Pielke, and W. R. Cotton, 1991b: Thermally Forced Gravity Wave in an Atmosphere at Rest. *J. Atmos. Sci*., **48**, 1869-1884

Weisman, M. L. and J. B. Klemp, 1982: The Dependence of Numerically Simulated Convective Storms on Vertical Wind Shear and Buoyancy. *Monthly Weather Review*, **110**, 504–520

Acknowledgements. This work was supported by NSF grant ATM-0554765.