Final Report

Bow Echo Development Associated with the Interaction of Convection with Complex Terrain: Blending Observations with Idealized Simulations

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1. Project Objectives and Accomplishments

The primary goal of this project was to improve our understanding of the changes that convective storms undergo as a result of interactions with complex terrain. Our work was motivated by observations from the National Weather Service (NWS) office in State College, Pennsylvania (CTP) of the development of bow echoes within convection traversing complex terrain. Local NWS studies documented several events in which convection interacting with the ridge-valley system of central Pennsylvania acquired bow echo characteristics. These bow echoes typically formed as thunderstorms moved off the higher terrain occupying western Pennsylvania and into the southwest-to-northeast oriented valleys that occupy central and eastern Pennsylvania. An example from 15 June 2000 appears in Figure 1.

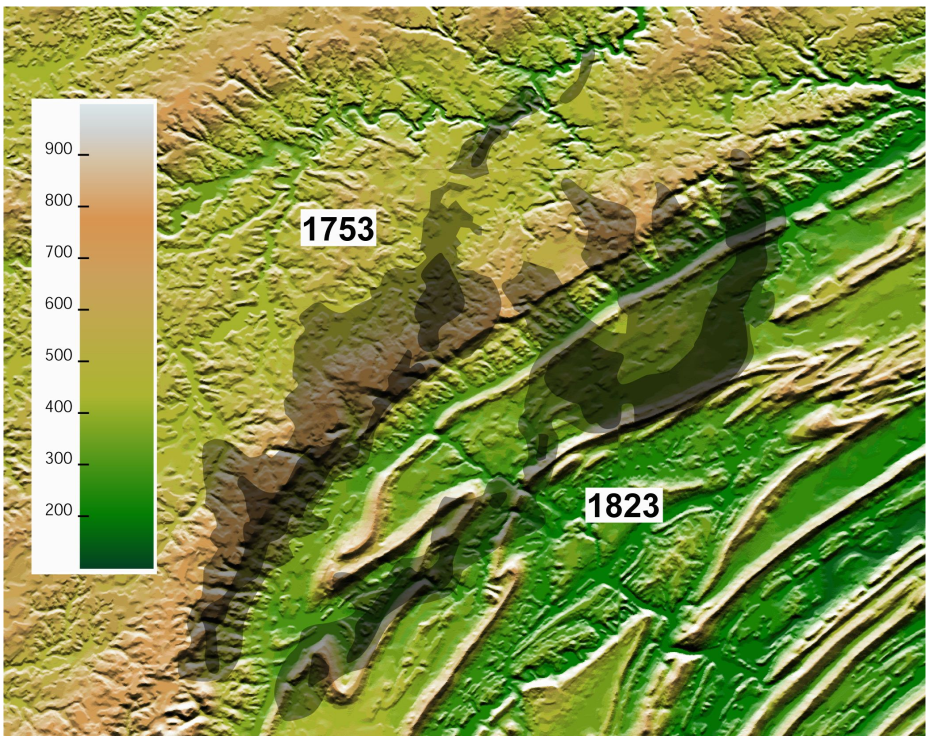

Figure 1: The development of a bow echo from quasi-linear convection on 15 June 2000. Radar echoes from the KCCX WSR-88D (0.5° elevation angle) are superimposed on terrain at 1753 and 1823 UTC. Regions of base reflectivity exceeding 35 dBZ are light gray, and regions exceeding 45 dBZ are dark gray. Units on the terrain height legend are in meters. At 1753 UTC, the convection is situated over relatively high terrain (> 600 m). As the convection moved eastward over significantly lower terrain (300–350 m), the echo acquired bow echo characteristics and was associated with damaging winds at the surface.

Prior to this study, aside from informal publications and anecdotal evidence, there had not yet been an attempt to systematically document changes in the finescale structure of convection as a function of changing elevation, nor had the research community considered modifications for sloping terrain in presently held theories regarding convective system maintenance, which were developed from idealized simulations conducted with horizontally homogeneous terrain. These deficiencies in our knowledge of terrain influences on convective storms were the motivation for our study, which used a blend of observations and numerical simulation experiments to produce new understanding of the association between convective storm characteristics and terrain features, as well as dynamical insight into the causes for the observed associations.

The following two-part strategy was designed for this project: (1) document changes in the WSR-88D presentation of convection (e.g., echo shape and intensity) associated with convection interactions with ridges and valleys.; (2) examine the terrain-induced dynamical changes within convective storms with a three-dimensional, cloud-resolving numerical model in order to understand how and why the morphology of convection is altered by terrain.

Following are the key activities that were undertaken in the during the two-year duration of the project:

a. Documentation of convection interactions with terrain

The National Weather Service assembled a severe weather database during the first year of the project. This database contains all of the severe weather reports associated with convection since 1950. A relational database also has been developed which allows forecasters to extract case studies and examples of specific weather events. The ultimate goal is to identify terrain-related events and have easy access to examples of these types of events.

The examination of WSR-88D data by the NWS has revealed that convective storm-terrain interactions may have been important in a number of recent tornadoes. On 19 January 1996, a weak tornado developed on the lee slope of a nearby mountain ridge. Damage surveys after several other tornadoes suggest that tornado damage has been enhanced on the lee slopes of ridges in some cases (e.g., 2 May 2002, 28 July 2002). The development of bowing convective line segments also has been noted, and seems to be favored when the line segments move northeastward down valleys oriented from southwest to northeast (e.g., the "Bald Eagle valley effect" observed on 16 and 19 August 2001 and 28 April 2002).

b. Numerical modeling

Jeff Frame (Penn State University), under the mentorship of Paul Markowski (Penn State University), has used numerical simulations of squall lines interacting with terrain to examine a large parameter space of terrain configurations, including mountain ridges, valleys, gently sloping terrain, gaps in mountain ridges, and multiple ridges. The three-dimensional simulations were conducted using the Advanced Regional Prediction System (ARPS) cloud-resolving model.

We have found that simulated squall lines weaken as they interact with terrain features, then reintensify downstream of these features. Although this study uses highly idealized terrain configurations and physical parameterizations, we believe the results presented herein will serve as a guide to both the operational community and to future researchers. What follows is a brief summary of results gleaned from our simulations. These results were the basis for Frame's M.S. thesis and are the subject of a pair of articles that have been submitted to *Monthly Weather Review*.

Squall lines weaken as they ascend a slope. In the case of a gradual slope, the gust front attains a significant upshear tilt as the cold pool is forced up the slope. A shallower cold pool nose results in less lift at the gust front, and, hence, a lessened chance that inflow air parcels will reach their level of free convection, reducing the amount and intensity of deep convective updrafts within the system. This is shown schematically in Fig. 2a. In the case of a steeper upslope, orographic gravity waves develop in the rear-to-front flow, and the rear inflow is forced to ascend, disrupting the flow of conditionally unstable low level air from the front of the system into the convective updrafts, as depicted in Fig. 2b. The system gradually reintensifies over the high terrain as the cold pool becomes deeper again.

Squall lines also weaken as they descend a slope, but this weakening is followed by a rapid reintensification at the bottom of the slope. The cold pool nose becomes shallower as it descends, and the propagation speed of the gust front increases slightly. This results in a transition from subcritical to supercritical flow in the cold pool nose, which reduces the lift at the front of the system, again weakening it, but less than in the upslope cases. At the bottom of the slope, the flow transitions back to subcritical, and a hydraulic jump forms near the leading edge of the cold pool. This creates deep lifting at the front of the system and rapid generation of a new convective line at the bottom of the hill. These new updrafts deprive the older ones of inflow and eventually replace them altogether as the new updrafts deepen downstream of the slope (Figs. 3 and 4). The downslope evolution is presented schematically in Fig. 2c.

A squall line weakens when it encounters a ridge of sufficient height and width because of a combination of the upslope and downslope dynamics discussed above. A wide ridge allows for more gradual intensity fluctuations than a steep ridge does. We find that the squall line updraft must remain over a ridge for O(10) minutes for the topography to have any appreciable effect on updraft intensity. This is only a rough estimate, however, and it likely depends on the environmental conditions. A squall line weakens more as it traverses a higher ridge because the terrain disrupts a greater portion of the quasi-two dimensional squall line circulation. We estimate that the topography must have a height of 600–700 m in order to noticeably weaken the squall line, although smaller amplitude terrain can have some subtle impacts. This estimate likely also depends on environmental conditions as they dictate important squall line characteristics, like the height of the rear inflow jet. Also, multiple ridges influence the squall line in a manner nearly identical to an isolated ridge.

The propensity for damaging winds increases immediately downstream from a ridge or downslope, on the tops of high ridges, and both within and several km downstream from gaps in a ridge. Gaps in ridges generate line-echo wave patterns within the convective line because of terrain-induced differences in the gust front propagation speed downstream of the gap (Fig. 5). If a ridge is at an angle to a squall line, the convective line reorients itself approximately parallel to the terrain following its passage over the terrain. Environmental and other factors may reorient the squall line yet again, once it is far enough removed from the ridge. Our simulations also show small scale rain shadows on the lee side of topographic features, which is expected because the updrafts within a squall line weaken as the convection interacts with the topography.

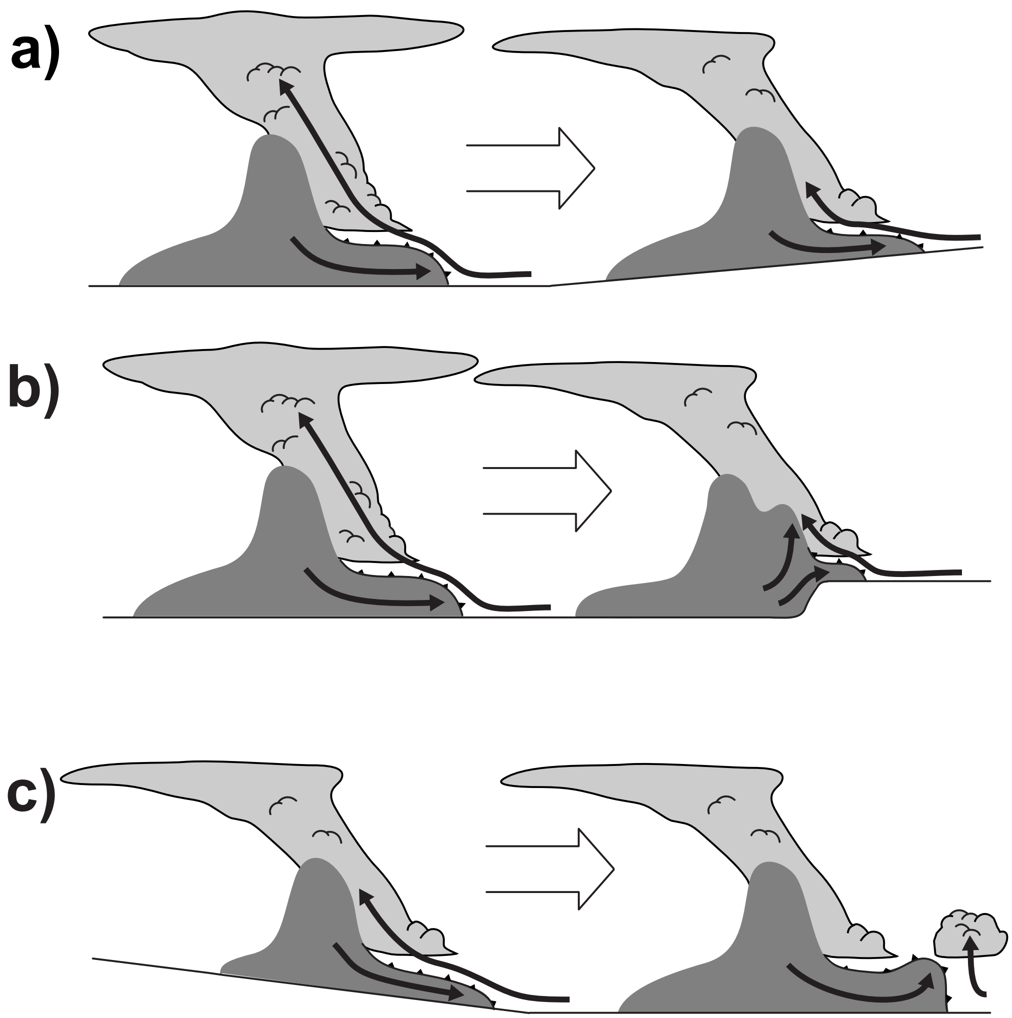

Figure 2: (a) Schematic diagram of a squall line ascending a gradual slope. The cloud outline is shown, the cold pool is shaded, and the gust front is marked by a bold line with triangles. Thin arrows denote downdrafts and outflow patterns. Thick arrows denote inflow. A large 'H' represents the surface mesohigh. (left) The squall line in its mature state over flat terrain. (right) A shallower cold pool results in reduced lift at the gust front as the convective system ascends the slope. (b) As in (a) except for a squall line ascending a steep slope. The ascent of the rear inflow jet is shown by thick arrow for emphasis. (left) The squall line in its mature state over flat terrain. (right) The rear inflow jet is forced to ascend, disrupting inflow to the updrafts. (c) As in (a) except for a squall line descending a slope. (left) Supercritical cold pool results in less lift at the gust front during descent. (right) Hydraulic jump forms at the bottom of the slope, resulting in enhanced lift at the gust front and the generation of a new convective line.

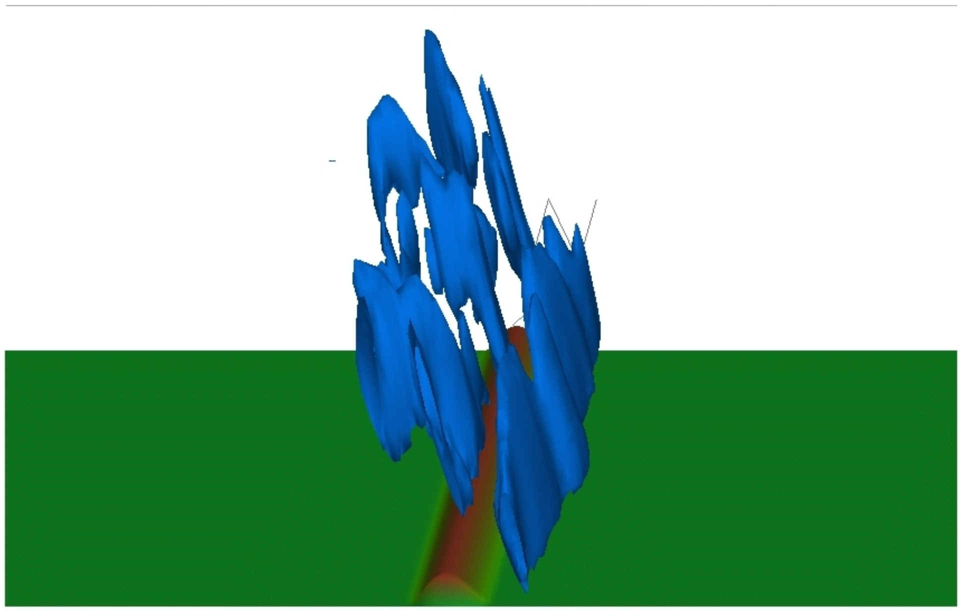

Figure 3: Isosurface of $w = 5$ m s^{-1} at $t = 10500$ s. Mountain height is 900 m and mountain width is 20 km. Notice the new updrafts developing at low levels just east of the mountain; these eventually become dominant. The old updrafts are located over the mountain and are decaying from the bottom up.

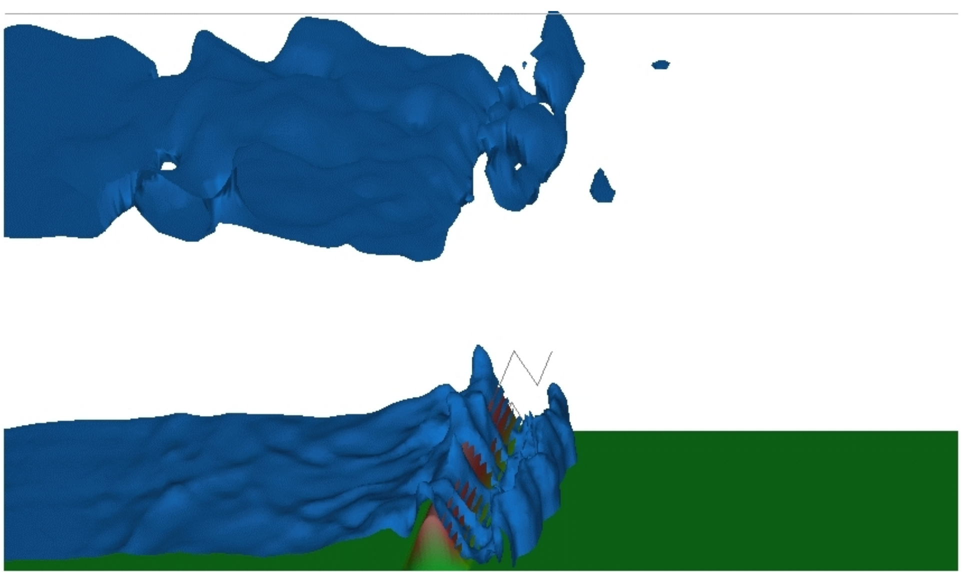

Figure 4: Isosurface of $T' = -2$ K at $t = 10800$ s. Mountain height is 1800 m and mountain width is 20 km. The feature at the leading edge of the cold pool appears to be similar to a hydraulic jump.

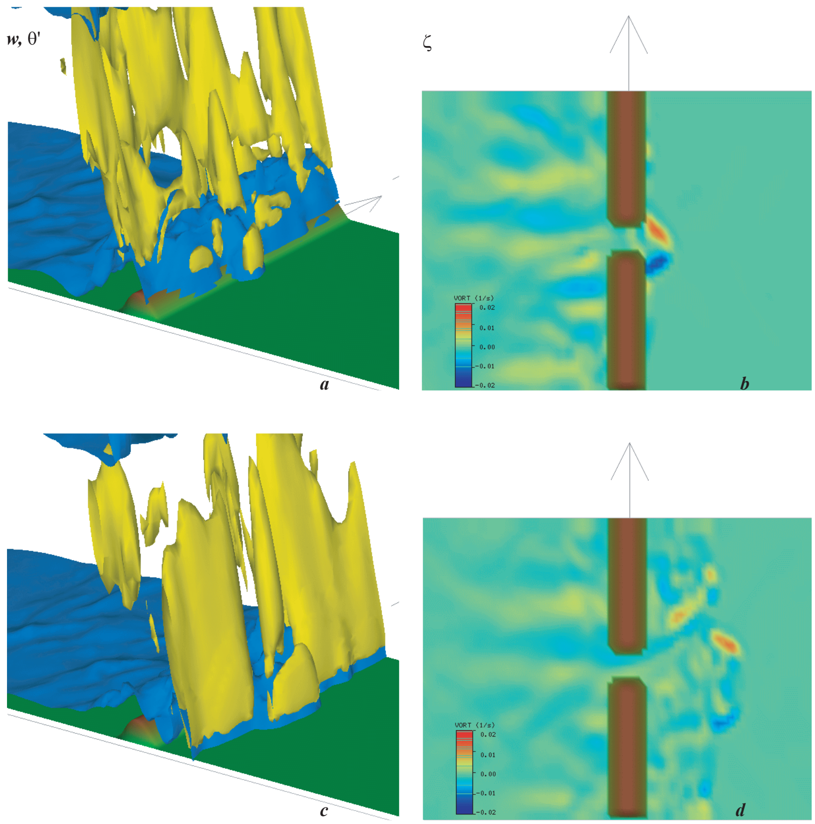

Figure 5: Simulation of a squall line encountering a mountain ridge having a gap. A pair of vortices are shed by the flow of outflow through the gap, leading to the development of a bow echo with counterrotating bookend vortices. (Left) Isosurfaces of outflow (blue) and updraft (yellow) 5 minutes (upper left) and 20 minutes (lower left) after the squall line encounters the mountain ridge and gap, viewed from the southeast. (Right) Vertical vorticity field 5 minutes (upper right) and 20 minutes (lower right) after the squall line encounters the mountain ridge and gap. Positive (negative) vorticity values are represented by warm (cool) colors.

2. Summary of University/NWS Exchanges

The exchange of new knowledge between PSU and the NWS has included annual joint workshops, at which Markowski has lectured on topics not directly related to this grant (e.g., the latest concepts related to forecasting tornadoes, damaging winds, and hail) and Frame has presented his M.S. thesis research. Furthermore, the development of the relational database by the NWS has improved the joint PSU/NWS website, which now run TOMCAT and allows java server pages to directly access an online database. As this evolves, case studies and simulations can be added to this database, allowing rapid access to these data.

3. Presentations and Publications

a.) Presentations

Frame, J. W., "Preliminary Simulations of Thunderstorms Interacting with Mountainous Terrain," Spring Severe Weather Workshop, NWS CTP; 4/2003

Markowski, P. M., "Maintenance of Long-Lived Convective Systems," Spring Severe Weather Workshop, NWS CTP; 4/2002

Markowski, P. M., "Forecasting Severe Storms," Spring Severe Weather Workshop, NWS CTP; 4/2003

b.) Publications

Frame, J. W., 2003: The interaction of simulated squall lines with idealized terrain. M.S. Thesis, Pennsylvania State University, 97 pp.

Frame, J. W., and P. M. Markowski, 2004: The interaction of simulated squall lines with idealized terrain. Accepted for publication in Preprint volume for 22nd Conf. on Severe Local Storms.

Frame, J. W., and P. M. Markowski, 2004: The interaction of simulated squall lines with idealized terrain. Part I: Sloped terrain experiments. Submitted to *Mon. Wea. Rev.*

Frame, J. W., and P. M. Markowski, 2004: The interaction of simulated squall lines with idealized terrain. Part II: Sinusoidal mountain ridge experiments. Submitted to *Mon. Wea. Rev.*

Grumm, R. H., and M. Glazewski, 2004: Thunderstorm types associated with the "broken-S" radar signature. Accepted for publication in Preprint volume for 22nd Conf. on Severe Local Storms.

4. Summary of Benefits

This research represents the first systematic investigation of the range of structural changes owing to the disruption or modification of convective storm circulations by terrain. A better understanding of the possible changes convection may undergo as a result of interacting with terrain, along with an improved understanding of the dynamics governing these changes, is expected to improve situational awareness and warning lead times, as well as dovetail into exciting future basic and applied research endeavors. For example, the Doppler On Wheels (DOW) radars were deployed in Pennsylvania in the October and November of 2003. Although no data were collected on squall lines and their possible interactions with local terrain (not a single report of thunder was made in State College during those two months; however, a wealth of significant data were obtained on other phenomena, such as boundary layer rolls, prefrontal rain showers, and lake-effect snowbands), future intercepts are likely in the fall months of 2004 and 2005. It is likely that some of the would-be unprecedented observations of convection obtained by the DOWs in this region can be used to test some of the theories that will be produced by the current numerical simulation research supported by COMET, and serve as a springboard for future studies combining observations with numerical simulations.

In addition to the broad benefits stated above, this research has been a positive educational experience for both Jeff Frame, a graduate student at Penn State, as well as undergraduate meteorology students enrolled in Markowski's mesoscale meteorology course at Penn State. Frame has gained much knowledge about computational meteorology from this work, which will be of great benefit to him, regardless of whether he chooses a career path in operational meteorology or research. Penn State mesoscale meteorology undergraduates were exposed to this ground-breaking research by way of supplemental lecture material obtained directly from Frame's results.