CAREER: A Study of the Radiative Effects of Cloud Shadows on the Dynamics of Long-Lived Convective Storms

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by

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Project Summary

This proposal seeks funding to investigate the radiative effects of cirrus anvils and their shadows on the dynamics of long-lived convective storms. The dynamical impacts will be examined using a three-dimensional cloud model with ice physics and radiation, in addition to a soil model and surface fluxes, which couple the radiative forcing at the surface to the overlying storm inflow within the boundary layer.

The educational component of this proposal is two-fold: (1) development of a suite of interactive numerical models for use in a variety of courses for undergraduate and graduate students; (2) creation of an interactive museum exhibit that showcases atmospheric research on severe storms and fully immerses visitors in the discovery process that defines science.

Intellectual Merit

Despite significant advances in computing power, radiative effects generally have been ignored in past three-dimensional numerical modeling studies designed to study the dynamics of convective storms. The exclusion often has been justified on the assumption that radiative effects are unimportant on the time scales that convection typically persists, and using the argument that convection is "dynamically driven" rather than "radiatively driven."

Even though the above arguments are true for many storms, significant low-level cooling (e.g., temperature deficits exceeding 5 K) is occasionally observed beneath the expansive anvils of long-lived convective storms. Idealized numerical simulations that have represented this effect in a crude manner strongly suggest that a potentially important forcing is being missed when such substantial low-level temperature modifications are not captured. Scale analysis indicates that the temperature gradients associated with anvil shadows can be large enough to generate a significant amount [$O(10^{-2})$ s^{-1}] of baroclinic horizontal vorticity. This horizontal vorticity can be converted to vertical vorticity through tilting by an updraft. On the other hand, cooling beneath the optically thick cloud of a convective storm reduces convective available potential energy and increases the convective inhibition. The proposed research will investigate the effects—which quite possibly compete with one another—of radiatively-induced storm inflow modifications, e.g., baroclinic horizontal vorticity generation, stability modifications, etc.

The research described in this proposal will address the following questions:

- What are the possible dynamical effects on convective storms from radiative transfer processes associated with anvils?
- What are the magnitudes of these dynamical effects?
- On what time scales are the radiative effects important?
- In which conditions (e.g., sounding and hodograph characteristics, surface characteristics, time of day) do radiative effects exert the largest influence on convective storm evolution?

Broader Impacts

The proposed work has ramifications in a potentially broad range of areas, such as (i) warm season precipitation forecasting, which often depends on the maintenance of convective systems, (ii) the representation of cloud radiative transfer processes in large-scale models (the technique introduced in this proposal for correctly accounting for the geometry of regions influenced by cloud shading could easily be implemented in such models), and (iii) the development or intensification of rotation within severe storms, which are sensitive to variations in horizontal vorticity present in the inflow.

The suite of simple, web-based numerical models in the proposed educational component will augment students' classroom instruction by way of simulation-based laboratory exercises designed to promote creativity and critical thinking. Such exercises will have the utmost flexibility, allowing students to formulate and test their own hypotheses and perhaps even expose areas ripe for future rigorous scientific research. The atmospheric sciences museum exhibit will provide a highly interactive, "hands on" learning experience to a target audience that ranges from elementary school to college. Even for visitors who will be choosing a career path toward science, being exposed to the discovery process of scientific research prior to their entrance to college or graduate school is of great benefit to both today's and tomorrow's investigators.

Project Description

1. Research Plan

a. Introduction and Motivation

1.) Long-lived convective storms and radiative transfer processes

Long-lived convective storms tend to be among the storms most likely to produce severe weather, such as flash floods, destructive straight-line winds, hail, and tornadoes. For this reason, long-lived storms, such as supercell thunderstorms and mesoscale convective systems (MCSs), have been some of the most intensely studied atmospheric phenomena, and both have been found to be highly amenable to numerical simulation (e.g., Klemp and Wilhelmson 1978; Weisman et al. 1988). Numerical simulations routinely produce convective storms that contain the salient characteristics of observed storms, despite the fact that simulations regularly make simplifications such as neglecting surface physics, radiation, and ice processes, especially idealized simulations designed to investigate fundamental storm dynamics or explore a large environmental parameter space (e.g., Rotunno and Klemp 1982, 1985; Weisman and Klemp 1982, 1984). Though this fact is likely an indication that such numerical simulations contain enough physics to represent the key governing dynamics, it does not exclude the possibility that additional important effects could be associated with physics that has been neglected. For example, although ice physics is not essential to include in a simulation of a supercell or MCS if the goal is to study the dynamics of midlevel mesocyclogenesis (e.g., Rotunno 1981) or the gust front updraft (e.g., Rotunno et al. 1988), respectively, it is now well-known that the inclusion of ice has important effects on other important aspects of these storms, e.g., the intensification of near-ground rotation in supercells (e.g., Snook and Xue 2006) and the development of trailing stratiform precipitation in MCSs (e.g., Parker and Johnson 2004).

This proposal will systematically study radiative effects on convective storms, which, like ice microphysics, also might exert a significant influence on convective storms in many situations. Some two-dimensional simulations of MCSs previously have included longwave radiative transfer processes. It has been shown that the formation of the well-documented "transition zone" in MCSs (Smull and Houze 1985; Rutledge and Houze 1987) can be sensitive to longwave radiation (Chen and Cotton 1988; Chin 1994; Braun et al. 1996). Longwave radiation effects also are known to affect the circulation within the trailing stratiform regions of simulated MCSs (Chen and Cotton 1988; Dudhia 1989; Churchill and Houze 1991; Tao et al. 1991), ultimately enhancing precipitation amounts within the stratiform regions (Tao et al. 1993), which typically account for a significant fraction of the total precipitation produced by MCSs (Houze 1977; Zipser et al. 1981; Gamanche and Houze 1983; Rutledge and Houze 1987; Johnson and Hamilton 1988). Although the studies cited above have made important contributions toward our understanding of MCSs, the full range of possible dynamical effects owing to radiative effects, especially those owing to shortwave radiative transfer processes, remains uncertain due to the model dimensionality of these previous studies. In three-dimensional modeling studies of MCSs (e.g., Weisman et al. 1988; Dudhia and Moncrieff 1989; Weisman 1992, 1993; Skamarock et al. 1994; Trier et al. 1997, 1998), radiative effects generally have not been considered, although Tucker and Crook (1999) recently simulated an MCS case with and without solar radiation. They found that the inclusion of solar radiative effects reduced the intensity of the MCS, although the details of how solar radiative effects were included were not presented.

Radiative effects also have virtually always been excluded from three-dimensional simulations of supercell storms, even though computing power has increased exponentially since the seminal studies of the late 1970s and early 1980s (e.g., Wilhelmson and Klemp 1978; Rotunno and Klemp 1982). Some recent three-dimensional case study simulations of supercellular convection have included radiation, but these parameterizations have been rather crude. For example, often clouds were seen only as areas of very high water vapor content, with the radiative characteristics of condensed liquid and ice species not taken into account (e.g., Finley et al. 2001), leading to overestimates of solar fluxes reaching the surface in cloudy regions and underestimates of longwave cooling at cloud tops. Furthermore, to the PI's knowledge, in the two- and three-dimensional simulations (of both MCSs and supercells) that *have* included radiation, no sensitivity analyses were done to quantify the effects of radiation on storm dynamics. The exclusion of radiative effects in the majority of convective storm simulation studies (particularly three-dimensional simulations) has been justified with the assumption that radiative processes are unimportant on the time scales of the model integration (Trier et al. 1997, 1998), and that the storms are "largely dynamically (not radiatively) driven" (Finley et al. 2001). Of course, all of the above statements are true in some sense, for the past apparent modeling successes likely would not have been achieved otherwise. However, what is argued here, and what is proposed to be examined, is the possibility that convective storms may be *modulated* in certain, and perhaps significant, ways by radiative effects.

2.) Observations of significant low-level temperature modifications attributable to shading beneath thunderstorm anvils

In the course of his M.S. research, the PI examined mesoscale surface observations for the presence of strong temperature gradients and wind shifts in proximity to tornadoes that occurred during the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX). The work was motivated by the fact that numerical simulations had earlier shown that low-level baroclinity can have an important influence on convective storm dynamics. For example, Klemp and Rotunno (1983) and Rotunno and Klemp (1985) showed that the forward-flank gust front of supercell thunderstorms (Lemon and Doswell 1979) may be an important source of horizontal vorticity for the updrafts of the storms. This horizontal vorticity is generated solenoidally along the boundary separating rain-cooled outflow from the relatively warm inflow. Large vertical velocity gradients associated with the updraft may tilt this horizontal vorticity to give rise to significant low-level vertical vorticity in supercell storms.

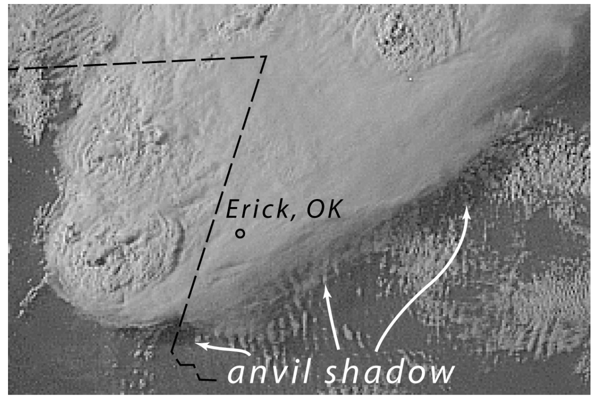

Figure 1. *GOES-8* visible image at 2315 UTC 8 June 1995. The complex of storms was associated with heavy rainfall and severe weather, including large hail and several tornadoes. A shadow is visible beneath the anvil canopy, and temperature deficits within this shaded region were as large as 5–6 K. Adapted from Markowski et al. (1998a).

The PI's research sought to establish whether or not larger-scale baroclinic boundaries (e.g., outflow boundaries produced externally by *other* storms, possibly even preexisting the tornadic storms) could have similarly important dynamical consequences. In a few cases, a surprising observation was made: the strongest surface temperature gradients were associated with the shadow of the anvil (Fig. 1). In the cases documented by Markowski et al. (1998a), surface air temperature deficits as large as 5–6 K were found to develop within the anvil shadows (Fig. 2), with the strongest horizontal temperature gradients occurring over distances of ∼25 km. Via the inviscid, Boussinesq horizontal vorticity equation, the rate at which horizontal vorticity is generated by such a baroclinic zone exceeds 0.02 s^{-1} h^{-1} (Markowski et al. 1998a)—a very significant rate indeed, by almost any measure (Fig. 3). Although the temperature gradients and associated vorticity generation rates owing to anvil shading may be smaller than the temperature gradients often associated with the gust fronts of convective storms (∼5 K km^{-1}), parcel residence times within anvil-generated baroclinic zones (perhaps ∼1 h) generally would be larger than parcel residence times within the baroclinic zones associated with storm-scale gust fronts (∼5–15 min) (the anvil shadow subtends a much larger area than the precipitation region of a storm). Thus, the total horizontal vorticity generated baroclinically may be comparable to that produced by low-level outflow [O(10^{-2}) s^{-1}]. It might be worth noting that the notion of radiative effects and effects associated with precipitation processes being of comparable importance is not a foreign one. Even in stratiform precipitation events (e.g., those associated with cold-air damming), radiative effects occasionally have been found to exert a greater influence on the low-level stability and horizontal temperature gradients than

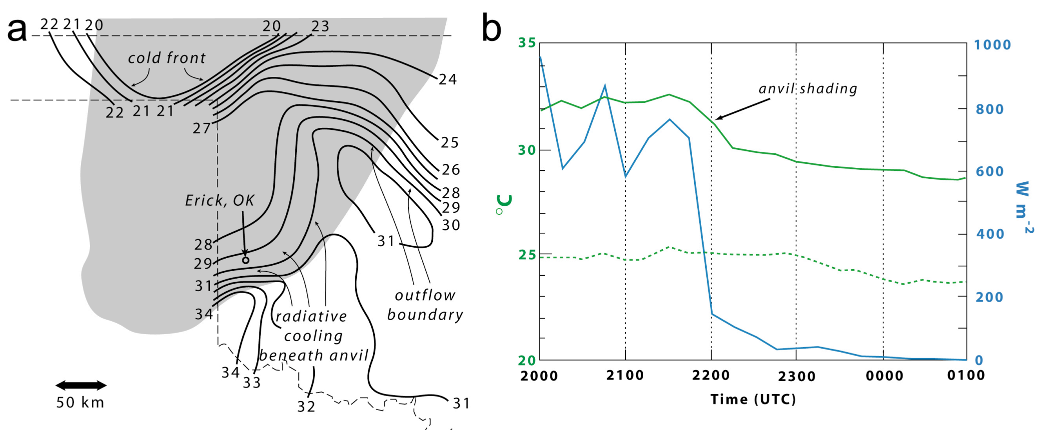

Figure 2. (a) Surface temperatures (contoured at 1°C intervals) obtained from the Oklahoma Mesonet at 2300 UTC 8 June 1995. The anvil canopy is shaded gray. Adapted from Markowski et al. (1998a). (b) Time series of temperature (solid green) and dewpoint (dashed green), both in °C, and solar radiation (solid blue), in W m^{-2}, from 1900–0100 UTC 8–9 June 1995 at Erick, Oklahoma [its location is indicated in (a) and in Fig. 1]. Adapted from Markowski et al. (1998a).

latent cooling associated with the evaporation of precipitation (e.g., Fritsch et al. 1992). Furthermore, cloud shading effects have been known for years to be important in driving many mesoscale circulations (e.g., Segal et al. 1986), some of which even initiate convective storms (e.g., Koch 1984).

One question that Markowski et al. (1998a) were unable to fully address was the depth over which the cooling and baroclinity developed. A few soundings indicated that the low-level baroclinity was likely several hundred meters in depth. Although it is not known how deep the baroclinity must extend for significant dynamical effects to arise (this will be addressed by the research proposed herein), there is growing evidence that modifications of just the lowest few hundred meters of the environmental vertical wind profile may have profound effects on storm behavior (Wicker 1996; Markowski et al. 2003a). Low-level temperature modifications by anvils also affect the convective available potential energy (CAPE) and convective inhibition (CIN) of the storm environment. It is not known what effects these alterations may have on convective storm behavior when included in a numerical simulation. Furthermore, it is not known how the effects of baroclinic vorticity differ depending on whether the baroclinic vorticity has been generated within a region in which equivalent potential temperature (θ_e) has been nearly conserved (as might be expected to be the case along some gust fronts if the cooling is largely due to evaporation of precipitation), or whether the baroclinic vorticity has been generated within a region in which θ_e deficits also have been generated (as might be expected to be the case where cooling owes to radiative effects). Even the forward speed of the convective storm might be expected to affect the magnitude of the radiative effects, at least those related to surface cooling due to a reduction of incident shortwave radiation. For example, a rapidly moving storm with its attendant anvil will constantly be encountering warm ground that it will have to cool in order to develop surface temperature gradients. On the other hand, a stationary storm can shade the same ground for a longer period of time, thereby producing correspondingly larger surface temperature gradients. Conversely, the development of surface temperature gradients in storms due to low-level evaporative cooling is Galilean invariant, since the precipitation region (which produces the cooling) moves with the storm. [The storm motion relative to the ground is a function of the ground-relative wind profile. Changes in the near-surface, ground-relative wind speeds, even if the hodograph (and therefore storm-relative winds) is held constant, also would alter the surface sensible heat flux, further contributing to the Galilean invariance of the problem.]

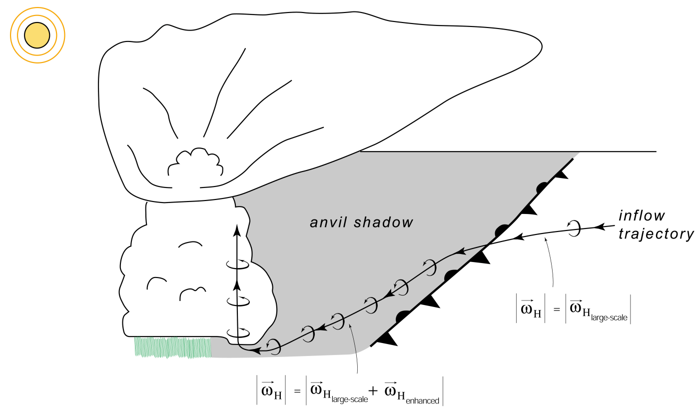

Figure 3. A schematic illustrating how an anvil might alter the horizontal vorticity ingested by the updraft of a convective storm. Air parcels distant from a storm, outside of the anvil shadow, contain some "ambient," large-scale horizontal vorticity ($|\vec{\omega}_H|$) due to the presence of mean vertical wind shear ($|\vec{\omega}_{H_{largescale}}|$). As these parcels pass through the anvil shadow, where significant temperature gradients may exist, the horizontal vorticity is modified (in this case, enhanced) by baroclinic vorticity generation. In other words, the updraft of the convective storm ingests air parcels that are associated with horizontal vorticity that has been modified with respect to large-scale values ($|\vec{\omega}_{H_{largescale}} + \vec{\omega}_{H_{enhanced}}|$). For other inflow-shadow configurations (not shown), it is also possible that the horizontal vorticity associated with the anvil shadow could *oppose* the large-scale horizontal vorticity. Adapted from Markowski et al. (1998a).

3.) Convective storm simulations with and without parameterized radiative cooling at the surface beneath the cloud

Motivated by the Markowski et al. (1998a) observations, Markowski and Harrington (2005) (hereafter MH05) performed a pair of simulations in order to demonstrate the potentially important effects of radiative transfer processes on convective storm dynamics. The simulations were initialized with the composited sounding from the well-documented 20 May 1977 Del City, Oklahoma, storm (Ray et al. 1981; Johnson et al. 1987), which has been used in several other modeling studies (e.g., Klemp et al. 1981; Klemp and Rotunno 1983; Grasso and Cotton 1995; Adlerman et al. 1999; Adlerman and Droegemeier 2002). This sounding is characterized by a CAPE of approximately 2600 J kg^{-1} and a 0–3 km storm-relative helicity of approximately 150 $\mathrm{m}^2\ \mathrm{s}^{-2}$ (Fig. 5). The hodograph was shifted by a mean velocity so that the mature, cyclonically rotating storm was nearly stationary. One of the simulations (the control) was run without surface physics and radiation, i.e., in the manner that most idealized convective storm simulations are performed. In the other simulation, radiative cooling due to anvil shading was crudely emulated by prescribing a cooling rate to the skin temperature of 5 K h^{-1} at any grid point at which cloud water was present overhead. This skin cooling rate is similar to that observed by Markowski et al. (1998a) (Fig. 4).

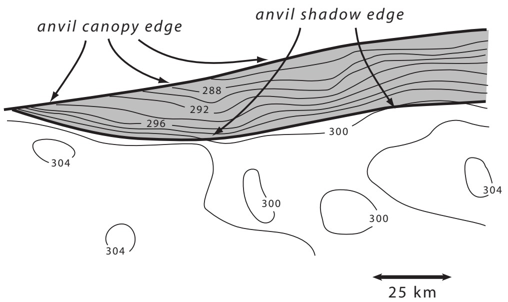

Figure 4. *GOES-8*-derived skin temperatures (contoured at 2 K intervals) at 2300 UTC 22 May 1995 beneath the anvil of an isolated convective storm in southwestern Oklahoma. The anvil shadow is shaded gray. Not surprisingly, skin temperature changes within anvil shadows have much larger amplitudes than air temperature changes. Cooling of the ground such as that seen above would have significant effects on surface fluxes and the energy budget.

Low-level air temperatures were coupled to the skin cooling in this second simulation by the inclusion of surface sensible heat fluxes using simple bulk aerodynamic drag laws (latent and soil heat fluxes were not included). *Though this emulation of radiative cooling was admittedly simple, it was designed to illustrate the potential effects that radiative cooling under the anvil may have on storm dynamics, in anticipation of the much more thorough parameter space exploration that is proposed herein, using a considerably more realistic radiation parameterization.*

The domain used for the pair of "demonstration simulations" was 200×200×20 km. The horizontal resolution was 1000 m, and the vertical resolution varied from 150 m in the boundary layer to 500 m near the tropopause. Warm-rain (Kessler) microphysics was used. Though this microphysical simplification wasn't necessary for the demonstration, warm-rain physics was chosen for two reasons: computational expedience and, more importantly, neglecting ice processes leads to an anvil of smaller areal extent. Hence, if radiative cooling was found to be important in this simple experiment, its importance would likely be amplified in the presence of a longer, thicker anvil. For additional details on the model physics, boundary conditions, and initialization, see MH05.

The purpose of the simulations is to show that, beyond roughly the first 60 min, there are *significant differences between the two supercells—differences that can only be due to effects associated with the emulated anvil shading.* The goal of MH05 was not to present detailed diagnostics of the model output, elucidating the precise dynamics responsible for the simulation differences—this is precisely one of the goals of the research proposed herein. *MH05 only sought to show that radiative effects associated with cirrus anvils can have a significant impact on convective storm characteristics.*

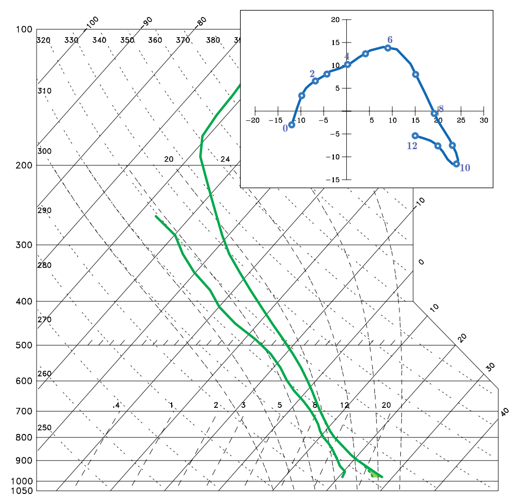

Figure 5. Skew T-log p diagram and hodograph (inset) used to initialize the demonstration simulations. The dashed low-level temperature profile on the sounding is the temperature profile at the location indicated by the star in Fig. 6b (within the anvil shadow). Units on the hodograph are m s^{-1}, and open circles (every other one is labeled in km) are placed along the hodograph at 1 km intervals.

Figures. 6 and 7 show the cloud water isosurface and low-level wind vectors, isotherms, and rain water fields for the control and emulated anvil shading simulations. The surface cooling beneath the anvil is readily identifiable in Fig. 6b (cf. Fig. 6a). Although the temperature deficits beneath the anvil might be considered to be small (only 1–3 K) and shallow (see Fig. 5), the expansive region of surface cooling in the storm inflow had an effect on subsequent storm morphology that can be regarded as substantial. For example, the time series of vertical velocity and vertical vorticity (Fig. 8) have large differences, with the maximum vertical velocity (low-level vertical vorticity) values observed during the simulations differing by 20% (100%) at times.

The supercell simulated without radiative effects generally had much stronger low-level rotation compared to the supercell simulated with the emulated anvil shading effect (Fig. 8). The near-surface vector wind fields are quite different at $t = 2$ h (Fig. 7), with the stronger rotation clearly evident in the control simulation. In fact, the differences in the near-surface vector wind fields in the simulated storms are much larger than those that have been observed between tornadic and nontornadic supercells (Blanchard and Straka 1998; Trapp 1999; Wakimoto and Cai 2000; Markowski et al. 2002). The low-level potential temperature fields, and especially the orientation and magnitude of the gradients, in close proximity to the storms, had readily discernible differences (Fig. 7); thus, it is not surprising that large kinematic differences (e.g., the vertical vorticity differences) would result, given the well-known relationship between temperature gradients, horizontal vorticity modulation, and vertical vorticity generation by tilting.

It is reiterated that a detailed investigation of the causes of these differences is beyond what was intended for demonstration purposes, but that the results displayed in Figs. 7 and 8 quite clearly indicate that substantial modifications of storm behavior can be brought about by radiative processes. In this pair of simulations, it appears as though low-level cooling beneath the anvil has had a detrimental effect on the convective storm. In other cases, e.g., cases in which the orientation of the low-level inflow with respect to the low-level baroclinity is more favorable, it is quite possible that anvils could have an enhancing effect on a convective storm. *The research that will be proposed herein is designed to determine precisely the situations in which radiation has a significant effect on convective storms, as well as to determine whether the effects are positive or negative, and just what the dynamical nature of the effects is.*

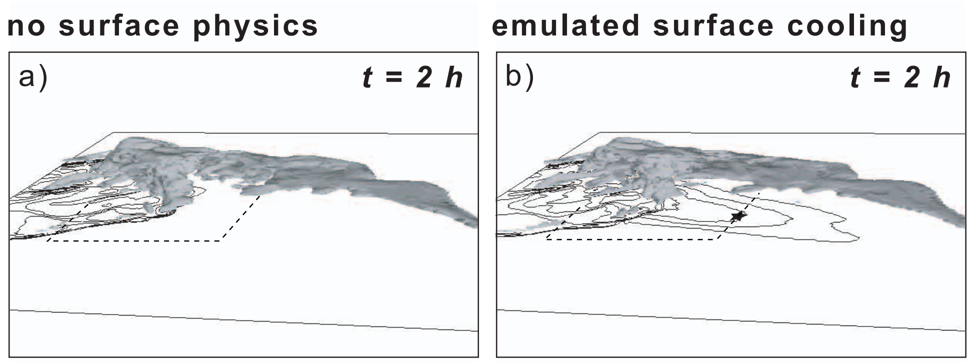

Figure 6. (a) Cloud isosurfaces and potential temperature perturbations at the lowest model level (75 m) at $t = 2$ h in the simulation in which no radiative parameterization was employed. The view is from the south. Potential temperature perturbations are contoured from -1 K to -8 K at 1 K intervals. (b) Same as (a), but for the simulation in which shortwave radiative cooling was emulated beneath cloud regions. The dashed rectangles in (a) and (b) enclose the regions depicted in Fig. 7. The star is (b) indicates the location of the dashed low-level sounding shown in Fig. 5.

A few additional comments are in order concerning the MH05 simulations. The long-lived supercell storms simulated in the pair of demonstration simulations were nearly stationary. Thus, it might seem that the simulation with emulated radiative cooling perhaps exaggerated the effect of anvil shading, due to shading of the same region for a long duration. However, the surface temperature deficit and associated horizontal baroclinity beneath the anvil were not as large as has been observed (cf. Figs. 2a and 6b), even after 3 hours (not shown). Furthermore, the hodograph structure (Fig. 5) was not ideal (hodograph structures will be discussed in more detail later)—not only did low-level inflow parcels fail to spend much time in the anvil-generated baroclinic zone, but the baroclinic zone itself was situated so that inflow entering the updraft did not pass through the (southern) portion of the baroclinic zone that would have augmented the horizontal vorticity associated with the base state vertical wind shear (Fig. 3). Instead, the horizontal vorticity produced by the anvil-generated baroclinic zone actually *opposed* the horizontal vorticity associated with the base state vertical wind shear. Perhaps this is why the storm associated with low-level anvil baroclinity had weaker near-surface rotation. Or, perhaps there are other reasons that will be discovered upon completing future diagnostics like those proposed, such as increased CIN in the inflow. It is also worth noting that the simulations did not include ice physics. The inclusion of ice physics leads to the production of more expansive anvils (and therefore

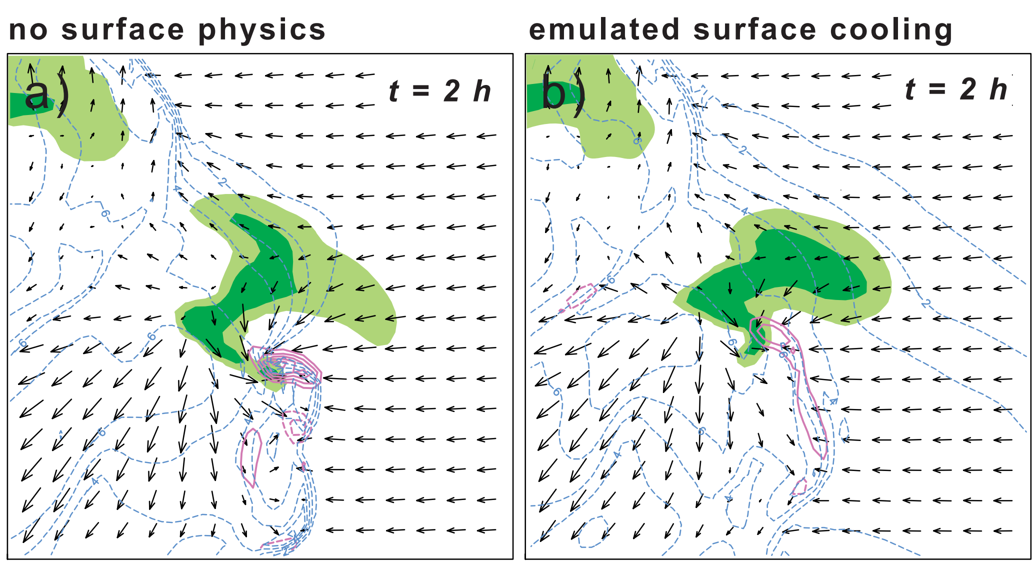

Figure 7. (a) Horizontal cross-sections of the rainwater (3 km), potential temperature perturbation (75 m), and vertical vorticity (75 m) fields at $t = 2$ h in the simulation in which no radiation parameterization was employed. The region shown is indicated in Fig. 6a. Light (dark) green shading denotes regions where rainwater exceeds 1 g kg^{-1} (3 g kg^{-1}). The vertical vorticity field is analyzed at 0.004 s^{-1} intervals using magneta contours (negative contours are dashed). Negative potential temperature perturbations are analyzed at 1 K intervals using blue dashed contours. Horizontal (ground-relative) wind velocity vectors at 75 m have been drawn at every third grid point. (b) As in (a), but for the simulation in which shortwave radiative cooling was emulated beneath cloud regions. The region shown is indicated in Fig. 6b.

more expansive surface temperature modifications) compared to the warm-rain microphysical parameterization used in the simulations (Gilmore et al. 2003), and the correct accounting of sun angle further enlarges the cloud shadow. Given the above-noted departures from what might be considered to be much more ideal conditions for magnifying the importance of anvil radiative effects on convective storms, it is believed that the MH05 simulations *quite conservatively* indicate that radiative effects can have a significant effect on convective storms.

It does not seem likely that radiative effects would be important in *all* convective storms. For example, short-lived storms probably would not be affected by radiatively-cooled shadow regions, owing to their relatively brief duration and small anvils. On the other hand, long-lived storms might be more prone to radiative effects on their dynamics, owing to their larger anvil canopies and longer storm time scales. Furthermore, long-lived storms tend to occur in environments containing large vertical wind shear, which promotes storm organization and longevity. Large vertical wind shear typically is associated with strong storm-relative winds at anvil level, leading to the formation of long anvils in the downstream direction, overlying the storm inflow region, where surface shading effects may have the largest impact. Also, the most dangerous convective storms often are isolated (Browning 1964), and thus may have a well-defined anvil shadow edge and associated low-level baroclinity.

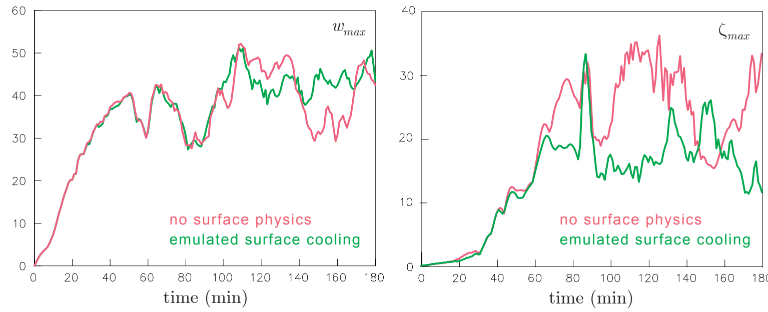

Figure 8. Time series of maximum vertical velocity, w_{max} (left; m s^{-1}), and maximum vertical vorticity below 2 km, ζ_{max} (right, $\times 10^3$ s^{-1}), in the demonstration simulations without radiative effects (red) and with emulated anvil radiative effects (green).

b. Proposed Research

1.) Overview

The goal of the proposed research is to explore the nature of radiative effects on convective storms, particularly those associated with shortwave radiative transfer processes. The proposed research will determine under which conditions (e.g., sounding and hodograph characteristics, surface characteristics, time of day) the effects are most significant, as well as the magnitude of the effects. The Markowski et al. (1998a) observations and the MH05 simulations may expose a shortcoming of numerical models that fail to simulate temperature contrasts associated with differential heating near an anvil edge. When a low-level temperature deficit >5 K (e.g., Fig. 2) is not captured in the inflow of a convective storm in a numerical simulation, an important forcing possibly is being missed.

Using a three-dimensional numerical model with a much more realistic radiation parameterization than used by MH05, the proposed research will investigate the following effects attributable to the radiative properties of anvils:

- the effect of modulations of potential buoyant energy and convective inhibition owing to low-level radiative cooling beneath anvils
- the magnitude and depth of horizontal vorticity augmentation within low-level baroclinic zones arising from cooling within the anvil shadow
- the degree of surface layer decoupling from the mixed layer and associated accelerations of conditionally unstable storm inflow at low levels
- changes in the nature of the above effects due to the onset of night
- the sensitivity of the effects to the microphysical parameterization, time of day (i.e., sun angle variations), and differences in surface characteristics (e.g., soil, soil moisture, and vegetation types)
- the sensitivity of these effects to changes in the base state environment (e.g., orientation of the storm-relative inflow relative to the cloud shadow, mean wind speed)

2.) Model specifications

The model simulations will be conducted using the Advanced Regional Prediction System (ARPS) version 5, a three-dimensional, compressible, nonhydrostatic model developed for storm-scale weather prediction (Xue et al. 2000, 2001). It is anticipated that a domain of at least 300 × 300 km will be used for simulations of isolated convective storms, and at least a 400 × 400 km domain will be used for simulations of mesoscale convective systems. Horizontal grid spacings of 1 km (2 km) should be sufficient for capturing the essential dynamics of isolated convective storms (convective systems) and the possible radiative effects on those dynamics. The grid spacing is perhaps relatively coarse by today's standards, but one computational limitation is that the model domain must be somewhat large so that it may accommodate the entire anvil and its shadow (which generally extends beyond the cloud edge). Furthermore, grid translation is not an option for these experiments owing to the fact that the effect of cloud shading-induced cooling is not Galilean invariant, as mentioned earlier. Supplemental experiments with smaller grid spacings will be done on a case-by-case basis in order to evaluate the sensitivity of the results to grid spacing.

The vertical grid will be stretched, with a minimum (maximum) grid spacing of approximately 75 m (300 m) at low levels (near the tropopause). The stretching allows for adequate vertical representation of the low-level storm structure, including the cold outflow, gust front, and low-level shortwave radiative cooling. A three-category, ice-phase (cloud ice, snow, and hail/graupel) microphysics parameterization (Lin et al. 1983; Tao and Simpson 1989) will be used. Experiments will be conducted with both free slip, limited slip (drag law), and full surface physics (stability-dependent fluxes) lower boundary conditions. The upper boundary is rigid, with a Rayleigh sponge layer above the tropopause. Zero-gradient lateral boundary conditions will be employed for all of the simulations. Such boundary conditions are known to be less desirable than wave-radiating (open) boundary conditions in many modeling applications (or the periodic boundary conditions used in many squall line simulations in the along-line direction); however, the inclusion of anvil radiative effects and surface physics, in conjunction with open lateral boundary conditions, is problematic along inflow boundaries. Thus, zero-gradient lateral boundary conditions will be used. (Preliminary tests indicate that this approach works satisfactorily if the boundaries are kept far from storm-altered fields.)

3.) Accounting for cloud shading effects

Sun angle variations are important since any sun angle departure from zenith will extend the anvil shadow horizontally. Unfortunately, two-stream (and multi-stream) models deal only with fluxes in the vertical and cannot handle this three-dimensional effect (Fig. 9). Consequently, a two-stream simulation would only lead to cooling directly beneath the anvil. For most solar zenith angles, however, there will be a significant extension of the shadowed region due to the slant angle of the solar direct beam. Because this effect is due primarily to direct beam attenuation, simple geometry can be used to adjust the cooled surface region produced by the two-stream model.

One method to include the angle of the sun in the radiative transfer calculation is to implement a new coordinate system within the radiative transfer model. The implementation of this coordinate system is straightforward and does not require significant portions of the existing radiative transfer code to be rewritten. In this new coordinate system (x',y',z'), the z' axis makes an angle with the true vertical (z) that is equal to the solar zenith angle, θ_s, and x' and y' depend on the solar azimuth angle, ϕ_s. The new coordinate system is used for the direct solar beam only; diffuse solar radiation and all infrared radiation is still transmitted vertically. A two-dimensional schematic of this coordinate system is illustrated in Fig. 10.

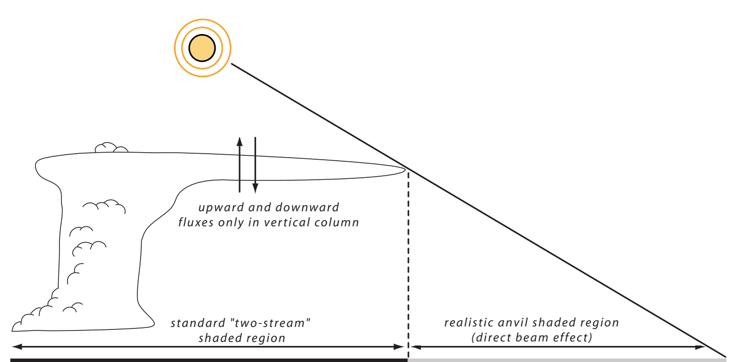

Figure 9. Schematic showing the shaded region computed by a standard two-stream model, and the surface region that should be in shadow if the direct solar beam was appropriately attenuated.

All grid points at the same vertical level remain on the same horizontal plane, so only a two-dimensional (bilinear) interpolation of the relevant data is required. Also, the grid points at the lowest model layer are identical between the two coordinate systems, meaning that no interpolation of surface variables is required. The data are stored prior to interpolation, so no reinterpolation back to the original grid is needed, which may introduce unnecessary error into the model output. Also, all vertical grid spacings in the radiative transfer model must be divided by the cosine of the zenith angle. If the new vertical axis slants outside of the domain, the data value at the new point is interpolated between the values at the two nearest grid points on the edge of the original grid at the same vertical level. This is consistent with the zero-gradient boundary conditions in the model.

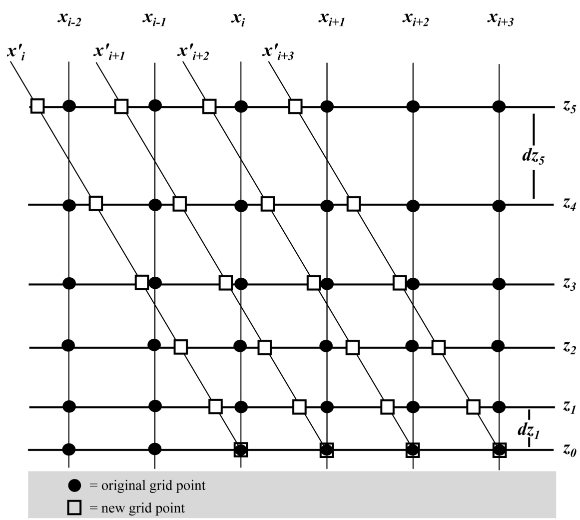

Figure 10. Schematic depiction of the manner by which a new coordinate system will be defined within the radiative transfer model in order to properly account for the geometry of the cloud shading. See text for further details.

In three dimensions, the following equations describe the new coordinate system,

$$x'_i = x_i + \Delta z_k \tan\theta_s \sin\phi_s \quad (1)$$

$$y'_j = y_j + \Delta z_k \tan\theta_s \cos\phi_s \quad (2)$$

$$z'_k = z_k \quad (3)$$

where (x,y,z) are the original model coordinates in the i, j, and k directions, respectively, ϕ_s (the local solar azimuth angle) is taken from the center of the domain and applied everywhere such that the homogeneity of the horizontal grid spacing is maintained (as is the case for θ_s), and

$$\Delta z_k = \sum_{l=1}^{k} dz_l. \quad (4)$$

At the conclusion of the solar radiation parameterization, the solar radiation values are interpolated back to the original coordinate system.

The methodology as described above is currently only performed when the solar zenith angle is less than 60°. This prevents interpolation far outside of the model domain, and precludes the possibility of a nearly infinite path length as the zenith angle approaches 90°. Furthermore, relatively little solar radiation reaches the top of the model atmosphere at these times because the sun is low in the sky.

The aforementioned technique already has been tested successfully by one of the PI's students (Jeff Frame) and found to result in realistic cloud shadows and surface cooling rates (compared to the observations) when used in conjunction with the soil model and surface physics parameterization that will be described below. Furthermore, the PI and the students supported by this project will be working in close collaboration with Dr. Jerry Harrington (Department of Meteorology, Penn State University), who has considerable expertise in the development of microphysics and radiative transfer algorithms from his prior work on the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University (please refer to the supporting documentation attached to this proposal).

In addition to solar zenith angle effects, the surface characteristics below the storm (e.g., soil type, soil moisture, surface vegetation) will also influence the response of the low-level atmosphere to anvil shading. A stability and roughness-length dependent surface flux model will be used in ARPS. This parameterization uses a modified Businger formulation (Businger et al. 1971) and an analytical procedure, instead of the commonly used iteration method, in the flux calculations for improved efficiency (Byun 1990). Additional modifications to Businger's formulation produce more realistic results for highly stable or highly unstable environments (Deardorff 1972). A two-layer diffusive soil-vegetation model, based on the parameterization developed by Noilhan and Planton (1989) and Pleim and Xiu (1995), also will be used, however, a more complicated soil model having more numerous vertical levels (e.g., Brotzge and Weber 2003) may be employed for some experiments.

4.) Initialization

Although imposing horizontal homogeneity on the pre-storm environment may be undesirable owing to the growing evidence of the importance of environmental heterogeneities on the structure and evolution of convection (e.g., Brooks et al. 1996; Markowski et al. 1998b; Richardson et al. 1998, 2000; Markowski and Richardson 2007), it is desirable for the storm environments to be free of preexisting heterogeneities so that the radiative effects of the convection can be readily isolated. The horizontally homogeneous initial conditions[1] of the idealized experiment design necessitate storm initialization by insertion of thermals at low levels (Klemp and Wilhelmson 1978), since the mean low-level convergence needed to initiate a storm is absent in a horizontally homogeneous pre-storm environment. For the isolated convective storm simulations, a single ellipsoidal warm bubble will be used to initiate the convection. In the simulations of convective systems, the convection will be initiated by a line thermal having small random perturbations (Rotunno et al. 1988; Weisman et al. 1988). Another approach would be to initiate convection in a less idealized manner, such as by way of a "case study" approach. This

[1]Note that the horizontal homogeneity (and probably grid spacing too) precludes the development of boundary layer dry convection (e.g., convective cells or rolls), despite the inclusion of a surface sensible heat flux.

approach is not favored for a few reasons. It would be difficult to obtain truly isolated convection, and the unavoidable presence of ambient mesoscale gradients of density, pressure, and momentum would not facilitate a straightforward interpretation of simulation results. Furthermore, the simulation results may be difficult to apply to more general situations.

In order to sustain a long-lived convective storm, the ambient environment must contain significant CAPE and vertical wind shear. The presence of relatively large wind shear, and significant storm-relative winds by association, limits the degree to which precipitation-induced outflow can interfere with the updraft, and thus allows the updraft to persist for a substantial period of time. Strong storm-relative winds at low levels restrain cold outflow, preventing it from undercutting the updraft (Droegemeier et al. 1993). It also has been demonstrated that significant horizontal vorticity (associated with mean vertical wind shear) in the inflow of mesoscale convective systems is necessary for a balance between relatively warm inflow and cold outflow—a balance that is vital for convective system longevity (Rotunno et al. 1988; Weisman et al. 1988). Furthermore, strong storm-relative winds in the middle and upper troposphere distribute hydrometeors far from an updraft, thereby reducing the amount of precipitation that falls back through the updraft (Browning 1964), as well as limiting the proximity of cold low-level outflow development to the updraft (Brooks et al. 1994).

By virtue of the strong vertical wind shear and associated strong storm-relative winds needed to sustain long-lived convection, anvils associated with long-lived convection tend to be long. That is, the conditions needed in order to support long-lived convection also promote the formation of long anvils, which would be the most likely candidates for having significant radiative effects on storm dynamics. The thermodynamic sounding used to initialize the base state will be similar to that used by Weisman and Klemp (1982), which contains slightly more than 2000 J kg^{-1} of CAPE. For the isolated convective storm simulations, vertical wind profiles will be used that are similar to those used by Weisman and Klemp (1982), but with some modifications. It is anticipated that the profiles will contain vertical wind shear above 6 km (which typically is present in observed storm environments), in order to enhance the length of the anvils. (Given the amount of CAPE and vertical wind shear to be used, it is expected that the isolated storms will be supercells.) Furthermore, the vertical wind profiles will be chosen, at least initially, to be those which maximize low-level inflow parcel residence times within the anvil-shaded region. The importance of hodograph structure will be expanded on below. For the simulations of convective systems, a vertical wind profile similar to that composited by Coniglio and Stensrud (2001) will be used. All of the profiles used will contain approximately 20–30 m s^{-1} of vertical wind shear over the lowest 10 km. It is anticipated that simulations of isolated convective storms will be carried out for at least 3 h, and simulations of mesoscale convective systems will be carried out for at least 4 h.

It is likely that the anvil orientation relative to the low-level storm-relative inflow will be important in determining the dynamical importance of radiative effects, especially for the isolated convective storm cases. Thus, it will be worthwhile to consider the structure of the environmental hodograph, along with storm motion (which depends on the hodograph to a large extent), in the parameter space to be explored. The orientation of the anvil of a convective storm, and the extent to which low-level inflow passes through regions modified by radiative effects associated with the anvils, are determined by the upper- and low-level storm-relative winds, respectively, and the storm-relative wind profile is determined by the hodograph and storm motion.

The amount of horizontal vorticity generated depends as much on the parcel residence time in a baroclinic zone as it does on the magnitude of the baroclinity. For this reason, hodograph shape, or more specifically, storm-relative winds near the ground and near the equilibrium level (where the anvil forms), are critical to generating horizontal vorticity within inflow parcels. Parcels that cross through an anvil-generated baroclinic zone at a large angle (e.g., $>45°$) will not spend nearly as much time in a baroclinic zone as those that cross at a much smaller angle. This crossing angle is ultimately dictated by hodograph structure. All else being equal, the residence time of parcels in a baroclinic zone is also inversely proportional to the strength of the storm-relative inflow; that is, parcels moving faster through a baroclinic zone will spend less time in the baroclinity.

In simplest terms, the anvil edge will generally stream away from an updraft in the direction of the storm-relative wind near the equilibrium level. (This simplification includes only the effects of translation. In reality, there is an additional divergent component to the anvil motion away from its updraft source.) Nearer to the surface, it is the direction of the storm-relative low-level inflow that dictates the trajectories parcels will follow en route to an updraft with respect to the storm.

To maximize the residence time of parcels in baroclinic zones generated by anvils (and to maximize the horizontal vorticity generated for a given baroclinity magnitude), the storm-relative wind vectors at low levels (e.g., 0–1 km) and near the equilibrium level should lie along the same line and in opposite directions (Fig. 11).

In other words, the parcel residence time, τ, is

$$\tau \le \frac{W}{U\cos(90-\phi)}, \tag{5}$$

where W is the width of the baroclinic zone (normal to the virtual isentropes), U is the storm-relative low-level wind speed, and ϕ is the angle between the virtual isentropes and the storm-relative low-level wind vector in degrees. Since parcels may enter an updraft or exit the boundary layer before crossing the entire baroclinic zone width, (5) is written as an inequality. Of course the baroclinic zone has finite length, L, so an ancillary inequality constraint derives from the advective timescale:

$$\tau \le \frac{L}{U\cos\phi}. \tag{6}$$

For $\phi = 90°$, the residence time reduces to the advective timescale, thus $\tau \le W/U$. Similarly, for $\phi = 0°$, $\tau \le L/U$. Stated another way, *to maximize horizontal vorticity generation in the near-ground inflow, the head of the storm motion vector should lie close to the line drawn from the heads of the low-level (e.g., 0–1 km) mean wind vector and the wind vector near the equilibrium level* (Fig. 11), assuming that any baroclinity generated by anvil shading is aligned closely with the anvil edge.

Not only would a small crossing angle between storm-relative inflow and an anvil-generated baroclinic zone ensure longer parcel residence times in the baroclinity, but the horizontal vorticity would have a larger streamwise component, thereby increasing the propensity for cyclonic updraft rotation (Davies-Jones 1984). For a 45° parcel crossing angle, the horizontal vorticity would be partitioned equally between the streamwise and crosswise components. For a 90° (0°) parcel crossing angle, the horizontal vorticity generated would be entirely crosswise (streamwise).

The isolated convective storm simulations will be commenced using a wind profile which produces an anvil that hypothetically is near-optimal for radiative impacts on the storm (although what turns out to be optimal may be later found to differ from the initial estimate). Later on, additional simulations will explore a variety of anvil orientations and storm motions (as discussed earlier, the forward *speed* of a storm, in addition to its direction, might be expected to play a role in the magnitude of radiative effects on storm dynamics). Other traits of the wind profile (e.g., hodograph length and curvature) eventually will be modified as well, in addition to characteristics of the environmental thermodynamic profile (e.g., the amount of CAPE). All such modifications will be based on typical ranges observed in storm environments.

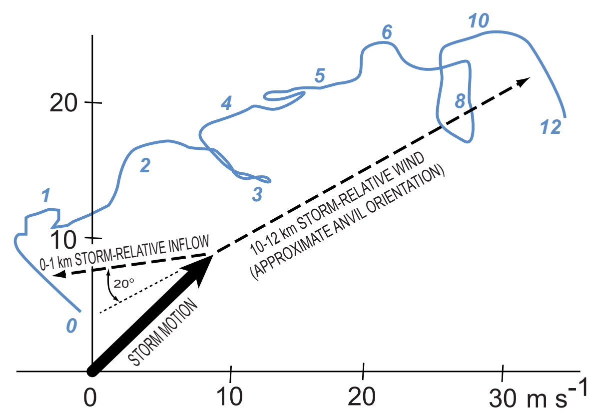

Figure 11. Hodograph obtained in the inflow of the convective storms shown in Fig. 1. The wind data were obtained from the 2230 UTC 8 June 1995 sounding launched in northwestern Oklahoma, near the town of Arnett. Units on the axes are m s^{-1}. Labels along the hodograph are heights above ground level in km. The observed storm motion vector is bold. The dashed vectors indicate the mean storm-relative winds in the 0–1 km layer and 10–12 km layer. Notice that these dashed vectors are nearly aligned. The low-level storm-relative inflow would therefore be expected to be roughly parallel to the orientation of the anvil and its associated low-level baroclinic zone, thereby leading to nearly the maximum horizontal vorticity augmentation possible for a given low-level storm-relative wind speed and baroclinity magnitude.

5.) Assessing radiative effects

Control simulations will be conducted for each class of convection (i.e., isolated storms and mesoscale convective systems) in a given pre-storm environment. In these simulations, no radiation parameterization will be included. Following the completion of the control simulations, the radiation parameterization will be included in additional experiments. Longwave (LW) radiation will be included first, followed by shortwave (SW) radiation, followed by the inclusion of both effects. It is expected that the effects of LW radiation will be small; however, for the sake of completeness, these studies will be undertaken. Shortwave radiative influences provide a greater challenge in that the solar zenith angle (θ_s) is changing with time and, therefore, the surface cooling rate and anvil shadow extent is also changing. The SW studies will initially fix the SW forcing at specific values of θ_s for each storm simulation. Once these studies have been accomplished, θ_s will be allowed to vary naturally with time during a long time integration. By first systematically fixing θ_s, and then undertaking "realistic" daytime simulations, effects should be able to be separated more easily.

Hypothesized outcome resulting from anvil radiative effects	Basis for hypothesis	Dynamical importance and implications	Unknowns that will be addressed by the proposed research
Low-level horizontal vorticity generation along the anvil shadow	Observations of significant temperature deficits within anvil shadows and significant baroclinity along the edges of anvil shadows	Horizontal vorticity is converted to vertical vorticity by large vertical velocity gradients associated with convective storm updrafts; nonhydrostatic vertical pressure gradients, which arise due to vertical vorticity gradients within updrafts, also contribute to vertical velocity	Magnitude and depth of horizontal vorticity generation (related to depth of baroclinity), effect on vertical vorticity following tilting by an updraft, sensitivities to storm motion and anvil orientation
CAPE reductions and CIN increases within the anvil shadow	Surface radiative cooling decreases θ_e	Updraft strength is dependent on contributions to vertical velocity from buoyancy; low-level stability changes may alter the relative threats posed by damaging surface winds, tornadoes, etc.; there may be broader implications for convection initiation for cases in which a convergence zone is overspread by high clouds	Magnitude of CAPE/CIN fluctuations, depth of cooling, magnitude of effect on updraft strength, sensitivities to storm motion and anvil orientation
Accelerations of inflow above the surface layer	Decoupling of mixed layer from surface layer results in decreased drag on inflow above the surface layer and inflow accelerations above surface layer	Low-level wind shear, to which convective storms have a large sensitivity, may increase; increases in moisture influx to convective storms may also alter the structure and precipitation output	Low-level stratification in radiatively cooled regions as a function of environmental wind shear, degree of decoupling and magnitude of associated accelerations above surface layer, sensitivities to surface physics, anvil size, orientation, and storm motion
Modification of outflow propagation speed	Gust front speed is largely determined by the density difference between the outflow and inflow air; modification of the inflow temperature by radiative effects should therefore modify gust front motion	Overall storm motion, structure, and severity are sensitive to outflow propagation	Magnitude of radiative effects on outflow propagation, sensitivities to anvil size, orientation, and environmental wind shear

Table 1. A listing of some of the possible effects resulting from the inclusion of radiation in three-dimensional numerical simulations of long-lived convective storms.

The "magnitude" or importance of anvil radiative effects on the dynamics of the convection will be quantified, for each case, by the deviations of the control from the simulations that include radiation. Trajectory analyses (including vorticity budget analyses along trajectories) also will be used to examine the nature of the dynamical effects. There are a wide range of possible effects that have been mentioned at various locations throughout the text. These effects are summarized in Table 1. There may be other effects in addition to those mentioned thus far, perhaps even related to longwave cooling at cloud top, that may be of nontrivial importance with respect to storm characteristics (e.g., the trapping of storm-generated gravity waves in the upper troposphere through cloud-top radiative destabilization; Tripoli and Cotton 1989a,b) and longevity (Chen and Cotton 1988; Dudhia 1989). Lastly, the pre-storm environmental conditions will be modified in order to examine the sensitivity of the radiative effects to the characteristics of the large-scale atmosphere (e.g., the potential buoyant energy and hodograph, as mentioned before), as will surface characteristics (e.g., soil type, soil moisture, vegetation cover) and time of day. Sensitivity tests will be performed on the surface physics and microphysics parameterizations.

2. Education Plan

a. Objectives and Significance of Education Goals

The research and educational components of this CAREER proposal are not distinctly separate activities. For example, I have used idealized numerical simulations in past research to achieve a physical understanding for observations collected and ascertain possible fruitful routes for future exploration. These same simple models can be used to illustrate class concepts and promote student creativity.

More specific plans for new teaching initiatives and continuing involvement in pre-college outreach programs are detailed below.

b. Planned Education Activities

1.) A Family of Simple, Web-based Models to Enrich Students' Classroom Experience

Although I have taught a wide range of courses in my first five years at Penn State (e.g., synoptic meteorology, radar meteorology, a technical writing class, introductory meteorology for non-majors, graduate-level atmospheric convection), I somewhat regularly teach an undergraduate mesoscale meteorology course. My goal is to produce a suite of simple numerical models for this course that students can run through a web interface. The family of idealized models will be constructed from what is largely pre-existing code that I have used for past research (e.g., Markowski et al. 2003b) and occasional lectures. A small portion of the budget is devoted to supporting an undergraduate meteorology student with programming experience who can make the necessary web interfaces.

I envision that students would use the models in order to reproduce what was learned in class and go beyond the traditional lecture to further their comprehension of the basic dynamics of the process they are investigating, by creatively modifying the model initialization and perhaps also the model physics and boundary conditions. As long as the models are not allowed to become mysterious "black boxes," I believe that they can provide a highly interactive, critical learning experience. Some of the idealized models I plan to utilize for classroom instruction and student assignments include a one-dimensional cloud model, a two-dimensional slab model, and an axisymmetric model. The models will need to run quickly in order to be most effective for course instruction; thus, I believe it is desirable to avoid more complex three-dimensional models. The purpose of the models is to demonstrate classroom concepts in the simplest way possible, and such exhibitions should be easily attainable with two-dimensional models. For the mesoscale meteorology course, I anticipate using a one-dimensional cloud model to explore the effects of entrainment, precipitation loading, and pressure perturbations on rising parcels of air. I expect to use the two-dimensional slab model for student laboratory exercises on phenomena such as squall lines and gust fronts, in order to facilitate understanding of concepts such as the importance of vertical wind shear in the development of long-lived convective storms and the role of hydrostatic pressure gradients in the propagation of thunderstorm outflow boundaries. I also expect to use an axisymmetric model for for student laboratory exercises on tornadoes and their associated dynamics.

I am enthused by the fact that the simple models developed above have great potential to complement other courses in my department. Not only can students in the mesoscale meteorology class benefit, but the graduate level geophysical fluid dynamics or atmospheric convection students also can use the family of models to study density currents, shearing instabilities, gravity waves, etc. Undergraduate students taking thermodynamics also can put the one-dimensional cloud model to use to investigate parcel theory and deviations from parcel theory. I even hope that some student experiments will uncover new areas worthy of expanded study in a research setting using more sophisticated models or new observations.

2.) An Interactive, Immersive, Severe Storms Museum Exhibit

The College of Earth and Mineral Sciences at Penn State University, within which the Department of Meteorology resides, is in the process of creating new exhibits to occupy the newly renovated Earth and Mineral Sciences Museum. The museum's audience is broad, ranging from elementary school students on field trips, to prospective college applicants, to undergraduate classes, and even extending to the weekend football crowd. This component of the educational plan proposes the creation of a permanent exhibit in the new museum that will immerse museum visitors in the data collection experience of a severe storms atmospheric scientist (an appropriate area, given the interests and past research of the PI). In close collaboration with Dr. Russell Graham, Museum Director (and former director of the highly acclaimed Denver Museum of Natural History; see attached letter of support), the proposed exhibit will feature a scaled-down Doppler On Wheels system, whereby visitors will sit "inside" the truck and experience the collection of data. (The PI has been involved in several past collaborative efforts with the Doppler On Wheels and Dr. Josh Wurman from the Center for Severe Weather Research, including past radar courses at Penn State whereby the Doppler On Wheels radars were used by the students in the course.) The data that will be displayed on the screens will be from actual cases, and it is envisioned that some sort of voiceover will explain to visitors what they are seeing on the displays as the data are "collected."

The proposed exhibit also will feature a roughly 8-foot tall tornado chamber (depending on the layout of the museum, it might even be possible for the radar truck to be "scanning" in this particular direction). Perhaps because their construction is fairly straightforward, it might seem like so many atmospheric sciences exhibits around the country (at least the relatively few that are in existence) have some sort of similar device. However, the tornado chamber that is proposed will provide an interactive, "hands on" learning experience. Museum visitors (or perhaps even an undergraduate meteorology class as part of a lab exercise) will be able to modify the updraft strength and inflow circulation in order to experiment with how these parameters affect the structure of a tornado. The PI is not aware of any such similar tornado chambers open to the public elsewhere.

Finally, the exhibit also will showcase student research in the department, especially undergraduate research. For example, an undergraduate radar course has been jointly taught by the PI over the last three years (more information is available at <`http://www.meteo.psu.edu/~marko/teaching.html`>), whereby a two-part, six-credit course sequence was embedded within a local field experiment, called the Pennsylvania Mobile Radar Experiment (PAMREX; <`http://www.meteo.psu.edu/~marko/pamrex`>). The students collected and analyzed data within the lake-effect snowbands, frontal rainbands, and orographic precipitation common to central

Pennsylvania. Some of their work was presented at the 2006 American Meteorological Society student conference. The proposed museum exhibit would be a natural venue at which such student research activities could be showcased.

The overall goal of the proposed museum exhibit is not simply to entice patrons with "eye candy," but rather to fully immerse them in the discovery process that defines what science is through the interactive nature of the exhibit. During their time at the exhibit, patrons will get to *be* atmospheric scientists; they will experience the excitement of real data acquisition; they will leave with an impression of what science really is—a process of discovery whereby the truth is sought by posing and answering one question at a time, and the ultimate outcome is unbeknownst even to the scientist as the work is being carried out.

The budget for the museum exhibit is a combination of expendable materials and labor for Penn State's exhibit construction shop. It is anticipated that all of the museum construction can be carried out in-house. The total cost estimate has been obtained from a thorough analysis carried out by the PI and Museum Director. This part of the budget also includes one semester of support for an undergraduate student assistant during the exhibit construction period, who will be closely mentored by the PI and Museum Director.

3. Significance of the Proposed Research and Education Plans and Expected Impacts

The proposed research has a potentially broad range of ramifications. For example, accelerations of moist inflow to MCSs arising from surface layer decoupling beneath a large anvil canopy might well affect the dynamics and precipitation production, and therefore might have relevance to quantitative precipitation forecasts. There may be additional operational benefits of the proposed research related to convection initiation. For example, forecasters often are concerned when the cirrus from an MCS (or any cirrus, for that matter) overspreads their region and limits surface heating and the potential for storm development, which is sensitive to the amount of incident shortwave radiation. There also are obvious entailments for the generation of vertical vorticity within the updrafts of more isolated, long-lived convective storms, as a result of horizontal vorticity production within anvil-generated baroclinic zones.

The representation of cloud radiative transfer processes in large-scale models could perhaps benefit from the technique introduced in this proposal for correctly accounting for the geometry of regions influenced by cloud shading, which could easily be implemented in such models. The proposed methodology should considerably reduce the direct beam over that of the erroneous "clear sky" value that two-stream models would normally predict. Moreover, investigating the influence of anvils on the surface radiative budget will, itself, be of significant value since anvil cirrus are thought to have a major impact on the radiative budget of the tropics (e.g., Ramanathan et al. 1989). Furthermore, there may be feedbacks to the microstructure and radiative state of the anvil itself. For example, one might imagine that changes in storm dynamics due to the storm shadow may alter anvil characteristics through changes in fluxes of water mass into the anvil, changes in microphysical characteristics of the parent updrafts, and so on. Because this work has previously not been attempted, it also is likely that some additional unexpected findings will be made that cannot be foreseen at this time.

Finally, is worth stating that the proposed research is relatively cost-effective (no fewer than three graduate student degrees likely will be supported over the five-year period), and is guaranteed to produce positive results. No new data collection is required, for observations of anvil-generated radiative effects already exist, as cited in section 1b. It is also felt that this is an ideal opportunity for collaboration between the radiation (e.g., J. Harrington) and mesoscale (convection) communities. Such interaction has been rare in the past, but it is hoped that the fostering of such interaction might lead to fruitful collaborations beyond the one proposed herein.

Regarding the education plan, the simple, web-based numerical models will augment students' classroom instruction by way of laboratory exercises designed to promote creativity and critical thinking. Such exercises will challenge students to formulate and test their own hypotheses, and perhaps even will expose areas ripe for future rigorous scientific research. The proposed museum exhibit will expose undergraduate and pre-college students to scientific thinking, research, and careers.

4. Work Plan

Year 1. *Research Objectives:* Modify and test the ARPS radiation code. Begin simulations of isolated convective storms (likely supercells, given the large wind shear needed to produce a long anvil), with and without radiation, and using a fixed solar zenith angle. *Teaching Objectives:* Complete source code for model laboratory. Plan museum exhibit layout and make construction arrangements.

Year 2. *Research Objectives:* Conduct simulations of isolated convective storms with a time-varying solar zenith angle, and also with a variety of vertical wind profiles (storm-relative winds will be varied in order to alter the orientation of the low-level cooling relative to the low-level inflow direction; ground-relative winds will be varied at both low levels and upper levels in order to alter the ground-relative storm motion and the magnitude of the surface sensible heat flux). *Teaching Objectives:* Begin work with an undergraduate assistant on the web interface for the models. Museum exhibit construction is completed.

Year 3. *Research Objectives:* Conduct simulations using variable surface characteristics (soil type, soil moisture, vegetation cover). Begin MCS simulations with and without radiation for simple wind profiles well-known to promote long-lived convective systems. *Teaching Objectives:* Complete the web interface for the mesoscale simulation laboratory with an undergraduate assistant. Evaluate and update the museum exhibit.

Year 4. *Research Objectives:* Explore the sensitivity of the radiative-dynamic feedbacks to the microphysical parameterization and its effects on the anvil characteristics in the isolated convection cases. Also perform sensitivity experiments by varying the surface physics parameters and the time of day at which convection is initiated in the isolated convection cases. In the MCS simulations, vary the environmental wind profiles and surface characteristics. *Teaching Objectives:* Continue evaluating and improving the mesoscale simulation laboratory and web interface. Continue evaluating and updating the museum exhibit.

Year 5. *Research Objectives:* Complete MCS experiments and test the sensitivity to the surface physics parameterization, microphysics parameterization, and time of day. Perform additional simulations with smaller grid spacing on a case-by-case basis. *Teaching Objectives:* Work on evolving and extending the mesoscale simulation laboratory continues. Continue evaluating and updating the museum exhibit.

Funding is requested for one graduate student in years 1–5, and an additional graduate student in years 4–5. I envision the project will result in no fewer than three advanced degrees, at least one of which will be a Ph.D. I expect the project to result in several manuscripts suitable for publication in *Monthly Weather Review* and the *Journal of the Atmospheric Sciences*.

4. Results from Prior NSF Support

ATM-010307 (1/15/2002–1/14/2005, $246,789, "Collaborative Research: Measurement and Analysis of the Pre-Convective Boundary Layer and Convection Initiation during the International H_2O Project (IHOP)"

Summary of results

High-resolution wind syntheses constructed from overdetermined multiple-Doppler radar observations were integrated with photogrammetric cloud observations and remote and in situ thermodynamic observations in order to improve our understanding of the boundary layer processes favorable for convection initiation (e.g., the role of vortices along mesoscale boundaries, interactions between thermals and/or convective rolls and mesoscale boundaries, etc.). The observations were obtained during the International H_2O Project (IHOP) conducted in the southern Great Plains region during May–June 2002. One interesting finding in one of the cases studied was that deep cumulus cloud development was confined to a mesoscale boundary even though the boundary layer vertical velocity field was dominated by boundary layer convection rather than by the circulation associated with the mesoscale boundary. Trajectories into the deep cumulus clouds that developed along the mesoscale boundary were much more vertical than those entering the shallow cumulus clouds observed away from the outflow boundary. It is believed that the role of the mesoscale boundary in promoting deep cumulus cloud formation was to promote updrafts that were less susceptible to the dilution of equivalent potential temperature, which controls the potential buoyancy, vertical velocity, and depth that can be realized by the clouds. Another finding, based on analyses of several other cases, is that the degree of along-boundary updraft contiguity (termed "slabularity") is strongly influenced by the baroclinity of a mesoscale boundary and the strength of vortices that may develop along a boundary (vortices reduce slabularity whereas baroclinity increases slabularity). The magnitude of the slabularity might influence the mode of convection initiation (i.e., discrete cells versus a solid line of convection).

In addition to two M.S. theses (Christina Hannon and John Stonitsch) and roughly a dozen conference/workshop and/or invited lectures resulting from this activity, the following peer-reviewed publications have appeared or are scheduled to appear in the near future:

Markowski, P. M., and Y. Richardson, 2007: Observations of vertical wind shear heterogeneity in convective boundary layers. *Monthly Weather Review*, **135**, in press.

Stonitsch, J. R., and P. M. Markowski, 2006: Unusually long-duration, dual-Doppler radar observations of a front in a convective boundary layer. *Monthly Weather Review*, **134**, in press.

Markowski, P. M., and C. Hannon, 2006: Multiple-Doppler radar observations of the evolution of vorticity extrema in a convective boundary layer. *Monthly Weather Review*, **134**, 355–374.

Markowski, P. M., C. Hannon, and E. Rasmussen, 2006: Observations of convection initiation "failure" from the 12 June 2002 IHOP deployment. *Monthly Weather Review*, **134**, 375–405.

ATM-0133506 (4/15/2002–4/30/2006), $482,978, "Studies of the Internal Structure and Dynamics of Convective Weather Systems"

Summary of results

The organizational mode of quasi-linear convective systems often falls within a spectrum of modes described by a line of discrete cells on one end ("cellular") and an unbroken two-dimensional swath of ascent on the other ("slabular"). Convective events exhibiting distinctly cellular or slabular characteristics over the continental United States were compiled, and composite soundings of the respective inflow environments were constructed. The most notable difference between the environments of slabs and cells occurred in the wind profiles; lines organized as slabs existed in much stronger low-level line-relative inflow and stronger low-level shear.

A compressible model with high resolution ($\Delta x = 500$ m) was used to investigate the effects of varying environmental conditions on the nature of the convective overturning. The numerical results show that highly cellular convective lines are favored when the environmental conditions and initiation procedure allow the convectively generated cold pools to remain separate from one another. The transition to a continuous along-line cold pool and gust front leads to the generation of a more "solid" line of convection, as dynamic pressure forcing above the downshear edge of the cold outflow creates a swath of quasi-two-dimensional ascent. Using both full-physics simulations and a simplified cold-pool model, it was found that the magnitude of the two-dimensional ascent in slabular convective systems is closely related to the integrated cold-pool strength.

It is concluded that slabular organization tends to occur under conditions that favor the development of a strong, contiguous cold pool. The tendency to produce slabular convection is therefore enhanced by environmental conditions such as large CAPE, weak convective inhibition, strong along-line winds, and moderately strong cross-line wind shear.

This research was led jointly by Prof. J.M. Fritsch (prior to his retirement in 2004) and the PI. Two graduate students completed their Ph.D. dissertations while being supported by the project (George Bryan and Jeremy Ross), and one research associate (Richard James) also worked on the project. Over two dozen conference/workshop and/or invited lectures resulted from this activity, as well as over a half-dozen peer-reviewed publications. The peer-reviewed publications that involved the PI are listed below.

James, R. P., P. M. Markowski, and J. M. Fritsch, 2006: Bow echo sensitivity to low-level moisture. *Monthly Weather Review*, **134**, 950–964.

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Professional preparation

Pennsylvania State University, Meteorology; B.S., 1996
University of Oklahoma, Meteorology; M.S., 1997
University of Oklahoma, Meteorology; Ph.D., 2000

Appointments

Assistant Professor, Department of Meteorology, Pennsylvania State University, 2001–present
Graduate Research Assistant, University of Oklahoma, 1996–2000

Publications relevant to this proposal

Markowski, P. M., and Y. Richardson, 2007: Observations of vertical wind shear heterogeneity in convective boundary layers. *Mon. Wea. Rev.*, **135**, in press.

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Other significant publications

Markowski, P. M., J. M. Straka, and E. N. Rasmussen, 2003: Tornadogenesis resulting from the transport of circulation by a downdraft: Idealized numerical simulations. *J. Atmos. Sci.*, **60**, 795–823.

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Educational activities

- Instructor for secondary and high school teachers summer weather camp at Penn State University (2002, 2003, 2004, 2005, 2006)
- Instructor for middle and high school students weather camp at Penn State University (2002)
- Instructor and consultant for the *Passport to Knowledge* program for PBS (2000, 2001)

- Research Experiences for Undergraduates (REU) mentor (2002, 2003)
- Two peer-reviewed publications with undergraduate students (Hoch and Markowski 2005, *J. Climate*; Markowski et al. 2003, *Weather and Forecasting*)
- Over fifty interviews given to local, national, and international media on severe storms and tornadoes since 1997
- Adviser to over twenty undergraduate students, including four Schreyer Honor College students
- Undergraduate courses taught: *Synoptic Meteorology Laboratory*, *Mesoscale Meteorology*, *Observing Meteorological Phenomena* (a "writing-intensive" class), *Radar Observations and Analysis I and II*, *Introduction to Meteorology* (non-majors)
- Graduate courses taught: *Atmospheric Convection*, *Advanced Synoptic-Dynamic Meteorology*

Synergistic activities

- American Meteorological Society Science and Technology Advisory Committee (STAC) on Severe Local Storms (January, 2003–December, 2005)
- Program Committee, 22nd and 23rd AMS Conferences on Severe Local Storms (2004, 2006)
- Program Chair, Symposium on the Challenges of Severe Convective Storms (2006)
- Associate Editor, *Monthly Weather Review* (2006–present)
- Associate Editor, *Weather and Forecasting* (2005–present)
- National Weather Service (NWS) Quick Response Team (a twenty-person panel responsible for surveying violent tornado damage; 2003–present)
- Observing Facilities Advisory Panel (2005–present)
- Field experiments: International H_2O Project (IHOP; 2002), Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX; 1995), Radar Observations of Thunderstorms and Tornadoes Experiment (ROTATE; 2006), Pennsylvania Area Mobile Radar Experiment (PAMREX; 2003, 2004)
- Seminars frequently delivered at NWS offices and headquarters, guiding forecasters in applying new research findings in a real-time forecasting setting; nearly a dozen seminars delivered at offices spanning three of the four NWS regions in the contiguous 48 states, including two of the four NWS Regional Headquarters.

Recent collaborators

C. Alexander (OU), G. Bryan (NCAR), D. Burgess (CIMMS), R. Davies-Jones (NSSL), C. Doswell (CIMMS), D. Dowell (NCAR), M. Gilmore (UIUC), R. James (PSU), E. Rasmussen (CIMMS), Y. Richardson (PSU), J. Straka (OU), J. Verlinde (PSU), L. Wicker (NSSL), J. Wurman (CSWR), C. Ziegler (NSSL)

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