A Sublimation-initiated Mesoscale Downdraft and Its Relation to the Wind Field below a Precipitating Anvil Cloud

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ABSTRACT

A simple, one-dimensional model is developed to examine the potential for a sublimation-initiated mesoscale downdraft to influence the dynamics of the subanvil region by advecting horizontal momentum from a high-level precipitating anvil cloud downward into the middle or lower troposphere. Model results suggest that this vertical advection can occur on a time scale of several hours or less, although it is found to be highly dependent upon the snow mixing ratio within the overlying anvil cloud and lapse rates in the environment below. The study is motivated by an examination of data from a 50-MHz radar wind profiler on 24 June 1985 that suggests downward momentum advection from anvil base may have produced unbalanced flow in midlevels, owing to strong flow within the anvil and weak midlevel geostrophic winds. For this situation, we hypothesize that as the anvil cloud both dissipated and was advected horizontally away from the profiler site by the strong, upper-level winds, the downdraft weakened and an inertial oscillation began that slowly altered the midlevel airflow below the anvil cloud. This inertial oscillation appears to have persisted for hours after the mesoscale convective system dissipated, likely owing to the weak midlevel flow. While the model is not used to explain fully the observed profiler wind observations, the similarity between the evolution of the simulated and observed wind fields emphasizes the importance of ice microphysics to the dynamics of regions below precipitating anvil clouds.

The thermodynamic structure of the model-produced atmosphere after several hours of integration resembles the onion soundings frequently found behind convective systems in the tropics and midlatitudes. Previous observational studies show that the midlevel, near-saturated portion of the onion sounding is associated with mesoscale ascent. However, in the model simulations this structure is found in conjunction with mesoscale descent, suggesting that this thermodynamic signature may be associated with either midlevel ascending or descending flow fields.

1. Introduction

The importance of microphysical processes to the dynamics of mesoscale weather systems has become clear during the past decade, although it was suspected much earlier. Riehl (1965, 1969) and Zipser (1969) first hypothesized that evaporation of rain falling from extensive anvil clouds is an important mechanism for dynamical processes on the mesoscale; in particular the initiation and maintenance of mesoscale downdrafts underneath precipitating stratusiform cloud regions. Brown (1979) explored this hypothesis quantitatively using a two-dimensional numerical model and showed that evaporative cooling can induce a mesoscale downdraft beneath anvil regions that accounts for a large portion of the observed subsidence. Leary and Houze (1979) further suggested that the effects of melting can help initiate and maintain mesoscale downdrafts. Leary (1980) then used a kinematic, one-dimensional, steady-state model to show that a mesoscale downdraft can produce the observed temperature and humidity profiles found beneath anvil clouds in tropical convective systems (Zipser 1977). These temperature and humidity profiles frequently are referred to as “onion soundings” and also have been found within midlatitude mesoscale convective systems (MCSs; Ogura and Liou 1980; Smull and Houze 1987; Leary and Rappaport 1987; Johnson et al. 1989; Brandes 1990).

The diabatic cooling effects of sublimation, melting, and evaporation induce perturbation pressure gradients, which in turn can influence both the vertical and horizontal momentum fields. This effect was seen in a Doppler radar study of mesoscale wind perturbations induced by melting snow that found the spatial frequency of the wind perturbations matches the variation in the precipitation pattern (Atlas et al. 1969). The numerical study of Szeto et al. (1988a) yielded similar results. Using a two-dimensional model, it was shown that melting associated with a banded precipitation system produced a thermally direct mesoscale circulation that caused significant velocity perturbations in the flow field. In a companion paper, Szeto et
al. (1988b) looked at circulations produced by melting and evaporation underneath a large region of stratiform cloud as would be found to the rear of many MCSs. These circulations agree with the observations of front-to-rear flow above the 0 °C level and rear-to-front flow below the 0 °C level within mesoscale convective systems (see observational studies of Smull and Houze 1985, 1987; Chong et al. 1987; Leary and Rappaport 1987), suggesting that microphysical processes may contribute to these circulations. This result was not confirmed by Chen and Cotton (1988) who concluded that, in a two-dimensional simulation of a midlatitude MCS, cooling due to melting had little influence on the mesoscale circulations, although it strongly modulated the strength of convective-scale updrafts. However, ice-phase microphysics was shown to assist in the formation of the stratiform cloud region that had a persistent mesoscale circulation.

Detailed numerical studies of mesoscale convective systems using two-dimensional, nonhydrostatic cloud models (Chen and Cotton 1988; Lafond and Moncrieff 1989), and a three-dimensional, hydrostatic, mesoscale model (Zhang and Gao 1989) all indicate that microphysical processes play an important role in determining the intensity of velocity perturbations within and near stratiform cloud regions. Unfortunately, the causes of all the modifiying effects attributed to microphysical processes on the dynamics of mesoscale weather systems remain somewhat uncertain, owing to the complexity of multidimensional models, and a lack of detailed observational studies of the microphysics in precipitating stratiform regions.

The present study is intended to examine the potential for a sublimation-initiated mesoscale downdraft to influence the dynamics of the subanvil region by advecting horizontal momentum downward from a precipitating anvil cloud to the middle or lower troposphere. A simple, one-dimensional model is developed to address this issue with the explicit purpose of avoiding complicated three-dimensional features within stratiform anvil cloud regions, focusing instead on the effects of vertical advection of horizontal momentum to the dynamics of the region below anvil base. The study is motivated by observations from a radar wind profiler and soundings underneath an anvil cloud region that are discussed in section 2. The model is developed and results compared to observations in section 3, while the sensitivity of the model to varying environmental conditions and snow mixing ratios within the anvil cloud are discussed in section 4.

2. Observations

Winds sampled underneath the anvil cloud of a mesoscale convective system by a 50-MHz radar wind profiler located at Liberal, Kansas, are shown in Fig. 1 at half-hour intervals. The convective line along the leading edge of the MCS passed near Liberal between 0330 and 0400 UTC 24 June, producing the data void. However, winds prior to the passage of the convective line resemble those observed in the preconvective environment at Dodge City (Fig. 2). Weak winds were sampled between 3 and 5 km MSL and stronger, more northwesterly winds were sampled above 8 km. A closer examination of the preconvective environment (Fig. 2) shows a distinct three-layer structure. The boundary layer was warm and moist with strong southwesterly winds. Above the boundary layer, an elevated mixed layer (Carlson et al. 1983) was sampled from 730 to 450 mb that was characterized by weak winds. The third layer was the more stable layer above 450 mb with strong westerly winds, veering to northwesterly at 300 mb.

After passage of the convective line, the winds became stronger and more uniform in the midlevels and had a westerly-to-northwesterly component only observed in the upper troposphere prior to convection. This suggests that downward advection of horizontal momentum from the 8–9 km layer down to 4 km may have been important to the evolution of this wind field, although buoyancy gradients and other multidimensional effects also may have been acting (see Rotunno et al. 1988; Weisman et al. 1988; Parsons et al. 1988; Lafond and Moncrieff 1989; Fovell and Ogura 1989; Schmidt and Cotton 1990). The winds at most levels remained nearly constant from 0500 until 0700 UTC when they began to veer. By 0900 UTC 24 June the winds between 4.5 and 7 km MSL were almost northerly. An examination of infrared satellite images (Fig. 3) indicates that the timing of the initial veering of the winds at 0700 UTC was roughly one-half hour after the anvil cloud was advected horizontally to the east of Liberal. This suggests that the scale of the perturbed circulations was larger than the cloud shield of the MCS and remained after the system passed. It is unlikely that this veering of the wind can be attributed to the large-scale environment, since the midlevels were characterized by weak winds across much of the central Plains states in contrast to the fairly strong northerly winds observed at 0900 UTC 24 June between 4.5 and 7.0 km MSL (Fig. 1).

A sounding from Russell, Kansas, at 0440 UTC 24 June (Fig. 4) is chosen to illustrate the environment within the cloud shield of the convective system. The temperature and dewpoint curves of this sounding are reminiscent of onion soundings found near the trailing stratiform regions of tropical and midlatitude convective systems (Zipser 1977; Houze 1977; Ogura and Liou 1980; Smull and Houze 1987; Leary and Rappaport 1987; Brandes 1990). The midlevel winds in this sounding were much stronger than those in the preconvective environment, and backed with height from the bottom of the dry-adiabatic layer at 650 mb to the anvil base at 320 mb. Surface observations from Russell between 2300 UTC 23 June and 0400 UTC 24 June mentioned rain showers south and southwest of the...
station with broken clouds at 5000 and 25 000 ft; it is apparent that significant amounts of precipitation had been falling out of the anvil but not reaching the ground (i.e., remarks indicating the presence of virga) prior to the sounding launch. Note the similarity between the wind profiles from the profiler data at 1130 UTC (Fig. 1) and the 0440 UTC Russell sounding (Fig. 4); both these observations occurred approximately 6-7 h after the anvil was first observed above these locations. This event is more completely described by Stensrud and Maddox (1988) and Johnson et al. (1989).

The close correspondence between the initiation of the veering winds and the disappearance of the anvil cloud over Liberal leads us to consider what effect an anvil cloud could have on the atmosphere below. We chose to explore further the effects of a precipitating anvil cloud on the temperature, moisture, and momentum field below anvil cloud base. We realize fully that the wind field observed by the radar wind profiler likely was strongly influenced by the three-dimensional circulations of the nearby MCS. Our goal is not to examine all the possible reasons for these observations, but rather to focus upon the effects of one possible causative mechanism. With these caveats in mind, we hypothesize that a sublimation-initiated mesoscale downdraft originating at anvil base can advect horizontal momentum downward into the middle troposphere within a few hours. When the midlevel geostrophic winds are different from the winds at the base of the precipitating anvil, this downward momentum advection produces an unbalanced, midlevel momentum field. As the anvil cloud dissipates (or is advected away), thereby stopping the downward advection of momentum, the unbalanced flow field responds by starting an inertial oscillation. This oscillation would produce veering winds if the wind perturbation is stronger than the geostrophic value, as indicated by the profiler data (Fig. 1).

The ageostrophic wind component is estimated from the profiler data to determine if the wind oscillation has a frequency near the inertial one. After examining upper-air analyses and time series of the profiler wind data prior to convection, a constant geostrophic wind of 5.0 m s⁻¹ from 300° is chosen for the 6.1-km level. The ageostrophic winds for this level are shown in Fig. 5. A pure inertial oscillation would rotate 90° in 5 h at the latitude of the profiler site; oscillations near this rate are found. Similar oscillations are found in the

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**Fig. 1.** Winds observed using the 50-MHz radar wind profiler located at Liberal, Kansas. The convective line passed near Liberal between 0330 and 0400 24 June 1985, causing the data void. Full barb equals 5 m s⁻¹.
profiler data between 5.0 and 7.0 km, suggesting that our hypothesis is viable.

3. One-dimensional model simulations

A very simple one-dimensional model is developed to investigate the role of sublimation in the initiation and maintenance of mesoscale downdrafts that may develop below precipitating anvil clouds. The model results are compared with the profiler and sounding data from 24 June 1985 to determine the plausibility that vertical advection of horizontal momentum plays a role in the wind field evolution below precipitating anvil clouds. The simplest possible framework that can be used to explore this hypothesis requires the incorporation of vertical advections of temperature, water substance, and momentum, the effects of buoyancy and water loading, and Coriolis and horizontal pressure gradient forces. Horizontal advective contributions are assumed small, the horizontal pressure gradient force is constant, and the ambient atmosphere is hydrostatic.

The model employs parameterized expressions for the form and phase changes of water substance and associated hydrometeor growth and decay (Lin et al. 1983; Ziegler 1985). The hydrometeor content is divided into separate, size-distributed categories of cloud droplets, rain drops, cloud ice, snow, and graupel. Thus, the model equations are

\[
\frac{\partial w}{\partial t} = -\frac{w\partial w}{\partial z} + g \left( \frac{\partial \theta}{\partial \theta} \right) - 1 + 0.61(q_v - \bar{q}_v)
\]

\[
- q_c - q_r - q_i - q_s - q_e + D_w
\]

\[
\frac{\partial u}{\partial t} = -\frac{w\partial u}{\partial z} + f(v - v_x) + D_u
\]

\[
\frac{\partial v}{\partial t} = -\frac{w\partial v}{\partial z} - f(u - u_x) + D_v
\]

\[
\frac{\partial \theta}{\partial t} = -\frac{w\partial \theta}{\partial z} + S_\theta + D_\theta
\]
\[
\frac{\partial M}{\partial t} = - \frac{\partial M}{\partial z} + S_M + D_M \\
\frac{\partial N}{\partial t} = - \frac{\partial N}{\partial z} + S_N + D_N,
\]

where \( D_i \) represents a diffusion term, \( S_i \) represents microphysical terms, \( f \) is the Coriolis parameter, \( u_p \) and \( v_p \) are the two components of the geostrophic wind, \( M \) denotes either the water-vapor mixing ratio \( q_v \), cloud mixing ratio \( q_c \), rain mixing ratio \( q_r \), cloud-ice mixing ratio \( q_{ci} \), snow mixing ratio \( q_s \), or graupel mixing ratio \( q_g \), and \( N \) denotes the concentrations of cloud water \( N_c \), rainwater \( N_r \), and graupel \( N_g \). Bars over individual variables refer to the initial undisturbed state. The \( S_i \) terms in the equations parameterize the effects of evaporation, condensation, nucleation, self-collection, accretion, deposition, sublimation, freezing, melting, riming and sedimentation following Ziegler (1985). The time-independent horizontal pressure gradient force is replaced by the geostrophic wind relationship at each model level. Thus, while the model equations are a very simplified, one-dimensional version of the ones used by Klemp and Wilhelmson (1978), they incorporate more realistic microphysics by including the effects of ice, snow, and graupel. A similar set of equations were used by Srivastava (1987) to examine the mechanisms of intense downdraft formation, while Leary (1980) used a kinematic, one-dimensional model to examine mesoscale unsaturated downdrafts.

For these studies the model domain is located between the top of the planetary boundary layer and the base of the stratiform anvil cloud. Thus, complicated boundary-layer processes and radiative effects also are neglected. The model grid resolution is 150 m and the integration is accomplished using forward-in-time, upstream differencing and a time-splitting procedure. The time-splitting procedure is used to reduce computational time by updating the microphysical processes every 20 s; whereas, the model advective time step is only 1 s. A zero-gradient outflow boundary condition is used at domain bottom, and at domain top when \( w > 0 \) (\( w = 0 \) otherwise at domain top).

Analysis of aircraft measurements in the anvil of a
High Plains MCS by Heymsfield (1986) reveals a lack of liquid water and a predominance of lightly rimed or unrimed snow crystals and aggregates. The observed ice-water contents can be used to calculate snow mixing ratios for the various aircraft penetrations. Penetration average values range from 0.6 to 1.4 g kg$^{-1}$ and were observed at least 50 km, but not more than 80 km, downwind of the updraft core at heights above 9 km. Based on sensitivity tests, and the fact that the convective line passed close to the profiler site, a snow mixing ratio of 0.7 g kg$^{-1}$ is used in the model to represent conditions within the anvil cloud. The water-vapor mixing ratio is assumed ice-saturated at the highest model level to approximate conditions within the anvil cloud. All other mixing ratios [refer to Eq. (1)] are initially set to zero.

The Dodge City sounding (Fig. 2) from 0000 UTC 24 June 1985 is used for the model initial conditions, since it was taken ahead of the convective line and was representative of the preconvective environment. The model does not incorporate boundary-layer effects, so the model bottom is chosen to be just above the boundary layer at 700 mb. Model top is chosen to be at 320 mb where the base of the anvil was sampled by several rawinsonde observations taken within the cloud shield at a later stage of the MCS lifecycle. The observed winds from Dodge City are assumed geostrophic and used in the calculations of the horizontal momentum tendencies. This is an approximation to the actual geostrophic value, but sensitivity tests indicate that the model results are not affected greatly by this simplification. Since the observed winds at 9.0 km during the time the anvil was above the wind profiler only change by 5.0 m s$^{-1}$ and resemble the winds in the preconvective environment (see Fig. 1), the winds within the anvil are assumed constant.

Half-hourly infrared satellite images are used to estimate the amount of time the anvil cloud was present above Liberal (see Fig. 3). These images indicate that anvil cloud was over Liberal between 0400 and 0630 UTC 24 June. Therefore, the snow mixing ratio within the anvil cloud is specified to be 0.7 g kg$^{-1}$ for the first
two model hours and then is decreased to zero within the next one half-hour. This approximates very crudely the observed evolution of the anvil cloud that was both dissipating and being advected horizontally away from the profiler site. It also is possible that graupel was present and falling out of this anvil cloud. Several simulations with graupel are conducted and discussed in section 4.

The location of the one-dimensional model within the region of the convective system requires some discussion. The model assumptions should apply wherever an extensive high-level anvil is introduced above a region void of active convection or strong mesoscale circulations. Exactly where in a mesoscale convective system these conditions are met is a difficult question. It is well known that convectively induced horizontal buoyancy gradients can generate horizontal momentum (Rotunno et al. 1988; Weisman et al. 1988; Parsons et al. 1988; Lafore and Moncrieff 1989; Fovell and Ogura 1989), and that mesoscale internal gravity waves can produce circulations that transport momentum both vertically and horizontally (Schmidt and Cotton 1990). The exact distribution of these, and other, multidimensional effects within any given anvil cloud system is unknown, as is the degree to which the model assumptions are valid. However, one way to assess the model assumptions using the available data is to compare the model results with observations.

The horizontal winds from this simulation are shown at half-hour intervals using a time–height cross section (Fig. 6). The descent of westerly winds with time indicates that horizontal momentum from anvil cloud base is advected downward to near the bottom of the model domain within only 2 h. When the downdraft ceases after 2.5 h, the winds veer rapidly between 3.3 and 6.3 km. This represents the flow response to being geostrophically unbalanced by the vertical advection of horizontal momentum. The mesoscale downdraft advects stronger westerly momentum into an environment characterized by weak geostrophic winds. As long as the downdraft is maintained, the downward momentum advection dominates the Coriolis terms in the simplified horizontal momentum equations (2)–(3). However, once the mesoscale downdraft diminishes, owing to reduction of snow in the anvil cloud, the Coriolis accelerations of the ageostrophic wind dominate, and the unbalanced wind field veers in response to the inertial force. A close examination of the model results indicate that while the model does not reproduce quantitatively the precise amplitude or phase of the observed wind oscillations, the similarity between the evolution of the simulated and observed winds is striking.

The model predicted sounding after 2 h of integration (Fig. 7) is typical of those observed within and behind the trailing stratiform regions of many tropical and midlatitude convective systems (Zipser 1977; Houze 1977; Ogura and Liou 1980; Smull and Houze 1987; Leary and Rappaport 1987; Brandes 1990), and is similar in many respects to the Russell sounding (Fig. 4) taken in a different region of the MCS. Thus, the model produces a reasonable vertical thermodynamic structure. Although the midlevel, near-saturated region in an onion sounding (the region above 450 mb in Fig. 7) frequently is associated with a mesoscale updraft (Ogura and Liou 1980; Leary and Rappaport 1987; Brandes 1990), these model results indicate that mesoscale downdrafts also may be associated with this thermodynamic structure (see Fig. 8). It appears that once an onion-type thermodynamic structure is established, there is little resistance to vertical motion of either sign as the forcing evolves. Indeed, the momentum field influenced by the sublimation-initiated mesoscale downdraft (Fig. 6) extends well below the simulated cloud base at 450 mb.

The model-predicted fields of vertical motion are shown in Fig. 8 at half-hour intervals for the first 2 h of model integration. At 30 min the vertical motion already is strong with a maximum downward motion just above the melting level. The regions above 500 mb where the vertical motion approaches zero are found to correspond to changes in the environmental thermodynamic structure. In particular, stable layers appear to neutralize the effects of sublimative cooling and ice loading on vertical motion fields in this one-dimensional model by the dry-adiabatic compressional warming associated with negative buoyancy-driven
downdrafts. This effect continues to be seen near the stable layer at 450 mb as the vertical motion approaches zero for all model times at this level. The buoyancy-driven downdraft is over 2.5 m s\(^{-1}\) within 30 min and thereafter slowly increases to nearly 4.0 m s\(^{-1}\) by 2 h into the simulation. This downdraft is stronger than areally averaged values calculated in studies of stratiform rain regions (Srivastava et al. 1986; Chong et al. 1987; Rutledge et al. 1988; Smull and Augustine 1989; Stumpf et al. 1991), but less than the observed localized downdrafts of up to 5 m s\(^{-1}\) described by Stumpf et al. (1991). The large values of vertical motion produced by the model are due partly to the neglect of mass continuity, and likely are larger than would be produced with a multidimensional model. After 2 h the model downdraft decreases rapidly as the snow mixing ratio within the anvil cloud is decreased to zero to approximate the effects of the movement of the anvil cloud away from the site.

The large values of vertical motion cause the horizontal momentum from the anvil region to be advected quickly into the middle troposphere. Smaller values of vertical velocity acting over the same time interval produce shallower layers characterized by veering winds. Thus, the qualitative evolution of the wind oscillations remains the same, while the depth of the atmosphere that is affected by these wind oscillations is sensitive to the magnitude of the vertical motion field. A secondary maximum in vertical velocity near 400 mb and a large gradient of downdraft speed from the melting level at 560 mb to the domain bottom are both present throughout the model run. These downdrafts at temperatures below freezing are forced by sublimation of water vapor from precipitating snow crystals and snow crystal loading, while the stronger downdraft at 575 mb is forced by the cumulative effects of sublimation, melting, evaporation, and loading. Further examination reveals that the downdraft initially is forced by sublimative cooling and particle loading, although within only 30 min the effects of melting and evaporation begin to increase the strength of the downdraft at and below the melting level located at 560 mb.

To illustrate the relative effects of sublimation, melting, and evaporation on the strength of the downdraft, the instantaneous cooling rates are calculated for these three processes at 2 h into the model integration (Fig. 9). The effects of sublimative cooling are seen over a very deep layer, with a decrease in cooling near the 450 mb stable layer due to a decrease in the sub-saturation with respect to ice. Below this stable layer
the environmental lapse rate becomes dry adiabatic and subsaturation increases, causing an increase in sublimative cooling. A maximum cooling due to sublimation of $-10^\circ C \text{ h}^{-1}$ is reached just above the melting level. Once the snow particles melt, evaporation becomes the dominant process for maintaining and strengthening the downdraft. The dry-adiabatic character of the atmosphere below the melting level, with increased subsaturation as parcels descend, leads to evaporation of most of the hydrometeors within the first kilometer below the melting level. The maximum cooling rate due to evaporation at 2 h into the model integration is $-12.8^\circ C \text{ h}^{-1}$. In contrast, the effects of melting are felt over a fairly shallow layer with a maximum cooling of $-9.5^\circ C \text{ h}^{-1}$. Although the cooling rate due to melting slowly increases during the model integration, it is the least important of the three mechanisms for maintaining and strengthening the downdraft. However, the total rate of cooling due to the additive effects of evaporation and melting is maximized at and just below the melting level.

The heating–cooling profile for this case (not shown) indicates the atmospheric temperature profile changed very little during the model simulation. Maximum temperature changes are less than $1^\circ C \text{ h}^{-1}$ throughout the entire vertical domain. This is in contrast to the heating–cooling profiles observed during deep convection in which temperature increases of $10^\circ C \text{ h}^{-1}$ are commonly observed (Fritsch and Chappell 1980). Thus, while the precipitating anvil produces a downdraft that advects horizontal momentum downward rapidly, and causes significant changes in the momentum field, the net heating is small.

4. Sensitivity tests

Sensitivity tests are conducted to determine the amount of snow necessary to create a strong $|w| > 1$
mesoscale downdraft within 2 h after the anvil cloud began precipitating. These results are summarized in Table 1 for various values of the snow mixing ratio. It is found that a snow mixing ratio of roughly 0.3 g kg$^{-1}$ is adequate to create a strong mesoscale downdraft. Indeed, a downdraft of $-1$ m s$^{-1}$ is created within 1 h. In this case, sublimation of water vapor from snow creates near ice-saturated conditions above 450 mb, allowing most of the snow to fall below this level before beginning to sublimate. Increased subsaturation below 450 mb causes greater sublimative cooling, yet numerous snow crystals still survive long enough to reach the melting level where the effects of melting and evaporation create a more vigorous downdraft. Snow mixing ratios much less than 0.3 g kg$^{-1}$ cause the model to take a long time (more than 2 h) to create near ice-saturated conditions above 450 mb, so the resulting mesoscale downdraft stays above that level. On the other hand, a snow mixing ratio of 0.5 g kg$^{-1}$ produces a strong mesoscale downdraft within 30 min. Also note that decreasing the snow mixing ratio leads to increasing the height of the maximum downdraft as well as diminished downdraft intensity. These differences highlight the sensitivity of the model to the snow mixing ratio assumed to represent conditions within the anvil cloud.

The model results also are compared against observational studies to determine if the model produces reasonable heating and cooling rates from the microphysical parameterizations. The diagnostic study of the stratiform region of a MCS by Rutledge and Houze (1987) suggests that snow mixing ratios within stratiform regions at least 80 km behind the leading convective lines are on the order of 0.1–0.5 g kg$^{-1}$. The cooling rate due to melting calculated by the model for a snow mixing ratio of 0.5 g kg$^{-1}$ is 3.6°C, in agreement with the observationally based calculation of the cooling rate due to melting from Smull and Houze (1987) for a midlatitude MCS, and within the range of cooling rates calculated by Leary and Houze (1979) for tropical convective systems. Leary and Houze (1979) calculated the cooling rate due to evaporation...
to be in the 0.2°–6.0°C h⁻¹ range, less than the model calculated rate of 10.6°C h⁻¹ for a snow mixing ratio of 0.5 g kg⁻¹, but in agreement with the cooling rates for lower snow mixing ratios.

Since the convective line passed near the radar wind profiler, it is possible that graupel was present and falling out of the anvil cloud. Simulations that included nonzero mixing ratios at anvil base for both snow and graupel are used to examine the effects of graupel on the development and maintenance of the mesoscale downdraft. Anvil mixing ratios of 0.5 g kg⁻¹ for both graupel and snow produce a strong downdraft that advects momentum from domain top to domain bottom within 2 h as in the control simulation (no graupel and a snow mixing ratio of 0.7 g kg⁻¹). Thus, less snow with the addition of graupel also can explain the rapid downward advection of horizontal momentum suggested by the profiler observations between 0330 and 0430 UTC 24 June (Fig. 1).

These sensitivity tests suggest that different environ-

![Figure 9](image)

**Fig. 9.** Plot of model predicted heating rates vs height and pressure at 2 h into the integration for sublimation (a), melting (b), and evaporation (c). Rates are in degrees Celsius per hour (°C h⁻¹).

**Table 1.** Sensitivity tests of one-dimensional model with various snow mixing ratios used to represent conditions within the anvil cloud. Model values of maximum downdraft strength (w), maximum instantaneous cooling rate due to the combined processes of sublimation, evaporation, and melting (ΔT), and pressure at which peak downdraft occurs (p_min) are listed for each test after 2 h of integration using initial soundings from Dodge City at 0000 UTC 24 June 1985, and from Wichita at 0547 UTC 24 June 1985.

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<td>q_s (g kg⁻¹)</td>
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ments would produce different responses to the input of snow falling from a stratiform anvil cloud. To explore the effects of differing environmental thermodynamic profiles on the development of a mesoscale downdraft further, the 0547 UTC 24 June sounding from Wichita (Fig. 10) is used for the model initial conditions. This sounding shows a significantly drier atmosphere in the midlevels with a lapse rate much more stable than that at Dodge City or Russell (Figs. 2 and 4). An anvil is indicated above 315 mb, suggesting the potential for snow to be falling and sublimating into the environment below. The model domain is again chosen between 700 and 320 mb. The snow mixing ratio within the anvil is set constant at 0.5 g kg$^{-1}$ throughout the integration, a value more appropriate to stratiform cloud regions at least 80 km away from active convection (Rutledge and Houze 1987).

The model-predicted sounding (Fig. 11) after 2 h of integration is moist throughout a deep layer between 600 and 330 mb and a significant westerly component is seen in the winds. This is a dramatic change from the initial sounding (Fig. 10) that captures a dry atmosphere with strongly veering winds above 600 mb. For the entire 2 h of the simulation the magnitude of the downdraft remains below $-1.0$ m s$^{-1}$ and varied with height owing to the lapse rate changes observed at Wichita. The dry character of the midlevel atmosphere over Wichita, in conjunction with the more stable lapse rate, produces a different response to the input of snow falling from the anvil cloud. The snow sublimates and quickly increases the water vapor to near ice-saturated conditions just below the anvil base above Wichita. However, the atmosphere is dry in the midlevels, requiring ice-saturated conditions to be created by sublimation before the snow could fall through the midlevels. In addition, conditionally unstable lapse rates are increasingly stable, with respect to forced vertical motions, the more they depart from the dry-adiabatic lapse rate (Krumm 1954; Brown et al. 1982; Srivastava 1987; Doswell 1987). Cold air parcels that
descend dry adiabatically quickly become warmer than the environment. Therefore, the downdrafts that form over Wichita are limited in vertical extent.

This effect also is seen in the sensitivity tests using different snow mixing ratios to represent the anvil cloud over Wichita (Table 1). Cooling rates are similar to those from the Dodge City simulation, yet the downdrafts are weaker and smaller in vertical depth for the lower snow mixing ratio simulations. The downdraft only becomes more intense after the dry-adiabatic layer near the bottom of the model domain is reached in the 1.0 g kg\(^{-1}\) snow mixing ratio simulation. This highlights the importance of the environmental lapse rates to the evolution of the sublimation-initiated downdraft.

5. Discussion

Data from a radar wind profiler on 24 June 1985 show that the horizontal winds observed underneath the anvil cloud of a mesoscale convective system were roughly uniform throughout a deep layer, in contrast to the sheared wind profile observed before convection. The midlevel winds underneath the anvil had a stronger westerly-to-northwesterly component only seen in the upper troposphere prior to convection, suggesting downward advection of horizontal momentum from upper-levels to midlevels as one possible explanation. As the anvil cloud overhead was advected horizontally away from the profiler site and dissipated a few hours later, these winds veered throughout a deep layer. We hypothesize that a sublimation-initiated mesoscale downdraft can advect horizontal momentum from a precipitating anvil cloud downward into the middle troposphere within a few hours. This downward momentum advection produces unbalanced flow in midlevels when the vertical wind shear is large in the upper troposphere. As the downdraft weakens, owing to the movement of the MCS away from the profiler site and
the dissipation of the cloud shield, an inertial oscillation begins that slowly alters the midlevel airflow below and behind the anvil cloud base.

A very simple, one-dimensional model is used to test the plausibility of this hypothesis. The model is formulated to incorporate only the most fundamental physical processes needed to explore the mechanisms involved. Thus, vertical advections of temperature, water substance, and momentum are allowed with nonzero Coriolis and a constant pressure gradient. The effects of buoyancy and water loading also are included. Horizontal advections are assumed small.

The model results indicate that a sublimation-initiated mesoscale downdraft originating at anvil base near 320 mb can advect horizontal momentum downward over a depth of 4 km within 1–2 h. The temperature and humidity profiles the model produces are typical of the onion soundings frequently observed behind convective systems (Zipser 1977), indicating that the model is capable of reproducing a reasonable thermodynamic structure for this region of the MCS. Although the midlevel, near-saturated portion of onion soundings frequently are associated with mesoscale ascent (Ogura and Liou 1980; Leary and Rappaport 1987; Brandes 1990), the model produces a similar structure with descending motion throughout the model domain. This suggests that mesoscale descent below a high-level anvil cloud also can produce this thermodynamic structure. The upper-level winds within the anvil are stronger than the geostrophic winds in the midlevels, so the downward advection of horizontal momentum unbalances the midlevel flow. When this vertical advection of momentum ceases, owing to the prescribed decrease of snow mixing ratio at anvil base (used to approximate the effects of a dissipating cloud shield and the movement of the MCS away from the region of interest), the unbalanced midlevel wind field responds by beginning an inertial oscillation. The similarity between the evolution of the simulated and observed wind fields suggest it is plausible that the effect of a sublimation-initiated mesoscale downdraft on the wind field underneath a precipitating anvil cloud could be important, especially in environments with weak midlevel winds and strong vertical wind shear in the upper troposphere. Indeed, the circulations produced by the downward advection of momentum may persist for hours after the anvil cloud is advected away or dissipates if the midlevel momentum field is weak.

These results can be synthesized with previous studies (Smull and Houze 1985, 1987; Leary and Rappaport 1987; Brandes 1990) to form a slightly modified conceptual picture of a mesoscale convective system that emphasizes the importance of cloud microphysical processes. A schematic cross section based on this synthesis is shown in Fig. 12. It is apparent that the area of surface stratiform rain encompasses only a portion of the cloud shield produced by the MCS. Some of the snow present in the stratiform rain region is likely carried into other regions of the cloud shield before melting. Therefore, snow is falling out of the anvil over an area much larger than just the stratiform rain region, initiating downdrafts that advect momentum through a deep layer (possibly up to several hundred millibars). While the magnitudes of the sublimation-initiated mesoscale downdrafts are less than the downdrafts observed near active convection, they likely occur over a much larger area. Hence, the global, or integrated, effect of sublimation-initiated mesoscale downdrafts on the subanvil momentum budget may be substantial.

The importance of ice microphysics to the dynamics of mesoscale convective systems has been shown in the modeling study of Zhang and Gao (1989). In a three-dimensional simulation of a MCS using a hydrostatic mesoscale model they found that the development of strong rear-to-front flow (rear inflow) is most sensitive to moist downdrafts, hydrostatic water loading, evaporative cooling, and ice microphysics, in that order. For their case the midlevel winds are strong and the strongest wind shear is confined to levels below 500 mb. Although ice microphysics is not found to be the

![Fig. 12. Illustration of the hypothesized flow with a mesoscale convective system. The 0° and −30°C isotherms are noted, as are the positions of the surface mesohigh and mesolow. Arrows denote horizontal and vertical flow directions, while the dashed-dotted line near the surface indicates position of surface outflow.](image-url)
most important parameterization, it is a necessary factor in the development of a strong rear inflow that reached the surface.

Rear inflow was present on 24 June 1985 and was sampled by the 0440 UTC 24 June Russell sounding (Fig. 4). This sounding is reproduced fairly well by the model (Fig. 7) and, more importantly, is typical of trailing stratiform cloud regions (Zipser 1977). The good agreement between the structure of the simulated winds and the observed winds at Russell make us wonder to what extent the rear inflow on this day was influenced by the vertical advection of horizontal momentum, and a subsequent inertial oscillation. Parsons et al. (1988) and Lafond and Moncrieff (1989) indicate that rear inflow can be generated by horizontal buoyancy gradients along the back edge of convective systems creating a circulation that accelerates the midlevel air toward the system. Schmidt and Cotton (1990) suggest that internal gravity waves and vertical perturbation pressure gradients may have a significant influence on MCS structure, including the development of rear inflow. These mechanisms also may explain the creation of the midlevel, ageostrophic wind components underneath the anvil cloud. But the veering winds observed after the MCS cloud shield dissipated are highly suggestive of an unbalanced flow field responding to Coriolis accelerations, regardless of how the imbalance is produced.

The results of our simple, one-dimensional model have interesting, and possibly important, implications in the field of multidimensional mesoscale numerical modeling. The initial temperature and water vapor profiles in the model affect the evolution of sublimation-initiated downdrafts markedly. Sensitivity tests generally suggest that dry (moist) environments take longer (shorter) periods of time to produce a deep, mesoscale downdraft, although the actual vertical distribution of lapse rates is crucial to the strength of the downdraft. Horizontal gradients of temperature and relative humidity also influence the circulations within multidimensional models. Vertical wind shear above 500 mb is necessary to produce unbalanced flow in the midlevel wind field once the downdraft begins. However, the vertical wind distribution often is simplified in modeling studies, with the wind shear confined to the lower levels of the atmosphere, and with idealized temperature and mixing ratio profiles that are assumed to be horizontally uniform. The results of the one-dimensional model suggest that these simplifications may be quite limited for examining the dynamics of inherently three-dimensional mesoscale convective systems.

This study suggests that the evolution and distribution of the snow mixing ratios within an anvil cloud affect where and when high-based mesoscale downdrafts initiate and dissipate. However, the snow mixing ratios are dependent upon the trajectories of individual snow crystals and the distributions of cloud ice and cloud water. Since snow mixing ratios are probably highly variable within the cloud shield of a convective system, they may be difficult to determine accurately. More complex and detailed parameterizations of the cold-cloud microphysics may be necessary to model properly the snow mixing-ratio evolution and distribution within anvil clouds. We hope that the interrelations of cloud microphysical processes to the dynamics of cloudy, precipitating weather systems may be better understood with the aid of improved cold-cloud microphysical parameterizations in mesoscale models, particularly if the model results lead to specific observational verification strategies.

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