Mesoscale Convective Systems in Weakly Forced Large-Scale Environments.  
Part II: Generation of a Mesoscale Initial Condition

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ABSTRACT

A series of five mesoscale convective systems (MCSs) developed within a weakly forced large-scale environment on 11 and 12 May 1982. Two of these systems had a large component of motion against the midtropospheric flow and propagated in a direction nearly opposite to that of the traveling upper-level disturbances. This description of the evolution of convection is very different from traditional ones in which convection develops and moves more or less in phase with traveling upper-level disturbances. Observations indicate that the initiation and evolution of convection are tied to mesoscale features that are not well observed by the conventional observing network, making the structure of the model initial condition a potentially crucial factor in the success or failure of any subsequent numerical simulation. It is found that the initial conditions created using the conventional initialization procedure of The Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model do not include several of the mesoscale-sized features observed at 1200 UTC 11 May 1982, 9 hours before the development of the first MCS. This is attributed to the lack of observed data with mesoscale resolution, and, therefore, likely is a deficiency in most initialization procedures in use today. Although it is true that new operational observing systems, such as the WSR-8DD radar and the 404-MHz radar wind profilers, provide more detailed information, the data density on the mesoscale remains subcritical. A methodology to include mesoscale features, based upon using subjective interpretations of all the available observations, is developed. It is found that the mesoscale initial condition created using this subjective approach produces a more reasonable representation of the observed mesoscale features in comparison with the conventionally produced initial condition.

I. Introduction

Mesoscale models have shown substantial skill in producing not only the correct rainfall magnitude during deep convective events but also the timing, placement, and evolution of convection (Anthes et al. 1982; Molinari and Corsetti 1985; Zhang and Fritsch 1986, 1988b; Zhang et al. 1989). However, this predictive skill has been documented only for cases in which strong large-scale forcing for upward motion was present (defined here as upward vertical motions of greater than 1 \( \mu \text{b s}^{-1} \) in the mid- and upper troposphere). In Stensrud and Fritsch (1993, hereafter Part 1), we documented the lack of strong large-scale forcing during the development and evolution of a series of five mesoscale convective systems (MCSs) during a 24-h period beginning 1200 UTC 11 May 1982. Observational evidence suggests that deep convection initiated only in regions where lifting associated with mesoscale features (such as an outflow boundary or dryline) was able to eliminate the restraining inversion and allow parcels to reach their level of free convection. The evolution of these five MCSs, owing to the importance of mesoscale forcing, was very different from the more typical scenario where convection develops and moves in association with a traveling upper-level disturbance (Maddox et al. 1986). Instead, the traveling disturbance on this day moved through the regions of convection in a direction opposite to the overall movement of the convective area. While this traveling disturbance modified the large-scale environment, it did not produce sufficient upward motion to dominate the movement of the MCSs.

The numerical simulation of this complex event presents a test of the ability of research mesoscale models to simulate convective events in the absence of strong and well-defined large-scale forcing. Whereas previous studies have demonstrated the importance of including appropriate model physics to the realistic simulation of MCSs (Zhang and Fritsch 1986, 1988a;
Zhang 1989; Zhang and Gao 1989), the importance of the mesoscale features to the development and evolution of convection (as indicated by the observations in Part I) strongly suggests that the realism of the model initial condition is equally, if not more, important to the successful simulation of this event. This is attributed to the difficulty of adequately sampling mesoscale features when the current, and proposed, observational networks have a minimum resolution on the large scale (defined here as features having wavelengths greater than 1000 km). While new observing systems, such as the WSR-88D radar and the radar wind profilers, provide more detailed mesoscale wind information, the thermodynamic structure of the atmosphere is sampled only twice a day using the large-scale resolution rawinsonde network. Since Blumen (1972) and Fritsch et al. (1992) have shown that for some small-scale and mesoscale features the winds tend to adjust to the mass field, it is apparent that thermodynamic data with mesoscale resolution are just as critical to the creation of a mesoscale initial condition as wind data. Moreover, except for regions within about 40 km of the WSR-88D radar sites, the winds in the lowest kilometer of the atmosphere are poorly defined.

The inability of the observational network to sample mesoscale features that may play important roles in the subsequent numerical simulations necessitates the use of other means to incorporate these features into the initial condition. Although four-dimensional data assimilation (FDDA) is a potential solution to this difficulty (e.g., Lewis and Derber 1985; Talagrand and Courtier 1987), the sensitivity of numerical models to the specific initial locations of deep convection (Fritsch and Chappell 1981) and to the details of the parameterization scheme and trigger function (Kain and Fritsch 1992) suggest that using FDDA to incorporate mesoscale features, especially when generated by convective activity, is an approach fraught with difficulty (Stensrud and Bao 1992). Using artificially constructed data to augment the observations is another potential solution. This approach was taken by Zhang and Fritsch (1986) in their simulation of the 1977 Johnstown flood, in which a special gridded dataset of temperature, dewpoint depression, and horizontal wind components (developed by L. F. Bosart) was used in creating the model initial condition. This also is the approach we have selected.

The purpose of the present paper is to present a methodology by which one can examine a particular model initial condition subjectively and create artificially constructed soundings to augment the operational datasets in order to include mesoscale features in the model initial condition. Augmentation of operational datasets appears to be particularly important in weakly forced large-scale environments in which knowledge of the mesoscale structure of the atmosphere is likely essential for a successful numerical simulation, although mesoscale features may play important roles in delineating where and when convection develops and organizes for events with stronger large-scale forcing as well (e.g., Fujita and Stiegl 1985; Doswell and Burgess 1988). This augmentation process is not a trivial undertaking, however, and it certainly is not an objective approach easily adaptable to automation. A great deal of subjective understanding, combined with knowledge of the particular model physics and model initialization procedures, is required. Nonetheless, results from this single case may provide some useful guidance on how to make an assessment of the quality of any model initial condition and will hopefully start a more active and open discussion on the difficulties involved in the generation of model initial conditions with inadequately observed mesoscale structures.

Section 2 reviews the conventional initialization process and discusses a few issues involving data quality control and representativeness. Section 3 illustrates a method to assess the quality of the conventional initial condition and discusses several important mesoscale features that are not well sampled by the operational observing network. A new mesoscale initial condition that includes several mesoscale features is produced and compared with both observations and the conventional initial condition in section 4. Rainfall totals from model runs using both a conventional and mesoscale initial condition also are discussed, although a more complete discussion of the model runs will be found in Part III of this study.

2. Conventional initialization

Conventional initial conditions for The Pennsylvania State University (PSU)—National Center for Atmospheric Research (NCAR) Mesoscale Model (Anthes and Warner 1978; Anthes et al. 1987) are produced from three-dimensional analyses of temperature, relative humidity, and horizontal wind components at constant pressure surfaces plus analyses of sea level pressure and ground temperature (or sea surface temperature over water) at the model coarse gridpoint locations. For this study, the number of grid points (x, y) on the coarse grid are (48, 46), the grid spacing is 75 km (Fig. 1), and the analyses are produced for 22 constant pressure surfaces. These pressure surfaces are created at 25-mb intervals from the surface to 750 mb, in order to reproduce adequately the boundary and inversion layer structures, and are created at 50–100-mb intervals from 750 to 100 mb. The first guess is produced from the European Centre for Medium-Range Weather Forecasts (ECMWF) global analyses (Lorenc 1981; Trenberth and Olson 1988). The first-guess fields are modified using observational and/or artificially created data with a successive-correction objective analysis technique (Benjamin and Seaman 1985) and a circular weighting function (Cressman 1959). After the analyzed three-dimensional fields are produced, these gridded data are interpolated to the 30
model sigma coordinate layers, and the integrated mean divergence in a column is removed to reduce error growth in the model simulation (Washington and Baumhefner 1975). The last step in the initialization process interpolates the coarse grid values to the nested grid. For more information on the PSU–NCAR model, see Anthes and Warner (1978), Zhang and Fritsch (1986), Anthes et al. (1987), and Zhang (1989).

The first step in the initialization process is to assess whether or not the sounding has any obvious errors (see Schwartz and Doswell 1991). For example, the Stephenville, Texas, sounding from 1200 UTC 11 May (Fig. 2a) shows a region of high lapse rates between 790 and 760 mb above the moist layer. Normally an inversion is present in this layer. This large separation between the heights of the inversion base and the moist-lower top suggests that the temperature sensor was wetted as it went through the stratus cloud deck and produced an inaccurate measurement (from evaporative cooling) until the sensor dried out. The base of the inversion is lowered to be just above the top of the moist layer to correct this problem.

The second step is to ascertain whether the sounding is representative of the surrounding environment. With the 400-km average station spacing of the rawinsonde network in the United States, the question of representativeness is an important one. Objective analysis schemes use weighted averages of nearby data points (observations) to construct the gridded analyses. Thus, the influence of one sounding extends far beyond its spatial location. Great care must be taken to assess the representativeness of each sounding with respect to the surrounding environment. If a sounding has been modified by local processes (i.e., convection, local wind circulations), then it should either be modified to make it more representative or discarded before producing the objective analysis.

Soundings from Omaha, Nebraska, and Topeka, Kansas, are found to be highly modified by local convective processes and are removed from the input dataset used in the objective analysis procedure. The Omaha sounding (Fig. 2b) is a typical onion-type sounding frequently found behind MCSs in the Tropics and midlatitudes (Zipser 1977; Ogura and Liou 1980; Smull and Houze 1987). It was taken on the back edge of the convection that developed over Nebraska and had moved into Iowa by the time of the sounding launch. In contrast, the Topeka sounding (Fig. 2c) shows a very deep moist layer with almost no restraining inversion. Surface data reports indicate that the outflow was approaching Topeka as the sounding was taken, suggesting that low-level rising motion ahead of the gust front likely had a strong influence on the sampling of the atmospheric thermodynamic structure. Both of these sounding structures owe their existence to local convective effects and likely are not representative of the environments more than 40 km distant. Indeed, these soundings may not be representative of the environments just a few kilometers distant.

The last difficulty in terms of raw sounding data is that the levels of the inversion bases across the southern plains states vary between 830 and 770 mb. In the initialization package, soundings are interpolated to selected constant pressure surfaces and then are objectively analyzed to model grid points. Therefore, representations of restraining inversions at the grid points in the initial conditions can vary substantially from the observations in regions between the observed sounding locations owing to the smoothing effect of objective analysis. Thus, on five soundings the inversion bases are either raised or lowered (by at most 30 mb) to 800 mb to provide a more uniform representation of inversion strength, while the observed values of convective inhibition are maintained. An alternate procedure would be to objectively analyze values of convective inhibition to the grid points and adjust the gridpoint soundings if their values of convective inhibition depart too far from the objectively analyzed values. This approach, however, is beyond the purpose of the present study. It may be that this particular aspect of the model initialization problem is related to the particular model initialization package being used; however, the importance of inversion strength to convective initiation suggests that this problem may arise in other initialization packages as well.

It also is important to examine the surface data for accuracy and the temporal continuity of features. The best approach is to examine carefully the surface data that are thrown out from the quality control routine to determine whether or not these data are truly erroneous. Data that are judged to be accurate can then be inserted.
into the input dataset and the objective analysis redone. Owing to a greater data density, this process is straightforward and needs little discussion.

3. Comparisons with subjective analyses

Once there is confidence in the observations used to initialize the model, the conventional initial condition is produced and compared with subjective analyses. In particular, regions in the conventional initial condition where high-gradient features are indicated by the subjective analyses are examined carefully to determine whether or not these features are reproduced well. For example, a number of high-gradient features that are potentially important in simulating mesoscale convective phenomena, and yet are not well sampled by the operational network, are the following.

1) Low-level jets. Maddox (1983) and Cotton et al. (1989) indicated that low-level jets are an important factor in the development and evolution of long-lived,
organized, mesoscale convection. Maddox (1985) illustrated that the low-level jet evolves differently under different environmental conditions. These evolutions are distinct in terms of the height and timing of the low-level wind maximum. Maddox found that warm, dry air masses produce a lower and earlier low-level wind maximum in comparison with the wind maximum produced in cool, moist air masses. This suggests that an inaccurate specification of the thermodynamic structure of the environment might lead to an inaccurate low-level jet evolution and adversely influence the simulation of convective development and evolution.

2) Cloud boundaries. It is well known that cloud-radiation interactions are important to numerical simulations of the flow within MCSs (e.g., Tripoli and Cotton 1989). However, the problem is exacerbated in mesoscale modeling, since the placement of cloud edges often is inaccurate owing to the use of low horizontal resolution rawinsonde data to produce the model initial condition. Observations indicate that relatively small differences in relative humidity occur between clear and overcast boundary layers (Betts and Boers 1990). Therefore, large horizontal differences in the local surface energy budget can be created easily through objective analysis procedures that smooth the horizontal boundary layer moisture content, since the low-level moisture influences the model-defined boundaries between cloudy and clear skies.

3) Frontal boundaries. In their study of an 8-day MCS episode, McAnelly and Cotton (1986) found that convective elements within MCSs tend to originate along meso-β-scale axes, such as frontal boundaries. Johns and Hirt (1987) found that MCSs producing strong winds frequently move along a quasi-stationary thermal boundary. Further studies by Fortune et al. (1992), Smull and Augustine (1993), and Trier and Parsons (1993) have documented the influence of frontal boundaries on MCS evolution. In all of these studies, warm and moist air is transported over and above the frontal surface, producing the conditional instability needed for deep convection. Convection to the north of the front typically is weaker and higher based in comparison with convection to the south of the front, where the convection is surface based and intense. The accurate placement and slope of the frontal boundary likely would be crucial to the successful simulation of these MCSs.

4) Drylines. The dryline is an extremely sharp moisture gradient that over the plains states separates moist air flowing northward from the Gulf of Mexico from drier air flowing eastward from the western states and Mexico. The sharpness of the changes in temperature and moisture along the dryline were documented by Beebe (1958), Fujita (1958), and the National Severe Storms Project (1963). Rhea (1966) found that convection often is initiated near the dryline, illustrating the importance of the dryline to the thunderstorm climatology of the plains states. An organized line of veering winds often is found in the vicinity of the dryline, although not necessarily coincident with the strongest moisture gradient (Matteson 1969).

5) Convective outflows. A convective outflow is a pool of evaporatively cooled downdraft air that spreads out horizontally along the ground beneath a precipitating cloud. Outflows are important because some of the environmental air approaching the outflow likely will be lifted up and over it. This lifting process is an important mechanism for the development of new convection as indicated by observational (Byers and Braham 1949; Wilson and Schreiber 1986; Schmidt and Cotton 1989) and numerical studies (Mitchell and Hovermale 1977; Droegemeier and Wilhelmson 1985a,b). Rotunno et al. (1988) further show that the balance between the vorticity in the outflow and the environment ahead of the convection may determine the vertical alignment of the convective updrafts. However, besides the study of Fujita (1959a), very little work has been done on both the observed mesoscale thermodynamic and wind structures within mesoscale-sized outflows.

6) Surface characteristics. The planetary boundary layer plays a critical role in the development of mesoscale convective weather systems. The large fluxes of heat, moisture, and momentum that occur in this layer often can set limits on the types of weather phenomena that can be produced on a given day. While the surface radiation balance drives the boundary layer evolution, characteristics of the landscape determine the relative amounts of sensible and latent heat flow in the boundary layer. During the past decade the importance of landscape characteristics, such as vegetation, soil moisture, surface roughness, and soil type, has been shown clearly through observational studies (Rabin et al. 1990) and the use of numerical models that attempt to simulate the boundary layer realistically over mesoscale-sized regions (Anthes 1984; Mahfouf et al. 1987; Chang and Wetzel 1991).

Subjective analyses of all available data are compared with the conventional initial condition to determine the likely importance of these six features to the subsequent numerical simulation. Of course, in the research mode there is the added educational benefit of being able to see how well the model simulates a given event before making any modifications to the initial condition, and we learned a great deal from this approach. However, subsequent experience with other MCS events leads us to believe that crucial mesoscale features can be determined prior to running the simulation. Comparisons between the conventional initial condition and the subjective analyses are discussed below for the five features that are considered to be represented inadequately at 1200 UTC 11 May 1982: (a) low-level moist tongue, (b) dryline, (c) frontal zone, (d) landscape characteristics, and (e) mesoscale convective outflows. While there are other localized fea-
tures apparent in the available data, these five features are the ones deemed most important for correctly simulating the evolution of deep convection.

It is important to note that while most of the mesoscale features are included by adding artificially created soundings to the input dataset and then running the objective analysis program, producing the mesoscale-sized convective outflow is done at the model gridpoint level after the objective analyses are complete (see Fig. 3). A feature as sharp and distinct as a convective outflow is impossible to create when using an objective analysis procedure that, by definition, analyzes the fields based upon the data values at nearby points. This process smoothes the mesoscale outflow over an unrealistically large area, and correspondingly, the vertical motion field forced by the outflow is reduced severely. Thus, the mesoscale convective outflow is added to the initial conditions after all the synoptic-scale objective analyses are completed and before the integrated mean divergence in a column is removed. Initially, the fields produced by the coarse mesh objective analysis procedure over the outflow region are constructed in an attempt to represent the preconvective environment that would have been present prior to the development of convection.

a. Low-level moist tongue

The subjective synoptic-scale analysis of the 850-mb surface (Fig. 4a) shows a moist tongue extending from the Gulf coast to Iowa. The eastern edge of the moist tongue passes to the west of Longview, Texas, and Monett, Missouri. The shape and position of this moist tongue is based upon 1200 UTC 11 May upper-air, surface, and satellite data from the previous 12 h. The 850-mb mixing ratio field generated by the conventional initialization (Fig. 4b) does not compare well to the subjective analysis, owing in large part to the removal of the Omaha and Topeka soundings from the input dataset. This is a good example of how removing data owing to their unrepresentativeness in certain key respects can produce difficulties at a later time in the modeling process. Therefore, artificially created soundings that represent a likely preconvective environment must be added to eliminate this deficiency (Fig. 5). In northern Kansas and Iowa the soundings are constructed to represent an environment having a deep moist layer off the surface capped by a moderately strong inversion. The resulting mesoscale initial condition (Fig. 4c) reproduces more accurately the approximate location and extent of the moist tongue as suggested in the subjective analysis.

b. Winds over sloping terrain and near the frontal zone

There are three regions where the observed wind field and the wind field from the conventional initial conditions do not agree well. First, surface observations indicate westerly winds across the sloping terrain of eastern New Mexico (Fig. 6a), whereas surface winds from the nested grid of the conventional initial condition are southwesterly (Fig. 6b). Second, surface data indicate northerly winds in east-central Colorado, whereas the model initial condition has southwesterly or westerly winds. Last, note the northwesterly winds reported in far northwestern Kansas (Goodland), where the model winds are northeasterly. Part of the difficulty in creating an appropriate representation of the surface in sloping, or complex, terrain in the United States is the progressively lower density of surface observations west of the eastern Colorado border, so artificially created surface stations are inserted in between the reporting stations to improve upon the conventional initial condition. The vertical consistency of the winds in regions of sloping
terrain also is examined, and artificially created soundings are added where the winds in the lowest few model levels switch abruptly from the surface values (Fig. 5). The vertical extent and turning of the low-level winds is guided by the boundary layer depth and turning indicated in the conventional initial condition.

The wind field from the mesoscale initial condition (Fig. 6c) shows that the low-level wind features along the sloping terrain and near the cold front are more in agreement with what one would expect based upon the surface data. In the simulation, the remaining errors in the wind field dissipate with time as the mass and wind fields approach a balanced state. It cannot be claimed that errors are eliminated through the use of the artificially created surface stations and soundings, but it is hoped that errors are reduced and that the observed mesoscale features suggested by the surface and upper-air data are retained to a larger degree within the mesoscale initial condition.

c. Surface characteristics

The distribution of land-use variables, such as roughness length, albedo, thermal capacity, and emissivity, are initially determined from land-use data available at NCAR. There are nine land-use categories in the dataset (Anthes et al. 1987) and at each grid point a rep-
representative value of land use is assigned. Since Zhang and
Anthes (1982) showed that changes in moisture availability
have the greatest effect on boundary layer evolution
in comparison with changes in the other land-use vari-
able, and since moisture availability can be highly vari-
able from week to week (or even day to day), the values
of moisture availability are altered from the climatological
ones. A modified distribution of moisture availability is
prescribed using sensitivity tests by assuming that the
model can reproduce a representative boundary layer
structure given the proper input land-use variables (see
Mahfouf 1991) based upon a conserved variable
approach as discussed by Stensrud (1992). Briefly, the
model boundary layer evolution produced using climato-
logical land-use variables is compared with the ob-
served evolution based upon surface observations. The
difference between the best-fit trends of boundary layer
potential temperature and mixing ratio derived from the
model output and the observations is used to define new
values for the land-use variables. These new values of
land use produce a boundary layer evolution that more
closely fits the observations.

d. Convective outflows

Incorporating the mesoscale convective outflow into
the model initial condition is the last step in the initial-
ization process. The mesoscale initial condition produced
above using the artificially created soundings does not
include any of the effects of deep convection. One im-
portant reason for not using artificially created soundings
to reproduce an outflow structure is that outflow features
change rapidly over short distances. This structure is dif-
ficult to reproduce using an objective analysis procedure
based upon data having large-scale, or even mesoscale,
resolution, especially near the edge of an outflow where
gradients in temperature, mixing ratio, and wind com-
ponents are large. In these regions, objective analysis pro-
cedures weaken the gradients in contrast with the ob-
servations. Instead, the observed surface data are used to
infer outflow depth, and the outflow is constructed di-
rectly on the model coarse grid points (see Fig. 5) using
a simple conceptual model of outflow structure.

Fujita (1959b) and Wakimoto (1982) concluded that
the pressure rise behind the gust front is due to the
increased hydrostatic pressure caused by the cold air.
This suggests that if a perturbation surface pressure due
to the outflow can be extracted from the observations,
and if the temperature lapse rate in the cold outflow can
be approximated reasonably well, then the outflow
depth can be estimated. The first step in incorporating
an outflow is to produce a mesoanalysis of the surface
pressure data and determine the extent and shape of
the outflow. There are only a few (usually less than 10)
surface reports available to define the outflow at any
given time; therefore, other information, such as sat-
ellite and radar data, is used to guide the analysis. The
satellite and radar images are examined to determine

FIG. 5. Map showing locations of observed soundings, as indicated
by their three-letter station identifiers, and artificially created sound-
ings. Parentheses enclosing the three-letter identifier indicates that
the sounding is discarded from the input dataset owing to concerns
with data representativeness. The symbol # indicates artificially cre-
ated soundings added to improve the representation of the moist
tongue, the symbol + indicates soundings added to improve the rep-
resentation of the low-level wind field, the symbol @ indicates
soundings added to improve the representation of the restraining
inversion, and the symbol * indicates locations of coarse grid dot points
that are modified to include the mesoscale outflow.

where cold-air production may still have been occurring.
Time-space conversion, which uses hourly and
special surface reports (Fujita 1963), is employed to
help generate the most accurate mesoanalysis of the
pressure field. A large-scale pressure analysis that ne-
glects all the surface reports within the outflow at the
initialization time is then subtracted from the com-
pleted mesoanalysis. The difference field (Fig. 7) rep-
resents the estimated perturbation surface pressure
cau sed by the convection.

Once a convective pressure perturbation is known,
the outflow depth is determined by assuming a moist-
adiabatic lapse rate and constant relative humidity
within the outflow. Observed surface temperatures and
dewpoints from within the outflow region are used to
determine a representative wet-bulb potential tempera-
ture and the relative humidity. The hydrostatic rela-
tionship is then used to calculate the cold-air depth re-
quired to produce the perturbation pressure at each
coarse mesh grid point. In the present case, the outflow
depth is restricted to be less than or equal to 100 mb.
This depth is a conservative estimate, since Fujita
(1959a) and Schmidt and Cotton (1989) have shown
outflows with maximum depths between 2 and 3 km (although these outflows had associated surface pressure perturbations between 3 and 7 mb!). If the surface pressure perturbation at a specific grid point is not reached at this maximum depth, then the wet-bulb potential temperature within the outflow is uniformly decreased (holding the relative humidity constant) until either the observed pressure perturbation is equaled or a value of wet-bulb potential temperature calculated for an undiluted downdraft initiated at the level of free sink (Foster 1958) is reached.

Specification of the wind field within the outflow is another important consideration. For example, the greatest uncertainty in the outflow surface winds at

Fig. 6. Analyses valid 1200 UTC 11 May 1982 from (a) surface observations showing temperature, dewpoint (°F), and winds (full barb is 5 m s⁻¹); (b) conventional initial condition showing lowest model surface winds; and (c) mesoscale initial condition showing model surface winds. Model surface winds are calculated by interpolating the lowest model-level winds to a 10-m height using a neutral log wind profile. The analysis conventions are from Young and Fritsch (1989).
1200 UTC 11 May occurs in far northeastern Kansas and Iowa (Fig. 6a), where there are few reporting stations. In northeastern Kansas the wind direction is chosen to be northwesterly, producing divergent surface flow within the mesohigh as frequently observed (Fujita 1959a; Stensrud and Maddox 1988; Schmidt and Cotton 1989), and the wind speed is chosen to be equal to that reported at the nearby site of Manhattan, Kansas. To produce divergent surface flow within the portion of the mesohigh in Iowa, the surface winds there are made to be southwesterly.

The outflow wind field above the surface largely is unobserved. The Omaha sounding is the only sounding that sampled this outflow; thus, observations of this highly variable mesoscale wind field are subcritical. Wakimoto (1981) presents evidence that the strong wind shifts associated with some outflows may be confined to the lowest 500 m or less, with wind directions shifting back to ambient values aloft. In addition, there may be substantial variability in the wind field from case to case (Fujita 1959a). Instead of producing an outflow with large variations in the vertical wind profile, a simple relationship is used to specify a uniform variation of the wind with height. The outflow winds are assumed to veer 40° and decrease 3 m s⁻¹ from their surface values for every 1000 m in height above the surface to a minimum wind speed of 3 m s⁻¹; therefore, maximum divergence occurs at the surface and decreases with height as depicted in the composite mesohigh in Fujita (1959a). It is emphasized that these specifications are arbitrary and based on very subjective decisions made after examining the references available on mesoscale-sized outflows (e.g., Fujita 1959a,b) and direct study of over 30 other outflow soundings. Fortunately, within the shallow, stratified outflow region the wind field should adjust to the mass field (Blumen 1972; Fritsch et al. 1992), suggesting that the initial winds are not as important to the model simulation as the initial thermodynamic structure.

While the Omaha sounding (Fig. 2) was discarded from the input dataset used to create the mesoscale initial condition (since it was altered by local convective processes) and while it was not sufficient by itself to provide a reasonable approximation to the wind field within the outflow, it does provide information on the thermodynamic structure of the atmosphere within the outflow region. As mentioned previously, this is an onion-type sounding typical of environments behind MCSs; the onion-shaped thermodynamic structure is produced through subsidence at the back edge of stratiform regions of MCSs (Johnson and Hamilton 1988; Johnson et al. 1989; Stumpf et al. 1991). The presence of the onion shape so close to the surface appears to be a local feature [surface pressure perturbations due to the outflow are a minimum near Omaha (Fig. 6), suggesting a weak mesowow may have formed behind the convective line]. Since a visible satellite image from 1345 UTC 11 May (Fig. 8) shows clear skies behind the outflow leading edge where convection was present earlier, suggesting that subsidence has occurred, it is likely that an onion-type thermodynamic structure is present in the midlevels above the surface outflow. Thus, the midlevel thermodynamic structure within the outflow region is altered to produce an onion profile. Temperatures within the onion are distributed vertically such that there is no change in the derived surface pressure, and winds in the layers above the low-level cold pool are not modified.

4. Mesoscale initial condition

Once the outflow structure is inserted at the appropriate grid points within the coarse mesh (Fig. 5), the
Fig. 9. Initial conditions at 1200 UTC 11 May 1982 from (a) mesoscale initial condition and (b) conventional initial condition. Surface plots depict temperature, dewpoint (°F), and winds (full barb is 5 m s⁻¹) interpolated to a 10-m height using the neutral log-wind profile. Sea level pressure contoured every 2 mb. Additional wind barbs are depicted in the outflow region in (a). The analysis conventions are from Young and Fritsch (1989).

Fig. 10. Differences between the low-level model winds (m s⁻¹) from the mesoscale initial condition and the conventional initial condition for (a) the u component of the wind and (b) the v component of the wind. Positive values in (a) indicate that the mesoscale initial condition has a larger westerly wind component than the conventional initial condition, while positive values in (b) indicate that the mesoscale initial condition has a larger southerly wind component than the conventional initial condition.
teractive nested grid (Zhang et al. 1986), the Fritsch-Chappell convective parameterization scheme (Fritsch and Chappell 1980), and an explicit bulk microphysics scheme for resolvable-scale precipitation (Hsie et al. 1984; Zhang 1989). The model framework is discussed in Part III, or the reader can refer to Zhang et al. (1989) for further details. Twenty-four-hour simulations using a conventional initial condition, where none of the input data are altered or deleted (to better approximate what is produced by automated initialization packages), and the mesoscale initial condition are conducted to illustrate the importance of the mesoscale features to the evolution of deep convection in the model. The model physics are the same in both simulations.

Rainfall totals from these two simulations at 24 h show significant differences in the location and magnitude of rainfall over the southern plains states (Fig. 12). As discussed in Part III, the rainfall pattern produced using the mesoscale initial condition is similar to the observations, with a zone of heavy (>5 cm) rainfall stretching from east-central Kansas south into Oklahoma, and only small rainfall totals in north-central Kansas. In addition, the simulation using the mesoscale initial condition produces significant rainfall in north-central and southern Oklahoma, whereas the simulation using the conventional initial condition keeps all the heavy rainfall in Kansas. This is attributed to the inability of the simulation using a conventional initial condition to produce a long-lived MCS that was observed in Oklahoma during the early morning of 12 May. Comparisons of the modeled rainfall totals with the observed totals over Iowa and Texas also show distinct improvements when using the mesoscale initial condition in producing not only the correct magnitude of rainfall but the location as well.

Admittedly, neither simulation produces a perfect evolution of events, but the difficulty of this particular situation was one of the deciding factors in choosing it for study. This event tests the ability of a mesoscale model to provide useful guidance in one of the most difficult forecasting situations—a day with the potential for both severe thunderstorms and heavy rainfall when the large-scale forcing is weak. Results presented here and in Part III indicate that mesoscale models may be capable of producing useful simulations of convective weather events when the large-scale forcing for upward motion is weak, including quantitative precipitation forecasts with the correct magnitude and approximate location of regions of heavy rainfall, but that the mesoscale features present at the model initial time must be included in the model initial condition.

5. Discussion

Producing model initial conditions that include mesoscale structure likely will be easier in the near future since mesoscale, tropospheric wind features will be observed routinely. The National Weather Service
(NWS) is beginning to deploy the WSR-88Ds across the United States. A nationwide network will be in place within the next decade. These radars can be used to monitor the evolution of the low-level wind field during clear-air conditions (Rabin and Zrnić 1980), as well as to monitor precipitation and precipitation motion (see Doviak and Zrnić 1984). In addition, a 30-unit demonstration network of 404-MHz radar wind profilers currently is in place across the plains states (Chadwick 1988). These profilers sample the horizontal winds from 0.5 to 16.25 km above ground level at 0.25-km vertical increments. Hourly averaged horizontal winds from the profiler network and hourly observed clear-air winds from the WSR-88D network will be disseminated routinely through the NWS operational data stream. Therefore, while it is not possible at
present to sample mesoscale variations in the environmental wind and thermodynamic structure, the more dense combination of WSR-88D and radar wind profiler networks will be able to detect mesoscale wind features that may have a significant influence on the initiation and subsequent evolution of convection. Unfortunately, a serious remaining difficulty with the new wind observing systems is their inability to sample the boundary layer winds over large portions of the intervening areas between observing sites. Moreover, the thermodynamic fields still are sampled only twice a day with the large-scale rawinsonde network, indicating that there remains a major deficiency in mesoscale observations for the foreseeable future.

To help in the creation of initial conditions that include mesoscale features when mesoscale observations are not available, or subcritical, this study has illustrated a methodology to examine a particular model initial condition subjectively and to create artificially constructed soundings to augment the operational datasets. Augmentation of operational datasets appears to be particularly important in weakly forced large-scale environments in which knowledge of the mesoscale structure of the atmosphere likely is essential for a successful numerical simulation, although mesoscale features may play important roles in events with stronger large-scale forcing as well (e.g., Fujita and Stiegl 1985; Doswell and Burgess 1988). Even though many ad hoc assumptions are necessary in the application of these techniques, owing to our less than complete understanding of mesoscale and convective phenomena, model results indicate that the initial condition that includes the observed mesoscale features (the mesoscale initial condition) produces a more accurate evolution of events than the initial condition that lacks these mesoscale features (the conventional initial condition). Rainfall magnitudes are more correct when using the mesoscale initial condition, and the locations of regions of heavy rainfall produced are qualitatively similar to the observations in general location, orientation of heavy rainfall regions, and areal coverage.

This sensitivity to the mesoscale features in the model initial condition illustrates the importance of incorporating such details in any operational initialization procedure. While we do not argue that the details artificially inserted into the initial condition are errorless, the importance of these details to the subsequent numerical simulation is clear. The subjectivity involved in producing mesoscale features in model initial conditions may be reduced by using four-dimensional data assimilation techniques. However, the assimilation approach must include the effects of parameterized convection, as indicated by radar or satellite during the assimilation period, and other high-gradient features that are not always well sampled by the observations, and this likely will prove to be a difficult problem (Fritsch and Chappell 1981; Kain and Fritsch 1992; Stensrud and Bao 1992). The benefit of using an assimilation method is that the model fields are internally consistent with the model physics, reducing any shock that a static initialization may create. At present, however, the best method to incorporate these mesoscale features into any model initial conditions appears to be human intervention within the initialization process.

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