The Influence of Mesoscale Humidity and Evapotranspiration Fields on a Model Forecast of a Cold-Frontal Squall Line

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(Manuscript received 26 June 1995, in final form 2 July 1996)

ABSTRACT

Satellite imagery and rain gauge data are combined to create mesoscale detail in the initial states of relative humidity (RH) and surface moisture availability (M) for a mesoscale model simulation. The most profound impact of inserting the mesoscale initial fields was the development of a strong vertical circulation transverse to an intensifying cold front that triggered an intense frontal rainband similar to a severe squall line that was observed to develop explosively. This paper explores the causative factors leading to the formation of this intense circulation and the sensitivity of the model to the mesoscale initial fields.

A substantial gradient in the initialized RH and M fields occurred across the cold front in the region where the observed frontal squall line formed. In contrast to the control run, the model simulations that incorporated the mesoscale initial analysis displayed considerable daytime warming just ahead of the front. This warming was due principally to a reduction in the RH (and, hence, low-level cloud cover) east of the front, although an increase in the cross-frontal M gradient did contribute about 25% of the warming. Increased sensible heat fluxes at the expense of decreased latent heat fluxes led to a much deeper and well-mixed prefrontal boundary layer, a more erect frontal surface, and an updraft jet just ahead of the front. A density current–like flow developed in the cold air immediately behind the front only in the presence of this cross-frontal gradient in sensible heating. Much improved forecasts of the location and timing of the frontal squall line and other precipitation systems resulted from the mesoscale initial analysis. The initial RH and M fields possessed sufficient resolution and consistency with the model dynamics to have a positive influence on the forecasts for a period of at least 12 h.

This study provides evidence that differential cloud cover and evapotranspiration fields can have important impacts on frontal behavior when strong synoptic dynamics are present. Future research should attempt to improve the modeling of evapotranspiration processes, develop more objective satellite-based humidity analysis techniques, and obtain in situ mesoscale data for verification of the retrieved atmospheric and soil moisture fields.

1. Introduction

This study was motivated by observations that cross-frontal cloud differences seem to intensify and contract the scale of continental cold fronts (Koch 1984; Dorian et al. 1988). The common feature in these events is the existence of an overcast low cloud deck behind the front and scattered clouds or clear skies in the warm air ahead of the front during the morning hours. A narrow (<10 km wide) band of shallow but vigorous “line convection” has been observed to develop at the leading edge of the front by early afternoon, with an associated narrow “clear zone” at the leading edge of the stratocumulus deck behind the line convection (Fig. 1). Koch (1984) hypothesized that the line convection, which occurs in the absence of precipitation, is a manifestation of a microscale updraft jet at the front driven largely by the differential sensible heating across the front. A multiple case investigation of line convection–clear zone events by Dorian et al. (1988) reveals that frontogenesis is related to the behavior of this phenomenon and that the nature of the clear zone is tightly coupled

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to the diurnal heating cycle. Their analysis suggests that if sufficient convective available potential energy (CAPE) is present in the local environment, then the thermally forced circulation caused by the precursor cloud contrast across the cold front is sufficient to trigger squall-line activity.

The motion of such fronts has been found to agree well with the speed of propagation of steady density currents. On the other hand, Smith and Reeder (1988) caution that frontal systems are often unsteady, and it is not clear that the cold air is advected toward the front by an extensive “feeder flow,” where the air moves faster than the front in a low-level region behind the front (Simpson 1987). Therefore, it is unknown if and when a density current balance can evolve in line convection situations and under what circumstances the vertical circulation will initiate organized deep convection.

Recent idealized frontal modeling studies also indi-
cated a frontogenetical role played by cross-frontal cloud contrast (Segal et al. 1993; Koch et al. 1995). These models have produced a thermally direct circulation with an intensity approaching that of a sea breeze. Thermally forced circulations are believed to be generated by a cross-frontal pressure gradient associated with the differential development of the mixed layer arising from the cross-frontal sensible heating gradient (Pinkerton 1978; Sun and Ogura 1979; Segal et al. 1986; Segal and Arritt 1992). The modeling results of Segal et al. (1993) suggest that cloud shading will enhance frontogenesis only if the shading is prolonged, there is sufficient cloud cover, and the ground moisture availability is low. Modeled cold fronts in the presence of a substantial horizontal gradient of surface sensible heating appear to develop a density current–like feeder flow (Reeder 1986; Physick 1988; Koch et al. 1995). Of course, these models are highly idealized and do not account for many factors that may exist in observed line convection events, such as land surface inhomogeneities and three-dimensional processes.

Dorian et al. (1988) noted that approximately 70% of line convection features erupt into frontal squall lines shortly after the clear zone reaches its greatest width. The implication from these observational and numerical studies is that detailed cloud initialization should be used in mesoscale prediction models. Cloud radiative effects are usually parameterized in mesoscale models as a simple function of the relative humidity. Mesoscale model forecasts of precipitation and (less frequently) mean sea level pressure appear to benefit from the addition of mesoscale detail in the initial state of humidity (Perkey 1976; Mills 1983; Mills and Davidson 1987; Mailhot et al. 1989; Bell and Hammon 1989). These benefits typically are realized only during the early stages of the forecast, thereby helping to alleviate the “precipitation spinup problem” that plagues mesoscale models (Tarbell et al. 1981; Wolcott and Warner 1981). The addition of such detail to the humidity field should also impact the surface heating fields in mesoscale models (through the effects of the humidity initialization on the cloud fractional coverage). However, it has not yet been shown whether significant thermally forced mesoscale circulation systems result across the front.

In the absence of cloud effects, moisture availability is the most important factor affecting the surface energy balance (McCumber and Pielke 1981; Zhang and Anthes 1982), since this parameter regulates the partitioning of solar energy into sensible and latent heat fluxes. Large contrasts in moisture availability or evapotranspiration from vegetation canopies can produce thermal circulations similar in intensity to that of sea-breeze circulations (Ookouchi et al. 1984; Segal et al. 1988). Spatial variations of vegetation and soil moisture caused a strengthening of a stationary front and the associated vertical circulation in a model study by Chang and Wetz (1991). On the other hand, Fast and McCorcle (1991) found that by lowering surface temperature and increasing the specific humidity ahead of the front, soil moisture and soil type variations weakened a summer cold front in a rather coarse resolution model. These studies dealt only with weak synoptic forcing. It has not yet been demonstrated that evapotranspiration fields can significantly impact frontal behavior in cases where strong synoptic dynamics and cross-frontal variations in cloud cover exist.

The present paper adapts an existing satellite-based cloud classification scheme to the purpose of specifying a mesoscale relative humidity field in the initial state of a mesoscale numerical weather prediction model and examines the multifaceted impact of these data on the simulation of a frontal squall line event. The relative impact of this humidity analysis and of soil moisture availability derived from rain gauge and satellite data is assessed with regard to the solar radiative flux at the ground, the boundary layer structure, the forecast precipitation fields, and the frontal dynamics. We have attempted to simulate the frontal line convection case of 16 April 1982 analyzed observationally by Koch (1984). That study hypothesized that the nonlinear interaction between the synoptically forced transverse frontal circulation (arising from the effects of geostrophic deformation) and the thermally forced circulation (arising from the cross-frontal cloud variations) created an intense vertical circulation that was the trigger for the development of a frontal squall line. Although the essence of these scale-interactive processes was corroborated in the idealized modeling study by Koch et al. (1995), it remains to be seen whether the complex sequence of events leading to the formation of the observed squall line can be simulated only when the observed cloud field is represented and what role moisture availability may have played.

This paper is intended to have value beyond the meteorological implications of this one event, in part because it presents a method for obtaining atmospheric moisture fields with sufficient resolution to resolve nonclassical mesoscale circulations. An important question that is immediately raised by the inclusion of mesoscale fields into the initial state of a model is whether the added detail is accurate (informative). Ideally, we would have liked to verify the initial analysis against an independent mesoscale dataset; however, such data were not available. Hence, other means including forecast impacts, improved meteorological consistency, and comparisons with radiosonde measurements (e.g., Mills 1983; Chou et al. 1986; Mailhot et al. 1989; Norquist 1988) were employed to test the worth of the mesoscale humidity analysis.

The impact of the cloud effects on the solar fluxes and other fields is dependent on there being a correct relationship between cloud depth, cloud fraction, and shortwave transmissivity in the model, as well as on the accuracy of the model's parameterization schemes. Although the effects would be expected to diminish with time, we show that substantial positive impacts are felt...
in the model forecast fields for at least 12 h. Following a brief description of the model and the experimental design, the humidity and soil moisture availability retrieval schemes and their impacts on the forecast fields are described.

2. The model and experimental design

The hydrostatic, primitive equation Mesoscale Atmospheric Simulation System (MASS) model was used in this study. Kaplan et al. (1982) document an earlier version of the model, which was comprehensively evaluated in Koch (1985) and Koch et al. (1985). Recent changes to MASS are described in Manobianco et al. (1994). MASS has been used in studies that include the dynamics of snowstorms and the preconvective environment, as well as impact assessments of satellite data (e.g., Kaplan et al. 1984; Kocin et al. 1985; Uccellini et al. 1987; Zack and Kaplan 1987).

The version of the model that was used had 32 unequally spaced levels to provide sufficient vertical resolution within the planetary boundary layer (PBL) for estimating the turbulent fluxes. A surface energy budget formulation based on the Blackadar (1976, 1979) force–restore model was used to compute the equilibrium ground temperature, together with a fixed soil-layer slab model that was modified to include evapotranspiration effects following Chang and Wetzel (1991), as is discussed in section 4. The parameterization of solar radiation in MASS included the effects of ground albedo, gaseous scattering and absorption, and the transmissivity due to cloudiness in each of three (low, middle, and high) model layers, but ignored diffuse radiation. The MASS model’s surface energy balance equation applicable during daytime hours is

$$-Q^*_s = S(1 - a)(\Psi \sin \phi) + LW_{\text{net}}$$

$$= Q_H + Q_E - Q_G. \quad (1)$$

The net upward radiation at the surface $-Q^*_s$, is composed of the net solar radiation (where $S$ is solar constant, $a$ albedo, $\Psi$ net transmissivity, and $\phi$ solar elevation angle) and the net longwave radiation. The net radiation is balanced by the sensible heat flux, the latent heat flux, and the ground conduction ($Q_H$, $Q_E$, and $Q_G$, respectively). The high-resolution Blackadar (1976, 1978) PBL model was used to vertically distribute turbulent fluxes. The Blackadar scheme computes the local exchange coefficients from first-order closure ($K$-theory) when the PBL is stably stratified and from an entraining plume model otherwise (Zhang and Anthes 1982). The necessity of using a multilevel boundary layer treatment when differential heating is being modeled, as in the present study, was demonstrated by Anthes et al. (1980, 1982).

Grid resolutions of either 48 km or 16 km were used in all experiments. The computational domains of the coarse grid model (CGM) and fine grid model (FGM) are shown in Fig. 2, along with the Geostationary Operational Environmental Satellite (GOES) analysis region. The FGM domain lies almost entirely within the satellite data region, whose size was dictated by computer limitations. The lack of a satellite moisture analysis at the extreme southwestern edge of the FGM domain was inconsequential, since both the control relative humidity analysis and the satellite imagery revealed clear skies. Problems related to lateral boundaries were not evident in the vicinity of the cold front, since it was situated near the center of the FGM domain. The CGM was initialized at 1200 UTC 16 April 1982 with a first-guess field provided by the National Meteorological Center’s Limited Fine Mesh (LFM) Model, which was reanalyzed using the available surface and sounding data in the manner described by Kaplan et al. (1982). A 12-h forecast was produced on the coarse grid. These forecasts provided initial and boundary conditions for the FGM, using one-way grid nesting. The 3-h CGM forecast (at 1500 UTC) was used to initialize the FGM, in order that initial mass–momentum imbalances would have settled down enough so as not seriously deteriorate the FGM forecasts.

The emphasis in this paper is on the impacts produced by the mesoscale fields of relative humidity (RH) and moisture availability ($M$). Numerical experiments were performed to test the effects of these fields, as well as the grid resolution and the method for cumulus parameterization. Six of these experiments are summarized in Table 1. The control run (CON) performed on the 48-km CGM contained no initial mesoscale alterations to the RH or $M$ fields and used the Molinari (1982) subgrid cumulus scheme, which parameterizes the convective rainfall on the basis of resolvable moisture convergence in a grid column. The mesoscale-enhanced run (ENH)
was identical to the control run, except that the satellite-retrieved RH data were used to provide mesoscale three-dimensional RH distributions for the initial state of the model. The CON-M and ENH-M experiments evaluated the effect of varying the mesoscale surface evapotranspiration fields in the absence of and in the presence of the mesoscale RH fields, respectively. We tested the use of the Molinari scheme in the nested grid runs, but do not report on those results here, because the Fritsch and Chappell (1980) cumulus parameterization scheme is more suitable for a model with a grid resolution of 16 km. Convective rainfall in the latter scheme is based on the amount of available buoyant energy. Moist downdrafts are parameterized, and convectively driven mesoscale pressure and wind systems, including mesohighs associated with evaporatively cooled downdrafts, are typically produced by the Fritsch–Chappell scheme. These FGM experiments are designated ENH16-M and CON16 for the runs that either include or do not contain the mesoscale RH and $M$ fields, respectively.

3. The mesoscale humidity analysis scheme

Visible and infrared satellite imagery was used to derive the mesoscale RH fields for the model’s initial state. Our procedure for obtaining three-dimensional relative humidity fields from the imagery is discussed in detail below, following a brief summary of the evolving cloud patterns during the case event and a review of current moisture retrieval techniques.

Examination of the satellite imagery on 16 April 1982 (Fig. 3) reveals the following important features: 1) the existence of a large, persistent contrast in cloud cover across the surface cold front in central Kansas; 2) the development of a line convection feature along this front in extreme eastern Kansas and a postfrontal clear zone (CZ), which reached its maximum width of 65 km by 1931 UTC immediately behind the line convection; 3) the subsequent formation of cumulonimbus clouds from the line convection and their growth into a solid line of severe thunderstorms by 2231 UTC; and 4) the occurrence of several mesoscale convective systems throughout the day along the stationary front near the Iowa–Missouri border. Corresponding surface analyses displayed in Fig. 4 illustrate the intense frontogenesis that accompanied the line convection along the front in eastern Kansas. The cross-frontal temperature gradient reached its maximum value when the clear zone was most pronounced, which nearly coincided with the initiation of the frontal squall line. The challenge for the MASS model was to correctly reproduce this sequence of events, including the observed surface temperature field evolution.

Data that have been used in the past to provide mesoscale detail in the initial state of model atmospheric moisture fields consist of various combinations of visible (VIS) and/or infrared (IR) satellite data, surface cloud reports, radiosonde relative humidity profiles, and aircraft measurements. Satellite-based moisture analysis schemes fall into one of three categories: nephanalysis, radiative transfer, and statistical methods. Nephanalysis schemes employ threshold values of satellite VIS albedo and/or IR brightness temperatures, radiosonde humidity profiles, and surface cloud reports to produce a three-dimensional cloud and relative humidity analysis (Perkey 1976; Mills 1983; Norquist 1988; Hamill et al. 1992). The Australian Region Primitive Equation Model (Mills and Davidson 1987), Canadian Regional Model (Mailhot et al. 1989), and British Meteorological Office mesoscale model (Bell and Hammon 1989) all utilize nephanalysis schemes. Nevertheless, these techniques suffer from important drawbacks, including their subjectivity in areas where little or no radiosonde or surface data are available, the lack of a unique relationship between cloud type and IR brightness values, and their requirement that each pixel is either totally free or totally filled with cloud. These schemes are particularly vulnerable to underrepresenting low clouds (which are of principal importance to the current study) because of their heavy reliance on single-channel IR data.

The second category of moisture analysis schemes involves the complete solution of the radiative transfer equations. The “CO$_2$ slicing” technique (Menzel et al. 1983; Schreiner et al. 1993) and the coupled model–satellite analysis system described by Lipton (1993) are examples of the radiative transfer approach. $^1$ The three CO$_2$ channels on GOES have peak absorptions

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$^1$ The Lipton (1993) method also retrieves the surface radiative fluxes as described in Eq. (1). This study demonstrated the substantial impact of satellite-retrieved cloud shading on the development of mesoscale circulations across a dryline and convective development, even in the presence of substantial errors in the cloud fraction.
are further limited to clear air and to above cloud tops, whereas microwave retrievals lack sufficient horizontal resolution and are unreliable over land due to the highly variable land surface emissivity. For these reasons, we chose not to employ radiative transfer schemes in this study.

The final category of satellite moisture retrieval schemes employs statistical methods. In particular, the DesBois et al. (1982) technique assumes that clusters in multidimensional brightness temperature (and albedo) histograms represent discrete cloud classes. These methods allow pixels to be partially cloud filled, although clusters may not always be recognizable in histograms. Schemes that combine elements of the above three approaches, or include additional complexities, have also been developed (e.g., Coakley and Bretherton 1982; Garand 1993).

The dynamic clustering technique of DesBois et al. (1982) scheme is employed in this paper. The four-step procedure for accomplishing the transformation of the satellite cloud imagery into model RH fields is explained below, but is summarized here for clarity.

1) Perform the clustering analysis to define the spectrum of cloud classes present in the bispectral satellite imagery.
2) Interpret cloud classes as cloud types and fractions by synthesizing the satellite imagery, surface cloud reports, and sounding humidity profile information. Although this step necessarily involves subjectivity, this has the benefit of allowing for human interpretation to evaluate whether the results are meteorologically significant and consistent with the data. This synthesis approach is similar in many respects to that used in the air force’s RTNEPH cloud analysis scheme (Hamill et al. 1992).
3) Convert the cloud fractions into relative humidity data and determine the cloud depth, in order to assign the RH profiles for each cloud class.
4) Map the moisture fields onto the MASS model grid in a manner that maintains the consistency between the new moisture field and the existing thermal field.

a. Cloud classification method

The cloud classification scheme was applied to the VIS and 11.6-mm IR imagery at 1400 UTC. The satellite moisture analysis was performed at this time in order to best utilize the visible imagery for cloud classification purposes (cumuliform clouds are more easily discernible at low sun angles). This mesoscale (“enhanced”) moisture analysis was then supplied to the
Fig. 4. Subjective surface isotherm analyses at 1400, 1600, 1800, 1900, 2000, and 2200 UTC 16 April 1982. Station data displayed are temperature (°C), dewpoint temperature (°C), and wind vectors (long barb—5 m s⁻¹). Low pressure center magnitudes are hectopascals minus 1000. Zone of maximum cross-frontal temperature gradient is denoted by the line AA (after Dorian et al. 1988).
CGM model at 1200 UTC. Since identical areal coverage and resolution of the VIS and IR images was required, the AOIPS/2 interactive meteorological processing system at NASA/Goddard Space Flight Center (Hasler and desJardins 1987) was used to produce identical VIS/IR pixel resolutions of 4 km. This was simply accomplished by averaging the VIS 1-km data down to a 4-km resolution and by duplicating the 8-km resolution IR pixels. The resulting satellite image was broken up into eight latitudinal strips, which allowed separate cloud mappings to be created and checked for spatial consistency across the subdomains.

The clustering scheme assumes that every definable cloud class can be identified by a specific signature in the bispectral (VIS/IR) histogram of the pixel brightnesses. The maximum allowable number of cloud classes (N) was varied from 5 to 15, but the number comprising each set of points chosen randomly (known as kernels) for the initial specification of each class was fixed at F = 30, as suggested by DesBois et al. (1982). The results were sensitive to the value of N, as is discussed below. The object was to assign each pixel to the cloud class whose median VIS/IR brightness values best matched those of the pixel. The cloud classification program was run several times, each with a different choice of kernels. These runs produced anywhere from six to nine cloud classes. The criteria used in making the final selection of which solution to use for each of the eight image subdomains were based on the following decision-tree algorithm.

- The convergent solution must display small differences between the “centers of gravity” (median brightness values) of the classes and of the kernels, as determined by the bispectral distance on the histogram (the smaller the distance, the better the choice).
- Each class must account for at least 2% of the observed image pixels and have a sufficiently small variance about its center of gravity.
- Spatially mapped distributions of the cloud classes must be consistent with the cloud distribution deducible from the surface reports and satellite imagery.
- Significant cloud types must be distinguished, as inferred from the coincident surface cloud-base heights/fractions, sounding RH profiles, and subjective interpretation of the satellite imagery.
- The continuity of cloud types across all eight mapped subdomains must be preserved.

The solution containing the maximum number of classes should be chosen, as long as the above constraints are satisfied and the mapped fields of cloud classes do not appear “noisy,” since such high variability indicates an unacceptable level of uncertainty in the retrieved cloud classes.

The results from the cloud classification run that best met these criteria are displayed in Fig. 5 for a subdomain centered over Kansas and Oklahoma. Seven cloud classes were statistically determined over this subdomain, even though only four or five “bull’s-eyes” (clusters) can be identified visually. The fact that the bull’s-eyes do not match the centers of gravity of the statistically determined cloud classes is characteristic of the DesBois et al. (1982) scheme. The reason for this perceived mismatch is that all image pixels must be assigned to a cloud class, including those that have bispectral values that lie outside of the bull’s-eyes. Hence, the center of gravity of the classes will be shifted to entrain additional regions on the histogram in an objective way that best matches the bispectral attributes of the classes and the pixels. The scheme assigns each pixel to the cloud class whose center of gravity is the closest to the VIS/IR value of the pixel, so no pixel goes unclassified. We discovered that important classes were suppressed when N was assigned too low of a value (e.g., class 2 was suppressed in one run, yet this class is shown below to be very important). Hence, use of a strong constraint on the number of classes was found to give undesirable results. On the other hand, another run that resulted in nine
cloud classes for this subdomain produced a noisy cloud field. Although this process is not unique, in practice it is relatively easy to make the proper choice for the best solution by employing the decision-tree process outlined above.

b. Determination of cloud types and fractions

The number and distribution of cloud classes were compared to the original visible and infrared satellite imagery, to the surface cloud-base height and fractional coverage reports, and to the sounding relative humidity profiles for consistency. The assignment of cloud types and fractions to each cloud class is the result of an iterative process of synthesizing these data in such a manner that consistency is attained, as discussed below.

The seven cloud classes in Fig. 5 (determined only over a small domain in Kansas and Oklahoma) plus another two classes found over the southernmost part of the satellite domain are mapped out as various combinations of cloud types and fractions in Fig. 6. This cloud field should be compared to the VIS/IR satellite imagery (Fig. 3a). The subtle distinction between class 2 (a scattered-to-broken stratocumulus cloud deck ahead of the surface front in central Kansas) and class 3 (an overcast stratocumulus cloud deck behind the front) is an important one, because of the different values of solar transmissivity for these cloud types (section 3c). This important differentiation is supported by the surface cloud observations, although they are of much coarser horizontal resolution than the cloud type field in Fig. 6.

It is important that the general cloud type/fraction distribution is consistent with the meteorological situation. While it is certainly true that the cloud classifications match the surface observations of cloud base/height at the station locations and the sounding relative humidity profiles as described below, they also extend the limited information available from discrete surface and sounding locations to the entire analysis domain in a continuous and meteorologically meaningful fashion. The cold front separates partly cloudy skies in eastern Kansas from overcast multilayer clouds and imbedded
convection in western Kansas and Nebraska. Cumulonimbus are identified northeast of a developing low pressure center in northeastern Kansas and Iowa. Clear skies occur behind a dryline in central Oklahoma, while stratocumulus and cumulonimbus clouds are correctly identified in the warm, unstable air along and east of the Mississippi River valley. Finally, cirrus clouds associated with the subtropical jet stream over the Gulf Coast region appear to be correct in nature.

Other criteria for an accurate analysis also were met. For example, continuity between cloud classes is generally preserved across the interfaces between the eight image subdomains (the most noticeable exception being in northern Mississippi and Alabama). Also apparent is that the criterion for a low "noise" level in the mapped distribution is met.

c. Assignment of relative humidity profiles to the cloud classes

This step in the procedure involves the greatest uncertainty: converting the cloud fraction $f$ into RH and determining the depths of the cloudy layers comprising each of the cloud classes, in order to arrive at vertical profiles of RH that can be used by the MASS model. The cloud fractions were converted to RH values by use of the Smagorinsky (1960) diagnostic method. Accordingly, the grid-averaged RH above some "critical RH" (typically 60%-90%) defines cloud fraction at level $i$ as

$$f(i) = \left[\frac{\text{RH}(i) - \text{RH}_c}{1 - \text{RH}_c}\right]^n,$$

(2)

where $n$ is some integer (typically 2) and RH$_c$ is the critical RH such that $f = 0$ for RH $< \text{RH}_c$. The threshold value RH$_c$ depends upon whether the clouds are low, middle, or high clouds in most models, including the MASS model. Values reported in the model literature vary widely and may depend upon model grid resolution, the lapse rate of temperature, the vertical velocity, and convective mass fluxes (Slingo 1987; Kristjánsson 1991; Xu and Krueger 1991; Wacl 1994). Alternatively, parcel-based methods can be used to diagnose the fractional coverage of shallow convective clouds (Wetzel 1990; Rabin et al. 1990). These complications are important issues in mesoscale modeling, but they are beyond the scope of this study.

The linear $f$-RH relationship employed by MASS (Kaplan et al. 1982) was changed to a quadratic one, and the threshold RH values for medium and high clouds were increased, so as to be more in line with prevailing relationships used in other mesoscale models. The net effects of these changes were to produce sharper horizontal humidity gradients at cloud edges and higher humidity at middle and upper levels (though the differences were no more than 15% in relative humidity).

The relationships between cloud cover and layer mean RH used in this study are depicted in Fig. 7. For example, low-level clouds are assumed to exist in MASS when the mean RH in the 1000–800-hPa layer exceeds 60%. These relationships were used for two purposes: to derive the initial RH from the retrieved cloud fraction and to diagnose cloud fraction from RH during the model integration. The relationships are also very important for computing the transmission of shortwave radiation to the ground, since the fractional cloud cover determines the effects of clouds on the surface energy balance. The net shortwave transmissivity at the surface is the product of the individual transmissivities through each of the three layers:

$$\Psi = \prod_{i=1}^{3} \{1 - f(i)[1 - \Psi_i(i)]\},$$

(3)

where $\Psi_i$ is the "critical transmissivity" for total cloud cover ($f = 1$). The critical transmissivity is the smallest value of transmissivity allowed by the model through each cloud layer due to the combined effects of absorption and scattering (Kaplan et al. 1982). The $\Psi$ values determined for all nine cloud classes (Table 2) reveal that substantial differences in surface heating rates can be expected across the cold front in Kansas, due to the presence of stratocumulus clouds that are overcast behind the front and scattered to broken in coverage ahead of the front. The ratio between these net transmissivity values (0.74/0.30 = 2.5) would be expected to translate into a sizable contrast in the rate of sensible heating, all other things being equal (wind speed, soil moisture, etc.).

Since the RH profile for each cloud class depends upon both the fractional coverage and the depth of each component cloud type, it was necessary to estimate cloud base and top levels for each of the nine cloud classes as accurately as possible with the data available. Cloud-top levels were estimated from both RH sounding profiles at representative rawinsonde sites in the satellite image area and the IR brightness temperatures of cloudy regions seen in the infrared satellite image. Cloud-base level assignments were determined from both the RH
sounding profiles and the nearby surface reports of cloud heights and fractions. These resulting cloud depths were then assigned to all image pixels characterized by clouds of the same class.

Due to the inherent uncertainties involved in this procedure for height assignment, as much averaging as possible was done in seeking to attain a reasonably accurate estimate of the cloud depths from the IR brightness temperatures, sounding humidity profiles, and surface reports. A simple average of the various sounding and IR satellite estimates was taken to define the cloud tops, except when the clouds were very thin, in which case the emissivity was clearly too low to obtain reasonable cloud-top estimates from the IR brightness temperatures. Similarly, an average of the sounding and surface estimates was taken to define cloud bases. The mean difference between the satellite and sounding cloud-top height estimates was 1.0 km, whereas the mean difference between the surface and sounding cloud base estimates was 0.4 km. These values help to define the accuracy of retrieved moisture field. The RH profiles assigned to each cloud type are displayed in Fig. 8.

d. Insertion of the satellite-derived relative humidity data into the MASS model

Having obtained the vertical profiles of RH for each cloud class as just explained, the model’s original RH field was replaced with this “enhanced” (ENH) humidity field at individual isobaric levels. When the model first-guess “control” (CON) RH field indicated the presence of clouds at an isobaric level, the original RH value was replaced by the enhanced RH value from the cloud classification analysis. At those pixels where the cloud class product showed no cloud cover at a given level, but the first-guess analysis indicated the presence of clouds, the RH value was set to values 10% lower than the threshold value for the occurrence of cloud at that level. It was our belief that the alternative of leaving clear pixels unaltered (i.e., incorrectly cloud-covered) would have been much less desirable than the knowledge gained of mesoscale clear and cloudy regions, and whether they were characterized by shallow or deep clouds, even if the exact RH value in the clear regions was unknown.

Three issues governing the quality of the satellite-based moisture analysis deserve mention. First, fictitious convection would likely have formed instantly in the model if high humidity values had been inserted within a dry, elevated mixed layer above a strong capping inversion, such as was present in the preconvective environment east of the dryline. Moisture was introduced where such an atmospheric structure was found only below the inversion base and/or above the top of the elevated mixed layer, the single exception being when cloud class 7 (cumulonimbus) existed in this environment.

The second requirement imposed on the analysis was that the virtual temperature field be unaltered by changes made to the moisture field. Troublesome gravity–inertia waves were excited when this constraint was not used, resulting from the fact that the hydrostatic equation utilized in MASS employs virtual temperature in determining the geopotential height fields. Application of this constraint meant that drying of a previously cloudy layer required an increase (typically 1–2°C) of the layer temperature, whereas introduction of cloudiness to a previously cloudless layer required cooling. Most of the temperature increase occurred beneath the capping inversion in eastern Oklahoma and southeastern Kansas, where the enhanced moisture analysis decreased the low-level RH values.

The final issue is that of subgrid-scale cloud variability. Since the satellite-based moisture analysis had an 8-km resolution, which is finer than that of either model grid used, there were many grid boxes that could contain more than one cloud type. The final enhanced humidity field used for both the 48-km CGM and 16-km FGM model runs was a 48-km smoothed analysis. Although more detail could have been provided for the FGM runs, we did not want the resolution of the RH data to be finer than that of the surface moisture availability fields (~30 km), since a major purpose of this study was to study the relative impacts of the RH and moisture availability fields on the model simulations. The enhanced mesoscale moisture analysis is dis-

<table>
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<tr>
<th>Cloud class</th>
<th>Cloud type and fraction (low/middle/high)</th>
<th>Net shortwave transmissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clear/clear/clear</td>
<td>Ψ = (1.00) (1.00) (1.00) = 1.00</td>
</tr>
<tr>
<td>2</td>
<td>SCT-BKN Sc/clear/clear</td>
<td>Ψ = (0.74) (1.00) (1.00) = 0.74</td>
</tr>
<tr>
<td>3</td>
<td>OVC Sc/clear/clear</td>
<td>Ψ = (0.30) (1.00) (1.00) = 0.30</td>
</tr>
<tr>
<td>4</td>
<td>OVC Sc/BKN Cu congestus/clear</td>
<td>Ψ = (0.30) (0.75) (1.00) = 0.23</td>
</tr>
<tr>
<td>5</td>
<td>BKN-OVC Sc/BKN As/SCT-BKN Cs</td>
<td>Ψ = (0.45) (0.75) (0.95) = 0.32</td>
</tr>
<tr>
<td>6</td>
<td>OVC Sc/OVC As/OVC Cs</td>
<td>Ψ = (0.30) (0.57) (0.88) = 0.15</td>
</tr>
<tr>
<td>7</td>
<td>OVC Cb</td>
<td>Ψ = (0.30) (0.57) (0.88) = 0.15</td>
</tr>
<tr>
<td>8</td>
<td>BKN-OVC St/clear/BKN-OVC Ci</td>
<td>Ψ = (0.45) (1.00) (0.90) = 0.41</td>
</tr>
<tr>
<td>9</td>
<td>Clear/clear/SCT-BKN Ci</td>
<td>Ψ = (1.00) (1.00) (0.95) = 0.95</td>
</tr>
</tbody>
</table>

Table 2. Cloud transmissivity values [see Eq. (3)] corresponding to the nine cloud classes identified by the cloud classification scheme (Fig. 6). Values shown are fractions of the net radiation for clear skies throughout the central and southern Plains region on the model day. Under such conditions, the actual net radiation was in the range of 550–700 W m⁻².
Fig. 8. Relative humidity profiles assigned to each of the eight cloud classes (CC 1 is clear sky) shown in Fig. 6. The shaded regions depict the incremental changes to RH values relative to clear sky conditions for the various cloud layers composing each cloud class. The RH values assigned to the cloud-free regions of the atmosphere between these cloud layers are shown by the solid lines, which represent values of RH that are 10% below the cloudy thresholds for low, middle, or high cloud types (Fig. 7). Note that overcast clouds are associated with values of slightly less than 100% relative humidity and that scattered cloud cover for cirriform clouds occurs for humidities that are quite low.
Fig. 9. Initial model fields of relative humidity at 850, 700, and 500 mb for the control case (top) and the satellite moisture enhanced case (bottom). Shading depicts regions where clouds are diagnosed (see Fig. 7).

played for three isobaric levels in Fig. 9. Comparison to the control analysis reveals that the added moisture detail creates considerably drier conditions at low levels in eastern Kansas and Oklahoma, portions of Iowa and Minnesota, and most of Missouri, whereas moisture at 500 hPa has been increased in the northern Plains and the extreme southeastern part of the domain. The drier regions in the mesoscale moisture analysis result because the satellite detected nearly cloudless conditions between the coarsely spaced rawinsonde sites, which together with the LFM analysis provided the information for the control humidity analysis. Since the drier conditions in the lower troposphere occurred east of the strong cold front, the enhanced moisture analysis could be anticipated to lead to considerably warmer prefrontal conditions due to increased shortwave transmissivity (Table 2).

The mesoscale moisture analysis at 500 hPa produced a larger areal coverage of humidity in the 70%–90% range at the expense of regions of RH ≤ 35% (Fig. 10). This systematic difference over the nested grid domain exists due to the classification of mid-to-upper-level cloud cover in the northern Plains (Fig. 6). On the other hand, the mesoscale moisture analysis at 850 hPa increased the areal coverage of RH in the range of 50%–60% (reflecting the clear regions with RH values 10% below the 60% threshold value), reduced coverage of regions where the RH ranges between 70% and 95% (primarily the cloudy regions in the control analysis that were cleared by the scheme), and increased the coverage...
Fig. 10. Histograms of relative humidity averaged over the nested grid domain for the control and enhanced moisture analyses at 500 mb (top) and at 850 mb (bottom).

of near-saturated areas [this being principally the result of the high RH values near the 850-mb level for cloud classes 6 and 7 (Fig. 8)]. Thus, the overall effects of the enhanced moisture analysis were to introduce significant systematic (rather than quasi-random) changes to the original field, while adding detail to the three-dimensional analysis of relative humidity.

4. Surface moisture availability analysis

Spatial variations of soil moisture and vegetation fields were initialized into the MASS model following the method of Chang and Wetzel (1991). The moisture availability \( M \), which is used to parameterize evapotranspiration, depends upon the fractional vegetation coverage \( P \) and the volumetric soil moisture in the top-soil \( (w_1) \) and the plant root zone \( (w_2) \):

\[
M = P w_2 + (1 - P) w_1. \tag{4}
\]

For surfaces covered by vegetation, the latent heat flux depends upon direct evaporation from bare soil and transpiration from the plant canopy according to the fraction of the surface covered by transpiring vegetation. The latent heat flux is proportional to the product of the moisture availability, the surface relative humidity, and the specific humidity gradient between the surface and the lowest model level, as long as the vegetation is not stressed by drought conditions. This formulation is equivalent to the geometric mean of a maximum supply rate and the unstressed evapotranspiration rate.

Soil moisture was obtained from rain gauge–based estimates of the antecedent precipitation index (API). The fractional soil moisture parameters \( w_1 \) and \( w_2 \) were determined by use of different values of the depletion coefficient \( k \) appropriate for April (0.75 and 0.975, respectively) in the simple recursive formula for the API:

\[
API_j = R_j + k \times API_{j-1}. \tag{5}
\]

where \( R_j \) is the 24-h rainfall for day \( j \) as obtained from daily rain gauge data from first-order National Weather Service stations and cooperative observations (average gauge spacing is 30 km). We initialized this equation with precipitation data beginning in early February, in order to estimate the soil moisture resident on 16 April 1982. The fractional soil moisture is defined as the ratio of API to the soil’s saturation (field capacity) value (Chang and Wetzel 1991).

The fractional coverage of transpiring vegetation \( (P) \) has been shown in previous studies to be highly correlated with the photosynthetically active plant mass, as represented by the normalized difference vegetation index (NDVI) obtainable from the NOAA-7 satellite (e.g., Tarpley et al. 1984). NDVI is calculated as the difference between the brightness values in the visible and near-infrared channels divided by their sum, and is a measure of the greenness of vegetation. The fractional vegetation coverage was calculated over a 2-week period centered on 16 April 1982 from the approximate 25-km resolution NDVI data according to the relationship (Chang and Wetzel 1991)

\[
P = \begin{cases} 
1.5(\text{NDVI} - 0.1), & \text{NDVI} \leq 0.547 \\
3.2(\text{NDVI}) - 1.08, & \text{NDVI} \geq 0.547.
\end{cases} \tag{6}
\]

The latent heat flux, as it appears in the Blackadar (1976) force–restore ground temperature equation, is somewhat different from the definition employed by Chang and Wetzel (1991). The Blackadar method is based on the similarity theory-based surface-layer profile relationship (Zhang and Anthes 1982), whereas the Chang and Wetzel (1991) method employs separate resistance equations for the plant canopy and bare soil. Since the Blackadar PBL scheme was employed in this study, we ran some tests comparing the fluxes resulting from the two approaches before implementing one for our use. The results of these tests conducted at several selected locations indicated acceptably small differences (not shown). We also note that Wetzel and Chang (1988) found soil type and roughness length to be relatively unimportant in determining the rate of evapotranspiration, which is fortunate considering that the version of
the MASS model used herein ignores variations in these surface-layer parameters.

The soil moisture, NDVI, and $M$ fields initialized into the mesoscale moisture availability runs are shown in Fig. 11. A strong west–east gradient of root zone moisture is apparent across the Plains states. Topsoil moisture is less than that in the root zone. These combined conditions are typically found in springtime in this region following soil moistening during the winter without significant evaporation of deep soil moisture. A local maximum in NDVI in central Oklahoma and Kansas is the signature of flourishing wheat crops, in contrast to low values nearly everywhere else. The resultant moisture availability field displays high values (i.e., greater than the default value of $M = 30\%$ used in MASS) throughout the northern Plains and the eastern portions of the model domain. However, the feature of greatest interest to this study is the substantial gradient of moisture availability across the cold front in southeastern Kansas. Since such a gradient of $M$ will tend to intensify the thermal contrast across the cold front, it is of interest to examine the importance of this feature relative to that of the cloud contrast across the front, in terms of their effects on frontal structure and dynamics.

5. Forecast impacts of mesoscale initial fields

The relative sensitivity of the model forecasts to the added mesoscale detail in the atmospheric relative humidity and surface moisture availability fields and to grid resolution is described in this section. After examining the impact on forecast sea level pressure and

![Fig. 11. Analyses of soil moisture content variables over the nested grid domain: (a) top soil moisture $w_1 (\%)$, (b) root-zone soil moisture $w_2 (\%)$, (c) normalized difference vegetation index, and (d) moisture availability $M (\%)$.](image-url)
surface temperature fields, we turn to the impacts on the boundary layer, frontal structure and dynamics, and precipitation fields.

a. Mean sea level pressure

Predictions of mean sea level pressure for 2100 UTC (9-h forecasts) appear in Fig. 12. Values less than 1005 hPa are shaded to emphasize the frontal zone and the relative impacts. Both of the fine grid experiments produced accurate magnitudes for the low pressure center, but displaced southwestward of the observed center over northern Missouri (Fig. 4).

It is obvious that increasing the grid resolution from 48 to 16 km produces the strongest impact among the four experiments. A slight increase of central pressure results from inclusion of the mesoscale humidity and $M$ fields in the coarse grid case, and a slight decrease occurs in the fine grid case. Since the major effect of adding mesoscale detail in the initial humidity field was to dry out the low-to-middle troposphere near and ahead of the cold front (Fig. 9), it is not surprising to see such little impact on the surface pressure field. Previous studies have examined only the impact of added detail in the moisture field for situations in which there was abundant rainfall, or for which the location of moisture bands was improved with the mesoscale moisture analysis (e.g., Perkey 1976; Mills and Davidson 1987; Bell and Hammon 1989). These earlier studies have emphasized the positive effects on low-level pressure forecasts of adding moisture detail to the initial state of mesoscale models. Our findings caution against drawing such general conclusions.

b. Surface temperature and energy budget fields

The surface temperature forecasts are shown in Fig. 13 for the coarse grid runs. We note that the forecast frontal movement was somewhat too slow. Comparison to the observations (Fig. 4) reveals that at 2100 UTC, the actual front was located along a line from southern Oklahoma to southwestern Missouri, whereas all of the
model runs have the front located along a line from central Oklahoma to eastern Kansas.

The mesoscale initialization strongly impacted the surface temperature forecasts. The ENH-M run, which benefited from both the satellite-enhanced humidity fields and the mesoscale moisture availability fields, exhibits substantially warmer temperatures than the CON run ahead of the entire cold front from northern Texas to northeastern Iowa. The evapotranspiration fields contribute only 1°–2°C of the total 5°–6°C of temperature differences (Fig. 13b). Furthermore, this evapotranspiration impact occurs only in a small region of eastern Kansas and Oklahoma. It is uniquely there that the values of mesoscale moisture availability are smaller than the control value of $M = 30\%$, and then by only a small amount. Throughout most of the remaining fine grid domain, the larger $M$ values might be expected to result in increased evaporation effects. However, general cooling relative to the CON run did not occur, because the considerable low-level cloud cover in those regions reduced both sensible and latent heating, and so the importance of the partitioning between the fluxes.

These surface temperature impacts have direct consequences for the depth of the planetary boundary layer. The PBL depth in eastern Kansas increases fourfold when the satellite-retrieved RH fields are inserted, irrespective of whether the mesoscale $M$ fields are added (Figs. 14c,d). The predicted surface temperature and boundary layer fields are sensitive to the initial RH and $M$ fields because the surface sensible and latent heat...
fluxes (Figs. 15 and 16) are strongly influenced by cloudiness and evapotranspiration. The sensible heat flux in the areas of reduced cloudiness in eastern Kansas in the ENH-M run is 225 W m$^{-2}$, compared to only about 100 W m$^{-2}$ in the CON run. This increase occurs because eastern Kansas is essentially the only area where both decreased $M$ values and decreased low-level cloud cover prevailed in the initial mesoscale fields. Approximately 500 W m$^{-2}$ of net radiation [see Eq. (1)] existed in this region at 2100 UTC, which had a fractional cloud cover of approximately 15% in the ENH-M run (compared to 65% in the CON run). The Bowen ratio in this region was calculated to be about 1.8, which is quite typical of dry grasslands (Stull 1988). This situation may be contrasted to that prevailing in eastern Oklahoma, which experienced increased sensible heating at the expense of decreased latent heating (cf. Figs. 15a,b and 16a,b) purely because of the lower values of moisture availability in the variable $M$ run.

c. Frontal structure and dynamics

We have seen that the cross-frontal temperature gradient from Iowa to Texas was strengthened by the insertion of the mesoscale fields of RH and $M$. Yet the satellite imagery shows that the frontal squall line initially formed only over extreme eastern Kansas (Fig. 3). We now discuss how boundary layer processes had important consequences on the frontal structure and dynamics in this latter area, and how this can serve to
explain why the squall line was generated in that location only.

The initial mesoscale RH field (resulting from the mesoscale distribution of clouds) and, to a lesser extent, the moisture availability gradient across the cold front (resulting primarily from the contrast in vegetation across the front), dramatically altered the structure of the front in eastern Kansas. Vertical cross sections constructed perpendicular to the front in this area (Fig. 13) enable study of these impacts. The isentropes, isohumes of mixing ratio, and frontal transverse ageostrophic circulation vectors are shown for the coarse grid runs CON and ENH-M in Fig. 17, and for the fine grid runs (CON16 and ENH16-M, respectively) in Fig. 18. A much deeper and well-mixed boundary layer is found ahead of the front in the mesoscale initial data runs, in contrast to the control runs. These features, which are not very noticeable in western Iowa, owe their existence to the increased solar insolation and sensible heating resulting from the decreased cloud cover in these runs.³ Notice also that the cold-frontal surface below 800 hPa is nearly erect in the mesoscale initial data runs, in contrast to the control runs. This feature is in agreement with those seen in idealized two-dimensional fronts subjected to differential sensible heating caused by cloud cover inhomogeneities (Segal et al. 1993; Koch et al. 1995).

Generally speaking, the transverse frontal circulation in all the experiments can be characterized as thermally direct, with warm air rising ahead of the front and cold air descending behind the front. The warm, moist air ascends in a slantwise fashion up and over the frontal

³ The mixing ratio values in the boundary layer are considerably lower in the mesoscale initialization runs, primarily because of the lower relative humidities ahead of the front in the mesoscale analysis (Fig. 9).
Similar (albeit smoother) features were analyzed by Dorian et al. (1988) for this case using a Sawyer–Eliassen diagnosis of the synoptic rawinsonde data (Fig. 17c). Notice that the analyzed isentropic structure agrees quite well with the predicted PBL depth and structure in the mesoscale initial data runs, but not the control runs. These comparisons provide support for the validity of the model simulation of general frontal structure and dynamics.

The thermodynamic differences produced by the mesoscale initial data fields strongly impact the frontal dynamics. The dramatically increased steepness of the isentropes in the boundary layer just ahead of the cold front in the ENH-M and ENH16-M runs results in a significant strengthening of the frontal transverse circulation. A strong, deep frontal updraft develops in these runs just ahead of the low-level front. In particular, the maximum upward motion is only 2.4 cm s$^{-1}$ in the CON run, compared to 8.5 cm s$^{-1}$ in the ENH-M run. These differences also exist in the fine grid simulations, with a 17.5 cm s$^{-1}$ frontal updraft jet developing at the 800-hPa level in the ENH16-M run. This latter value is nearly identical to the 21 cm s$^{-1}$ produced in the 10-km grid resolution model study of boundary layer effects on idealized frontogenesis reported by Koch et al. (1995). These results suggest that the more erect frontal surface in the ENH-M run acted as a stronger barrier to the warm air flowing toward the front and that the lifting occurred at a rate proportional to the steepness of the frontal surface. Locatelli et al. (1994) discovered a similar role of frontal topography acting with cold-frontal rainbands. It appears that the stronger transverse circulation in the ENH-M run is not explained by the reasoning offered by Sun and Ogura (1979) in their study of the differential mixed layer development across a modeled dryline, which emphasized the role of the cross-frontal pressure gradient, since we can detect no significant difference in the pressure gradient between the model runs.

The ageostrophic wind component relative to the mo-
**d. Convective and stratiform precipitation**

The insertion of the satellite-derived RH fields into the model’s initial state resulted in a large reduction in the area of overforecast precipitation (both grid-scale and convective), irrespective of the horizontal grid resolutions and whether the mesoscale moisture availability fields were inserted. This represents a significant im-
e. Verification of model forecasts

How should mesoscale model forecasts be verified when special mesoscale datasets do not exist? Frequently, investigators rely upon impacts made to precipitation forecasts as verification. Having already addressed this matter by comparing the satellite imagery to the precipitation forecasts, we now compare the analyzed relative humidity fields at 0000 UTC 17 April 1982 to the CON, ENH-M, and ENH16-M 12-h forecasts at 700 hPa (Fig. 20). Such comparisons must be understood in the light of the fact that the humidity analyses are based on just the rawinsonde-enhanced LFM fields. The model forecasts all appear equally valid when compared to such smooth fields, that is, they all show moist conditions in the region extending from southern Minnesota across eastern Nebraska, northeastern Kansas, and most of Iowa, as well as in a separate area in southeastern Colorado.
We suggest that it is much more meaningful to make a qualitative comparison against the satellite cloud imagery for purposes of verifying mesoscale moisture fields. Indeed, careful inspection of why the LFM moisture analysis showed the major moist area to be where the MASS model simulations all showed a narrow dry wedge revealed that the crude synoptic-scale analysis aliased small-scale features poorly resolved by the ra-winsondes to the synoptic scale. A comparison of the model relative humidity fields at 700 mb to the 2231 UTC imagery (Fig. 3c) reveals that many of the moisture features that may be inferred from the imagery are present only in the fine grid run that utilized all the mesoscale initial fields (ENH16-M). Specifically, we note the following.

- The thin band of near-saturation along the cold front associated with the predicted frontal precipitation agrees very well in shape and orientation, though displaying a phase lag, with the thin band of cold cloud tops along the frontal squall line.

- A small southwestward extension of high humidity in northeastern Kansas agrees with thick low/mid-level clouds in that region.

- The comma-shaped cloud pattern that includes both the frontal squall line and the large mass of stratiform cloud cover centered over Iowa agrees in most respects with the overall synoptic-scale cloud features.

These results indicate that the initial mesoscale detail in the cloud field was maintained well enough into the 12-h forecast period to be able to capture the important mesoscale cloud and precipitation events that occurred during that time.

6. Conclusions

This paper has described the application of a satellite-based cloud classification scheme to the problem of specifying a detailed three-dimensional relative humidity field for the initial state of a mesoscale model, the specification of mesoscale variation in soil moisture
availability as derived from rain gauge and satellite data, and the relative impact of these mesoscale fields on the structure and dynamics of a cold front that produced severe convection. The numerical experiments indicate that these fields contained sufficient resolution and accuracy to produce dramatic improvements in the forecasts of surface temperature, frontal dynamics, and precipitation, and that much of the mesoscale information present in the initial fields was retained by the model for at least 12 h. Since a high-density dataset was not available for purposes of forecast verification, the value of the mesoscale initial fields was judged in terms of their impacts on the forecasts, as well as comparisons of the humidity and precipitation forecasts against satellite cloud imagery.

Our method for enhancing atmospheric moisture detail in the initial state of the mesoscale model is based on an adaptation of the dynamic clustering scheme (DesBois et al. 1982), which classifies clouds from multispectral satellite imagery with 8-km resolution. A significant uncertainty in this approach is the task of converting the cloud fraction for each of the cloud classes into vertical profiles of relative humidity (RH), since there is no unique relationship between cloud fraction and RH. A synthesis of the infrared satellite measurements, radiosonde humidity profiles, and surface cloud reports was employed to assign cloud depths for each cloud class. Special care was taken to ensure that consistency was maintained between the moisture and thermal structures at all grid points, in particular, by not permitting the addition of moisture to dry, elevated mixed layers and by requiring that virtual temperature be conserved in the process.

Spatially inhomogeneous moisture availability was initialized into the MASS model following the method of Chang and Wetzel (1991). Their approach obtains moisture availability \( (M) \) from estimates of the topsoil and root zone soil moisture, derived from the antecedent precipitation index (API), and from the fractional vegetation coverage, given by the normalized difference vegetation index (NDVI) that is available from polar-orbiting satellite data.

The impact of the mesoscale initialization was investigated in several ways. Decreasing the grid size from 48 to 16 km produced improvements in the forecast mean sea level pressure (MSLP) field, but no significant impact resulted on MSLP from inclusion of satellite-derived RH and \( M \) fields. These findings differ from most past research results indicating positive impacts of mesoscale moisture analyses on model pressure field forecasts, because our mesoscale initial field of relative humidity was decreased in the active zone where convective precipitation developed. On the other hand, the satellite-derived RH and \( M \) fields together resulted in at least 5°C warmer temperatures and a dramatically increased boundary layer depth ahead of the cold front, compared to the control case.

We also examined the impact of the mesoscale initialization on the frontal dynamics and precipitation fields. The variability of relative humidity (and, hence, cloud cover) across the cold front, and to a considerably lesser extent, the horizontal gradient of moisture availability (primarily due to the NDVI variability), resulted in stronger cross-frontal gradients in sensible heating, and the development of an erect frontal surface, a strong, deep frontal updraft, and a density current-like feeder flow structure. The more erect frontal surface acted as a stronger barrier to the warm air flowing toward the front. Thus, frontal lifting occurred at a rate proportional to the steepness of the frontal surface, similar in nature to the observational findings of Locatelli et al. (1994) regarding the importance of frontal topography. The strength of the transverse circulation could not be explained by the cross-frontal pressure gradient (Sun and Ogura 1979), since we could not detect significant difference in the pressure gradient between the model runs. Comparison of the model forecasts to the satellite imagery indicated that the satellite-derived humidity fields also resulted in a large improvement in the areal distribution and timing of the intense frontal precipitation band in the model forecasts. The explosive frontal “squall line” only occurred when the mesoscale initial fields were introduced to the model, because only then did the strong frontal updraft develop.

These findings are consistent with the results from idealized frontal studies showing the strong impact made by differential sensible heating on frontal structure and dynamics. Our results also strongly support the hypothesis of Koch (1984) that the nonlinear interaction between the adiabatic transverse frontal circulation and the thermally forced circulation arising from the cross-frontal difference in cloud cover was the trigger for the frontal squall line in this case. Our results indicate that mesoscale evapotranspiration fields can impact frontal behavior even in cases where strong dynamics are present, though the impact of the moisture availability field was secondary to that of the cloud (RH) field.

This study points to the great need to execute special field experiments to develop databases for verifying detailed atmospheric and soil moisture fields. The simple technique used herein for inferring the evapotranspiration distribution in the model’s initial state could be improved with future research that couples hydrologic models with mesoscale atmospheric models to produce the initial conditions. This is desirable because of the paucity of soil moisture measurements over regional-scale areas. Finally, since a density current-like structure developed in our simulation, future modeling efforts should use fully nonhydrostatic physics and a bulk water continuity approach for explicitly predicting water substance instead of relying upon a cumulus parameterization scheme as in this study.

Acknowledgments. Support of this research was provided by NASA RTOPs 460-23-53-20 and 460-21-17-20, NASA Grant NAG 5-2589, and the NOAA South-
east Consortium on Severe Storms and Tornadoes Grant NA27RP029201. We are also grateful to Dr. Gerard Szejwach for providing the cloud classification software for our use in this project, to Dr. Compton J. Tucker for providing the NDVI datasets, to Harold Pierce and Paul Dorian for help with the satellite analysis, and to Dr. Mohan Karyampudi at NASA/GSFC for assistance with modeling issues. Much appreciation is also extended to the reviewers of this paper for their helpful comments and suggestions, which greatly improved the quality of the paper.

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