Comments on "Parameterization of Convective Precipitation in Mesoscale Numerical Models: A Critical Review"

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1. Introduction

In their recent review paper, Molinari and Dudek (1992, hereafter MD) discussed a number of factors that should be considered when parameterizing deep convection in mesoscale numerical prediction models. Many of the issues they raised are important for understanding and numerically predicting mesoscale convective systems (MCSs) and other precipitating weather systems. Their discussion on the interaction between parameterized convection and grid-scale moist physical processes, and their suggested classification of convective parameterization schemes (CPSs) based on the degree of the subgrid- and grid-scale interaction are of particular interest. In these respects, we feel that MD have overemphasized the significance of certain physical processes and they have also misinterpreted some of the results from previous studies of MCSs.

The purpose of this comment is to clarify the relationships among various parameterized cloud processes and grid-scale physical representations and to more fully describe how these relationships influence the simulation of MCSs. In section 2 we explore the effects of water vapor versus hydrometeor (i.e., cloud and precipitation-sized particles) detrainment from parameterized clouds to the grid scale and discuss the impact of the cloud detrainment on the simulations of midlatitude MCSs. (The method by which cloud detrainment is represented in a CPS was used extensively by MD to classify current modeling approaches and to challenge some of the previous simulation studies.) Section 3 discusses MD's criteria for classifying modeling approaches and elucidates the individual roles played by parameterized convective schemes and explicit moisture schemes in the simulation of MCSs. Section 4 addresses the importance of other physical representations in mesoscale models. Concluding remarks are given in the final section.

2. Cloud detrainment feedback from parameterized clouds

a. Water vapor versus hydrometeor feedback to grid scale

In their review, MD argue that the difference between vapor and hydrometeor feedbacks from the subgrid scale to the grid scale "can be significant," because "vapor detrained into a saturated environment immediately becomes liquid, but only after heat is released; no such heat release occurs with particle detrainment." So they question the validity of simulations of MCSs using the Fritsch and Chappell (1980, hereafter FC) CPS (and others) since it does not transfer convective cloud *particles* directly to the grid-scale environment. Hence, it is appropriate here to describe briefly how cloud detrainment is represented in the FC scheme. In this scheme, the effects of condensate detrainment are introduced through a water vapor–condensate feedback cycle. Specifically, starting at cloud top, a fraction of the convective condensate is allowed to evaporate into the cloud environment. If this condensate is more than enough to saturate the environment at this level, the remainder is allowed to "fall" into the layer below. If the lower layer is subsaturated, more of the condensate is evaporated. This process continues through successively lower layers until all of the specified condensate is evaporated. This approach crudely simulates the sedimentation of cloud and precipitation particles (within a convective timescale of

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about 30–60 min) in models without explicit representation of these entities. The effects of condensate detrainment are thus included in the CPS's feedback to the grid scale as a part of the net convective water vapor tendency.

We have noted from our previous studies that the parameterized detrainment effect in the FC scheme tends to saturate the upper troposphere, while drying out the lower and middle troposphere. For example, we have recently computed heat and moisture budgets from a simulation of the 10–11 June 1985 squall line. This simulation has been verified extensively against all available observations during the Preliminary Regional Experiment for STORM-Central (PRE-STORM) (see Cunning 1986). The model reproduced the general evolution of the squall system as well as much of the internal structure (see Zhang et al. 1989; Zhang and Gao 1989; Zhang 1992; Johnson and Hamilton 1988; Rutledge et al. 1988; Biggerstaff and Houze 1991). Figure 1 shows a vertical cross section of the hourly water vapor tendency produced by the FC scheme. The cross section is for the mature phase of the squall system. As one can see, the FC scheme produces only a relatively small increase in absolute humidity (through vapor detrainment) above 400 mb. However, the *relative humidity* tendency is substantial because the upper-tropospheric saturation vapor pressures are so small. In general, when deep convective clouds extend over most of the troposphere, the FC scheme tends to saturate a layer of 200–300-mb depth near cloud top while producing strong drying below this layer.

Consider now the diabatic heating effects associated with condensate detrainment in this case. In the FC scheme, the evaporative cooling associated with the conversion of convective condensate to water vapor is included as a part of the net convective temperature tendency. If the grid scale becomes saturated during feedback of the convective tendencies, any heating associated with the subsequent condensation of this vapor would simply offset the evaporative cooling component of the net temperature tendency at a given level. On the other hand, when the grid scale remains subsaturated, the evaporative cooling component of the net temperature tendency would be equal in magnitude to the cooling that would occur if the same amount of condensate were fed back directly to the grid scale and subsequently evaporated. Furthermore, in grid-scale microphysical parameterizations typically used in mesoscale models (e.g., Zhang 1989; Dudhia 1989), *any water vapor concentration in excess of the saturation value is converted to cloud water (ice) each time step. Conversely, cloud water (ice) introduced into a subsaturated environment is converted to vapor.* These phase changes are, of course, accompanied by latent heating or cooling. Thus, for a given convective contribution to the grid-scale tendency of water substance, any difference between vapor and liquid (ice) feedbacks should be approximately reconciled each time step. Dudhia (1989) also used these feedbacks interchangeably.

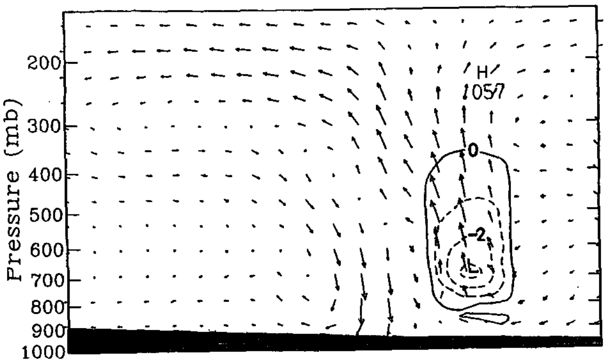

FIG. 1. Vertical cross section of the instantaneous hourly tendency of specific humidity at intervals of 1 g kg^{-1} h^{-1}, superposed with relative flow vectors along a line normal to the squall line from 15-h integration using the FC scheme, valid at 0300 UTC 11 June 1985. Dashed contours indicate convective drying.

b. The impact of moisture detrainment on model simulations

We agree, in principle, that it may be better to feed back both water vapor and liquid (ice) to minimize the differences between subgrid- and grid-scale moist physics. However, we feel that the *magnitude* of the moisture detrainment rates is a much more important factor than the particular category in which the feedback is manifested. In particular, we feel that MD have misinterpreted some of our previous results and the results of other studies in forming their hypotheses about the effects of hydrometeor detrainment. For example, MD rely heavily on the results of Cohen and Frank's (1987) simulations, noting that "when upper-tropospheric detrainment of hydrometeors was suppressed, they found that cloud lifetimes were shorter, grid-scale (stratiform) precipitation did not occur, and mesoscale structure did not develop." This statement is true but misleading and out of the proper context. Specifically, Cohen and Frank's experiments were designed to test the effects of *total mass detrainment* from parameterized convective clouds, where hydrometeors are only one component of the total mass that also includes dry air and water vapor. So these experiments were not intended to isolate the effects of hydrometeor detrainment. Cohen and Frank (1987) state that they "are convinced that the most essential process required to form these nimbostratus clouds is large detrainment of cloud updraft air in the *middle*[1] troposphere." Moreover, since hydrometeor concentration is limited to 0.5 g

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[1] The word *middle* is emphasized here by the authors.

kg^{-1} in their cloud model, *water vapor detrainment would tend to have a much stronger moistening effect than hydrometeor detrainment* in the midtroposphere. Cohen and Frank also mentioned that a significant moisture source at midlevels appears to be instrumental in obtaining their successful simulations. Thus, it seems likely that the hydrometeor component of the detrainment feedback is of secondary importance. More importantly, it should be noted that when the upper-level detrainment is suppressed in Cohen and Frank's cloud model, updraft mass flux maximizes just below cloud top, favoring an upper-level convective heating maximum. This effect could be very significant since numerous investigators have documented the strong sensitivity of the mesoscale response to the vertical distribution of convective heating (e.g., Anthes and Keyser 1979; Gyakum 1983; Hack and Schubert 1986; Fritsch 1986). As noted by Cohen and Frank (1987), their results are consistent with the hypothesis that the development of organized MCSs is less likely when diabatic heating is concentrated in the upper troposphere. Therefore, it does not necessarily follow that the failure to develop mesoscale circulations in their "suppressed detrainment" run stems from a deficiency in *hydrometeor* detrainment.

To our knowledge, the impact of hydrometeor detrainment on numerical simulations of MCSs has never been isolated from other effects by previous studies. We have attempted to focus on this process by running a series of numerical simulations of the 10–11 June 1985 squall line. In these simulations, we use the Kain–Fritsch (1990, 1993; hereafter KF) CPS substituted for the FC scheme in The Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model. The KF scheme is based upon the same closure assumptions as the FC scheme but uses a cloud model that is designed to allow updraft *entrainment and detrainment* rates to vary realistically as a function of environmental conditions. In particular, the latest version of the KF scheme allows the direct feedback of both vapor and hydrometeors to the grid scale, thereby eliminating the uncertainty associated with the sedimentation process in the FC scheme. Using the KF scheme, we first obtained a successful simulation of the 10–11 June squall system that compares favorably with the previous observational analyses (e.g., Johnson and Hamilton 1988) and the simulation of Zhang et al. (1989) using the FC scheme (not shown). Then, this simulation was used as a control run to investigate the impact of hydrometeor and vapor detrainment by varying different detrainment parameters in the KF scheme. We found that the model simulation is indeed sensitive to the *magnitude* of moisture detrainment. However, for a given amount of the moisture feedback, changing the category [i.e., cloud water (ice), rainwater (snow), or vapor] into which moisture is fed back to the grid scale has a relatively insignificant impact on the simulation. These results will be presented in detail in a forthcoming journal article.

3. The representation of moist physics in mesoscale models

a. Model classification

An important (but not new) message from MD is that the coupling of parameterized convection and explicit moisture schemes could provide the preferred solution for high-resolution simulations of MCSs. We have also supported this important concept. It can be said that Kreitzberg and Perkey (1977) were the first to propose this approach for mesoscale models, and Zhang et al. (1988) were the first, using numerous sensitivity simulations, to demonstrate its importance in simulating the internal structure and evolution of MCSs. Zhang et al. (1988) referred to the simultaneous use of convective parameterization and explicit schemes as the "full physics approach."

In their review, MD speculated that an extension of the full physics approach by including hydrometeor detrainment would have an important impact on mesoscale simulations. Specifically, they extended the full physics approach to include *the direct feedback of hydrometeors from subgrid-scale convection to grid-scale predictive equations.* They termed this extension the "hybrid" approach and referred to all other moist physics parameterizations, regardless of the degree of sophistication, as "traditional" methods. We feel that this classification system is inappropriate. First, by "hybrid," it should mean the simultaneous use of a convective parameterization and an explicit moisture scheme. Second, it is conceptually misleading to classify approaches similar to our moist physics parameterization in the traditional category. Our full physics approach involves incorporation of prognostic equations for cloud water (ice) and rainwater (snow), whereas the traditional approach removes condensed water instantaneously as rain reaching the ground. The two approaches represent totally different ways to handle grid-scale phase changes: *one allows condensate to move with the flow, and the other does not.* Thus, with our approach, grid-scale downdrafts could be induced by cooling from sublimation, melting, and evaporation as condensate falls into a subsaturated column. As a result of the latent heating and cooling occurring at different locations, mesoscale models are capable of reproducing mesolows, mesohighs, mesovortices, and other internal structures of MCSs as demonstrated by our previous simulation studies (Zhang and Fritsch 1986, 1988b; Zhang et al. 1989). These scenarios could be especially significant when there is strong system-relative flow, such as that in the 10–11 June 1985 squall system. However, with the traditional approach, the model would be more likely to either fail to reproduce the observed meso-β-scale structure and evolution or overpredict the intensity of mesoscale circulations (see Zhang and Gao 1989; Zhang et al. 1988). Therefore, *any moist physics classification system should be based on the coupled subgrid- and grid-scale parameterization, not just on the details of cloud detrainment feedbacks.*

b. *Effects of parameterized and explicit schemes*

Molinari and Dudek (1992) indicated that "unrealistic" conditions develop in our simulations of MCSs because of improper interactions between the FC scheme and the grid-scale explicit moisture scheme. In particular, they noted that a saturated layer in which equivalent potential temperature θ_e decreases slightly with height sometimes occurs in our simulations of MCSs. Such a thermodynamic stratification is absolutely unstable. They acknowledged that this feature also develops in simulations using the hybrid approach. However, they speculated that its existence in our simulations is "fundamentally different" than in simulations with the hybrid approach because the "cumulus parameterization was not supplying the grid with hydrometeors" (again through condensate detrainment). They believed that "the hybrid approach most cleanly separates" the grid and subgrid-scale production of hydrometeors, even though the grid-scale equations would also contribute to the production of hydrometeors (as occurred in our simulations).

We agree that proper communication between parameterized and explicit schemes is a critical component of successful simulations (see Zhang and Fritsch 1987; Zhang et al. 1988). As discussed by Zhang and Fritsch (1987), there exists "energy competition" between these two schemes in all numerical simulations of MCSs, cyclones, and other precipitating weather systems. In other words, if any parameterization scheme fails to effectively remove the necessary amount of potential instability in a column, the remaining portion will be consumed by the grid-scale processes. Since the grid-scale circulation operates layer by layer, it occurs on a timescale much longer than that associated with parameterized convection. Furthermore, as horizontal resolution decreases, it is likely that the time it takes for the grid scale to remove the existing potential instability will increase. Still further, more energetic circulations begin to develop when the grid-scale saturation occurs in the potentially unstable layer, thereby leading to the occurrence of absolute instability. If the model does not contain a mechanism (e.g., moist downdrafts or any convective adjustment scheme) to stabilize the absolute unstable column rapidly, the grid-scale processes may lead to the development of CISK-like (conditional instability of the second kind) or "numerical gridpoint storms," and excessive grid-scale rainfall (see Kalb 1987; Zhang et al. 1988; Giorgi 1991). This type of instability has not developed in our simulations. Rather, our simulations have typically shown a smooth transition from parameterized to grid-scale precipitation processes, accompanied by the development of realistic mesoscale circulations.

In the following, we use the results produced by an earlier version of the KF CPS, in which only the cloud water (ice) component of the detrained condensate was fed back to the grid scale, to illustrate the relative importance of parameterized and explicit schemes in the simulation of an MCS— that is, the 10–11 June squall line. It should be mentioned that excluding the cloud water detrainment produces little effect on the simulation of the case (not shown). The distribution of parameterized heating and grid-scale hydrometeor concentration from the 15-h simulation is given in Fig. 2, which shows a significant amount of stratiform precipitation lagging behind the convective region with some overlap between these two processes. These structures have also been documented in other simulations with the hybrid approach (e.g., Cohen and Frank 1987) and they also conform to previous observational studies (e.g., Johnson and Hamilton 1988; Gallus and Johnson 1991). Figure 3 shows vertical cross sections of equivalent potential temperature, the hourly tendency of parameterized convective heating, and grid-scale latent heating along a line perpendicular to the squall system. It is apparent from Fig. 3a that a deep layer of potential instability (i.e., θ_e decreasing with height) exists over the southeastern half of the cross section. Correspondingly, Fig. 3b shows that this is the only region where

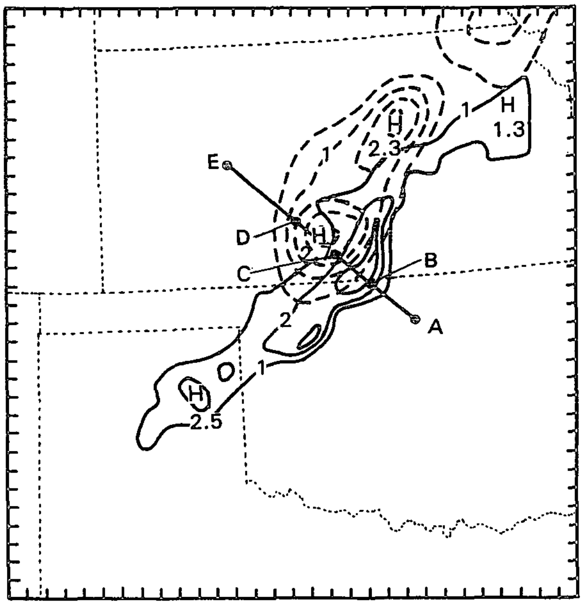

FIG. 2. Horizontal distribution of the vertically integrated instantaneous hourly convective heating rate (solid lines, every 1 K h^{-1}) and total hydrometeor concentration (dashed lines, every 0.5 g kg^{-1}) from 15-h simulation using the KF convective scheme, valid at 0300 UTC 11 June 1985.

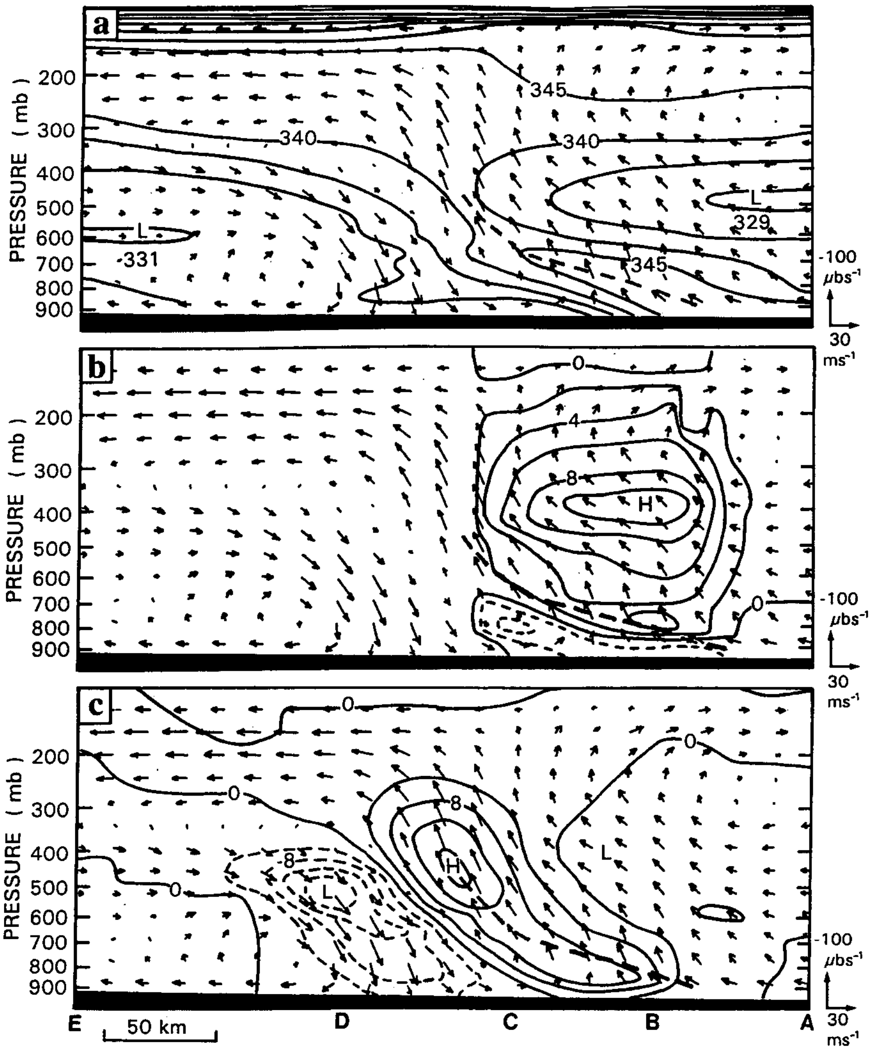

FIG. 3. As in Fig. 2 but for vertical cross sections of (a) equivalent potential temperature θ_e (solid lines, every 5 K); (b) the hourly temperature tendency due to parameterized convection (every 2°C h^{-1}); and (c) the hourly temperature tendency due to grid-scale latent heat release (every 4°C h^{-1}) along line *AE* in Fig. 2. Solid (dashed) lines are for positive (negative) values. The heavy dashed lines indicate the axis of the maximum values of θ_e and mark the transition zone between convectively stable and unstable overturning.

the KF convective parameterization scheme is operating. In contrast, the grid-scale latent heating is occurring in both stable and unstable regimes (cf. Figs. 3a and 3c). It is important to note that the grid-scale heating is peaked at upper levels at a height (i.e., 450 mb) slightly lower than the parameterized heating (i.e., 400 mb). This is clearly due to the removal of a significant amount of moisture in the low to middle levels by the KF CPS and the use of the explicit moisture scheme. Meanwhile, the axis of maximum grid-scale heating closely parallels the axis of transition between convectively unstable and stable circulations, with the most intense heating and ascent concentrated in the region of near-neutral stability. The picture that emerges is that of a transition from a convectively unstable environment in which the convective parameterization dominates to a neutral and then to a convectively stable environment in which slantwise grid-scale overturning dominates. The simulated system displays a spatial distribution of stability and associated mode of overturning consistent with that observed by Leary and Rappaport (1987), Zipser et al. (1981), Smull and Augustine (1993), and others in studies of the structure of MCSs. It should be noted that the coexistence of parameterized and explicit clouds over the transition region is extremely important for obtaining realistic simulations of the meso-β-scale structure and evolution of MCSs, especially in situations in which deep convective towers are embedded within mesoscale stratiform regions (e.g., Churchill and Houze 1984). Bélair et al. (1994) have recently tested the effects of using different convective parameterization schemes on the simulation of the 10–11 June 1985 squall system, and they found that, when any convective scheme failed to generate grid-box saturation in the middle to upper troposphere, the model would be unable to produce the above-mentioned transition, so that the strong descending rear inflow, surface pressure perturbations, and other mesoscale details could not be reproduced.

Recently, Zhang and Cho (1992) showed that the stratiform region, though convectively stable to pure vertical displacement, is considerably unstable to saturated slantwise displacement along the system's broad front-to-rear ascending flow. This reveals that a parameterized convective scheme should be used to handle potentially unstable columns, while an explicit scheme is needed to deal with slantwise unstable conditions, with the coexistence of the two schemes over some transition regions. Thus, in a certain sense, parameterized schemes communicate with explicit schemes through convectively stabilizing the lower troposphere but symmetrically destabilizing the middle to upper troposphere (Zhang and Cho 1992). The degree of the two-scale communication very likely depends on the particular thermodynamic conditions and larger-scale forcing. Clearly, the parameterized and explicit schemes must, and do, simulate clouds of distinctly different character associated with the 10–11 June 1985 squall line, as shown in Fig. 3.

To gain further insight into the processes by which various mesoscale structures were simulated by our parameterized and explicit schemes, Fig. 4 shows four soundings taken along the same vertical cross section as indicated in Fig. 2: (a) just ahead of the leading convective line, (b) within the convective region, (c) at its back edge, and (d) within the trailing stratiform region. At this time, the sounding just ahead of the squall line (Fig. 4a) shows a conditionally unstable environment with relatively dry air at low levels. High-level outflow from the convective system is also evinced by saturated conditions aloft (cf. Figs. 3 and 4a). Farther west, within the leading portion of the squall line, the thermodynamic profile (Fig. 4b) again shows a conditionally unstable environment but with saturated conditions between 800 and 700 mb. Still farther west, at the back edge of the convective line, the sounding is saturated at nearly all levels (Fig. 4c). Moreover, other important changes have taken place as well. Specifically, parameterized convective downdrafts have introduced substantial cooling and drying in the layer below 700 mb (cf. Figs. 1 and 4a–c). This drying effect tends to remove low-level moisture that otherwise would be available on the grid scale, thereby suppressing the development of CISK-like instability. Meanwhile, maximum convective available potential energy (CAPE) has been significantly reduced and the level from which new convective cells are most likely to originate has risen from about 850 to about 650 mb.

As this sequence of soundings indicates, the convective scheme tends to stabilize the atmosphere from the bottom up—that is, it begins with the lowest model layers and proceeds upward, sequentially modifying convectively unstable layers. Therefore, as the squall line passes over a given location, unstable air from progressively higher levels is replaced by cooler, drier air through the action of parameterized convective overturning. This trend is reflected by the cross section of convective heating given in Fig. 3b, which shows that the vertical level at which the convective temperature tendency crosses over from cooling to warming (which is indicative of the cloud-base level) also rises from about 850 to about 650 mb from east to west across the leading convective region.

At some point, virtually all of the instability is removed and convective activity ceases. From this point rearward, the atmosphere is dominated by grid-scale (stratiform) precipitation processes. For example, the sounding taken beyond the back edge of the convective line, within the stratiform region (Fig. 4d), shows that the conditional instability has been removed but the middle to upper levels remain saturated.

Although CAPE is steadily reduced during the passage of the squall line, a substantial amount of grid-scale latent heating also occurs within the leading convective region before the model atmosphere is completely stabilized with respect to vertical overturning (see Figs. 3a,c). Within this overlap region, an absolutely unstable (i.e., saturated with a vertical lapse rate greater than the moist-adiabatic value) vertical structure sometimes develops. It is not clear whether this type of vertical structure ever exists in the real atmosphere. (If it does exist, such absolutely unstable layers are likely to occur on the convective scale.) Evidently, if this condition persists sufficiently long in any coarse-resolution model, ''spurious'' grid-scale mesocyclones might develop (see Zhang et al. 1988). Its existence in the model may be due to several factors. First, it must be remembered that gridpoint values in the model represent the mean conditions over a relatively large area, 625 km^2 in our simulations. Considerable variability and sharp horizontal gradients in thermodynamic conditions are likely to exist within a single grid element, especially in a convectively active environment. It is possible that the degree of absolute instability that is apparent in our model soundings is exaggerated by the implicit horizontal averaging inherent in any grid point modeling system (i.e., aliasing), since this instability occurs only on the smallest grid-resolvable scale (i.e., $2-3\Delta x$). Second, development of this vertical structure could also be related to the procedure used by the KF and FC schemes to select the source layers for convective clouds. These schemes begin checking for potential source layers at the surface. Working up from this

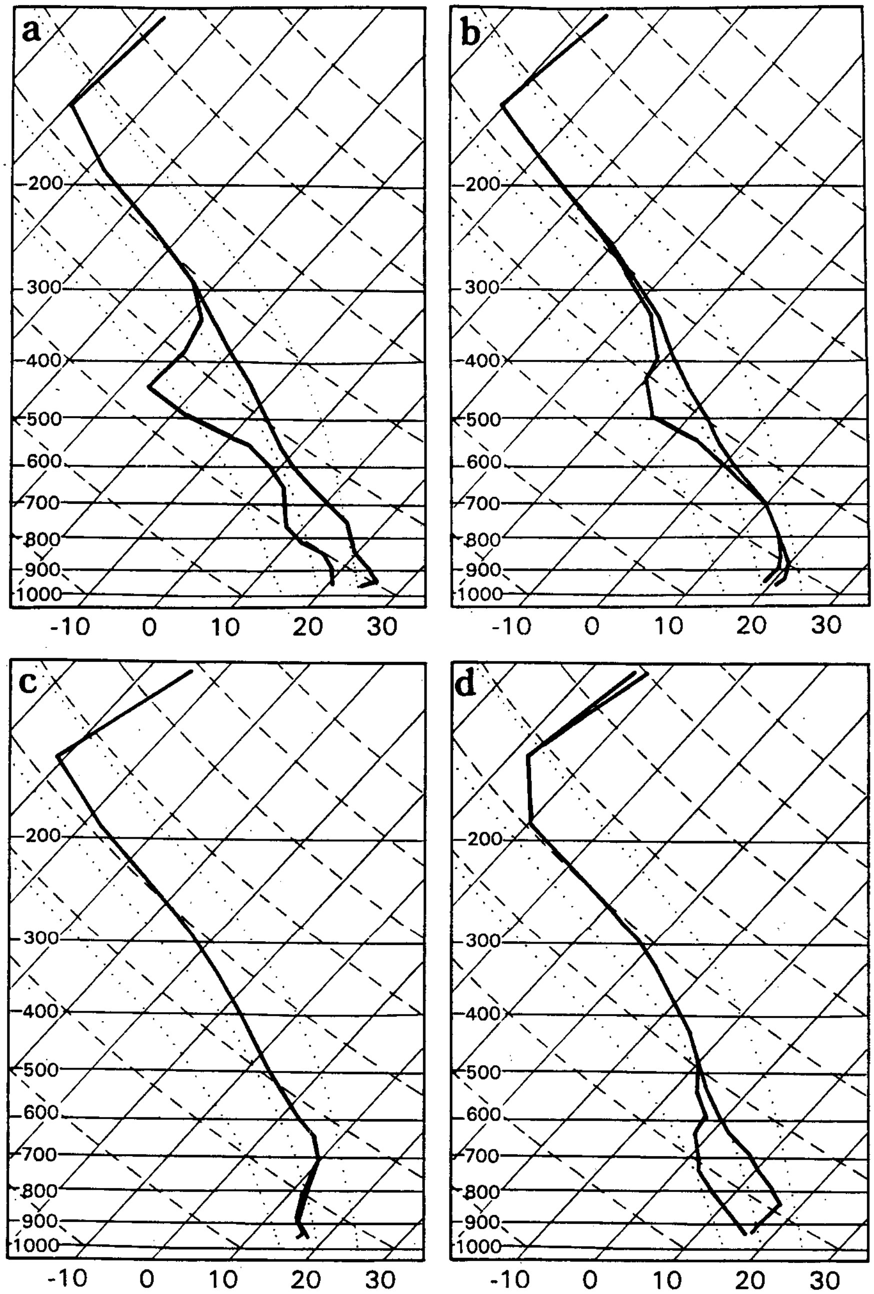

FIG. 4. As in Fig. 2 but for skew T–log$p$ diagrams taken (a) ahead of the leading line; (b) within the leading convective region; (c) in the transition region; and (d) within the trailing stratiform region. Their locations are given in Figs. 2 and 3 by points A, B, C, and D, respectively.

point, the first layer of depth 50–100 mb that can reach its level of free convection is used as the source layer (see Fritsch and Chappell 1980; Kain and Fritsch 1992). In this way, if (saturated) absolute instability develops over a significant depth in the model atmosphere, only the lowest 50–100 mb of the absolutely unstable layer may be stabilized by these convective schemes during the initial convective time period (30–60 min). Consequently, there may be a systematic time lag between stabilization of successive vertical layers. Although this rigid dependence on the convective time interval may be artificial, the concept of stabilization from the bottom up appears to be consistent with what happens in nature. Third, it may be that, under certain conditions, convective tendencies parameterized by these schemes are not strong enough to keep pace with the larger-scale environment. In particular, when grid-scale destabilization tendencies are exceptionally strong, as they are in the 10–11 June squall line, it may be desirable to update the convective tendencies more often than every 30–60 min.

On the other hand, these saturated layers could be regarded as a favorable ingredient for the development of slantwise convection as discussed by Zhang and Cho (1992). Specifically, note that grid-box saturation associated with the shallow unstable layers elevates rearward from 800–700 mb at point *B* to 700–600 mb at point *C* and above 500 mb beyond point *D* (cf. Figs. 3c and 4). The tilted grid-scale saturation of grid boxes clearly explains the generation of slantwise latent heating and the development of the slantwise unstable front-to-rear ascending flow (see Fig. 3c). The latter has been shown to be an important component of squall systems that are trailed by stratiform precipitation (e.g., Johnson and Hamilton 1988; Houze et al. 1989). The slantwise distribution of grid-scale latent heating also resembles the observational heat budget results of Gallus and Johnson (1991).

In spite of the above-mentioned uncertainties, the absolutely unstable layers that sometimes develop in our simulations appear to be benign and transient features. For example, in the 10–11 June squall line case, this type of vertical structure does not appear to have an adverse impact on the simulation, and complete stabilization occurs over a 1–2-h time period as the leading convective line passes. This time period is comparable to observational analysis of convective stabilization (e.g., Fritsch et al. 1976; Betts 1986), and it has also been used by Betts (1986) and Betts and Miller (1986) as a relaxation timescale for adjusting thermodynamic fields toward a reference quasi-equilibrium structure in their convective adjustment scheme. It should be noted, though, that the grid-scale sublimative, melting, and evaporative cooling must have also played an important role in stabilizing these columns across the leading convective region (Zhang and Gao 1989). The results clearly indicate that the FC and KF schemes are capable of interacting with the explicit scheme to stabilize vertically the leading portion of the MCS within a reasonable time period and produce slantwise unstable conditions to the rear.

4. Effects of other model physics

In their review, MD provided little discussion of the effects of other model physics on the simulation of MCSs. They have also attributed the success of MCS simulations primarily to the CAPE concept used in the Fritsch–Chappell scheme. Their comment is partly correct since the CAPE concept is important in providing a constraint for the aforementioned "energy competition." However, we feel that several other physical processes are also instrumental in the realistic simulations of MCSs. They include parameterized moist downdrafts (Zhang and Fritsch 1988a; Zhang and Gao 1989), boundary layer parameterization, hydrostatic water loading (Zhang et al. 1988), and ice microphysics (Zhang 1989; Zhang and Cho 1992). As a supplement to MD's review, our understanding of the effects of these model physics is briefly summarized below.

- Parameterized moist downdrafts have a significant impact on the general evolution of MCSs, especially those that develop in weak-gradient environments. On the one hand, moist downdrafts tend to stabilize the atmosphere vertically at the place deep convection occurs, and thus, further convection may be suppressed. On the other hand, downdraft cooling produces pressure and temperature gradients that can enhance the low-level flow into the convective region, leading to a horizontal destabilization of the environment. In addition, downdraft drying tends to remove moisture that otherwise would be available for grid-scale latent heating, thereby suppressing the development of CISK-like instability. Consequently, further development of moist convection will be determined by the interaction between convection and larger-scale energy supply. Moreover, moist downdrafts are an important component of the mesoscale dynamics of MCS development and evolution.
- The diurnal cycle of the boundary layer plays an important role in creating and destroying CAPE. When coupled with certain terrain features, it is also responsible for the formation of the nocturnal low-level jets commonly associated with nocturnal MCSs over many land areas of the globe. It has been found that without the diurnal cycle the model fails to initiate deep convection associated with the 10–11 June 1985 squall line.
- Water loading reduces the magnitude of upward motion when latent heating in updrafts is large, thereby controlling unrealistic development of grid-scale CISK-like instability.
- Ice microphysics accounts for the effects of deposition/sublimation and freezing/melting that are essential for realistic simulation of the structure and circulations of the stratiform portion of MCSs. Its effect could be more significant in longer model integrations of MCSs in which the cloud–radiation interaction processes are important.

With the aforementioned physics implemented, the Penn State–NCAR model has performed consistently for all of the real-data simulations that we have undertaken. These results suggest that both subgrid- and grid-scale physics have to be treated realistically—the Fritsch–Chappell scheme is but one component of the overall physical system represented by the model. It should be mentioned that Grell (1993) has also obtained a successful simulation of the 10–11 June 1985 squall line using a modified (CAPE based) form of the Arakawa and Schubert (1974) scheme while keeping everything else identical to that described in Zhang et al. (1989). This further indicates that our success depends more on a comprehensive system of model physics than on a particular parameterization scheme.

5. Concluding remarks

In this paper, we have discussed the effects of various parameterized cloud processes and grid-scale physical representations on the simulation of MCSs. We support many of the important issues raised by MD in their recent review. We agree with MD that there is indeed a considerable amount of uncertainty involved in convective parameterization as grid lengths in numerical models are scaled downward toward the size of individual cumulonimbus clouds. However, we feel that some of the results from previous studies of MCSs have been misinterpreted by MD and that some emphasis in their review has been misdirected.

In general, we agree that for the sake of consistency it is more appropriate to implement both vapor and hydrometeor detrainment feedbacks in simulations with the FC scheme. We have argued, however, that the FC scheme implicitly includes the effects of hydrometeor detrainment in such a way that any procedural differences are likely to have minimal impact on the net grid-scale moisture tendencies. In our recent tests, we have found that the model simulations are sensitive to the amount of water substance that is fed back to the grid scale from a parameterization scheme. However, they are much less sensitive to whether the feedback is manifested in the form of rainwater (snow), cloud water (ice), or vapor. Thus, we have contended that the interaction between grid-scale processes and parameterized convection in our previous simulations is realistic and conceptually similar to MD's hybrid approach.

We have shown that the model-simulated thermodynamic structures conform to previous observations, even with the development of some local absolutely unstable layers. We acknowledged that these unstable layers can be partly attributable to the use of the relatively limited horizontal resolution of the model. Molinari and Dudek (1992) also noted the development of such absolutely unstable layers in simulations with a hybrid approach. We emphasized, however, that the parameterized moist downdrafts in the FC scheme tend to produce substantial cooling and drying in the lower troposphere. This drying effect could remove efficiently low-level moisture that otherwise would be available on the grid scale. Thus, these vertical structures do not lead to excessive vertical motion or "grid-point storms" in our simulations, because the vertical instability is still removed primarily by the convective scheme, not the grid-scale circulations. On the other hand, we pointed out that these structures are consistent with the observed existence of convective clouds embedded within stratiform rain regions (and broad areas of saturation along convective lines).

In conclusion, we reiterate that the coupling of parameterized convection with explicit moisture schemes tends to have the greatest potential success in reproducing various scales and different types of mesoscale precipitating weather systems. We recommend that MD's model classification and hybrid concept be revised so that it is based only upon whether or not an explicit moisture scheme is implemented and cloud detrainment is realistically treated. We emphasize that to simulate realistically the structures and evolution of MCSs, mesoscale models have to include other important physical processes, such as surface representations, boundary layer transports, moist downdrafts, water loading, and cloud and ice microphysics.

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