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

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ABSTRACT

Current approaches for incorporating cumulus convection into mesoscale numerical models are divided into three groups. The traditional approach utilizes cumulus parameterization at convectively unstable points and explicit (nonparameterized) condensation at convectively stable points. The fully explicit approach uses explicit methods regardless of stability. The hybrid approach parameterizes convective scale updrafts and downdrafts, but "detrains" a fraction of parameterized cloud and precipitation particles to the grid scale. This allows the path and phase changes of such particles to be explicitly predicted over subsequent time steps.

The traditional approach provides the only alternative for numerical models with grid spacing too large to resolve mesoscale structure. As grid spacing falls below 50 km, the traditional approach becomes increasingly likely to violate fundamental scale-separation requirements of parameterization, particularly if mesoscale organization of convection is parameterized as well. The fully explicit approach has no such limits, but it has repeatedly failed in mesoscale models in the presence of large convective instability. Although it is preferable under certain specialized circumstances, the fully explicit approach cannot provide a general solution for models with grid spacing above 5–10 km.

The hybrid approach most cleanly separates convective-scale motions from the slow growth, fallout, and phase changes of detrained hydrometeors that produces mesoscale organization of convection. It is argued that this characteristic removes the need to parameterize the mesoscale and thus reduces the scale-separation problems that may arise when the traditional approach is used. The hybrid approach provides in principle the preferred solution for mesoscale models, though such promise has yet to be fully realized.

In the absence of large rotation, the fundamental assumptions of cumulus parameterization begin to break down once grid spacing falls below 20–25 km. For models with such resolution, the time scale of the convection being parameterized approaches the characteristic time scale of the grid, and parameterized and unparameterized *convective* clouds often exist simultaneously in a grid column. Under such ambiguous circumstances, successful simulations have been produced only because parameterized convection rapidly gives way in the model to its grid-scale counterpart. It is essential to understand the interactions between implicit and explicit clouds that produce this transition, and whether they represent physical processes in nature, before cumulus parameterization can be widely used in such high-resolution models. In a broader sense, more detailed analysis of why convective parameterizations succeed *and* fail is needed.

1. Introduction

The pioneering work of Riehl and Malkus (1958) showed that in convectively unstable regions, vertical transports of mass and moist static energy were not accomplished by the synoptic-scale circulation but by individual cumulonimbus clouds. The concept of cumulus parameterization in numerical models was required to incorporate these otherwise unresolvable subgrid-scale transports. Subsequent development has been active, as indicated by the large number of review and overview papers in recent years (Ooyama 1982; Frank 1983; Arakawa and Chen 1987; Tiedtke 1988; Cotton and Anthes 1989). Without exception, these authors agree that cumulus parameterization is required in large-scale numerical models (grid spacing greater than 50–100 km) at convectively unstable grid points.

As computer power has continued to advance, very high-resolution mesoscale numerical models have been developed. Cotton and Anthes (1989) suggest that the conceptual basis for cumulus parameterization becomes "muddy" and "not well posed" when the model grid spacing falls below about 50 km. Along these lines, some researchers have omitted cumulus parameterization in high-resolution models and instead directly simulated cumulus convection on the grid (e.g., Yamasaki 1977; Rosenthal 1978). Conversely, other authors have designed cumulus parameterizations expressly for grid spacings well below 50 km (Fritsch and Chappell 1980; Frank and Cohen 1987). The choice of what and whether to parameterize in mesoscale models has been further complicated by the recognition

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that convection in nature often develops mesoscale organization. This resolvable mesoscale structure develops from initially unresolvable cumulonimbus clouds and thus provides a major challenge to mesoscale modelers. As a result of the above difficulties, greater uncertainty exists in cumulus parameterization than in any other aspect of mesoscale numerical weather prediction.

In a thorough discussion of the conceptual basis for cumulus parameterization, Arakawa and Chen (1987) noted that in principle the solution to the problems above lies in using a grid spacing on the order of 100 m. This does not remove the necessity of parameterizing microphysics and turbulence, nor does it address the source of initial data on such scales. It does, however, allow the direct simulation of clouds and thus eliminates the need for cumulus parameterization. Unfortunately, computer power will not currently allow use of 100-m resolution in three-dimensional mesoscale models. Even if such resolution were possible within the decade, interpretation of literally billions of model output points would be extraordinarily challenging due to the stochastic nature of the scales being simulated (Ooyama 1982). The need for simpler models that represent larger scales of motion will not disappear. As a result, the question of how to parameterize cumulus convection will likely remain for an indefinite period.

In the current paper, the goal is to provide a framework for choosing the form for cumulus parameterization in mesoscale models. The discussion will be confined primarily to three-dimensional models, because limited-area two-dimensional models are (or soon will be) able to use cloud-model resolution for idealized studies. In this paper, the term *mesoscale model* will refer to any hydrostatic model with grid spacing between 10 and 50 km, which could include regional or even global models of such resolution. Cumulus parameterization in current-generation general circulation models (grid spacing > 80–100 km), for which the problem is better defined, will not be addressed. Parameterization in theoretical models such as wave CISK (Lindzen 1974; Raymond 1986) will be omitted, as will nonhydrostatic cloud models, for which the parameterization problem exists more with regard to cloud microphysics and turbulence. Only thermodynamic aspects of the problem will be considered because convective momentum transports remain too poorly understood to parameterize. Parameterization of slantwise convection will be dealt with only in terms of how it may impact upright cumulus parameterization. Emphasis will be given to (i) conceptual grouping of current approaches in mesoscale models; (ii) fundamental and practical limitations of each; (iii) problems presented by mesoscale organization of convection and by slantwise convection; (iv) recommendations for the optimum approach as a function of model grid spacing; and (v) suggestions for directions of future work.

Definitions and terminology. Cumulus parameterization requires the creation of subgrid-scale *implicit* clouds, which vertically transport heat, water vapor, and other quantities, generally in the absence of grid-scale saturation. Closure assumptions are required to define the relationship between these implicit clouds and the grid-scale variables. For mesoscale models, the form of closure may have to differ from that for large-scale models (Fritsch and Chappell 1980; Frank 1983). Details of the closure issue will not be discussed in the current paper. A conceptual classification of closure assumptions has been provided by Arakawa and Chen (1987).

The unparameterized or *explicit* condensation method allows clouds to exist only when grid-scale saturation occurs. To the extent possible in a hydrostatic model, the cloud is directly simulated on the grid. This definition of the explicit method holds, regardless of the level of microphysics, from the simplest form where no cloud stage is present and condensed water is assumed to fall immediately as rain, to a complex form in which prediction equations exist for cloud water and ice, rainwater, and various forms of frozen particles. In all of these explicit formulations, no subgrid-scale clouds are accounted for. A single characteristic unambiguously distinguishes the two methods: in implicit methods, the properties of the cloud(s) differ from those of the grid; in explicit methods, cloud and grid are synonymous.

In large-scale numerical weather prediction models, both implicit and explicit methods have traditionally been used, following the historical division of precipitation in nature into convective and stratiform, respectively (see, for example, Houghton 1968). Thus, cumulus parameterization was used at convectively unstable grid points, and explicit condensation at nonconvective (i.e., convectively stable) grid points (Krishnamurti and Moxim 1971). In practice, nonconvective condensation represents simply the removal of supersaturation (see, for example, Kanamitsu 1975; also described by Molinari and Corsetti 1985, appendix B).

In mesoscale models, this broad consensus on the form of incorporating cumulus convection has not been maintained. In Table 1, a conceptual division of current approaches is proposed. The *traditional* approach uses implicit or explicit methods depending upon local convective stability, as described earlier.[1] The *fully explicit* approach uses only the explicit formulation, re-

[1] In large-scale models, nonconvective precipitation may also be parameterized, typically in terms of areal coverage (Sundqvist 1978). Such variations will not be considered in this discussion of mesoscale models.

TABLE 1. Description of approaches to cumulus parameterization in mesoscale models.

Approach	Convectively unstable points	Convectively stable points
Traditional	Implicit	Explicit
Fully explicit	Explicit	Explicit
Hybrid	Hybrid	Explicit

gardless of convective stability. A third category, which will be labeled *hybrid,* is proposed in this paper. The hybrid approach (see, for instance, Frank and Cohen 1987) uses cumulus parameterization to provide a vertical distribution of cloud and precipitation particles in convectively unstable regions. A fraction of these particles is "detrained" into the cloud environment, then is predicted *explicitly* over subsequent time steps using nonconvective forecast equations and advection by grid-scale motions. In convectively unstable regions, the hybrid approach is thus partly implicit and partly explicit.

The hybrid approach should be distinguished from pure cumulus parameterization found in the traditional approach. For example, Fritsch and Chappell (1980) and Emanuel (1991) compute condensate in their entraining updrafts and downdrafts and incorporate the influence of evaporation of convectively generated condensate. These and other similar procedures do not classify as hybrid, however, because microphysical influences must be incorporated all at once. Water content is implicit and not carried to subsequent time steps, and it does not communicate with its grid-scale counterpart.

In practice, the definition of hybrid used here requires grid-scale, nonconvective prediction equations for cloud and precipitation particles. In addition, these equations must contain convective source terms in which implicit particles are transferred to the grid scale. Thus, the presence of cumulus parameterization plus nonconvective microphysical equations alone is insufficient. For example, Zhang and Gao (1989) use the Fritsch–Chappell (1980) cumulus parameterization at unstable grid points, plus rather detailed microphysical forecast equations at stable grid points or upon supersaturation. This qualifies as a traditional approach because the cumulus parameterization does not supply explicit precipitation particles to the grid scale. It will be argued in section 4 that the difference between the traditional and hybrid approaches is fundamental.

For large-scale models, only the traditional approach has been utilized (e.g., Krishnamurti et al. 1983; Albrecht 1983; Betts 1986; Tiedtke 1989). In mesoscale models, however, each of the three approaches has been tried, with a bewildering variety of results. This review will attempt to establish a basis for the choice between approaches.

2. The traditional approach

a. Arguments in favor of cumulus parameterization

The traditional approach remains the dominant choice in numerical weather prediction models, including (to the authors' knowledge) 100% of operational models. The traditional approach requires cumulus parameterization at convectively unstable grid points when conditions are met for its initiation. This implicit inclusion of cumulus clouds has been justified for the following reasons.

(i) The preferred scale for convective instability (initially) is less than the grid spacing of any hydrostatic model (e.g., Lilly 1960). If saturation were allowed in the presence of convective instability, unstable growth would be aliased onto the smallest resolvable scales of the model. Cumulus parameterization attempts to avoid this problem by allowing convective instability to be removed without grid-scale saturation in unstable layers.

(ii) Significant convective precipitation (and thus a net heat source in the column) occurs in nature when the grid-scale area is unsaturated. A model that allowed condensation only upon grid-scale saturation would fail to reproduce this heat source.

(iii) Large vertical fluxes of heat, moisture, and other quantities by cumulus convection occur on scales unresolvable by hydrostatic model grids. A model that did not implicitly include such subgrid-scale source terms could not accurately predict grid-scale evolution when convection was active.

The sum of net condensation heating (or moistening) in the column [(ii) above] and convective eddy flux convergence [(iii) above] can in principle be measured from observations using residuals from large-scale budgets. These residuals are known as the apparent heat source Q_1 and the apparent moisture sink Q_2 (Yanai et al. 1973). Molinari and Dudek (1986) noted that if the vertical profiles of Q_1 and Q_2 differ, eddy fluxes are nonzero and cumulus parameterization is required. If Q_1 and Q_2 are nearly identical, heating is determined by the local condensation rate and parameterization becomes unnecessary.

On the synoptic scale in convectively unstable regions, precipitation occurs without mean saturation and vertical subgrid-scale fluxes are large, so that Q_1 is nonzero and differs from Q_2 (Riehl and Malkus 1958; Yanai et al. 1973). Observations thus support the need for cumulus parameterization in models with grid spacing on the order of 100 km or larger. In practice, the omission of cumulus parameterization in such models may produce gross underestimates of observed convective precipitation (Molinari and Corsetti 1985).

In contrast to the synoptic scale, data on the scale of mesoscale model grid points are insufficient to accurately determine the budget residuals that make up

Q_1 and Q_2. Even high-resolution Severe Environmental Storm and Mesoscale Experiment (SESAME) data had at best an 80-km mean station separation and a 3-h time resolution. Kuo and Anthes (1984) found that spatial and temporal averaging were required to produce a coherent signal, and the resultant Q_1 and Q_2 were valid only for large-scale models.

Current datasets thus cannot prove the need for the parameterization of cumulus convection in mesoscale models. Instead, numerical models themselves must be used empirically to make such determinations. The results of such numerical experiments will be discussed in the following sections.

b. Arguments against cumulus parameterization in mesoscale models

Regardless of what observations might show, conceptual problems arise in cumulus parameterization as grid spacing decreases. Arakawa and Chen (1987) discussed the need for a distinct scale separation and a gap in the energy spectrum between the scale being parameterized and that being explicitly resolved by the grid. They noted the lack of a spectral gap in nature between the cloud scale and mesoscale. In practice, this means that in a mesoscale model, explicit clouds may form at a grid point while *essentially similar* clouds are simultaneously being parameterized. Calculation techniques are such that modelers do not allow "double counting": energy and moisture are conserved in such situations because grid-scale condensation is computed at the end of the time step after all other processes have acted (e.g., Kanamitsu 1975). Nevertheless, the presence of the same physical process in parameterized and unparameterized forms at the same grid point seems ambiguous at best. This difficulty can be avoided in practice only by a cumulus parameterization that always maintains subsaturation in convectively unstable layers. As the grid spacing becomes smaller, however, grid-scale saturation is more likely to be observed, and an approach that prevented its occurring would not simulate nature. This issue will be addressed further in section 4.

As part of the spectral gap assumption in cumulus parameterization, the subgrid-scale eddies are assumed to have a time scale much smaller than grid-resolvable disturbances (Ooyama 1971). This allows the integrated influence of the life cycle of convection to be inserted during a given time step in the model. In reality, the deep convection may take 1 h (or more, if mesoscale organization is included; see section 2c) to produce this cumulative effect. In mesoscale models, the time scale of grid-scale motions may be comparable to the characteristic life cycle of the convection being parameterized.

Related to the time-scale issue is the fractional coverage of convection over a grid area, which is formally assumed to be much less than unity in some cumulus parameterizations (e.g., Arakawa and Schubert 1974). Although this assumption can be extended if the fractional coverage is assumed to represent only areas of active updrafts (Ogura and Kao 1987), it must break down when the grid spacing becomes small enough to be filled by active cloud in nature.

Ooyama (1982) addressed the time-scale problem in terms of local rotational constraints. Ooyama noted that under strong rotation, the local deformation radius can shrink enough to produce a long-lasting, inertially stable disturbance. In such cases, divergent circulations are controlled by the slowly varying primary circulation. By this reasoning, the time-scale separation requirement is indeed met, even in mesoscale models, under sufficiently strong rotation. Ooyama noted it was this characteristic that allowed the success of cumulus parameterization in numerical simulation of mature hurricanes. He warned against uncritically using the same approaches to understand hurricane formation, for which rotational constraints are weaker and the constraints imposed by closure may be too restrictive.

Arakawa and Chen (1987) note that two closure conditions are required because four unknowns exist in the cumulus parameterization problem (Q_1, Q_2, $\partial T/\partial t$, and $\partial q/\partial t$), but only two equations. As noted by Ooyama (1982), these closures constrain, sometimes strongly, the allowed interactions between the grid scale and the convection. For mesoscale models, the lack of observations makes it impossible to verify any current closure. As a result, this fundamental aspect of mesoscale cumulus parameterizations remains on an ad hoc basis.

The ambiguities arising from questionable scale-separation assumptions and closure conditions may cause problems in practice as well. Frank (1983) noted that when rotational constraints are weak, local divergent circulations may become dominant in mesoscale models. Grid-scale forcing may initiate parameterized convection, but once heat is released at the model grid point, the local circulations under weak forcing may grow rapidly in a manner determined by the details of the cumulus parameterization. The implicit assumption that the grid scale deterministically controls the convection (Arakawa and Chen 1987) appears to be violated. Most cumulus parameterizations have free parameters whose actual value in nature is unknown; under the above circumstances the solution may become overly sensitive to such parameters (Rosenthal 1979).

The arguments against cumulus parameterization may be summarized as follows: (i) at some small grid spacing, which is less than 50 km and greater than 5 km, the requirements for scale separation in time and space between convection and grid-scale flows may not be met except locally under strong rotation; and (ii) for any model with less than 50-km grid spacing, key aspects of the parameterization remain ad hoc due to the lack of observations on such small scales. In the following section, it will be shown that the presence of mesoscale organization of convection makes these problems worse.

c. Complications of mesoscale organization

The role of cloud-scale downdrafts in removing convective instability by cooling the planetary boundary layer has long been accepted. Over the last two decades, however, the presence of unsaturated downdrafts on scales much larger than individual cumulus clouds has been recognized (Zipser 1969, 1977; Houze 1982; Leary and Rappaport 1987). These downdrafts are part of a mesoscale organization of upper-tropospheric updrafts and lower-tropospheric downdrafts, which typically evolves as follows: (i) Intense individual cumulonimbus cells break out over an area in the presence of large convective instability and favorable, though often not intense, dynamical forcing (e.g., Maddox 1983); (ii) These cells detrain large numbers of frozen hydrometeors, mostly in the upper troposphere (Houze 1989); (iii) These frozen particles are advected by upper-tropospheric flow and slowly fall out; as they fall they may grow by vapor deposition if an anvil has already developed (Rutledge and Houze 1987; Houze 1989; Dudhia 1989); (iv) When these particles reach the freezing level they melt and later evaporate or reach the ground as widespread stratiform rain; (v) As a result of (iii) and (iv), fusion heating occurs above the freezing level and cooling by melting occurs immediately below the freezing level, as well as evaporative cooling occurring in the lower troposphere; (vi) Associated with these heating and cooling patterns, widespread upward motion occurs in the anvil and downward motion occurs in the region of stratiform rain below. The downdraft region typically remains unsaturated and relatively warm, and a strong inversion often develops above a cool, moist boundary layer (Betts 1973). As a result, the column may stabilize and limit active convection to the leading edge of the system (Leary and Rappaport 1987). The mesoscale circulations may extend 100 km or more from the convective sources. This evolution may take 6 h or more, although in a propagating system it may be experienced more rapidly at a given location (Leary and Rappaport 1987). A significant fraction of total rainfall with the convective system occurs in the stratiform region (Cheng and Houze 1979; Gamache and Houze 1982). Recently, Gallus and Johnson (1991) provided a well-documented example of mesoscale organization in a severe squall line in the PRE-STORM experiment.

As a result of these processes, the vertical distribution of heating for the mature mesoscale convective system differs significantly from that for isolated cumulonimbus (Houze 1982; Johnson 1984). Hartman et al. (1984) found that a "mature cluster" heating profile, which included mesoscale influences, reproduced tropical divergent circulations in a linear steady-state model more accurately than a heating profile characteristic of isolated cumulonimbus clouds. The authors suggested that the mesoscale heating profile represents the dominant mode of diabatic heating in the tropics. Taken together, the studies reviewed in this section indicate that mesoscale organization of convection cannot be overlooked.

Mesoscale organization is also present in the pressure and wind fields, often with rather complex vertical structure. It appears, however, that this structure develops primarily as a result of the diabatic sources and sinks associated with the processes described above (Zhang and Gao 1989; Chen and Cotton 1988). As a result, this paper will not deal directly with surface mesohighs and mesolows, midlevel vortices, and other manifestations of mesoscale organization of convection. Rather, it will be assumed that if the heat sources associated with convective processes are well simulated, the wind and pressure structure will follow in the model. Further detail concerning the mesoscale structure of convective systems is provided by Houze (1989), Cotton and Anthes (1989), and Emanuel and Sanders (1983).

The development of mesoscale organization in precipitating convection complicates the already difficult cumulus parameterization problem. In large-scale models, for which the entire mesoscale circulation remains subgrid scale, Arakawa and Chen (1987) provide convincing evidence that mesoscale effects are parameterizable in principle. Emanuel (1991) has proposed a specific parameterization of unsaturated mesoscale downdrafts for large-scale models. The mesoscale modeler, however, faces additional difficulties. Initially the convection is subgrid scale and must be parameterized. As the convective cluster matures, mesoscale downdrafts and associated stratiform rain cover an increasing portion of the grid area. Eventually, as the column stabilizes, convective updrafts may stop, leaving only the mesoscale circulation (Johnson and Kriete 1982); or the convectively active region may propagate to an adjacent grid point, leaving a mesoscale circulation in its wake (Leary and Rappaport 1987). In either case, the upper-tropospheric updraft and lower-tropospheric unsaturated downdraft become (at the original point) convectively stable, grid-scale phenomena, unaccompanied by the convective scale, and are no longer parameterized. The mesoscale modeler must simulate (i) the vertical distributions of subgrid-scale heat, moisture, *and hydrometeor* sources due to subgrid-scale convection; (ii) their time variation over the life cycle of the system, as mesoscale downdrafts increase in areal coverage; and (iii) the explicit updraft–

downdraft couplet, saturated aloft and unsaturated below, which is left behind.

Microphysical processes play a major role in the development of mesoscale organization. In a traditional approach with no parameterized source of hydrometeors on the grid scale, no precipitation particles are available to be advected horizontally and vertically during subsequent time steps. It is possible empirically to simulate the evolution of vertical motion and stability with a traditional approach, so that the cumulus parameterization produces an appropriate updraft–downdraft couplet on the grid scale in the correct time period (Molinari and Corsetti 1985). Once this occurs in a model with traditional cumulus parameterization, however, the explicit formulation must then spin up cloud water and ice, as well as precipitation, from zero. This produces a spurious gap in the model precipitation while such processes occur. Alternatively, stratiform rain may never develop to the intensity observed (Molinari and Corsetti 1985). It thus appears that most traditional approaches, because they do not supply the grid scale with hydrometeors, cannot reproduce a realistic transition between convective and stratiform rain. An apparent exception to the views in this paragraph, the work by Zhang and Gao (1989), will be discussed in section 4b.

A more fundamental problem with parameterization of mesoscale processes arises as well. The life cycle of convective systems described above may take hours to develop (Houze 1982). The time-scale separation requirement is thus more severe in mesoscale models when mesoscale convective organization is included in the parameterization because the life cycle of the subgrid-scale eddies is clearly not less than that of grid-scale motions. Molinari and Corsetti (1985) mitigated this problem by delaying the onset of parameterized mesoscale downdrafts for 2 h, then linearly increasing their influence to its full value in the parameterization over an additional 2 h. The cost of this procedure is that a single parameter, whose true value is unknown, must be used to represent all the processes that enter into the delay in nature.

The fully explicit approach provides an alternative to the difficulties above. Such complex processes as generation, advection, and interaction of hydrometeors can be addressed using direct prediction equations, without the need for arbitrary parameters relating the grid scale and the cloud. The following section explores this alternative to cumulus parameterization.

3. The fully explicit alternative

a. Benefits

Yamasaki (1977) and Rosenthal (1978) were the first to successfully adopt into mesoscale models the fully explicit alternative, that is, use of the explicit approach in both convectively unstable and stable regions. The approach has several immediate benefits over the traditional approach. No scale-separation or fractional-area assumptions are required, nor are closure assumptions, because no implicit clouds exist. As noted by Rosenthal (1978), the fully explicit approach allows a broad spectrum of interactions between the convective scale (to the extent it is resolved) and larger scales. In Rosenthal's hurricane simulations, squall lines propagated across the incipient storm with little or no interaction, but eventually the convection coupled with the grid-scale vortex and the hurricane developed. In principle, the fully explicit approach may simulate closure assumptions associated with any form of cumulus parameterization, without restricting the interaction to any one. For instance, the Kuo (1974) closure relating convective intensity to moisture convergence, which probably holds for strongly forced, high relative humidity cases, could be simulated, while simultaneously the area-averaged fields might follow the Arakawa–Schubert (1974) quasi-equilibrium assumption. Similarly, regions or scales where moisture convergence or quasi-equilibrium assumptions were not met could also be simulated. In addition, convective momentum fluxes, which are not well enough understood to parameterize in most situations, are directly simulated by the fully explicit approach in a manner consistent with fluxes of other quantities.

If computer limitations were not a factor, the fully explicit approach would be the logical choice. As noted earlier, a grid spacing on the order of 100 m would allow direct simulation of individual clouds in a nonhydrostatic model and move the parameterization question down in scale to turbulence and microphysics. Although the latter is anything but well understood, the 100-m mesh would make cumulus parameterization as it is practiced today obsolete. Because computer power does not allow such a solution, the resolution requirements must be relaxed. It must be asked whether the fully explicit approach retains its benefits at some currently achievable resolution sufficiently well to make it superior in practice to cumulus parameterization. This question is addressed below for hydrostatic models with 10–50-km grid spacing.

b. Explicit method successes

1) TROPICAL CYCLONES

The fully explicit approach in mesoscale models has had its greatest success in the modeling of hurricanes (Yamasaki 1977; Rosenthal 1978; Jones 1986; Rotunno and Emanuel 1987; Baik et al. 1990). Yamasaki (1977), like Willoughby et al. (1984), used cloud-model resolution in a nonhydrostatic model. Such work is not relevant to the current discussion of models with 10–50-km grid spacing. In each of the remaining fully explicit hurricane simulations, grid spacing (and thus cloud diameter) of 10–20 km imposed obvious limitations, but the explicit approach made it possible to interpret mature hurricane structure while avoiding arbitrary assumptions of cumulus parameterizations (Rosenthal 1979). Nevertheless, the fully explicit approach has been tested in only a narrow way in hurricane simulation. The formation process has not been simulated in three dimensions [the initial vortex of Jones (1986) was already tropical storm strength], and no real-data simulations have been attempted. A real-data case makes greater demands on the fully explicit approach because cloud water and rainwater are poorly observed at best, and their initial values in disturbed regions may greatly influence the simulation. In the results noted above, the models were integrated to a quasi-steady state, and the final results did not depend on initial microphysical quantities. In contrast to the fully explicit approach, the traditional approach has been used both for hurricane formation studies in three dimensions (Kurihara and Tuleya 1981) and for real-data prediction of hurricanes (e.g., Krishnamurti 1989; Heckley et al. 1987). The fully explicit approach remains inadequately tested in hurricane simulation.

2) Midlatitude cyclogenesis

A second area in which the fully explicit approach has had some success is in the prediction of explosive cyclogenesis in midlatitudes. Anthes et al. (1983) made real-data simulations of an Atlantic storm on 45- and 22.5-km grid spacing using the simplest form of explicit condensation, whereby all condensed water fell immediately as rain. They had mixed success; the predicted intensity was superior to a parallel integration with a Kuo (1974) cumulus parameterization, but the track was far worse. Liou et al. (1987) also used a simple form of fully explicit heating on an 80-km grid spacing for a rapidly intensifying cyclone over the southeastern United States. Compared to a parallel integration with a Kuo form of parameterization, the explicit approach better forecasted storm intensity with no degradation of the track forecast. In the parameterized integration, precipitation started too soon and covered too wide an area. Even in the parameterized integration, however, most of the total latent heat release occurred in nonparameterized heating, indicating that upright convective instability was relatively rare.

Kuo and Reed (1988), in a case of explosive cyclogenesis over the midlatitude Pacific Ocean, used detailed microphysical equations following Hsie and Anthes (1984), on both 80- and 40-km grid spacings. Although they did not capture all of the deepening, their fully explicit simulations were quite successful in predicting track and intensity. The parameterized simulation (which was a traditional, nonhybrid approach) eventually achieved the appropriate intensity, but the intensification itself was associated with latent heating from nonparameterized heating. Kuo and Reed (1988) attributed a delay in development in the parameterized case to high levels of maximum heating versus the fully explicit case.

Kuo and Low-Nam (1990) tested nine cases of explosive oceanic cyclogenesis in order to avoid the potential case-study dependence of previous work. Averaged over the nine cases, the Arakawa–Schubert (1974) parameterized integrations and the fully explicit integrations did almost equally well. The major reason for this was that the Arakawa–Schubert scheme considers only boundary-layer–based convection, and thus rarely turned on in these frontal cyclone cases. Instead, extensive nonparameterized precipitation occurred ahead of the warm front in both the Arakawa–Schubert and the fully explicit experiments, and storm track and intensity were similar. By contrast, a traditional approach based on Kuo (1974) produced significant amounts of high-based convection in the region of the warm front. The resulting lapse rate along the frontal surface remained unstable, whereas slantwise neutrality would be expected in midlatitude oceanic cyclones (Emanuel 1988). Overall, the fully explicit integrations were the equal or better of their parameterized counterparts. It must be noted, however, that little verifying data exist in explosively growing midlatitude oceanic storms, and traditional approaches have also successfully reproduced what little was known from observations (Liou et al. 1990; Chang et al. 1989; Monobianco 1989; Sanders 1987; Nuss and Anthes 1987; Uccellini et al. 1987). More detailed verification is needed before a consensus can be reached on the optimum approach for condensation heating in midlatitude cyclogenesis.

3) Other phenomena

Bougeault and Geleyn (1989) compared a fully explicit approach on a 10-km grid with two Kuo-based cumulus parameterizations for a Florida sea-breeze case. The fully explicit approach produced far better rainfall forecasts than the others in this single case.

The explicit approach has also been used successfully in frontal simulations (Ross and Orlanski 1978, 1982; Hsie et al. 1984) with grid spacings ranging from 20 to 61.5 km. These works are difficult to incorporate into the current framework for a variety of reasons. Ross and Orlanski effectively parameterized cumulus convection within the explicit approach by enhancing vertical diffusion in regions of (i) convective instability (1978 paper) or (ii) large, presumably diabatically forced, vertical motion (1982 paper). This explicit approach with parameterized convective diffusion does not represent a fully explicit approach as described in this paper. Hsie et al. (1984) used an initial relative humidity of 98% at all grid points. This unrealistically large value artificially avoided the problem of initiation of convection in the explicit approach, which will be addressed below.

c. *Explicit method failures*

With the exception of the Bougeault and Geleyn (1989) results, the above successful applications of the fully explicit approach have the following in common: (i) strong grid-scale forcing and (ii) lack of intense convective instability. When either or both of these conditions are absent, fully explicit simulations have been considerably worse. Dudek (1988) used a 40-km grid spacing in a modified version of the NCAR MM4 mesoscale model (Anthes and Warner 1978) to simulate two cases of formation of mesoscale convective complexes. These provided an extreme test for explicit condensation because the observed MCCs did not form in nature until more than 12 h into the simulation. In both cases the onset of precipitation was unrealistically delayed, areal coverage of rainfall was strongly underestimated, localized overprediction of rainfall occurred, and the location of rainfall maxima was in much greater error than the parameterized control integration.

Figure 1 shows the evolution of temperature and moisture in a fully explicit integration at a point that experienced overprediction of rainfall. The grid column shown was initially unstable and experiencing upward motion due to large-scale forcing. Conditions were such that cumulus parameterization would have initiated had it been present. In the fully explicit approach, however, relative humidity simply kept rising until saturation was reached, initially near 700 mb in this case. The existence of saturation in a conditionally and convectively unstable sounding produced an unrealistic evolution: strong localized heating in the vertical generated superadiabatic lapse rates. The explicit bulk Richardson number–dependent diffusion in the model adjusted these to nearly dry adiabatic (Fig. 1b). Eventually a deep dry-adiabatic but saturated layer formed as the heating layer deepened (Fig. 1c). This layer rapidly overturned, producing intense precipitation on the grid scale and ultimately a near-neutral lapse rate (Fig. 1d; note that the neutral lapse rate includes water-loading effects and, thus, differs from the traditional definition). Figure 1 displays all the weaknesses of the fully explicit approach:

(i) Rainfall was unrealistically delayed because precipitation could not occur until the grid saturated, and the grid-scale updraft was not vigorous enough to produce saturation in a timely manner.

(ii) Once the grid saturated in the convectively unstable layer, the instability could not be removed by eddies as in nature because updrafts and downdrafts could not occur simultaneously. Instead, only the grid-scale $\bar{\omega}$ acted and advected the high low-level θ_e upward, producing a tropospheric-deep layer of convective instability, similar to that shown by Molinari and Dudek (1986). This represents the reverse of what was found in nature by Riehl and Malkus (1958) and Betts (1974), in which the area-averaged midtropospheric θ_e minimum remained in place during convection.

(iii) This absolutely unstable column overturned on the scale of the grid, stabilizing only by entraining air from adjacent grid points, while producing extreme overprediction of rainfall in the process. A structure remarkably similar to Fig. 1c was produced by P. Pauley (personal communication 1988) using a fully explicit approach in a midlatitude explosive cyclogenesis case, as simulated by the nested-grid model at the National Meteorological Center.

The behavior described above has several similarities to that shown by Molinari and Dudek (1986; also an MCC case), but occurred in a model with a much more sophisticated multilevel boundary layer and more detailed microphysics, including the inhibiting effects of water loading and evaporation of rain. The evidence suggests that the fully explicit approach was entirely unsuitable on a 40-km grid spacing for these cases with modest grid-scale forcing and large instability.

Zhang et al. (1988) found similar problems with fully explicit approaches in mesoscale models. Using a 25-km grid spacing, they noted that a fully explicit approach produced too much rain and too intense a surface mesolow in an MCC case. They attributed the overprediction to the unrealistically low level of maximum heating that occurred with the explicit formulation, which produced excessive low-level spinup. In addition, a squall line observed in nature was not simulated because the low-level transient upward motion that initiated it failed to produce saturation on the grid scale. Doubling the resolution (to 12.5 km) produced the same errors and also introduced a spurious second mesolow that was apparently orographically induced. These results support the weaknesses of the fully explicit approach described above: the unrealistically low level of maximum heating relates to the lack of parameterized vertical eddy fluxes, and the failure to simulate the squall line arises from the spurious delay in the start of convection. Zhang et al. (1988) argued that cumulus parameterization was required even for a 10-km grid spacing and that optimum results also required detailed microphysical forecast equations for nonconvective precipitation.

Sardie and Warner (1985) and Nordeng (1987) found spurious overprediction of polar lows with the fully explicit method on grid spacings of 80 and 50 km, respectively. They attributed the problem to excessive heat release at low levels, which again points to the need for parameterized vertical eddy fluxes. In both cases, a traditional approach with cumulus parameterization produced a superior simulation.

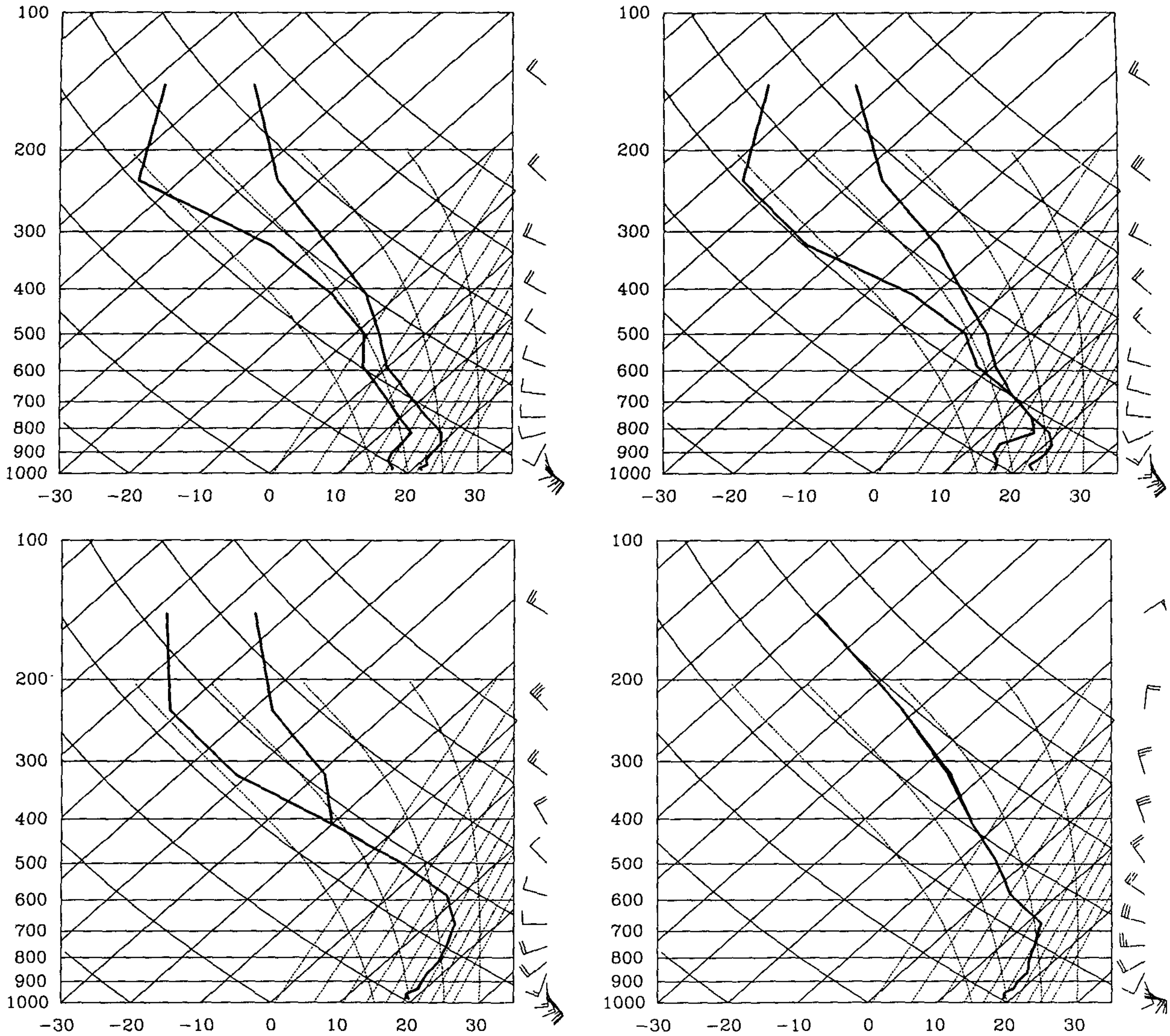

FIG. 1. Evolution of the sounding at a point of excessive precipitation in the fully explicit integration of Dudek (1988) at (a) hour 3; (b) hour 6; (c) hour 9; and (d) hour 12.

Tripoli (1986) and Tripoli et al. (1986) used a 14-km grid spacing and attempted to reproduce an orographically induced mesoscale convective system that was simulated earlier with a high-resolution (1-km) nonhydrostatic model. The authors found that (i) convection initiated 2 h later than the control and (ii) excessive precipitation and a spuriously intense mesoscale convective system (MCS) occurred once the explicit condensation turned on. Similar difficulties were encountered by Kalb (1987) using a 70-km grid spacing.

d. Summary of results for the fully explicit approach

As noted above, the fully explicit approach is most likely to succeed when grid-scale forcing is large and instability is relatively small. Large forcing ensures that vertical motions will be sufficient to minimize the delays in precipitation onset caused by the need for grid-scale saturation and spinup of cloud and rainwater. Modest convective instability suggests the vertical eddy fluxes are sufficiently small to minimize errors in the vertical distribution of explicit heating. Conversely, when grid-scale forcing is weak and/or instability is large, the onset of saturation is spuriously delayed. Once saturation occurs, energy is released essentially as conditional instability of the first kind over an unrealistically large area, producing localized excessive precipitation.

In addition to the problems described above, the fully explicit approach has not successfully simulated mesoscale organization of convection in a model with 10-km or greater grid spacing. In principle, explicit forecast equations for microphysical particles should allow the key processes of lateral transport and subsequent phase changes of hydrometeors to be modeled directly. The results reported in section 3c showed, however, that the explicit method does not accurately simulate the onset of intense convection, except possibly under strong local forcing. This early period of intense convection provides much of the source of later stratiform rain in mesoscale downdrafts. The fully explicit approach has thus proven to be no panacea, even on grid spacings as fine as 10 or 15 km, where, as noted earlier, cumulus parameterization has difficulties as well.

The obstacles that the traditional approach and the fully explicit approach face in the important problem of mesoscale organization have given rise to a third alternative: the hybrid approach. This alternative is presented in the following section, along with the Fritsch–Chappell scheme, which alone among traditional approaches has simulated mesoscale organization of convection.

4. Alternative methods

a. Hybrid approaches

The hybrid approach is a cumulus parameterization in that implicit clouds are defined on the basis of, but different from, grid-scale fields, so that closure conditions must be specified. Unlike traditional cumulus parameterizations, however, once convective sources of condensate are determined, a fraction of this (implicit) condensate is added to the grid-scale cloud and rainwater equations. In effect, the hybrid approach parameterizes *convective-scale* evaporation, condensation, and vertical eddy fluxes, but does not parameterize heat and moisture sources that arise from the more slowly evolving process of detrained precipitation-sized particles falling between (or downwind of) convective clouds. This latter process, with its associated phase changes, develops independently of the cumulus parameterization over subsequent time steps.

Kreitzberg and Perkey (1976) originated the idea of detraining a fraction of parameterized rainwater to the grid scale. Their grid-scale microphysical equations (Kreitzberg and Perkey 1977) did not, however, contain source terms from the convective parameterization, so the communication between implicit and explicit processes was not as complete as in later approaches. Kreitzberg and Perkey (1976) also were the first to propose using a Lagrangian cloud model in a mesoscale model cumulus parameterization. This step, which allows realistic inclusion of microphysics, is a critical component of the most successful of current approaches, including the Frank–Cohen (1987) and Fritsch–Chappell (1980) methods discussed in this paper.

Hammarstrand (1987) and Sundqvist et al. (1989) defined and explicitly predicted cloud water generated within a Kuo (1974) cumulus parameterization. These do not represent hybrid approaches as described here, because little communication occurred between the convective and stratiform cloud water. Hammarstrand assumed that each grid point could have only convective or stratiform cloud water, but not both. Sundqvist et al. convert implicit cloud water to explicit only when $T \leqslant -20°C$. Neither approach provides for the conversion of implicit rainwater to the grid scale. Brown (1979) developed a more complete approach with formal prediction equations for cloud water and rainwater. Brown included no ice phase and detrained only cloud water, not precipitation; the latter occurred in nonconvective equations only when cloud water exceeded a critical value. Because only cloud water was detrained, evaporation was excessive in detraining layers, and Brown's vertical distribution of heating had too much cooling aloft.

Yamasaki (1987) developed a hybrid approach in which source terms from parameterized clouds were included in explicit equations for both cloud water and rainwater. The source term took the form of a detrainment in the cloud water equation. In the rainwater equation, implicit rain was converted to explicit rain at a constant rate. Yamasaki applied the scheme in a tropical cyclone model. His solution produced more extensive and realistic mesoscale rainband structure than had been achieved with earlier traditional and fully explicit formulations. Yamasaki did not, however, address the process by which mesoscale organization developed in the model.

The most complete hybrid approach was presented by Frank and Cohen (1987) and Cohen and Frank (1987). They included convective source terms in grid-scale prediction equations for cloud water and ice, rainwater, and one form of frozen precipitation. As with Kreitzberg and Perkey (1976), Frank and Cohen (1987) specified the fraction of convective precipitation that fell within clouds (thus, in parameterized cumulus downdrafts) and that fell between clouds (i.e., that had been detrained from implicit clouds); the latter was treated explicitly in subsequent time steps. Using a 25-km grid spacing, Cohen and Frank (1987) were able to simulate many aspects of mesoscale organization in GARP Atlantic Tropical Experiment (GATE) convective systems. 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.

Dudhia (1989) used the Frank–Cohen approach with more sophisticated ice microphysics and a 10-km grid spacing to simulate the mesoscale structure of a winter monsoon cluster. In his simulations, parameterized convective updrafts smoothly evolved to grid-scale mesoscale downdrafts below and updrafts aloft as the system propagated, so that at a grid point the transition from convective to stratiform precipitation occurred without discontinuity. Dudhia (1989) showed that the mesoscale updraft aloft was driven by fusion heating associated with vapor deposition onto ice and snow in the anvil. Removing ice-phase physics virtually eliminated stratiform precipitation.

The benefits of the hybrid approach lie in its potential for realistic simulation of mesoscale organization. It allows convective updrafts and downdrafts (which are parameterized) to coexist with stratiform rain (which is explicit), as is often observed (Churchill and Houze 1984). The hybrid approach accomplishes this by directly incorporating the processes that occur in nature: detrainment of hydrometeors and subsequent phase changes of such hydrometeors. A traditional approach does not include these subgrid-scale sources of particles.

The hybrid approach also has one major advantage over the fully explicit formulation. As noted earlier, the explicit approach does poorly at initiating convection at the right time and place, especially under weak forcing, even for a 10- or 15-km grid spacing. Once initiation occurs in the explicit approach, spurious instability often follows, as was shown in section 3c. In the hybrid approach, the initiation of convection at a grid point is determined by the cumulus parameterization. Although this too is imperfect, it is likely to be superior to explicit approaches, especially for grid spacings of 30–50 km (Molinari and Dudek 1986).

The hybrid approach thus has clear advantages over both the traditional and fully explicit approaches. Unfortunately, these advantages are accompanied by both conceptual and practical limitations. It shares with pure cumulus parameterization the difficulty of choosing a closure, which cannot be verified in mesoscale models with current datasets. For very fine grids, in which characteristic time scales approach those of the convective scale, the hybrid approach may suffer the same scale separation problems as the traditional approach. For example, Dudhia (1989) noted on a 10-km grid spacing that (i) results were sensitive to parameters of the convective parameterization; and (ii) if convective instability passed some threshhold, grid-scale instability developed that resembled that occurring with fully explicit approaches, except parameterized heating replaced explicit condensation.

An additional limitation of the hybrid approach arises because detrained particles are carried by grid-scale motions. In nature, such particles fall between clouds and thus experience an environment that differs from the grid-scale average. This difference may be large; Soong and Ogura (1980), in nonhydrostatic cloud-model integrations, found that the average between-cloud ω was close to an order of magnitude less than its area-averaged counterpart. In hybrid approaches in mesoscale models, the resultant water loading, evaporation, and other processes may be influenced adversely. The importance of this limitation varies with model resolution: for 40–50-km grid spacing, terminal velocity is usually much greater than either grid-area averaged or between-cloud vertical velocity, so that particle evolution may not differ dramatically in the two cases. For a 10-km grid spacing, however, the grid-scale updraft may approach in strength a convective updraft in nature, and convective precipitation intended to fall between clouds may be unrealistically suspended. The resultant distortion of particle interactions may be significant, especially for frozen particles with small terminal velocities.

The one remaining problem of the hybrid approach is the lack of knowledge of actual precipitation detrainment profiles for deep convection. The fraction of frozen or liquid particles that detrains, and its vertical distribution, depend upon buoyancy, conversion of cloud matter to precipitation in the updraft, turbulence, and many other poorly understood processes. The uncertainty is mirrored by values used in previous work: Kreitzberg and Perkey (1976) specified precipitation detrainment as decreasing upward; Frank and Cohen (1987) as increasing upward; and Dudhia (1989) as fixed with height. In addition, it is conceivable that with strong forcing but marginal convective instability, precipitation detrainment in nature may nearly vanish because a mesoscale saturated updraft develops rather than intense localized cumulonimbus clouds. The results of Frank and McBride (1989) give indirect evidence for this. They found during some stages of a tropical system near Australia that Q_1 and Q_2 were nearly equal and representative of saturated updrafts, with no evidence of mesoscale unsaturated downdrafts. In current hybrid approaches, the lack of development of mesoscale updraft–downdraft couplets cannot be simulated because precipitation detrainment is fixed. The detrainment problem is solvable in principle, however, and recent buoyancy sorting detrainment models (Raymond and Blyth 1986; Kain and Fritsch 1990) may contribute to an appropriate formulation. Emanuel (1991) has applied the Raymond–Blyth scheme in a traditional cumulus parameterization designed for general circulation models.

In summary, the hybrid approach shares with cumulus parameterization the difficulties of defining a closure condition on the mesoscale and has potential problems with vertical advection of convectively generated particles. Both problems become significant as grid spacing reaches 10–15 km. The current rather arbitrary specification of precipitation detrainment profiles should not present a major obstacle.

Offsetting the weaknesses of hybrid approaches are the desirable separation of fast and slow processes into parameterized and explicit forms and the simulation of mesoscale organization and evolution superior to almost all traditional approaches. Because mesoscale organization occurs so frequently and so strongly affects some fundamental inputs to the grid scale such as the vertical heating distribution, these characteristics of the hybrid approach offer significant advantages.

b. *Fritsch–Chappell scheme*

Zhang and Gao (1989) produced a remarkably successful simulation of mesoscale organization in a PRE-STORM convective system, including the vertical structure of flow through the line, midlevel vorticity generation, and surface mesohighs and lows. They did so using a *traditional* approach made up of the Fritsch–Chappell (1980) cumulus parameterization plus formal microphysical forecast equations for nonconvective precipitation, with a grid spacing of 25 km. It was argued in the previous section that this method would not succeed because a cumulus parameterization in which no hydrometeors were detrained to the grid scale could simulate neither mesoscale organization nor the transition from convective to stratiform precipitation.

Zhang and Fritsch (1987; 1988), Zhang and Gao (1989), and Zhang (personal communication 1990) have described the processes by which mesoscale organization was simulated. The cumulus parameterization produced saturation in the column by (i) detraining moisture and (ii) driving a grid-scale circulation that by itself produces saturation. Figures from Zhang and Fritsch (1988) and Zhang and Gao (1989) show that saturation developed in a column in which θ_e slowly decreased upward, producing an absolutely unstable column. As a result, these clouds behaved as grid-scale cumulus clouds; Zhang and Fritsch (1987), for instance, show a maximum instantaneous grid-scale condensation heating rate of nearly 800°C day^{-1}. In later papers (Zhang et al. 1988; Zhang and Gao 1989), these explicit convective clouds were kept under control by the presence of evaporation and water loading in the explicit microphysical equations. Because the grid-scale clouds developed while cumulus parameterization was still active, they filled the column with hydrometeors and helped produce a smooth transition from parameterized to grid-scale condensation.

Two difficulties occur with this method. The first relates to details of the detrainment process. The Fritsch–Chappell scheme evaporates all liquid water above the equilibrium level of the parameterized cloud ("anvil evaporation"). If the detrainment level is saturated, however, this liquid water is evaporated at the next lower unsaturated level, rather than being allowed to remain as liquid at its detraining level (this is an essential difference between a traditional approach and a hybrid approach). This has the effect of saturating the column at progressively lower levels. In addition to anvil evaporation, the Fritsch–Chappell scheme detrains vapor, but not cloud water or ice. The difference can be significant: vapor detrained into a saturated environment immediately becomes liquid, but only after heat is released; no such heat release occurs with particle detrainment. Similarly, particles detrained into an unsaturated environment become vapor, but only after cooling occurs. Thus, the vertical distribution of heating may differ significantly when vapor and not cloud particles are detrained. As a result of the above evaporation and detrainment characteristics, the Fritsch–Chappell cumulus parameterization appeared to simulate realistic mesoscale organization of convection by a somewhat different process than occurs in nature.

The remaining difficulty of the Zhang and Gao (1989) simulation relates to the ambiguity that arises when implicit and explicit clouds of the same type coexist, as was noted in section 2b. The hybrid approach also allows parameterized precipitation to coexist with explicit grid-scale precipitation. This coexistence, however, is fundamentally different from that in Zhang and Gao (1989), because in the hybrid approach, parameterized clouds are convective (i.e., have small time and space scales), while the explicit clouds have much longer time scales. The hybrid method appears to more cleanly separate implicit and explicit clouds, and in a way that reflects processes in nature. In the Zhang and Gao simulation, parameterized clouds and explicit clouds both behave as convective, and their interrelationships are difficult to untangle.

It should be emphasized that the Fritsch–Chappell approach has been the focus of this section precisely because it has been so successful. No cumulus parameterization has done as well in real-data cases. It is clear that many characteristics of the approach are extremely well suited to simulating severe convective events. The key property of the parameterization is that the intensity of parameterized convection is proportional to the amount of convective available potential energy (CAPE), a point emphasized by Fritsch and Chappell (1980) in their original work. This allows enormous amounts of moisture to be transported vertically (and detrained) when instability is large, a characteristic not present in, for instance, the Kuo (1974) and Arakawa–Schubert (1974) schemes. The successful simulations of Zhang and Fritsch (1987), Zhang et al. (1988), and Zhang and Gao (1989) depend upon the use of the Fritsch–Chappell approach. It is proposed, however, that certain aspects of the detrainment parameterization may be producing the right result for the wrong reason. If (i) cloud water and ice were detrained to the grid-scale cloud-water equation, (ii) cloud-to-precipitation conversion was defined in the parameterized updrafts, and (iii) the vertical profile of precipitation detrainment to the grid scale was defined, the scheme would become a hybrid approach. This procedure would retain the beneficial characteristics of the Fritsch–Chappell approach in mesoscale models, while formally including precipitation detrainment, which is important in nature.

Any cumulus parameterization in which microphysical quantities are tracked, including those of Arakawa and Schubert (1974; see Lord 1979) and Emanuel (1991), can in principle be converted to hybrid. The Kuo (1974) approach would require a one-dimensional cloud model along the lines proposed by Anthes (1977). No clear-cut way exists to convert to hybrid the approaches of Betts (1986) or moist convective adjustment (Kurihara 1973).

Finally, it should be noted that as grid spacing decreases to 20 km or less, the simultaneous occurrence of both subgrid-scale and grid-scale convective clouds can occur with the hybrid approach as well (Chen 1990). This problem may relate primarily to violation of scale separation requirements, as discussed in section 2b. This issue will be addressed further in section 6.

5. Slantwise convection

The existence of upright convective instability has been assumed throughout this paper, while instability on a slanted path (Bennetts and Hoskins 1979) has been ignored. Slantwise (symmetric) instability carries its own mesoscale organization, typically in the form of bands. It is not the intent in the current paper to review slantwise convection, which could fill an additional manuscript. Rather, the issue is how the possible presence of slantwise instability impacts the choice of a parameterization for upright convection.

Emanuel (1983) has noted that in the presence of both types, upright instability dominates. This implies that slantwise convection can be separated in numerical models from upright convection, in that slantwise convection would be considered only for upright stable cases. As is true of upright convection, further choices must be based on empirical evidence from numerical prediction models because observations are limited and the theory of symmetric instability is not developed for primitive equation dynamics.

Knight and Hobbs (1988), using a fully explicit approach, simulated banded structure in the presence of slantwise convective instability on a 10-km grid. Reducing the grid spacing did not significantly change the solution, suggesting that 10 km is sufficient resolution. Symmetrically unstable bands also formed at 40-km resolution, but were wider and fewer in number than in the high resolution integrations. The fully explicit approach failed to simulate banded structure at 80-km resolution. The results suggest that for mesoscale models the fully explicit approach is capable of simulating slantwise convective instability if resolution is sufficient.

Symmetric neutrality has been observed in midlatitude explosive cyclogenesis cases (Emanuel 1988), suggesting that symmetric instability had previously occurred. Kuo and Low-Nam (1990) simulated such a neutral state with a fully explicit approach in the vicinity of warm fronts using a grid spacing of 40 km. Kuo and Low-Nam also simulated such neutrality using a traditional approach with the Arakawa–Schubert cumulus parameterization, but explicit condensation alone was responsible for the neutral region. In the same case, a Kuo (1974) cumulus parameterization allowed slantwise convective instability to remain, which is probably less realistic.

Nordeng (1987) simulated two polar lows using a 50-km grid spacing. Nordeng included an upright parameterization, a slantwise parameterization (using a closure following Kuo 1974), and explicit condensation for fully stable regions. The slantwise parameterization produced a sounding closer to slantwise neutral and shifted maximum vertical motion toward the frontal region compared to when only the upright parameterization was included. Nevertheless, the slantwise convection parameterization had a much smaller influence on the simulations than did upright parameterization.

The limited results reported above make it difficult to make definitive conclusions. Three options for simulating slantwise convection in mesoscale models arise: (i) parameterize slantwise convection separately from both upright convection and explicit grid-scale condensation; (ii) use a fully explicit approach with no parameterization of either upright or slantwise convection; and (iii) use a traditional or hybrid approach for parameterization of upright convection, leaving slantwise convection to occur explicitly on the grid.

For the first option, a closure condition must be provided to relate the grid scale and subgrid scale. Because data on the mesoscale are lacking, and the nonlinear evolution of localized regions of symmetric instability remains uncertain (Thorpe and Rotunno 1989), the appropriate closure condition is not known. Definition of slantwise neutrality, which would be required in a parameterization, must assume some sort of dynamic balance. No such balance can be defined in a primitive equation model and the resulting "neutral" sounding will in fact be stable in the presence of cyclonic vorticity (Nordeng 1987).

Option two, the fully explicit approach, bypasses both of these problems if resolution is sufficient. It allows localized unstable regions to evolve on the grid with no constraints from poorly understood closure conditions. By explicitly resolving the slantwise updrafts, a "primitive equation neutrality" can be generated that includes all physical and dynamical processes. The fully explicit approach cannot be used, however, if upright instability exists in other parts of the forecast region, as noted in section 3c. As a result, the fully explicit approach is appropriate in mesoscale models only when slantwise, but not upright, instability is present on the model grid, a rather narrow condition unlikely to be met in most real-data applications. It thus appears that traditional or hybrid approaches that parameterize upright convection but allow slantwise convection to evolve on the grid scale (option three) will prove to be most generally applicable. Care must be taken, however, to ensure that the upright cumulus parameterization does not adversely influence development of explicit slantwise convection, as noted by Kuo and Low-Nam (1990).

On the basis of these brief arguments, it will be assumed in this paper that slantwise convection in mesoscale models can be incorporated as part of the upright stable formulation in a traditional or hybrid approach and requires no special parameterization. Further discussion of parameterization of slantwise convection is provided by Emanuel (1983), Seltzer et al. (1985), Thorpe (1986), and Nordeng (1987).

6. Discussion

a. *Choice of a cumulus parameterization*

The simulation of mesoscale organization of convection presents a major challenge for mesoscale numerical weather prediction models. A significant fraction of the water in the mesoscale circulations originates in subgrid-scale convective updrafts, but the mesoscale updrafts and downdrafts themselves are not subgrid scale in either space or time and must be resolved explicitly. The hybrid approach parameterizes only the convective scale while allowing mesoscale structures driven by detrained hydrometeors to develop slowly and separately through the grid-scale equations. As a result, although implicit and explicit clouds are simultaneously present, they fundamentally differ in character and no ambiguity is present. Arakawa and Chen (1987) argued that at least some part of mesoscale organization has to be parameterized due to the lack of a spectral gap between cloud and mesoscale. It is proposed that the hybrid approach, by separating out the forcing mechanism for the mesoscale component, removes the need to parameterize the mesoscale any further. This property may allow the hybrid approach to be used for smaller grid spacings than the traditional approach without encountering severe scale-separation problems. These conceptual benefits of the hybrid approach have not been clearly stated by its originators.

The essence of the hybrid scheme can be seen as follows. Assume it is possible to define a "perfect" mesoscale cumulus parameterization that, if it persists long enough, produces grid-scale saturation and moist neutrality simultaneously, as well as appropriate lower-tropospheric subsidence and upper-tropospheric updrafts. The model could then in principle smoothly make the transition to explicit grid-scale microphysics. This scheme would fail, however, if the cumulus parameterization were not supplying the grid with hydrometeors, because the grid-scale equations would then have to spin up cloud and precipitation particles, and a spurious gap in precipitation would occur. The hybrid approach avoids this problem by separating the mechanisms that produce mesoscale organization. The best of the current cumulus parameterizations, that of Fritsch and Chappell (1980), simulates mesoscale organization somewhat differently by producing grid-scale saturation and subsequently generating particles in explicit updrafts while the cumulus parameterization is still active. It is argued that their approach would be improved if cloud and especially precipitation detrainment to the grid scale were added. Either way, grid-scale forecast equations for microphysical quantities, including frozen and liquid precipitation, are required on the grid scale, a point emphasized by Zhang et al. (1988) and Zhang and Gao (1989).

Figure 2 presents recommended solutions as a function of grid spacing. The optimum solution depends more upon local rotational constraints than upon grid spacing, as noted by Ooyama (1982). In most applications of mesoscale models, however, several dynamical regimes are likely to be present, so Fig. 2 represents the most general solution for each grid spacing.

For large-scale models (grid spacing > 50–60 km), the traditional approach provides the only solution. The hybrid approach cannot drive realistic mesoscale circulations in such models because the mesoscale cannot be resolved. For models with grid spacing less than 2–3 km, the fully explicit approach is clearly superior to parameterized approaches, even though a 1-km grid spacing can fully simulate only the largest of convective clouds (Lilly 1990).

It is between these two extremes of resolution that the choices become more complex. For the hybrid approach to be effective, grid spacing must be small enough to resolve mesoscale organization, but not so small that scale separation problems arise. It is suggested that the hybrid approach is the preferred choice for grid spacings from 20 or 25 to 50 km.

For grid spacings from about 3 to 20–25 km, it remains uncertain whether a general solution exists. When grid-scale forcing is large and convective instability is small or moderate, the fully explicit approach

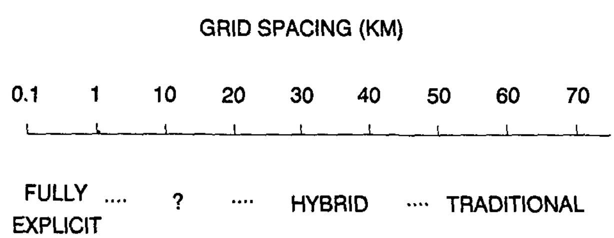

FIG. 2. Proposed form for cumulus parameterization in regional mesoscale models as a function of grid spacing. The scale is logarithmic below 10 km and linear above. The question mark indicates the lack of an obvious solution, and the dots represent transition regions between the choices. It is assumed the model covers a wide enough area that the approach must simulate convective effects over a range of thermodynamic and inertial stability regimes.

may suffice (see, for instance, Rosenthal 1978). In such cases the grid-scale forcing quickly produces saturation, and the vertical distribution of heating by the explicit approach differs only slightly from that in nature. The explicit approach otherwise fails at these intermediate grid spacings because resolution is insufficient to realistically model cloud initiation and subgrid-scale transports.

Cumulus parameterization also has problems for grid spacings between 3 and 25 km, even with the hybrid approach. The possibility that convective clouds will grow directly on the grid scale increases with increasing resolution. As this occurs, it becomes difficult to identify separate physical processes with the grid-scale and subgrid-scale clouds. Under such circumstances, successful simulations are likely only if parameterized clouds quickly become secondary to grid-scale convective clouds. The process by which parameterized convection produces the transition to saturation must be understood and compared to that occurring in nature. Cumulus parameterization remains insufficiently tested on such fine grids.

b. Recommendations for further work

The cumulus parameterization problem in mesoscale models can be addressed using four types of studies: observational, semiprognostic, cloud ensemble modeling, and mesoscale modeling.

Observational studies provide the primary means for improving individual cumulus parameterizations. Arakawa and Chen (1987) described the need for studies of individual convective elements, the larger-scale influences of such elements, and the interactions between convection and the larger scale. A critical question for the topics discussed in this paper is to determine under what circumstances convective updrafts evolve into deep mesoscale saturated updrafts, versus when they will evolve to the classic mesoscale structure of Houze (1982), with most of the stratiform rain falling in lower tropospheric downdrafts. Logic would suggest that under strong forcing and marginal instability, saturated mesoscale updrafts would form; detrainment would be small, thus limiting mesoscale downdrafts. For large instability and modest forcing, convective updrafts would detrain huge amounts of water and mesoscale downdrafts would dominate, pushing the convection to a leading edge where unstable air remains. Observational studies can establish the answers to such questions, but space and time resolution of the observations most likely will have to be greater than in many previous data collection efforts such as SESAME.

Semiprognostic studies (Lord 1979; Krishnamurti et al. 1980; Grell et al. 1991) provide a means of evaluating from real data the instantaneous heating and moistening profiles and rainfall rates produced by cumulus parameterizations. Such tests are limited because they do not measure time evolution. This particularly holds for the hybrid approach, in which several hours of integration are required for evaluation. Nevertheless, semiprognostic tests provide a necessary step in the evaluation of a cumulus parameterization.

Cumulus ensemble models, which resolve individual clouds but cover a wide region, provide another major tool for improving individual cumulus parameterizations. Given the lack of observations on small scales, such models provide the greatest potential for testing closures and other aspects of cumulus parameterization. Most current efforts fix the large-scale forcing and determine the convective response (e.g., Soong and Ogura 1980; Tao et al. 1987; Kreuger 1988). Advancing computer power will eventually allow the large scale as well as the cloud scale to be predicted, so that two-way interaction between the convection and larger scales can be simulated. At the very least, interactive cumulus ensemble models will tell whether relatively simple assumptions, such as those regarding precipitation detrainment profiles, can be relevant for a wide range of stability and grid-scale forcing. In general, the validity of both closure assumptions and parameter values can be tested using suitable averaging of cumulus ensemble model output. Encouraging progress in this direction has been made by Xu (1991).

Because cumulus parameterization contains many empirical aspects, its ultimate value must be measured by actual performance in numerical models. The interpretation of such behavior can be extraordinarily complex for several reasons. First, cumulus momentum transports may often be as important as heat and moisture transports (Schubert et al. 1980), but an appropriate parameterization of such transports in upright convection has proven elusive. Second, other physical processes interact with parameterized convection in models in a highly complex nonlinear fashion, making intercomparison studies tricky to interpret. As an example, Molinari and Corsetti (1985) found that inclusion of cumulus and mesoscale downdrafts in a cumulus parameterization dramatically reduced rain volume to a value much closer to that observed. Using the same cumulus parameterization in a different case study, but with the NCAR MM4 model (Anthes and Warner 1978), Dudek (1988) found only slight reductions in rain volume when downdrafts were included. The differences appeared to relate (Dudek 1988) to the more sophisticated multilevel planetary boundary layer parameterization in the latter model. The higher PBL resolution made the excitation of convective updrafts adjacent to cold downdrafts more likely than in the bulk aerodynamic low-resolution boundary layer used earlier. The earlier comparison study apparently gave misleading results about cumulus parameterization because the boundary-layer resolution was inadequate. Interactions of radiative processes and orography with parameterized cumulus clouds further complicate interpretation of model output.

Caution is required in the analysis of model output in the vicinity of strong convection, because energy often enters the model grid at the smallest resolvable scales with both parameterized and fully explicit approaches. These limiting scales are where finite-difference truncation produces the greatest inaccuracies (Haltiner and Williams 1980). Simultaneously, explicit diffusion strongly damps such scales, producing an energy cycle (convective source, diffusive sink) that is unlikely to resemble that observed in nature.

Because of the factors listed above, it becomes essential to establish the robustness of results in cumulus parameterization. This can be accomplished by doing multiple case studies using one or more cumulus parameterizations. Two examples are work by Kuo and Low-Nam (1990) and Anthes et al. (1989). Kuo and Low-Nam chose nine case studies of explosive cyclogenesis and compared two traditional cumulus parameterizations with a fully explicit approach (discussed in section 3b). Anthes et al. (1989) also compared several cumulus parameterization approaches for a large number of case studies and 50–100-km grid spacing and determined statistically significant differences in various quantities between each set of experiments. Because verifications are not required (rather, differences from control integrations are examined), similar studies for the high-resolution models discussed in this paper could establish the overall sensitivity of the results to various physical processes, including cumulus parameterization.

c. *Final comments*

The evidence presented earlier from numerical modeling studies strongly suggests that cumulus parameterization must be included in mesoscale models. In such models, it is not possible to claim to have understood the *interaction* of the convective scale and mesoscale, because cumulus parameterization fixes that interaction a priori through closure conditions. In the words of Ooyama (1982), modelers must not "play the game with loaded dice." Even a perfect forecast on the mesoscale does not mean the process by which individual clouds produced a mesoscale disturbance has been understood. Interpretation is further complicated by the development within models of explicit convective clouds that coexist with parameterized clouds and only crudely simulate real clouds. Such difficulties occur even with the hybrid approach once grid spacing drops to 20 km or below. It is conceivable that for study of convectively driven disturbances, mesoscale modelers should either increase grid spacing to avoid grid-scale cumulus clouds, or decrease grid spacing to 1–2 km to avoid the need for cumulus parameterization. Regardless, it is argued that caution must be exercised in interpreting model output when cumulus parameterization is used in high-resolution models. Additional detailed studies of both successes and failures of cumulus parameterizations are needed.

Keyser and Uccellini (1987) have emphasized the potential value of mesoscale numerical models, which provide a uniform, high-resolution, dynamically consistent dataset, for understanding natural phenomena that otherwise cannot easily be observed. A mesoscale model provides a powerful tool, but the more powerful the tool, the more care is required to interpret its results. Such care is particularly warranted when cumulus parameterization is involved.

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