Summary of A Mini-Workshop on Cumulus Parameterization for Mesoscale Models

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Revised on 6 August 1996

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1. Introduction:

Cumulus convection plays an important role in determining the behavior of weather and global climate systems. Yet, for weather and climate prediction models the physical processes associated with cumulus convection occur on scales which cannot be resolved by the models. Representing the effects of cumulus convection in numerical models, known as cumulus parameterization, is of fundamental importance in atmospheric sciences. The interaction of cumulus convection and the larger-scale circulations is a complex and highly nonlinear process. It involves the modulation of convection by the larger-scale circulations, and the feedback of convection on larger-scale circulation. Since cumulus convection is a subgrid-scale process for most general circulation and weather prediction models, we have to formulate the collective effects of subgrid-scale clouds in terms of prognostic variables of grid scale (Arakawa 1993). Over the past three decades, significant effort has been devoted to improving our understanding of the interaction between cumulus convection and larger-scale circulations and to modeling such interaction in various approaches of cumulus parameterization. Despite these efforts, a general theory of cumulus parameterization does not exist, and no one single scheme is found to outperform other schemes consistently in a wide range of weather situations. An excellent review of the cumulus parameterization problem and various schemes with different closure assumptions is provided by an American Meteorological Society monograph edited by Emanuel and Raymond (1993).

With the advancement of computing technology and research on atmospheric processes and numerical techniques, significant progress has been made in the development of mesoscale models over the past decade. Mesoscale models with extremely high horizontal and vertical resolution and explicit physical parameterization have become a versatile tool for research and operational forecasting. If cumulus parameterization for global models is a difficult problem, it is an even harder one for a mesoscale model with a grid size of 1-20 km. At such a resolution, a portion of a convective system (e.g., the mesoscale circulation induced by convection, stratiform precipitation) is resolved by the model. There is a continuous spectrum of motions within the atmosphere while a numerical model introduces an artificial spectral gap between the resolvable and unresolvable scales of motion making it difficult to develop a general theory of cumulus parameterization. In addition, the current computing power does not allow the use of cloud-resolving models (CRMs) directly for climate and weather prediction. Even if such computing power is available, it is not readily apparent that a cloud model will do a better job in weather forecasting given the predictability limit of cloud-scale motion and the difficulties in the initialization of cloud models with real data. An excellent review of the problem of cumulus parameterization for mesoscale models is given by Molinari and Dudek (1992). Past research has generally found that the results of model prediction are highly sensitive to the way convection is treated in a mesoscale model. Yet, there is no consensus for a general approach.

In order to provide a forum for a focused discussion on the problem of cumulus parameterization for mesoscale models, the Mesoscale and Microscale Meteorology Division of NCAR organized a mini-workshop on 11-12 September 1995 at the NCAR Foothills Laboratory in Boulder, Colorado. Approximately 50 scientists participated in this workshop. Seventeen papers were presented, with ample time reserved for discussion. Participants were asked to discuss a list of scientific questions, including:

a. Should cumulus parameterization be used for mesoscale models with a grid size of 1-20 km? Should we work with a totally explicit scheme? Or, should we take a "hybrid" approach?

b. How important is the grid-resolvable-scale precipitation parameterization relative to the subgrid-scale convective parameterization?
c. What are the key interactive processes between resolvable- and subgrid-scale convection that have to be explicitly treated in a mesoscale model?
d. How important are the momentum fluxes? How should we include their effects in a mesoscale model?
e. What approach in handling the combined effects of subgrid-scale and grid-scale precipitation will have the best chance of success?
f. What is the best strategy for verifying different parameterization schemes?

The scientific presentations and the discussion of these specific issues are summarized below from reports submitted by the session chairs.

2. Session Summaries:

Session 1: Overview of the Cumulus Parameterization Problem (Chair: W.-K. Tao)

Akio Arakawa (University of California at Los Angeles) opened the workshop with a presentation entitled, "To what extent is cumulus convection parameterizable?" He raised the following questions: "Is it really possible to ‘parameterize’ cumulus convection even for conventional large-scale models? If yes, why and to what extent?" This is an important question because the logical structure of a parameterization should represent an answer to these questions. A cumulus parameterization has to represent (1) large-scale forcing and (2) adjustment processes. To assess the degree of "parameterizability" based on this framework, Arakawa constructed an empirical cumulus parameterization scheme (CPS), which consists of an empirical classification of cloud organization (replacing the spectral cumulus model used in the original Arakawa-Schubert--AS scheme) and an empirically-determined measure of moist convective instability (replacing the cloud work function in the AS scheme). A "rotated principal component (RPC) analysis" was used to determine the cloud organization. By using the Global Atmospheric Research Program Atlantic Tropics Experiment (GATE) diagnostically determined Q1 (apparent heating) and Q2 (apparent drying) profiles, Arakawa showed that various tropical cloud organizations (i.e., squall cluster, non-squall cluster and scattered convection) could be represented realistically by each RPC. The quasi-equilibrium of the empirical cloud work function (ECWF), which is a linear combination of lapse-rate and humidity parameters (large-scale prognostic variables) that has minimum observed variance, is assumed. Results of the empirical CPS constructed from the Asian continental data (Q1 and Q2) and verified against GATE data are encouraging. Based on these results, Arakawa concluded that cumulus convection is basically parameterizable for large-scale models. Arakawa also reviewed a simple system illustrating the modulation of cumulus ensembles by large-scale forcing (Arakawa and Xu 1990; Xu 1991; Randall and Pan 1993).

Arakawa argued, however, that "cumulus" convection (subgrid scale) and "large-scale" processes (grid-scale) could not be separated in mesoscale models. A cumulus parameterization is supposed to formulate the "collective effects of cumulus convection" in terms of "large-scale prognostic variables". Because of the ambiguities in defining grid-point (large-scale prognostic) variables in mesoscale models, Arakawa suggested that "cumulus parameterization" in mesoscale models should be an "ensemble parameterization" rather than a "subgrid-scale parameterization." The structure of cumulus parameterization needs to change from (1) diagnostic to prognostic for the purpose of incorporating the "history of cumulus-convection"; (2) single-column to multiple-column for the purpose of considering the "horizontal-nonlocal effects"; and (3) deterministic to non-deterministic for the purpose of reflecting the "statistical significance of the mean model grid variables". In addition, a "unified cloud parameterization" needs to be constructed so that a single physics package can be used for both "grid-scale" and "subgrid-scale" convection.

Jack Kain's (Pennsylvania State University) presentation focused on identifying and distinguishing the roles played by CPS and resolved circulations in simulations of mesoscale convective systems (MCSs) that have been judged as successful. He argued that mass-flux-type CPS represents only the smallest-scale, most rapid transports by individual convective elements. Such schemes are based on simple variations of a statistically steady-state plume model, representing convective clouds in a highly simplified linear framework. In contrast, precipitating convective clouds in the atmosphere evolve, interact, and multiply in a highly non-linear fashion. Furthermore, they develop mesoscale components of circulation that are typically significantly larger, slower, and more dynamically complex than the convective elements represented by a CPS. When a mesoscale model is configured with a grid length in the range from about 5 to 50 km, the limit that is imposed on the horizontal resolution falls in the middle of a continuous spectrum of motions that have the potential to be highly energetic. Since mass-flux-type CPS represent only the smaller-scale component of the total subgrid-scale energy spectrum, a model configured in this way is left with a void in the place where a link between individual convective elements and meso-β-scale circulations must be established. His talk then focused on the mechanisms by which a mesoscale modeling system acts to establish this link, or to "bridge the spectral gap."

Kain used the Penn State/NCAR mesoscale model (MM5) and the Kain-Fritsch convective parameterization to investigate the interactions between grid-scale circulations and parameterized convection in simulations of a well-documented midlatitude squall line. He identified the roles played by subgrid-scale (parameterized) and grid-scale precipitation processes in the formation of "convectively-induced" features. He found that a critical ingredient in this successful simulation was the development of a deep layer of saturation in a conditionally unstable atmosphere, i.e., an absolutely unstable grid-scale structure. He showed that once this structure was created, convective overturning proceeded as a combination of the relatively fast-mode parameterized transports and the more slowly-evolving grid-scale circulations - the modeling system's manifestation of the continuous transition from convective to mesoscale overturning that occurs in nature. He concluded that a realistic partitioning of convective effects between parameterized and explicitly-resolved scales proved to be a critically important ingredient in the successful simulation of this system.

Kain addressed two questions related to his model results. First, was the simulated mesoscale convection a realistic system or simply an artifact of the limited resolution of the grid-point model? He showed Doppler radar observations indicating that mesoscale convective circulations with horizontal widths of at least 10 - 20 km are quite common in MCSs. Furthermore, the higher-resolution radar images indicate the presence of distinct, smaller-scale, more rapidly ascending bubbles embedded within these mesoscale updrafts. He stressed that the larger-scale component of these circulations is still too small to be well-resolved with 20-25 km grid spacing, but that it is clearly manifested as mesoscale overturning on the smallest resolvable scales of the modeling system. Moreover, he suggested that the smaller-scale component seems to be a direct analog to the fast-mode convective effects represented by the parameterized convection.

The second question he addressed is whether it would be preferable to force a CPS to completely remove grid-point instability before condensation is allowed to occur on the mesoscale grid, that is, to force a convective scheme to parameterize all convective circulations that are too small to be explicitly simulated on the model grid. Kain outlined several weaknesses in existing CPSs, pointing out that existing schemes cannot represent convective clouds that slope with height; they handle momentum transports very poorly, if at all; the vertical distribution of heating and moistening effects is typically based on simplistic cloud models. He emphasized that a CPS provides necessary, but not always sufficient, representations of atmospheric convection in a mesoscale model. He acknowledged that explicit convection on a mesoscale grid clearly involves some aliasing of smaller-scale processes, but argued that the full equations of motion provide continuity and all-encompassing effects that a CPS lacks. He suggested that artificially suppressing grid-scale latent heat release until conditional instability is removed is likely to be detrimental to the quality of mesoscale simulations of MCSs with existing CPSs.

In summary, Kain suggested that (1) with mesoscale model resolution, simulation of MCSs is likely to be most successful when convective overturning occurs on both parameterized and resolved scales; (2) convective parameterization may be necessary even at grid lengths approaching cloud scale; (3) traditional convective parameterization theory seems to break down on the mesoscale, but the need for convective parameterization does not, and (4) it is necessary to establish guidelines, limitations, and a theoretical framework for the implementation of convective parameterization at higher (mesoscale) model resolutions.

Several questions were raised at the end of this session: (1) With a two-way interactive nesting technique, the grid size of a fine-mesh model can be 1-3 km. Do we still need cumulus parameterization at such a resolution? Also, what microphysical processes need to be included in a CPS? Arakawa's answer was that cumulus parameterization is still needed in the coarse-mesh part of the model. For the fine-mesh part, ensemble predictions may be needed due to uncertainties in the initial conditions. Such a model will be useful to provide guidance on the formulation of microphysical processes in a CPS. (2) If the empirical parameterization is so good, why do we need the "original" AS CPS? Arakawa replied by saying that because empirical CPS is based on a linear algorithm; it cannot deal with details, and it is useful only in simple models. However, it can guide improvement of a physically based parameterization, such as the AS parameterization. (3) Is it better to treat the parameterized and explicitly resolved processes in a mesoscale model as a whole, or as separate processes? Kain argued that parameterized and explicitly resolved processes can interact in a nonlinear fashion. Obviously, it would be ideal to have a unified approach, but this is not possible within the framework of existing CPSs. (4) Is the modeled saturated sounding a transient behavior, and has it been observed? Kain's reply was that this type of sounding was never unambiguously observed (i.e.g, without concerns about sensor wetting, etc.). (5) ECMWF models indicate that parameterized momentum transport could be very important for 5- to 10-day forecast, particularly for dynamic features (i.e., strength of easterly waves). In almost all CPSs, no momentum transport is being considered. Jack Kain suggested that a simple momentum transport could be included in the Kain-Fritsch CPS for sensitivity tests.

Session 2: Cloud Model Perspectives (Chair: D. B. Parsons)

In recent years, studies have shown that CRMs are powerful tools for investigating cumulus cloud systems. These investigations have typically ranged from idealized simulations to investigate convective dynamics to simulations aimed at replicating and studying a particular aspect of an observed convective system. These studies, particularly the latter type, indicate the potential utility of using CRMs to develop and test CPSs. The three presentations in this session were intended to provide a perspective on cumulus parameterization from a number of researchers working with CRMs.

The first talk, presented by Morris Weisman, was entitled, "The Resolution Dependence of Explicitly Modeled Convection." In this study, two-dimensional simulations were conducted with the Klemp-Wilhelmson cloud model with the horizontal resolution varied between 1 and 12 km. The motivation for this study was that mesoscale models presently have a horizontal grid spacing that does not allow for a clear separation of scale between the resolved mesoscale and the unresolved convective-scale motions making the parameterization of convection difficult (e.g., Molinari and Dudek 1992). Through varying the horizontal grid spacing, this study was able to document the degradation in model response as the resolution was decreased and establish a minimum resolution necessary to adequately represent convective processes. For the mesoscale convective system simulated, the study established that a horizontal resolution of 4 km or smaller is needed to adequately represent the net vertical transport of momentum and heat and the system circulations. At grids coarser than 4 km, the system evolution was too slow, while the net system circulation, heating and rainfall rates were too large. These results are consistent with past studies (e.g., Zhang et al. 1988, Kato and Saito 1995). The overprediction seems to be due to the inability of the coarse grid to capture the small-scale, nonhydrostatic effects. These results suggest that a CPS in a mesoscale model needs to account for the potential overprediction of the heat transports and circulation, and underprediction of the system evolution that can happen if the convective transports take place on the coarse mesoscale grid.

The second talk, presented by Bill Skamarock, was entitled, "Adaptive Grid Modeling of

Mesoscale Convective Systems." The motivation for this presentation is that adaptive grid modeling in some circumstances allows for a modeling system that resolves convection as an alternative to parameterizing it through assigning finer, more computationally demanding grids only in regions of active convection. Details on this approach and its relationship to previous efforts that use nested modeling to study atmospheric flows is described in Skamarock and Klemp (1993). The technique developed is a local adaptive-grid technology that uses a nonhydrostatic split-explicit model that automatically refines the grid in selective regions where convection occurs. The basic technology is an adaptation of techniques developed by Berger and Oliger (1984). The grids behave similarly to conventional two-way interactive nesting, but allow for overlapping grids that change in size, shape, orientation and number. The model has produced realistic simulations of MCSs observed in the middle latitudes (Skamarock et al. 1994) and the tropics (Trier et al. 1995). While the modeling system is an extremely powerful research tool for investigating convection systems and the feedback of convection on the larger scales, the authors were cautious about this type of approach replacing coarser-grid models on a routine basis in the near future, since the technique is still relatively computationally demanding and difficult to implement in regions where widespread cellular convection is taking place. The authors also cautioned that more research is needed to quantify where convection is first triggered in the model. Currently the authors use the vertical motion fields to diagnose where the nested grids should be placed.

The final talk, by Wei-Kuo Tao, was entitled, "The Effects of Clouds on Mesoscale and Large-scale Environments: Model Results." This research presented heat, moisture, and water budgets associated with simulations of convective systems observed in several field experiments (i.e., TOGA COARE, EMEX, TAMEX, CaPE and PRE-STORM). These studies included a wide variety of geographical locations from over the tropical oceans to the midlatitude continent so that the simulations cover a wide range of ambient conditions thought to be important for determining convection structure (i.e., convective available potential energy--CAPE, vertical shear, moisture profiles). The model used for this experiment was the Goddard cumulus ensemble model discussed in Tao and Simpson (1993) and Simpson and Tao (1993). The model includes a Kessler-type microphysics (two-phase liquid water, three-phase ice) and a parameterization for long- and short-wave radiation. The study included an overview of past studies into the interaction between clouds and the larger-scale flow. The results presented included (1) verification of the simulations against observations and other modeling work, (2) an investigation into the similarities and differences between the various cases simulated, (3) in-depth studies into the relationship between convective processes and the stratiform anvils (Tao et al. 1993) and (4) how the stratiform processes depend on the ambient large-scale flow.

A number of issues were raised in the discussion period after these presentations, including whether the resolution studies indicated problems for convective parameterization. The potential problem is that the scales between the resolved motions and those meant to be represented in the cumulus parameterization may be aliased onto the larger-scale grid producing the problems discussed in Weisman's presentation. To eliminate that problem, one would have to parameterize all the convective-mesoscale processes that are subgrid-scale to the mesoscale model, but that would be difficult. However, the possibility does exist that the convective parameterization may remove most of the subgrid-scale energy so that the response may be close to the correct one. Other discussion focused on how to best use cloud models to test a parameterization, including how to initialize the models for a test.

Session 3: Model Sensitivity to Convective Parameterization (Chair: Jack Kain)

The recent development of the MM5 modeling system and other nonhydrostatic mesoscale models, coupled with continuing advances in computing power, has made it feasible to perform routine numerical simulations and forecasts of weather systems using increasingly higher model resolution. Numerous studies (e.g., Zhang et al. 1988; Molinari and Dudek 1992) have suggested that methods of treating diabatic heating in numerical models must change as model grid length decreases and convective systems become partially resolved. Since parameterized subgrid-scale convection contributes an essential element to the total diabatic heating when convective clouds are not well resolved, it is important to assess the efficacy of currently available CPSs at higher resolutions and to make plans to allow convective parameterization theory and applications to keep pace with developments in other aspects of numerical prediction.

Talks in the first half of this session focused on the sensitivity of meso-β-scale simulations with the MM5 modeling system to different CPSs and the identifiable weaknesses of existing approaches. Bill Kuo began the session with a detailed comparison of MM5 simulations of the ERICA (Experiment on Rapidly Intensifying Cyclones over the Atlantic) IOP5 (Intensive Observation Period) storm using the different CPS options that are available in MM5 (Kuo et al. 1996). Observational studies of this storm have identified the existence of MCSs in the early stages of development and the formation of mesoscale vortices embedded within the larger-scale cyclone (Reed et al. 1993; Blier and Wakimoto 1995; Wakimoto et al. 1995). These features are very difficult to reproduce in a numerical simulation without a realistic representation of convection. Thus, this storm was judged to be ideally suited for this type of analysis.

Kuo compared simulations using the Betts-Miller (BM - Betts 1986), Grell (GR - Grell et al. 1994), Kain-Fritsch (KF--Kain and Fritsch 1993), and Kuo-type (Anthes et al. 1987; Grell et al. 1994) CPSs as well as a test with no parameterization of subgrid-scale precipitation (NC) and an additional run with no latent heat release on any scales (FD - Fake Dry). One set of experiments used a single 60-km mesh, and a second set nested a 20-km grid within the original mesh. Kuo demonstrated that the intensity, distribution, and character of precipitation as well as the development and evolution of mesoscale pressure systems varied strongly as a function of the different CPSs. This result was contrasted with the relative insensitivity of a third set of experiments to different parameterizations of grid-scale microphysics. He also found that the characteristics of simulated precipitation for a given CPS were very similar with the 60-km and 20-km grid lengths.

Kuo hypothesized that many of the differences that developed as a function of the various CPSs were closely related to the ability of each scheme to work in conjunction with grid-scale processes to bring about convective stabilization in a reasonable and timely manner. He showed that the Kuo and GR schemes appeared to be relatively inefficient at removing convective instability, allowing the development of deep layers of absolute vertical instability (i.e., saturated layers with a lapse rate considerably greater than moist adiabatic). This unphysical feature also developed in the two runs with no convective parameterization, i.e., NC and FD. In the GR and NC runs, this type of structure led to the development of intense localized circulations and small-scale low-level pressure and potential-vorticity disturbances. These circulations may be due to grid-point instabilities that emerge as a result of CISK-like (Conditional Instability of Second Kind) positive feedback between low-level convergence and grid-scale latent heat release in this highly unstable (model) environment (Zhang et al. 1988).

The FD simulation did not show this pattern of response because it did not include latent heating feedback, while the Kuo simulation did not suffer from this excessive response, apparently because the Kuo scheme continued to process essentially all of the moisture that converged into unstable grid columns. The version of Kuo scheme used specifies the vertical distribution of convective heating such that heating is always maximized in the upper half of the unstable layer, whereas the grid-scale latent heating that developed in the GR and NC runs appeared to maximize in the lower troposphere, inducing a stronger mesoscale response (e.g., Hack and Schubert 1986). Thus, the GR and NC runs suffered from exaggerated mesoscale perturbations and localized rainfall maxima, apparently because of an excessive grid-scale response to unrealistic vertical structures, while the FD and Kuo schemes failed to develop strong enough mesoscale perturbations, apparently because the latent heating was artificially constrained as grid-scale circulations attempted to respond to these unstable structures.

Simulations using the KF and BM schemes showed superior agreement with the observations of this case. Model soundings indicated that these schemes were more efficient at maintaining stable vertical structures and the simulations were less susceptible to CISK-type instabilities. Furthermore, these schemes appeared to promote a realistic blend of sub-grid and grid scale precipitation. The BM simulation showed good agreement with observations on the location and configuration of the cyclone and its associated frontal boundaries and precipitation patterns. However, the central pressure of the cyclone was 5 mb higher than observed. The KF simulation produced a remarkably realistic evolution of the complex development of this cyclone, showing excellent agreement with observations on the 24-h central pressure, frontal structures, and precipitation fields.

While Kuo demonstrated that the KF scheme provides a very realistic representation of subgrid-scale moist convection in a rapidly developing ocean cyclone which is strongly forced by larger-scale processes, Jim Bresch followed up on Kuo's presentation by showing that this scheme has considerably more difficulty when large-scale signals are weak or absent. Bresch showed results from simulations of three different cases: the 3-4 June 1985 case from the PRE-STORM (Preliminary Regional Experiment Storm-scale Operational and Research Meteorology) study, the 1 August 1985 Cheyenne, Wyoming flood, and the 15 June 1992 high precipitation supercell over Kansas. He identified weaknesses in the KF performance related to formulations of the convective triggering mechanism; interactions between sub-grid and grid scale parameterization of precipitation, especially the exchange of hydrometeors between the two scales; and the strength of parameterized moist downdrafts. He also stressed that appropriate behavior of the scheme is strongly dependent upon the inclusion of realistic mesoscale details, both at the surface and aloft, in the model initial conditions. Details in the moisture field aloft, unobserved by the routine upper-air sounding network, were particularly important for the 3-4 June case.

Bresch examined the impact of different trigger function formulations based on: 1) grid-scale vertical velocity, 2) the depth over which a parcel must be lifted before it can reach its level of free convection, and 3) strength of convective inhibition, or negative area below the level of free convection. He found that the effectiveness of any of the tested formulations varied not only from case to case, but often within the domain of a single model grid. For example, in the widely varying types of convective environments (including both the nocturnal convection associated with overrunning of a surface front and a more typical boundary-layer rooted convection) of the 3-4 June case, a formulation that works well over one part of the domain may fail in other parts of the domain. He found that improvements in simulations could be engineered through systematic manipulation of these basic formulations, but he emphasized the need for additional study aimed at developing a universally applicable trigger function for convective parameterization on the mesoscale. This is particularly important in weakly forced environments because feedback from the parameterized convection itself can dominate the evolution of the mesoscale flow under these circumstances.

Bresch also showed that in his simulations, stratiform precipitation is significantly underpredicted in some areas. Thus, he suggested that the rate of feedback of hydrometeors from parameterized convection to the grid scale is underestimated by the KF scheme. This result illustrates the difficulty in parameterizing convection in mesoscale models, as the convective scheme is directly coupled to the mesoscale resolved motions. Furthermore, he linked inconsistencies in his simulations to parameterized downdrafts intensity, suggesting that the KF formulation relating downdraft strength to vertical wind shear should be reexamined, particularly in light of the ambiguous relationship between wind shear and precipitation efficiency.

Wei Wang gave a brief summary of her recent systematic evaluation of the five different CPSs in MM5 (NC, Kuo, GR, BM, and KF; Wang and Seaman 1996). In this study, which involved the simulation of six different cases that occurred over the continental U.S. during both the warm and cold seasons, none of the convective schemes consistently outscored the others when a variety of statistical measures of skill was applied. However, the KF scheme appeared to be the most robust out of this group in that it showed no signs of serious systematic failure on skill measures.

Wang devoted most of her presentation to an extension of this study which was designed to identify: 1) general problems with the KF and GR schemes in warm-season (squall-line) simulations and 2) systematic differences between simulations with 36- and 12-km grids. She showed that, during the early stages of system development and independent of grid length, both schemes tended to overestimate the areal coverage of convective rainfall and underestimate its intensity. Precipitation patterns in each of the simulated systems were dominated by parameterized convection initially, followed by a transition to coexisting parameterized convection and grid-scale precipitation. When the grid length was reduced from 36 to 12 km, Wang found that the transition from convective (parameterized) to grid-scale precipitation occurred earlier, but the total rainfall contribution from each source and the characteristics of the transition did not change significantly. She also showed that surface precipitation patterns developed more fine-scale structure in the higher-resolution runs and that the areas of rainfall were displaced horizontally because the simulated systems tended to propagate more rapidly with the smaller grid lengths. Changes in the precipitation characteristics, however, were not nearly as significant as those that occurred in the sea-level-pressure fields. The higher-resolution simulations developed considerably more fine-scale structure and much stronger mesoscale pressure perturbations. As with Kuo's results from the ERICA IOP5 storm, the existence of these mesoscale structures cannot be confirmed or rejected with available observations.

Wang also investigated the viability of simulating these systems with a 12-km grid length and without parameterized subgrid-scale convection. She showed that convective stabilization is extremely inefficient at this resolution, resulting in excessive and localized mesoscale perturbations in precipitation and surface pressure. This finding is consistent with previous studies that have indicated that some type of CPS is necessary even at this relatively small grid length (e.g., Zhang et al. 1988; Weisman et al. 1996).

Xiaoping Zhou closed the first half of this session by sharing his insight into considerations that must be made when selecting a CPS for use in an operational forecast model. He showed preliminary results from his evaluations of the Kuo, Fritsch-Chappell (FC - Fritsch and Chappell 1980), and KF schemes as possible candidates for use in an operational forecasting system for China. He focused on the numerical prediction of a flooding rainfall event during the Mei-Yu season in China using the MM4 modeling system. In this case, steady heavy rainfall occurred for nearly three days, with rainfall in some locations totaling 500 mm.

Zhou showed that, on the basis of surface precipitation fields alone, simulations with the KF scheme yielded the best agreement with observations in these preliminary results. The agreement was not exceptionally good, however, particularly with finer resolution. Thus, Zhou suggested that making the transition from a theoretical representation of moist convection to a robust scheme that can be used in an operational environment is likely to be extremely challenging.

The second half of this session provided an examination of the physical processes that are important for a CPS. Some of these processes are included within a CPS, while others are represented by other routines within the modeling system, but have a significant impact upon the behavior and feedbacks of the CPS itself. One component of deep moist convection that cannot be ignored is the convective downdrafts. Although its significance has been widely recognized (Johnson 1976; Cheng 1989; Wang and Seaman 1996), there is no universally accepted method for representing this feature in a CPS. Ming-Dean Cheng started the second half of this session by discussing the development and implementation of a technique for including the effects of moist downdrafts in the AS CPS (Arakawa and Schubert 1974; Cheng 1989). Cheng showed that their technique relies on the calculation of an effective tilting angle for convective updrafts, which allows for an estimation of convective rainwater flux out of the cloud and into the clear-air environment. This rainwater is assumed to be available for evaporation and loading in a convective downdraft. Thus, the downdraft's mass flux can be estimated as a function of the updraft mass flux and the updraft tilting angle for each cloud type.

Cheng showed the results of a stability analysis of stationary solutions of the coupled rainwater and vertical momentum budget equations for a steady-state plume model. He identified two types of solutions: 1) solutions for small tilting angles, which are unstable, and 2) solutions for large tilting angles, which are stable. The smallest tilting angle in the stable range was selected as the optimal value. Cheng then showed results from the implementation of the modified AS scheme in both semi-prognostic and fully prognostic tests. The most significant result from the semi-prognostic tests, which were based on GATE phase III data, was that inclusion of the downdrafts shifts a significant portion of cumulus drying downward from the cloud layer to the subcloud layer. The modified drying profiles gave much better agreement with profiles diagnosed from observations than did the original scheme. In fully prognostic tests using the UCLA GCM, Cheng revealed that the addition of downdrafts led to a significant decrease in the rate of precipitation over land. In addition, he noted that surface precipitation and evaporation generally increased over ocean and appeared to become more organized.

Kuan-Man Xu then discussed applications of explicit cumulus ensemble simulations (e.g., Xu et al. 1992) in the evaluation of cumulus parameterization techniques. He began by showing that domain-averaged surface precipitation rates follow cycles of imposed large-scale destabilization rate quite closely in the model. He then presented a statistical analysis (Xu 1994) of the dependency of three fundamental cumulus parameterization closure assumptions on averaging distance (analogous to a grid length in a larger-scale model). Following Arakawa and Chen (1987), he characterized these closure assumptions as: 1) constraint on the coupling of the time tendencies of large-scale temperature and water vapor mixing ratio, 2) constraint on the coupling of cumulus heating and drying, using a statistically-steady cloud model, and 3) direct constraint on the intensity of a cumulus ensemble. Xu's results revealed that types 1 and 2 closure assumptions were nearly independent of equivalent grid length in the range from 64 to 512 km. He found that type 3 closure was somewhat dependent upon the horizontal resolution, but improved as grid length became smaller.

Xu next presented results from semi-prognostic tests of the AS CPS based on the cumulus ensemble model and evaluated the applicability of the AS scheme on large-scale and meso-β-scale grid lengths. His results (Xu and Arakawa 1992) indicate that the AS cloud-work-function quasi-equilibrium, in the range of 64 to 512 km, is more accurate when mesoscale processes are at least partially resolved, i.e., when grid lengths are smaller. He explained this by showing that, on average, the magnitude of large-scale forcing increases significantly as the averaging distance decreases, while the magnitude of the time rate of change of the AS cloud work function changes very little. He also pointed out that the nondeterministic errors become larger as the grid lengths become smaller. He then showed that the performance of the AS scheme on meso-β grid lengths (between 10 and 80 km) depends on the time interval over which the input data are averaged. For example, the correlation between parameterized (in a semi-prognostic sense) rainfall and explicitly-simulated rainfall at a length of 40 km weakened as the time interval for averaging decreased. Xu suggested that there appears to be a preferred time interval for a given grid size. Finally, he suggested that, in the context of the proper conceptual framework, a scale separation between parameterized subgrid-scale clouds and the grid-resolvable circulations does not appear to be essential for a CPS with grid lengths over 10 km.

Dave Parsons gave the next talk in the session, using test results from both cloud-scale and mesoscale models to deduce critical ingredients of simulations of convective processes at both scales and to aid in the evaluation of CPSs. Initial conditions for his simulations were derived from two actual events. First, he presented results of mesoscale simulations initialized with a single sounding (horizontally uniform) from the 10-11 June 1985 PRE-STORM squall line (Johnson and Hamilton 1988; Zhang et al. 1989). Using the hydrostatic version of the Penn State/NCAR mesoscale model (MM4) with a 25-km grid length, Parsons compared simulations with: 1) grid-scale resolved motions without any CPS, 2) the FC CPS with no grid-scale microphysics (i.e., no mesoscale resolved cloud motions), and 3) grid-scale microphysics and the FC CPS. He found that (a) the simulation with only grid-scale resolved motion produced a gradually sloping system, as was observed in this case, but development was far too slow, and the convective response was too strong, especially in the early and middle stages of evolution; (b) the CPS alone leads to a system with an unrealistic mesoscale structure (i.e., little or no vertical tilt) and (c) the combination of grid-scale microphysics and the FC CPS yields some favorable results such as the circulation had approximately the correct mesoscale slope present in the simulation without a CPS but without the slower evolution and the overprediction of convective response. This simulation still shows weaknesses in the triggering of convection and the magnitude of the response. Through comparison of simulations with these same initial conditions but performed with cloud-scale resolution using the Klemp-Wilhelmson cloud model, he was able to show that it was difficult for the simulation to provide the correct convective response. These results were presented previously in Parsons and Gao (1989).

Parsons next showed results from simulations of the 24-25 June 1993 ARM (Atmospheric Radiation Measurement) squall line. In this case, the nonhydrostatic version of the

PSU/NCAR model (MM5) was used with initial conditions designed to replicate observed atmospheric conditions. He used multiple nesting with the grid length on the outermost mesh being 60 km, and successive inner meshes going down to 20, 6.67, and 2.2 km. The two finest-resolution grids used no CPS, while the 20- and 60-km grids used the GR scheme. Results from the explicit simulation on the 2.2-km mesh were encouraging, showing good agreement with observations. However, the simulation was degraded at coarser resolutions as convective mass flux decreased with increasing grid length. This trend was in contrast to results presented earlier by Weisman, who showed that convective mass flux unrealistically increased with increasing grid length in idealized convective environments. Weisman hypothesized that this tendency was due to the neglect of nonhydrostatic effects in his simulations, while Parsons attributed the opposite trend in his results to poor resolution of convective triggering processes at coarser resolution, hence a reduced areal coverage of convection. Parsons emphasized that it is unclear which effect might dominate more often in realistic simulations. He suggested that slight changes in model physics can lead to significant changes in the convective response, and that a correct prediction of convection with a cloud-resolving model may require accurate treatment of other physical processes. Furthermore, he concluded that CPSs are likely to suffer from a sensitivity to a host model's parameterization of other physical processes to at least the same degree as the explicit representations of convective clouds did in his experiments. Some preliminary aspects of this analysis can be found in Dudhia and Parsons (1995).

The last talk in this session was given by Da-Lin Zhang from McGill University. Zhang elaborated on Parsons' concerns about interactions between a CPS and other physical parameterization, stressing that a CPS represents only one part of a spectrum of complex physical processes that are not explicitly resolved by the hydrodynamic equations of motion in a numerical model. He emphasized that numerical simulations have the best chance for success when all of these physical processes are well-represented and interact with each other in a realistic manner (Zhang et al. 1994). He identified three prominent physical parameterizations that interact strongly and nonlinearly with a CPS: planetary boundary layer (PBL), atmospheric radiation, and grid-scale microphysics.

Zhang pointed out that the diurnal cycle of the PBL strongly modulates CAPE and convective inhibition, and hence the potential for convective triggering, over land areas. He also noted that the diurnal cycle and parameterized PBL processes play an essential role in the formation of nocturnal low-level jets, which are commonly associated with nocturnal MCSs over many land areas of the globe. Furthermore, he emphasized that a PBL parameterization must be able to respond realistically to the sudden jolt imposed when parameterized convective downdrafts sharply interrupt normal PBL cycles, and allow for a realistic boundary layer recovery from convection.

Zhang cited several examples of the sensitivities of numerical simulations to parameterization of atmospheric radiation. He indicated that there is no general agreement on how the radiative properties of subgrid-scale (parameterized) clouds should be represented, but stressed that convective clouds have a potentially dominating effect on the local radiation budget, which can in turn have a significant impact on the evolution of convective systems. The radiative properties of a simulated convective system are also strongly dependent upon the rate at which hydrometeors are transferred from parameterized convection to the grid-scale environment. Long-term integrations are especially sensitive to radiative feedback from anvil clouds.

Zhang emphasized that representation of the radiative effects of hydrometeors requires a parameterization of grid-scale microphysical processes. A microphysical parameterization including predictive equations for hydrometeors is essential for a realistic prediction of MCSs because, unlike CPS for deep convection, a realistic formulation for microphysical processes allows condensation/deposition and evaporation/sublimation processes to occur over widely separated horizontal distances, as they do in nature. Furthermore, he indicated that a microphysical parameterization should include the ice phase, since, in addition to evaporation and water loading, sublimation and melting have been shown to be essential for a realistic simulation of the structure and circulations of the stratiform portion of MCSs (Zhang 1989; Zhang and Gao 1989).

In discussions at the end of this session a number of issues were raised. The overriding theme of these discussions involved concerns related to the absence of a spectral gap between parameterized (subgrid-scale) and resolved circulations in meso-β-scale models. It was pointed out that existing mass-flux CPSs represent clouds as simple stochastic, non-interacting plumes. Thus, it was argued that some manifestation of convective-like circulations must develop on a mesoscale model's resolved scales before the mesoscale organization of convective elements can evolve on these scales. In this context, the fundamental question asked was: How should the physical processes associated with convection be partitioned between parameterized and explicitly-resolved components of a mesoscale model?

Mesoscale simulations of convective systems with MM5 often include the formation of saturated layers in vertical columns that are conditionally unstable, even though subgrid-scale convection is actively being parameterized. When saturation is reached within these layers, the conditionally-unstable structure becomes absolutely unstable and, as discussed by Zhang and Fritsch (1987), a grid-scale (mesoscale) manifestation of a convective cloud can develop.

In an earlier session, Jack Kain emphasized that the development and explicit release of this type of instability was critically important in his simulations of a mid-latitude squall line using the KF scheme. In particular, he argued that this instability was necessary to induce mesoscale circulations of sufficient strength to generate realistic perturbations in the meso-β-scale structure of the simulated system. In this session, Bill Kuo showed that, in simulations of a rapidly deepening oceanic cyclone, all of the convective schemes available in MM5 showed some propensity to allow absolutely unstable structures to develop. In fact, Kuo suggested that the KF scheme was less likely than the other schemes to degrade the solution by allowing unrealistic vertical structures to develop in the vicinity of active parameterized convection. Moreover, simulations with the KF scheme also provided the best overall agreement with observations for this case.

Because the KF scheme yielded superior results in these two cases, much of the discussion focused on this scheme. A key element of its success appears to be its ability to effect a smooth transition between parameterized and explicitly resolved precipitation processes, a transition that is sometimes accompanied by the development of absolutely unstable vertical structures. As discussed in Zhang et al. (1994), these unstable structures tend to develop with the KF scheme when significant levels of conditional instability exist over a deep layer and grid-scale destabilizing processes are stronger than the stabilizing tendency of the parameterized convection. Generally, these conditions are met at only a small fraction of the total number of convectively active grid points and for a short period of time, even in strongly forced convective systems. It appears that the KF scheme yields optimal numerical solutions when a transition to 'mesoscale convection' is allowed, yet severely constrained by robust parameterized convection.

There was a general consensus that, of the CPSs currently available in MM5, the KF scheme gives the most consistently favorable performance. However, it is not always the best choice for a given convective environment. Most importantly, the physical mechanisms that allow the KF scheme to distinguish itself from the others are not well understood. The best hope for true progress with the current generation of CPSs appears to lie in the verification and calibration of the different approaches using cloud-resolving numerical models.

Session 4: Mesoscale Organization and Momentum Transport (Chair: D.-L. Zhang)

Despite considerable work in cumulus parameterization, much less attention has been paid to the incorporation of convective momentum transport into the existing mesoscale or larger-scale models. Peggy LeMone opened the session by presenting observational evidence of consistent vertical profiles of momentum fluxes diagnosed from various MCSs over both midlatitude and tropical regions around the world, in spite of their highly variable environments, in which the MCSs were embedded. The associated vertical flux divergence profiles reveal that convection with linear structure tends to accelerate the momentum normal to axis of linear-band MCSs in such a way that the winds are accelerated in the direction of line motion at the low levels, and in the opposite direction higher up (see LeMone 1983; LeMone et al. 1984; Gallus and Johnson 1992; LeMone and Moncrieff 1994; Gao et al. 1990).

LeMone noted that both the degree of convective organization and the alignment of convective bands seem to be related to the vertical shear of the horizontal wind at least in the tropics. When shear is very small, local forcings, such as outflow boundaries, determine whatever organization there is. When shear gets larger, convective bands aligned by local forcing have actually been observed to realign according to the shear (e.g., Keenan and Carbone 1992). In the midlatitudes, dynamic forcing (e.g., cold fronts) is probably a more significant factor in convective-system alignment. Momentum transport along the convective line or in more random convection is generally downgradient, and it could be parameterized according to Schneider and Lindzen (1976). Comparisons with the results of LeMone and Moncrieff showed that cloud models can do a fair job of representing momentum transports. However, the one mesoscale squall-line simulation available at the time (Gao et al. 1990) overpredicted the rearward acceleration of the line-normal flow. (In subsequent discussion, Zhang mentioned that this discrepancy was due to the lack of appropriate treatment in the grid-scale diabatic heating and the parameterized convection).

LeMone stressed the importance of MCS structure in determining the surface fluxes. Using TOGA COARE convection as an example, she showed how squall lines oriented normal to the shear led to the largest momentum at the surface -- larger than anywhere in the environment. On the other hand, bands parallel to the shear produced less acceleration in the band-normal direction, and tended to have relatively weaker winds at the surface, with strongest winds simply transported downward from aloft. The circulation in the convection also determines the level from which the new surface air comes, and hence its thermodynamics. Because of the influence of convective structure on both momentum transports and surface fluxes, LeMone suggested that it is important to distinguish the linear convective system from other types of convective clouds and to determine how it is oriented with respect to vertical wind shear.

Mitch Moncrieff presented several examples in which mesoscale organization of convection can influence larger-scale circulations and transport momentum and energy upscale. When these transport processes are poorly treated in meso- and larger-scale models, significant errors in the wind field occur, which have an important impact, if not on short-range forecasts, certainly on medium- and long-range forecasts. He then showed how idealized dynamical models of the total momentum transport can be used, within its limit of validity, to improve existing parameterization schemes by including the convective momentum transport and to provide a consistent treatment of thermodynamic tendencies and momentum fluxes associated with organized convection (e.g., Moncrieff 1981, 1992; LeMone and Moncrieff 1994). A question was then raised as to the relative importance of mesoscale dynamics versus cloud microphysics in producing the internal circulations of MCSs. He suggested examining this issue with CRMs using the platform of the GEWEX Cloud System Study (GCSS) Working Group on Precipitating Convective Cloud Systems.

Moncrieff also emphasized the significance of incorporating the interaction of convective momentum transport with boundary-layer processes. Because of the subgrid-scale nature of convection, Moncrieff suggested combining the deterministic and stochastic approaches to pursue the parameterization of organized convection. For example, the triggering of convection and in-cloud pressure distribution could be treated in a statistical manner, whereas momentum fluxes and heating/moistening profiles could be parameterized deterministically. He speculated that in some situations, less sensitivity to the convective momentum transport might be attributable to the treatment of numerical diffusion in the existing numerical models. Finally, Moncrieff mentioned his plan (again involving the GCSS) to conduct a comprehensive analysis of the systematic errors involved in operational numerical weather prediction models during the warm season over the U.S., using a hierarchy of numerical and dynamical models. This would examine whether or not these errors are a consequence of the imprecise treatment of MCSs.

Two questions were raised during the discussion period. First, how important is the convective momentum transport in determining the quality of numerical prediction of MCSs, as compared to the convective parameterization of heat and moisture? This question was asked because convective momentum transport has not been considered in most of the existing schemes, but considerable successes achieved with these schemes have been reported in the literature. It is recommended that the idealized conceptual model of Moncrieff (1981, 1992, 1995) or other types of momentum parameterization be built into the existing CPSs and tested with some MCS cases to gain insight into the sensitivity of numerical simulations on different time scales. It is speculated that convective momentum transport may be more important in simulating tropical MCSs in which the wind field dominates, and for climate studies using GCMs. A second question concerns how to isolate the effect of convective momentum transport from other factors in determining model sensitivity. This question is also a general one regarding the issue of convective parameterization when coupled with other model physical processes.

Section 5: Mesoscale Observations and Verification of Schemes (Chair: M-D. Cheng)

A successful simulation of a mesoscale convective system requires accurate treatment of various physical processes, including subgrid scale convection and resolvable scale motions. The mesoscale dynamical and thermodynamical structures of MCSs described in Johnson's talk, entitled "Some Challenges for Mesoscale Modeling of Convection," provide challenges for future cumulus parameterization development. Johnson described two observationally significant features of MCSs that are not yet successfully simulated by numerical models: (1) intense surface pressure gradients, strong low-level downdrafts and high surface winds found in trailing stratiform precipitation regions of many MCSs and (2) the highly broken structure of many squall lines. Concerning (1), there was a dispute on the relative importance of ice microphysics versus dynamical forcing associated with MCSs on the initiation and maintenance of the intense mesoscale surface pressure gradients. Johnson speculated that cooling due to sublimation of falling ice crystals below the anvil is essential for a strong, descending rear inflow. Recent MM5 simulations of the 10-11 June 1985 squall line by Braun and Houze (1996) support this idea. The rapidly descending rear inflow in turn produces a mesoscale pressure perturbation that produces intense surface pressure gradients. However, in addition to sublimative effects, buoyancy gradients associated with the front-to-rear flow aloft and evaporation at low levels can serve to dynamically enhance the rear inflow circulation (e.g., Lafore and Moncrieff 1989), thereby also contributing indirectly to the intense surface pressure gradients. With regard to (2), the distinction between squall lines with nearly contiguous convection and those that are highly broken may be related to the degree of convective inhibition or CIN (Johnson et al. 1995). The challenge to numerical prediction is then how to accurately represent CIN and how it is modulated by a variety of processes including the convection itself.

Xiaolei Zou, in her talk entitled, "Verification of Cumulus Parameterization via Data Assimilation," introduced a method for testing cumulus parameterization schemes based on a 4-dimensional variational (4DVAR) data-assimilation technique (Zou and Kuo 1996). In the past, three different methods have been used to verify a CPS, which are known as diagnostic, semi-prognostic, and full prognostic tests. Each of these methods has its shortcomings. For example, in a full prognostic test, the quality of the initial condition and errors from other physical parameterization schemes can affect the performance of a given CPS. On the other hand, the Q1 and Q2 profiles needed for diagnostic or semiprognostic tests have only limited accuracy, due to limitation in the temporal and spatial resolution of the sounding data and their measurement errors. Zou proposed to perform a 4DVAR assimilation of both remote and in-situ observations collected in a field program (such as TOGA COARE). Such a four-dimensional, dynamically consistent data set can then serve as a test bed for verification of various CPSs. Moreover, the amount of adjustment to the initial condition required in the 4DVAR assimilation and the fit between the assimilated fields and the observations can also reflect the quality of the CPS used in the 4DVAR system. Different schemes can be used and tested in a 4DVAR framework.

The parameter estimation using the adjoint model is another method to assess the strength and weakness of a given CPS. In particular, the 4DVAR technique can be used to determine the "optimal" values for a large number of parameters for a given CPS. Some of these parameters cannot be easily determined based purely on either theoretical or observational considerations. For example, one can use the 4DVAR technique to determine the optimal intensity of convective downdrafts that would allow a best fit to all the available observations. Such a sensitivity analysis will identify strength and weakness of a given scheme, and provide direction for future improvements.

Session 6: Summary and General Discussion (Chair: Y.-H. Kuo)

The presentations and discussions during the two-day workshop raised many important yet difficult and unanswered issues. Session chair Bill Kuo synthesized these issues into five summarizing questions to facilitate a final discussion.

Question 1) Is cumulus parameterization fundamentally different between mesoscale and large-scale models?

Two contrasting views were discussed. First, since moist convective processes are entirely a sub-grid scale process for large-scale models, but can be partially resolved on a mesoscale grid, it can be argued that the manner in which cumulus convection is parameterized does depend on the grid length. Zhang suggested that since organized convective systems include both stratiform and convective components, they should be treated differently in a numerical model. Kuo pointed out that the resolvable-scale parameterization only considers grid-scale saturation -- whether the saturation arises due to stable ascent or grid-scale convectively unstable motions is of no consequence. Small grids, therefore, are resolving both the convective and stratiform components of an organized convective system. One cannot simply associate the stratiform component of a convective system with the resolvable scale microphysical parameterization and the convective component with the sub-grid scale convective parameterization.

Arakawa argued that it is unreasonable to consider supersaturation across a grid box 20 km on a side. This condition arises solely due to deficiencies in current parameterization approaches. He suggested that the parameterization problem is the same regardless of the grid size since a convective system knows nothing about the grid attempting to resolve it.

Moncrieff pointed out that the non-deterministic nature of the problem must be considered, and suggested that determining convective behavior within a certain set of confidence limits is needed.

Kain raised the issue of non-local compensating subsidence. Current convective parameterizations assume that convective clouds occupy only a fraction of a grid box, and that compensating subsidence occurs entirely within that box. For small grid sizes, this clearly does not represent nature. Kain described a parameterization scheme under development which treats convective clouds as mass sources and sinks, thereby letting the non-hydrostatic model rearrange the mass.

Question 2) How can a cumulus parameterization scheme that is valid for a range of grid sizes (e.g. 2-20 km) be developed?

Since the application of a parameterization determines, in part, the development approach, three potential goals were listed. A CPS might be used for a) simulation of MCSs, b) the daily operational forecasting, and c) climate studies. Some discussion ensued about how, with the ever-increasing computational power, it might be possible to resolve convection explicitly. It was decided that a parameterization would still be necessary since there would be sub-grid scale features that needed to be considered. Three possible approaches were discussed:

Kain described what modifications to existing schemes would be necessary to develop a more general parameterization. First, a cloud life cycle would need to be added. This would allow features such as the delayed onset of a downdraft to be included in the parameterization. Second, mass sources and sinks should be fed back to the model so that subsidence occurs on surrounding grid cells. Third, hydrometeor feedback should be included, which may require better compatibility between microphysical parameterization used in both the grid and sub-grid scale schemes. For example, ice crystals produced by a convective cell are transferred to stratiform precipitation in return.

An adaptive grid approach was discussed by Skamarock. While high-resolution modeling of convective areas should produce good results, major problems with this approach include objectively determining initiation and termination of fine grids and having sufficient computer power to resolve all of the convective regions, particularly, in the presence of random, widespread convection. Currently, no adequate algorithm exists to start and finish high-resolution nests. Although the adaptive-grid approach attempts to explicitly resolve cloud scale motions, parameterization is still needed to treat sub-grid scale features (e.g., turbulent mixing).

A third approach, proposed by Arakawa, is termed a unified cumulus parameterization since it would account for both convective and stratiform precipitation, both deep and shallow convection, and both liquid and ice processes. In this method, there is no distinction between the grid and sub-grid scales, a spectrum of moist processes is treated as a single package, and the non-deterministic nature of the problem is not hidden. This approach is an extension of the cumulus ensemble modeling approach, but still requires the development of an appropriate statistical closure.

Question 3) Should momentum transport be included in existing schemes?

Moncrieff suggested that to thoroughly address the momentum transport problem, it is necessary to determine whether significant errors exist in numerical weather prediction models due to momentum transport by MCSs. Does this error feed back and have an impact on forecasts? The momentum transport problem could be considered more broadly as an energy dissipation mechanism on the mesoscale. A parameterization could be developed based on cloud model results for organized convective systems. While a complete parameterization might be years away, a simple scheme that includes the basic characteristics of momentum transport by MCSs such as non-conservation of momentum, could be developed fairly quickly.

Subsequent discussion suggested that wind measurements from the profiler and WSR-88D networks over the United States could be used to verify the momentum transport parameterization. Ideally though, a field experiment with a dense sounding network would be most useful.

Question 4) How can the different schemes and approaches be verified?

Two approaches to verification were suggested by the participants. One possibility, suggested by Zhang, would be to use a set of standard cases, such as a well-behaved sea breeze case that doesn't have complicating synoptic conditions. The problem with using real-data cases is that the initial data may be inadequate, and that the convective triggering process is not accurately represented. Another way to verify parameterization, suggested by Joe Klemp, is to use CRMs. He pointed out that while these models are not perfect, they are more accurate than the parameterizations that are to be tested, there can be more control over the evaluation than for real-data cases, and these models avoid the problems associated with observations. Again it was pointed out that even with this approach, the initialization and triggering are significant unresolved problems. Of course, a careful verification of models and parameterization schemes against observed data (or data 'filled in' by models -- as suggested in the 4DVAR approach discussed in Zou's presentation) should also be pursued.

Question 5) Where should we go from here?

Research into the cumulus parameterization problem continues on many fronts. It was suggested that coordination of efforts might be accomplished through the GCSS working group structure already in place. In the future, model and parameterization intercomparison studies would be necessary. Finally, it was pointed out that to fully understand convective system behavior, it will be necessary to measure the entire life cycle of MCSs. For that, the participants would welcome the long-awaited field experiments of the United States Weather Research Program.

Acknowledgment

We thank Bob Gall at the NCAR MMM division for providing financial support for this workshop. This workshop was conducted as part of a research project funded by NASA under Order Number: S-41381-F.

List of Acronym

4DVAR	four-dimensional variational data assimilation
ARM	Atmospheric Radiation Measurement
AS	Arakawa-Schubert
BM	Betts-Miller
CaPE	Convection and Precipitation/Electrification Experiment
CAPE	convective available potential energy
CIN	convective inhibition
CISK	Conditional Instability of the Second Kind
CPS	cumulus parameterization scheme
CRM	cloud-resolving model
ECMWF	European Center for Medium Range Forecast
EMEX	Equatorial Mesoscale Experiment
ERICA	Experiment on Rapidly Intensifying Cyclones over the Atlantic
FC	Fritsch-Chappell
FD	fake dry
GATE	Global Atmospheric Research Program Atlantic Tropics Experiment
GCM	general circulation model
GR	Grell
GEWEX	Global Energy and Water Cycle Experiment
GCSS	GEWEX Cloud system Study
IOP	Intensive Observation Period
KF	Kain-Fritsch

MCS	mesoscale convective system
MM4/5	mesoscale model version 4/5
NCAR	National Center for Atmospheric Research
NC	no cumulus
PBL	planetary boundary layer
PRE-STORM	Preliminary Regional Experiment Storm-scale Operational and Research Meteorology
PSU	Pennsylvania State University
RPC	rotated principal component
TOGA-COARE	Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment
TAMEX	Taiwan Area Mesoscale Experiment
UCLA	University of California at Los Angeles

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