Final Report for:

EXPLICIT SIMULATION AND PARAMETERIZATION OF MESOSCALE CONVECTIVE SYSTEMS

U.S. Department of Energy
Atmospheric Radiation Measurement Program
Grant #: DE-FG03-94ER61749

William R. Cotton, Principal Investigator

Colorado State University
Dept. of Atmospheric Science
Fort Collins, CO 80523-1371

Period of Activity: November 1, 1993 - April 30, 1997

Date: August 12, 1997

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Contents

1 Introduction
   1.1 Parameterization of heating, moistening, and momentum transports by MCSs 2
   1.2 Activation and de-activation of the MCS scheme 5
   1.3 Testing and evaluation 10

2 Adaptive-grid Single-column model for parameterization of middle and high clouds (cirrus) generated by active MCSs and cumulonimbi outflow 16

3 Future Plans 19

4 References 19

5 Publications Supported 23

6 Theses supported 25
1 Introduction

This research has focused on the development of a parameterization scheme for mesoscale convective systems (MCSs), to be used in numerical weather prediction models with grid spacing too coarse to explicitly simulate such systems. This is an extension to cumulus parameterization schemes, which have long been used to account for the unresolved effects of convection in numerical models. Although MCSs generally require an extended sequence of numerous deep convective cells in order to develop into their characteristic sizes and to persist for their typical durations, their effects on the large-scale environment are significantly different than that due to the collective effects of numerous ordinary deep convective cells. These differences are largely due to a large stratiform cloud that develops fairly early in the MCS life-cycle, where mesoscale circulations and dynamics interact with the environment in ways that call for a distinct MCS parameterization. Comparing an MCS and a collection of deep convection that ingests the same amount of boundary layer air and moisture over an extended several-hour period, the MCS will generally generate more stratiform rainfall, produce longer-lasting and optically thicker cirrus, and result in different vertical distributions of large-scale tendencies due to latent heating and moistening, momentum transfers, and radiational heating (Houze, 1977; Cotton et al. 1995; Gallus and Johnson, 1991; Alexander and Cotton, 1997; Machado and Rossow 1993).

In spite of the distinct nature of MCSs relative to ordinary convective clouds, current general circulation models (GCMs) do not contain convective parameterization schemes that specifically account for contributions from MCSs. Most GCMs have upright, deep convective parameterization schemes such as Arakawa and Schubert’s (1974) but do not consider contributions by the more slantwise ascending and descending branches of the stratiform anvil clouds of MCSs. Since our research (Cotton et al., 1995; Alexander and Cotton, 1997) indicates that the slantwise branches can vertically transport a great deal of lower troposphere moisture into the upper troposphere independent of the deep convective clouds, the absence
of such a parameterization can lead to a substantially drier and less radiatively-active upper troposphere than occurs in reality.

1.1 Parameterization of heating, moistening, and momentum transports by MCSs

We have developed an MCS parameterization scheme that is suitable for use in GCMs. The MCS parameterization scheme is designed such that it is compatible with the view that GCMs are widely variable in terms of their horizontal resolution. The GCMs with finer resolution may explicitly resolve some of the slow manifold or balanced responses to MCS heating and momentum transports. The GCMs with coarser resolution, on the other hand, will require parameterization of all the impacts of MCSs. The parameterization scheme must, therefore, be modular in structure with components retained or removed, depending upon the GCM resolution.

Our strategy was to perform fully three-dimensional cloud-resolving simulations of both the deep convective, and more slantwise, stratiform components of MCSs in middle and tropical latitudes. From analysis of these 'synthetic' or simulated data, a parameterization scheme has been fabricated and calibrated. The reason we have selected observed cases rather than idealized simulations is that it allows us to evaluate the credibility of those simulations before we undertake the major effort of analyzing them and using the model-output data to guide us in the development of the parameterization scheme.

The simulations are initialized from the objective analysis of observed large-scale data on a relatively coarse grid (say, grid spacing of 50 km or more). Following initialization, the model is integrated forward for 6 to 10 hours or more, and the results are compared with observed data. If the results appear credible, then successively finer grids, each nested within its larger host grid, are spawned until grid spacing of 1 to 2 km is obtained. For these organized systems, this grid spacing is adequate to resolve explicitly both the deep convective drafts and the mesoscale flow branches. It is the fine grid, which we call the cloud-resolving grid, that is used to perform analysis for formulating the MCS parameterization scheme.
Before we could perform these simulations, a convective parameterization scheme had to be devised which can be applied on coarse grids with a range of mesh sizes down to the host grid of the cloud-resolving grid. The scheme reported by Weissbluth and Cotton (1993) was developed using the methodology of performing cloud-resolving simulations of steady, intense convective storms such as exist in most MCSs. This scheme, which we call a level 2.5 scheme, predicts on vertical velocity variance, instead of turbulence kinetic energy as in a standard Mellor and Yamada (1974) turbulence closure scheme. This scheme has performed adequately in a tropical MCS simulation (Alexander and Cotton, 1994), as well as a mid-latitude squall line (Hertenstein et al., 1994) and a mid-latitude mesoscale convective complex (MCC) (Olsson and Cotton, 1997a,b; Alexander and Cotton, 1997). Originally we planned to use it as the basis of the convective engine which would be interfaced with the mesoscale flow branch parameterization scheme. However, subsequent testing of the scheme revealed that it did poorly in representing the less intense, non-steady modes of convective clouds. It also represents only one convective cell within a grid volume, which is an undesirable property for use in GCMs. We therefore elected to interface our MCS parameterization scheme to the Arakawa and Schubert (1974) scheme, which represents a full spectrum of cloud types, and which was extended by Randall and Pan (1993) to include predicted vertically-integrated cloud kinetic energy. Rafkin (1996) has further extended the Randall and Pan (1993) scheme to allow use in a broad range of grid sizes from GCMs to fine-resolution mesoscale models.

The MCS scheme that we have devised is derived from cloud resolving simulations with the Regional Atmospheric Modeling System (RAMS) of a tropical MCS observed during the 1987 Australian monsoon season (EMEX9), and one of a midlatitude MCC observed during a 1985 field experiment in the central plains of the U.S. (PRE-STORM 23-24 June 1985). In each case, the finest grid of RAMS covers an area on the order of tens of thousands square kilometers (\(\sim 18,000 \text{ km}^2\) for EMEX9, \(\sim 17,300 \text{ km}^2\) for PRE-STORM). Large scale data are assimilated in the coarse grid of RAMS and then the model is run forward with two grids for several hours using the Weissbluth and Cotton (1993) cumulus parameterization scheme. Then each simulation is run for several hours using all grids and no convective
parameterization (over 6 hours for EMEX9, 3.5 hours for PRE-STORM 23-24 June). In both cases, the model simulates organized convection and an adjacent stratiform region which closely resemble the observed system. The analysis of these data then focuses on conditional sampling of the stratiform region of each system. The conditional sampling of the fine grid data of each MCS simulation attempts to identify mesoscale updrafts and mesoscale downdrafts within the stratiform region of each system. Once these mesoscale updraft and downdrafts are identified, analyses of heat and moisture sources and vertical transports (discussed further below) in these conditionally-sampled mesoscale updrafts and downdrafts are used to determine the shapes of vertical profiles of various physical processes as well as relationships between various components of an MCS's water budget.

The thermodynamic part of the MCS parameterization that we have developed is analogous to the formulation of Donner (1993), with improvements of a more sophisticated convective driver (the Arakawa-Schubert convective scheme with convective downdrafts) and inclusion of the vertical distribution of various physical processes obtained through conditional sampling of the two cloud-resolving MCS simulations. The Wu and Yanai (1994) convective momentum parameterization has also been included as a separate component of the parameterization scheme. The mesoscale parameterization is tied to a version of the Arakawa-Schubert convective parameterization scheme which is modified to employ a prognostic closure, as described by Randall and Pan (1993). The parameterized cumulus convection provides condensed water, ice, and water vapor to the anvil cloud, where the distinct processes associated with mesoscale circulations are parameterized.

The mesoscale thermodynamic parameterization depends on knowing the vertically-integrated values and the vertical distributions of the following quantities: (1) deposition and condensation in mesoscale updrafts, (2) freezing in mesoscale updrafts, (3) sublimation in mesoscale updrafts, (4) sublimation and evaporation in mesoscale downdrafts, (5) melting in mesoscale downdrafts, and (6) mesoscale eddy fluxes of entropy and water vapor. The relative magnitudes of these quantities are constrained by assumptions made about the relationships
between various quantities in an MCS's water budget deduced from the cloud-resolving simulations.

The scheme is then tested by comparing the heating and drying tendencies produced by feeding it mean soundings from the simulations with tendencies diagnosed from the conditional sampling of the simulations. Further details of the scheme and its evaluation can be found in Alexander (1995) and Alexander and Cotton (1997).

1.2 Activation and de-activation of the MCS scheme

The most critical issue for implementing such an MCS parameterization scheme is when and where to activate it and shut it down. Jiang et al. (1996) formulated a means of activating and deactivating the MCS scheme, depending on the intensity and longevity of the parameterized convection. They partitioned the total unresolved kinetic energy into contributions from the deep convection (CKE) and the mesoscale circulation branches (MKE). An example of diagnosed CKE and MKE evolution based on conditional sampling of the PRE-STORM explicit simulation is shown in Fig. 1. It shows rapid development of CKE due to strong convection early in the simulation, followed by the lagged development of MKE existing in the mesoscale flow branches. The MKE curve is an underestimate of the actual MKE maximum and longevity, because the explicit domain covered only a portion of the active MCS that was observed and modeled in the larger host grid.

Two prognostic equations are developed for vertically-integrated CKE and MKE, respectively. The CKE equation is given by

$$\frac{dCKE}{dt} = MBA - \frac{CKE}{\tau_{CKE}} - S_{ac},$$

where $A$ is the cloud work function defined in Arakawa and Schubert, $MB$ is cloud base mass flux, $\tau_{CKE}$ is the CKE dissipation time, and $S_{ac}$ denotes the auto-conversion of CKE to MKE. The MKE equation is given by

$$\frac{dMKE}{dt} = S_{ac} + GB - GL - GS - Gp - \frac{MKE}{\tau_{MKE}},$$

5
Figure 1: Evolution of CKE and MKE in an explicitly simulated mid-latitude MCS.

where

\[ G_B = \int_{0}^{\infty} g \rho_0 \left[ \theta' \left( \frac{\theta'}{\theta} + 0.608 \right) + q_v \right] dZ \]  

is thermal buoyancy production rate,

\[ G_L = \int_{0}^{\infty} g \rho_0 \left[ w' q_{\text{condensate}} \right] dZ \]  

is loading buoyancy production rate,

\[ G_S = \int_{0}^{\infty} \rho_0 \left( \frac{\partial U}{\partial Z} w' + \frac{\partial V}{\partial Z} v' w' \right) dZ \]  

is shear production rate,
\[ G_P = \int_0^\infty \rho_0 \theta_0 \left[ \frac{\partial \pi'}{\partial X} w' + \frac{\partial \pi'}{\partial Y} v' + \frac{\partial \pi'}{\partial Z} w' \right] dZ \]

is pressure gradient force, and \( \tau_{MKE} \) is the dissipation time of MKE.

The CKE is primarily generated by convective updrafts and downdrafts, and once generated, CKE dissipates at a specified rate \([O(1h)]\). CKE is a prognostic quantity used in the Randall and Pan (1993) scheme, and an extension of that scheme to a broad range of grid spacings in the host model has recently been developed by Rafkin (1996). The MKE equation has two fundamental sources. Some of the CKE generated by the deepest convective clouds is converted to MKE. If sufficient convection is maintained to generate a certain threshold in MKE, then the MCS scheme is activated. Once activated, the second source accounts for further MKE generation due to mesoscale heating and water loading, pressure gradient forces, and shear production within the mesoscale circulation branches of MCSs. The sink of MKE is defined as a simple dissipation term with a dissipation that is slower than ordinary deep convection \([O(5h)]\).

The threshold value of MKE used to activate the MCS scheme is determined from the cloud work function (similar to CAPE), as Lord (1982) pointed out that the cloud work function is a generalized measure of moist convective instability. The cloud base mass flux \( M_B \) is related to CKE by \( CKE = \alpha \cdot M_B^2 \) as first proposed by Arakawa and Xu (1990). The parameter \( \alpha \) depends on the cloud fractional area, the depth of the clouds, and the fraction of the total kinetic energy that comes from the vertical component of the velocity, and is set to a constant for now. Considering a steady state, the CKE equation becomes

\[ A = \frac{\sqrt{CKE \cdot \alpha}}{\tau_{CKE}}. \]  

Given a CKE value of 4000 J m\(^{-2}\), \( \alpha = 5 \times 10^8 \) m\(^4\) kg\(^{-1}\), and \( \tau_{CKE} = 600 \) s, the cloud work function has a value of \( A = 2357 \) J kg\(^{-1}\). Convection persisting for a few hours in an environment with CAPE exceeding 2000 J kg\(^{-1}\) is likely to organize and develop into an MCS. Therefore we have tested values of this order, such that when MKE exceeds 3000 or
4000 J m$^{-2}$ the MCS heating, moistening, and momentum parameterization is activated. If MKE recedes below the given threshold value, the MCS scheme will be turned off. Once the MCS scheme is activated, additional MKE sources will further modify the MKE evolution.

An example of parameterized CKE and MKE evolution, based on a single-column model application of the scheme for a TOGA COARE case is shown in Fig. 2. It shows that CKE reaches a maximum in 6 h and then decreases as environmental CAPE is consumed. The lower MKE curve is due to the auto-conversion and dissipation terms in (2), while the curve MKEMOD includes the additional terms after activation of the MCS scheme.

Figure 2: Evolution of parameterized CKE and MKE in a single-column model, based on a tropical MCS case. The lower MKE curve is due to the auto-conversion and dissipation terms in (2), while the curve MKEMOD includes the additional terms after activation of the MCS scheme.

reaches a maximum in 6 h and then decreases as environmental CAPE is consumed. The lower MKE curve is due to the auto-conversion and dissipation terms in (2). Its lagged development and dissipation reflect the typical time-dependence of the mesoscale flow branches relative
to the generating convection in MCSs, as seen in our explicit simulations (Fig. 1) and as
generalized by Zipser (1982). Above the activation threshold of MKE, the additional source
terms in (2) begin producing self-reinforcing contributions to the MCS lifecycle. The upper
MKE curve includes additional sources due to thermal buoyancy and water loading buoyancy.

The two orders of magnitude smaller values of CKE and MKE in Fig. 2 than in Fig. 1 are
due to the assumption in the Arakawa-Schubert scheme that convection occupies a small
fractional area in a GCM grid column, whereas the simulated MCS in Fig. 1 essentially filled
the entire fine grid.

We are also considering normalizing the magnitudes of the MCS heating, moistening, and
momentum transport rates to the magnitude of MKE above the threshold values, to account
for the greater role by the stratiform region in larger MCSs. A major issue we have faced is
whether there is a universal threshold value of MKE for defining an MCS. Our basic research
on MCSs suggests that there probably is not and that the threshold value will at the very
least vary with latitude. This is because we associate the development of the mesoscale flow
branches of an MCS to the degree of balance of the system (Cotton et al., 1989; Hertenstein et
al., 1994; Olsson and Cotton, 1997a,b). The more balanced is the MCS, the more systematic
are the mesoscale ascending and descending flow branches and their associated heating and
moistening rates.

An important feature of this MCS parameterization is that it attempts to replicate effects
which are scale dependent on the size of the system, as reviewed in Cotton et al. (1995).
That is, given adequate large-scale forcing, large production rates of CKE lead to significant
production of MKE. This is consistent with the initial upscale evolution of strong convection
into an incipient organized MCS as described by McAnelly et al. (1997). In turn, MKE
drives the parameterized, self-reinforcing effects of the slantwise mesoscale flow branches.
For instance, the deep convergence and mesoscale ascent in mature MCSs produce a deeper
source layer of moisture and increases precipitation efficiency, compared to ordinary deep
convection (Cotton et al., 1995). In addition, the mesoscale ascent helps produce a larger
and longer-lasting cirrus canopy that is colder, more reflective and optically thicker than in smaller, less organized deep convective systems (Machado and Rossow, 1993).

Better understanding of the behavior of CKE and MKE is apparently the key to guide us to complete the MCS parameterization component. Data collected from the Southern Great Plains ARM CART and from TOGA COARE were analyzed to identify a wide range of MCS cases and ordinary deep convective cases to finalize the MCS scheme. We began our testing with the data collected from TOGA COARE field experiment since it covers a concentrated four month period and the data are more complete.

1.3 Testing and evaluation

A single-column model (SCM) was used to test the MCS trigger mechanism and the effect of the MCS scheme on the large-scale temperature and moisture to the extent possible. The single column model consists of the Randall and Pan (1993) cumulus parameterization scheme coupled to our MCS parameterization scheme. The SCM was driven by observations of soundings and run forward for a period of 12 to 48 hours. Local tendencies due to large-scale vertical advection are also included, based on prescribed large-scale forcing that initially equals the observed precursor conditions and then diminishes to zero over a several hour period.

Cases were selected for testing based on their temporal minimum in IR temperature, averaged over the Intensive Flux Array (IFA). Classes 1, 2 and 3 achieved average IR temperatures colder than 230K, between 250K and 230K, and between 270K and 250K, respectively; Fig. 3a shows the composite evolution of IFA-averaged IR temperature for the three classes. Figure 3b,c shows a more detailed composite evolution for classes 1 and 3, respectively, based on IRA-fractional areas colder than several IR thresholds. As can be seen, class 1 had larger, colder, and longer-lasting cloud tops, and consists of cases with strong MCSs. Class 3 consisted of deep convection that was less organized, and class 2 was intermediate. The composite Q1 and Q2 budgets of the three classes (Fig. 4), derived from observational data, confirms the hierarchy of the classes in terms of their large-scale impacts. The strong
Figure 3: Composite IR lifecycles for convective systems in TOGA COARE. (a) IFA-averaged IR temperature for classes 1, 2 and 3. Each class consists of 9 cases, and the minimum for each case is aligned at hour 36 in the composite. (b)(c) Fractional area with IR temperatures colder than several thresholds, for classes 1 and 3, respectively.
36-h lifecycle of class 1 in terms of apparent heat source is shown in Fig. 4a, and Fig. 4b,c shows the 36-h average of Q1 and Q2, respectively, for all three classes.

SCM testing of cases in these different classes revealed the importance of the MCS scheme to producing parameterized heating and moistening profiles that were consistent with the Q1 and Q2 budgets. Figure 5a shows the 24-h average heating in a class 1 case due to the convective scheme, the MCS component and total heating. A significant MCS component contributes to heating in the mid-upper troposphere that is comparable to the convective maximum heating, and also contributes to significant low-mid tropospheric cooling. A class 2 case (Fig. 5b) shows a relatively minor contribution due to the MCS scheme, while in the class 3 case (Fig. 5c) the MCS scheme never became activated. The MCS scheme contributed to the total Q2 budget (not shown) in a similar manner according to class.

The parameterized surface precipitation from the SCM runs for different classes similarly revealed that the class 1 cases were stronger, longer lasting and greater impacted by the MCS scheme. Figure 6a shows the evolution of hourly rainfall rates for a class 1 case, and shows a significant stratiform component due to the MCS scheme. A class 2 case (Fig. 6b) shows that it produces less rainfall, with a smaller proportion due to the MCS scheme. Table 1 shows the 24-h total rainfall amounts due to the convective and MCS components of the parameterization. The class 3 case, with little MCS organization, produces only about 25% as much precipitation as the class 1 case, and no rainfall due to the MCS component. The proportion of mesoscale rain in the class 1 case is comparable with observationally derived estimates of stratiform rainfall in MCSs (Houze, 1977).

In summary, our testing showed that the MCS scheme we developed is able to distinguish the strong MCS activities from non-MCSs. Our objective has been to achieve parameterized CKE and MKE evolution, along with their associated effects on the large-scale environment, which mirror the observed degree and effects of deep convection and mesoscale flow branches across the entire scale spectrum of convective systems. Our initial development of the MCS parameterization has shown promise in meeting this objective.
Figure 4: (a) Composite evolution of Q1 profile for class 1. (b) 36-h average Q1 profile, centered at composite hour 36, for classes 1, 2 and 3. (c) Same as (b) except for Q2.
Figure 5: 24-h average Q1 heating in a SCM for a class 1, 2 and 3 case (a, b and c, respectively). Convective (solid), MCS component (short dashed), and total heating (long dashed).
Figure 6: Hourly precipitation rates for a class 1 case (a) and a class 2 case (b). Total heights of bars give total rain rate, while shorter bold bars give stratiform contribution due to the MCS scheme.
2 Adaptive-grid Single-column model for parameterization of middle and high clouds (cirrus) generated by active MCSs and cumulonimbi outflow

Among the feedbacks of MCS to the general circulation is the increase of upper level moisture that remains after the MCS has decayed or propagated out of the region. Therefore, to parameterize the complete impact of MCS on the larger scales, the GCM must adequately model upper level clouds. To obtain the vertical and temporal resolution necessary for cloud-scale physics, an adaptive-grid single-column cloud model has been created to nest in time and space in a localized area with limited frequency in a large-scale model. Nebuda (1996) examined the feasibility of the approach by using the existing physics in RAMS at that time. The three basic components of the nested 1D cloud model are microphysics, turbulence, and radiation.

The structure of the nested cloud model includes the three components of microphysics, radiation, and turbulence to capture the essential features of an upper-level cloud. The microphysical component (Walko et al., 1995) of the nested model requires the host model to provide the mass and concentration of liquid and ice water. The nested model uses this information to predict the seven water categories of total water, water vapor, rain,
small ice (pristine ice), large ice (snow), and aggregates. Cloud water is computed as a residual of the other water categories. By increasing the two hydrometeor species in the host model to five in the nested model, a bimodal ice spectra of cloud ice is possible along with improvements in the modeling of riming, collection, and variable fall speeds. A turbulence model (Weissbluth and Cotton, 1993) which predicts the vertical velocity variance, $(w'w')$, is applied to model the mixing created by the radiative destabilization. The broadband radiation model (Chen and Cotton, 1983), which distinguishes liquid water from ice, can create the maximum heating/cooling rates at the correct location due to the increased vertical resolution of the nested model. Using these components, the adaptive, nested cloud model provides microphysical information which can be used in the host radiation scheme as well as improve budgets of heat and water.

To determine the resolution necessary to model upper-level clouds, RAMS was used in a 1D format to simulate several cirrus clouds at various altitudes with a range of vertical resolution and timesteps. Simulations were also computed for both five and two hydrometeor species to determine the impact of microphysical complexity on the results. These sensitivity tests revealed that the results were dependent on both the timestep and vertical resolution. When the timestep was much longer than 180 seconds, the microphysical scheme would over-predict the amount of nucleated ice in one timestep which would significantly dictate the following behavior of the cloud ice. A large timestep such as those found typically in large-scale models also failed to correctly simulate melting, evaporation, sublimation, and sedimentation. Poor vertical resolution would not capture the smaller details of the cloud species’ vertical profiles. A vertical spacing on the order of 100 m to 200 m was necessary to capture the physical processes of collection and sedimentation. When the number of cloud species is limited to the general categories of liquid and ice, the deepening and precipitation trails created by the sedimentation of larger ice does not occur. As a result, the cloud will exist in a shallower layer and have higher ice water mixing ratios. This fact will alter the computed radiative heating rates changing the cloud feedback to the general circulation. The sensitivity studies indicate that a nested cloud parameterization is necessary to obtain the
resolution and accuracy of the upper-level cloud feedback while maintaining the affordability of the large-scale model.

As part of his M.S. thesis Chris Golaz has developed a stand-alone version of an adaptive-grid single column model. The model uses different types of turbulence closure schemes. They include two 1.5 order and one 2.5 order schemes. Lower order schemes include an $e - l$ closure based on Bechtold et al. (1992) and an $e - \epsilon$ closure based on Langland and Liou (1996) and Dyunkeke and Driedonks (1987). Both use a prognostic equation for the turbulent kinetic energy coupled either with a mixing length diagnosis scheme for $e - l$ or an additional prognostic equation for the turbulence kinetic energy dissipation rate $\epsilon$ for $e - \epsilon$. The higher order closure is based on Galperin et al. (1988).

Several options are available for the computation of cloud water and fractional cloudiness. The simplest is an all-or-nothing cloudiness scheme which diagnoses cloud water as a residual between the total mixing ratio and the saturation mixing ratio. Alternatively, fractional cloudiness can also be computed using an empirical scheme developed by Ek and Mahrt (1991). Finally, the subgrid-scale condensation scheme from Sommeria and Deardorff (1977) and Mellor (1977) has also been implemented. This scheme has the ability to simultaneously predict fractional cloudiness and cloud water mixing ratio.

The single column model has been fully coupled with the microphysical parameterization from RAMS (Walko et al., 1995). This parameterization can include up to eight different categories of water; it is a bulk microphysics scheme that predicts one moment, mixing ratio, for each water category and uses a generalized gamma distribution as basis function for the number concentration distribution. A two-stream radiation module (Harrington, 1997), which interacts with the hydrometeor size distributions in the Walko et al. scheme has also been implemented in the single-column model.

This version of the adaptive grid single-column model is transportable to any host model including GCMs with appropriate interfacial codes.
3 Future Plans

If continuation funding is obtained, our plans are to:

- Further refine and test the MCS initialization scheme using DOE ARM Great Plains and Tropical Western Pacific CART site data.
- Further develop and test the momentum parameterization scheme.
- Test the SCM using ARM CART site data.
- Implement the MCS parameterization in coarse grid spacing versions of RAMS and test the scheme performance in a number of situations, including comparison with several cloud-resolving simulations.

4 References


Arakawa, A and K.-M. Xu, 1990: The macroscopic behavior of simulated cumulus convection and semiprog nostic tests of the Arakawa-Schubert cumulus parameterization. Proc. of
the Indo-U.S. seminar on parameterization of sub-grid scale processes in dynamical models of medium-range prediction and global climate. Pune, India.


Harrington, Jerry Youngblood, 1997: The effects of radiative and microphysical processes on the simulation of warm and cold season Arctic stratus. Ph.D. dissertation, Col-


5 Publications Supported


6 Theses supported
