**PARAMETERIZATION OF CONVECTIVE CLOUDS,
MESOSCALE CONVECTIVE SYSTEMS,
AND CONVECTIVE-GENERATED CIRRUS**

Final Report

for Period September 15, 1990 - October 31, 1993

William R. Cotton, Principal Investigator

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

November 5, 1993

Prepared for

**THE U.S. DEPARTMENT OF ENERGY
ATMOSPHERIC RADIATION MEASUREMENT PROGRAM
AGREEMENT NO. DE-FG02-90ER61066**

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, makes 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.

RECEIVED

NOV 19 1993

OSTI

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, sub-contractors, or their employees, makes any warranty, express or implied, or assumes any legal liability of responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or progress disclosed or represents that its use would not infringe privately-owned rights.

CONTENTS

2

Contents

1 Introduction	3
2 The convective draft parameterization scheme	4
3 Explicit Simulation of MCSs	9
4 The MCS residue parameterization scheme	34
5 References	35
6 Publications, Reports and Conference Presentations	39

Abstract

The overall goal of this research is to develop a scheme to parameterize diabatic heating, moisture/water substance, and momentum transports, and precipitation from mesoscale convective systems (MCSs) for use in general circulation models (GCMs). Our approach is to perform explicit cloud-resolving simulations of MCSs in the spirit of the GEWEX Cloud Systems Study (GCSS), by using the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University (CSU). We then perform statistical analyses (conditional sampling, ensemble-averages, trajectory analyses) of simulated MCSs to assist in fabricating a parameterization scheme, calibrating coefficients, and provide independent tests of the efficacy of the parameterization scheme.

A cloud-resolving simulation of ordinary cumulonimbi forced by sea breeze fronts has been completed. Analysis of this case and comparison with parameterized convection simulations has resulted in a number of refinements in the scheme.

Three three-dimensional, cloud-resolving simulations of MCSs have been completed. Statistical analyses of model-output data are being performed to assist in developing a parameterization scheme of MCSs in general circulation models.

1 Introduction

The overall goal of this research is to develop a scheme to parameterize diabatic heating, moisture/water substance, and momentum transports, and precipitation from mesoscale convective systems (MCSs) for use in general circulation models (GCMs). Our approach is to perform explicit cloud-resolving simulations of MCSs in the spirit of the GEWEX Cloud Systems Study (GCSS), by using the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University (CSU). We then perform statistical analyses (conditional sampling, ensemble-averages, trajectory analyses) of simulated MCSs to assist in fabricating a parameterization scheme, calibrating coefficients, and provide independent tests of the efficacy of the parameterization scheme. The so-developed scheme will then be tested against independent field data sets acquired at ARM CART sites and be exercised in NWP models emulating GCM grid resolutions.

Because we view GCMs as a moving target in terms of grid resolutions, computational speed, and permitted level of sophistication of model physics, we are designing the scheme so that it is modular in structure. In this way a coarse resolution GCM may use all modules of the MCS parameterization scheme, while a GCM with 100 km grid spacing may use half of the modules, while a high-resolution GCM with, say, 50 km grid spacing may only use one or two components of the scheme.

The MCS parameterization scheme under development has the following components:

- (1) A deep convective component that is unique in that it does not force compensating subsidence in its immediate surroundings. It is viewed that the slantwise ascending and descending flow branches comprise a portion of the compensating motions to the convective drafts. Therefore, assigning all compensating motions to weak, cloud-free subsidence would be incorrect. Compensating motions will be considered once all convective and mesoscale flow branches are accounted for in the scheme.
- (2) A fast manifold (unbalanced) mesoscale component that consists of the slantwise ascending and descending flow branches of MCSs. The heating, moistening, momentum transports by the major flow branches is treated as an instantaneous adjustment to the convective heating and environmental shear profiles.
- (3) A slow manifold (balanced) mesoscale component that requires the introduction of some memory of the sub-grid-scale MCS in the host model(e.g., the GCM). In this component we are evaluating if it is feasible to develop a sub-grid-scale potential vorticity (PV) equation that can provide a memory of the existence of the more balanced components of an MCS and be able to communicate to the host model that an MCS has developed and is propagating through the host model grid.
- (4) A small-scale turbulence/radiative/cloud physics component that will simulate the effects of the residue of cloud debris left by the active convection and mesoscale flow branches of the system. This component will respond to radiative/convective interactions within the residue layer, and to the effects of any stratiform precipitation including cirrus crystal fall streaks.

In the following sections we describe our progress in research aimed at these long term, ambitious goals.

2 The convective draft parameterization scheme

The convective draft parameterization scheme builds on the work of Weissbluth (1991) as described by Weissbluth and Cotton (1993). The scheme which we call the 2.5w scheme contains

a small-scale turbulence component and a deep convective draft component. This equation set is similar to the level 2.5 model in the Mellor-Yamada scheme except that vertical velocity variance is treated explicitly rather than TKE, therefore the scheme is called a level 2.5w. This is because we have shown that convective-generated transport is more directly linked to vertical velocity variance than to TKE (Weissbluth and Cotton, 1993). Thus the equation is of the form

$$\frac{\partial}{\partial t} \overline{w'w'} = \text{ADV} + \text{SHRPRD} + \text{BUOPRD} + \text{EDYTRN} + \text{PRS} + \text{DIS}. \quad (1)$$

Here, ADV, SHRPRD, BUOPRD, EDYTRN, PRS and DIS are the mean advection, shear production, buoyant production, eddy transport, pressure diffusion and dissipation of $\overline{w'w'}$, respectively. Furthermore, the buoyancy contributions include the micro-scale vertical buoyancy flux and, if deep convection is indicated, the cumulus buoyancy flux:

$$\text{BUOPRD} = \text{BUOPRD}_m + \text{BUOPRD}_c. \quad (2)$$

The micro-scale buoyancy flux and the shear production terms are calculated through the down-gradient diffusion equations which result from the Level 2.5w closure, and the host model calculates the advective tendencies. The eddy diffusion and pressure diffusion terms are based on the work of Zeman and Lumley (1976) which was originally formulated for a convectively-driven atmospheric boundary layer.

The deep convective component uses a simple one-dimensional cloud model based on a convective adjustment scheme first proposed by Manabe et al. (1965) and investigated by Betts (1986), Bougeault (1985) and others (Weissbluth and Cotton, 1993).

Remembering that the host model is hypothesized to resolve all compensating motions around the parameterized cloud, the draft fluxes, BUOPRD_c are specified as

$$\overline{w'\chi'} = \sigma_{u,d}(W_u - W_e)(\chi_{u,d} - \overline{\chi}) = \sigma_{u,d}w^*(\chi_{u,d} - \overline{\chi}), \quad (3)$$

as first proposed by Arakawa (1969). Because only the cores of the convective drafts are considered, we choose to interpret $\sqrt{\overline{w'w'}}$ as the average convective velocity of the cumulus draft cores. The interpretation of $\overline{w'w'}$ then changes in this scheme as one moves from the boundary layer into the free atmosphere. Aloft, when cumulus convection is diagnosed to be active, $\overline{w'w'}$ represents the

average variance of the draft cores without regard to compensating environmental motions. In the PBL, $\overline{w'w'}$ represents the average variance of all subgrid-scale motions.

These draft-scale fluxes are used in addition to the micro-scale calculated buoyancy fluxes to drive the vertical variance through the buoyancy forcing term in Eq. 1.

The tendencies to the model variables are specified so that the cumulus forcing is

$$\left(\frac{\partial \bar{\chi}}{\partial t}\right)_{\text{cumulus}} = \sigma_{u,d} \left[w^* \frac{\partial \bar{\chi}}{\partial z} + \frac{1}{T} (\chi_{u,d} - \bar{\chi}_e) \right], \quad (4)$$

where $w^* = \sqrt{\overline{w'w'}}$. The second term on the RHS of Eq. 4 is the convective adjustment term where T is the time scale over which convection modifies the environment. This time scale is determined from forcing the moist static energy of the convective tendencies to be zero, i. e.

$$T = \frac{\int_0^{ct} [L(r_{su} - \bar{r}_u) - L(r_{tu} - \bar{r}_t) + C_p(T_u - \bar{T})] \rho dz}{\int_0^{ct} w^* [L \frac{\partial \bar{r}_t}{\partial z} - L \frac{\partial \bar{r}_u}{\partial z} - C_p \frac{\partial \bar{T}}{\partial z}] \rho dz}. \quad (5)$$

There are several interpretations of Eq. 4 which can be made. When cumulus forcing is diagnosed, the first term on the RHS combines with the resolvable advection. Bougeault (1985) then interprets the first term on the RHS as a subsidence term since the resolvable vertical motion in large-scale models is negligible compared to w^* . The second term is then interpreted as the detrainment term. In large scale models, then, the subsidence term prompts warming and drying while the detrainment term prompts warming and moistening.

In mesoscale models, the resolved vertical motion may be comparable to w^* and a different interpretation of the term is needed. In this case, the advection by the resolved motions and the first term on the RHS (now called the compensation term) combine to give near zero net advection which is desirable since the advection of the scalars is now being accomplished by the convective adjustment term. Double counting is then explicitly eliminated since the convective adjustment term wholly handles the updraft core warming and moistening. Furthermore, the continuous behavior of the compensation term as the grid size changes allows this parameterization scheme to be generally applicable on all grid resolutions.

In Eq. 4, either w^* or T could be specified and the remaining coefficient determined from a moist static energy balance. Bougeault specified the convective flux as a function of height and

diagnosed the detrainment time scale. We also feel that forcing w^* to vary as $\sqrt{w'w'}$ is best since it allows a realistic vertical distribution of the compensation term which closely resembles the vertical distribution of the mean vertical motion. If the integral of the vertical gradient of moist static energy is negative, then this forces $T < 0$. We disallow convection under this condition since a negative time scale for convection is clearly unrealistic. Presumably, explicit overturning will occur in the grid column when this condition appears, thus precluding the specification of parameterized convection.

The scheme has been extensively tested against an explicit numerical simulation of deep convection forced by sea breeze fronts along the Florida Peninsula. The specifics of this simulation are described in Hertenstein et al. (1992). This simulation was a three-dimensional extension of the Nicholls et al. (1991) two-dimensional simulation of deep convection along sea-breeze fronts in Florida. The third dimension was large enough to fully capture individual cumulonimbus, yet small enough to avoid excess computational expense, hence our domain resembles a channel. To further reduce computational expense we used the nested-grid capability of RAMS so that the explicit grid (1.5 km horizontal grid spacing) is only located over the convectively-active land areas. Figures 1 and 2 show the grid structure of the channel and a three-dimensional depiction of the simulated clouds, respectively.

Figure 1: Relative sizes and positions of the 4.5 and 1.5 km grids for the Florida simulation with explicitly resolved convection.

During the simulation two modes of convection form, more transient cumulonimbus and a steadier line of cumulonimbus as sea-breeze fronts collide. Comparisons with the parameterization for these two modes provides an even more rigorous test of the scheme. The results of this quantitative test are to appear in a forthcoming paper.

Figure 2: Three-dimensional view of condensate (greater than 0.1 g kg^{-1}) for the fine grid looking from the north, (a) at 1430 local time showing the transient mode of convection, (b) at 1900 local time showing the steady mode of convection.

Quantitative testing of the Level 2.5w parameterization scheme required the development of various diagnostic tools, which allow us to conditionally sample specific regions of transient or more organized deep convection. For example, we can isolate dynamically important quantities for convective updrafts and downdrafts of a specified strength and thus determine their relative importance. These diagnostic tools are also important in the development of other components of the MCS parameterization. Additional development tools include the use of the Lagrangian Particle Dispersion Model (LPDM) with which we can identify forwards and backwards trajectories as well as quantities along the trajectories.

Advantages of using the explicit simulation as a synthetic data base include spatial and temporal coverage of data that is better than observations and the elucidation of physical processes. For example, the equivalent potential temperature of the cloud model updraft was found to be up to ten degrees warmer than the explicit conditionally-sampled updraft during the transient phase. In order to remedy this, a dew point trigger mechanism is proposed so that air within the cloud model is drawn from around a layer where the dew point depression is minimized, rather than from deep within the boundary layer.

3 Explicit Simulation of MCSs

As noted previously, our approach is to perform explicit cloud-resolving simulations of MCSs and then to analyze the model output data to assist us in formulating an MCS parameterization scheme. As a result we have performed three fully three-dimensional simulations of MCSs. They include two mid-latitude cases observed during PRE-STORM and a tropical case observed during EMEX.

We have used RAMS to simulate EMEX9, a tropical convective system that occurred on 2-3 February 1987, during the ninth flight mission of EMEX (Equatorial Monsoon Experiment). The 1987 Australian monsoon season and the EMEX precipitation systems have been studied extensively (Gunn et al., 1989; Hendon et al., 1989; Keenan et al., 1989; Mapes and Houze, 1992; Mapes and Houze, 1993; Gamache et al., 1987; Bograd, 1989; Webster and Houze, 1991; Mapes, 1993; and Houze et al., 1988).

The prevailing synoptic feature at the time of EMEX9 was a deep westerly monsoon trough extending from 500 mb to the surface which oriented itself across Arnhem Land of northern Australia and into New Guinea. The monsoon trough provided a primary lifting mechanism for EMEX9. A composite sounding of the EMEX9 environment, which was assembled using all available aircraft and synoptic data, has a CAPE of 1484 J kg^{-1} and a bulk Richardson number of 51, typical of multicellular convection. EMEX9 propagated northeastward along the monsoon trough at a speed of approximately 12 ms^{-1} and lasted for about 12 hours.

Infrared satellite imagery provides an overview of EMEX9's life cycle (Figure 3). EMEX9 developed off the coast of Australia along the mid-level monsoon trough before 1530 UTC (0100 LST) on 2 February 1987. By 1730 UTC (0300 LST) EMEX9 was fully developed and had moved out into the Arafura Sea. At 2030 UTC (0600 LST) EMEX9 merged with another cluster that, after forming in the Gulf of Carpentaria approached EMEX9 from the southeast. At 2330 UTC (0900 LST) the newly merged system had its minimum recorded cloud top temperature (about -70° C) which, according to the 2300 UTC Darwin sounding corresponds to a cloud top at about 150 mb (15 km). By 0230 UTC (1200 LST) EMEX9 had slowly decayed as it approached New Guinea.

The model setup for this three-dimensional simulation is as follows. We initialize RAMS with the AMEX FGGE 3B data set (1.25° grid spacing and 11 vertical levels) at 1100 UTC (2130 LST) 2 February 1987. The model's horizontal grid spacing is 24 km on Grid #1, 6 km on Grid #2, and 1.5 km on Grid #3 (Figure 4). We use 33 vertical levels, stretched from a spacing of 100 m near the surface to 1000 m at the model top, which is at about 20 km. During the first hour of the simulation, we activate the coarsest grid only. After that hour, we activate the two finer grids. The timesteps are 24, 8, and 4 seconds for Grids #1, #2, and #3, respectively. We use the Level 2.5w convective parameterization scheme on Grids #1 and #2 for the entire simulation. On Grid #3 it is activated for 30 minutes in order to initiate convection and is left off for the remainder of the simulation. We explicitly simulate the convection in EMEX9 for 3.5 hours, between 1330 and 1700 UTC — about a third of the lifetime of the system.

Figure 3: Infrared satellite images at (a) 1530 UTC, 2 February 1987, (b) 1730 UTC, 2 February 1987, (c) 2030 UTC, 2 February 1987, (d) 2330 UTC, 2 February 1987, and (e) 0230 UTC, 3 February 1987.

Figure 4: Grid setup for the EMEX9 simulation. Grid spacing is 24, 6, and 1.5 km on the three grids.

The RAMS simulation captures many of the key features of EMEX9. For instance, the simulation results support the suspicion that EMEX9 was originally forced along a land breeze convergence line just north of Australia's Top End peninsula. The simulation accurately reproduced EMEX9's northeastward propagation along the monsoon trough, toward the south coast of New Guinea (Figure 5).

Vertical velocity fields on the fine grid reveal the detailed horizontal structure of the convective elements within EMEX9. Figure 6 shows the 500 mb vertical velocity at 1530, 1545, and 1600 UTC. Three elongated — approximately 30 km in length — areas of convection are present. These convective cells are arranged along a west-northwest to east-southeast line and are propagating towards the northeast. Maximum vertical velocities in the convective cells are $10\text{--}12\text{ ms}^{-1}$. Examination of similar plots at previous times reveals that new cell development is occurring ahead of older convective cells at distances of up to 20 km.

Figure 5: Simulated convective precipitation rate (mmh^{-1}) on Grid #1 at (a) 1330 UTC, 2 February 1987, (b) 1500 UTC, 2 February 1987.

Figure 6: Simulated 500 mb vertical velocity (ms^{-1}) on Grid #3 at (a) 1530 UTC, 2 February 1987, (b) 1545 UTC, 2 February 1987, (c) 1600 UTC, 2 February 1987.

A vertical cross-section through the one of the convective elements reveals the vertical structure of both the convective and stratiform regions (Figure 7). The convective updrafts are tilted rearward, as observed by the airborne Doppler radar on the P3 (Webster and Houze, 1991). The

Figure 7: North-south cross section through the westernmost convective element of Fig. 6, showing simulated vertical velocity (ms^{-1}) at 1530 UTC, 2 February 1987.

height of the updraft top is simulated to be near 14.5 km, also in agreement with observations. A stratiform anvil stretches both ahead of and behind the convective line. Simulated cloud base in the anvil region is between 4.5 and 5 km (agreeing with the 4.8 km base observed by the P3); simulated cloud top is at about 14.5 km (as compared to roughly 15 km according to infrared satellite imagery). Vertical velocities in the anvil region are generally upward above the 6.5 km level. Note that this level is about 2 km above the melting level, in agreement with the P3 observations and as observed previously in other tropical MCSs (e.g., Houze, 1982). Peak mesoscale updraft magnitudes are about $2.5 ms^{-1}$ at 10 km. Vertical velocities are mostly downward below the melting level, and are generally weaker than $0.5 ms^{-1}$. A three-dimensional plot of the $0.5 gkg^{-1}$ surface

of condensate mixing ratio at 1530 UTC (Figure 8), shows the true extent of the convective towers and the overhanging anvil, which extends both ahead of and behind the convection.

Figure 8: Three-dimensional plot of the 0.5 g kg^{-1} condensate surface on Grid #3 at 1530 UTC. Perspective is from the northeast.

Conditional sampling our fine grid is based on the criterion that any grid point with a rain mixing ratio of at least 0.5 g kg^{-1} at the lowest model level is convective. If this rain mixing ratio is greater than 0 but less than 0.5 kg^{-1} the grid point is stratiform.

Figures 9a-b show time series of vertical velocity versus height evaluated in the two conditionally sampled regions between 1430 and 1600 UTC. For the convective region, the mean vertical velocity is upward just about everywhere. The level of the maximum upward velocity varies between 5 and 11 km, and vertical velocity has a peak value which pulses between 0.9 and 1.2 m s^{-1} in this 90 minute period. In the stratiform region, vertical velocities are initially upward everywhere, before downward motion initially appears at 4 km, and eventually dominates between 1 and 7 km (the freezing level is at about 5.5 km). Examination of the mean vertical pressure gradient force and buoyancy force within the mesoscale downdraft shows that the pressure gradient dominates the descent, and in fact, in the latter half of the time series, air below the melting level is actually positively buoyant. Turning to the upper troposphere, the mean vertical velocity is positive throughout

Figure 9: Simulated vertical velocity (ms^{-1}) between 1430 UTC and 1600 UTC for (a) convective and (b) stratiform regions of Grid #3.

the 90 minute period, with a maximum mean value at about 11 km which pulses between 0.2 and 0.4 ms^{-1} . In the non-raining region, mean vertical velocities are generally downward below 12 km.

We have also evaluated divergence in the two conditionally sampled regions. Figure 10a shows a time series of horizontal divergence versus height evaluated in the convective regions. The mean divergence time series for the convective region shows the familiar pattern — strong low-level convergence (maximum amplitude at about 1 km, but extending as high as 9 km) and strong divergence in the upper troposphere (maximum amplitude at various altitudes between 9 and 14 km). Initially, there is an elevated convergence maximum between 4 and 5 km which is almost as large as the near-surface convergence. Divergence fluctuates wildly just above this level — 30 minutes later there is a *divergence* maximum near 5.5 km (the melting level). Mapes and Houze (1993), who presented Doppler-derived vertical profiles of horizontal divergence for EMEX systems, observed both of these features in convective regions — 1) an elevated convergence maximum at 4 km or so, and 2) a relative maximum in standard deviation of divergence near the melting level. Mapes (1993) argues that an elevated convergence maximum is significant because it promotes upward displacements at low levels in the nearby atmosphere, thereby favoring additional convection. Mapes and Houze attributed the maximum in standard deviation of divergence near the freezing level to fluctuations in the presence and strength of an isothermal layer often found there. Towards the end of the time series in Figure 10a, when the downdraft outflows overcome the updraft inflows, there is a thin layer of surface divergence.

Figure 10b shows a time series of horizontal divergence versus height evaluated in the stratiform regions of EMEX9. The zero divergence line gradually rises with time, from about 3.5 km to 5.5 km, with divergence below (peaking at about 1 km) and convergence above (peaking at between 8 and 10 km and extending up to 11-12 km). Divergence dominates between 11 and 15 km. This pattern of convergence in the middle troposphere sandwiched by divergence below and above is common to the stratiform regions of most tropical MCSs that have been observed (Houze, 1989).

Lagrangian particle dispersion releases (Figure 11) show 90-minute system-relative trajectories for particles that the LPDM releases at 1 km. In each case, the LPDM releases one particle from each of 81 evenly spaced horizontal locations on Grid #3 at 1430 UTC. We track each of these

Figure 10: Simulated divergence (s^{-1}) between 1430 UTC and 1600 UTC for (a) convective and (b) stratiform regions of Grid #3.

Figure 11: System-relative trajectories of particles released at an altitude of 1 km. In Grid #3, 81 evenly-spaced particles are released at 1430 UTC. The four perspectives of Grid #3 are from (a) the northeast, (b) the top, (c) the east, and (d) the north. Tick marks along the horizontal axes are at 1.5 km intervals (the grid spacing on Grid #3). Tick marks along the vertical axis are at 1 km intervals, from the surface to 16 km.

81 particles for 90 minutes. Particles released at 1 km move in a front-to-rear direction. Two vertical branches are evident — one on the west-central part of the grid in which particles travel in a front-to-rear slantwise fashion from 1 km to as high as 7 km, and another in the south-central part of the grid in which particles begin their paths in a front-to-rear direction before reversing direction once they get to about 4 km. Particles originating at 7 km (not shown) generally move from the west towards the east. In the southwest part of the grid, however, there is a flow branch towards the southeast in which particles gradually climb to altitudes of up to 14 km. Comparison

with the plot of particles released at 1 km shows this flow branch to essentially be a continuation of the slantwise branch originating at 1 km.

We are able to compute the ambient value of a number of quantities along a particle's trajectory. For illustration, we will show values of the buoyancy term and the vertical pressure gradient term in the vertical equation of motion along a representative front-to-rear system-relative trajectory (Figure 12). Figure 13 shows the magnitude of the buoyancy force (proportional to the deviation

Figure 12: System-relative trajectory of a particle released at 1 km. This trajectory ascends from the front to the rear of EMEX9. The perspective views are as in Fig. 11.

of potential temperature from a mesoscale mean) and vertical pressure gradient force (proportional to the vertical gradient in pressure perturbation) along this trajectory. A maximum in the vertical pressure gradient force appears just as the particle begins its ascent, about 40 minutes after the particle's release. The particle is near neutral buoyancy at this time, indicating that the ascent is

Figure 13: Values of a) vertical pressure gradient force (ms^{-2}), and b) buoyancy force (ms^{-2}) along the trajectory depicted in Fig. 12.

dynamically forced, initially. We will use this capability of evaluating quantities along a trajectory to test the validity of conservation equations for system-relative flow branches in mesoscale convective systems (e.g., Moncrieff, 1989). If the conservation equations hold, we may be able (with the help of the LPDM) to employ the theory of Moncrieff (1992) for a parameterization of the fluxes of mass and momentum by mesoscale convective systems.

We have also used the LPDM to estimate the rate at which EMEX9 removes air from the boundary layer. To do this, we release 4000 particles in the fine grid. These particles are released from 10 evenly-spaced vertical levels (400 per level) between the surface and 1 km over the fine

grid. We run the LPDM for 90 minutes, between 1430 and 1600 UTC. We find that during this 90 minute period, 32 percent of the particles are removed from the boundary layer. Assuming that this also means that 32 percent of the boundary layer air is removed, we infer that approximately 6.72×10^{12} kg of air are removed from the fine grid's boundary layer between 1430 and 1600 UTC, or 1.24 billion kilograms per second!

We have performed a simulation of a squall line which occurred on 10-11 June 1985 during the PRESTORM field study. For our purposes, this squall line was interesting in that it represents an example of a strongly forced, baroclinic MCS. We also chose this squall line because it is one of the most thoroughly studied mesoscale convective systems (MCS) on record, hence we have a good basis for model verification. Extensive observational studies have been performed (e.g., Johnson and Hamilton, 1988; Rutledge et al., 1988; Rutledge and MacGorman, 1988; Johnson et al., 1990; Gallus and Johnson, 1991, 1992; Biggerstaff and Houze, 1991a,b). These include examination of precipitation, pressure, and flow fields, using sounding and radar data, and budget studies of heat, moisture, and momentum. Beside the numerical study of Zhang et al. (1989), Zhang and Gao (1989) used model output for an analysis of flow fields, surface pressure perturbations and precipitation, while Gao et al. (1990) present a momentum budget study for this case. More recently, Tao et al. (1993), used a two-dimensional cloud model to study heat, moisture, and water budgets for this case and compared those results to a modelled tropical squall line.

To our knowledge, no three-dimensional simulations have been performed of an observed system with domains large enough to include large-scale dynamics, yet with grid spacings fine enough to explicitly resolve convection. The reasons for this are: 1. a large domain with fine enough grid spacing to resolve convection is computationally not feasible, and 2. until very recently a parameterization scheme which could be used for grid spacings between about 5 and 20 km did not exist. The development of the Level 2.5w cumulus parameterization has made it possible to use the scheme on three nested grids (80, 20, and 6.66 km) and finally to nest down to a fourth 2.22 km grid in which only a bulk microphysical parameterization is used. The configuration of the grid structure used is shown in Figure 14a,b.

Figure 14: Location and sizes of the grids for the four-nested-grid simulation of the 10-11 June 1985 MCS. (a) The 80, 20, and 6.66 km grid (b) The 20, 6.66, and 2.22 km.

We first ran the simulation on the 80 km grid alone using the Level 2.5w parameterization scheme. The simulation was started at 1200 UTC 10 June using standard observations (i.e., ECMWF, rawinsonde, and surface data) and was run for 24 hours. By 2200 UTC the convective system had formed in southeast Colorado and by 0000 UTC 11 June it expanded and moved into the PRESTORM network. Over the next several hours the system continued to propagate towards the southeast through primarily Oklahoma, before beginning to weaken around 0500 UTC. After 0600 UTC, the system continues to weaken before dissipating during the evening hours. Even on this coarse grid, the system's evolution and structure were captured very well. Our major criticism is that the system's initiation occurred somewhat too far northwest of where the observed system first fired. Thus, throughout the simulation the simulated squall line was about an hour behind (i.e., toward the northwest) the observed squall line.

Encouraged by our results on the 80 km grid, we activated the 20 km grid at 0000 UTC on 11 June. Our goals with the additional grid were: 1. to better capture the structure and evolution of the squall line, 2. examine some of the observed flow features, e.g., the rear inflow, and 3. test the Level 2.5w convective parameterization scheme with an intermediate grid spacing. Results from the 20 km grid provided guidance for the timing and location of the finer grids. At 0400 UTC, we activated the 6.66 and 2.2 km grids and ran these for one hour, with the Level 2.5w parameterization used on all but the finest grid.

The model configuration for the four-nested-grid simulation was set up based on our experience with earlier simulations using two grids. Our goal was to capture the system with the finest nests during the mature stage of the squall line, so that both the convective line and stratiform regions could be captured. The simulation with four grids is computationally very expensive (each coarse-grid 90 second timestep required about 8000 CPU seconds on an IBM RISC-6000 workstation) and was first run for one hour. During this time the system is in its mature stage, in which the stratiform precipitating region is increasing in size. We have recently completed another 30 minutes of simulation. In this additional time, the squall line starts to transition from a mature system to the beginning of its dissipating stage. For this extension of the simulation we wrote out model

output at high temporal resolutions (every three minutes) so that we can better understand the nature of the leading convective line updrafts.

Figure 15 shows the structure of the system from four-grid simulation at 0500 UTC. All figures are for the 2.22 km grid only. Condensate mixing ratio greater than 0.1 g kg^{-1} is shown with a view from the southeast. From this perspective, the storm is approaching the viewer. Figure 16 again shows condensate mixing ratio at the same time, however now the view is from the north. From this perspective the convective line and trailing stratiform region are seen. Note the slope of the stratiform cloud, indicating the eroding effects of the dry rear-inflow jet. Also seen is some new weak convection that was observed to the rear of the system. Figures 17 and 18 show vertical velocities greater than 5 ms^{-1} , with the view from the northeast. At 0415 UTC (Figure 17) the convective line dominates but by 0500 UTC (Figure 18) it has weakened and the remnants of some decaying cells can be seen. Some of the detail of the convective line can be seen by a horizontal slice through the domain at about 5 km (Figure 19). The main convective updraft and downdraft as well as decaying convective cells ahead of the mesoscale updraft (weaker vertical velocities to the northwest) are evident.

An explicit simulation of the 3-4 June 1985 PRE-STORM MCS using 4 nested grids having resolutions of 80, 20, 5 and 1.7 km has also been performed. The simulated storm was the first of four which traversed the PRE-STORM network. Several attempts at obtaining the observed system included moving the fine grid to the observed genesis region and using heat and moisture bubbles to initiate convection. However, only stratus clouds formed on the finest grid. The successful simulation began with a forcing function on the finest grid in the Texas panhandle. Sustained convection was finally achieved, and MCS organization was obtained as the finest grid moved into the observed genesis region. The initial and final grid 4 positions are shown in Figure 20.

Shown in Figure 21a-h is the evolution of vertical velocity at 1.5 km above the surface at selected times. In Figure 21a, the vertical velocity field indicates remnants of the initial bubble forcing function. The memory of this forcing soon disappears and the evolution of the system at low levels is shown hourly starting at 1700 UTC. The system first evolves into a linear system, and then an interesting hook, shown best in Figure 21e, appears in the southern part of the system. After the

Figure 15: Three-dimensional view of condensate (greater than 0.1 g kg^{-1}) for the 2.22 km grid at 0500 UTC. The view is from the southeast.

Figure 16: Three-dimensional view of condensate (greater than 0.1 g kg^{-1}) for the 2.22 km grid at 0500 UTC. The view is from the north.

Figure 17: Three-dimensional view of vertical velocity (greater than 5 ms^{-1}) for the 2.22 km grid at 0415 UTC. The view is from the northeast.

Figure 18: Three-dimensional view of vertical velocity (greater than 5 ms^{-1}) for the 2.22 km grid at 0500 UTC. The view is from the northeast.

Figure 19: Section through the 2.22 km grid at 5.2 km and 0500 UTC showing vertical velocities. Solid contours are positive (upward) values and dashed contours are negative (downward) values, with a contour interval of 0.5 m s^{-1} .

southern part of the system is dominant for several hours, the system once again reverts to a loosely linear organization.

The condensate mixing ratios at 10.5 km are shown in Figure 22a-f and correspond to the times 1800–2200 UTC on Figure 21c-h. Even though the simulated cloud shield is circular, as observed by satellite, the cell alignment is linear, except from 1930 to 2100 UTC. This linear structure also is in agreement with radar observations.

Finally, the longitudinal wind speed is shown in Figure 23. Several simulated features agree well with observations of classical MCSs, including a strong front-to-rear updraft and a weak downward-sloping rear-to-front downdraft mesoscale downdraft. Work is continuing in identifying the mesoscale characteristics of the MCS so that the convective adjustment scheme can be extended to represent these processes and statistical analysis of the explicitly simulated data can be accomplished.

Figure 20: Initial and final positions of the 5 km and 1.7 km moving grids for the 3-4 June PRESTORM simulation.

Figure 21: Vertical motion fields at 1.5 km above the surface at selected times. Contour intervals are 1 m s^{-1} unless otherwise noted. a) 1300 UTC with max of 2.6 m s^{-1} and contour interval of 0.2 m s^{-1} , b) 1700 UTC with max of 9 m s^{-1} and contour interval of 0.9 m s^{-1} , c) 1800 UTC with max of 19 m s^{-1} , d) 1900 UTC with max of 14 m s^{-1} , e) 1930 UTC with max of 12 m s^{-1} , f) 2000 UTC with max of 11 m s^{-1} , g) 2100 UTC with max of 16 m s^{-1} , h) 2200 UTC with max of 10 m s^{-1} .

Figure 21: Continued.

Figure 22: Condensate mixing ratio fields at 10.5 km above the surface at selected times. Contour intervals are 1 g kg^{-1} . a) 1800 UTC with max of 19 g kg^{-1} , b) 1900 UTC with max of 16 g kg^{-1} , c) 1930 UTC with max of 17 g kg^{-1} , d) 2000 UTC with max of 19 g kg^{-1} , e) 2100 UTC with max of 19 g kg^{-1} , f) 2200 UTC with max of 17 g kg^{-1} .

Figure 23: Longitudinal cross-section of the longitudinal wind through an intense cell at 1800 UTC. Contour interval is 5 ms^{-1} .

4 The MCS residue parameterization scheme

Once the active MCS has died, water vapor and hydrometeors remain in the middle and upper troposphere. These often result in the formation of cirrus clouds and stratiform cloud decks. These clouds can experience radiative cooling which will result in destabilization of the cloud layer and the production of condensate (e.g., cloud droplets or ice crystals), which may settle out. A parameterization scheme of the MCS residue is being developed which is based upon Weissbluth and Cotton's (1993) small scale turbulence model.

Because GCM vertical grid spacing is typically too coarse to properly resolve the vertical structure of cirrus and middle tropospheric layer clouds, an adaptive, finer resolution grid will be used. The scheme is being designed to mesh with the GCM vertical grid structure and be activated for short bursts of time with finer grid spacing than is permitted in the GCM. The intent would be to activate this adaptive grid in regions where cloud formation is diagnosed to occur at times when the radiation scheme in the GCM is called upon. By interfacing with the radiation calculations, the small scale turbulence scheme could develop resolvable (on the fine adaptive grid) condensate and turbulence transport. In addition, the scheme will interface with the new microphysics model

developed in RAMS (Walko et al., 1994). The goal is for the host model (e.g., the GCM) to predict on cloud and ice crystal mixing ratios as well as the number concentration of ice crystals. All other hydrometeor species will be computed as diagnostic variables similar to Ghan and Easter (1992). The output from the adaptive grid model will be heating and moistening rates that are assumed to be constant until the radiation scheme is called upon again.

At this point only the basic structure of the one-dimensional adaptive grid model has been developed.

5 References

- Arakawa, A., 1969: Parameterization of cumulus convection. Proc. WMO/IUGG Symposium Numerical Weather Prediction. Tokyo, Japan Meteor. Agency, IV, 8, 1-6.
- Betts, A. K., 1986: A new convective adjustment scheme. Part I: Observational and theoretical basis. *Quart. J. Roy. Meteor. Soc.*, 112, 677-691.
- Biggerstaff, M.I. and R.A. Houze, Jr., 1991a: Kinematic and precipitation structure of the 10-11 June 1985 squall line. *Mon. Wea. Rev.*, 119, 3034-3065.
- Biggerstaff, M.I. and R.A. Houze, Jr., 1991b: Midlevel vorticity structure of the 10-11 June 1985 squall line. *Mon. Wea. Rev.*, 119, 3034-3065.
- Bograd, S.J., 1989: The mesoscale structure of precipitation in EMEX cloud clusters. M.S. thesis, University of Washington, 143 pp.
- Bougeault, P., 1985: A simple parameterization of the large-scale effects of cumulus convection. *Mon. Wea. Rev.*, 113, 2108-2121.
- Gallus, W.A., Jr., and R.H. Johnson, 1991: Heat and moisture budgets of an intense midlatitude squall line. *J. Atmos. Sci.*, 48, 122-146.

- Gallus, W.A., Jr., and R.H. Johnson, 1992: The momentum budget of an intense midlatitude squall line. *J. Atmos. Sci.*, **49**, 422-450.
- Gamache, J.F., F. Marks, Jr., and R.W. Burpee, 1987: EMEX data report: The Equatorial Mesoscale Experiment. AOML/HRD Report, National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division, Miami.
- Gao, K., D.-L. Zhang, M.W. Moncrieff, and H.-R. Cho, 1990: Mesoscale momentum budget in a midlatitude squall line: A numerical case study. *Mon. Wea. Rev.*, **118**, 1011-1028.
- Ghan, S., and R.C. Easter, 1992: Computationally efficient approximations to stratiform cloud microphysics parameterization. *Mon. Wea. Rev.*, **120**, 1572-1582.
- Gunn, B.W., J.L. McBride, G.J. Holland, T.D. Keenan, N.E. Davidson, and H.H. Hendon, 1989: The Australian summer monsoon circulation during AMEX Phase II. *Mon. Wea. Rev.*, **117**, 2554-2574.
- Hendon, H.H., N.E. Davidson, and B. Gunn, 1989: Australian summer monsoon onset during AMEX 1987. *Mon. Wea. Rev.*, **117**, 370-390.
- Hertenstein, R.F.A., W.R. Cotton, and M.J. Weissbluth, 1992: Quasi-three-dimensional simulations of deep convection. Preprints, 5th Conf. on Mesoscale Processes, Jan. 6-10, 1992, Atlanta, GA, Amer. Met. Soc.
- Houze, R.A., Jr., 1982: Cloud clusters and large-scale vertical motions in the tropics. *J. Meteor. Soc. Japan*, **60**, 396-410.
- Houze, R.A., Jr., 1989: Observed structure of mesoscale convective systems and implications for large-scale heating. *Quart. J. Roy. Meteor. Soc.*, **115**, 425-461.

- House, R.A., Jr., S.J. Bograd, and B. Mapes, 1988: An atlas of horizontal patterns of radar reflectivity observed during EMEX aircraft missions. Dept. of Atmospheric Sciences, University of Washington.
- Johnson, R.H. and P.J. Hamilton, 1988: The relationship of surface pressure features to the precipitation and airflow structure of an intense midlatitude squall line. *Mon. Wea. Rev.*, **116**, 1444-1472.
- Johnson, R.H., W.A. Gallus Jr. and M.D. Vescio, 1990: Near-tropopause vertical motion within the trailing stratiform region of a midlatitude squall line. *J. Atmos. Sci.*, **47**, 2200-2210.
- Keenan, T.D., J. McBride, G. Holland, N. Davidson, and B. Gunn, 1989: Diurnal variations during the Australian Monsoon Experiment (AMEX) Phase II. *Mon. Wea. Rev.*, **117**, 2535-2552.
- Manabe, S., J. Smagorinsky, and R. F. Strickler, 1965: Simulated climatology of a general circulation model with a hydrologic cycle. *Mon. Wea. Rev.*, **93**, 769-798.
- Mapes, B.E., 1993: Gregarious tropical convection. *J. Atmos. Sci.*, **50**, 2026-2037.
- Mapes, B., and R.A. Houze, Jr., 1992: An integrated view of the 1987 Australian monsoon and its mesoscale convective systems. I: Horizontal structure. *Quart. J. Roy. Meteor. Soc.*, **118**, 927-963.
- Mapes, B., and R.A. Houze, Jr., 1993: An integrated view of the 1987 Australian monsoon and its mesoscale convective systems. II: Vertical structure. *Quart. J. Roy. Meteor. Soc.*, **119**, 733-754.
- Moncrieff, M.W., 1989: A hydrodynamical theory of conservative bounded density currents. *J. Fluid Mech.*, **198**, 177-197.

- Moncrieff, M.W., 1992: Organized convective systems: Archetypal dynamical models, mass and momentum flux theory, and parameterization. *Quart. J. Roy. Meteor. Soc.* , 118 , 819-850.
- Nicholls, M.E., R.A. Pielke, and W.R. Cotton, 1991: A two-dimensional numerical investigation of the interaction between sea breezes and deep convection over the Florida Peninsula. *Mon. Wea. Rev.*, 119, 298-323.
- Rutledge, S.A., R.A. Houze, Jr., M.I. Biggerstaff and T. Matejka, 1988: The Oklahoma-Kansas mesoscale convective system of 10-11 June 1985: Precipitation structure and single-Doppler radar analysis. *Mon. Wea. Rev.*, 116, 1409-1430.
- Rutledge, S.A., and D.R. MacGorman, 1988: Cloud-to-ground lightning activity in the 10-11 June 1985 mesoscale convective system observed during Oklahoma-Kansas PRE-STORM project. *Mon. Wea. Rev.*, 116, 1393-1408.
- Tao, W.-K., J. Simpson, C.-H. Sul, B. Ferrier., S. Lang, J. Scala, M.-D. Chou, and K. Pickering, 1993: Heating, moisture, and water budgets of tropical and midlatitude squall lines: Comparisons and sensitivity to longwave radiation. *J. Atmos. Sci.* , 50 , 673-690.
- Walko, R.L., W.R. Cotton, and J.L. Harrington, 1994: New RAMS cloud microphysics parameterization. Part I: The single moment scheme. Submitted to *Atmos. Res.*
- Webster, P.J., and R.A. Houze, Jr., 1991: The Equatorial Mesoscale Experiment (EMEX): An overview. *Bull. Amer. Meteor. Soc.* , 72 , 1481-1505.
- Weissbluth, M.J., 1991: Convective parameterization in mesoscale models. Ph.D. Dissertation, Atmos. Sci. Paper No. 486, Colorado State University, Dept. of Atmospheric Science, Fort Collins, CO 80523, 211 pp.
- Weissbluth, M.J., and W.R. Cotton, 1993: The representation of convection in mesoscale models. Part I: Scheme fabrication and calibration. *J. Atmos. Sci.* , in press.

Zeman, O. and J.L. Lumley, 1976: Modeling buoyancy driven mixed layers. *J. Atmos. Sci.*, **33**, 1974-1988.

Zhang, D.-L., and K. Gao, 1989: Numerical simulation of an intense squall line during 10-11 June 1985 PRE-STORM. Part II: Rear inflow, surface pressure perturbations and stratiform precipitation. *Mon. Wea. Rev.*, **117**, 2067-2094.

Zhang, D.-L., K. Gao and D.B. Parsons, 1989: Numerical simulation of an intense squall line during 10-11 June 1985 PRE-STORM. Part I: Model verification. *Mon. Wea. Rev.*, **117**, 960-994.

6 Publications, Reports and Conference Presentations

Cotton, W.R., D. Alexander, R. Hertenstein, and M. Wiessbluth, 1994: Analysis techniques using data from explicit simulations of mesoscale convective systems. Proc., 8th Conf. on Atmospheric Radiation, 23-28 January 1994, Nashville, TN.

Cotton, W.R., G. Thompson, and P.W. Mielke, Jr., 1993: Realtime mesoscale prediction on workstations. Accepted *Bull. Amer. Met. Soc.*

Hertenstein, R.F.A., W.R. Cotton, and M.J. Weissbluth, 1992: Quasi-three-dimensional simulations of deep convection. Preprints, 5th Conf. on Mesoscale Processes, Jan. 6-10, 1992, Atlanta, GA, Amer. Met. Soc.

Thompson, G., and W.R. Cotton, 1992: Prototype real-time forecasting of clouds and precipitation using a mesoscale model. Preprints, 11th Conf. on Clouds & Precipitation, 17-21 Aug. 1992, Montreal, Quebec, CANADA.

Weissbluth, M.J., and W.R. Cotton, 1991: A cumulus parameterization scheme designed for nested grid meso- β scale models. Preprints, 9th Conf. on Numerical Weather Prediction, 14-18 Oct 1991, Denver, CO., Amer. Met. Soc.

Weissbluth, M.J., and W.R. Cotton, 1992: An approach for parameterizing mesoscale precipitating systems. Preprints, 5th Conf. on Mesoscale Processes, Jan. 6-10, 1992, Atlanta, GA, Amer. Met. Soc.

Weissbluth, M.J., and W.R. Cotton, 1993: The representation of convection in mesoscale models. Part I: Scheme fabrication and calibration. Accepted *J. Atmos. Sci.*

Weissbluth, M.J., R.F.A. Hertenstein and W.R. Cotton, 1993: Model Output Diagnostics from Explicitly Simulated MCSs. Preprints, Fourth Symposium on Global Change Studies, 17-22 January 1993, Anaheim, CA.

END

DATE
FILMED

5/9/94