Use of ARM Data to Test An Improved Parameterization of Upper Tropospheric Clouds for use in Climate Models

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1. Research accomplishments

Below we list the tasks that were proposed for this project, and describe the current status of each.

Task 1: *Develop, implement, and test an improved parameterization of upper tropospheric cloudiness, with emphasis on cloud formation, maintenance, and destruction (as opposed to cloud optical effects).*

We have developed a new cloud microphysics parameterization for use in climate models (Fowler et al. 1994; Fowler and Randall 1994 a, b). Methods have been devised to compute the cloud optical properties from the predicted microphysical variables. Some results are presented in the discussion of Task 4, below.

The current version of the parameterization does not include subgrid fractional cloudiness. We have developed a new method to determine this quantity, however, and are preparing to test it in the GCM (Xu and Randall 1994 c). The parameterization is currently being tested in the CEM as driven by data from GATE and ASTEX, pending the availability of suitable ARM data. The basic idea of the parameterization can be understood from Fig. 2, which shows results based on ASTEX data, which were collected in a regime dominated by shallow convective clouds with occasional thin stratiform clouds near the top of the convective layer. The figures shows that the cloud amount is poorly predicted by the large-scale average relative humidity (top panel), but is very well predicted by the domain-averaged cloud water mixing ratio (bottom panel). We have obtained similar results with GATE data, which were collected in a regime dominated by deep convection with extensive upper tropospheric stratiform clouds.

Our approach is to parameterize the cloud amount in terms of the predicted large-scale average mixing ratios of cloud water and cloud ice. The method used is discussed later, in the section on "Proposed Research." As discussed there, the predicted cloud amount will be used for both radiative transfer and microphysics, as well as in the parameterization of cloud dynamics.

We expect to perform preliminary tests of a first version of the cloud amount parameterization in the three-dimensional GCM within the next few months.

Task 2: *Conduct tests of the new parameterizations in the SCM, including tests in which the one-dimensional model is "forced" with observations (e.g., of large-scale vertical motion) collected at ARM sites.*

The SCM is essentially a one-dimensional version of the CSU GCM, which is descended from the UCLA GCM, which in turn was developed at UCLA, beginning in the early 1960s,

Figure 1: Plots of cloud amount against relative humidity (top panel) and average cloud water mixing ratio (bottom panel), as predicted by the CEM when driven by ASTEX data.

under the direction of Prof. A. Arakawa, with the participation of his colleagues and students. The model uses a special vertical coordinate in which the planetary boundary layer top is a coordinate surface. It uses the radiation parameterization of Harshvardhan et al. (1987) and the second-generation land-surface parameterization called "SiB 2" (Sellers et al., 1994; Randall et al. 1994). It also employs a version of the Arakawa-Schubert parameterization that makes use of a prognostic cumulus kinetic energy (Randall and Pan 1993), which permits more realistic coupling between convective and stratiform clouds, drastically simplifies the computational algorithm, and significantly improves the computational speed of the GCM. Finally, it includes the new cloud microphysics parameterization mentioned above (Fowler et al. 1995; Fowler and Randall 1994).

The SCM represents a single vertical column in the GCM. The 1-D model includes all of the physical parameterizations of the GCM, including cloud formation. It is not based on a copy of the GCM; instead, the 1-D model is the GCM itself, simply recompiled and with appropriate input data. Provisions have been made to include the effects of prescribed large-scale divergence, pressure-gradient forces, and horizontal advection terms. This makes the 1-D model a very convenient testbed for new parameterizations that are intended for use in the global model. It can also be used to isolate particular physical processes.

We have spent considerable effort in using the SGP rawinsonde data to compute vertical motions, advective tendencies, apparent heat sources and moisture sinks, and the like. These fields can be used to drive the SCM. In our exploratory studies, however, we have used them to investigate the "GCAPE quasiequilibrium hypothesis," which is explained below.

Lorenz (1955, 1978, 1979) developed the concept of the "moist available energy" (MAE) of the atmosphere. This he defined as the portion of non-kinetic energy (NKE) available for conversion to kinetic energy (KE). Randall and Wang (1992) and Wang and Randall (1994) showed that it is possible to consider the component of the MAE that resides in the vertical structure of the atmosphere as a "generalized convective available potential energy" (GCAPE).

We have used data recently made available by the Atmospheric Radiation Measurement (ARM) program to test the GCAPE quasi-equilibrium hypothesis (Arakawa and Schubert, 1974). This hypothesis asserts that cumulus convection "consumes" GCAPE as quickly as it is produced by large-scale (non-convective) forcing such that the convectively active atmosphere remains close to a state of conditional neutrality. The data used in the investigation comes from radiosonde

measurements collected at ARM's Cloud and Radiation Testbed (CART) site located in north-central Oklahoma during Intensive Operation Periods (IOPs) run periodically throughout the year.

Since this is one of the first studies to make extensive use of this data, a further goal was to evaluate the reasonableness of the wind and thermodynamic measurements being produced by the CART site.

In order to evaluate the GCAPE of an atmospheric column, we require time-continuous measurements of atmospheric variables, such as pressure, temperature and moisture, at various levels, from the ground to the tropopause. Additionally, we need to know the horizontal and vertical temperature and moisture advective tendencies if we wish to investigate the production rate of GCAPE due to large-scale processes. Determining these advective tendencies requires further knowledge of the horizontal and vertical wind fields in the column. Consequently, radiosonde data collected from the Southern Great Planes (SGP) CART site during an IOP are ideally suited as input data for the purposes of our investigation. In particular, a period of deep and vigorous convection was essential to our test of the GCAPE hypothesis. Thus, one of the IOPs we chose to focus on was the one conducted from 11-29 April 1994. Example of the radiosonde data used and the results of our investigation are shown below.

As previously mentioned, in addition to fulfilling the need for thermodynamic and wind data, this study dovetailed with the testing phase of the IOP data. Foremost in this testing phase was a check on the proper functioning of the data collecting instruments and data ingest. The CART site itself was responsible for carrying out these checks. Our study was more directly involved at the subsequent stage, in the processing phase of the raw radiosonde data conducted by the ARM Experiment Support Team at Lawrence Livermore National Laboratories (LLNL). Initially, simply consulting weather maps and NWS observations for the time in question served as a means of verifying the plausibility of the raw data. Then, once the data had been satisfactorily given a spot check, the next phase involved further processing to produce the derived fields, such as wind divergence, and moisture and temperature advective tendencies. The check on this phase entailed a verification of the algorithms employed and the mathematics used to construct them. Again, some knowledge of what the atmosphere was doing at the time of the data collection served as a plausibility control. It was also important to have some idea of what reasonable values would be expected for such derived variables as divergences and advective tendencies, given the observed meteorological conditions. Once these issues were addressed to everyone's satisfaction, it was then possible to proceed with the investigative portion of this study.

Shown in Fig. 2 and Fig. 3 are time series plots of temperature and water vapor mixing

Figure 2: 19-day time series plots of temperature from SGP CART radiosonde data, starting at 00 UTC on 11 April 1994 and ending at 21 UTC on 29 April 1994. Contours are in K, and numbers on the abscissa represent multiples of 8 observations spaced 3 hours apart (8 observations per day).

ratio, respectively, taken from the processed April 1994 IOP radiosonde data. Due to some difficulties in telemetry (mostly due to interference with neighboring wind profilers), occasional anomalies and gaps in the data are evident. However, the main synoptic features of the period are captured well by the radiosonde measurements. In particular, the strong temperature gradients associated with the passage of cold fronts on 15 and 27 April (observations 32-40 and 128-136, respectively) in Fig. 2 are in close agreement with the weather summary provided by the Experiment Center (EC). Similarly, notable features in the water vapor mixing ratio plot (Fig. 3), corroborated by the weather summary, include a gradual increase in moisture, advected by strong southerly winds over the CART site from 24-25 April (observations 110-122), as well as the subsequent passage of a dry-line during the day on 25 April (observations 125-128).

Since the GCAPE equilibrium hypothesis implies that the presence of GCAPE is directly related to cumulus convection, the derivation of vertical pressure velocity was also a key component of our study. Fig. 4 shows a time-series plot of vertical pressure velocity for the April IOP, as derived from wind divergence calculated along pressure surfaces. Once again, the periods of upward and downward motion coincided well with the weather summary. For example, the outbreaks of strong thunderstorm activity reported on 11 April (observations 1-8) and 27-28 April

APRIL 1994 IOP RADIOSONDE WATER VAPOR MIXING RATIO

Figure 3: 19-day time series plots of water vapor mixing ratio from SGP CART radiosonde data, starting at 00 UTC on 11 April 1994 and ending at 21 UTC on 29 April 1994. Contours are in g kg^{-1} , and numbers on the abscissa represent multiples of 8 observations spaced 3 hours apart (8 observations per day).

(observations 134-144) are confirmed by strong upward (negative) pressure velocities. This agreement gives us confidence that the derived fields (based on the raw radiosonde data from the CART site) are indeed accurate and can therefore be used to draw significant conclusions regarding the GCAPE equilibrium hypothesis.

Fig. 5 is a time-series plot of the actual (observed) and predicted amounts of GCAPE, based on the numerical algorithm developed by Randall and Wang (1992) and using the SGP CART radiosonde data as input. The predicted amounts of GCAPE are derived from hypothetical soundings that have been constructed using the large-scale forcing in effect at the time of the previous observation. As expected, we found the actual GCAPE to be considerably less than that predicted by large-scale forcing. The implication is that cumulus convection consumes the GCAPE produced by the large-scale forcing almost as rapidly as it is produced. This would be especially true during periods of strong thunderstorm activity, when large-scale forcing would be at a maximum. Indeed, as Fig. 5 indicates, there are several instances where the predicted GCAPE amounted to over 1000 J kg^{-1} . These are all associated with strong-to-severe thunderstorm development. On the other hand, the concomitant amounts of observed GCAPE were relatively

Figure 4: 19-day time series plots of vertical pressure velocity from SGP CART radiosonde data, starting at 00 UTC on 11 April 1994 and ending at 21 UTC on 29 April 1994. Contours are in mb hr^{-1} (dashed contours represent negative values), and numbers on the abscissa represent multiples of 8 observations spaced 3 hours apart (8 observations per day).

Figure 5: 19-day time series plot of the moist available energy (GCAPE) from SGP CART radiosonde data, starting at 00 UTC on 11 April 1994 through 21 UTC on 29 April 1994. Units are J kg^{-1} , and numbers on the abscissa represent multiples of observations. Negative values indicate data missing for that observation. To keep scaling consistent between plots, outlier data is identified at top of radiosonde plot.

small, which suggests the cumulus convection was efficiently consuming the GCAPE as it was being produced by large-scale forcing.

Another method of interpreting these results is shown in Fig. 6. The scatter plot of

Figure 6: Scatter plot comparing the time rate of change of the observed GCAPE (ordinate) with the GCAPE rate of production by large-scale processes (abscissa) from SGP CART radiosonde data. Each of the points represents the GCAPE calculations corresponding to a pair of temporally adjacent observation times. To keep scaling consistent between plots, outlier data is listed on the right-hand margin of the radiosonde plot.

observed GCAPE tendency versus the production rate of GCAPE by large-scale processes indicates the majority of points distributed along the positive x-axis, and very close to zero in relation to the y-axis. These are the points that confirm the GCAPE quasi-equilibrium hypothesis. They show that, although there was considerable production of GCAPE by large-scale processes over the 3-hour time interval between observations, the observed GCAPE tendency was virtually unchanged. Again, the implication is, therefore, that strong cumulus convection was efficiently consuming the produced GCAPE practically as fast as it was being produced. If this were not the case, we would expect to see points lying along a 45° line in the first quadrant, indicating that the rate at which GCAPE was produced by large-scale processes and the observed GCAPE change were the same. This in turn would imply that cumulus convection was leaving the produced GCAPE untouched, and was instead drawing upon some other mechanism as a source of instability.

In the mean time, we have been using GATE and ASTEX data to drive the SCM, and in fact early tests of the new cloud microphysics parameterization were performed in just this way. The results shown in Fig. 2 were produced by driving the CEM with ASTEX data.

Task 3: *Use the CEM to perform further tests of the parameterization, in part by simulating observations collected during ARM, and to suggest model-development strategies.*

The UCLA / U. Utah cloud ensemble model (CEM) is a two-dimensional cloud model which can be used to simulate the formation of an ensemble of clouds under a given large-scale condition (Krueger 1985, 1988; Xu, 1991). The CEM includes a third-moment turbulence closure, a three-phase microphysical parameterization and the Coriolis force. Radiative heating is included following the methods of Harshvardhan et al. (1987), using the predicted distribution of cloud mass variables to determine the cloud optical properties. The horizontal domain is 512 km wide with a 2 km grid size. The depth of the CEM domain is typically 19 km, with a stretched coordinate and 33 layers. Near the surface the grid interval is 100 m, while near the model top it is 1000 m. The upper and lower boundaries are rigid. The lateral boundary conditions are cyclic. The initial thermodynamic conditions in a simulation are typically horizontally uniform. Clouds are initiated by introducing small, random temperature perturbations into the lowest model layer after the first 30 minutes of integration, so that their location and intensity are not pre-determined. The CEM is currently being modified by S. Krueger of the University of Utah to use an advanced flux-corrected transport algorithm for advection. This will eliminate numerical problems with undershoots, overshoots, and negative mixing ratios.

The CEM has been endowed with the same radiative transfer parameterization used in the GCM (Xu and Randall, 1994). A method has been devised to distinguish, in analysis of the CEM results, between convective and stratiform cloudiness (Xu 1994). We have performed some interesting experiments to determine the sensitivity of the CEM results to the radiation, and have found realistic responses to the diurnal cycle.

2) Assessing the limit of parameterizability of cumulus convection

A series of three papers (Xu et al. 1992; Xu and Arakawa 1992; Xu 1994) were prepared at CSU for publication based on K.-M. Xu's dissertation completed at UCLA (Xu 1991). In addition, a review paper (Xu 1993 a) was published in an AMS *Meteorological Monograph*. Xu (1994) includes results of some research performed at CSU. This series of papers attempts to assess the limit of parameterizability of cumulus convection with simulated data from a cloud ensemble model (CEM).

Xu et al. (1992) examined the modulation of cumulus activity by time-varying large-scale processes. They found that in all simulations cumulus activity is rather strongly modulated by large-scale processes but also undergoes high-frequency fluctuations. The degree of modulation is somewhat dependent upon the large-scale conditions, such as the large-scale advective effects and the basic wind shear. The modulation is usually stronger for stronger large-scale advective effects. When the basic wind shear is strong, there are some phase delays in the modulation due to the existence of mesoscale convective organization.

Xu and Arakawa (1992) investigated the sensitivity of the Arakawa-Schubert (1974) cumulus parameterization to the horizontal resolution of large-scale models. Their main finding is that the Arakawa-Schubert (1974) cumulus parameterization is basically valid in spite of the existence of mesoscale organization in cumulus convection. In particular, the assumption of cloud work function (CWF) quasi-equilibrium, i.e., an approximate balance between the generation of CWF by large-scale processes and its destruction due to cumulus convection itself, is more accurate for inputs averaged over shorter distances that can partially resolve mesoscale processes. The explanation for this puzzling result is that the large-scale forcing, which is defined as the change of CWF when large-scale processes act alone, increases more than does the net change of the CWF as the averaging distance decreases. For large averaging distances, which do not resolve mesoscale processes, the net change of the CWF is relatively important.

Xu (1994) examined the dependency of three types of closure assumptions used in cumulus parameterizations, as classified by Arakawa and Chen (1987), on the averaging distance. Two of them are not significantly dependent on the averaging distance. This implies that a proper combination of closure assumptions can be chosen so that cumulus convection can be parameterizable with the influence of mesoscale processes. However, it is not possible to single out mesoscale processes for causing the weak dependency of closure assumptions on the averaging distance.

Xu (1995) is a by-product of directly ARM-supported research, which requires development of a partitioning method for separating convective regions from mesoscale stratiform regions of simulated cumulus ensemble. The details of the partitioning method will be described later. Xu (1995) examined the relative role of the mesoscale component in the mass, heat, and moisture budgets of cumulus ensemble. The main conclusion is that the effects of mesoscale processes may have to be included in any parameterization of cumulus convection for use in large-scale models if cumulus convection is organized on the mesoscale. The eddy heat and moisture flux convergences in mesoscale regions are found to be parameterizable only if the

vertical motions and properties of both mesoscale updrafts and downdrafts are known. In addition, the relative role of each phase-change process in the heat and moisture budgets is very different between convective and mesoscale regions, due to the different kinematic characteristics.

Xu (1993 b) discussed the applicability of the Arakawa-Schubert cumulus parameterization to mesoscale models, extending the work of Xu and Arakawa (1992).

3) Improvement of the CEM for simulation with observational data sets

The version of the UCLA CEM used before 1991 did not have an interactive radiative transfer parameterization and was used to perform simulations with idealized large-scale conditions (see Xu et al. 1992). We cannot achieve the ARM research objectives with that version of CEM because cloud-radiation interactive processes cannot be simulated. A series of major and minor modifications have been made to the CEM since 1991, as described below.

A broadband interactive radiative transfer model has been incorporated into the UCLA CEM, based on the work of Harshvardhan et al. (1987) with cloud optical properties as formulated by Stephens et al. (1990). Major modifications to the Harshvardhan et al. model are related to the reformulation of cloud optical properties such as cloud optical depth, single scattering albedo, asymmetry factor, and cloud emissivity, which are now directly related to cloud microphysical properties [see Xu et al. (1993) and Xu and Randall (1995 a) for details]. Other modifications include (i) the deletion of the calculation of planetary boundary layer stratus heating rate, (ii) the addition of extra layers above the CEM top, and (iii) the division of the lowest CEM layer into a very thin layer near the ground and a thick layer above.

Both diagnostic and prognostic tests of the modified radiative parameterization were performed (Xu et al. 1993; Xu and Randall 1995 a). Diagnostic tests compared the accuracy of this parameterization with a more complicated, multiband radiative transfer model. Prognostic tests addressed an important issue of how to eliminate the spatial errors of the time-averaged radiative heating rates (over the time interval for calling a radiation module, ΔT) due to infrequent computation of radiative transfer processes. Several sensitivity tests were performed to compare two methods for invoking the radiation module. For the conventional method, which keeps the heating rate constant until the radiation module is called again, ΔT has to be very small, while ΔT can be at least twice as large with the "accumulated" method, which accumulates and averages cloud microphysical properties within ΔT as input to the radiation module and applies the amount of radiative heating over ΔT at the time when the radiation module is called. The

value of ΔT is mainly determined by the horizontal resolution of CEMs and the propagation speed of individual cloud cells; i.e., a fast moving cell in a high-resolution CEM requires a very small ΔT . Additional sensitivity tests were also performed to justify the omission of the radiative effects of rapidly falling precipitating particles.

A modified ice-phase microphysical parameterization (Krueger et al. 1995) has been incorporated into the CEM, which is able to simulate realistically the microphysical processes that occur in upper-tropospheric clouds. The earlier version (Lin et al. 1983) produced too little ice which resulted in errors in the radiative heating rate in simulations with interactive radiation.

Another major modification to the CEM is to allow simulations with observational data sets; i.e., the observed large-scale advective cooling and moistening rates are continuously imposed to the CEM. The large-scale horizontal wind components cannot be well simulated by the CEM due to the lack (inaccuracy) of the horizontal pressure gradient information, which affects the simulated structures of cloud organization. Thus, a nudging procedure was adopted; i.e., an extra term is added to each of the horizontal wind component equations (Xu and Randall 1995 c)

In addition, a flux-corrected-transport (FCT) algorithm has been included in the CEM for simulation of stratocumulus clouds, in collaborating with Professor S. Krueger of Utah, a member of ARM science team. This algorithm can give a more accurate transport in the presence of sharp gradients such as an inversion. Also, a more realistic turbulence length scale formulation has been incorporated into the CEM.

4) *Developing a cloudiness parameterization of stratiform clouds*

A cloudiness parameterization should be physically based, as far as possible. Any such parameterization may have some empirical content but the empiricism is introduced in such a way that the formulation is universally applicable, i.e., not tied to a particular cloud regime or a specific grid size of large-scale models. Xu and Krueger (1991) used the UCLA CEM to investigate the utility of several empirical cloudiness parameterizations based on different "predictors" such as the large-scale relative humidity (RH), the large-scale vertical motion, the surface precipitation rate $\langle P \rangle$ and the convective mass flux M_c . All of these predictors showed some utility, in particular, RH for stratiform cloudiness and M_c for convective cloudiness. None of them were, however, skillful enough for quantitative applications in large-scale models. In the present study, we are particularly interested in parameterizing the stratiform cloudiness.

In a large-scale model that predicts the mass of condensed water, the condensate mixing ratio itself is an obvious candidate for use as a predictor of cloud amount. Such an approach can only be developed with the aid of a CEM because it can provide detailed information of the mixing ratio of cloud water and ice and that of fractional cloud amount, as well as other large-scale predictors. Our research has been progressing in three interrelated directions: 1) simulation of tropical cloud clusters and subtropical stratocumulus clouds with observational data sets, 2) development of a partitioning method which separates convective from stratiform regions, and 3) understanding the relationships between stratiform cloud amount and large-scale predictors.

e) Simulation with observational data sets:

In the early stage of this research (Xu and Randall 1992), performed were simulations with idealized large-scale conditions and noninteractive radiation as those in Xu and Krueger (1991). They differed from those in Xu and Krueger (1991) in that a modified ice-phase microphysical parameterization was used. Simulations with interactive radiative transfer were later performed (Xu et al. 1993; Xu and Randall 1994 b) for some idealized large-scale conditions. More recently, simulations with GATE [Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment] Phase III and ASTEX (Atlantic Stratocumulus Transition EXperiment) data sets are performed (Xu and Randall 1994 c, 1995 d). These data sets are useful because they provide large-scale conditions which are not observed in the ARM data set. The ARM data set will be used shortly.

f) Development of a partitioning method:

In analyzing simulations of tropical cloud clusters, it is necessary to separate convective regions from stratiform regions. Historically, partitioning methods were based on observations of surface precipitation rate $\langle P \rangle$ at a single station, radar reflectivity or satellite data (e.g., Churchill and Houze 1984; Adler and Negri 1988). The data used in these studies had very low temporal resolutions. CEM data can resolve the temporal evolution and spatial structures of convective cells and stratiform anvils much better than the observational data. Thus $\langle P \rangle$ alone may not adequately characterize convective and stratiform regions in simulated data because the vertical structures of these regions are not considered. A new partitioning method has been proposed by Xu (1995), based on kinematic characteristics of convective cloud systems. The partitioning method uses the *horizontal distribution* of the maximum cloud draft strength $|w_{max}|$ below the melting level in a CEM grid column as the primary variable. The convective region includes a core and two adjacent grid columns. A core consists of at least one grid column. A core satisfies

one of the following three conditions: 1) $|w_{max}|$ is twice as large as the average over the four adjacent grid columns, 2) $|w_{max}|$ is greater than 3 m s^{-1} , or 3) $\langle P \rangle$ exceeds 25 mm h^{-1} . The stratiform region consists of the remaining grid columns where the total liquid-water path exceeds 0.2 kg m^{-2} . Some of these regions may, however, be occupied by shallow convection or new convective cells. Additional criteria, i.e., positive layer-mean (ground to 0° C level) vertical velocity, rainwater path below the melting layer less than 0.1 kg m^{-2} and cloud-water path below the melting layer greater than 0.4 kg m^{-2} , are used to identify these shallow clouds as a part of the convective region. Further details of this method can be found in Xu (1995). Earlier attempts to developing the partitioning method can be found in Xu and Krueger (1991), Xu and Randall (1992) and Xu and Randall (1994 b).

g) *Understanding the relationship between stratiform cloudiness and large-scale predictors:*

The key question to be addressed is what determines fractional cloud amount for any cloud regime. Large-scale variables such as RH, grid-averaged mixing ratio of condensates and convective activity should be related to fractional cloudiness. They are related to each other, too. Therefore, it is not likely that a single regression relationship can be obtained using all interrelated variables mentioned above. Such an example was given by Xu and Randall (1992): liquid water path is extremely highly correlated with cloudiness, while RH is moderately correlated with cloudiness. When both variables are used in a regression, the explained variances are only slightly larger than when liquid water path is used only. Thus, an approach based on a multiple regression cannot result in a physically-based parameterization. Understanding the relationship between cloudiness and large-scale predictors is the key for the development of such a cloudiness parameterization.

Fig. 7 shows scatter plots of stratiform cloud amount c_s vs. (a) RH, (b) mixing ratio of cloud water and cloud ice q_c , and (c) M_c in stratiform regions. All variables are averaged over 64 km subdomain in the horizontal and 1 h in time. The partitioning method mentioned earlier was used to separate stratiform regions from convective regions of simulated tropical cloud clusters with the GATE Phase III data set. The correlation coefficient is also shown on each plot. It appears that there is some correlation between RH and c_s and between M_c and c_s . The correlation coefficient between q_c and c_s is the highest. The high correlation means that c_s represents the statistical distribution of cloud water and cloud ice on the subgrid scale. When an ensemble of clouds is included in the averaging, such a relation between q_c and c_s is expected.

Figure 7: Scatter plots of cloud amount versus (a) RH, (b) cloud water plus ice mixing ratio, and (c) cloud mass flux in the stratiform regions at 300-mb level of GATE simulation.

To understand the interrelationship between large-scale predictors, scatter plots are shown for cloudiness vs. two predictors for a given range of variation of the third predictor (Fig. 8).

Figure 8: Same as Fig. 7 except for a range of variations for a specific predictors: (a1) and (a2) for $0.97 < RH < 0.99$, (b1) and (b2) for $0.09 < q_c < 0.11 \text{ g kg}^{-1}$; and (c1) and (c2) for $0.9 < M_c < 1.1 \text{ Pa s}^{-1}$.

For a given RH variation between 0.97 and 0.99, c_s is shown to exponentially increase with the increase of q_c but linearly increase with small M_c . The scatter points in Fig. 8 a correspond to those with the steepest slopes in Fig. 7 b and c. For very large M_c , the cloud amount is decreased, suggesting that some convective cells may exist. For a given q_c variation between 0.09 and 0.11 g kg⁻¹, the cloud amount increases with increase of RH, but decreases with the increase of M_c . This suggests that convective circulations within stratiform regions tend to reduce c_s . Finally, for a given M_c variation between 0.9 and 1.1 Pa s⁻¹, c_s is shown to increase with either RH or q_c . The increase of c_s with RH (Fig. 8 c1) is slower than that for a given q_c (Fig. 8 b1). Another feature in Fig. 8 is that the scatter in c_s is not small at all, indicating that (i) all three large-scale predictors have to be used in the cloudiness parameterization and/or (ii) some convective cells may be treated as stratiform regions. Simulation of stratocumulus clouds with ASTEX data shows the similar features as seen in Figs. 1 and 2. Further analyses will be performed to give a more quantitative description of the relationship between cloud amount and large-scale predictors.

h) Investigating mechanisms for cloud-radiation interactions and diurnal cycle of precipitation

Xu and Randall (1994 a, 1995 b) performed two simulations, one with fully interactive radiative transfer and the other with horizontally uniform radiative heating rates determined from the domain-averaged heating rates of the fully interactive simulation. The diurnal variation of solar radiation and a time-invariant large-scale advective forcing are included in both simulations. The simulations were run for 15 days of physical time. A comparison of this pair of simulations can reveal whether or not the radiation-dynamics-convection hypothesis is important in the diurnal variation of oceanic precipitation. It is shown that surface precipitation rate exhibits a diurnal variation in both simulations regardless of whether or not radiation is interactive or non-interactive, thus suggesting that the direct radiation-convection interaction is the dominant mechanism for the diurnal cycle. The difference between the two simulations is, however, not totally negligible, in terms of the 2-3 h phase delay in the interactive simulation. The phase difference is related to the lagged response of the upper-tropospheric clouds to the radiative destabilization/stabilization in the interactive simulation.

In addition, Xu and Randall (1995 b) performed statistical analyses to further quantify the importance of several cloud-radiation interaction mechanisms. A two-step process can be described for the radiative destabilization mechanism. The radiative destabilization enhances the turbulent-scale motions more or less instantaneously. It then takes a longer time to enhance the

cloud-scale motions. The destabilization is more effective for thin clouds which generally possess the greatest amount of radiative destabilization. It is found that continuous destabilization acts on the cloud-scale motions through Lilly's (1988) mechanism of radiative destabilization in the cloudy upper troposphere. On the other hand, the mechanism of horizontal differential heating between cloudy and clear regions, generating secondary circulations, is not supported by the results of this study. A simple explanation for this can be based on the differences between the horizontal and vertical scales of convective circulations, and the magnitudes of the differential heating. The effects of vertical differential heating are simply much stronger than those of horizontal differential heating.

Task 4: *Perform climate simulations with the full three-dimensional version of the CSU GCM.*

The new cloud microphysics parameterization mentioned under Task 1 above has been extensively tested in the three-dimensional version of the CSU GCM. We have also linked the microphysics with the model's radiative transfer routines. One paper has been published and three more have been submitted (Fowler et al. 1994; Fowler and Randall 1995 a, b, c).

Analysis of the GCM results shows that both the hydrologic cycle and the Earth's radiation budget are simulated more realistically with the new model than with the earlier version. Fig. 3, taken from Fowler and Randall (1994 a), shows an example of simulations of the outgoing longwave radiation with the new microphysics parameterization, with the older "control" version of the GCM, and as observed by ERBE. The improvements obtained with the new parameterization are quite noticeable. Further analysis of these results is in progress.

As described by Fowler and Randall (1994 b), we have discovered an interesting mode of interaction between the hydrologic cycle and the radiative effects of cloudiness. This involves a *global* negative feedback loop involving the formation of upper-tropospheric stratiform clouds, atmospheric radiative cooling (ARC), and convective activity. We call it "a global radiative-convective feedback." It works as follows: Strong convective activity produces a radiatively thick upper-tropospheric cloud shield by detrainment of cloud water and cloud ice from the tops of cumulus towers. The formation of thick stratiform anvils and cirrus debris lead to a decreased ARC and a more statically stable atmosphere. Cumulus convection is then suppressed and the total precipitation rate decreases. The upper-level fractional cloudiness diminishes accordingly. The system equilibrates when the ARC and latent heating are in balance, as shown in Fig. 4. The reduction in the precipitation rate due to decreased ARC does not necessarily occur in the same

Figure 9: The top two panels show simulations of the OLR with the new microphysics parameterization (left) and by the older, "control" version of the model (right). The ERBE data is shown in the lower panel, for comparison.

place where the ARC increases; nevertheless, in a global average, the reduction in the ARC leads to a reduction in the latent heating. This is why we describe the feedback as "global."

Task 5: *Make the improved parameterizations available and adaptable for use in other models.*

The cumulus parameterization that we have developed will be tested in CCM2 later this year. Both the cumulus parameterization and the current version of the microphysics parameterization will be shared with other ARM groups, on request, during the period of the proposed research.

9. Contributions to ARM program development

2.1 Initial planning stages

As Principal Investigator, D. Randall has been very heavily involved in the development of the ARM program since its inception, participating strongly in several of the early planning

A Global Radiative-Convective Feedback

Figure 10: Schematic diagram illustrating the negative Global Radiative-Convective Feedback. An external perturbation tends to force more vigorous convection. This leads to more upper-tropospheric cloudiness, which reduces the atmospheric radiative cooling. Convection must then weaken to satisfy the global energy balance.

meetings, and writing a critique of the first version of the Science Plan. I also made presentations to JASON about the emerging ARM program.

2.2 ARM-CHAMMP Workshop

An ARM-CHAMMP Workshop, hosted by the P.I., was held at Colorado State University (CSU) in Fort Collins, Colorado on September 8 and 9, 1993. The focus of the Workshop was on problems of cloud parameterization for climate models, involving scientific issues of interest to both ARM and CHAMMP. The primary goals of the Workshop were: to bring into closer focus the current state of GCM simulations of cloud and radiation quantities for the ARM sites; to encourage communication between ARM GCM investigators, CHAMMP investigators, and some interested parties who are currently not involved in either ARM or CHAMMP; and to fill each other in on what we are doing about cloud and radiation parameterization development, in the setting of a small group of specialists. About 30 scientists attended, including members of the ARM and CHAMMP science teams, as well as other interested scientist.

Prior to the Workshop, January and July ARM-site simulation results were collected, in digital form, from a total of 9 GCMs. These were plotted up at CSU. Three types of plots were prepared: Color regional maps centered on the ARM sites; simple graphical summaries of the values of various parameters, as simulated by the various models, for the ARM sites themselves; and line plots of various quantities as functions of height, again for the ARM sites, as simulated by the various models.

The first day of the Workshop focused on our current ability to simulate the present climate, and especially cloud and radiation variables, at three current and/or planned ARM sites: the Southern Great Plains, the Tropical Western Pacific, and the North Slope of Alaska. Results were presented from the 9 GCMs, and each modeling group had an opportunity to present a detailed analysis of their model's simulation. The most revealing of these analyses was that presented by J. Hack of NCAR. G. Stokes presented a summary of recent data collected at the Southern Great Plains ARM site. As might be expected, both good and bad model simulations were in evidence. The results brought home the degree to which the current GCMs disagree about such fundamental climate variables as the precipitable water and cloud radiative forcing. On the other hand, it was also clear that some of the GCMs do a remarkably good job of simulating the observed climates of the ARM sites. Near the end of the first afternoon, R. Cess presented a comparison of surface and satellite data with GCM results.

The second day focused on future developments in cloud and radiation parameterization. Keynote talks were given by W. Schubert of CSU and J. Kiehl of NCAR. Additional talks dealt with such diverse topics as cloud microphysics, fractional cloudiness parameterization, cloud condensation nuclei, mesoscale convective systems, and parameterization development based on large-eddy simulations.

At the close of the Workshop, the participants agreed to undertake a further analysis of the GCM results contributed, and in particular to perform more comprehensive comparisons with observations, including ARM data collected at the Southern Great Plains site. The ultimate goal of the exercise is a formal publication of the results. D. Randall, R. Cess, and T. Barnett agreed to share responsibility for this follow-up effort. It was also agreed that a CD-ROM should be produced in order to make easily available climate observations suitable for comparison with GCM simulations of ARM-site climates. G. Stokes and J. Hack expressed interest making this happen. Finally, enthusiasm was expressed for closer and continuing ties between ARM and FANGIO.

A Second ARM-CHAMMP Workshop was held, at the instigation of the P.I., in Boulder Colorado in the fall of 1994.

2.3 *SCM algorithm development and testing*

As discussed earlier, the P.I. and his graduate student D. Cripe have been working with ARM's Experiment Support Team to define and get into production the algorithms needed to

support the Single Column Modeling component of ARM. Software written at CSU has been provided to the Experiment Support Team.

2.4 Science Team Executive Committee

The P.I. has been a member of the Science Team Executive Committee since it was formed, and is currently its Chairman.

In this capacity, he has organized, with G. Stokes, a "reach-out-and-touch-someone" campaign involving extended conference calls with selected Science Team members to determine how their data needs can be more effectively met, in order to maximize near-term scientific productivity by the Science Team. Eight such calls have been made to date and more are planned.

In addition, the P.I. has organized a panel of Science Team members to re-think the scientific strategy of ARM from the perspective of 1994, and to produce a short document summarizing this thinking, by June 1994.

10. Summary

We have developed new cloud parameterizations, and tested them in an SCM, a CEM, and a full three-dimensional GCM. We have demonstrated the ability to drive the SCM and the CEM with observations similar to those that we are about to receive from ARM. We have used the three-dimensional GCM to investigate some aspects of the role of clouds in climate. The climate simulation, and especially the Earth's radiation budget, has been substantially improved through use of the new parameterizations.

In addition the P.I. has played a substantive role in the definition, development, and execution to date of the ARM program.

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a) Refereed publications

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