Development and Testing of a Life Cycle Model and a Parameterization of Thin Mid-level Stratiform Clouds

Final Report

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Contents

1 Executive Summary

We used a detailed computer model of cloud systems to evaluate and improve the representation of clouds in global atmospheric models used for numerical weather prediction and climate modeling. We also used observations of the atmospheric state, including clouds, made at DOE's Atmospheric Radiation Measurement (ARM) Program's Climate Research Facility located in the Southern Great Plains (Kansas and Oklahoma) during Intensive Observation Periods to evaluate our detailed computer model as well as a single-column version of a global atmospheric model used for numerical weather prediction (the Global Forecast System of the NOAA National Centers for Environmental Prediction).

This so-called Single-Column Modeling approach has proved to be a very effective method for testing the representation of clouds in global atmospheric models. The method relies on detailed observations of the atmospheric state, including clouds, in an atmospheric column comparable in size to a grid column used in a global atmospheric model. The required observations are made by a combination of in situ and remote sensing instruments.

One of the greatest problems facing mankind at the present is climate change. Part of the problem is our limited ability to predict the regional patterns of climate change. In order to increase this ability, uncertainties in climate models must be reduced. One of the greatest of these uncertainties is the representation of clouds and cloud processes. My project, and ARM taken as a whole, has helped to improve the representation of clouds in global atmospheric models.

2 Comparison of Actual Accomplishments with Project Goals

2.1 1993–1996

The ultimate goal of the research accomplished during this period was to develop and test (using ARM-CART measurements) a physically-based parameterization for thin mid-level stratiform cloud ("altocumulus") layers for use in GCMs. A related goal was to increase our understanding of the physical processes that determine the distribution of altocumulus clouds and their effects on the atmosphere. During this period, we made significant progress toward the ultimate goal, and fulfilled the related goal.

2.2 1996–1999

Our goals during this period of support were to develop and test GCM parameterizations for (1) vertically sub-grid scale altocumulus (Ac) layers and (2) cloud-topped boundary layers by integrating high frequency and high vertical resolution ARM-CART cloud radar measurements with other observations and with cloud-resolving model simulations.

During this period, we developed an elevated mixed layer model for altocumulus that is suitable for use as a GCM parameterization. We also tested a cloud fraction parameterization using retrievals based on cloud radar measurements of boundary layer cloud properties at Porto Santo for the entire month of June 1992. We found that such an observational test is difficult because of biases in the radiosonde relative humidities, the effect of limited sampling of the relative humidity field (one radiosonde every 3 hours), problems in defining the cloud fraction using the cloud radar measurements (i.e., partly cloudy radar volumes), and the difficulty of estimating spatial averages from temporal averages. We also became involved in several additional research efforts that are described in Section 4.

2.3 1999–2001

Our goal was to improve the cloud and convection parameterizations in the National Centers for Environmental Prediction (NCEP) global numerical weather prediction model using ARM observations, a 2D cloud resolving model (CRM), a single-column model (SCM), and the NCEP global model itself.

We initiated a GCSS (GEWEX Cloud System Study)/ARM model intercomparison project that evaluated cloud resolving models and single-column models by testing their ability to determine the large-scale statistics of precipitating convective cloud systems during the Summer 1997 SCM IOP at the ARM SGP site. We compared cirrus statistics obtained from a CRM simulation for the Summer 1997 SCM IOP at the SGP site to cirrus statistics retrieved from cloud radar observations at the SGP (Southern Great Plains) site. We used observations, CRM simulations, and NCEP SCM simulations to evaluate the NCEP model's representation of the effects of deep cumulus convection on the boundary layer over the southern Great Plains of the United States during the 1997 Summer SCM IOP. We began collecting twice-daily column output files from the NCEP global model forecasts in November 2000 for the four ARM sites. The column output files contain all the information necessary to run SCMs and CRMs, and allow one to evaluate the global model's cloud and radiation fields at all ARM sites on a continuous basis.

2.4 2001–2006

Our goals were to (1) use ARM cloud and radiation observations to evaluate the performance of the NCEP global model's new operational prognostic cloud parameterization, and (2) develop, implement, and test more physically complete versions of selected aspects NCEP's prognostic cloud parameterization. We planned to focus on improving the representation of cirrus clouds and boundary layer clouds in the NCEP model.

Using cloud radar observations of cirrus cloud properties obtained at the ARM SGP (Southern Great Plains) site and results from a CRM (cloud-resolving model) simulation, we evaluated the cirrus properties simulated by a SCM based on the NCEP global forecast model, which includes cloud water/ice as a prognostic variable. We used CRM results to evaluate the NCEP global forecast model's representation of the physical processes that determine the properties of simulated cirrus: specifically, cumulus detrainment and ice microphysics. We found several deficiencies and suggested possible methods to improve the global forecast model's physics. We also evaluated cloud type occurrences and radiative forcings simulated by a CRM and the NCEP global forecast model SCM using observations from satellite and cloud radar. Finally, we evaluated the NCEP global forecast model's cloud fraction parameterization by comparing archived column output to cloud radar observations at the ARM SGP site.

3 Project Activities: 1993–1996

The ultimate goal of the research accomplished during this period was to develop and test (using ARM-CART measurements) a physically-based parameterization for thin mid-level stratiform cloud ("altocumulus") layers for use in GCMs. A related goal was to increase our understanding of the physical processes that determine the distribution of altocumulus clouds and their effects on the atmosphere. This is necessary before an altocumulus parameterization based on general physical principles can be developed. To increase our understanding, we made extensive use of ARM-CART measurements and a high-resolution cloud scale numerical model, the University of Utah Cloud Resolving Model (UU CRM).

3.1 Altocumulus formation and structure

We used the UU CRM to perform numerical simulations of altocumulus cloud layers in idealized and observed large-scale environments. The goal was to determine in detail how the large-scale motion field, in combination with the cloud-scale radiative, microphysical, and dynamical processes, governs the life cycle and structure of altocumulus layers. A closely related goal was to determine the extent to which altocumulus clouds are indeed parameterizable in terms of large-scale processes.

A CRM is a numerical model that explicitly calculates cloud-scale motions, while parameterizing the 3D turbulent motions. It includes the effects of specified large-scale vertical motion, horizontal advection, and horizontal pressure gradients. Its domain could represent a GCM grid column, in which case the CRM essentially becomes a very detailed "single column model." Since Ac clouds are convective layers destabilized by cloud top radiative cooling, an important aspect of the UU CRM is the inclusion of Ac cell-scale dynamics, a third-moment turbulence closure, interactive radiation, and cloud microphysics. The UU CRM is further described in Krueger (2000).

We used the following types of CRM simulations to study the relationship between Ac formation and the larger-scale motion field:

1. Idealized studies of the formation of Ac cloud layers with a variety of larger-scale motion fields. These simulations provide insight into the importance of various physical processes, and suggest simplifications that can be made, such as are employed in 1D turbulence closure models, or mixed layer models.

2. Eulerian ("single column") simulations of Ac layers observed at the ARM-CART site. This approach uses ARM-CART measurements of large-scale vertical and horizontal advection of potential temperature and water vapor to "force" the CRM, just like a column version of a GCM. We compared the predicted Ac structure with that observed at the ARM-CART site.

Following is a summary of our accomplishments using these two approaches.

3.1.1 Idealized simulations

We completed a series of 2D simulations of an idealized Ac layer using the CRM (Liu and Krueger 1996a). This series is an extension of Starr and Cox's (1985b; SC) 1-hour 2D simulation of altocumulus (called altostratus by Starr and Cox). The simulations were designed to investigate the effects of (1) specified large-scale vertical velocity, (2) solar radiation, (3) initial cloud thickness, (4) vertical grid size, and (5) 1D vs. 2D simulations.

To simulate altocumulus, we used essentially the same initial profile as SC used. The model domain was 6.4 km long and 8.9 km high. The horizontal grid interval was 100 m, while the vertical grid interval was 1 km from the surface to 5 km, 500 m to 5.5 km, and either 100 m or 50 m from 5.5 to 8.9 km.

We first simulated a nocturnal case with the large-scale vertical velocity (w_0) equal to 2 cm/s. This is the same as the "altostratus" case of SC. The agreement with SC's domain-averaged liquid water content ($\widetilde{\rho_0 l}$) and profiles of horizontally-averaged liquid water content is good. In our simulations, the cloud top and base heights increase a little faster than those in SC.

The effects of large-scale control via w_0 were examined in a series of three nocturnal 3-hr simulations with various specified values of w_0. With w_0 =2 cm/s, $\widetilde{\rho_0 l}$ increases with time, while with $w_0 = -2$ cm/s, $\widetilde{\rho_0 l}$ decreases to zero. It is interesting that $\widetilde{\rho_0 l}$ is almost steady when w_0=0. In this case, the cloud top rises at a rate of 3 cm/s, and the cloud base nearly as rapidly. The cloud depth decreases only slowly. These results suggest that altocumulus may last a long time even when there is no large-scale vertical motion.

We set w_0= 0 to investigate solar radiative effects. Two 6-hour simulations were considered: a nocturnal case and a diurnal case. During the simulations, $\widetilde{\rho_0 l}$ decreased 20% in the nocturnal case and about 70% in the diurnal case. These results show that solar radiation tends to significantly decrease $\widetilde{\rho_0 l}$ and that nocturnal conditions favor a longer lasting cloud.

Heymsfield et al. (1991) mentioned that strong radiative cooling occurs in the upper part of Ac layers and radiative heating occurs in the lower part of Ac layers (unless the layer is very thin). We obtained the same radiative structure in our simulations.

Because the cloud depth for SC's profile is larger than that usually observed for altocumulus, we also performed a simulation with half the initial cloud thickness of SC's profile. For these nocturnal simulations, we set $w_0 = 0$. For the thin cloud case, $\widetilde{\rho_0 l}$ increases slowly with time, while for the thick cloud case, it slowly decreases. The thin cloud rises more slowly than the thick cloud and slowly thickens. Randall (1984) and Betts (1989) noted that cloud-top entrainment may deepen stratocumulus clouds in the upper part of a surface-based mixed layer if the entrained air is sufficiently moist. Betts found that the *equilibrium* thickness of a well-mixed cloud layer uncoupled from the surface will always decrease by cloud-top entrainment.

We tested the effect of changing the vertical grid size from 100 m to 50 m. With the 50-m grid size, the temporal oscillation in $\widetilde{\rho_0 l}$ (which is due to the ascent of cloud top from one grid level to the next) decreases.

The 1D simulations used a third-moment turbulence closure model (TCM) (a 1D or "single column model" version of the CRM) to simulate *all* of the convective circulations. In the 1D simulations, the overall evolution was similar to that in the 2D simulations. This indicates that 1D TCMs are able to capture the essential physics of Ac layers.

In August 1994, we participated in the NCAR/GCSS Workshop on Boundary Layer Clouds (Moeng et al. 1996, Bechtold et al. 1996). The workshop allowed us to compare 2D CRM and 1D TCM simulations of a nocturnal stratus-topped marine boundary layer (STBL) with 3D large eddy simulations (LES). A STBL and an Ac layer are similar since the convective circulations in both are driven by radiative destablization of the cloud layers. The agreement among STBL simulations using the NCAR 3D LES, the 2D CRM, and the 1D TCM is good. In fact, the results are well within the range of scatter of the various 3D LES results presented at the workshop. This intercomparison was an important test of the CRM.

3.1.2 Simulations based on ARM-CART observations

We selected a case (April 24) from the Spring 1994 SGP IOP. An Ac layer occurred over the SGP central site on this day as shown by the lidar and ceilometer observations. Also, flights by the Citation research aircraft sampled these clouds.

To perform a CRM simulation, we need the observed large-scale "forcing" (large-scale vertical velocity profiles and horizontal advective tendencies of temperature, water vapor, and liquid water). For this case, we used three different sets of forcing profiles based on analyses by M. Leach and M. Zhang. However, the most realistic results were obtained with no forcing.

The sounding was conditionally unstable below a stable layer at about 4500 m. Ceilometer observations at the central facility at 21 UTC showed cloud bases at two levels, 1500 m (cumulus?) and 4000 m (altocumulus). Aircraft observations indicated that the Ac layer top was near 4500 m. No clouds had been detected during the previous hour.

With no forcing, the CRM produced a cumulus cloud based at 1500 m. The cumulus cloud detrained at 4500 m and formed a scattered to broken Ac layer about 500 m thick. To correctly predict the occurrence of such an Ac cumulogenitus layer in a GCM would require diagnosing detrainment of cloud liquid water from cumulus clouds.

In situ aircraft measurements of temperature, relative humidity, liquid water content, vertical velocity, and cloud droplet spectrum are available for the 24 April 1994 Ac case. The aircraft was flown in a series of horizontal legs at different altitudes. Statistics have been calculated for each leg, including means, variances, and updraft and downdraft properties. The measurements have been compared with results from our 2D CRM simulation based on this case. There is general agreement between them. Most importantly, the measurements show that this Ac layer is approximately well-mixed, with small differences in average updraft and downdraft properties, and nearly equal average updraft and downdraft speeds.

We also compared measurements of cloud frequency, cloud base height, and liquid water path made at the SGP central site on 24 April 1994 with the results of our 2D CRM simulation. Again, there is general agreement between them.

3.2 Parameterizing altocumulus formation and structure

Ac occurrence and structure will be parameterizable in principle if Ac layers are maintained by a balance between cloud-scale processes and larger-scale processes. Based on our numerical simulations, it appears that Ac structure can be obtained using the 2D CRM or 1D TCM if detailed vertical profiles of temperature, water vapor, large-scale vertical velocity, and sources of water vapor and liquid water from cumulus detrainment are provided. The resulting structure (i.e., cloud thickness and liquid water content) depends on the cloud-scale interactions of radiative destabilization and the resulting turbulent transport. For the conditions considered in our simulations, the Ac structure is evolving. For this reason, we chose to develop a simple model that predicts the evolution of Ac structure as our first step toward parameterizing vertically sub-grid scale Ac for GCMs.

The effects of Ac on the atmosphere are primarily to modulate the radiation field, although our simulations indicate that turbulent transport by Ac may be significant as well. Parameterizing the radiative effects of vertically sub-grid scale Ac layers in a GCM is similar to parameterizing the radiative effects of grid-scale cloud layers. The main problem is to specify realistic optical properties, including the mean effective radius (r_e) and the liquid water path (LWP), for the Ac layers. The key quantity to determine is the Ac layer depth. From this we can calculate the LWP.

Our idealized CRM simulations and the *in situ* measurements show that Ac layers are approximately well-mixed. However, unlike stratocumulus mixed layers, Ac mixed layers are decoupled from the surface. Therefore, we have developed an elevated mixed layer model (MLM) to parameterize the evolution and structure of Ac layers (Liu and Krueger 1996b,c). The MLM includes prognostic equations for moist static energy (h), total water mixing ratio (q_w), Ac mixed-layer top height (z_T), and Ac mixed-layer base height (z_B). The turbulent fluxes of h and q_w just below z_T are derived from the budget equations for the cloud-top inversion layer. We found no jumps in h and q_w at z_B in 13 out 14 Ac soundings at Salt Lake City, Utah. We therefore assumed that the turbulent fluxes are zero at z_B. In order to calculate the radiative fluxes, we divide the cloud layer into ten equal layers and use the same radiation code as used by the CRM. To close the MLM, the entrainment velocity at z_t and the detrainment velocity at z_B must be parameterized. For the former, we used the closure of Wyant and Bretherton (1992), while, for simplicity, we set the latter to zero.

The cloud top and base heights predicted by the MLM are in reasonable agreement with those from an idealized CRM simulation. However, whereas the the cloud thickness and the LWP for the CRM simulation decrease, those for the MLM simulation increase. The MLM predictions can be improved by allowing detrainment at the mixed layer base.

To incorporate the vertically sub-grid scale MLM into a GCM will require a parameterization of GCM sub-grid scale vertical structure related to Ac formation. We have collected soundings, ceilometer observations, and photographs of Ac and altostratus (As) layers occurring at Salt Lake City for 3 years in order to characterize the typical vertical thermodynamic structure associated with each. The most significant feature of Ac layers is a dry, stable layer above a distinct cloud top, much like stratocumulus, while As have an indistinct cloud top with no dry, stable layer above. There usually are no large gradients at the bases of Ac layers. Our simulations show that Ac tend to increase the cloud-top gradients. Should we expect the typical vertical structure associated with Ac to exist before an Ac cloud layer forms? This remains to be answered.

3.3 Parameterizing altocumulus radiative effects on the atmosphere

To include the radiative effects of vertically sub-grid scale Ac layers in climate models, we developed and tested parameterizations of Ac optical properties (liquid water path and mean effective radius). The solar radiative effects of Ac are determined by the LWP and r_e. The IR effects of an Ac layer on the atmosphere depend on its temperature and its "blackness", as measured by its effective upward and downward emissivities. Due to their thinness, Ac layers are often nonblack.

The LWP is determined by an Ac mixed layer model. To develop a simple parameterization of r_e in Ac clouds, we used a droplet growth model and *in situ* measurements of Ac droplet spectra. So far, we have used K. Sassen's detailed droplet growth model to predict the droplet spectrum evolution in a non-entraining parcel rising from cloud base to cloud top of the Ac layer observed on 24 April 1994. Compared to the aircraft-measured droplet spectra, the calculated spectra are too narrow and contain too much liquid water. This is most likely due to neglecting the effects of entrainment and mixing. However, the measured and calculated profiles of r_e agree remarkably well. The results suggest that a simple parameterization of effective radius for Ac layers can be obtained using this model that depends only on cloud base temperature, cloud thickness, and droplet concentration.

4 Project Activities: 1996–1999

Our original goals during this period of support were to develop and test GCM parameterizations for (1) vertically sub-grid scale altocumulus (Ac) layers and (2) cloud-topped boundary layers. However, we also became involved in several additional research efforts. Each of these is briefly described below.

4.1 Altocumulus formation, structure, and parameterization

Ac layers are usually thin. Out of 14 Ac layers observed at Salt Lake City, 7 were less than 250 m thick based on radiosonde measurements. Two were less than 100 m thick. For this reason, vertically sub-grid scale cloud layers may need to be better represented in GCMs.

Our research on Ac clouds during this period was a continuation of research begun during the period 1993-96 under ARM support. A large part of this research formed the basis of Shuairen Liu's Ph.D. dissertation (Liu 1998). In addition to increasing our knowledge of the formation and structure of Ac clouds, we developed an elevated mixed layer model for Ac clouds, which provides a framework for parameterizing vertically sub-grid scale Ac layers in GCMs (Liu and Krueger 1998a,b,c).

During this period, we continued to use a high-resolution cloud-scale numerical model, the University of Utah Cloud Resolving Model (UU CRM), to perform numerical simulations of altocumulus cloud layers in idealized and observed large-scale environments. The goal was to determine in detail how the large-scale motion field, in combination with the cloud-scale radiative, microphysical, and dynamical processes, governs the life cycle and structure of altocumulus layers. A closely related goal was to determine the extent to which altocumulus clouds are indeed parameterizable in terms of large-scale processes.

4.1.1 Effects of radiation in simulated altocumulus cloud layers

Our cloud climatology of the SGP site (section 4.4) revealed that Ac layers have a diurnal maximum in cloud amount around sunrise, and that it is most pronounced during the summer. We decided to test the hypothesis that this diurnal cycle is radiatively driven.

Numerical simulations for idealized nocturnal (no solar radiation) and diurnal (with diurnally varying solar radiation) altocumulus (Ac) cases were carried out with the 2D University of Utah Cloud Resolving Model (CRM) (Liu and Krueger 1997). In the nocturnal case, feedbacks between the liquid water path (LWP), IR radiation, and entrainment lead to a relatively thick Ac layer with a nearly steady structure and circulation. The solar radiation in the diurnal case leads to decreases in the LWP, circulation intensity, and entrainment rate during the day relative to the nocturnal case. In the diurnal case, solar radiative heating in the cloud layer eliminates the radiative convective destabilization and evaporates most of the cloud. However, a thin cloud layer in which the net radiative heating is near zero is able to be maintained through the afternoon. The cloud thickens again after sunset.

4.1.2 Elevated mixed layer model

Our idealized CRM simulations and in situ measurements show that Ac layers are approximately well-mixed. Therefore, we developed a 1D elevated mixed layer model (MLM). The

Ac MLM uses a method for determining the entrainment rate at the mixed layer top that is used in many MLMs of stratocumulus-topped boundary layers (STBLs). In 1996, we noted that we hoped to improve the MLM predictions by allowing detrainment at the mixed layer base. The Ac MLM was revised so that it detrains at the mixed layer base at a rate that keeps BIR, the ratio of buoyant consumption of turbulent kinetic energy in the subcloud layer to buoyant production in the cloud layer, equal to BIRmax. This approach is based on that used by Turton and Nicholls (1987; TN) in their multiple mixed layer model. The numerical value of BIRmax determined from our CRM simulations of Ac layers is about -0.02. This is about a tenth of the values used by TN and by Brethterton and Wyant (1997) for decoupled STBLs. At present, there is no theory for determining this ratio.

To test the Ac MLM, we made a comparison of 20-hour simulations Ac layers from the MLM and CRM. The resulting LWP, cloud top, cloud base, and mixed-layer base heights for the two models agree quite well. The profiles of scalar variables and fluxes for the two models also agree well or reasonably well.

Sensitivity tests for the MLM indicate that the entrainment rate at the top of Ac layers and the detrainment rate at the bottom depend on both the constant in the entrainment rate equation and BIRmax. The LWP is sensitive to these two constants and the above-cloud inversion layer thickness. However, the cloud top, cloud base, and mixed layer base heights are not sensitive to these factors.

We also used a 1D version of the CRM to study the turbulent kinetic energy budget of Ac layers and the effect of the relative humidity (RH) above cloud top.

The TKE budget shows that the TKE is produced by buoyancy in the cloud region, redistributed upward and downward through turbulent transport, and destroyed by dissipation. Other TKE generation terms are small. The evolution of the TKE budget is strongly related to the diurnal cycle. The buoyant production and dissipation are large at night, become weak in the daytime, and recover after sunset. The transport is large at night and has no impact in daytime. The magnitudes of the budget terms for our simulated nocturnal Ac clouds are larger or comparable to those for a simulated nocturnal STBL.

The results from the simulations with no large-scale vertical motion indicate that Ac clouds become thicker when the RH above the cloud is high (80%), which is similar to the results for stratocumulus clouds found by Randall (1984). The Ac cloud was maintained for more than 36 hours even when the RH above the cloud is as low as 20%. This is an interesting result.

4.2 Testing a cloud fraction parameterization using retrievals based on cloud radar measurements

Our ARM-supported research on cloud-topped boundary layers was begun during the period 1996-99 in collaboration with Shelby Frisch (CIRA/CSU and NOAA/ETL). We used Frisch's cloud radar retrievals of boundary layer cloud properties to test a cloud fraction parameterization. We used retrievals based on measurements taken at Porto Santo during ASTEX (Atlantic Stratocumulus Transition Experiment) because the insect contamination of boundary layer radar echoes so prevalent at the ARM SGP (Southern Great Plains) site did not occur at Porto Santo. Frisch has provided retrievals of boundary layer cloud properties at Porto Santo for the entire month of June 1992.

We evaluated a cloud fraction parameterization developed by Xu and Randall (1996; XR) that depends on the liquid water content and the relative humidity (Lazarus et al. 1999a,b). In order to perform these tests, we used time series of the input quantities including vertical profiles of the liquid water content retrieved from observations of reflectivity and liquid water path from a microwave radiometer (Frisch et al. 1995) and relative humidity from radiosondes. The output quantity, the cloud fraction profile, was then compared to the cloud fraction profile obtained from the cloud radar.

We found that such an observational test is difficult because of biases in the radiosonde relative humidities, the effect of limited sampling of the relative humidity field (one radiosonde every 3 hours), problems in defining the cloud fraction using the cloud radar measurements (i.e., partly cloudy radar volumes), and the difficulty of estimating spatial averages from temporal averages. Results from high-resolution CRM simulations of cloud-topped boundary layers (e.g., Krueger et al. 1995) helped to resolve some of these issues (Frisch and Krueger 1997).

4.3 Altocumulus and stratocumulus radiative effects on the atmosphere: Comparison of calculated and measured radiative fluxes

An indirect way of testing cloud parameterizations (including cloud overlap assumptions) is to compare the predicted and observed cloud radiative forcing at the surface and/or the top of the atmosphere. This approach is commonly used to test (and tune) GCM cloud parameterizations. However, this approach can also be applied to cloud-resolving models, single-column models, and to single columns of NWP models. A meaningful application of such a test requires an accurate radiative transfer code and realistic cloud optical properties.

In order to gauge the potential usefulness of this method, we used observed cloud properties and an accurate radiative transfer code to calculate the downwelling broadband solar and infrared radiative fluxes at the surface and compared them to measured values for a scattered to broken altocumulus layer observed at the Southern Great Plains ARM CART site on April 24, 1994, and for an overcast stratocumulus layer observed on April 30, 1994 (Xia et al. 1997, 1998). Good estimates (that is, with errors that are small compared to the differences between the clear-sky and cloudy-sky fluxes) of the downwelling solar and IR fluxes at the surface were obtained during mostly cloudy periods under both cloud layers. Estimates of the downwelling fluxes under the Ac layer based on the ceilometer's temporal cloud fraction were not very good, and indicate an underestimate of the actual cloud fraction.

The cloud properties required for the radiative transfer calculations were obtained with a combination of microwave radiometer measurements of the time-varying LWP and aircraft measurements of the average cloud base height, cloud top height, and effective radius profile.

We also calculated the temporal variations of the downwelling broadband solar and infrared radiative fluxes at the surface using cloud properties retrieved by Shelby Frisch from cloud radar and microwave radiometer measurements and compared them to measured values for a stratocumulus layer observed at Porto Santo, Madeira Islands, on June 17, 1992 during ASTEX. The calculated solar fluxes systematically underestimate the observed flux. Unfortunately, there were no aircraft measurements of cloud properties at Porto Santo during ASTEX, so the retrieved cloud properties could not be validated.

These results suggest that frequent whole-sky cloud cover measurements as well as accurate cloud optical properties are required to obtain realistic estimates of the downwelling solar flux at the surface.

4.4 A cloud climatology of the ARM SGP CART

We constucted a cloud climatology of the ARM SGP site based on ARM Belfort Laser Ceilometer (BLC) and Micropulse Lidar (MPL) measurements of cloud-base height, ISCCP (International Satellite Cloud Climatology Project) cloud statistics, and Edited Cloud Reports (ECRs) from synoptic weather reports (Lazarus et al. 1998, 2000). We examined the annual, seasonal and diurnal cycles of cloud amount as a function of cloud height and type. The three data sets best agree for total cloud amount. The agreement is especially good between the ISCCP and ECR datasets; the differences between the two are not statistically significant.

We applied the random overlap assumption to estimate low, middle, and high cloud amounts. We found good agreement in the ECR and MPL/BLC monthly low cloud amounts. With the exception of summer and midday in other seasons, the ISCCP low cloud amount estimates are generally 5-10% less than the others. This finding is consistent with the satellite literature which indicates that IR threshold techniques (used to distinguish between the clear and cloudy sky) have diculty detecting low clouds. The ECR high cloud amount estimates are typically 10-15% greater than those obtained from either the ISCCP or MPL/BLC data sets. Even though they are unobscured, ISCCP high cloud amounts are likely underestimated, in part due to a relatively conservative IR threshold.

We found that low cloud coverage is at a minimum during summer. The peak in summer cumulus (Cu) are offset by a minimum in both stratocumulus (Sc) and stratus (St). The Cu diurnal maximum (minimum) occurs at 12 LST (00 LST) with summer (winter) experiencing the largest (smallest) diurnal variation. St are most common in winter while Sc are observed more frequently during spring. St exhibits a diurnal maximum at 06 LST and Sc at 12 LST. Cumulonimbus are most commonly observed during the summer rather than spring. Ac are more common than both altostratus and nimbostratus (Ns) for all seasons with the exception of winter Ns. Winter and spring cirrostratus (Cs) display similar diurnal cycles with increasing amounts from 00 LST to 18 LST. Cirrus (Ci) nocturnal amounts are less than their daytime values. Both Ci and Cs amounts show relatively little seasonal variation.

4.5 Intercomparisons of multi-day simulations of convection

4.5.1 GCSS WG 4: Case 2, TOGA COARE

We led a GCSS (GEWEX Cloud System Study) Working Group 4 (Precipitating Convective Cloud Systems) model intercomparison project that evaluated cloud resolving models and single-column models by testing their ability to determine the large-scale statistics of precipitating convective cloud systems during a multiday period of TOGA COARE (Tropical Oceans Global Atmosphere Coupled Ocean-Atmosphere Response Experiment) (Moncrieff et al. 1997, Krueger 1997a,b; Krueger and Lazarus 1998, 1999a,b, 2000). The large-scale quantities required for the simulations (initial conditions, upper and lower boundary conditions, and large-scale forcing) were based on observations averaged over the Intensive Flux Array (IFA, about 500 km by 500 km). The participating models included seven 2D CRMs, one 3D CRM, and nine SCMs.

We evaluated the models by comparing the results of the simulations to observed large-scale (average) quantities, including the temperature and water vapor profiles, cloud cover, cloud (liquid plus ice) water path (CWP) derived from visible optical depth, surface turbulent fluxes, and the surface and TOA solar and IR radiative fluxes.

The similarities between the results from the CRMs and the observations for tropospheric enthalpy, precipitable water, OLR, and cloud (liquid plus ice) water path, among others, confirms that the bulk characteristics of convection are determined (in a diagnostic sense) by the large-scale thermodynamic advective tendencies, and suggests that CRMs are useful tools for performing this diagnosis.

We expect, in general, that the representation of cloud processes is more realistic in CRMs than in SCMs. The results confirm this. The CRM results in general are in much better agreement with the OLR and CWP observations than are the SCM results. Systematic differences between the SCM and CRM results were identified for several other quantities, as well, and suggest that the CRM results should be useful for improving the SCMs.

Additional CRM results suggest that the ice water path, the cloud fraction, and the TOA radiative fluxes due to deep tropical cumulus convection are basically parameterizable in terms of the cloud mass flux. (However, this conclusion may need to be modified in when hydrometeor advection is significant.)

4.5.2 GCSS WG 4 and ARM SCM WG: Case 3, SGP CART

Ric Cederwall, Dave Randall, and I initiated a collaborative intercomparison of SCMs and CRMs that focused on the Summer 1997 SCM Intensive Observation Period (IOP) at the SGP site (Cederwall et al. 1998, 1999). The study involved the ARM Single-Column Model (SCM) Working Group, the ARM Cloud Working Group (CWG), GCSS WG 4 (Precipitating Convective Cloud Systems), and the NCEP's Environmental Modeling Center. The Summer 1997 IOP provided a 30-day data set that includes a range of meteorological conditions, but is dominated by deep convection.

4.6 Radiative fluxes and heating rates during TOGA COARE

In order to better evaluate cloud and radiation models, including those that participated in the GCSS WG 4 Case 2 intercomparison described in the previous section, we used the surface radiation measurements taken at five surface sites in the Intensive Flux Array (IFA) during TOGA COARE and satellite-derived TOA fluxes to estimate the 3-hourly time series of the atmospheric radiative heating rate in the IFA (Burks and Krueger 1999, Krueger and Burks 1998, 1999). This research formed the basis of a Master's thesis by Jason Burks (Burks 1998).

We used a simple average of the surface IR downwelling flux measured at the five surface sites to estimate the IFA-averaged surface IR downwelling flux. Based on Barnett et al.'s (1998) study of the correlation between point and area-averaged measurements of the downwelling solar radiative flux averaged over various time intervals, we concluded that the measurements of downwelling solar flux from the five IFA surface sites were not likely to be representative of the entire IFA when averaged over 3-hour time intervals (although they would be when averaged over longer time intervals, such as a month). Therefore, we determined the relationship between the solar transmission and the co-located satellite-derived albedo and used this relationship to estimate the IFA-averaged surface solar downwelling flux from the satellite-derived albedoes.

We used three TOA broadband radiative flux datasets to estimate the IFA-averaged TOA radiative fluxes: ISCCP Flux Cloud, Minnis, and Collins. While the outgoing IR estimates were quite similar, there was a significant range in the estimated global albedoes averaged over the four months of COARE: 0.23, 0.28, and 0.29. (The person who provided the dataset with the lowest average albedo later discovered that he made a processing error that contributed to the low albedoes.)

4.7 Comparisons of Cloud Cover Estimates and Cloud Fraction Profiles

I collaborated with Dan Rodriguez to compare estimates of cloud cover and cloud fraction profiles at the SGP site derived from measurements by geostationary satellite, millimeter cloud radar (MMCR), whole sky imager, micropulse lidar, and Belfort laser ceilometer (BLC) (Rodriguez and Krueger 1999).

We were we are especially concerned about (1) the accuracy and correspondence between various estimates of cloud properties within a narrow vertical column above the SGP Central Facility (CF) (results are usable by both SCM and IRF needs); and (2) the accuracy and correspondence between various estimates of average cloud properties over the SGP CART site (results satisfy SCM needs specifically).

We found that (1) The old Whole Sky Imager algorithm severely underestimates cloud amounts. (2) Estimates of the daytime cloud cover over the CF during the Summer 1995 SCM IOP obtained from satellite data (using the Minnis algorithm) exceed the estimates from MPL/BLC data . (3) The 3-hourly daytime cloud fraction profiles over the CF during the Summer 1997 SCM IOP obtained from satellite data (using the Minnis algorithm) agree well with those from the MMCR for high clouds, but are an underestimate for low clouds. (No cloud overlap assumptions were applied.) (4) The 3-hourly daytime cloud fraction profiles obtained from satellite data during the Summer 1997 SCM IOP over the CF and over the entire CART are also highly correlated. This indicates that the 3-hourly cloud fraction profiles obtained using the MMCR are representative of the entire CART, and thus will be very useful for SCM evaluation.

5 Project Activities: 1999–2001

5.1 Summary

- We tested a GCM cloud fraction parameterization derived from cloud resolving model (CRM) results using retrievals of LWC profiles based on cloud radar and microwave radiometer measurements (Lazarus et al. 2000). We investigated the impact of the observational uncertainties involved due to sampling by sampling the results of CRM simulations in the same manner. We found that due to the mesoscale variability of LWC, the LWC must be time-averaged for at least 3 hours in order to obtain a sufficiently accurate estimate of its large-scale value for use in the cloud fraction parameterization.

- We initiated a GCSS (GEWEX Cloud System Study)/ARM model intercomparison project that evaluated cloud resolving models and single-column models by testing their ability to determine the large-scale statistics of precipitating convective cloud systems during three multiday periods during the Summer 1997 SCM IOP at the SGP site (Xu et al. 2000, 2002; Xie et al. 2002). The time-averaged CRM results for periods of deep convection show consistenly smaller biases of time-averaged temperature and water vapor than do the SCM results using traditional forcing methods. The time-averaged CRM cloud fraction profiles are in reasonable agreement with the observations from the cloud radar, while many of the SCM profiles are not. The CRM and SCM mass flux profiles show significant differences in the lower troposphere.

- We compared various macroscopic cloud properties, including the cloud fraction profiles, for the entire Summer 1997 SCM IOP as observed by the MMCR, simulated by the UCLA-CSU CRM, and simulated by the NCEP SCM. Observed and simulated cloudiness during Case 3 was dominated by high clouds. Many of these cirrus clouds were initially generated by deep convection, while others formed in situ due to large-scale ascent in the upper troposphere.

- We compared cirrus statistics (frequency distributions of IWP, IWC, layer thickness, mid-cloud height, etc.) obtained from the UCLA-CSU CRM simulation for the Summer 1997 SCM IOP at the SGP site to Mace et al.'s (2001) statistics (which are for an entire year) (Luo et al. 2003). The results demonstrated that CRM results can be sampled in a way that allows direct comparison to ARM cirrus cloud property retrievals. This type of comparison allows an unprecedented evaluation of a CRM's representation of cirrus cloud physics.

- We used observations, cloud-resolving model simulations, and NCEP single-column model simulations to evaluate the NCEP model's representation of the effects of deep cumulus convection on the boundary layer over the southern Great Plains of the United States during the 1997 Summer SCM IOP (Krueger et al. 2000a,b; 2001).

- NCEP's Global Modeling Group began to produce twice-daily column output files from the global model forecasts in November 2000 for the four ARM sites. The column output files contain forecasts every 3 hours out to 48 hours and include all the information necessary to run SCMs and CRMs (i.e., initial fields and time-dependent boundary conditions), and allow one to evaluate the global model's cloud and radiation fields at all ARM sites on a continuous basis (Lazarus and Krueger 2002b, Yang et al. 2006).

5.2 Using ARM Measurements to Test a Cloud Fraction Parameterization

We submitted a paper to the Journal of Geophysical Research in which we compared observed boundary layer cloud fractions with a cloud fraction parameterization developed by Xu and Randall (1996, hereafter XR). XR proposed to relate the large-scale cloud fraction to the large-scale cloud water mixing ratio and relative humidity. By "large- scale" we refer to space and time scales resolved by a global NWP model or a global climate model.

We used both CRM results and observations to examine various aspects of this parameterization. The observations, collected during ASTEX, include relative humidity (obtained from 3-hourly radiosonde soundings), and liquid water content and cloud fraction (obtained from millimeter cloud radar measurements and cloud water content retrievals).

Results indicate that proper evaluation of the parameterization depends on how one estimates both the observed and parameterized cloud fractions. In particular, differences in observed cloud fraction estimates (obtained from a millimeter cloud radar) depend on how one defines cloud occurrence as well as radar sensitivity.

We examined the scale dependency of the parameterization by varying the temporal average of the inputs (i.e., liquid water content LWC, and relative humidity RH). We found that for values of LWC and RH typical of ASTEX, that the relationship between the LWC and parameterized cloud fraction is approximately linear (for a fixed RH) while that between the RH and parameterized cloud fraction is biased towards low cloud fraction (for a fixed LWC).

Estimates of the parameterized cloud fraction were, however, relatively insensitive to varying temporal averages (on the order of 1-3 h) of LWC. This indicates little mesoscale variability in the retrieved liquid water content.

Using a CRM stratus-to-cumulus simulatio to determine whether or not the sonde RH and retrieved liquid water content were representative of their large-scale values, we showed that the mesoscale variability (i.e. time/space averages varying from 0-3 h and 0-200 km) of LWC is greater than that of the RH. In contrast, the ASTEX results indicated only slight differences between the parameterized cloud fraction profiles estimated using 40 and 180 minute averages of the retrieved LWC.

5.3 Evaluation of multi-day simulations of continental deep convection

The goal of GCSS (GEWEX Cloud System Study) is to improve our understanding of and ability to parameterize cloud systems through numerical simulations with cloud resolving models. Input from large-scale modeling centers has been very helpful in guiding the efforts of GCSS. Large-scale modelers at NCEP and ECMWF identified the following processes as two of those most in need of improved representation in their parameterizations of precipitating convective cloud systems.

- The occurrence (frequency and intensity) of deep convection. This includes the diurnal cycle over land, and other interactions with the boundary layer.
- The production of upper tropospheric stratiform clouds by deep convection. A related issue: How much microphysical complexity is required in GCMs?

The importance of these processes has influenced the aspects of cloud parameterization testing and improvement that GCSS Working Group 4: Precipitating Convective Cloud Systems has focussed on. It has motivated WG 4 to shift the emphasis of its research from oceanic precipitating convective cloud systems (i.e., TOGA COARE) to continental ones (i.e., ARM SGP). GCSS WG 4 collaborated with the ARM SCM WG in its Case 3 intercomparison project. This case involved evaluation of simulations of continental deep convection based on intensive measurements taken at the ARM SGP site during the Summer 1997 SCM IOP. The millimeter cloud radar (MMCR) was operational during this time and provided profiles of cloud fraction. In addition, Jay Mace has performed retrievals of thin cirrus cloud properties for this period (Mace et al. 2001).

Case 3 included three 4- or 5-day subcases for CRMs to simulate. Participation by CRMs (mostly unaffiliated with ARM) and SCMs was excellent. Seven CRMs (two with both 2D and 3D simulations) and seven SCMs submitted results. Two papers were published based on Case 3 (Xu et al. 2002; Xie et al. 2002).

The results of Case 3 strongly confirm what Case 2 (based on multiday period of TOGA COARE) suggested: (1) The CRM results for periods of deep convection show consistenly smaller biases of temperature and water vapor than do the SCM results using the same large-scale advective forcing methods. (2) The time-averaged CRM cloud fraction profiles are in reasonable agreement with the observations from the cloud radar, while many of the SCM profiles are not. (3) The CRM and SCM mass flux profiles show significant differences in the lower troposphere. (4) The CRM surface precipitation rates are better correlated with the observations than those from SCMs.

Observed and simulated cloudiness during Case 3 was dominated by high clouds. Many of these cirrus clouds were initially generated by deep convection, while others formed in situ due to large-scale ascent in the upper troposphere. The SCM cloud fractions were typically too large in the upper troposphere. This, and the dominance of cirrrus, motivated us to focus further cloud evaluation on cirrus clouds by comparing the properties of those retrieved by Jay Mace to those simulated by the CSU CRM (see below).

In addition, we found that the convection (and associated clouds) produced in the CRM simulations is sometimes delayed by a few hours relative to observations. The delayed convection is usually more intense than observed as well. This, and the its generation of cirrus clouds by deep convection, motivated us to examine the processes that determine the occurrence and intensity of deep convection, specifically, the effects of deep convection on the boundary layer (see below).

5.3.1 Cloud fraction profiles: Simulated compared to observed

We began our analysis of the NCEP SCM's cloud parameterization by comparing the cloud fraction profiles for the entire IOP as observed by the MMCR, simulated by the UCLA-CSU CRM, and simulated by the NCEP SCM (Figure 1).

The UCLA-CSU Cloud Resolving Model is identical to the UU CRM except for the radiation code. Both include 2D anelastic dynamics, a 3d-moment turbulent closure, bulk 3-phase microphysics, and interactive radiative transfer. The domain used was 512 km wide and 18 km deep. The horizontal grid size was 2 km; the vertical grid size ranged from 100 to 800 m.

Barnett et al. (1998) found that a 3-hour time average of solar radiation (with diurnal cycle removed) on cloudy days at a single point has a correlation of 0.6 with the average over a region of radius 90 km. Thus, even with a perfect model and 3-hour time averaging, we cannot expect perfect correlation of the simulated cloud fraction over the large-scale CRM/SCM domain (radius 150 km) with the cloud fraction observed by the cloud radar (a point measurement).

Given the above limitation on the expected agreement on short time scales, the CRM cloud fraction is in mostly good agreement with the observed, except on the first day, and around the middle of the simulation when a clear period was observed. A plausible explanation for these difference is that specifying the large-scale advective tendency of condensate to be zero in the CRM simulation (due to lack of observations) does not allow clouds that formed outside the domain to move in, or clouds that formed inside the domain to move out.

There are significant differences between the NCEP SCM and observed cloud fraction profiles, most notably in the SCM's underestimate of cloud fraction at high levels. In this version of the NCEP SCM, stratiform cloud fraction was diagnosed according to the relative humidity, and the convective cloud fraction according to the intensity of the convection. The total cloud fraction equals the convective cloud fraction if present; otherwise, it equals the stratiform cloud fraction.

As noted above, this initial evaluation of the clouds in the NCEP SCM directed our

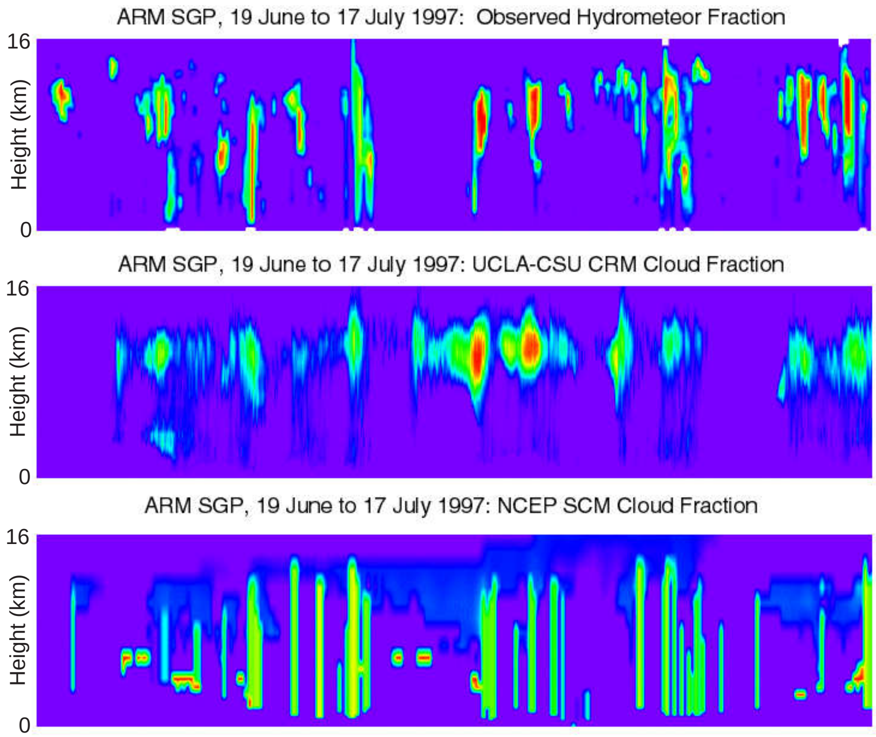

Figure 1: Time-height cloud fraction at ARM SGP, 19 June to 17 July 1997, surface to 16 km: (top panel) observed by MMCR (3-hour averages), (middle panel) simulated by UCLA-CSU CRM (1-hour averages), and (bottom panel) simulated by NCEP SCM (3-hour averages). Color indicates cloud fraction, which ranges from 0 (violet) to 1 (red).

attention to its representation of cirrus clouds, and the effects of deep convection on the boundary layer. The results of these efforts are described briefly in the next two sections.

5.3.2 Cirrus Cloud Statistics: Simulated Compared to Observed

Mace et al. (2001, hereafter MCA) used cloud radar and IR spectral radiometer measurements to retrieve 3-minute-averaged thin cirrus properties over the ARM SGP site when there were no lower clouds. We sampled results (provided by Kuan-Man Xu) of a 29-day simulation by the UCLA-CSU CRM of the Summer 1997 SCM IOP at the ARM Southern Great Plains site at 8 grid columns (64 km apart) every 5 minutes using the same criteria.

We compared the CRM's thin cirrus and all-cirrus statistics (frequency distributions of IWP, IWC, layer thickness, and mid-cloud height) to MCA's statistics. The comparisons are shown in Figure 2. From these comparisons, we concluded that the CRM is able to reproduce the important aspects of the observed properties of cirrus clouds. We are also able to conclude that the fall speed of large ice crystals is probably too large in the CRM.

This study demonstrates that CRM results can be sampled in a way that allows direct comparison to MCA's cirrus cloud property retrievals. This allows evaluation, in a statistical sense, of the CRM's representation of cirrus cloud physics. Note that SCM results cannot be directly compared to Mace's retrievals because the retrieval criteria must be applied locally, not on the scale of GCM grid cell. However, SCM results can be compared to CRM results

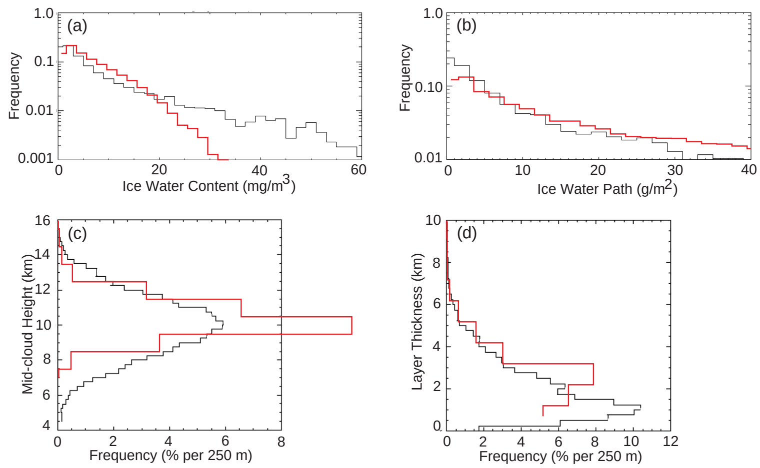

Figure 2: **Red:** From a UCLA-CSU CRM simulation of a 29-day period (19 June to 17 July 1997). **Black:** From Mace et al. (2001) based on one year (Dec. 1996 to Nov. 1997) of MMCR measurements (a) Frequency distribution of layer-mean IWC (ice water content) for thin cirrus clouds.(b) Frequency distribution of IWP (ice water path) for thin cirrus clouds. (c) Frequency distribution of mid-cloud height for for thin cirrus clouds (CRM) and for all cirrus clouds (Mace et al.).(d) Frequency distribution of cirrus thickness for thin cirrus clouds (CRM) and for all cirrus clouds (Mace et al.).

(when horizontally averaged). Thus, CRM simulations can be used to link observations and SCMs.

As they stand, MCA's cirrus property statistics could be used as the basis of empirical parameterizations of cirrus properties as functions of temperature and other large-scale quantities. However, in agreement with the authors, we believe that the next step should be to better understand the underlying physics of cirrus clouds that lead to such statistics. The excellent qualitative agreement between the CRM simulation and MCA's cirrus statistics demonstrates that the essential physics of cirrus cloud formation, maintenance, and decay are exhibited in the CRM simulation.

Previous studies of cirrus cloud-scale physics, for example those by Starr and Cox (1985a,b) and Köhler (1999), have shown the utility of idealized cloud-resolving model simulations to better understand the roles of various physical processes in cirrus clouds. Heymsfield and Donner (1990), Donner et al. (1997), and Köhler (1999), among others, have proposed physically based parameterizations for cirrus cloud properties and/or processes.

These investigations, taken in conjunction with MCA's cirrus statistics and our corresponding analysis of CRM results, suggest that the properties of cirrus clouds that form in situ as a result of large-scale ascent ("large-scale" cirrus) can be largely explained as an approximate balance between ice production by deposition, due to the decrease of saturation mixing ratio, and ice loss due to sedimentation, as proposed by Heymsfield and Donner. We used a parcel model that includes the CRM's microphysics parameterization, but not radiation or cloud-scale circulations, to examine this hypothesis. In this model, ice production,

P, depends primarily on temperature and vertical velocity, (greater at higher temperatures and for larger vertical velocities), while sedimentation loss, L, depends on the ice mixing ratio, q_i, and the residence time of ice in the layer, τ. The residence time depends on the layer thickness, h, and the ice fall speed, V_i. The result is

$$\frac{dq_i}{dt} = P - L = P - \frac{q_i}{\tau} = P - \frac{q_i V_i}{h}.$$

The steady-state ice mixing ratio is then given by $q_i = P\tau = Ph/V_i$. In this model, the steady-state ice mixing ratio depends on several large-scale parameters (temperature, vertical velocity, and cloud thickness) as well as a microphysical parameter (the ice fall speed). For small vertical velocities (e.g., 2 cm/s), a steady state ice mixing ratio is achieved about three hours after cloud formation in this model. This analysis confirms what is well-known from observational studies of cirrus. It also shows that a parameterization of cirrus ice mixing ratio that depends only on temperature is not universal, because it depends on (at least) the joint frequency distribution of ice water mixing ratio with temperature, vertical velocity, cloud thickness, and fall speed.

5.3.3 Interactions of Deep Cumulus Convection and the Boundary Layer over the Southern Great Plains

Over most of the planet, the occurrence and intensity of deep convection is highly correlated with destabilizing processes, such as large-scale ascent, or boundary layer heating. Convection itself generally stabilizes the atmosphere: Compensating subsidence warms and dries the atmosphere above the boundary layer, while convective downdrafts generally cool and dry the boundary layer. Convective downdrafts are especially difficult to represent in large-scale models. Case 3 offered an exciting opportunity to study the effects of continental deep convection on the boundary layer, so we analysed these effects and compared our analysis to results from the UU CRM and the NCEP SCM.

We used observations, cloud-resolving model simulations, and single-column model simulations to better understand how to parameterize the effects of deep cumulus convection on the boundary layer over the southern Great Plains of the United States. The observations were from the 29-day DOE ARM Single Column Model (SCM) Intensive Observation Period (IOP) that took place at the ARM Southern Great Plains (SGP) site during June and July 1997.

The SCM IOP observations included temperature, humidity, and wind profiles from radiosondes launched at 3-hourly intervals from the CF and the four BFs, surface turbulent and radiative fluxes, rainfall rates based on a combination of radar and rain gauge measurements, top-of-atmosphere radiative fluxes, cloud amounts, and cloud fraction profiles obtained from a cloud radar. The surface turbulent fluxes were measured every thirty minutes by 10 EBBR stations located at the CF and several of the Extended Facilities.

The ARM DSIT processed the observations using a constrained variational analysis technique (Zhang and Lin 1997) in order to obtain estimates of the advective tendencies of temperature and water vapor averaged over the SCM domain, an area that corresponds approximately to the SGP site. These estimates, along with those of the surface turbulent fluxes and the radiative heating rate profile, make it possible to perform diagnostic studies of the interaction between convection and the boundary layer, as well as simulations of this interaction using CRMs and SCMs. We undertook all three approaches.

The cumulus effects in the boundary layer are due to rain evaporation and the fluxes due to cumulus updrafts and downdrafts. We distinguish cumulus fluxes from boundary layer turbulence fluxes. For simplicity, we assumed that the actual turbulent flux profiles are linear with height above the surface at all times, that they equal the observed surface fluxes at the surface, and vanish at the boundary layer top. We also assumed that the fluxes due to cumulus convection vanish at the surface.

With these assumptions, we estimated the cumulus effects in the boundary layer using ARM observations obtained during the SCM IOP. The ARM variational analysis provides Q_1 (the large-scale heat source due to sub-grid scale processes) and Q_2 (the large-scale water vapor sink due to sub-grid scale processes). In addition, we have observational estimates of Q_R (the large-scale radiative heating rate), the surface fluxes of sensible and latent heat due to turbulence, and the boundary layer depth.

We performed simulations of the Summer 1997 SGP SCM IOP with two models: the UCLA/CSU Cloud Resolving Model. and the NCEP Single Column Model. In the NCEP Single Column Model, the cumulus parameterization considers only the deepest cloud type. The parameterization includes a downdraft, which can detrain into the boundary layer, and precipitation evaporation. Boundary layer turbulent transport is represented as vertical diffusion plus non-local vertical transport. The profile of diffusivity is specified to match surface fluxes. The PBL height is diagnostically determined. Shallow (non-precipitating) convection is parameterized as an extension of the vertical diffusion scheme.

Observations show that cumulus effects in the boundary layer are significant, and approximately balance those due to turbulence. The effects of cumulus convection and turbulence in the boundary layer in the NCEP SCM are in general agreement with those in the CRM.

The surface fluxes of water vapor are much larger, while those of sensible heat are smaller, in the NCEP SCM than in the CRM. This leads to larger cumulus and turbulence effects on the water vapor budget (at all levels) and smaller effects on the sensible heat budget (near the surface and > 150 mb above the surface) in the NCEP SCM than in the CRM. In the CRM's boundary layer, drying by cumulus transport dominates moistening by rain evaporation, while both cumulus transport and rain evaporation cool near the surface.

6 Project Activities: 2001–2006

6.1 SCM Cirrus Cloud Statistics: Simulated Compared to Observed (Luo et al. 2002b,c, 2005)

Using cloud radar observations of cirrus cloud properties obtained at the ARM (Atmospheric Radiation Measurement program) SGP (Southern Great Plains) site and results from a CRM (cloud-resolving model) simulation, we evaluated the cirrus properties simulated by a SCM (single-column model). The SCM is based on the NCEP (National Centers for Environmental Prediction) MRF (Medium Range Forecast) model, which includes cloud water/ice as a prognostic variable. We used SCM and CRM simulations based on intensive observations made at the ARM SGP site for 29 days from 19 June to 17 July 1997. During this period, cirrus clouds, many generated by deep convection, were observed about 30 percent of the time by the cloud radar.

To produce cirrus statistics from the SCM results that are comparable to the cloud radar observations, we used a method described by Klein and Jakob (1999) that uses the SCM cloud fraction profile and the SCM's overlap assumption (random or maximum/random) to create a synthetic cloud field. The SCM's cloud water/ice is assumed to be uniformly distributed in the clouds at each level. We sampled the synthetic cloud fields like a cloud radar would to determine the statistical properties of "cirrus" and "thin cirrus", as defined by Mace et al. (2001). We compared the SCM's cirrus cloud properties to those obtained by Mace et al. using the ARM cloud radar and the corresponding CRM simulation.

In our study, we analyzed two extreme situations. For one, the presence of snow and rain are neglected completely, so the SCM cirrus clouds consist of cloud ice only. This is the NOSNOW analysis. At the other extreme, the SCM cirrus clouds are considered to consist of both cloud ice and snow. This is the SNOW analysis.

We compared the cirrus cloud occurrence frequency, the cirrus macro-scale statistics, and the "thin cirrus" microscale (or microphysical property) statistics to observations, as well as to the corresponding CRM results described in Luo et al. (2003). Our analysis method and results are described in Luo et al. (2005). We will summarize only the most interesting results here.

Compared to the cloud radar observations, the NOSNOW SCM cirrus cloud base heights are too high and the cloud layers are too thin: many of them occur in a single model layer. The SNOW cirrus cloud base heights are too low and the cirrus cloud layers are too thick. We conclude that the treatment of snow (i.e., precipitating ice) affects how well cirrus clouds are represented in a SCM.

For the SCM NOSNOW and SNOW "thin cirrus" clouds, we found that, compared to Mace's cirrus microphysical property retrievals:

(a) Large IWP and large layer-mean IWC occur too often relative to small IWP and IWC, resulting in too large mean IWP and IWC.

(b) The IWP and layer-mean IWC are too large for average and warm cirrus layer-mean temperatures.

(c) The layer-mean IWCs *decrease* with cloud physical thickness, which is opposite to the retrievals and CRM results. The reason could be that detrainment from cumulonimbus clouds occurs in a single model layer in the SCM, rather than in many layers, as in the corresponding CRM simulation.

(d) The distribution of layer-mean effective radii covers too narrow a range with a maximum at about 75 microns.

6.2 Evaluation of Cloud Type Occurrences and Radiative Forcings Simulated by a Cloud Resolving Model Using Observations from Satellite and Cloud Radar (Luo 2003, Luo and Krueger 2003)

Comparing the total TOA (top-of-atmosphere) CRF[1] and total cloud amount from a model simulation with observations is a traditional method for model evaluation. However, these alone do not give many clues about the causes of differences/similarities between models and observations. We evaluated clouds simulated by a CRM in a way that dissects the TOA CRF and cloud amount into cloud type distributions, and reveals considerably more cloud information than the traditional method does.

[1]Cloud radiative forcing (CRF) is defined here as the difference between the net downwelling radiative flux under all-sky and clear-sky conditions

We used data from ARM millimeter cloud radar (MMCR) observations and geostationary satellite pixel-level cloud products over the ARM SGP CART (provided by Pat Minnis group at NASA Langley Research Center) to evaluate the occurrence frequencies and radiative effects of eight cloud types in a 29-day CRM simulation (using a version of the Univ of Utah CRM) of the summer 1997 SCM IOP (Single-Column Model Intensive Observation Period) at the ARM SGP CART. Such a study has not been done before. Because the large-scale advection of hydrometeors was not measured, and therefore had to be neglected in the simulation, we selected 3 subperiods (A, B, and C) during which clouds mainly formed and dissipated within the SCM domain.

To compare with MMCR observations of cloud occurrence, we defined cloud bases and tops by reflectivity of hydrometeors. For the entire IOP, the CRM simulation reproduced the dominance of high cloud occurrence observed by the MMCR, but underestimated high cloud amount by 0.13. The difference could be due to errors in the large-scale forcing data, vertical resolution that is too low in the mid- and upper-troposphere of both the CRM simulation and of the large-scale forcing data, large ice crystals falling too fast in the CRM simulation, and/or other resons.

To compare the CRM results with satellite data, the ISCCP (International Satellite Cloud Climatology Project) simulator was used to calculate cloud-top pressure and cloud optical depth (τ) values, for each CRM column (2-km in horizontal extent), that are comparable to those retrieved by Minnis from multi-channel satellite radiance measurements. The results are used to determine the occurrence frequencies of eight cloud types defined by cloud-top pressure and cloud optical depth: 4 high-top types: very thin (τ: 0.1 - 1.3), thin (τ: 1.3 - 3.6), moderate (τ: 3.6 - 9.4), and thick ($\tau > 9.4$), 2 mid-top and 2 low-top types: thin (τ: 0.1 - 9.4) and thick ($\tau > 9.4$). These, as well as results from a SCM (see the next section) are shown in Fig. 3, panel (a).

The differences between the retrieved and CRM-simulated cloud type frequencies are due to a combination of retrieval uncertainties and CRM simulation (forcing and model) deficiencies. By comparing Minnis amounts to MMCR cloud amounts for low-, mid-, and high-topped clouds, we found that the daytime retrieval missed or misclassified about half of the high-top clouds compared to the MMCR. The CRM simulation underestimated the mid-top and low-top cloud amounts compared to Minnis during the day, but not compared to the MMCR. These Minnis cloud amounts may be overestimated because the Minnis cloud-top heights are underestimated during the day (see cloud-top heights comparison, below). However, the MMCR amounts are almost certainly underestimated due to problems detecting thin mid-level clouds and insect-contaminated low clouds.

Another way to evaluate CRM-simulated cloud type occurrence is to calculate the temporal correlation of simulated and satellite-observed 3-hourly cloud type amounts. The CRM thick clouds (visible optical depth greater than 10) temporally correlated better with the satellite observations (0.67 and 0.62 during ABC subperiods and entire IOP, respectively) than did CRM thin clouds (0.47 and 0.16 during ABC subperiods and entire IOP, respectively), partly due to relatively less large-scale advection compared to local formation and dissipation of clouds. The better correlations for the ABC subperiods compared to the entire IOP result from less large-scale horizontal advection of hydrometeors during these subperiods.

Fig. 3 panels (c) and (d) show that the CRM-simulated CRFs agree reasonably well with

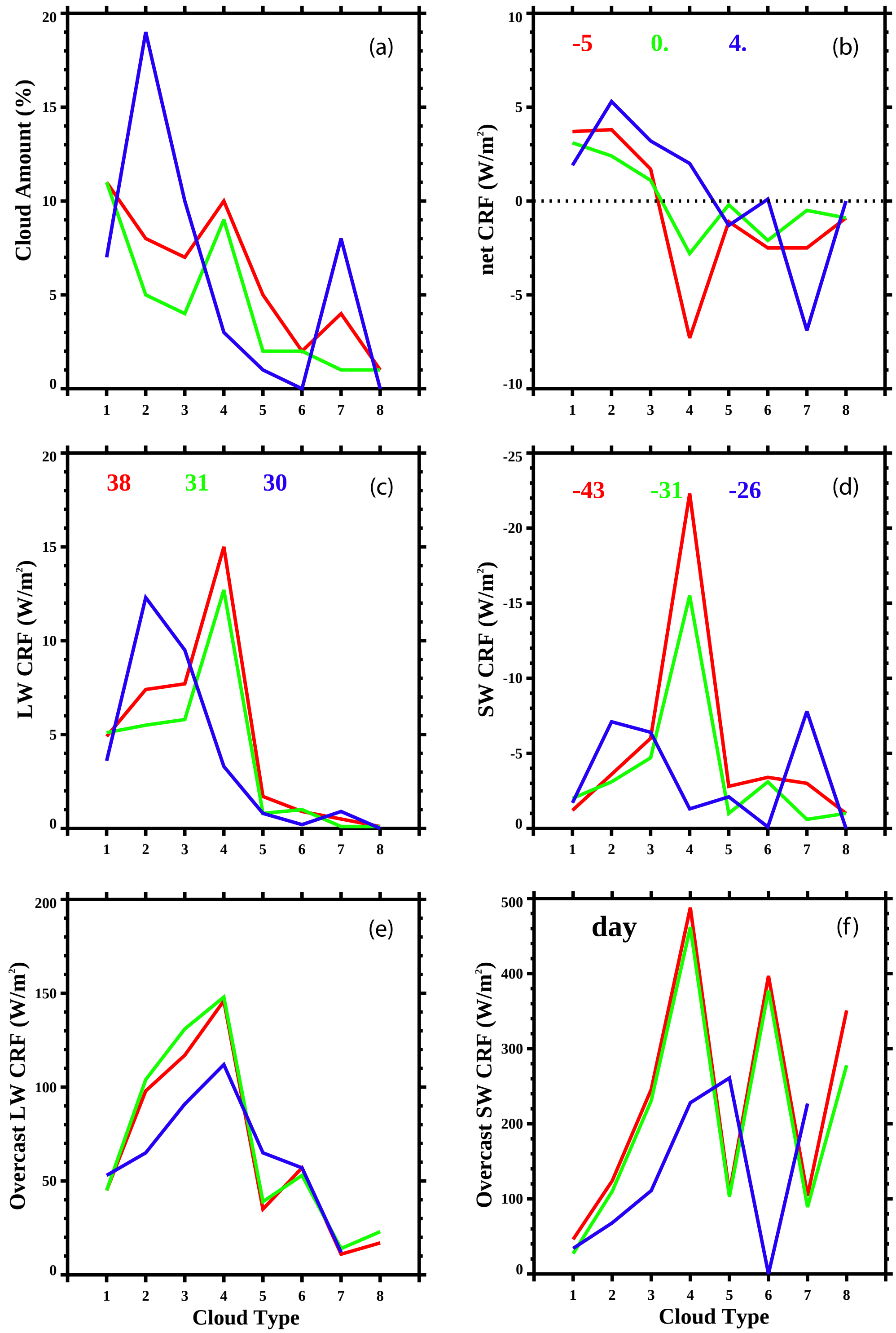

Figure 3: For the eight cloud types for the ABC subperiods: (a) cloud amount, (b) net CRF, (c) LW CRF, (d), SW CRF, (e) overcast LW CRF, (f) overcast SW CRF. Red: Minnis satellite retrievals. Green: UU CRM. Blue: NCEP GFS SCM. The numbers indicate the CRFs for all cloud types.

the LW and SW CRFs of the various cloud types obtained from the satellite observations. The retrievals and the CRM results in panel (b) indicate that the net CRF of the optically thin high-top clouds had a warming effect at the TOA while the other cloud types had a cooling effect. The thick high-top cloud type had the most significant cooling effect. The net TOA CRF by all cloud types averaged over the ABC subperiods from the Minnis data is -5 W m^{-2} and from the CRM is 0 W m^{-2}.

This study demonstrates that results from satellite retrievals, radar observations, and CRM simulations complement each other. We used the pixel-level satellite data to evaluate the occurrence frequencies and TOA radiative effects of various cloud types in a CRM simulation, while radar observations helped to determine the uncertainties in the satellite retrievals. We extended the cloud type analysis to evaluate SCM results, as described next.

6.3 Cloud Types Simulated by the NCEP GFS Single-Column Model (Luo and Krueger 2004b)

To determine the occurrence frequencies of cloud types (defined by cloud-top pressure and cloud optical depth) and the associated CRFs in a SCM simulation, we again used the ISCCP simulator, but in this case, synthetic cloud fields consistent with the NCEP SCM's cloud overlap and horizontal inhomogeniety assumptions must first be constructed from the SCM's predicted cloud fraction and cloud water/ice content profiles. The SCM assumed random overlap and no horizontal inhomogeniety. The results from the NCEP SCM are shown in Fig. 3 in blue, along with those already described from satellite retrievals and a CRM.

For this particular case, the CRM results are generally much more realistic than the SCM's. Interestingly, and perhaps not surprisely, the SCM quantity that agrees most closely with the observations and CRM is total net CRF, a quantity that is tuned in GCMs to obtain a global TOA energy balance (but not a local balance as in this case). However, when the SCM's net CRF is decomposed into cloud type components, (Fig. 3, panel (b)), it is evident that the total net CRF is a result of compensating errors in the CRFs of individual cloud types: the high clouds have too great a warming effect, while the low clouds have too great a cooling effect. Most notably, the net CRF of the SCM's thick high-top clouds (type 4, typically associated with deep convection) is positive, instead of strongly negative. When the net CRF by cloud type is separated into LW and SW components, the type 4 cloud errors become even more apparent.

6.4 Cloud-Top Height Comparison (Luo 2003)

We used the cloud boundary information from the ARSCL dataset at the SGP CF to evaluate the cloud-top heights from the Minnis data and the CRM simulation.

6.4.1 Cloud-top height comparison: MMCR vs Minnis

Our major conclusions about the Minnis cloud-top heights obtained by comparing them with the ARSCL observations include: (a) Minnis cloud-top heights are closer to the ARSCL observations at night than in the day. (b) Little dependence is found for Minnis cloud-top heights on the ARSCL cloud amount and number of cloud layers at the CF. (c) Minnis cloud-top heights are closer to the ARSCL observations for optically thick clouds than for optically thin clouds. A possible reason is problems associated with the VIS-adjustment, such as errors in surface albedo leading to errors in retrieved visible optical depth. These results may also explain why some daytime thin high clouds were misclassified as lower-level clouds

6.4.2 Cloud-top height comparison: MMCR vs CRM

The CRM shapes are generally consistent with the MMCR results. Both the CRM and MMCR have relatively few cloud tops below 8 km and have many cloud tops between 9-14 km. However, in both day and night, the CRM underestimates the relative frequency of cloud tops at 13-14 km, and overestimates it at 12 km. The CRM simulation has a few cloud-tops above 14 km which are not observed in the ARSCL data.

6.5 Cloud Ice Water Path Comparison (Luo 2003)

6.5.1 Cloud ice water path comparison: Minnis vs MCA

We compared the Minnis retrieved IWPs (ice water paths) to the MCA (Mace et al. 2001) SGP radar-radiometer retrievals during the ARM SGP summer 1997 IOP. We compared only at times when single-layer thin cirrus clouds were observed by the MMCR during the entire half hour. During the IOP, there are only 11 such half hours. The mean IWPs retrieved by Minnis group and MCA are 7.1 and 9.2 g m^{-2}, respectively. The 90 percent confidence intervals are 3.5 and 4.1 g m^{-2}. In other words, the Minnis time-averaged IWP for single-layer thin cirrus clouds is the same as the radar-radiometer retrieval at the 90 percent confidence level, with an uncertainty (confidence interval) of about 50 percent.

6.5.2 Cloud ice/liquid water path comparison: Minnis vs CRM

The ABC subperiods daytime large-scale (i.e., SCM-domain averaged) cloud liquid and ice water paths are 20 g m^{-2} (ISCCP), 108 g m^{-2} (CRM) and 133 g m^{-2} (Minnis), respectively. The Minnis retrievals and the CRM simulation show that the thick clouds contributed to about 92 and 89 percent, respectively, of the total daytime IWP+LWP. Compared to the Minnis retrievals, the CRM simulated comparable large-scale cloud liquid+ice water paths for thin clouds (11.7 vs 10.1 g m^{-2} in daytime, 12.3 vs 10.9 g m^{-2} in nighttime), but somewhat less for daytime thick clouds (96 vs 123 g m^{-2}), and daytime thick high clouds (82 vs 118 g m^{-2}).

We compared the overcast IWP+LWPs from the CRM and Minnis retrievals for each of the 8 cloud types. The CRMs IWP+LWPs are generally close to or greater than their counterparts from the Minnis retrievals, except that for the high-level thick clouds (100 g m^{-2}) which is only 90 percent of the Minnis value (1220 g m^{-2}).

6.6 Evaluation of Detrainment and Microphysics in the NCEP SCM using Results from a Cloud Resolving Model (Luo 2003, Luo and Krueger 2004a, Luo et al. 2006)

We found that cirrus properties simulated by the NCEP GFS single-column model for the summer 1997 ARM SCM IOP (Case 3) significantly differ from cloud radar observations while the UCLA/CSU CRM simulation reproduced most of the cirrus properties as revealed by the observations. Both models were driven using the ARM variational analysis. We used the CRM results to evaluate the SCM's representation of the physical processes determining the simulated cirrus: specifically, cumulus detrainment and ice microphysics.

We found that in the SCM: (a) detrainment occurs too infrequently at a single level at a time, though the detrainment rate averaged over the entire IOP are comparable to that in the CRM simulation, (b) too much detrained ice is sublimated when first detrained, and that (c) snow sublimates over too deep of a layer due to assuming that snow source and sink terms exactly balance.

Possible methods to improve the SCM's physics include: (a) including multiple cloud types (detrainment levels) in the cumulus parameterization, and/or using greater horizontal resolution and/or a smaller time step so that the distribution of possible detrainment levels (cloud types) will be better represented, (b) using a prognostic equation for cloud fraction instead of a diagnostic one, so that the detrained ice increases the cloud fraction according to the volume of detrained air, while other processes can also act to change the cloud fraction, and (c) using a prognostic snow equation.

6.7 The Evolution of Convectively Generated Stratiform Ice Clouds (Krueger et al. 2003, Krueger and Luo 2004, Krueger and Zulauf 2005)

Observations show that cirrus clouds often result from the life cycle of convective cloud systems. Detrainment is an important source of ice water path (IWP) and ice cloud fraction (ICF). In an ice cloud produced by detrainment, ICF (and IWP) can increase due to formation and spreading by internal circulations. ICF can also increase due to spreading by vertical shear. IWP (and ICF) decrease by fallout and sublimation.

In an effort that was jointly supported by my NASA CRYSTAL-FACE project, "Cloud-Scale and Large-Scale Modeling of Tropical Anvils and Cirrus Layers," we used a simple Lagrangian column model in conjunction with Minnis pixel-level satellite retrievals of IWP and ICF at high time resolution (every 15 or 30 minutes) over a large-scale region to understand and model the evolution of the PDF (probability density function) of IWP. The column model appears to be useful for understanding the evolution of observed IWP PDFs.

We were motivated to perform this study by the following facts:
1) The SGS variability of the IWP significantly affects the representation of radiative and microphysical processes.
2) The definition of the convective region affects the parameterization of the detrainment rate and the non-convective (stratiform) IWP and cloud fraction.
3) A diagnostic relationship between ice cloud fraction and IWP does not exist because of the evolving IWP distribution.

6.8 Evaluating the Performance of the MRF Subgrid-Scale Cloud Fraction Parameterization (Lazarus et al. 2003)

This research was performed by Steven M. Lazarus under a subcontract to the Florida Institute of Technology from the University of Utah.

As part of a collaborative effort with the National Centers for Environmental Prediction (NCEP), we archived column output as it was produced in real time from the NCEP Medium Range Forecast model (MRF; in April 2002, the MRF and AVN models were combined into a single system referred to as the Global Forecast System or GFS). Column output was collected at model grid points corresponding to over a dozen sites (5 of which directly coincide with Atmospheric Radiation Measurement (ARM) facilities at Manus, Nauru, Darwin, Barrow, and the Southern Great Plains (SGP) Central Facility [CF]). The archive, which dates back to November 2000, consists of twice daily (00 and 12 UTC) 48-hr MRF/GFS forecasts with 3-hourly output, and once daily Global Data Assimilation System analyses (00, 06, 12, and 18 UTC) and 3-hr forecasts (03, 09, 15, and 21 UTC).

Lazarus focused on the short-term prediction of subgrid scale cloud amount and cloud properties as diagnosed from MRF forecast hours 24-48. He identified large-scale, low-level, stratiform cloud events in order to evaluate model performance under conditions whereby one might expect a subgrid-scale cloud parameterization to perform well. The stratiform events were identified using the Dong et al. (1998) retrieval criteria to flag potential stratus periods. He examined two such extended (significant) periods from 15 GMT 12 December to 00 GMT December 14, 2001, and a second period from 00 GMT December 16, to 06 GMT December 17, 2001.

Because the MRF subgrid-scale stratiform cloud fraction parameterization is a function of the large-scale relative humidity (RH), water vapor mixing ratio, and liquid water content, Lazarus compared ARM SGP soundings with model forecast soundings. When compared to ARM soundings, Lazarus found that the MRF often failed to capture the low-level inversion layer, or when it did, it did not resolve its vertical gradient, magnitude or depth. The MRF under-predicted the RH throughout the lower troposphere (i.e. below 750 hPa), and often overestimated the RH in the mid-troposphere (750-600 hPa), especially for those cases where the model did not capture the inversion.

6.9 Mesoscale Cumulus Parameterization

The horizontal grid size in NWP models will continue to decrease. There are many benefits of decreasing the horizontal grid size in large-scale models. However, until horizontal grid sizes decrease to 4 km or less, deep cumulus convection will still need to be parameterized. As horizontal grid sizes decrease, parameterized convection becomes more localized. That is, a smaller fraction of the grid columns are convective columns (i.e., columns that contain areas of cumulus convection) and these columns include larger fractional areas of cumulus convection. What are the implications for cumulus parameterization as horizontal grid size decreases and convection becomes more localized? Can we quantify the implications? We made a preliminary exploration of this topic (based on a CRM simulation of the summer 1997 SCM IOP) in preparation for a presentation at ECMWF on current issues in cumulus parameterization (Krueger 2002).

7 Contributions to the ARM Program: 1993–2006

In addition to the research activities described above—which are directly related to those we proposed—we have been involved in several activities related to ARM as a whole, but only indirectly related to our specific project. These are listed below.

ARM Single Column Model Working Group In collaboration with Dave Randall (CSU) and Marty Leach (LLNL), we helped to assemble a "Showcase Dataset" for Single Column Models based on data collected during the Fall 1994 IOP at the SGP ARM-CART site. Our group focused on cloud properties as measured by surface remote sensors. I helped Ric Cederwall set up ARM's first SCM intercomparison project (based on the July 1995 SCM IOP).

ARM Clouds Working Group I co-chaired (with Jay Mace) this working group. We held our first workshop in June 1997 in Boulder, CO, our second in February 1998 in Salt Lake City, UT, and our third in October 1998 in Pleasanton, CA.

ARM Cloud Parameterization and Modeling Working Group With the help of Ric Cederwall and John Yio, I led the second SCM intercomparison project based on the July 1997 SCM IOP, which was performed in collaboration with GCSS WG4 (see below). I also served on the Steering Committee of the CPM WG, and was one of the CPM WG's liason's to the TWP-ICE (Tropical Warm Pool International Cloud Experiment) planning committee.

ARM management I was elected to the STEC in 1997 and served for 3 years. I also served on the ARM NSA/AAO Site Advisory Panel.

GCSS (GEWEX [Global Energy and Water Cycle Experiment] Cloud System Study) The goal of GCSS is to improve our understanding of and ability to parameterize cloud systems through numerical simulations with cloud resolving models. I have been actively involved with GCSS since 1994. I co-chaired the 2d GCSS Boundary Layer Cloud Model Intercomparison Workshop which was held in August 1995 in the Netherlands and included simulations of the two Atlantic Stratocumulus Transition Experiment (ASTEX) Lagrangian experiments by six 1D and 2D models. I was the leader for one of the two cases for the 1st GCSS Deep Precipitating Convective Cloud Systems Model Intercomparison Workshop (held in October 1996) which focused on convective cloud systems over the Tropical Western Pacific. I gave an invited talk about GCSS at the 1996 ARM Science Team Meeting. I was chair of GCSS Working Group 4: Precipitating Convective Cloud Systems from Jan 1998 to Dec 2000, and chair of GCSS from Jan 2001 to Dec 2003. I led two GCSS model intercomparison projects, including one that was a successful collaborative effort with ARM's SCM/CPM WG. WG 4 held several joint meetings with the ARM SCM/CPM group. I was a co-author of the paper "Confronting Models With Data: The GEWEX Cloud Systems Study" (Randall et al. 2003).

I arranged and organized the GCSS-ARM Workshop on the Representation of Cloud Systems in Large-Scale Models, which was held 20-24 May 2002 in Kananaskis, Alberta, Canada. Over 70 scientists from 9 countries attended the Workshop, which was sponsored by ARM, and included an ARM-organized evening breakout session on "Making Connections Between Data and Climate Models" that generated lively discussion. GEWEX News for May 2000 contains a summary of the workshop (`http://www.gewex.org/May2002.pdf`).

NCEP My research group began a collaboration with NCEP's Environmental Modeling Center in 1999. Partly because of our interest, NCEP developed a SCM based on its global forecast model. We have used this model extensively. At our request, NCEP has been providing twice-daily column output from the NCEP global model for the five ARM sites since 2001. NCEP is continuing to collect and archive their model output for ARM research. Dr. Hua-Lu Pan, Head of the Global Modeling Branch, EMC/NCEP, served on the Ph.D. Advisory Committee of my former student, Yali

Luo, who was actively involved in this project. NCEP hosted an ARM CPM/GCSS WG 4 meeting.

Simulated cloud fields for radiative transfer calculations We provided the simulated cloud fields used by Qiang Fu (under ARM support) and colleagues to investigate the effects of 3D cloud geometry and inhomogeneity on the radiative energy budget, including the atmospheric absorption of solar radiation.

8 References

Barnett, T. P., J. Ritchie, J. Foat, and G. Stokes, 1998: On space-time scales of the surface solar radiation field. *J. of Climate,* **11,** 88–96.

Betts, A. K. 1989: Idealized model for stratocumulus layer thickness. *Tellus,* 41A, 246–254.

Bretherton C. S., and M. C. Wyant, 1997: Moisture transport, lower tropospheric stability and decoupling of cloud-topped boundary layers. *J. Atmos. Sci.*, **54**, 148-167.

Dong, X., T. P. Ackerman, and E. E. Clothiaux, 1998: Parameterizations of microphysical and radiative properties of boundary layer stratus from ground-based measurements. *J. Geophys. Res.*, **102**, 31,681–31,693.

Donner, L. J., Seman, C. J., Soden, B. J., Hemler, R. S., Warren, J. C., Strom, J., and Liou, K.-N., 1997: Large-scale ice clouds in the GFDL SKYHI general circulation model. *J. Geophys. Res.,* **102,** 21745–21768.

Frisch, A. S., C. W. Fairfall, and J. B. Snider, 1995: Measurement of stratus cloud and drizzle parameters in ASTEX with a K_α- band Doppler radar and a microwave radiometer. *J. Atmos. Sci.*, **52,** 2788–2799.

Heymsfield, A. J., and L. J. Donner, 1990: A scheme for parameterizing ice-cloud water content in general circulation models. *J. Atmos. Sci.*, **47**, 1865–1877.

Heymsfield, A. J., L. M. Miloshevich, A. Slingo, K. Sassen, and D. O'C. Starr, 1991: An observational and theoretical study of highly supercooled altocumulus. *J. Atmos. Sci.,* **48,** 923–945.

Klein, S. A., and C. Jakob, 1999: Validation and sensitivities of frontal clouds simulated by the ECMWF model. *Mon. Wea. Rev.,* **127**, 2514-2531.

Köhler, M., 1999: Explicit Prediction of Ice Clouds in General Circulation Models. Ph.D. Dissertation, UCLA, 166 pp.

Krueger, S.K., G.T. McLean, and Q. Fu, 1995: Numerical simulation of the stratus-to-cumulus transition in the subtropical marine boundary layer. Part I: Boundary-layer structure. *J. Atmos. Sci.,* **52,** 2839–2850.

Mace, G. G., E. E. Clothiaux, and T. P. Ackerman, 2001: The composite characteristics of cirrus clouds: Bulk properties revealed by one year of continuous cloud radar data. *J. Clim.*, **15**, 2185–2203.

Randall, D. A., 1984: Stratocumulus cloud deepening through entrainment. *Tellus*, **36A**, 446-457.

Starr, D.O'C., and S.K. Cox, 1985a: Cirrus clouds. Part I: A cirrus cloud model. *J. Atmos. Sci.,***42,** 2663–2694.

Starr, D.O'C., and S.K. Cox, 1985b: Cirrus clouds. Part II: Numerical experiments on the formation and maintenance of cirrus. *J. Atmos. Sci.,***42,** 2682–2694.

Turton, J. D., and S. Nicholls, 1987: A study of the diurnal variation of stratocumulus using a multiple mixed layer model. *Quart. J. R. Met. Soc.*, **113**, 969-1009.

Wyant, M. C., and C. S. Bretherton, 1992: The dynamics of decoupling in a cloud-topped boundary layer. *Proc. 11th Int. Conf. on Clouds and Precipitation,* Vol. 1, Montreal, Quebec, Canada, International Commission on Clouds and Precipitation and International Association of Meteorology and Atmospheric Physics, 417–420.

Xu, K.-M., and D. A. Randall, 1996: A semiempirical cloudiness parameterization for use in climate models. *J. Atmos. Sci.*, **53,** 3084–3102.

Zhang, M. H., and J. L. Lin, 1997: Constrained variational analysis of sounding data based on column-integrated budgets of mass, heat, moisture, and momentum: approach and application to ARM measurements. *J. Atmos. Sci.,* **54**, 1503-1524.

9 Publications

Refereed Publications

Bechtold, P., S. K. Krueger, W. S. Lewellen, E. van Meijgaard, C.-H. Moeng, D. A. Randall, A. van Ulden, and S. Wang, 1996: Modeling a stratocumulus-topped PBL: Intercomparison among different 1D codes and with LES. *Bull. Amer. Meteor. Soc.,* **77,** 2033–2042.

Bretherton, C. S., S. K. Krueger, M. C. Wyant, P. Bechtold, E. van Meijgaard, B. Stevens, and J. Teixeira, 1999: A GCSS boundary layer model intercomparison study of the first ASTEX Lagrangian experiment. *Bound.-Layer Meteor.,* **93,** 341–380.

Fu, Q., M. Cribb, H. Barker, S. K. Krueger, and A. Grossman, 2000: Cloud geometry effects on atmospheric solar absorption. *J. Atmos. Sci.,* **57,** 1156-1168.

Ghan, S. J., D. Randall, K.-M. Xu, R. Cederwall, D. Cripe, J. Hack, S. Iacobellis, S. Klein, S. Krueger, U. Lohmann, J. Pedretti, A. Robock, L. Rotstayn, R. Somerville, G. Stenchikov, Y. Sud, G. Walker, S. Xie, J. Yio, and M. Zhang, 2000: A comparison of single column model simulations of summertime midlatitude continental convection. *J. Geophys. Res.,* **105** (D2), 2091–2124.

Krueger, S. K., 2000: Cloud system modeling. *General Circulation Model Development,* D. A. Randall, ed., Academic Press, San Diego, 605–640.

Lazarus, S. M., S.K. Krueger, and G. G. Mace, 2000: A cloud climatology of the Southern Great Plains ARM CART. *J. Climate,* **13,** 1762–1775.

Liu, S., and S. K. Krueger, 1998: Numerical simulations of altocumulus using a cloud resolving model and a mixed layer model. *Atmos. Res.,* **47–48,** 461–474.

Luo, Y., S. K. Krueger, G. G. Mace, and K.-M. Xu, 2003: Cirrus cloud properties from a cloud-resolving model simulation compared to cloud radar observations. *J. Atmos. Sci.,* **60,** 510–525.

Luo, Y., S. K. Krueger, and S. Moorthi, 2005: Cloud Properties Simulated by a Single-Column Model. Part I: Comparison to Cloud Radar Observations of Cirrus Clouds. *J. Atmos. Sci.,* **62,** 1428–1445.

Luo, Y., S. K. Krueger, and K.-M. Xu, 2006: Cloud Properties Simulated by a Single-Column Model. Part II: Evaluation of Cumulus Detrainment and Ice-phase Microphysics Using a Cloud Resolving Model. *J. Atmos. Sci.,* **63,** 2831-2847.

Moeng, C.-H., W.R. Cotton, C. Bretherton, A. Chlond, M. Khairoutdinov, S. Krueger, W.S. Lewellen, M.K. McVean, J.R.M. Pasquier, H.A. Rand, A.P. Siebesma, R.I. Sykes, and B. Stevens, 1996: Simulation of a stratocumulus-topped PBL: Intercomparison of different numerical codes. *Bull. Amer. Meteor. Soc.,* **77,** 216–278.

Moncrieff, M. W., S. K. Krueger, D. Gregory, J.-L. Redelsperger, and W.-K. Tao, 1997: GEWEX Cloud System Study (GCSS) Working Group 4: Precipitating Convective Cloud Systems. *Bull. Amer. Met. Soc.*, **78**, 831–845.

Randall, D., S. Krueger, C. Bretherton, J. Curry, P. Duynkerke, M. Moncrieff, B. Ryan, D. Starr, M. Miller, W. Rossow, G. Tselioudis, and B. Wielicki, 2003: Confronting Models With Data: The GEWEX Cloud Systems Study. *Bull. Amer. Met. Soc.*,**84,** 455–469

Xie, S. C., K.-M. Xu, R. T. Cederwall, P. Bechtold, A. D. Del Genio, S. A. Klein, D. G. Cripe, S. J. Ghan, D. Gregory, S. F. Iacobellis, S. K. Krueger, U. Lohmann, J. C. Petch, D. A. Randall, L. D. Rotstayn, R. C. J. Somerville, Y. C. Sud, K. von Salzen, G. K. Walker, A. Wolf, J. J. Yio, G. J. Zhang, and M. Zhang, 2002: Intercomparison and evaluation of cumulus parametrizations under summertime midlatitude continental conditions. *Q. J. Roy. Meteor. Soc.,* **128,** 1095 –1136.

Xie, S., M. H. Zhang, M. Branson, R. T. Cederwall, A. D. Del Genio, Z. A. Eitzen, S. J. Ghan, S. F. Iacobellis, M. Khairoutdinov, S. A. Klein, S. K. Krueger, W. Lin, U. Lohmann, D. A. Randall, R. C. J. Somerville, Y. C. Sud, G. K. Walker, A. Wolf, X. Wu, K.-M. Xu, J. J. Yio, G. Zhang, and J. Zhang, 2005: Simulations of Midlatitude Frontal Clouds by SCMs and CRMs during the ARM March 2000 Cloud IOP. *J. Geophys. Res.,* **110,** D15S03, doi:10.1029/2004JD005119.

Xu, K.-M., R. T. Cederwall, L. J. Donner, W. W. Grabowski, F. Guichard, D. E. Johnson, M. Khairoutdinov, S. K. Krueger, J. C. Petch, D. A. Randall, C. J. Seman, W.-K. Tao, D. Wang, S. C. Xie, J. J. Yio, and M.-H. Zhang, 2002: An intercomparison of cloud-resolving models with the Atmospheric Radiation Measurement summer 1997 Intensive Observation Period data. *Q. J. Roy. Meteor. Soc.,* **128,** 593–624.

Yang, F., H.-L. Pan, S. K. Krueger, S. Moorthi, and S. J. Lord, 2006: Evaluation of the NCEP Global Forecast System at the ARM SGP Site. *Mon. Wea. Rev,* **134,** 3668–3690.

Dissertations and Theses

Burks, J. E., 1998: Radiative Fluxes and Heating Rates during TOGA COARE over the Intensive Flux Array. M.S. Thesis, Dept. of Meteorology, University of Utah, 83 pp.

Liu, S., 1998: Numerical Modeling of Altocumulus Cloud Layers. Ph.D. Dissertation, Dept. of Meteorology, University of Utah, 147 pp.

Luo, Y., 2003: Evaluation of Cloud Properties in Atmospheric Models using Cloud-Scale Observations. Ph.D. dissertation, University of Utah, Salt Lake City, 203 pp.

Other Publications

Barker, H.W., L.H. Chambers, B. Stevens, and S.K. Krueger, 1996: Parameterizing sub-grid scale radiative properties of oceanic boundary layer clouds in atmospheric circulation models. *Abstracts, International Radiation Symposium,* Fairbanks, Alaska, 37.

Burks, J. E., and S. K. Krueger, 1999: Radiative fluxes and heating rates during TOGA COARE over the Intensive Flux Array. *Preprints, 23rd Conference on Hurricanes and Tropical Meteorology,* Dallas, TX, Amer. Meteor. Soc., 773–775.

Cederwall, R. T., J. J. Yio, and S. K. Krueger, 1998: The ARM SCM Intercomparison Study – Overview and Preliminary Results for Case 1. *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Tucson, Arizona , DOE, 123–126. Extended Abstract: `http://www.arm.gov/publications/proceedings/conf08/extended_abs/cederwall_rt.pdf`

Cederwall, R., Krueger, S. K., Rodriguez, D. J., and Randall, D. A., 1999: The ARM-GCSS Intercomparison Study of Single-Column Models and Cloud System Models. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* San Antonio, Texas, DOE. Extended Abstract: `http://www.arm.gov/publications/proceedings/conf09/extended_abs/cederwall_rt.pdf`

Frisch, S., and S. K. Krueger, 1997: A comparison between stratus cloud observations using a cloud Doppler radar and the University of Utah cloud model. *Preprints, 12th Symposium on Boundary Layers and Turbulence,* Vancouver, B.C., Canada, Amer. Meteor. Soc., 90–91.

Fu, Q., M. Cribb, H. W. Barker, and S. K. Krueger, 1998: A Study of Atmospheric Absorption of Solar Radiation Using Cloud Fields Derived from a Cloud Resolving Model. *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Tucson, Arizona, DOE, 277. Extended Abstract: `http://www.arm.gov/publications/proceedings/conf08/extended_abs/fu2_q.pdf`

Ghan, S., Cederwall, R., Cripe, D., Hack, J., Iacobellis, S. F., Klein, S., Krueger, S. K., Lohmann, U., Randall, D. A., Robock, A., Rotstayn, L., Somerville, R. C., Stenchikov, G., Sud, Y., Walker, G., Xie, S. C., Xu, K.-M., Yio, J., and Zhang, M. H., 1999: An Intercomparison of Single Column Model Simulations of Summertime Convection at a Midlatitude Continental Site. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* San Antonio, Texas, DOE. Extended Abstract: `http://www.arm.gov/publications/proceedings/conf09/extended_abs/ghan_sj.pdf`

Krueger, S. K., 1995: Parameterization of thin mid-level stratiform clouds. *Proceedings of the Fourth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* February 28–March 3, 1994, Charleston, South Carolina, DOE, 211. `http://www.arm.gov/publications/proceedings/conf04/extended_abs/krueger_sk.pdf`

Krueger, S. K., and C.-H. Chen, 1995: Testing a boundary layer cloud parameterization using CEM results. *Proceedings, Workshop on Cloud Microphysics Parameterizations in Atmospheric Circulation Models,* 23–25 May 1995, Kananaskis, Alberta, Canada, WCRP, 47-56.

Krueger, S. K., C.-H. Chen, M. C. Wyant, and C. S. Bretherton, 1996: Simulations of the ASTEX Lagrangian experiments with 1D and 2D boundary layer models. *Proceedings, 12th International Conference on Clouds and Precipitation,* Zurich, Switzerland, 709–713.

Krueger, S. K., 1997a: A GCSS Intercomparison of Cloud-Resolving Models based on TOGA COARE Observations. *Proceedings of the ECMWF/GCSS Workshop on New Insights and Approaches to Convective Parameterization,* Reading, England, U.K., ECMWF, 113–127.

Krueger, S. K., 1997b: Intercomparison of multi-day simulations of convection during TOGA COARE with several cloud-resolving models. *Preprints, 22nd Conference on Hurricanes and Tropical Meteorology,* Fort Collins, CO, Amer. Meteor. Soc., 63–64.

Krueger, S. K., S. M. Lazarus, G. G. Mace, and K. Sassen, 1997: Structure of a continental stratocumulus-topped boundary layer observed by aircraft and cloud radar. *Preprints, 12th Symposium on Boundary Layers and Turbulence,* Vancouver, B.C., Canada, Amer. Meteor. Soc., 66–67.

Krueger, S. K., and J. E. Burks, 1998: Radiative fluxes and heating rates during TOGA COARE over the Intensive Flux Array. *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Tucson, Arizona , DOE, 399–402. Extended Abstract: `http://www.arm.gov/publications/proceedings/conf08/extended_abs/krueger_sk.pdf`

Krueger, S. K., and S. M. Lazarus, 1998: Intercomparison of multi-day simulations of convection during TOGA COARE with several cloud-resolving and single-column models. *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Tucson, Arizona , DOE, 391–397. Extended Abstract: `http://www.arm.gov/publications/proceedings/conf08/extended_abs/krueger2_sk.pdf`

Krueger, S. K., and J. E. Burks, 1999: Radiative fluxes and heating rates during TOGA COARE over the Intensive Flux Array. *COARE-98: Proceedings of a Conference on the TOGA Coupled Ocean-Atmosphere Response Experiment (COARE),* Boulder, CO, USA, 7–14 July 1998, WCRP, 239–240. [WMO/TD-No. 940]

Krueger, S. K., and Lazarus, S. M., 1999a: Intercomparison of multi-day simulations of convection during TOGA COARE with several cloud-resolving and single-column models. *COARE-98: Proceedings of a Conference on the TOGA Coupled Ocean-Atmosphere Response Experiment (COARE),* Boulder, CO, USA, 7–14 July 1998, WCRP-107, 351–352. [WMO/TD-No. 940]

Krueger, S. K., and S. M. Lazarus, 1999b: Intercomparison of multi-day simulations of convection during TOGA COARE with several cloud-resolving and single-column models. *Preprints, 23rd Conference on Hurricanes and Tropical Meteorology,* Dallas, TX, Amer. Meteor. Soc., 643–647.

Krueger, S. K., and S. M. Lazarus, 2000: Intercomparison of multi-day simulations of convection during TOGA COARE with several cloud-resolving and single-column models. *Proceedings, Workshop on Cloud Processes and Cloud Feedbacks in Large-Scale Models,* ECMWF, Reading, Berkshire, UK, 9–13 November 1998, WCRP-110, 84–91. [WMO/TD-No. 993]

Krueger, S. K., S. M. Lazarus, Y. Luo, and K.-M. Xu, 2000: Interactions of deep cumulus convection and the boundary layer over the Southern Great Plains. *Preprints, 14th Symposium on Boundary Layers and Turbulence,* Aspen, CO, Amer. Meteor. Soc., 114–117.

Krueger, S. K., S. M. Lazarus, Y. Luo, and K.-M. Xu, 2000: Interactions of deep cumulus convection and the boundary layer over the Southern Great Plains. *Proceedings, 13th International Conference on Clouds and Precipitation,* Reno, Nevada, 1141–1144.

Krueger, S. K., M. A. Jenkins, S. M. Lazarus, Y. Luo, and K.-M. Xu, 2001: Interactions of Cumulus Convection and the Boundary Layer over the Southern Great Plains. *Proceedings of the Eleventh Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Atlanta, Georgia, DOE. Poster Abstract: `http://www.arm.gov/publications/proceedings/conf11/poster_abs/P00239.stm`

Krueger, S. K., 2002: Current Issues in Cumulus Parameterization. *ECMWF Seminar on Key issues in the Parametrization of Subgrid Physical Processes,* ECMWF, Reading, 3–7 September 2001, 25–51.

Krueger, S. K., Y. Luo, and M. A. Zulauf, 2003: The life cycle of convectively generated stratiform clouds. in Meighen, P. J., and Hollis, A. J. (eds.), *Current issues in the parameterization of convection: extended abstracts of presentations at the fifteenth annual BMRC modelling workshop,* 13-16 October 2003. Melbourne, Australia, Bureau of Meteorology Research Centre, pp. 53–56. (`http://www.met.utah.edu/skrueger/preprints/BMRC-preprint-2003.pdf`)

Krueger, S. K., M. A. Zulauf, and Y. Luo, 2004: The life cycle of convectively generated stratiform clouds. *Proceedings, 14th International Conference on Clouds and Precipitation,* Bologna, Italy, 1687–1690.

Krueger, S. K., and M. A. Zulauf, 2005: Radiatively-Induced Anvil Spreading. *Proceedings of the Fifteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Daytona Beach, Florida, DOE. Extended Abstract: `http://www.arm.gov/publications/proceedings/conf15/extended_abs/krueger_sk.pdf`

Lazarus, S. M., S. K. Krueger, and G. G. Mace, 1998: A cloud climatology of the ARM SGP CART. *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Tucson, Arizona , DOE, 413–416. Extended Abstract: `http://www.arm.gov/publications/proceedings/conf08/extended_abs/lazarus_sm.pdf`

Lazarus, S. M., S. K. Krueger, and A. S. Frisch, 1999: An evaluation of the Xu-Randall cloud fraction parameterization using ASTEX data. *Preprints, 13th Symposium on Boundary Layers and Turbulence,* Dallas, TX, Amer. Meteor. Soc., 582–585.

Lazarus, S. M., Krueger, S. K., and Frisch, A. S., 1999: An Evaluation of the Xu-Randall Cloud Fraction Parameterization using ASTEX Data. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* San Antonio, Texas, DOE. Extended Abstract: http://www.arm.gov/publications/proceedings/conf09/extended_abs/lazarus1_sm.pdf

Lazarus, S. M., Krueger, S. K., and Frisch, A. S., 2000: Evaluation of a Cloud Fraction Parameterization Using Observations and Model Data. *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* San Antonio, Texas, DOE. Extended Abstract: http://www.arm.gov/publications/proceedings/conf10/extended_abs/lazarus_sm.pdf

Lazarus, S. M., S. K. Krueger, M. A. Jenkins, and H.-L. Pan, 2001: Evaluating the NCEP Global Forecast Model Clouds. *Proceedings of the Eleventh Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Atlanta, Georgia, DOE. Poster Abstract: http://www.arm.gov/publications/proceedings/conf11/poster_abs/P00234.stm

Lazarus, S. M., and Krueger, S. K., 2002: An Intercomparison of MMCR and NCEP Global Model Cloud Fraction and Cloud Overlap at the ARM SGP, NSA, and TWP Sites. *Proceedings of the Twelfth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* St. Petersburg, Florida, DOE. Poster Abstract: http://www.arm.gov/publications/proceedings/conf12/poster_abs/P00086.stm

Lazarus, S. M., and S. K. Krueger, 2002: An intercomparison of MMCR and NCEP Global Model Clouds at the ARM SGP Site. *Preprints, 11th Conference on Cloud Physics,* Ogden, UT, Amer. Meteor. Soc., P1.1 (CD). (http://ams.confex.com/ams/pdfpapers/44892.pdf)

Lazarus, S. M., S. K. Krueger, and H.-L. Pan, 2003: Evaluating the Performance of the MRF Subgrid-Scale Cloud Fraction Parameterization: Examination of Two Significant Stratiform Cloud Events Over the ARM SGP. *Proceedings of the Thirteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Broomfield, CO, DOE. Extended Abstract: http://www.arm.gov/publications/proceedings/conf13/extended_abs/lazarus-sm.pdf

Liu, S., and S. K. Krueger, 1996a: Numerical simulations of altocumulus with a cloud-resolving model. *Proceedings of the Fifth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* March 19–23, 1995, San Diego, California, DOE, 167–171. Extended Abstract: http://www.arm.gov/publications/proceedings/conf05/extended_abs/liu_s.pdf

Liu, S., and S. K. Krueger, 1996b: Numerical simulations of altocumulus using an eddy resolving model and a mixed layer model. *Proceedings of the Sixth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* San Antonio, Texas, DOE, (submitted but not included!).

Liu, S., and S. K. Krueger, 1996c: Numerical simulations of altocumulus using an eddy resolving model and a mixed layer model. *Proceedings, 12th International Conference on Clouds and Precipitation,* Zurich, Switzerland, 895–898.

Liu, S., and S. K. Krueger, 1997: Effects of radiation in simulated altocumulus cloud layers. *Preprints, Ninth Conference on Atmospheric Radiation,* Long Beach, Calif., Amer. Meteor. Soc., 330–334.

Liu, S., and S. K. Krueger, 1998a: Development of an elevated mixed layer model for parameterizing altocumulus cloud layers. *Proceedings of the Seventh Atmospheric Radiation Measurement (ARM) Science Team Meeting,* San Antonio, Texas, DOE, 227–231. Extended Abstract: http://www.arm.gov/publications/proceedings/conf07/extended_abs/liu_s.pdf

Liu, S. and S. K. Krueger, 1998b: Further evaluation of an elevated mixed-layer model for altocumulus clouds. *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Tucson, Arizona , DOE, 441–445. Extended Abstract: http://www.arm.gov/publications/proceedings/conf08/extended_abs/liu_s.pdf

Luo, Y., S. K. Krueger, G. G. Mace, and K.-M. Xu, 2001: Cirrus Cloud Statistics from a Cloud-Resolving Model Simulation Compared to Cloud Radar Observations. *Proceedings of the Eleventh Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Atlanta, Georgia, DOE. Poster Abstract: http://www.arm.gov/publications/proceedings/conf11/poster_abs/P00236.stm

Luo, Y., Krueger, S. K., Moorthi, S., and Pan, H.-L., 2002a: Evaluation of cirrus properties simulated by a single-column model using cloud radar observations and results from a cloud-resolving model simulation. *Proceedings of the Twelfth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* St. Petersburg, Florida, DOE. Poster Abstract: http://www.arm.gov/publications/proceedings/conf12/poster_abs/P00181.stm

Luo, Y., Krueger, S. K., Moorthi, S., and Pan, H.-L., 2002b: Evaluation of cirrus properties simulated by a single-column model using cloud radar observations and results from a cloud-resolving model simulation. *Extended Abstracts, GCSS-ARM Workshop on the Representation of Cloud Systems in Large-Scale Models,* Kananaskis, Alberta, Canada, 20-24 May 2002. (http://www.met.utah.edu/skrueger/gcss-2002/luo.pdf)

Luo, Y., S. K. Krueger, G. G. Mace, and S. Moorthi, 2002c: Cirrus properties simulated by NCEP MRF SCM compared with cloud radar observations and a CRM simulation. *Preprints, 11th Conference on Cloud Physics,* Ogden, UT, Amer. Meteor. Soc., P3.17 (CD). (http://ams.confex.com/ams/pdfpapers/42786.pdf)

Luo, Y., and Krueger, S. K., 2003: Evaluation of Cloud Type Occurrences and Radiative Forcings Simulated by a Cloud Resolving Model Using Observations from Satellite and Cloud Radar. *Proceedings of the Thirteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Broomfield, CO, DOE. Extended Abstract: http://www.arm.gov/publications/proceedings/conf13/extended_abs/luo-y.pdf

Luo, Y.-L., and Krueger, S. K., 2004a: Evaluation of Detrainment and Microphysics Parameterizations in the NCEP GFS Single-Column Model. *Proceedings of the Fourteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Albuquerque, NM, DOE. Extended Abstract: http://www.arm.gov/publications/proceedings/conf14/extended_abs/luo2-y.pdf

Luo, Y.-L., and Krueger, S. K., 2004b: Cloud Types Simulated by the NCEP GFS Single-Column Model. *Proceedings of the Fourteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Albuquerque, NM, DOE. Extended Abstract: http://www.arm.gov/publications/proceedings/conf14/extended_abs/luo3-y.pdf

Rodriguez, D. J., and Krueger, S. K., 1999: Comparisons of Cloud Cover Estimates and Cloud Fraction Profiles from Data Provided by GOES-8 and ARM's Cloud-Detecting Instruments. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* San Antonio, Texas, DOE. Extended Abstract: http://www.arm.gov/publications/proceedings/conf09/extended_abs/rodriguez_dj.pdf

Xia, D., S. K. Krueger, and K. Sassen, 1997: Comparison of calculated radiative fluxes with ARM-CART site measurements under an altocumulus cloud layer. *Preprints, Ninth Conference on Atmospheric Radiation,* Long Beach, Calif., Amer. Meteor. Soc., 51–54.

Xia, D., S. K. Krueger, and K. Sassen, 1998: Comparison of calculated and measured radiative fluxes under altocumulus and stratocumulus cloud layers. *Proceedings of the Seventh Atmospheric Radiation Measurement (ARM) Science Team Meeting,* San Antonio, Texas, DOE, 181–186. Extended Abstract: http://www.arm.gov/publications/proceedings/conf07/extended_abs/xia_d.pdf

Xu, K.-M., S. K. Krueger, L. J. Donner, F. Guichard, W. Grabowski, D. E. Johnson, M. Khairoutdinov, J. C. Petch, D. A. Randall, C. J. Seman, W.-K. Tao, R. T. Cederwall, S. Xie, J. Yio, and M.-H. Zhang, 2000: Cloud-resolving Model Intercomparison with the ARM July 1997 IOP Data. *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* San Antonio, Texas, DOE. Extended Abstract: `http://www.arm.gov/publications/proceedings/conf10/extended_abs/xu2_km.pdf`

Xu, K.-M., Krueger, S.K., Randall, D.A., Cederwall, R.T., Xie, S.C., and Yio, J.J., 2002: Comparison of Cloud-Resolving with Single Column Simulations of Summertime Midlatitude Convection. *Proceedings of the Twelfth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* St. Petersburg, Florida, DOE. Poster abstract: `http://www.arm.gov/publications/proceedings/conf12/poster_abs/P00223.stm`

Yang, F., H.-L. Pan, S. Moorthi, S. Lord, and S. Krueger, 2005: Evaluation of NCEP Global Weather Forecast at the ARM SGP Site - Cloud and Radiation. *Proceedings of the Fifteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Daytona Beach, Florida, DOE. Poster Abstract: `http://www.arm.gov/publications/proceedings/conf15/poster_abs/P00064.stm`

10 Invited Presentations

Simulating Cloud Systems with a Cloud-Resolving Model. Global Studies Program, Batelle Pacific Northwest Laboratories, Richland, WA, 11 April 1994.

Interactions of Radiation and Convection in Simulated Cloud Clusters. Geophysical Fluid Dynamics Laboratory, Princeton University, Princeton, NJ, 30 March 1995.

Using Cloud-Resolving Models to Develop and Test Microphysics Parameterizations for Use in Climate Models. Workshop on Microphysics in GCMs, Kananaskis, Alberta, Canada, 23–25 May 1995.

Simulating Cloud Systems with a Cloud-Resolving Model. JASON DOE/ARM Program Review, GA Technologies, La Jolla, CA, 10–11 July 1995.

Cloud-Resolving Model Simulations of Tropical Cumulus Ensembles. GCSS Science Panel Meeting, International GEWEX Project Office, Washington, D.C., 11–15 December 1995.

GCSS: GEWEX Cloud System Study. ARM Science Team Meeting, San Antonio, TX, 4–7 March 1996.

Modeling Stratocumulus Clouds. Talk presented at the 4th International WMO Cloud Modeling Workshop, Clermont-Ferrand, France, 12–16 August 1996.

A GCSS Intercomparison of Cloud-Resolving Models based on TOGA COARE Observations. Talk presented at the ECMWF/GCSS Workshop on New Insights and Approaches to Convective Parameterization, Reading, England, U.K., 4–7 November 1996.

Testing Cloud Parameterizations. Talk presented at the ARM Science Team Meeting, San Antonio, TX, 3–7 March 1997.

Cloud-Resolving Modeling. Talk presented at AA Fest: A Symposium on General Circulation Model Development: Past, Present, and Future, University of California, Los Angeles, CA, January 20–22, 1998.

Intercomparison of Multi-Day Simulations of Convection During TOGA COARE with Several Cloud-Resolving and Single-Column Models. Talk presented at GCSS-WGNE Workshop on Cloud Processes and Cloud Feedbacks in Large-Scale Models, ECMWF, Reading, England, 9–13 November 1998.

Modeling Entrainment, Fine-Scale Mixing, and Droplet Spectral Evolution in Cumulus Clouds. Talk presented at the Mixing and Reactive Turbulence Workshop, NCAR, Boulder, Colorado, 13-16 July 1999.

GCSS and ARM. Talk presented at the ARM Science Team Meeting, San Antonio, TX, 13–17 March 2000.

GCSS Efforts to use Field Experiments to Evaluate Single-Column and Cloud System Models. Talk presented at the Gordon Research Conference on Solar Radiation and Climate, Connecticut College, New London, Connecticut, 24–29 June 2000.

A Review of Current Issues in Cumulus Parameterization; GCSS (GEWEX Cloud System Study) Overview and WG 4 (Precipitating Convective Cloud Systems) Activities. Talks to be presented at the ECMWF Seminar on Key issues in the Parametrization of Subgrid Physical Processes, ECMWF, Reading, 3–7 September 2001.

A Review of Current Issues in Cumulus Parameterization; GCSS (GEWEX Cloud System Study) Overview and *WG 4 (Precipitating Convective Cloud Systems) Activities.* Talks presented at the ECMWF Seminar on Key issues in the Parametrization of Subgrid Physical Processes, ECMWF, Reading, 3–7 September 2001.

Evaluation of Cloud Parameterizations Using Cloud-Resolving Model Simulations and ARM Observations. Talk presented at the Twelfth ARM Science Team Meeting, St. Petersburg, Florida, 8–12 April 2002.

The GEWEX Cloud System Study (GCSS). Talk presented at the Second International Conference of the Atmospheric Model Intercomparison Project: Towards Innovative Climate Model Diagnostics, Toulouse, France, 12–15 November 2002.

Observed and Simulated Cloud Types and Cloud Radiative Forcing for Case 3. Talk presented at the Thirteenth ARM Science Team Meeting, Broomfield, Colorado, 31 March–4 April 2003.

Cloud Properties Simulated by a Single-Column Model. Talk presented at the Bureau of Meteorology Research Centre, Melbourne, Australia, 9 October 2003.

Cloud system dynamics and the role of radiation. Talk presented at the Workshop on Radiative Transfer and the Modelling and Observing of Cloudy Atmospheres, Victoria, B.C., Canada, 13–14 November 2003.

Metrics for CRMs. Talk presented at the 3rd Pan-GCSS meeting on Clouds, Climate and Models, Athens, Greece, 16–20 May 2005.

11 The University of Utah 2D Cloud Resolving Model

The University of Utah Cloud Resolving Model (UU CRM) is a 2D cloud-scale model. It explicitly resolves the motions associated with clouds, but parameterizes the 3D turbulent motions. It can be considered as a very detailed sub-grid scale parameterization for a GCM grid column. This makes it ideal for simulating cloud-scale processes that must be parameterized in a GCM.

11.1 General features

The original version of the UU CRM was developed by the P.I. when he was a graduate student at UCLA. It was designed for long-term (e.g., 5-30 days), large-domain (e.g., 500 km) simulations of cloud systems, primarily in order to study the large-scale properties, rather than their detailed structure, of cloud systems. For this reason, the model is 2D and uses a bulk microphysics parameterization. The model has also been successfully used as a small-scale "eddy-resolving" model to study stratiform cloud systems, in the same way that

Starr and Cox (1985a,b) used their 2D cirrus model (e.g., Krueger et al. 1995c,d). Krueger (2000) describes CRMs and their usefulness in general, as well as applications of the UU CRM to a variety of cloud systems. Whenever possible, the results of model simulations have been checked against observations and comparable 3D simulations. Some of these model evaluations are described below.

The UU CRM is a 2D model (x-z) that is based on the anelastic set of equations, and includes the Coriolis force and prescribed large-scale forcing. The model is more fully described in Krueger (1988), Xu and Krueger (1991), Krueger et al. (1995a), and Fu et al. (1995). The current version includes third-moment turbulence closure, a turbulence scale condensation scheme, a bulk ice-phase microphysics parameterization (Lin et al. 1983; Lord et al. 1984; Krueger et al. 1995a; Fu et al. 1995) and an advanced radiation code. The microphysics parameterization is described in more detail below.

The radiative transfer parameterization used in the UU CRM is described in Fu et al. (1995) and Krueger et al. (1995b). It is a plane-parallel broadband approach with 6 solar and 12 infrared bands. It is based on the correlated k-distribution method (Fu and Liou 1992) and uses the δ-four stream scheme (Liou et al. 1988) for both the solar and infrared regions of the spectrum. It can efficiently and accurately compute the detailed vertical structure of the heating rate profile within clouds.

My research group has used the UU CRM to simulate tropical cumulus ensembles and the results have been used to study aspects of cumulus parameterization (e.g., Krueger 1988, Xu et al. 1992), large-scale cloud parameterization (Xu and Krueger 1991), the interactions of radiation, convection, and cirrus anvils in tropical cloud clusters (Fu et al. 1995, Krueger 2000), parameterization of the enhancement of large-scale surface fluxes over tropical oceans due to cumulus circulations (Zulauf and Krueger 1997, Krueger 2000, Zulauf 2001), and to evaluate the UU CRM (Xu et al. 2002). We have also used the UU CRM to study the trade cumulus boundary layer (Krueger and Bergeron 1994), the stratocumulus-to-cumulus transition in the subtropical marine boundary layer (Krueger et al. 1995b,c; Krueger 2000), a stratocumulus-topped boundary layer (Moeng et al. 1996), the ASTEX Lagrangian experiments (Bretherton et al. 1999), altocumulus formation and structure (Liu 1998, Liu and Krueger 1998, Krueger 2000), and convective plumes produced by Arctic leads (Krueger 2000, Zulauf 2001, Zulauf and Krueger 2003a,b).

The UU CRM has been extensively used by Akio Arakawa's group at UCLA to study parameterization of cumulus convection, cirrus anvil clouds, and boundary-layer stratocumulus clouds. A version of the UU CRM that differs mainly in the radiative transfer code has also been extensively used by Kuan-Man Xu (at UCLA, CSU, and now LARC).

11.2 Microphysics parameterization

We will focus the description of the microphysics parameterization on those aspects that are most important for cirrus clouds. The bulk ice microphysics parameterization includes five hydrometeor species: cloud water, cloud ice, snow, graupel, and rain. The parameterization currently uses size distributions and particle densities that are appropriate for tropical oceanic deep convection (Lord et al. 1984; Krueger et al. 1995a). Very few measurements have been available until recently for evaluating the scheme's representation of cirrus cloud microphysics.

The predominant species in cirrus clouds are small ice crystals and large ice crystals. In the CRM, these are represented as "cloud ice" and "snow." Cloud ice has zero fall speed, and snow has a mass-weighted mean terminal velocity that depends on the density and size distribution assumed. For snow, the exponential size distribution is assumed. (A modified gamma distribution is probably more realistic for the large ice crystals in cirrus clouds.) Representing ice in cirrus clouds with two species provides the scheme with the advantages of a two-size-class model, which includes sedimentation size sorting. For comparison, Starr and Cox's model (1985a) used a single class of ice, so all ice at a grid point falls at the same speed. Another advantage of two size classes is that the effective radius or size of the ice particles (needed by the RT code) can vary according to proportions of small and large ice crystals.

The microphysics parameterization includes a generalized saturation adjustment scheme for cloud water and cloud ice (Lord et al. 1984) and an ice-crystal nucleation process (Lin et al. 1983). The combination of these is able to reproduce the observed large supersaturation with respect to ice that occurs just before ice forms, and the lower but still significant supersaturation that persists once ice is present.

The ice microphysics scheme produces IWC values as a function of temperature and large-scale vertical velocity that are comparable to measurements presented by Heymsfield and Donner (1990) (Fu et al. 1995). In order to better evaluate the UU CRM's representation of cirrus clouds, we compared cirrus statistics obtained from a CRM simulation to Mace et al.'s (2001) observed statistics (Luo et al. 2003). This comparison allowed a valuable evaluation of a CRM's representation of cirrus cloud physics.

Mace et al. (2001) used cloud radar and IR spectral radiometer measurements to retrieve 3-minute-averaged thin cirrus properties over the DOE ARM program's SGP site during 1997. We sampled results of a 29-day simulation of continental summertime deep convection at the ARM SGP site at 8 grid columns every 5 minutes using the same criteria. We compared thin cirrus and all-cirrus statistics, including frequency distributions of IWP, IWC, layer thickness, and mid-cloud height. We found that the CRM's IWP and mid-cloud heights are about right, while its IWC is too small and layer thickness too large. This suggests that the fall speed of large ice crystals is probably too large in the CRM. Comparison of "thin cirrus" IWP versus temperature shows that the dependence of thin cirrus IWP on temperature simulated by the CRM generally agrees with the retrieved dependence. Comparisons of "thin cirrus" layer-mean IWC in terms of temperature, cloud-layer thickness, and large-scale vertical velocity shows that the CRM reproduces the observed dependence of IWC on these quantities. The excellent qualitative agreement between the CRM simulation and the observed cirrus statistics demonstrates that the essential physics of cirrus cloud formation, maintenance, and decay are exhibited in the CRM simulation.

11.3 References

Bretherton, C. S., S. K. Krueger, M. C. Wyant, P. Bechtold, E. van Meijgaard, B. Stevens, and J. Teixeira, 1999: A GCSS boundary layer model intercomparison study of the first ASTEX Lagrangian experiment. *Bound.-Layer Meteor.,* **93,** 341–380.

Fu, Q., and K.N. Liou, 1992: On the correlated *k*-distribution method for radiative transfer in nonhomogeneous atmospheres. *J. Atmos. Sci.,* **49,** 2139–2156.

Fu, Q., S. K. Krueger, and K.N. Liou,1995: Interactions of radiation and convection in simulated tropical cloud clusters. *J. Atmos. Sci.,* **52,** 1310–1328.

Heymsfield, A. J., and L. J. Donner, 1990: A scheme for parameterizing ice-cloud water content in general circulation models. *J. Atmos. Sci.*, **47**, 1865–1877.

Krueger, S.K., 1988: Numerical simulation of tropical cumulus clouds and their interaction with the subcloud layer. *J. Atmos. Sci.,* **45,** 2221–2250.

Krueger, S. K., 2000: Cloud system modeling. *General Circulation Model Development,* D. A. Randall, ed., Academic Press, San Diego, 605–640.

Krueger, S.K., and A. Bergeron, 1994: Modeling the trade cumulus boundary layer. *Atmos. Res.*, **33,**, 169–192.

Krueger, S. K., Q. Fu, K. N. Liou, and H.-N. S. Chin, 1995a: Improvements of an ice-phase microphysics parameterization for use in numerical simulations of tropical convection. *J. Appl. Meteor.*, **34,** 281–287.

Krueger, S.K., G.T. McLean, and Q. Fu, 1995b: Numerical simulation of the stratus-to-cumulus transition in the subtropical marine boundary layer. Part I: Boundary-layer structure. *J. Atmos. Sci.,* **52,** 2839–2850.

Krueger, S.K., G.T. McLean, and Q. Fu, 1995c: Numerical simulation of the stratus-to-cumulus transition in the subtropical marine boundary layer. Part II: Boundary-layer circulation. *J. Atmos. Sci.,* **52,** 2851–2868.

Lin, Y.-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Clim. Appl. Meteor.,***22,** 1065–1092.

Liou, K.N., Q. Fu, and T.P. Ackerman, 1988: A simple formulation of the delta-four-stream approximation for radiative transfer parameterizations. *J. Atmos. Sci.,***45,** 1940–1947.

Liu, S., 1998: Numerical Modeling of Altocumulus Cloud Layers. Ph.D. Dissertation, Dept. of Meteorology, University of Utah, 147 pp.

Liu, S., and S. K. Krueger, 1998: Numerical simulations of altocumulus using a cloud resolving model and a mixed layer model. *Atmos. Res.,* **47–48,** 461–474.

Lord, S. J., H. E. Willoughby, and J. M. Piotrowicz, 1984: Role of a parameterized ice-phase microphysics in a n axisymmetric, non-hydrostatic tropical cyclone model. *J. Atmos. Sci.,***41,** 2836–2848.

Luo, Y., S. K. Krueger, G. G. Mace, and K.-M. Xu, 2003: Cirrus cloud properties from a cloud-resolving model simulation compared to cloud radar observations.

Mace, G. G., E. E. Clothiaux, and T. P. Ackerman, 2001: The composite characteristics of cirrus clouds: Bulk properties revealed by one year of continuous cloud radar data. *J. Clim.*, **15**, 2185–2203.

Moeng, C.-H., W. R. Cotton, C. Bretherton, A. Chlond, M. Khairoutdinov, S. Krueger, W.S. Lewellen, M.K. McVean, J.R.M. Pasquier, H.A. Rand, A.P. Siebesma, R.I. Sykes, and B. Stevens, 1996: Simulation of a stratocumulus-topped PBL: Intercomparison of different numerical codes. *Bull. Amer. Meteor. Soc.,* **77,** 216–278.

Starr, D. O'C., and S. K. Cox, 1985a: Cirrus clouds. Part I: A cirrus cloud model. *J. Atmos. Sci.,***42,** 2663–2694.

Starr, D. O'C., and S. K. Cox, 1985b: Cirrus clouds. Part II: Numerical experiments on the formation and maintenance of cirrus. *J. Atmos. Sci.,***42,** 2682–2694.

Xu, K.-M., and S. K. Krueger, 1991: Evaluation of cloudiness parameterizations using a cumulus ensemble model. *Mon. Wea. Rev.,* **119,** 342–367.

Xu, K.-M., A. Arakawa, and S. K. Krueger, 1992: The macroscopic behavior of cumulus ensembles simulated by a cumulus ensemble model. *J. Atmos. Sci.,* **49,** 2402–2420.

Xu, K.-M., R. T. Cederwall, L. J. Donner, W. W. Grabowski, F. Guichard, D. E. Johnson, M. Khairoutdinov, S. K. Krueger, J. C. Petch, D. A. Randall, C. J. Seman, W.-K. Tao, D. Wang, S. C. Xie, J. J. Yio, and M.-H. Zhang, 2002: An intercomparison of cloud-resolving models with the Atmospheric Radiation Measurement summer 1997 Intensive Observation Period data. *Q. J. Roy. Meteor. Soc.,***128,** 593–624.

Zulauf, M. A., 2001: Modeling the effects of boundary layer circulations gener-ated by cumulus convection and leads on large-scale surface fluxes. Ph.D. dissertation, University of Utah, Salt Lake City, 177 pp.

Zulauf, M., and S. K. Krueger, 1997: Parameterization of mesoscale enhancement of large-scale surface fluxes over tropical oceans. *Preprints, 22nd Conference on Hurricanes and Tropical Meteorology,* Fort Collins, CO, Amer. Meteor. Soc., 164–165.

Zulauf, M. A., and S. K. Krueger, 2003a: Two-dimensional numerical simulations of Arctic leads: Plume penetration height. *J. Geophys. Res.,* **108 (C2),** 8050–8062, doi:10.1029/2000JC000495.

Zulauf, M. A., and S. K. Krueger, 2003b: Two-dimensional cloud-resolving modeling of the atmospheric effects of Arctic leads based upon midwinter conditions at the Surface Heat Budget of the Arctic Ocean ice camp. *J. Geophys. Res.,* **108 (D10),** 4312–4325, doi:10.1029/2002JD002643