Summary of Cumulus Parameterization Worskhop

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Abstract

A workshop on cumulus parameterization took place at the NASA Goddard Space Flight Center from December 3 - 5, 2001. The major objectives of this workshop were (1) to review the problem of representation of moist processes in large-scale models (mesoscale models, Numerical Weather Prediction models and Atmospheric General Circulation Models), (2) to review the state-of-the-art in cumulus parameterization schemes, and (3) to discuss the need for future research and applications. There were a total of 31 presentations and about 100 participants from the United States, Japan, the United Kingdom, France and South Korea. The specific presentations and discussions during the workshop are summarized in this paper.

1.   Introduction

Each spring and fall, the Laboratory for Atmospheres in the Goddard Earth Sciences Directorate presents a seminar series on a wide range of atmospheric topics. These seminars are a general forum for the presentation of new and interesting results in the atmospheric sciences to the entire group of branches[1] in the laboratory. The talks have proven to be quite popular not only within the Goddard Space Flight Center (GSFC) atmospheric community, but also with the other groups of atmospheric scientists in the Baltimore-Washington region, including National Atmospheric and Oceanic Administration (NOAA) National Centers Environmental Prediction (NCEP), the University of Maryland, and the Johns Hopkins University. It was decided to host a workshop on the topic of cumulus parameterization schemes used in large-scale models because the principal limitation of global modeling at this point is the representation of clouds and their effect on the radiation balance both locally and on the global scale. The major objectives of this workshop were (1) to review the problem of representation of moist processes, (2) to discuss the state-of-the-art in cumulus parameterization schemes and (3) to discuss the need for future research and applications.

The workshop brought together a broad range of scientists including large-scale modelers (climate and numerical weather prediction) and their associated parameterization developers (the latter are a very small community); single column (SCM), cloud-resolving (CRM) and cloud-system modelers (mesoscale/regional); as well as observationalists involved in field experiments and satellite analysis, especially TRMM. Such as interaction does not often occur. The workshop was also quite notable because of recent new developments including superparameterization (the direct use of CRM's embedded within global model grid cells) and the implementation of statistical parameterizations based on the analysis of CRM output. These approaches have been facilitated by dramatic progress over the last decade associated with activities of the GEWEX Cloud System Study (GCSS) working groups and by the availability of suitable satellite and field data. The contrasting requirements for climate and Numerical Weather Prediction (NWP) applications were also highlighted and discussed.

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[1]   The laboratory consists of Data Assimilation Office, Mesoscale Atmospheric Processes Branch, Climate and Radiation Branch, Atmospheric Experiment Branch and Atmospheric Chemistry and Dynamics Branch.

The workshop consisted of two parts: keynote (invited) presentations and general presentations. There were four invited presentations given by Professor A. Arakawa (University of California, Los Angeles) on the basic concepts of cumulus parameterization, Dr. J. Kain [NOAA/National Severe Storms Laboratory (NSSL)] on cumulus parameterization used in mesoscale models, Dr. D. Randall (Colorado State University) on the use of CRMs and SCMs in the cumulus parameterization problem, and Dr. A. Del Genio [NASA/Goddard Institute Space Science (GISS)] on cumulus parameterization schemes used in climate models. The general presentations were grouped into four sessions: Observations, Cloud-Process and Cloud-Resolving Models, Parameterization, and Global Circulation Models. The workshop also had a plenary session discussing the challenges and future directions of "convective parameterization".

2.   Session summaries

Dr. F. Einaudi, the Director of the NASA Goddard Earth Sciences Directorate, opened the workshop and welcomed the participants. Dr. Einaudi stated that the highest science priority identified in the World Climate Research Program (WCRP) is Climate and Hydrological Systems, with the role of clouds being the topmost sub-element. In particular, cloud-radiation feedback mechanisms and Global Circulation Model (GCM) representation of cloud mechanisms are the most problematic issues facing global change studies. The effects of deep cumulus convection, especially in the tropics, has long been recognized as one of the singularly most important linkages between these major components of the global climate system. The latent heat release in precipitating convective systems, and the vertical structure thereof, provides strong forcing to the global circulation and acts to substantially balance the radiative forcing of the atmosphere. The radiative effects of the cloud systems, especially the upper tropospheric outflow of ice and vapor, is also a key element. The effects of deep convective systems must be well represented in global models in the face of limited computational resources - thus parameterization has been and remains a necessity at least for the next few decades.

Dr. Einaudi mentioned that it is especially gratifying to see that research into improving cumulus parameterization is again a vibrant area of endeavor with new ideas, new data, and new uses of existing data - and new and old faces. We at NASA and GSFC are particularly pleased to play a role in facilitating progress in this critical

area for the US Global Change Research Program (USGCRP) and NASA's own Earth Science Enterprise.

2.1.   Observations [chaired by Dr. Jack Kain (NOAA/National Severe Storms Laboratory) and Dr. Wei-Kuo Tao (Goddard Space Flight Center)].

Professor A. Arakawa (University of California, Los Angeles) gave an invited talk overviewing the basic concepts in cumulus parameterization and a related "*short history*" of numerical modeling of the atmosphere (from a very simple numerical weather prediction model in 1950 to current Coupled Atmospheric-Oceanic GCMs). Cumulus parameterization was introduced somewhat reluctantly in early 1960 by Charney and Eliassen, Manabe *et al.* and Ooyama. Now, cumulus parameterization is defined as "*the problem of formulating the collective effects of moist convection in terms of the explicitly formulated processes in the model to obtain a closed system for prediction*". In general, two types of closure assumptions were assumed. The first type of closure (called principal closure) constrains the existence and overall intensity (e.g., cloud base mass flux) of cumulus activity. The other type of closure constrains cloud properties or processes, especially on their vertical distributions based on simplified clouds or empirical results. The requirements for principal closure are (1) not to lose the predictability of the large-scale fields and (2) reflect our understanding of the parameterizability of moist convection. Dr. Arakawa also showed the advection equations for boundary-layer water vapor mixing ratio and emphasized that local Eulerian budget considerations and Lagrangian advection considerations should not be confused.

Dr. Arakawa also gave an overview of the controversies in the cumulus parameterization problem. First, he presented the controversy between conditional instability of the second kind (CISK) and wind-induced surface heat exchange (WISHE) in the context of tropical cyclone simulations. He pointed out that the controversy largely depends on a confusion between local Eulerian budget and Lagrangian advection in the moisture convergence closure. The results with the moisture convergence closure, however, can be interpreted from another point of view: adjustment. Dr. Arakawa also presented the different roles of surface heat flux on the boundary layer moisture balance in the core and outer regions between the CISK and WISHE theory. Dr. Arakawa gave a list of several parameterization schemes that constructed with very different rationale (i.e., explicit vs implicit in forcing and adjustment, diagnostic vs prognostic) but can work comparably well. The controversy

over adjustment schemes lies in the choice of the adjustment coefficient which can be optimally selected.

In many parameterization schemes, a cloud model is needed to calculate the vertical structure of cloud properties for each "cloud type". Controversies with such schemes involve the selection of cloud type (single, parallel multiple or sequential multiple) and cloud model (simple or detailed). Dr. Arakawa indicated that cloud dynamics is itself a complicated subject. However, cumulus parameterization is an attempt to look at clouds as a forest, for which no theory has been established.

Quasi-geostrophic approximation can be viewed as a closure in the sense that it has a simpler closed theoretical framework because only the potential vorticity is a prognostic variable. An analogy between cumulus parameterization and quasi-geostrophic dynamics was presented. The adjustment time-scales are a problem for both and present a limit of applicability. However, there is no well-established theory for cumulus adjustment comparable to the geostrophic adjustment theory. Dr. Arakawa also stressed that cumulus parameterization is a "young" science problem compared to quasi-isotropic turbulence.

Dr. Arakawa pointed out that different processes (e.g., radiation, clouds, turbulence) usually interact through grid-scale variables, losing most of their subgrid-scale interactions in existing parameterizations. A single nonphysical scale (grid size) determines the separation between processes that can be highly transient, and those can only be near quasi-equilibrium. In addition, the resolution dependency of "required physics" is mostly left to blind tuning. Dr. Arakawa also briefly discussed the difference between "required physics" that define the physics needed for model predictions to be correct and "real physics" that are the local and instantaneous physics.

Furthermore, Dr. Arakawa suggested that we need to move from "diagnostic parameterization" to "prognostic parameterization", from "cumulus parameterization" to "unified cloud parameterization", from "single-column parameterization" to "multiple-column parameterization", and from "deterministic parameterization" to "non-deterministic parameterization". He also recommended more prognostic equations giving more degrees of freedom to subgrid-scale processes. A unified cloud parameterization would treat stratiform and cumuliform clouds together without artificially separating them to "grid-scale" and "subgrid-scale". "Multiple-column

parameterization" can reduce the dependency on the artificial scale determined by the grid scale. Inclusion of non-deterministic components in the parameterized results reflects the uncertainties in the initial conditions for small-scale processes, those in formulating triggering, and a poor statistical significance of the "mean". Dr. Arakawa concluded his talk by emphasizing the absolute necessity in using a hierarchy of models and observations for the unified modeling effort.

Ms. Wen-wen Tung and Professor Michio Yanai (University of California at Los Angeles) gave a talk entitled "Convective Momentum Transport Observed during the TOGA COARE IOP". Ms. Tung first showed the mass flux representation of cumulus momentum transport (CMT) and discussed particularly the importance of vertical wind shear and the organization of convection in determining the CMT. There are essentially two methods, aircraft measurement and the residual from the large-scale momentum budget that can estimate CMT from observations. Measuring eddy vertical momentum flux by aircraft is suitable for detailed studies but often can not cover entire convective systems. The budget calculation is good for estimating CMT over longer time and larger spatial scales, but data quality had been a major problem. During the TOGA-COARE IOP (November 1992-February 1993), quality sounding data were obtained over the western Pacific. With ECMWF reanalysis as the first guess field, objective analysis was performed on UCAR merged radio-sound and wind profiler data to calculate the momentum budget residual and evaluate the CMT. The results indicated that there was a link between cumulus convection and the large-scale tropical circulation through CMT. Similarity has been found among the power spectra of the wind, the momentum budget residual, and the GMS deep convection index, showing modulations by various tropical disturbances. Nonlinear convection tends to decelerate the large-scale wind (down-gradient transport or vertical mixing). Linear convection (i.e., squall lines) accelerates (non-mixing or up-gradient transport) the lower-to-middle level wind in the line-normal direction. The results also indicated that up-gradient CMT occurred during the initial phase of a westerly wind burst (WWB), but down-gradient CMT is associated with very deep convection that can lift westerly momentum upward during the strong and mature phase of a WWB. It was concluded that even though the four-month average showed large-scale kinetic energy is transferred downscale in the troposphere, upscale kinetic energy transfer associated with convective events such as squall lines and super cloud clusters during the MJO is observed at scales comparable to the size of a GCM grid. Very few GCMs consider the effect of cumulus momentum

transport. Subgrid-scale cloud regimes are not part of any existing parameterization schemes.

The 1974 GATE (GARP Atlantic Tropical Experiment) was planned to provide a basis for developing appropriate schemes for estimating the effects of smaller tropical weather systems on the larger-scale circulation. It served to accelerate work related to parameterization. Professor Richard H. Johnson (Colorado State University) presented a talk entitled "Some Observational Aspects of Cumulus Parameterization". He noted that one of the most important findings from GATE was the nearly ever-present mesoscale organization to convection, suggesting that there is no spectral gap between larger-scale circulations and small-scale weather systems. Three important findings relevant to the parameterization problem emerged from TOGA COARE (November 1992 to February 1993): observations of a trimodal cloud population (shallow cumulus, congestus and cumulonimbus) associated with a trimodal distribution of atmospheric stability (the tradewind stable layer, the melting layer, and the tropopause); the importance of radiative effects of cloud systems (cirrus clouds extending great distances from their convective sources significantly modulating the radiation budget on the time scale of the Madden-Julian Oscillation or MJO); and the influence of convection on the atmospheric boundary layer (large variability of mixed-layer depth and properties on weekly to monthly time scales in association with the MJO). It was found that following westerly wind bursts during the active phase of the MJO, drying in the lower troposphere reduced shallow cumulus populations and allowed the mixed-layer depth to grow to nearly 1 km. Eventual recovery of shallow cumulus gradually reduced the mixed-layer depth and remoistened the lower troposphere, a process likely important in controlling the timescale for the MJO. Dr. Johnson also showed that GCMs and CRMs with high vertical resolution are able to resolve the melting layer and associated congestus and midlevel clouds. The impact of midlevel cloud layers on radiation deserves study within the context of parameterization.

A detailed review of South American precipitation regimes was presented by Drs. Tom Rickenbach and Jeff Halverson (Joint Center for Earth Systems Technology, UMBC and NASA GSFC). The title of their talk is "*Application of TRMM[2] field campaign observations in Brazil to cumulus parameterization*". Observational studies have suggested that three major South American summertime precipitation regimes, monsoonal, South

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[2]   TRMM stands for Tropical Rainfall Measuring Mission.

Atlantic Convergence Zone (SACZ) and larger nocturnal mesoscale convective systems in the La Plata river basin, can be identified. The "dipole" between SACZ and La Plata precipitation is closely related to the low level jet (LLJ) position. Mesoscale observations from radar and soundings during TRMM LBA in southwestern Amazonia (January and February 1999) also revealed that strong low level westerlies occur there when the SACZ is well-established, while easterly flow characterized the periods when the SACZ was not present. Periods influenced by the SACZ are more characteristic of frontal rain with high stratiform rain percentages, large rain areas and less convective rain intensity compared to non-SACZ periods. The vertical reflectivity structure between SACZ and non-SACZ systems is quite distinct. Higher reflectivity values in the mixed-phase region for the non-SACZ periods point to larger ice particle sizes, stronger updrafts, high CCN concentrations, and active electrification, in contrast to the SACZ regime. These differences may be in part related to different source airmass characteristics during each regime. The diurnal variation of rain intensity showed afternoon maxima for both regimes, but with important differences suggesting explosive convective growth in the non-SACZ regime and the dominance of nocturnal stratiform rain processes in the SACZ regime. This picture is generally consistent with the diurnal changes in the apparent heat source and moisture sink from sounding analysis. For example, the SACZ regime budgets indicate heating and drying in the upper troposphere, with weak diurnal changes, consistent with the diurnal variation of radar-derived rainfall. It was concluded that the SACZ, manifested in SW Amazonia by a stationary frontal zone extending into the deep Tropics, is a strong modulator of convection in southwestern Amazonia. Low-level wind direction, related to the presence or absence of the SACZ, may help guide cumulus parameterization assumptions and modeling studies of South American tropical convection.

Professor MingHua Zhang (State University of New York at Stony Brook) gave a talk entitled "*Integrated measurements from field experiments relevant to the thinking of cumulus convection parameterizations in GCMs*". The implementation design for Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) was presented that involved the integrated balloon soundings, profiler winds, surface energy fluxes, rain gauge data, radar images and rainfall, duel Doppler analyses, surface meteorological variables, TOA measurements, and operational analyses. These measurements and analysis can aid in the budget analysis and the understanding of physical processes in both numerical models and in satellite data. Since the observed quantity at one location and one time was sometimes quite different between the

various instrument platforms, a variational objective analysis was employed to compute and minimize the "cost function" that constraints the difference between the different measurements. This method can produce reliable budget analyses of temperature, moisture and wind. This integrated analysis can be used to provide forcing as well as to validate heating and moistening profiles for CRMs and SCMs. Several examples observed during ARM (1995 and 1997) were provided. Issues related to triggering conditions for convection (i.e., propagation, self-excitation and initial triggering), closure assumptions (large-scale conditions or self-limitation on smaller scales) and validation were also discussed.

2.2   Cloud-Process and Cloud-Resolving Models (Chaired by Dr. Y. Sud, NASA/Goddard Space Flight Center).

In this invited talk, Dr. David Randall (Colorado State University) emphasized that despite significant progress in modeling atmospheric processes, climate change simulations with GCMs at year-end 2001 remain uncertain. This is largely due to deficiencies in the representation of cloud and cloud-radiative processes in climate models. To make further progress, his talk focused on two themes: what are we doing about cloud uncertainty issues? And what (more) can we do about them?

First, he pedagogically described the history of cumulus models- starting with observations of hot towers and translation of this knowledge into mass flux schemes due to Arakawa some 30-40 years ago. Regarding the complexity of cloud schemes, he alluded to the ever-evolving inclusion of details of cloud-processes such as representation such as updrafts and downdrafts, sub-grid scale saturation and condensation, and explicit calculations of area fractions for rising cumulus and subsiding environment together with cumulus updraft velocities and detrainment identifying towers and anvils. Evidently, all such upgrades have helped to better represent cloud dynamics and microphysics in the present-day schemes. However, large variations in arbitrary assumptions in modeling these processes have contributed to large intra-model variability as evidenced in the Atmospheric Radiation Measurement (ARM) - Cloud and Radiation Testbed (CART) Single Column Model (SCM) evaluations.

Dr. Randall argued there is virtually no representation of the mesoscale in GCMs, and yet we all know there is mesoscale out there and that it strongly influences clouds and cloud-radiative effects. This mesoscale is a thermodynamically active

extension of the cumulus clouds (with momentum and energy fluxes across them), and it needs to be included in a cloud model. He stated that the radiation problem is now solved. Radiative transfer codes will give accurate answers only if the input: cloudiness and cloud microphysical parameters are realistically provided. He thus made a strong case for the need to improve cloud input into the radiative transfer models. Referring to the over-whelming complexity of clouds, Randall listed the following: cloud fractions, cloud water substance inhomogeneity, microphysical parameters, and cloud overlap among the layers. Consequently, he felt that we still have several years of work ahead of us for improving clouds and cloud processes; but an alternative approach invoking Cloud-System-Resolving Models (CSRMs)[3] holds an outstanding promise. This involves introducing CRMs as cloud samplers within the grid-cell of a GCM. With the cloud-scale resolution, all cloud dynamics and cloud interactions will be resolved; naturally cloud processes similar to or better than ARM-CART data tests would be expected.

Even with today's computer power, Randall felt, this is a doable exercise. The concept has been tested already at NCAR and CSU with successful simulations and useful results (e.g., the CRM-GCM simulates a realistic MJO). However, implementing the CRMs optimally is still a Grand Challenge and taking climate system models to that stage is not a plug and go exercise. There will still be parameterized microphysics, radiative transfer, turbulence, and small-scale convection. There will be issues relating to consistency and compatibility between GCMs and CRMs but "None of these are show-stoppers" argued Randall. Also, there will be high cost of running these super parameterizations in a GCM, but on the positive side, he described how massive parallelism would rescue this effort. In closing, he stated that the conventional cloud parameterizations for long integration will still be around, but the new approach with embedded CRMs which he termed a "super-parameterization" will help to understand and address the present day uncertainty of climate change simulation with GCMs.

Dr. S. Krueger gave a talk entitled "*The nature of convectively-generated cirrus clouds in models and observations*". He demonstrated the usefulness of field data for evaluating and improving the representation of cirrus clouds in both single column models (SCMs) and cloud-resolving models (CRMs). His research and development outlay aims at SCMs to also benefit from CRMs as well as GCMs. Dr. Krueger evaluated CRMs using 3-months of ground-based cirrus cloud data to statistically

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[3] Cloud-system-Resolving Model is basically a Cloud-Resolving Model (CRM). Hereafter, it is named as CRM for consistency.

evaluate 29-day CRM simulations using ARM-CART data. He noted some biases in cloud thickness (too large), cloud-base height (too low), and ice water content (IWC) (too small) even though the essential aspects of cirrus clouds were quite realistic. Dr. Krueger expects to reduce these biases by reworking the hydrometeor fall speeds and better treatment of sublimation. In a corresponding SCM evaluation, he noted that the random overlap assumption caused the cirrus cloud occurrence frequency to become too large, whereas with maximum random overlap it turns out to be too small. In addition, cirrus ice water path (IWP) and IWC were too large while the specified effective cloud-particulate radii were too small. Since cloud ice formed in convective updraft is an important source of cirrus ice in anvils, this ice naturally is a function of cumulus parameterization. However, the properties of cirrus anvils also significantly depend on the representation of large-scale cirrus cloud physics (microphysics, radiation, and turbulence). Differences in how these processes are parameterized can produce large variations in simulated cloud-radiation interaction.

Dr. B. Mapes (NOAA/ Climate Diagnostics Center) presented a talk entitled "*Mixing assumptions and scheme performance*". Dr. Mapes examined the entrainment assumptions in mass-flux cumulus schemes and applied the "eyeball" and area average divergence tests for optimizing it in the MM5-Regional Climate Model environment. He considered different cumulus schemes that either use or not use entraining plumes. Through a variety of tests modifying these parameters, he showed a huge influence on the simulated precipitation. He noted that more entrainment restrains the amount of convection (desirable) but limits the convective height (undesirable). He concluded that there is a need to re-examine the whole entrainment formulation. The existing schemes are too simple and regional models can provide a useful environment to improve them. The challenges that confront us are including mesoscale organizations, multiple cloud populations with middle, shallow, and high clouds. The key aspects of convection are cirrus clouds, coupling between convection and the boundary layer, and sub-cloud layers. He emphasized the need for developing datasets for such tests and carefully designed field experiments to better understand and simulate the diurnal aspects of convection.

Dr. M. Khairoutdinov gave a talk entitled "*The statistical properties of cumulus convection derived from cloud-resolving modeling*". Dr. Khairoutdinov showed simulation results from a CSU 3D-CRM that was used to simulate five short (5-14 hrs) convective episodes in the ARM-CART Intensive Operation Period (IOP) in July 1997. The similarity

in the second and third statistical moment budgets together with triple correlations revealed the dynamic similarity among the five events. Moreover, the diagnosed Convective Kinetic Energies (CKE) showed: 1) CKE dissipation is small compared to buoyancy production, transport, and pressure correlation; 2) the large negative buoyancy flux that is typical of deep anvils is very small for shallow convection; and 3) tripple correlation can be formulated as an upward advection of corresponding second-moments. In agreement with earlier studies, Marat noted that CKE largely resides in the horizontal branches of the mesoscale circulation. The so-called bulk CKE dissipation time-scale varies between 4 to 8 hours. Accordingly, the bulk CKE contained in the horizontal branches of a mesoscale circulation associated with deep convective systems would persist much longer than the lifetime of an individual convective cloud. He also found that the fraction of the bulk CKE associated with vertical motions was about the same for all of the events simulated; this suggests a strong correlation between the bulk CKE and the strength of convective updrafts. It was also shown that the bulk CKE dissipation time-scale is inversely proportional to the square root of the bulk CKE itself.

Dr. Steve Derbyshire presented a talk entitled "*CRM-SCM comparisons under the European Cloud Systems Project (EUROCS)*". The EUROCS programme includes simulation of observed cases, some idealized case studies and tests of parametrization in NWP models. The presentation to this Workshop concerned an idealized case, designed to test the sensitivity to mid-tropospheric humidity. This case was simulated with five different SCMs and two different CRMs. The two CRMs were in good agreement, whereas the SCMs showed a wide range of responses. In the CRMs the drier cases gave shallow convection, but the moist cases gave deep convection. Initial tests in an NWP environment showed encouraging results for a convective closure sensitive to relative humidity.

Drs. Tomoe Nasuno and Kazuo Saito gave a talk entitled "*Resolution dependence of a tropical squall line*". Dr. T. Nasuno discussed the results of simulations with a high-resolution model [Meteorological Research Institute (MRI) - Non-hydrostatic Model (NHM)] that would adequately resolve mesoscale convective systems. The intent was to determine the best resolution for representing the explicit physics. TOGA COARE data (including a 22/02/1993 squall line case) was used in the study. The model had 45 vertical layers and was run at five different horizontal resolutions varying from 1.25 to 8 km in an 880 x 880-km region. The results showed dramatic variations between the different horizontal resolutions. They were evident in the vertical velocity, winds,

potential temperature, and humidity fields after 12h of integration. At low resolution, cloud organization is weak and squall line propagation speeds are under-estimated while the grid-scale circulation and storm intensities are over-estimated. These sub-grid scale effects are especially significant at low levels where rain evaporation and rear-to-front flows get accelerated.

Drs. Joon-Hee Jung and A. Arakawa (University of California, Los Angeles) presented a talk entitled "*Resolution Dependence of Model Physics Under the Existence of Conditional Instability: Preliminary Results from CRM Experiments*". This study also investigated the influence of resolution on cumulus convection in both a CRM and an ideal cloud parameterization. The model was run at three horizontal resolutions (2, 8, 32 km) over a 512-km domain with 34 layers in the vertical. The results show huge differences in the development of cloud systems, winds, vertical and horizontal kinetic energies, temperature, humidity, and moist static energy as a function of resolution when the model does not include any cumulus parameterization. The differences suggest the need for resolution-dependant cloud parameterization, which has an adjustment to the microphysical and dynamical consequences of a lack of resolution. Similar analyses on the choice of physics time-step were also investigated. The findings again suggest that systematic errors can appear on large-scale thermodynamic fields even though the domain-average vertical profile of the source and sink terms are virtually the same. An ideal model physics, which includes sub-grid scale transports, will be resolution dependent. By comparing simulations at selected resolutions, one can hope to discern the nature of required physics that can be used in high resolution models with the goal of producing a semi-empirical cumulus parameterization.

Dr. Andrew E. Dessler (University of Maryland) gave a talk entitled "*The effect of deep convection on the tropical tropopause layer.*" The tropical tropopause layer (TTL) is the region between 14-18 km or 355-420 K in potential temperature. Most of the air entering the stratosphere travels through the TTL. Importantly, it is during transit through this region that air is dehydrated to stratospheric abundances — a few parts per million by volume (ppmv). Recent increases in stratospheric water vapor have focused attention on the physics of this region. Dr. Dessler discussed the two current theories of how stratospheric air is dried: the "cold trap dehydration" mechanism, and his own "convective dehydration" mechanism. Dr. Dessler then discussed how the level of neutral buoyancy of most tropical convection is around 14 km, coincident with the base of the TTL. It is well known, however, that convection routinely overshoots this

level and penetrates into the TTL. However, it was an open question whether these overshooting convective events transport significant mass into the TTL. He then used a simple model to show that significant detrainment of mass in the TTL is necessary to explain the vertical distribution of carbon monoxide and ozone. He concluded by calling for increased observations of water and other trace gases in this part of the atmosphere.

2.3   Parameterization (Mesoscale Models and GCMs) [Chaired by Dr. A. Arakawa (UCLA) and Dr. David Starr (Goddard Space Flight Center)]

Dr. Jack Kain of NOAA National Severe Storms Laboratory (NSSL) gave an invited lecture on "*Convective Parameterization in Mesoscale Models*". He defined mesoscale models as those with grid spacing from 50 to 200 km and noted the hybrid subclass of models with grid resolution from 10-50 km that lie between the higher resolution cloud resolving models and traditional mesoscale models. Dr. Kain stated that a convective parameterization must decide three things: 1) activation via trigger function, 2) intensity via closure assumption, and 3) vertical distribution via cloud model or specified profile. He then reviewed in a compact and informative way the trigger, closure and vertical distribution approach for seven convective parameterization schemes used in a variety of models including Eta, Rapid Update Cycle (RUC), fifth-generation of the Penn State University/NCAR mesoscale model (MM5), Weather Research Forecast (WRF), Climate, European Centre for Medium-Range Weather Forecasts (ECMWF) and the French operational model. All these parameterizations had dependencies on at least 2 parameters, some use 4, for their trigger function with all using Convective Available Potential Energy (CAPE) and a significant fraction also using cloud depth, convective inhibition (CIN) or both, and a few using moisture or mass convergence. Closure assumptions generally involve CAPE, though not all. An entraining/detraining plume cloud model is used to derive the vertical distribution of mass and moisture in 5 of the schemes. It was noted that comparable levels of success have been achieved with many different parameterization strategies. Thus, we continue to have a good number of them.

A key question is: What do we hope to achieve with mesoscale parameterization that we cannot achieve at coarser resolution? Ultimately, we would like to explicitly resolve the mesoscale organization of convective systems and parameterize the ensemble of individual convective elements. At hybrid scales, "grid-point instability"

can develop in a mesoscale model. This can suppressed by parameterized convection in a semi-implicit representation. Following this work a decade ago, there was great enthusiasm about the prospect for operational prediction of the mesoscale organization and evolution of Mesoscale Convective Systems (MCSs). The semi-implicit representation showed that it was possible to simulate the mesoβ-scale structure of an MCS, but has this capability making its way into operations?

Dr. Kain walked the audience through a comparison of MCS simulations with NCEP's eta model using two disparate convection schemes (Betts-Miller-Janjic and Kain-Fritsch) illustrating the differing sensitivity of precipitation rate and CAPE consumption to cloud-layer relative humidity. In the eta model, cloud water/ice is treated as a prognostic variable, rain and snow are diagnosed and there is no advection or storage of precipitation-sized particles. Despite having comparable Quantitative Precipitation Forecast (QPF) skill scores, one version of the model creates a mesoscale downdraft and structure that resembles a propagating squall line, but it does this almost entirely through parameterized effects. The other version struggles to activate with over-intensification of grid-resolved precipitation downstream. Another comparison simulation was shown but using the new Weather Research Forecast (WRF) model with the same convective parameterization options. In this case, improved simulations were obtained for both versions. A healthy partitioning was found between parameterized and resolved processes. Dr. Kain concluded that there should be renewed optimism about operational numerical prediction of MCSs.

In hindsight, Dr. Kain noted that the expectations of a decade ago went unfulfilled because operational centers must take a conservative approach and have limited resources, and operational microphysical parameterizations have been relatively crude. Furthermore, we still don't understand how to control "grid-point instability" and partition the consumption of CAPE between parameterized and resolved processes. Thus, even now, the mesoscale parameterization problem will be with us for the foreseeable future.

Dr. George Grell of NOAA Forecast Systems Laboratory discussed: "*Incorporating Uncertainty in a Convective Parameterization*". Dezso Devenyien was co-author. An ensemble approach to Numerical Weather Prediction (NWP) is presently used in operational centers to account for the effects of uncertainty in the initial description of atmospheric state due to measurement errors and inadequacy of data coverage.

However, there are also uncertainties associated with the physics package used in a specific model. In the case of convective parameterization, the diagnosis of convective initiation and development (strength) depends on the closure assumption such as trigger functions, stability closures, quasi-equilibrium closures, moisture convergence, etc. Further, the effect of convection on the environment and, thus, on subsequent development (feedback), depends on the localized airflow (entrainment, detrainment, convective mass fluxes, subsidence) and microphysical profiles which must also be represented parametrically with assumptions and some uncertainty. Dr. Grell asserted that we do not know what are the proper assumptions to make and should consider a parameterization comprised of an ensemble of approaches, e.g., a selection of dynamic closures, feedback assumptions and cloud mixing assumptions. He showed an example with the RUC20 (20 km version of the Rapid Update Cycle) model where a 72-member ensemble was used and the ensemble mean fed back into the 3-D model. He noted an alternative approach with MM5 where the standard deviation is used to weight a sub-ensemble in which closures yielded similar results. The ensemble approach yields insight into the performance of different closures and allows assessment of what are the most sensitive parameters. Entrainment/detrainment, downdraft strength, and the dynamic closure assumptions were found to be key components. Comparison of closures does not reveal systematic ranking at each grid point, e.g., more-to-less latent heat release. Future plans are to implement the ensemble approach in a series of models [RUC, MM5, WRF, Regional Atmospheric Modeling System (AMS)] and to seek to define the optimal ensemble members for each.

Dr. William Cotton of Colorado State University presented *"Parameterization of Cumulonimbus and MCSs"*. Coauthors were William Cheng and Jean-Christophé Golaz. The formulation of a mesoscale convective system parameterization (MCSP) was described. The MCSP interacts with a convective parameterization scheme. The MCSP and Cumulus Parameterization Scheme (CPS) were implemented in the RAMS and results were shown for a test case. The MCSP accounts for the water vapor redistribution, deposition, condensation and freezing within mesoscale updrafts, sublimation evaporation, and melting within mesoscale downdrafts, and the mesoscale eddy fluxes of entropy and moisture. The CPS uses a cumulus kinetic energy prognostic closure and the rate of change of cloud fraction in the adjustment feedback. A grid-spacing dependent filter function is used in the MCSP and CPS. The MCSP is triggered when mesoscale kinetic energy exceeds a specified threshold. Results from a test case (100 km grid resolution) were compared to a cloud-resolving model run

(nested RAMS to 2.5 km grid spacing). Results were encouraging during the incipient stage of mesoscale convective system where the general shape of heating profiles were similar but with differences in magnitude. The areas of organized convection were reasonably well captured. More work is needed to calibrate the mesoscale precipitation rate and on scaling the mesoscale tendencies for feedback into the host model. More cases will be studied. Dr. Cotton also discussed a probability density function (PDF)-based parameterization of boundary layer clouds and suggested possible extension to deep convection. For boundary layer clouds, subgrid-scale variability is represented by a joint PDF for vertical velocity, temperature and moisture. A double Gaussian family has been used and compared against aircraft measurements and large-eddy simulations (LES). The PDF is used to diagnose cloud fraction, liquid water and higher-order moments. Application to a wide range of field data sets shows results comparable to LES results without case-specific adjustments. This approach could potentially be extended to deep convection.

Mr. R.C. Muñoz of Pennsylvania State University presented a talk entitled: "*Sensitivities of Shallow Cloud Fields to Environmental and Surface Variables in the New PSU Shallow Convection Scheme*". Dr. N.L. Seaman, Dr. D.R. Stauffer and Mr. A. Deng were co-authors. Improvements to the Pennsylvania State University (PSU) shallow convection scheme, an extension of the Kain-Fritsch parameterization for deep convection, for use in mesoscale models are described. The changes, primarily to the updraft algorithm, were motivated by the consequences of more frequent use (calls) of the parameterization and the more subtle thermodynamic perturbations associated with shallow clouds. The changes involve use of a transition level to address noise associated with discretization in the vertical and modification of the definition of the critical mixing fraction near cloud base to address the high sensitivity (flip-flop behavior) of entrainment/detrainment to parcel buoyancy, typically a small value. The new scheme performs reasonably well in reproducing mass flux profiles and exhibits physically realistic sensitivities to its important parameters and changes in prescribed forcing. Results of the sensitivity study suggest an interesting further approach to address the common tendency of shallow convection parameterizations to produce detrainment profiles that are uniform or increase with height versus the observed decrease with height. If ensembles of diagnoses are made by forcing the one-cloud parameterization with varying properties for the initial updraft parcel (buoyancy, velocity or mass flux) according to a prescribed distribution, the aggregate result would represent a more realistic ensemble of shallow clouds of various depths.

Dr. P. Bechtold of Laboratoire d'Aérologie in Toulouse gave: "*A Little Tour of Toulouse Group Activities: Mass Flux, Forecast, Chemistry, Cloud Fraction Wavelet and Related Experiments*". Co-authors were Drs. Jun-Ichi Yano, Jean-Pierre Chaboureau, Béatrice Josse, Dominique Paquin and Jean-Luc Attié. Dr. Bechtold gave examples of three approaches to evaluating a convective parameterization: 1) as a single column model (SCM) in comparison to highly detailed cloud resolving model simulations of observed case studies as in the GEWEX Cloud System (GCSS) Working Group on Convective Cloud Systems (WG4), 2) within a forecast model with traditional scores for quality of precipitation and wind fields, 3) within long-term simulations (climate) by evaluating quality of conserved chemical tracer fields. He briefly described the Bechtold-Kain-Fritsch (BKF)) scheme that has been implemented in the French mesoscale research model Méso-nh, the ARPEGE/IFS global climate model, its chemistry counterpart MOCAGE, and the Canadian Regional Climate Model. Dr. Bechtold noted the improvements in the SCM via (1) due to addition of cloud fraction and improved surface parameterizations and showed the relative insensitivity of skill scores for precipitation to forecast model resolution for the 6-day GCSS WG4 TOGA case. He also showed the improved stability of soil moisture in a seasonal simulation using the BKF parameterization and presented some impressive comparisons of simulated Radon fields to observed summertime radon profiles over the USA, and reported about ongoing comparisons of simulated CO fields with global observations derived from Measurements of Pollution In The Troposphere (MOPITT) on the Earth Observing System (EOS) Terra satellite Dr. Bechtold also described a new simple statistical cloud parameterization derived from cloud resolving model data (2 km resolution over 256 by 256 domain). The parameterization is developed from CRM data for both diagnostic and prognostic application, the latter with an explicit microphysical scheme. Comparisons were shown versus Meteosat observations for Fronts and Atlantic Storm Tracks Experiment (FASTEX) using model fields to compute the satellite-observed radiances. Finally, discrete wavelets were presented, and their ability to objectively compress and filter convective data sets (including condensate and wind fields) was assessed using CRM data for TOGA-COARE. Their group is involved in 2 major field campaigns: Tropical Convection, Cirrus and Nitrogen Oxydes (TROCCINOX, 2003) that considers NOx production by lightning and chemistry in continental tropical thunderstorms, and the African Monsoon Project (2004/5) where their focus will be on the assimilation of satellite data.

Dr. Jean-Yves Grandpeix of the Laboratoire de Météorologie Dynamique in Paris presented the paper "*A Cumulus Parameterization Accounting for the Coupling Between Deep Convection and Low Level Lifting Processes*". Co-authors were Frederique Cheruy, Alain Lahellec, and Remi Tailleux. Two new interface variables are introduced in order to couple their deep convection scheme with low level lifting processes: available lifting energy for triggering, and available lifting power for closure. The scheme applies to a variety of sub-cloud lifting processes and is applicable to CIN-dominated cases, where there is convective inhibition, and to free lifting cases, i.e., squall lines and convection generated by boundary layer processes. A 7-hour simulation of a TOGA squall line was described where the mass flux was found to be in reasonable agreement with results of cloud resolving model simulations.

2.4   Global Circulation Models [Chaired by Drs. David Randall (CSU), P. Newman (Goddard Space Flight Center), S. Krueger (U. of Utah), and A. Hou (Goddard Space Flight Center)]

This session opened with an invited talk by Dr. A. Del Genio of NASA/GISS on "*Observational constraints on cumulus parameterizations used in climate models*". He pointed the need for observations to test the microphysical aspects of cumulus parameterizations and presented results from recent studies based on several spacecraft and surface remote sensing missions, which provided statistics on a number of properties of convective cloud systems.

The NASA Tropical Rainfall Measuring Mission (TRMM) measures rainfall rates and infers hydrometeor profiles from passive microwave (TRMM Microwave Imager, TMI) and radar (Precipitation Radar, PR) instruments. TRMM also detects lightning occurrence (Lightning Imaging Sensor, LIS), a proxy for cumulus updraft strength, and measures broadband top-of-the-atmosphere (TOA) shortwave and longwave radiative fluxes (Cloud's and the Earth's Radiant Energy System, CERES). The properties of 8,786 precipitating storms in the 15°-15° latitude band have been analyzed for the time period February 1-5, 1998. Storms are defined as contiguous precipitating regions with hydrometeor content above the 5 km level by a clustering algorithm.

Cumulus parameterizations are now beginning to predict not only mass fluxes but also cumulus updraft speeds. This is a prerequisite for the accurate prediction of vertical condensate transport and detrainment. Lightning occurrence is believed to require strong updraft speeds (at least ~6-7 m/s) so that supercooled liquid water can

be lifted into the ice phase region of the convective cloud. TRMM storms are separated according to the presence or absence of LIS-detected lightning. Lightning storms are only a few percent of the total number of storms, and are more frequent over land than ocean. Results show that lightning storms are larger, rain more heavily, and are deeper than non-lightning storms over both land and ocean. Over ocean, lightning storms have albedos almost twice as large on average as non-lightning storms, but over land, lightning storm albedos are only a few percent brighter than their non-lightning counterparts. This is consistent with the general impression that updraft speeds over land exceed those of ocean, i.e., the typical storm over land has an updraft speed closer to the lightning threshold than does the typical ocean storm. It also highlights the connection between updraft strength and detrained ice, a test which must be passed by any cumulus parameterization used in a climate GCM. The distribution of outgoing longwave radiation shows that midlevel cumulus congestus, i.e., storms with tops between the freezing and -10° levels, account for 30-40% of all ocean storms but only 15-20% of all land storms.

Storm properties are correlated with monthly sea surface temperature (SST) and 500 mb vertical velocities from NCEP/NCAR reanalysis to isolate temperature dependency from some aspects of dynamical influences. For storms in general, rain rates and storm heights increase with increasing SST and upward motion; the SST dependence is strongest for the largest storms. Storms in general increase in size as SST increases. Storms albedos are insensitive to SST except for the largest storms, which get brighter as the ocean gets warmer. Both precipitation efficiency and the ice water path of storms increase systematically with SST, but the former increases more rapidly while the latter appears to approach an upper limit at the warmest SSTs. Thus, convective cloud systems partition more of their available updraft water into rain rather than detrainment as the surface warms, but nonetheless convective clouds become more massive, spatially extensive, and deeper with warmer SST.

Over ocean, storms tend to rain more heavily as they get deeper and their shortwave albedos increase. A similar tendency can be seen for land storms but to a lesser extent. However, there are a significant number of land storms that rain heavily despite modest cloud top heights. Furthermore, there is a second population of land storms with high albedos, weak rain rates, and tops below the -35° level. One possible explanation for this second population of storms is that in the presence of a polluted continental boundary layer, storms develop large numbers of small supercooled liquid

droplets in which coalescence and glaciation are suppressed. If so, there may be a previously unaccounted for indirect effect of aerosols on clouds - since these storms have lower cloud tops but similarly high albedos to deeper storms, they imply a net negative contribution to cloud feedback.

The radiative and microphysical properties are modeled for 17 convective storms that were observed simultaneously by TRMM from above and from Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program surface remote sensing instruments from below at Manus and Nauru Islands. TRMM PR radar reflectivities are used to parameterize liquid and ice water contents for large particles. Above the radar echo top and below the altitude corresponding to the IR cloud top observed in geostationary satellite images, we assume a layer of small ice particles of specified number concentration and ice content. These are used as inputs to a radiative transfer model that predicts TOA albedos and surface shortwave fluxes. The modeled and the observed fluxes agree to within 20% for all cases. For midlevel storms, the radar echo top matches the IR cloud top, implying an absence of small ice particles. For deeper storms, though, a significant layer of small ice particles must be present. In general, the radiative fluxes are much more sensitive to the depth of small ice particles and their assumed properties than to variations in either the large ice or large liquid particles below.

Lastly, surface-based millimeter cloud radar data from the DOE ARM Southern Great Plains (SGP) and Tropical West Pacific (TWP) sites were used to distinguish the microphysical properties of cirrus clouds formed from convection vs. other sources. Results show that convectively-generated cirrus clouds show large particle sizes uncorrelated with the ice water contents of the clouds, in contrast with synoptically-generated cirrus at the SGP whose particle sizes increase with increasing ice content. There is also evidence of another population of cirrus, especially prevalent in the TWP, whose particle sizes decrease with increasing ice content. Circumstantial evidence from cloud base temperatures, satellite imagery, humidity soundings, and previous field experiments suggest the possibility that these cirrus may be the result of homogeneous nucleation in environments not directly affected by convection.

Dr. S. Klein of NOAA/Geophysical Fluid Dynamics Laboratory (GFDL) gave a talk *on "The use of CRM data to inform statistical cloud parameterizations for large-scale models"*. In some large-scale models, 50% of the condensate in neutrally buoyant

saturated air or 'stratiform clouds' is condensed in convective updrafts. This spatial inhomogeneity is difficult to parameterize in terms of a few empirical parameters such as a critical relative humidity for cloud formation. Statistical cloud schemes may be useful for determining the empirical parameters. The underlying assumptions of these schemes may be tested in CRM experiments. Based on a UCLA CRM simulation for the July 1997 ARM IOP at the SCP site, results suggest that (1) the dependence of the variance and skew of the total water distribution on convection could be parameterized using traditional mass flux sources and sinks for the higher order moments of the total water distribution, (2) a simple beta probability distribution function appears capable of representing the mean cloud fraction and the mean, variance, and skew of cloud condensate if the corresponding statistics of the total water distribution are known, (3) temperature variability is secondary to water variability in explaining the variability in clouds, (4) the size of the domain affects the variability of total water, and (5) clouds tend to be randomly overlapped in the absence of convection if their vertical separation is greater than a few kilometers, but at times of strong convection, the cloud overlap is intermediate maximum and random overlap.

Dr. L. Donner of NOAA/GFDL gave a talk on "*Parameterizing mesoscale circulations associated with cumulus convection in general circulation models*". He examined properties of cumulus parameterizations with and without the representation of mesoscale circulations against satellite and field observations. He showed that the Donner scheme, which includes upper-tropospheric mesoscale circulation, is more realistic and does not lead to excessive convective mass flux and tracer transport characteristic of schemes with only convective cells. The physical reason is that evaporative cooling in the middle and upper troposphere destabilizes and requires greater convective mass flux (and subsidence warming) for balance. In the presence of mesoscale circulations, evaporation is less in the middle and upper troposphere, thus leading to less convective mass flux. Results from Model for Atmospheric Transport and CHemistry (MATCH) using a synthetic tracer show that the Donner parameterization, which includes mesoscale circulations produces lower mass flux that the Zhang scheme without mesoscale circulations.

Dr. W. Grabowski of NCAR presented a paper on "*Investigation of tropical intraseasonal oscillations and MJO using cloud-resolving convection parameterization (CRCP)*". As a first step to demonstrate the viability of "super-parameterization", he embedded a 2D cloud-resolving model (with a horizontal resolution of 1 km) in each model column

(of the horizontal extent of several hundred km) of a 3D GCM to examine the interaction between moist convection, radiation, boundary-layer processes, and large-scale dynamics in forming Madden and Julian Oscillation (MJO)-like coherent structures. Results show that the model produces MJO-like features with either prescribed radiation or interactive radiation in aqua-planet simulations with a constant SST. Interactive surface fluxes are essential for the development of coherent MJO-like structure but not required for its maintenance. The enhanced surface fluxes occur in the westerly wind burst area, to the west from the leading-edge deep convection, which is different from the Wind-Induced Surface Heat Exchange (WISHE) mechanism.

Dr. Yogesh Sud (NASA/Goddard Space Flight Center) discussed two outstanding issues related to the parameterization and simulation of convective processes and clouds in GCMs. One is the lack of condensation due to sub-grid scale orography, and the other refers to persistent deficiencies in simulated cumulus clouds. Dr. Sud demonstrated that a much simpler implementation of a more elaborate sub-grid scale physics scheme, such as that used in the Pacific Northwest National Laboratory's regional climate model, has the ability of capturing enhanced precipitation over high topography while drying and warming the airmass downstream. Dr. Sud also showed that three primary problems in most present day cumulus schemes, namely insufficient shallow clouds, a higher than observed incidence of a double Intertropical Convergence Zone (ITCZ), and clouds in too many layers, could be ameliorated by a physically constrained implementation of a relaxed Arakawa-Schubert architecture. This implementation requires: (i) all clouds, including the shallow clouds, to start with cloudy bases or a near-saturated environment, (ii) evaporation of in-cloud water in neutrally buoyant but unstable clouds through an imposed initial ascent and continuous entrainment. Dr. Sud implemented these changes and tested them in the four available ARM-CART SCMs as well as in a 4-year integration in the Goddard Earth Observing System (GEOS) 2 GCM of the Data Assimilation Office (DAO). Preliminary results showed a significant improvement in the simulated shallow clouds. While the saturated cloud bases yielded more realistic shallow clouds, the seasonal rainfall climatology remained robust. Moreover, a fraction of shallow clouds are required to evaporate in some implementations of the Arakawa-Schubert scheme for better results. With the new considerations, in-cloud water can now be evaporated in a physically defensible implementation.

Dr. J.-L. Li of NASA/GSFC spoke on "*Sensitivity of latent heating profile to cloud top detrainment and subcloud layer processes in the GEOS3 AGCM*". He examined the precipitation and latent heating fields produced by the GEOS3 GCM against TRMM observations for Feb 1998. The comparison showed that the horizontal distribution of the total monthly mean rain rates in the GEOS3 GCM is in reasonable agreement with TRMM estimates, but the fractional rain and latent heating profiles associated with the convective and stratiform processes are substantially different from observations. The reason for this discrepancy is that in the GCM all of the cloud liquid water detrained at the cloud top from the convective core is assumed to precipitate, thus providing no available moisture source for large-scale condensates. By changing the fraction of the total detrained cloud liquid that evaporates into the large-scale environment, the modified scheme produces more realistic convective and stratiform rain rates and latent heating profiles. This shows the potential of using satellite observations to improve physical parameterizations for modeling or provide instantaneous observational constraints on parameterized processes in data assimilation.

Dr. W. Chao of NASA/GSFC gave a talk on "Single and double ITCZ in aqua-planet models with globally and temporally uniform sea surface temperature and solar insolation angle: An interpretation". Studies have shown that an aqua-planet model with globally and temporally uniform sea surface temperature and a constant solar insolation angle can generate one or more intertropical convergence zone (ITCZ) depending on the choice of cumulus parameterization schemes, settings within cumulus parameterization schemes, and other model factors such as the horizontal resolution. He offered an interpretation for these divergent results under different model conditions by hypothesizing that the latitudinal position of the ITCZ is determined by the balance of two types of forcing acting on the ITCZ, both related to the earth's rotation. The first type, which acts to pull the ITCZ toward the equator, is directly related to the Coriolis parameter and is not sensitive to model design changes. The second type, which pulls the ITCZ poleward, is related to the convective circulation and is sensitive to model design changes. Depending upon the shape and magnitude of these two "attractors", these two types of attractions can reach a balance either at the equator or more than 10 degrees away from the equator, leading to a single ITCZ over the equator or a double ITCZ straddling the equator.

Dr. Hua-Lu Pan (NCEP/EMC) spoke on the "*Evolution of a convective parameterization scheme in an operational environment*." Dr. Pan first described NCEP's

criteria for convection schemes in the global modeling system: provide accurate precipitation forecast for North America in the 6-72 hour time range, and provide accurate forcing of the maintenance of the tropical large scale circulation. He then went on to describe the both the evolution of schemes from 1991 to the present and the tests used to validate those changes. The Grell scheme was implemented in 1991, with modifications to enforce conservation for updraft and downdrafts as well as to allow a quasi-equilibrium closure. In 1995, a non-local PBL scheme was implemented which led to many improvement to the forecast, but also produced a few problem such as false alarm tropical storms. In 2001, cumulus momentum mixing was added. Dr. Pan illustrated his talk with hurricanes Michelle and Octave that formed in late October 2001.

Dr. Shaocheng Xie of Lawrence Livermore National Laboratory (LLNL) reported on "*Intercomparison and evaluation of cumulus parameterizations under summertime midlatitude continental conditions*". Based on comparisons of 15 SCMs, he showed that the different treatments of cumulus convection lead to large differences between the models. Under summertime midlatitude conditions over land, the convection schemes that use the CAPE-based triggering mechanisms without additional appropriate constraints are generally more active than those using triggers that are based on local parcel buoyancy since CAPE is strongly affected by the solar diurnal heating over land. This leads to large systematic warm/dry biases in the troposphere. Results also show that a non-penetrative type of convection scheme usually underestimates the depth of instability, leading to a cold bias in the upper troposphere. A common problem with most cumulus convection schemes is that they are too active at midlatitudes, leading to significant underestimation of stratiform precipitation. All SCMs significantly underestimate downdraft mass fluxes compared to CRMs. It is important that mesoscale convective mass fluxes be incorporated into cumulus parameterizations.

It is important that convective parameterizations accurately represent convection timing, convection location, cloud mass flux, cloud tops, and detrainment profiles. Relatively short-lived chemical tracers such as carbon monoxide (CO) can be used to evaluate the cloud mass fluxes and detrainment. Dr. Kenneth Pickering (University of Maryland) and colleagues presented material on the "*Evaluation of deep convection over the central United States in the GEOS-DAS using satellite imagery and chemical tracer transport calculations.*" Dr. Pickering and colleagues have developed a global chemical transport model (CTM) that uses NASA GSFC's GEOS data assimilation system (DAS) archived winds, upward cloud mass flux, and cloud detrainment profiles. The GEOS-

DAS output from the Relaxed Arakawa-Schubert convection scheme was compared with the ISCCP deep convective cloud cover data, and the CTM output was compared with observed CO profiles. Variations between CTM runs were sensitive to different GEOS assimilation data sets. Dr. Pickering concluded by demonstrating that convective transport of precursors can enhance the photochemical production of ozone in the middle and upper troposphere. This ozone enhancement in turn alters both the short wave and long wave radiative forcing. Therefore, the accuracy of convective parameterizations is critical for producing correct assessments of anthropogenic influence on climate.

Ozone is an important radiative gas in both the longwave and shortwave portions of the spectrum. Further, ozone is a key component of tropospheric chemistry. Accurate simulations of tropospheric ozone require specification of all NOx sources, including lightning. Global CTMs specify lightning flash using information on convective processes from GCMs. Dr. Dale Allen and Kenneth Pickering (U. of Marymand) presented "*Evaluation of lightning flash rate parameterizations based on GEOS DAS convective fields using National Lightning Detection Network (NLDN) and Optical Transient Detector (OTD) lightning data.*" They used the GEOS-DAS mass fluxes, precipitation, and cloud heights to fit the NLDN data, and then validated the fit against the OTD observations. They concluded that the mass flux based flash rates were superior to the either the cloud height or precipitation fits. Such a parameterization should improve model estimates of NOx sources in the free troposphere.

Dr. Mitchell W. Moncrieff (NCAR) gave a presentation on *"Organized convection, super-rotation and the MJO: Basic principles.*" Dr. Moncrieff began by summarizing a recent study of using a 2-dimensional cloud resolving model that is embedded in each column of a 3-dimensional, nonhydrostatic global model. This model produces an organized cloud cluster that bears a remarkable resemblance to the Madden and Julian Oscillation. Dr. Moncrieff went on to derive a two-scale analytic model of the MJO representing the large-scale circulation, and organized convection embedded within it. He concluded by noting that: 1) this was a preliminary study, 2) the analytic model represents the most simple (archetypal) dynamics of the MJO, 3) sensitivity to quantities on which the model is based is being investigated, and 4) the analytic model and CRCP are hierarchical idealizations of the real MJO.

3.   Future Directions

There was a plenary session with the discussion focused on "What is the future of cumulus parameterization".   The panel consisted of Drs. A. Del Genio, J. Kain, S. Krueger, L. Donner, S. Klein, and E. Zipser. Dr. D. Starr was the moderator and opened the session by listing the following key issues that need to be addressed in future cumulus parameterization:

- What is the role of mesoscale circulation/organization? How can it be included and how much detail is needed?
- How much detail is required in the microphysics, particularly in the ice phase?
- How will scale dependency be handled? Should the approach change with grid resolution?
- What is the role of convective momentum transport? How can it be included?
- Is it time to consider a major field program aimed at cumulus parameterization?
- What are the requirements for future field experiments?

The discussion from the plenary session can be summarized as follows:

- Three major approaches to cumulus parameterization, traditional, statistical and super-parameterization, were discussed. The traditional approach is to use the large-scale parameters to represent the moist processes. The statistical approach is to use the data simulated from cloud-resolving models to derive multiple moments of scalar and dynamic properties associated with clouds and cloud systems. This statistical approach describes convection in terms of mean vertical profiles, variances and fluxes, averaged across both clouds and clear air. The super-parameterization approach replaces the traditional cumulus parameterization scheme with a two-dimensional cloud-resolving model. There is no preferred approach among these three and each approach has its own strength and was recognized by the participants. Scientists will be using all of the above approaches over the next 5 to 10 years.

- All three approaches need to use the cloud-resolving model (CRM), and there was an extensive discussion on whether the cloud-resolving model could become a really good test bed for all the approaches. CRMs need to demonstrate that they simulate continental and oceanic clouds and cloud systems realistically.   CRMS can be a

hypothesis tester and generator of statistics that fill gaps in the theories for cumulus parameterization. The key ingredients in CRMs are the interactions among microphysics, turbulence, radiation and the surface. CRMs perform better than SCMs under using observed large-scale forcing. There was also a consensus that validating CRMs with thermodynamic properties (i.e., temperature and water vapor) is not enough. Lightning, microphysics (liquid water path or ice profiles) and tracer transports are needed. However, two-way interaction between the large-scale environment and processes simulated by the CRM is prohibited. In addition, using the CRM results to improve SCMs does not guarantee an improvement in the performance of three-dimensional GCM.

- Partnerships between observationists (what is seen in the field in detail) and modelers are important. GCSS, NASA/TRMM and DEO/ARM projects are a good example. These projects made some progress in making realistic CRM simulations of clouds and cloud systems over ocean and land in the tropics and midlatitutes. Future emphasis on more detailed analyses of CRM results in terms of probability distribution functions (PDFs) of vertical velocity and microphysics is still needed.

- There was a consensus that a consistent, comprehensive cloud database (associated with clouds and cloud systems that developed in different geographic locations) should be generated by the ensemble of cloud-resolving models (CRMs) and provided to the large-scale modeling communities, specifically, to the parameterization developers, for use in the development and/or improvement of cumulus parameterization schemes. The ensemble approach is a measure of the uncertainty provided by the spread of model results. This cloud data will be generated in close collaboration with or as requested by the developers of the cumulus parameterization schemes. However, new and innovative ideas for the optimal way to use the CRM data sets are needed.

- Convective momentum transport (CMT) might not appear to be of much interest to long-term climate modelers, but the GMT allows the modeler to tune the strength of CMT which has a tremendous effect on circulation within the model and where the ITCZ is. In addition, the performance of the NCEP global model was improved by including a simple cumulus momentum mixing.

- The microphysics used in the CRMs must respond correctly in various types of clouds and cloud systems to strong or weak cloud vertical velocities. A few cm s^{-1} vs 0.5 m s^{-1} for cirrus is the difference between homogeneous nucleation versus heterogeneous nucleation. The difference between 5 and 10m s^{-1} is the difference between rapid graupel growth and lofting in the clouds versus efficient rainout of cloud without much graupel.

- Focused field campaigns conducted over a wide range of climate regimes are needed to determine accuracies of cumulus parameterizations and CRMs. Understanding how accuracies of model outputs (e.g., temperature and moisture tendencies) relate to input environmental conditions and correction of such state-dependent systematic errors are crucial to improving the performance of cumulus schemes for climate simulation and forecast applications. It was recognized that more effort is needed in considering how to obtain and establish accurate environmental conditions and humidity profiles, which are crucial, in future field campaigns.

- In order to resolve or simulate mesoscale convective systems, a very high resolution NWP is needed. However, there is still a concern that double counting (where both a model resolved process and a parameterization are attempting to accomplish the same thing at the same time and scale) is not avoidable even at grid sizes of 1 to 5 km. The statistical approach may benefit climate applications.

4.   Acknowledgments