# Cloud Resolving Modeling

Wei-Kuo Tao

## Popular Summary

One of the most promising methods to test the representation of cloud processes used in climate models is to use observations together with cloud-resolving models (CRMs). CRMs use more sophisticated and realistic representations of cloud microphysical processes, and they can reasonably well resolve the time evolution, structure, and life cycles of clouds and cloud systems (with sizes ranging from about 2-200 km). CRMs also allow for explicit interaction between clouds, outgoing longwave (cooling) and incoming solar (heating) radiation, and ocean and land surface processes. Observations are required to initialize CRMs and to validate their results.

This paper provides a brief discussion and review of the main characteristics of CRMs as well as some of their major applications in past four decades. These include the use of CRMs to improve our understanding of: (1) convective organization, (2) cloud temperature and water vapor budgets, and convective momentum transport, (3) diurnal variation of precipitation processes, (4) radiative-convective quasi-equilibrium states, (5) cloud-chemistry interaction, (6) aerosol-precipitation interaction, and (7) improving moist processes in large-scale models. In addition, current and future developments and applications of CRMs, as well as the requirement of observational data for model validation, are presented.

# Cloud Resolving Modeling

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# Abstract

One of the most promising methods to test the representation of cloud processes used in climate models is to use observations together with cloud-resolving models (CRMs). CRMs use more sophisticated and realistic representations of cloud microphysical processes, and they can reasonably well resolve the time evolution, structure, and life cycles of clouds and cloud systems (with sizes ranging from about 2-200 km). CRMs also allow for explicit interaction between clouds, outgoing longwave (cooling) and incoming solar (heating) radiation, and ocean and land surface processes. Observations are required to initialize CRMs and to validate their results.

This paper provides a brief discussion and review of the main characteristics of CRMs as well as some of their major applications. These include the use of CRMs to improve our understanding of: (1) convective organization, (2) cloud temperature and water vapor budgets, and convective momentum transport, (3) diurnal variation of precipitation processes, (4) radiative-convective quasi-equilibrium states, (5) cloud-chemistry interaction, (6) aerosol-precipitation interaction, and (7) improving moist processes in large-scale models. In addition, current and future developments and applications of CRMs will be presented.

# 1.    Introduction

Understanding the hydrological cycle is crucial in climate modeling and climate change. The hydrological cycle distinguishes the Earth from the other planets. A key link in the hydrological cycle is the rain that falls from clouds and cloud systems in the Tropics, which amounts to about two-thirds of the global precipitation. The vertical distribution of latent heat release by these clouds/convective systems can also modulate the large-scale tropical circulation (Hartmann *et al.* 1984; Sui and Lau 1989; and others), which, in turn, impacts midlatitude weather through teleconnection patterns such as those associated with El Nino. Furthermore, changes in the moisture distribution at middle and upper levels of the troposphere as well as the radiative responses of cloud hydrometeors to outgoing longwave and incoming shortwave radiation are a major factor in determining whether the earth system will warm or cool as the cloud systems respond to changes in their environment (Ramanathan and Collins 1991; Lindzen 1990a, b; Betts 1990; Lau *et al.* 1993).

Recently, global change research has clearly indicated that it is necessary to understand the interactive processes associated with the radiative effects of clouds both locally and on the global scale in order to properly address climate warming issues. Clearly, if the prediction of regional/global climate change is to be reliable, the effects of clouds/cloud systems (microphysical processes) must be accurately represented in climate models. An international program, the GEWEX (Global Energy and Water Cycle Experiment) Cloud System Study (GCSS), was initiated to improve the representation of cloud processes in climate and numerical weather prediction (NWP) models. The GCSS Science Team (1993) and Randall *et al.* (2003a) recommended that improved cloud-resolving models (CRMs) should be used as a test bed to develop and evaluate cloud parameterization in large-scale models. In addition, the NASA Earth Science Enterprise indicates the use of CRMs as process models to understand the physical processes associated with clouds and their roles in the water and energy cycles.

*(a)    A brief history of cloud resolving models*

The earliest kind of cloud model, the one-dimensional (1D) entraining bubble or plume that simply parameterizes the lateral entrainment of environmental air, was used extensively in cloud-seeding research (Simpson et al. 1965, 1967). A two-dimensional (2D) anelastic cloud model was developed to study cloud development under the influence of the surrounding environment (Ogura and Phillips 1962). In the 1970's, three-dimensional (3D) cloud models with grid sizes of 1-2 kilometers were developed (Steiner 1973; Wilhelmson 1974; Miller and Pearce 1974; Sommeria 1976; Klemp and Wilhelmson 1978a; Cotton and Tripoli, 1978; Schlesinger 1978; and Clark 1979). The effect of model designs (i.e., slab vs axis-symmetric, and 2D vs 3D) on cloud development and liquid water content were the major foci in 70's (i.e., Soong and Ogura 1973). Also, the dynamics of midlatitude supercells, that are usually associated with tornados, was another major focus in the 70's (i.e., Klemp and Wilhelmson 1978b; Wilhelmson and Klemp, 1978). After GATE (1974), cloud ensemble modeling[1] was developed to study the collective feedback of clouds on the large-scale tropical environment with the aim of improving cumulus parameterization in large-scale models (i.e., Soong and Tao 1980; Tao and Soong 1986; Lipps and Helmer 1986; Tao et al. 1987; and many others), a quest that continues to this day. The effect of ice processes on cloud formation and development, stratiform rain processes and their relation to convective cells, and the effect of wind shear on squall line development were the other major areas of interest involving CRMs in the 1980's (i.e., Nikajima and Matsuno 1988; Rotunno et al. 1988; Fovell and Ogura 1988; Tao and Simpson 1989; Tao 1995; and many others). The impact of radiative processes on cloud development was also investigated in the late 80's. In the 1990's, CRMs were used to study multi-scale interactions (i.e., Tripoli and Cotton 1989), cloud chemistry interaction (see a review by Thompson et al. 1997), idealized climate variations (i.e., Held et al. 1993; Lau et al. 1993, 1994; Sui et al. 1994; Tao et al. 1999; and more discussion in Section 3), and surface processes (i.e., Lynn et al. 1998; Wang et al. 2003). The CRM was also used for the development and improvement of satellite rainfall (see a review by Simpson et al. 1996) and latent heating (see a review by Tao et al. 2006) retrieval algorithms. Table 1 lists the major highlights of CRMs over the past four decades.

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[1]    The unique feature of cloud ensemble models (a special type of CRM) is to allow several convective clouds to develop simultaneously inside the model domain. Typically, cyclic lateral boundary conditions are used.

*(b)    Recent trends*


During the past generation, voluminous datasets on atmospheric convection have accumulated from radar, instrumented aircraft, satellites, and rawinsonde measurements in field campaigns (e.g., GATE, TOGA COARE, SCSMEX, KWAJEX, DOE/ARM[2] and many others), enabling detailed evaluation of CRMs. Improved numerical methods have resulted in more accurate and efficient dynamical cores in models. Also, over the last few years, CRMs have become increasingly sophisticated through the introduction of improved (spectral bin) microphysical processes (for studying the cloud aerosol-chemistry interactions), radiation (for studying the energy and radiation budgets), and turbulent parameterizations for subgrid-scale processes. In addition, CRMs have been coupled with sophisticated surface models for studying the water and energy cycle.


In recent years, exponentially increasing computer power has extended CRM integrations from hours to months, the number of computational grid points from less than a thousand to close to ten million. Three-dimensional CRMs are now more prevalent. Much attention is devoted to precipitating cloud systems where the crucial 1 kilometer scales are resolved in horizontal domains as large as 10,000 km in two-dimensions (i.e., Peng *et al.* 2001; Grabowski and Moncrieff 2001) and 1,000 x 1,000 km$^2$ in three-dimensions (Yoshizaki *et al.* 2004) to study the multi-scale interactions. The CRM results now can provide statistical information useful for developing physically based parameterizations for climate and global circulation models.


The basic physical feathers of CRMs including new improvements will be described in section 2. In section 3, the applications of CRMs (not all) will be presented. The future developments, applications and critical issues will be discussed in Section 4.

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[2]    GATE stands for GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment; TOGA COARE for Tropical Oceans Global Atmosphere (TOGA) - Coupled Ocean Atmosphere Response Experiment (COARE); SCSMEX for South China Sea Monsoon Experiment; KWAJEX for Kwajalein Experiment; and the DOE-ARM for Department of Energy-Atmospheric Radiation Measurement.

## 2.     Major Characteristics of Cloud Resolving Models

CRMs are generally applied to the study of precipitation processes using two distinct approaches. The first termed "*cloud ensemble modeling*" (Soong and Ogura 1980; Soong and Tao 1980; Tao and Soong 1986; Krueger 1988; and many others) allows many clouds of various sizes and stages of their lifecycles to be present at any simulation time. Large-scale effects derived from observations are imposed into the CRMs as forcing, and cyclic lateral boundaries are used. The advantage of this approach is that model results in terms of rainfall, temperature and water vapor budget usually are in good agreement with observations (Tao 2003, Randall *et al.* 2003a and many others). In addition, the model results can provide cloud statistics that represent different types of clouds/cloud systems during their lifetime (life cycle). The second approach (c.f., the classical cloud model), convective evolution over periods of hours is simulated and the initiation (or triggering) of convection is the primary issue: cold pools, surface fluxes or stochastic perturbation excite locally forced convection. Such simulations are very useful for model development especially when conducted in conjunction with field campaigns (e.g., in-situ surface-based and aircraft observations; ground-, aircraft- and space-based remote sensing) that provide high-resolution data for model validation. Henceforth the terms cloud model, cloud-resolving model (CRM), cumulus ensemble model and cloud system resolving model (CSRM) will be used interchangeably.

Cloud-microphysical processes (phase changes of water and precipitation) must be parameterized in CRMs, as does atmospheric turbulence, turbulent processes at oceanic or terrestrial boundaries (latent and sensible heat fluxes into the atmosphere), and radiative transfer processes, which can be complex in the presence of clouds. These processes have to be allowed to interact explicitly. In addition, these processes have to interact with cloud dynamics (i.e., cloud draft/circulation, pressure gradient force, convection generated gravity waves, and cool pool). Figure 1 shows a schematic of the main characteristics of typical CRMs.

*(a)      Anelastic and compressible dynamics*

CRM has to be non-hydrostatic and its flow can be either anelastic (Ogura and Phillips 1962), filtering out sound waves, or compressible (Klemp and Wilhelmson 1978a), which allows the presence of sound waves. The sound waves are not important in thermal convection, but their processes can place severe restrictions on the time step in numerical integrations. For this reason, most CRMs use an anelastic system of equations in which sound waves have been removed by neglecting the local variation of air density with time in the mass continuity equation. A 3D diagnostic (elliptic) pressure equation can be solved using direct (*e.g.*, Fourier Transform) or iterative methods.

In the compressible system, a very small time step (2 s for a 1000 m spatial resolution) is needed for time integration due to the presence of sound waves. However, Klemp and Wilhelmson (1978a) developed a semi-implicit time-splitting scheme, in which the equations are split into sound-wave and gravity-wave components, to achieve computational efficiency. One advantage of the compressible system is its numerical code remains a set of explicit prognostic equations and alterations such as surface terrain can be incorporated into the numerical model without complicating the solution procedure.

Ikawa (1988) found that both simulated systems are similar if sound waves are damped enough in the compressible system involving orography. Tao and Simpson (1993) also found that the differences between the anelastic and compressible systems are quite small, and their differences are much less than those obtained by changing microphysical processes and advection schemes.

*(b)      Microphysics and Precipitation*

One of the unique characteristics of CRMs, is their sophisticated microphysical and precipitation processes. One-moment bulk microphysical schemes (e.g., Lin *et al.* 1983 and Rutledge and Hobbs 1984) with two-class liquid (cloud water and rain) and three-class ice (cloud ice, snow and graupel/hail) have been widely used over the past 20 years. The shapes

of small liquid and ice are usually assumed to be spherical. The size distributions of the precipitating particles (rain, snow and graupel/hail[3]) are taken to follow a three-parameter gamma distribution function such that

$$N(D) = N_0 D^{\alpha} \exp(-\lambda D),$$

where $No$ is the intercept parameter, $\lambda$ the slope of the particle size distribution and $\alpha$ the shape parameter[4]. In the one-moment scheme, only the hydrometeor mass content (proportional to $N(D)$) is predicted. In two-moment bulk schemes (i.e., Murakami 1990; Ferrier 1994; Resiner et al. 1998; Walko et al. 2000; Morrison et al. 2005; and Seifert and Beheng 2005), both mass content and the total number concentration are predicted variables. In the multi-moment bulk microphysical scheme (Milbrandt and Yau 2005), $\alpha$ is allowed to vary as a function of the mean-mass diameter. The importance of ice processes on surface rainfall was identified (Fovell and Ogura 1988; Tao et al. 1989; Gao et al. 2006a and many others).

With increasing computer power, explicit bin-microphysical schemes have been developed for CRMs to study cirrus development and cloud-aerosol interaction (e.g., Chen and Lamb 1994; Khain et al. 2004). The formulation for the explicit bin-microphysical processes is based on solving stochastic kinetic equations for the size distribution functions of water droplets (cloud droplets and raindrops), and ice particles of different habits (i.e., columnar, plate-like, dendrites, snowflakes, graupel and frozen drops). Each type is described by a special size distribution function containing over 30 categories (bins). Nucleation (activation) processes are also based on the size distribution function for cloud condensation nuclei (also over 30 size categories). Because of the numerous interactions involved in bin-microphysical schemes, computational domains are small and simulation times are short (more discussion in Section 3). These detailed microphysics calculations can

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[3]     Graupel has a low density and a high intercept (i.e., high number concentration). In contrast, hail has a high density and a small intercept. The choice of graupel or hail depends on where the clouds or cloud systems developed (McCumber et al. 1991). For tropical clouds, graupel is more representative than hail. For midlatitude clouds, hail is more representative.

[4]     For $\alpha = 0$, the equation reduces to an inverse-exponential distribution that was assumed in Lin et al. (1983) and Rutledge and Hobbs (1984).

provide a useful framework for evaluating and ultimately improving bulk microphysical schemes.

*(c)     Turbulence*

While large cloud (or convection) eddies are resolved in CRMs, eddies smaller than the grid-scale must still be parameterized. An implicit assumption is that all turbulent motions are sub-grid scale (SGS) and hence an ensemble-mean turbulence model is often used to represent the net effect of unresolved turbulence. Typical CRMs used simple k-type (first-order) turbulence closure to determine diagnostically the k-coefficient or prognostically from the turbulent kinetic energy (TKE) equation (one-and-a-half order). In the prognostic TKE method, thermodynamic stability, deformation, shear stability, diffusion, dissipation, moist processes and transport of sub-grid energy are included (Klemp and Wilhelmson 1978a). In the diagnostic method, deformation and stability are used for computing the k coefficient.

The most sophisticated turbulence parameterization presently used in CRMs is a third-order closure (Krueger 1988). Third-order turbulence closures perform very similarly to the one-and-a-half order TKE approach when simulating deep convective systems but are found to be necessary for simulating realistic shallow cumuli and boundary-layer cumulus clouds (i.e., Cheng and Xu 2006). Cheng *et al.* (2004) improved it to minimize a spurious oscillation in their liquid water field. The third-order turbulence scheme has mostly been used in 2D CRMs.

It is unclear whether 2D CRMs can resolve large convective eddies, which are 3D in nature. A detailed discussion on the performance of 2D numerical models in representing 3D convection in the planetary boundary layer (PBL) was presented in Moeng *et al.* (2004).

*(d)     Radiation*

Emission and absorption by water vapor and cloud droplets are represented by two-stream longwave radiative transfer schemes in CRMs. Broadband methods for longwave radiation

include the interactions among the gaseous absorption and scattering by clouds, aerosols, air molecules (Rayleigh scattering), and the surface. The treatment of shortwave radiation is also based on broadband approximations. The use of a fully explicit microphysics scheme (with size distributions of liquid and ice) and a fine horizontal resolution can provide relatively realistic cloud optical properties[5], which are crucial for determining the radiation budgets and diurnal variation of precipitation processes. With high spatial resolution, each atmospheric layer is considered either completely cloudy (overcast) or clear. No partial cloudiness is assumed. Table 2 shows the optical properties parameterized in some of major CRMs.

CRM results indicated that radiative processes could either enhance or reduce precipitation processes. For example, long-wave radiative cooling was found to enhance precipitation anywhere from 5 to 36% in simulations that included longwave radiative processes over those that did not. Please see Tao (2003) for a review on mechanisms of cloud-radiation interaction and comparisons among different CRMs.

*(e)    Ocean Surface fluxes*

Surface fluxes are temporally and spatially complex in the region of active convection. Two types of surface-flux schemes are typically used in CRMs. The first is a simple bulk aerodynamic formula wherein the transfer coefficients for momentum, sensible heat, and latent heat fluxes are a function of wind speed only. The second type is more complex but, nevertheless, primarily a bulk approach, is based on the Monin-Obukhov similarity theory (Fairall *et al.* 1996). The exchange coefficients in the simple bulk aerodynamic formula method and in the second bulk flux algorithm differ in two ways. First, the coefficients in the simple bulk aerodynamic formula linearly increase with respect to the wind speed. Second, in the lower wind speed regime (less than 4 m s$^{-1}$), the exchange coefficients in the

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[5]    Parameterizing the cloud optical properties (optical thickness), especially in the presence of the ice phase is still a key issue. Only limited observations are available upon which to base parameterizations for ice clouds.

complex bulk scheme increase with decreasing wind speed in order to account for convective exchange at low wind speeds but decrease if the wind speed is greater that 5 m s$^{-1}$.

CRMs have been used to conduct the sensitivity tests using a simple bulk aerodynamic approximation has predicted much larger latent and sensible heat fluxes than those obtained using the Monin-Obukhov similarity theory - flux algorithm. Consequently, much more surface rainfall was simulated using a simple aerodynamic approximation. The boundary layer structure, and convective available potential energy (CAPE) in clear and cloudy areas are also sensitive to the ocean flux algorithms. In addition, fine vertical resolution (at the lowest model grid point) is needed in order to study the interactive processes between the ocean and convection using CRMs (Wang *et al.* 1996).

*(f)*     *Land Surface Processes*

Detailed interactive land surface process models of the heterogeneous land surface (soil, vegetation, and land cover/land use) and adjacent near-surface atmosphere have recently been linked with CRMs to study the effect of soil moisture distribution and surface fluxes on cloud structure and rainfall. A land-surface model usually has three elements: (1) a soil module that calculates water and heat transfer into typically at least four water reservoirs (i.e., surface material, a topsoil root layer, a subsoil root layer, and two or more deeper layers that regulate seasonal and inter-annual variability of the soil hydrology; (2) a surface slab of vegetation, litter and other loose material that shades the soil and acts as the source for latent heat flux via transpiration and root water update, intercepts precipitation and dew, and may include plant internal storage; and (3) the surface layer of the atmosphere (up to the lowest grid level of the model to which it is coupled), within which the fluxes of sensible heat and water vapor are calculated. Modeling these coupled surface-atmospheric processes is crucial to the understanding and simulation of local and regional climate system interactions.

High-resolution coupled CRM-land surface models have been used to investigate how land surface conditions affect the growth of mesoscale circulations (Lynn *et al.* 2001) and the cloud and precipitation processes of both organized convective lines (Baker *et al.* 2001;

Mohr *et al.* 2003; Alonge *et al.* 2006) and less-organized convective clouds (Lynn *et al.* 1998; Zeng *et al.* 2006).

Recently, the role of anthropogenic and natural land cover and land use change has motivated a new generation of land surface process models that include such human-induced land use changes as irrigation, urbanization and agriculture. In addition, the role of vegetation phenology and biogeochemical cycles of Carbon and Nitrogen are critical controls on photosynthesis, and therefore transpiration and are included in the newest land surface models. Therefore, it is expected that CRMs will be coupling with this next generation of land surface models in the near future.

## 3. Applications

*(a)* *Convective Organization*

Deep convection in the western Pacific region is usually in the form of super cloud clusters (SCCs) with horizontal scales (in satellite imagery) of 2000-4000 km. Each SCC is composed of many individual westward-moving cloud clusters that have a typical lifetime of 2-3 days and a spatial extent of 500-1000 km. Each cloud cluster is composed of mesoscale convective systems (MCSs) with horizontal scales of 200-300 km and life spans of less than two days[6]. The MCSs can be further decomposed into many individual cloud ensembles with scales less than 100 km (Nakazawa 1988). CRMs could be a useful tool to study the physical processes that determine the development of these tropical large-scale cloud systems.

The past few decades have witnessed advances in the understanding of organized convection with convection over the tropical oceans being a focus. For example, 3D CRM-simulated and observed convective cloud systems in the South China Sea region (SCSMEX)

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[6]     One of the major findings from GATE was the important contribution to rainfall from mesoscale convective systems (MCSs). It was also estimated that the widespread stratiform rain accounted for about 32%-49% of the total rainfall from the GATE MCSs (Houze 1977; Zipser *et al.* 1981; Gamache and Houze 1983).

and Central Pacific (KWAJEX) region, respectively, were shown in Fig. 2. The SCSMEX simulation produces an intense tropical squall line without significant stratiform cover, whereas the KWAJEX simulation produces a random distribution of convective cells with extensive stratiform debris. The simulated organization for both cases is in very good agreement with observations (Johnson *et al.* 2002; Yuter *et al.* 2005). Although both of these tropical ocean cases describe distinct dominant modes of rainfall behavior within their domains, most of the surface precipitation in either regime originates as graupel. Many other CRMs can also simulate the various types of tropical cloud system organization. For example, Grabowski *et al.* (1998) used a 3D CRM to successfully simulate a non-squall cloud cluster, a squall line and scattered convection observed during GATE. Vertical wind shear and large-scale ascent play major roles in determining the organization of convection, which leads into distinct regimes.

The above modeling studies have quantified many of the observed properties of convection and its organization. The challenge now is to understand how this organization affects and is controlled by atmospheric properties, a fundamental issue in fluid dynamics.

*(b)*    *Heat and Moisture Budget, and Momentum Transport*

Heat and moisture transports by convection strongly affect the general circulation of the atmosphere. Transports are estimated from the objective analysis of sounding networks as thermodynamic budget residuals - the apparent sources of heat ($Q_1$) and moisture ($Q2$) as defined by Yanai *et al.* (1973). Figure 3 shows $Q_1$, $Q_2$ and their corresponding components (e.g., latent heating due to phase changes of water, radiative cooling/heating, vertical eddy heat and moisture flux convergence/divergence) simulated with CRMs for SCSMEX, KWAJEX and TOGA COARE cases. The sounding-estimated $Q_1$ and $Q_2$ are also shown for comparison and validation. The CRM-simulated results indicate that: (1) net condensation (sum of condensation / deposition heating, and evaporation / sublimation cooling) is the largest term for both the $Q_1$ and $Q_2$ budgets, (2) vertical eddy convergence / divergence of moisture by clouds/cloud systems is quite important for the $Q_2$ budget in transporting moisture from the lower to the upper troposphere, (3) vertical eddy heat convergence /

divergence by clouds/cloud systems in the lower and middle troposphere cannot be neglected in the $Q_1$ budget[7], (4) net radiation results in cooling that compensates for about 20-30% of the condensational heating for both SCSMEX and KWAJEX, (5) net radiation is very small for TOGA COARE (shortwave heating and longwave cooling tend to cancel each other as a result of the larger stratiform and anvil clouds simulated in the TOGA COARE case compared to the other two cases, please see Fig. 3 in Tao *et al.* 2004 for discussion), (6) CRM-simulated $Q_1$ and $Q_2$ are in very good agreement with observations for TOGA COARE and SCSMEX, and (7) the overestimation for KWAJEX is caused by an overestimate in rainfall (vertically-integrated Q1 and Q2 are proportional to surface rainfall and see Table 4).

The vertical transport of momentum by convection affects the conversion of kinetic energy from sub-grid-scale eddies to the mean flow, the rate of frictional dissipation and, therefore, the atmospheric energy spectrum. However, the large-scale effects of momentum transport are poorly understood. The horizontal pressure gradient force within cloud systems, which is the primary quantity affecting momentum transport, is difficult to measure through observations. Moreover, the representativeness of measurements is an issue because the pressure field is a strong function of convective dynamics. Theoretical models and some CRMs show that convective momentum transport can either be up-gradient, which enhances the mean flow, or down-gradient in which case it is a mixing process (e.g., Soong and Tao 1984; Trier *et al.* 1996). The existence of these (opposing) effects is supported by observations. Entropy considerations would suggest that, on average, momentum transport must be down-gradient, with up-gradient transport occurring only in special conditions (e.g., in highly-organized squall systems). However, the strongest momentum fluxes occur in organized flow. Please see LeMone and Moncrieff (1994) and Moncreiff (1992, 2004) for review on momentum transport by organized convection.

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[7]     The eddy flux convergence basically acts to re-distribute heat vertically. The relative large eddy flux convergence at middle troposphere is related to the localized cooling by the melting processes (see Tao *et al.* 2003a). Previous CRM studying only indicated that eddy flux convergence is very small except below cloud base and the ice processes is the main reason is the main reason for the difference.

The collective effects of convection need to be represented as parameterizations in large-scale models. The CRM-simulated $Q_1$ and $Q_2$ budgets and their respective components are useful in this regard. The CRMs can also be used in quantifying convective momentum transport and in deriving a physically based parameterization.

*(c)     Diurnal Variation of Precipitation Processes*

The diurnal variation of tropical oceanic convection is one of most important components in tropical variability and plays a crucial role in regulating tropical hydrological and energy cycles. The dominant diurnal signal is the nocturnal peak in precipitation that occurs in the early morning (i.e., Kraus 1963; Gray and Jacobsen 1977; Randall *et al.* 1991; Sui *et al.* 1997). The thermodynamic response of clouds to radiative heating (cloud development is reduced by solar heating and enhanced by IR cooling - Kraus 1963; Randall *et al.* 1991) and a large-scale dynamic response to the radiational differences between cloudy and clear regions (Gray and Jacobson 1977) have been suggested as the mechanisms responsible for the diurnal variation of precipitation over tropical oceans. Daytime heating of the boundary layer by solar radiation plays a dominant role in the diurnal variation of convection over tropical continents [see references in Lin *et al.* (2000). A successful simulation of the diurnal variability of the hydrologic cycle and radiative energy budget provides a robust test of physical processes represented in atmospheric models (e.g., Slingo 1987, Randall *et al.* 1991, Lin *et al.* 2000).

CRMs have been used to quantify the mechanisms responsible for the diurnal cycle of precipitation processes over tropical oceans associated with the diurnal variation of radiation (Tao *et al.* 1996; Sui *et al.* 1998; and Liu and Moncrieff 1998). Rainfall continues to vary even in the absence of diurnally varying sea surface temperature (SST); however, the maximum rainfall shifts from nighttime (0200 LST) to early morning (about 0500 LST). Thus, the diurnal variation of SST modulates rainfall but may only play a secondary role in its diurnal variation (Sui *et al.* 1998). CRM studies also indicate that convection is modulated by the diurnal change in available precipitable water [APW=W-RHsW*, the difference

between the vertically integrated water vapor amount (W) and a quasi-equilibrium value of W (RHsW*, a function of climate regimes)] as a function of temperature and is responsible for the nighttime maximum in rainfall (see Sui *et al.* 1998 and Fig. 4). This implies that the increase (decrease) in surface precipitation associated with longwave cooling (solar heating) may be due to an increase (decrease) in relative humidity (Tao *et al.* 1996). However, the interaction of radiation with organized convection can affect the diurnal variability of rainfall as well- (less-) organized cloud systems can produce strong (weak) diurnal variations in rainfall. Ice processes enhance the diurnal variation of precipitation (Liu and Moncrieff 1998).

GCMs have very little skill in predicting the diurnal cycle of convective precipitation over land for reasons that are not completely understood. The diurnal development of the convective boundary layer, the role of orography, and the effect of land-surface processes are all involved. As for the diurnal cycle of precipitation over tropical islands, land/sea breezes and their interaction with coastlines and orography are the key mechanisms. CRMs could be used to address these aspects in considerable detail.

*(d)      Radiation-Convective Quasi-equilibrium Processes*

In more of an idealized approach, CRMs were used in a series of studies on radiative-convective systems and their respective interactions with the atmospheric large-scale environment in the Tropics. The focus of the CRM studies was on the organization of deep convective systems and their accompanying anvils with respect to SST, vertical shear of horizontal wind, water vapor distribution and horizontal momentum transport. The models are typically run for several weeks until the temperature and water vapor fields reach a quasi-equilibrium state (termed a radiative-convective equilibrium state).

Three different types of large-scale forcing have been imposed into CRMs to study tropical radiative-convective equilibrium: (1) large-scale lifting derived from observations (i.e., Lau *et al.* 1993; Sui *et al.* 1994; Xu and Randall 1998; Tao *et al.* 1999; Gao *et al.* 2006b), (2) constant radiative cooling (i.e., Robe and Emanuel 1996; Tompkins and Craig

1998; Grabowski and Moncrieff 2001)[8], and (3) large scale lifting based on the weak temperature gradient approximation (WTG, Raymond and Zeng 2005). The constant radiative cooling approach cannot affect water vapor explicitly in contrast to the other two approaches. This could lead to a drier quasi-equilibrium state (Tompkins and Craig 1998; see Fig. 5).

Some of the quasi-equilibrium studies focused on identifying the physical processes responsible for different quasi-equilibrium states (warm and humid versus cold and dry) that were obtained using similar initial thermodynamic profiles and a fixed SST (Fig. 5). It was found that stronger surface winds and strong vertical wind shear tend to produce a warmer and more humid thermodynamic equilibrium state (Tao et al. 1999; Tompkins 2000). Net large-scale forcing in both temperature and water vapor and surface fluxes (particularly, latent heat flux) were the two major physical processes involved in the variation in quasi-equilibrium states. In recent CRM studies by Grabowski and Moncrieff (2001) and Grabowski (2003), a very warm, humid radiative-convective equilibrium state was simulated. Note that a very large 2D domain (20,000 km) was used in their studies. In another recent CRM study, Gao et al. (2006b) found that the simulation with a time-invariant solar zenith angle produced a colder, drier equilibrium state than did the simulation with a diurnally varied solar zenith angle.

Results from these radiative-convective studies have been used to quantify hypotheses relating to global warming (i.e., Lau et al. 1993; Sui et al. 1994). The key results to date are: (1) the conversion of ice-phase water into vapor due to dissipating upper-level stratiform/cirrus clouds contributes to upper tropospheric moisture on the same order as moisture transport from deep convection, (2) cloud activity is much more sensitive to convergence in the large-scale atmospheric circulation over an oceanic warm pool than it is to the local SST, and (3) the organization of cloud systems largely determines the magnitude of the upper-level cloudiness and moisture profiles. The above conclusions do not say

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[8]     Radiative cooling is on the order of -2 K day-1 and is equivalent to about 0.5 cm s-1 of lifting assuming a constant potential temperature lapse rate [i.e., 5-6 K/km, see Tao et al. (1996)].

whether or not global warming is occurring, only that if cloud processes are neglected or poorly formulated, the consequences could lead to substantial errors in important climate hypotheses.

Based on the results from the radiative-convective studies, several theories on the physical processes that organize tropical convection were developed. For example, Tompkins (2001a) indicated that water vapor plays an active role in determining the location of convection. Moreover, Tompkins (2001b) developed a "self-aggregation" theory, in which convection can locally moisten its atmosphere, making it favorable for future convection. Grabowski and Moncrieff (2001) suggested that convective momentum transport and the impact of convective systems on temperature and moisture near the surface are key processes responsible for the development and organization of large-scale convection system. These differences in the proposed mechanisms for convective development and organization could be due to the differences in the dimensions and/or size of the computational domains used in the studies. The differences could also be caused by differences in the simulated radiative-convective equilibrium states.

Real clouds and cloud systems are three-dimensional. Because of the limitations in computer resources, either 2D CRMs with relatively large domains or 3D CRMs with relatively small domains were used in the radiative-convective equilibrium state studies. Only recently, Tompkins (2001a, b) applied a 3D CRM with a large domain (1024 by 64 km$^2$ in the horizontal with 2 km resolution) to study the relationship between tropical convection and SST. Tompkins (2000) investigated the impact of dimensionality on long-term radiative-convective equilibrium states and concluded that a 3D CRM is highly preferable for random or clustered convection and especially in low wind environments.

*(e)    Chemistry-Convective Interactive Processes*

Organized mesoscale convection provides an effective means for the rapid transport of air from the boundary layer into the overlying free troposphere. The transport within convective-scale updrafts and downdrafts, and the mixing of cloud-free tropospheric air with

cloud-processed air can produce a post-storm trace chemical distribution that differs markedly from pre-storm values. The degree of vertical redistribution (or overturning) is indicative of the intensity of the convection, and reflects the transport structure responsible for the mixing. The use of CRMs for studying the impact of organized convection on Ozone can be found in a review paper by Thompson et al. (1997).

CRMs are now being used to drive transport of trace gases and aerosols and their associated chemistry in either an on-line or off-line fashion. Processes which can be simulated include transport by the model wind fields, turbulent mixing, ozone photochemistry, sulfur chemistry, perturbations to photolysis rates due to hydrometeors, wet scavenging of soluble trace gases and aerosols by hydrometeors, and production of NO by lightning. Temperatures and water vapor from the CRM are used in the chemistry calculations. For example, Pickering et al. (1998), DeCaria et al. (2000) and Pickering et al. (2001) performed chemical tracer transport simulations using a 2D CRM to develop a realistic parameterization of lightning NO production. This same lightning NO scheme was incorporated into a Cloud-scale Chemical Transport Model (CSCTM; DeCaria et al. 2005) containing ozone photochemistry and driven by the 3D CRM (Stenchikov et al. 2005). The CSCTM has been used to deduce the magnitudes of average NO production by cloud-to-ground flashes and by intra-cloud flashes for particular storms (DeCaria et al. 2005; Ott et al. 2006). Figure 6 shows the fields of $NO_x$ and $O_3$ at 9 km from a simulation by the CSCTM of a storm system observed in the European Lightning $NO_x$ Experiment (EULINOX). NOx is enhanced within the storm cells due to transport from the polluted boundary layer and due to production by lightning. An ozone minimum is found in the cores of these cells due to transport of lower ozone mixing ratios from the boundary layer and due to titration losses resulting from the large NO mixing ratios produced by lightning. Enhanced ozone around the edges of the cells is a result of downward transport from the vicinity of the tropopause.

Future work in chemistry using CRMs will focus primarily on the following areas: 1) the development of improved lightning schemes and better estimates of NO production by lightning, 2) improving the representation of soluble gas-related processes, and 3) developing more realistic perturbations for clear-sky photolysis rates by clouds. More comprehensive

atmospheric chemistry field experiments focusing on deep convection are needed to provide datasets to test these algorithms in CRMs.

*(f)     Aerosol-Precipitation Interactive Processes*

Aerosols and especially their effect on clouds are one of the key components of the climate system and the hydrological cycle.   Yet, the aerosol effect on clouds remains largely unknown and the processes involved not well understood.   A recent report published by the National Academy of Science of United States states *"The greatest uncertainty about the aerosol climate forcing - indeed, the largest of all the uncertainties about global climate forcing - is probably the indirect effect of aerosols on clouds NRC [2001]."*  This "indirect effect" includes the traditional "indirect" or "Twomey" effect on the cloud microphysics (Twomey 1977; Twomey *et al.* 1984), the "semi-indirect" effect on cloud extent and lifetime (Hansen *et al.* 1997; Ackerman *et al.* 2000), and effects on precipitation formation (termed $2^{nd}$ indirect effect) recently observed from TRMM and other satellite studies (Rosenfeld 1999, 2000).   For example, Rosenfeld (2000) found that smoke and air pollution may act to suppress both liquid-phase and ice processes involved in precipitation development and that this effect can occur over large areas.   Rosenfeld and Woodley (2000) used aircraft measurements to infer that suppression of coalescence can reduce areal rainfall by as much as a factor of two.   Such pollution effects on precipitation potentially have enormous climatic consequences both in terms of feedbacks involving the land surface via rainfall and the surface energy budget and changes in latent heat input to the atmosphere.

Recently, the CRMs were used to examine the role of aerosol concentrations on precipitation processes (see Table 4).   These modeling studies had many differences in terms of model configuration (2D or 3D), domain size, grid resolution (150 – 3000m), microphysics (two-moment bulk scheme, simple or sophisticated spectral bin microphysics), turbulence ($1^{st}$ or 1.5 order TKE), radiation, lateral boundary conditions (closed, open and cyclic), cases (isolated convection to tropical/midlatitude squall lines) and model integration time (2.5 h – 48 hours).  Almost all of the model results indicated that aerosol concentration had a significant impact on precipitation.   For example, Khain *et al.* (2004, 2005) indicated

that an increase in aerosol concentration (or cloud condensational nuclei, CCN) could reduce precipitation processes (and rainfall) for both an East Atlantic squall line and a Texas convective cloud. They also found that increasing the CCN could enhance precipitation for an Oklahoma squall line. On the other hand, Wang et al. (2005) found that precipitation could either be enhanced or reduced by increasing the CCN for a squall line that developed in the ITCZ. Fan et al. (2006) found that ice microphysics, clouds and precipitation changed considerably with aerosol chemical properties for a convective event occurring in Houston, Texas. Fridlind et al. (2004) found mid-tropospheric aerosols were important as subtropical anvil nuclei for an isolated cloud, but Khain and Porovsky (2004) showed that lower-tropospheric aerosols penetrating cloud base dominated for deep convective clouds. These differences could be due to model physics, cases and/or set-ups (e.g., domain size, lateral boundary conditions).

Regional-scale models with fine mesh grid (3 km) have also been used to study the impact of aerosols on precipitation. For example, Lynn et al. (2005) found that precipitation processes and rainfall were suppressed by enhancing the aerosol concentration for a Florida squall line. Chen et al. (2006) also found that increasing aerosols inhibited precipitation for a Oklahoma warm cloud system.

In almost all cases, idealized aerosol concentrations[9] were used in the model simulations. Furthermore, almost none of these CRM studies compared the model results with observed cloud structures, organization, radar reflectivity and rainfall. Some of the CRM domains were too small to resolve the observed clouds or precipitation systems (the domain size has to be at least twice as large as the simulated features). It may require major field campaigns to gather the data necessary to both initialize (with meteorological and aerosol) and validate (i.e., in situ cloud property observations, radar, lidar, and microwave remote sensing) the models. Even CRM-simulated results can provide valuable quantitative estimates of the indirect effects of aerosols; however, CRMs are not global models and can only simulate clouds and cloud systems over a relatively small domain. Close collaboration

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[9]    Aerosol concentrations observed/measured from a previous day were used in Fridlind et al. (2004). Observed cloud structure and rainfall were used for comparison in Fan et al. (2006).

between the global and CRM communities is needed in order to expand the CRM results to a regional and global perspective.

*(g)    The Representation of Moist Processes in Large-scale Models*

In a cumulus parameterization workshop, there was a consensus that a consistent, comprehensive cloud database (containing clouds and cloud systems from different geographic locations) should be generated by CRMs and provided to the large-scale modeling communities, specifically to the parameterization developers, for use in the development and/or improvement of the representation of moist processes and their interactions with radiation (Tao *et al.* 2003b)[10]. For example, it was demonstrated that the mosaic treatment of sub-grid cloud variability (Liang and Wang 1997) using CRM cloud statistics (Fig. 7) generated by NCAR/Iowa State University (Wu and Moncrieff 2001; Wu *et al.* 2003; Wu *et al.* 2006) can faithfully simulate the CRM domain-averaged radiative fluxes at the surface and top of the atmosphere (TOA) as well as the radiative heating profiles (Liang and Wu 2005). The GCM with the modified radiation scheme enables the use of more realistic cloud amounts as well as cloud water contents while producing net radiative fluxes closer to observations. The improved vertical distribution of cloud water path based on the CRM simulations increases the radiative heating in the upper troposphere over the Tropics, which reduces the long-standing cold bias in the temperature field (Wu and Liang 2005).

However, the cumulus parameterization workshop also recommended that an ensemble approach be used (i.e., cloud data should be generated from different CRMs). The ensemble approach gives a measure of the uncertainty as contained in the spread of the model results. This cloud data will be generated in close collaboration with or as requested by those developing moist parameterizations. In addition, new and innovative ideas for the optimal way in which to use the CRM datasets are required.

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[10]    The CRM can also provide 4D cloud data to large-scale dynamicists studying the relationships between moisture distribution, vorticity and the development of tropical convection (i.e., Gao *et al.* 2006c).

## 4. Current and Future Research

### (a) CRM improvements

Current CRMs can reasonably simulate the evolution, structure, and life cycles of cloud systems. They can also explicitly calculate the interaction between clouds, longwave and solar radiation that are difficult, if not impossible, to measure observationally. However, Cotton (2003) has discussed some of the limitations (i.e., prediction of ice particle concentrations, initial broadening of cloud droplet spectra in warm clouds, details of hydrometeor spectra evolution, quantitative simulations of entrainment rates) of current CRMs. These limitations (or deficiencies) must be resolved in the coming years. In addition, cloud microphysical processes, heat fluxes from the warm ocean, land and radiative transfer processes should interact with each other explicitly. How these processes interact under different environmental conditions should be a main focus of modeling studies in the future. Also, a major area in need of development involves scale interactions and how cloud processes must be included in simulations of mesoscale to global-scale circulation models.

### (b) Future Research and Applications

Many current CRMs need large-scale advective forcing in temperature and water vapor, either from intensive sounding networks that are deployed during major field experiments or from large-scale model analyses, to be imposed as an external forcing (termed "*a semi-*

*prognostic approach*", see Soong and Tao 1980). The advantage of this approach is that model results in terms of rainfall, temperature and water vapor budget are usually in good agreement with observations (see Tao 2003 for a brief review and Randall *et al.* 2003a). However, CRM simulations with observed forcing only allow one-way interaction and cannot address the effects of cloud and radiation feedbacks on GCMs.

Recently Grabowski and Smolarkiewicz (1999); Khairoutdinov and Randall (2001); and Randall *et al.* (2003b) proposed a multi-scale modeling framework (MMF, termed a "*super parameterization*"), which replaces the conventional cloud parameterizations with a CRM in each grid column of a GCM. The MMF can explicitly simulate deep convection, cloudiness and cloud overlap, cloud-radiation interaction, surface fluxes, and surface hydrology at the resolution of a CRM. It also has global coverage and two-way interactions between the CRMs and their parent GCM. The MMF could be a natural extension of current cloud resolving modeling activities. MMFs can also bridge the gap between traditional CRM simulations and current and future non-hydrostatic global cloud-resolution models (Fig. 8). For example, a global non-hydrostatic grid model with icosahedral structure is being developed in Japan (Satoh *et al.* 2005). This model is intended for high-resolution climate simulations with cloud-resolving physical processes (i.e., cloud microphysics, radiation, and boundary layer processes[11]). It has been performed on an aqua planet setup with grid intervals of 7 and 3.5 km. The model simulates reasonable features in the Tropics, like the diurnal cycle of precipitation, hierarchical structure of clouds, and intra-seasonal oscillations (Tomita *et al.* 2005, Miura *et al.* 2005; Nasuno *et al.* 2006). It is expected that a close

collaboration between CRMs, MMFs and non-hydrostatic high-resolution global cloud resolving models can enhance our ability to simulate realistic weather and climate in near future.

## 5. Acknowledgments

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[11]    MMFs can be used to identify the optimal grid size and physical processes (i.e., microphysics, cloud-radiation interactions) needed for future non-hydrostatic global CRMs.

# Figure Captions

Fig. 1    Schematic diagram showing the characteristics of the GCE model. Arrows with solid lines indicate a two-way interaction between different physical processes.

Fig. 2    The 3D GCE model-simulated cloud hydrometeor mixing ratios for a SCSMEX (center upper panel) and KWAJEX (right upper panel) case. The white isosurfaces show the cloud water and cloud ice, blue the snow, green the rainwater, and red the graupel. Also shown are the GCE-simulated surface rainfall rates (mm/hr) for SCSMEX (center lower panel) and KWAJEX (right lower panel) corresponding to the same cloud fields in (a) and (b), respectively. Most of the surface rainfall results from the melting of graupel [red surface in (a) and (b)] near 0 °C. This indicates the importance of ice processes even in tropical environments. The rain patterns resemble the radar observations shown in the left panels.

Fig. 3    Heating (a) and moistening (b) budgets for the May SCSMEX case averaged over the 9-day simulation time (in red). Contributions from net condensation (condensation + deposition – evaporation – sublimation, in orange) and the total vertical eddy-flux convergence [includes both cloud-scale and sub-grid-scale (turbulence) effects, in blue] are shown. The net radiation (in yellow) and the diagnostically-determined heating and moistening budgets derived from atmospheric sounding data are also shown for comparison (in green). (c) and (d) are the same as (a) and (b), except for the KWAJEX 14-day simulation. (e) and (f) are the same as (a) and (b), except for the TOGA COARE 8-day simulation.

Fig. 4    The change of APW is first caused by the direct radiative cooling/heating cycle that is proportional to the time rate of change of saturation columnar water vapor amount. The convective response to this direct forcing can induce further changes in temperature and moisture that lead to a corresponding change of APW. The estimated diurnal distribution of $-\partial W^*/\partial t$ is shown by the solid curve that can be regarded as a theoretical limit. It shows a clear nocturnal maximum and noon

minimum due to the diurnal temperature distribution. The diurnal composite of simulated surface precipitation from a 15 day CRM is shown by the dashed curve.

Fig. 5    Scatter plot of domain-averaged mass-weighted temperature vs water vapor after 25 days of integration from GCE (runs 1 to 4 and 1W to 4W) and UCLA/CSU CRM simulations (using the same Marshall Islands data). Observations from the TOGA COARE (TC) and Marshall Islands (MI) regions are shown. Simulations cM, cW, and vW are from Xu and Randall (1998). Runs 1W to 4W are the runs that produced warm & humid SE states similar to Grabowski et al. (1996) (grouped with G in the same box). Runs 1 and 2 are centered at 259 K and 57 mm and are grouped with cM in the same box. Runs 3 and 4 are the runs that produced very cold and dry SE states. The results from Sui et al. (1994) after 25 days of integration are denoted as S, those of Tompkins and Craig (1998) as AC, and those of Grabowski and Moncrieff (2001) as GM.

Fig. 6    Chemical fields at 180 minutes from the CSCTM simulation of the July 21, 1998 EULINOX storm. The black line indicates the 20 dBZ contour of computed radar reflectivity from the GCE model. (a) NOx mixing ratios at 9 km elevation assuming the production of NO is 360 moles NO/flash for both IC and CG flashes. The box indicates the grid cells sampled for comparison with aircraft observations, which verify this NO production scenario; (b) O3 mixing ratios at 9 km.

Fig. 7    CRM simulated cloud frequency ($10^{-4}$) distribution as a function of the base and top heights. The calculation uses all 15-minute samples during the 26-day period over the 200 CRM columns. For each CRM grid, a vertical layer is assumed to be uniformly filled by a cloud of local liquid droplets and/or ice crystals if their total cloud water path is greater than a threshold (0.2 g $m^{-2}$), or otherwise completely clear. Rain and graupel are neglected, as their radiative impact is small. Four major cloud clusters are identified in the centers as convective (*Cc*), anvil cirrus (*Ci*) and stratiform (*Cs*) clouds that are distinguished by the mosaic approach (Liang and Wu 2005).

Fig. 8    Schematic diagram showing the relationship between traditional CRMs with a semi-prognostic approach developed almost 25 years ago, MMFs and a high-resolution non-hydrostatic global cloud simulator/model.

# Table Captions

Table 1   Major highlights of cloud model development over the past four to five decades.

Table 2   Characteristics of the radiation parameterizations used in CRMs. Assumed cloud optical properties (for various types of hydrometeors, including cloud water, cloud ice, snow, rain, and graupel/hail) and radiative transfer model update frequency for different CRMs are listed. Some CRMs contain additional radiation layers (from 2 to 7) above the cloud model domain to avoid excessively large radiative cooling/heating rates at the top of the cloud model domain. Except for one, all CRMs use maximum overlap in their radiative transfer model calculations. Main references for specifying the cloud optical properties are listed for each CRM. GSFC/GCE stands for Goddard Space Flight Center / Goddard Cumulus Ensemble, CSU / UCAL for Colorado State University / University of California at Los Angles, CSU /RAMS for Colorado State University / Regional Atmospheric Modeling System, CNRM for Centre National de Recherches Meteologiques, UW / MM5 for University of Washington / NCAR Penn State Mesoscale Modeling Version 5, NCAR for National Center for Atmospheric Research, UU / UCLA for Utah University / University of California at Los Angles, NOAA / GFDL for National Oceanic and Atmospheric Administration / Geophysical Fluid Dynamics Laboratory.

Table 3   Initial environmental conditions expressed in terms of CAPE (convective available potential energy) and precipitable water for TOGA COARE (December 19 -27 1992), SCSMEX (2-11 June 1998), KWAJEX (August 29 - September 9 1999), and GATE (September 1 - 7 1974) as well as the corresponding CRM-simulated domain-average surface rainfall amounts and stratiform percentages for these cases. Rainfall amounts and stratiform percentages estimated from TRMM PR, TMI and sounding network data are also shown.

Table 4   Key papers using CRMs to study the impact of aerosols on precipitation.  Model dimensionality (2D or 3D), microphysical scheme (spectral bin or two-moment bulk), turbulence (1st or one and a half order TKE), radiation (with and without), domain size (km), resolution (m), time step (second), lateral boundary condition (closed, cyclic or radiative open), case and integration time (h) are listed.

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| | Major Highlights |
|---|---|
| 1960's | Loading, Buoyancy and Entrainment |
| 1970's | Slab- vs Axis-symmetric Model<br><br>Cloud Seeding<br><br>Cloud Dynamics & Warm rain |
| 1980's | Ensemble of Clouds - Cumulus Parameterization<br><br>Cloud interactions and Mergers<br><br>Ice Processes<br><br>Super Cell Dynamics<br><br>Squall Line<br><br>Convective and Stratiform Interactions<br><br>Wind Shear and Cool Pool<br><br>Gravity Wave and Density Current<br><br>Cloud Radiation Interaction |
| 1990's | 2D vs 3D<br><br>Cloud-Radiation Quasi-Equilibrium – Climate Variation Implications<br><br>Cloud Transport and Chemistry<br><br>Diurnal Variation of Precipitation<br><br>GEWEX Cloud System Study (GCSS)<br><br>Coupled with microwave radiative model for satellite cloud retrieval (TRMM) |
| 2000's | Land and Ocean Processes<br><br>Multi-scale Interactions<br><br>Energy and Water Cycle<br><br>Cloud Aerosol-Chemistry Interactions<br><br>Cumulus Parameterization Improvements |

Table 1

| Model | Cloud water | Cloud ice | Rain | Snow | Graupel/hail | Frequency (second) | Additional Layers above Model Top | Cloudiness | References |
|---|---|---|---|---|---|---|---|---|---|
| GSFC/GCE-1 | 0.0003 cm | T, size spectra | Size spectra | T, size spectra | Size spectra | 180 | 7 - 0.01 mb | 1, 0 | Sui *et al.* (1994); Tao *et al.* (1996) |
| GSFC/GCE-2 | Size spectra | Size spectra | Size spectra | Size spectra | Size spectra | 180 | 7 - 0.01 mb | 1, 0 | Fu *et al.* (1995) |
| CSU/UCLA | Gamma | Gamma | Size spectra | Size spectra | Size spectra | 600 | 5 - 2 mb | Max overlap | Xu and Randall (1995) |
| CSU/RAMS | Gamma | Gamma | Gamma | Gamma | Gamma | 100 | 0 - 50 mb | 1, 0 | Harrington (1997) |
| CNRM | 0.0015 | 0.0040 | No | No | No | 60 and 900 | 2 - 10 mb | 1.0 | Morcrette (1990) |
| UW/MM5 | 0.0010 | 0.0050 | 0.010 | 0.025 | No | 1800 | 0 - 50 mb | 1, 0 | Su *et al.* (1999) |
| NCAR | 0.0010 | 0.0030 | Size spectra | No | Size spectra | 150 | 0 - 40 km | 1, 0 | Kiehl *et al.* (1996) |
| UU/UCLA | 0.0010 | 0.0030 | Size spectra | Size spectra | Size spectra | 300 | 2 - 0.2 mb | 1, 0 | Fu *et al.* (1995) |
| NOAA/GFDL | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 600 | 75 mb | 1, 0 | Held *et al.* (1993) |

Table 2

| | Mean CAPE $m^2\ s^{-2}$ | Precipitable Water $(g\ m^{-2})$ | Simulated Rainfall (mm day$^{-1}$) & Stratiform % | Observed Rainfall (mm day$^{-1}$) |
|---|---|---|---|---|
| TOGA COARE December 19 – 27 1992 | 898 | 56.48 | 20.7 45% | 20.1 |
| SCSMEX June 2 – 11 1998 | 1324 | 62.34 | 17.0 31.4% | 20.7 17.9 (TRMM) |
| KWAJEX August 29 – September 9 1999 | 2025 | 55.69 | 9.9 36% | 8.9 |
| GATE September 1 – 7 1974 | 736 | 47.61 | 13.9 31% | 13.5 |

Table 3

| | | Microphysics | Turbulence | Radiation | Domain | Grid Size & Time step | Lateral Boundary Conditions | Cases | Integration |
|---|---|---|---|---|---|---|---|---|---|
| Khain *et al.* (2004) | 2-D | Spectral Bin (33 bin) 6 types of ice | 1st order | No | 64 x 16 km | dx=250 m dz=125 m dt=5 s | Closed | A squall lines (E. Atlantic) and a convective cloud (Texas) | ~2 h |
| Khain and Pokrovsky (2004) | 2-D | Spectral Bin (33 bin) 6 types of ice | 1st order | No | 64 x 16 km | dx=150 m dz=125 m dt=5 s | Closed | A convective cloud (Texas) | 2.5 h |
| Khain *et al.* (2005) | 2-D | Spectral Bin (33 bin) 6 types of ice | 1st order | No | 128 x 16 km | dx=150 m dz=125 m dt=5 s | Closed | Two squall lines (E. Atlantic and Oklahoma) and a convective cloud (Texas) | 2 and 4 h |
| Fridlind *et al.* (2003) | 3-D | Spectral Bin (16 bins) 1 type of ice | 1st order | No | 48 x 48x 24 km | dx=dy=500 m dz=375 m dt=5 s | Closed | A convective cloud (Florida) | 3 h |
| Wang (2005) | 3-D | Two moment bulk scheme | 1st order | 6 Broad Bands for Solar and 12 for IR. Four-stream discrete-ordinate scattering, k-distribution | 400 x 200x 25 km | dx=dy=2000 m dz=500 m dt=5 s | Cyclic | A squall line (ITCZ) | 4 h |
| Cheng *et al.* (2006) | 3-D | Two moment bulk scheme (Warm rain only) | 1st order | A simple broad-band solar and emissivity (IR) | 810 x 810 km x 100 Pa | dx=dy= 3000m dz=stretched dt=5 s | Radiative Open | A shallow Stratus (ARM-SGP) | 72 h |
| Lynn *et al.* (2005) | 3-D | Spectral Bin (33 bin) 3 types of ice and Bulk scheme | TKE | A broad-band two-stream for solar and an emissivity for IR | 400 x 199 x 25 km | dx=dy=1000 m dz=stretched dt=9 s | Radiative Open | A squall line (Florida) | 13 h |
| Fan *et al.* (2006) | 2-D | Spectral Bin (33 bin) 6 types of ice | TKE | No | 512 x 22 km | dx=500 m dz=stretched (250 – 1260 m) dt=6 s | Radiative Open | A sea-breeze induced convective event (Houston, Tx) | 3 h |

Table 4
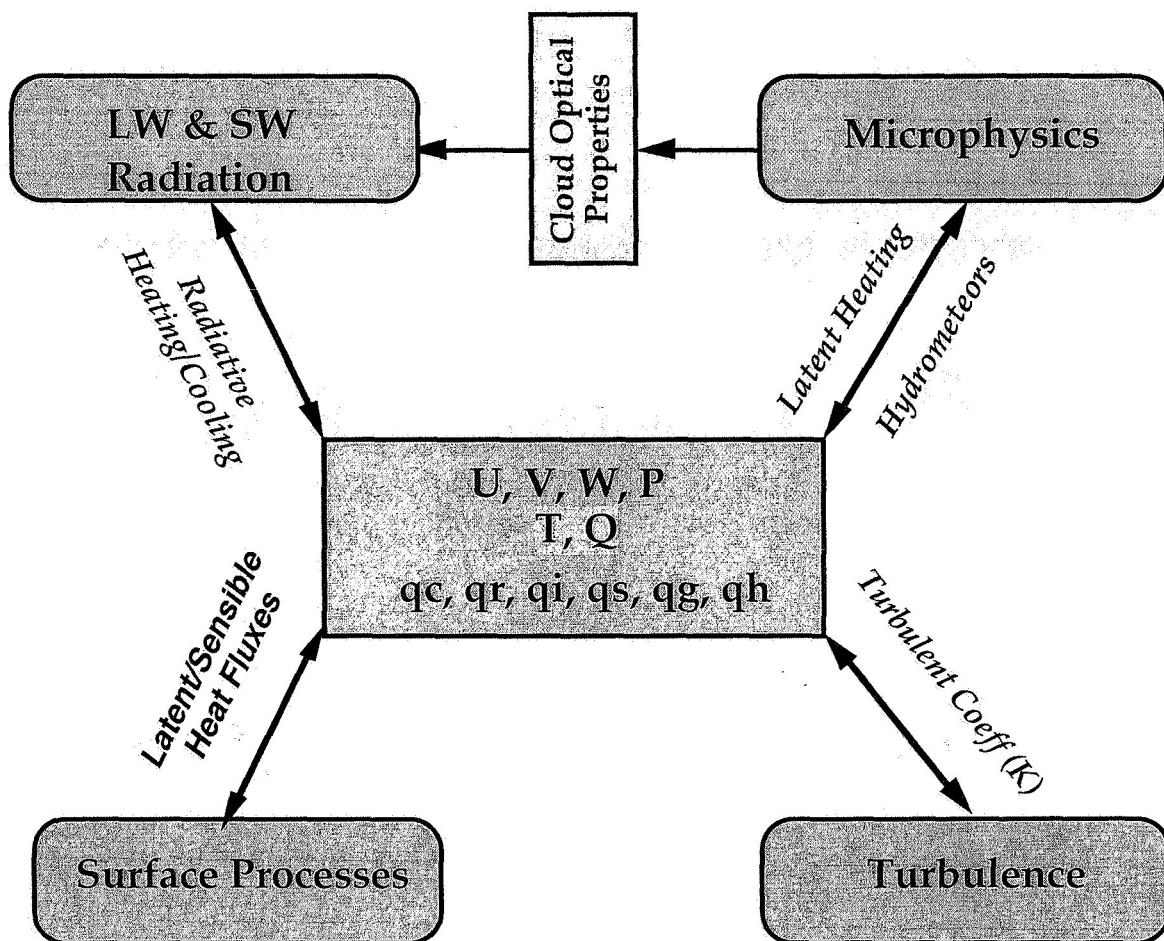
Figure 1

# SCSMEX (S. China Sea) and KWAJEX (W. Pacific)
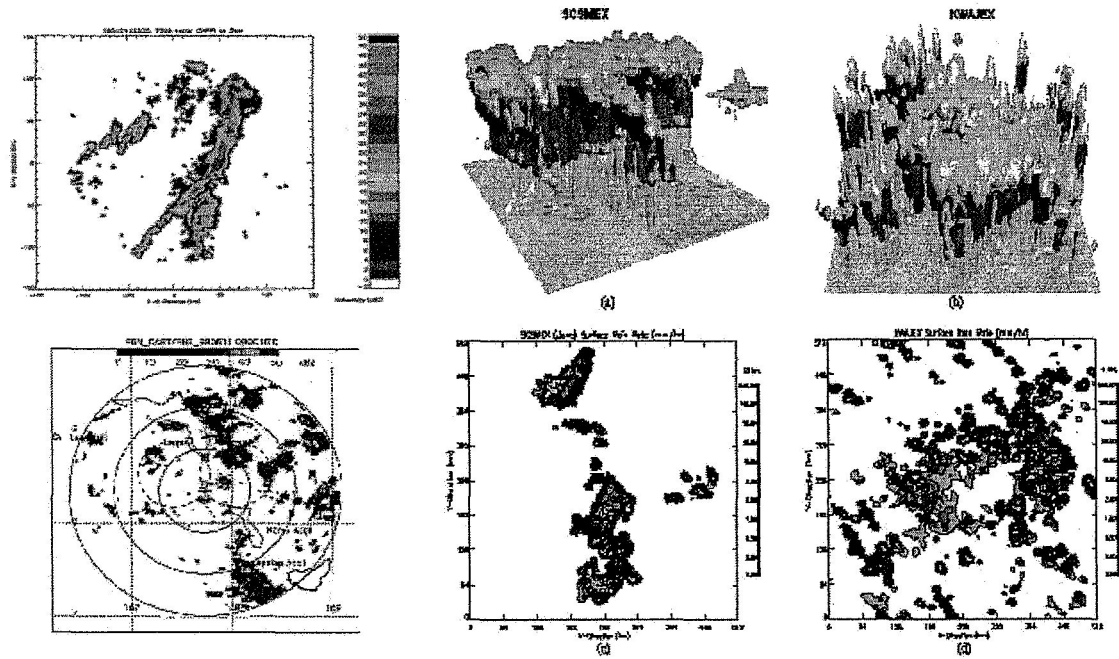


Radar Observations (dBZ) from SCSMEX (upper left panel)and KWAJEX (lower left panels). Linear cloud systems typically propagated from west to east in SCSMEX. Less organized and short-lived clouds/cloud systems dominated in KWAJEX
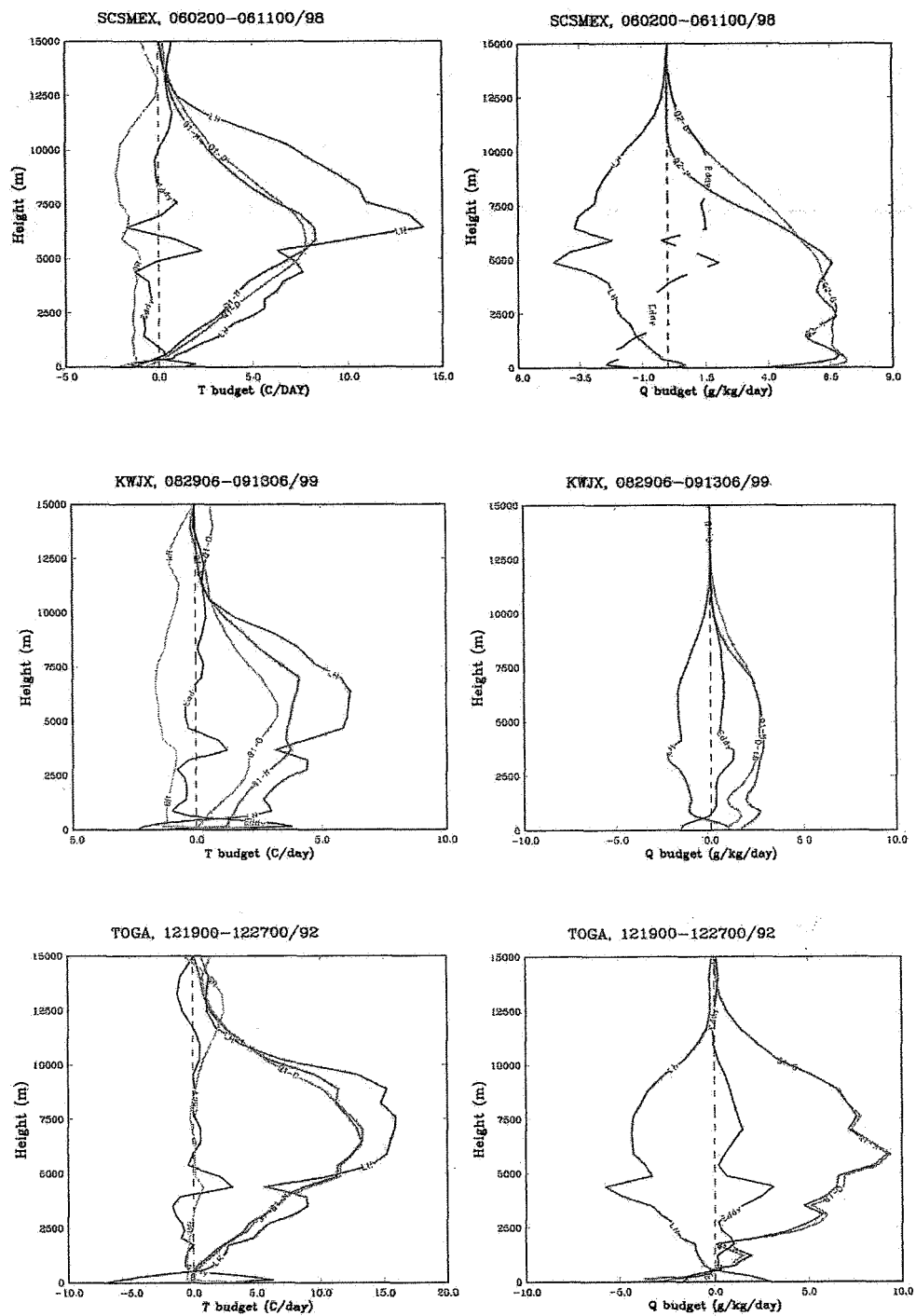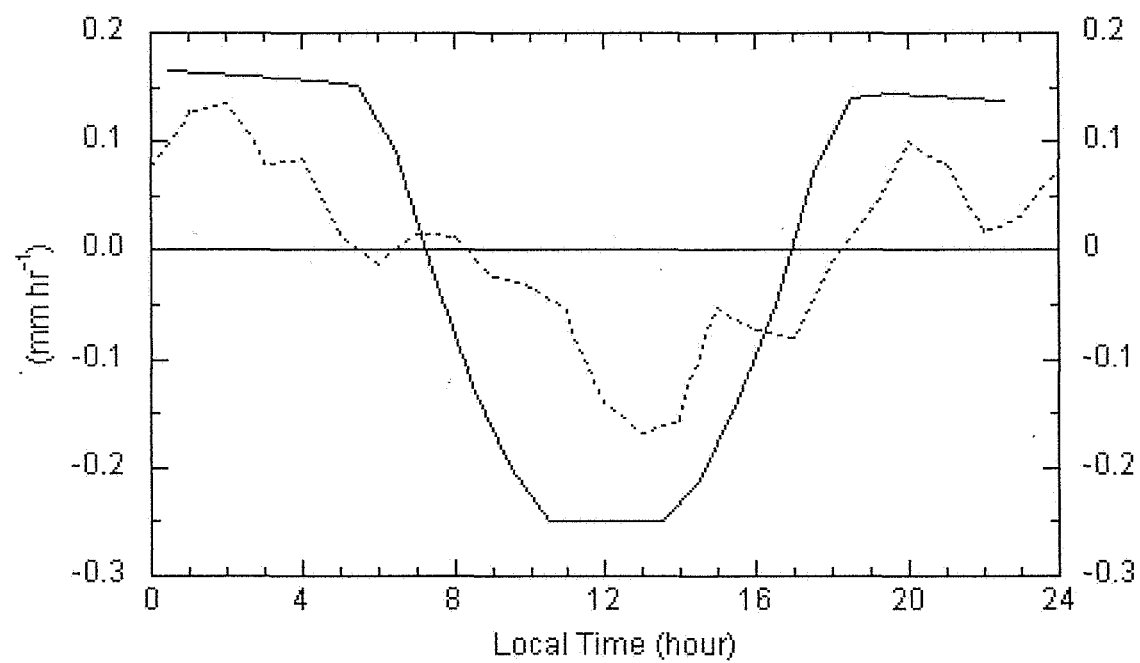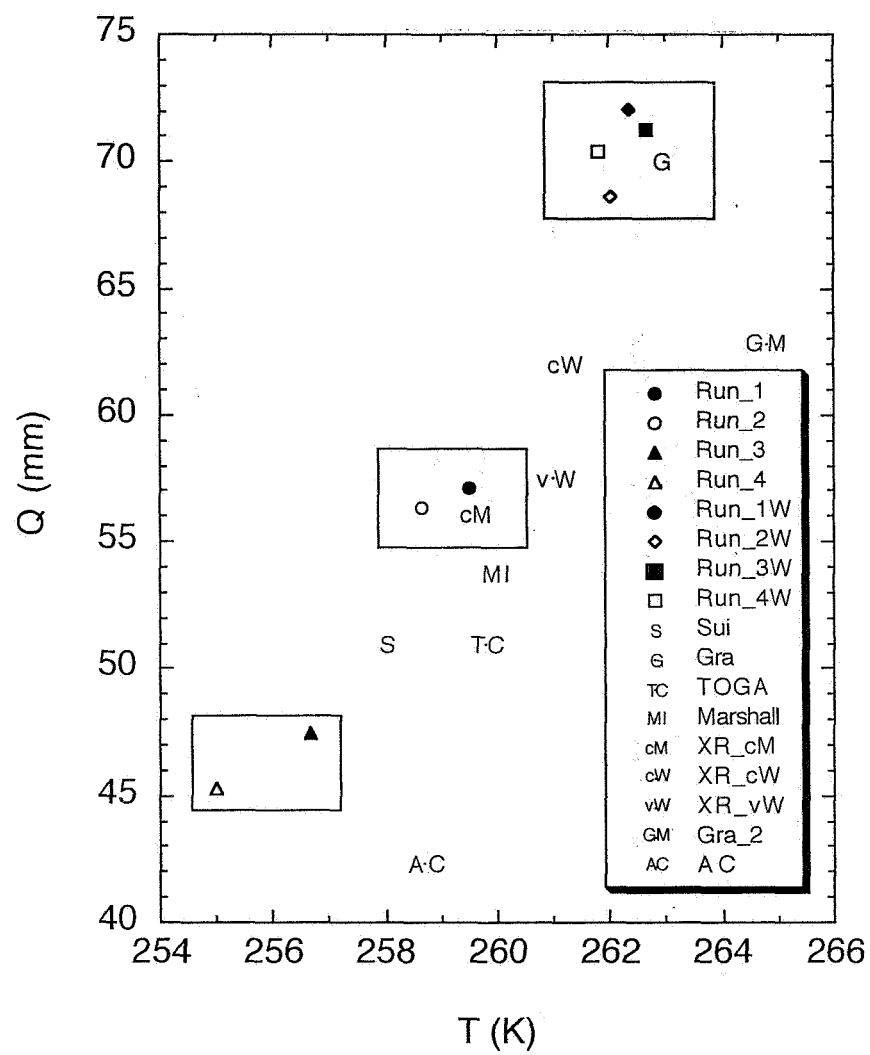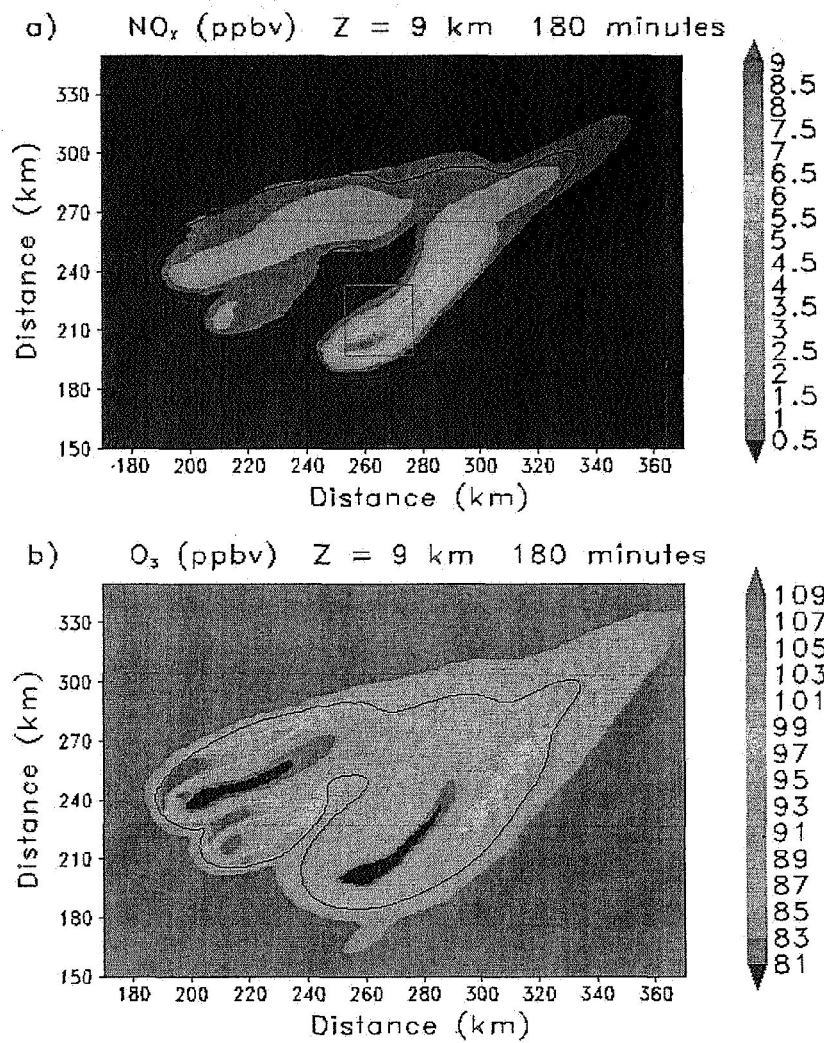
Fig. 2

Fig. 3

Fig. 4

Fig. 5

a) NO$_x$ (ppbv)   Z = 9 km   180 minutes



b) O$_3$ (ppbv)   Z = 9 km   180 minutes



Fig. 6

Cloud Frequency (10⁻² %)
SGP 1997 Jun 22-Jul 17 All-Cells



Fig. 7

Fig. 8