ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 25, NO. 2, 2008, 202–212

A Review of Cloud-Resolving Model Studies of Convective Processes

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(Received 2 April 2007; revised 27 June 2007)

ABSTRACT

Convective processes affect large-scale environments through cloud-radiation interaction, cloud microphysical processes, and surface rainfall processes. Over the last three decades, cloud-resolving models (CRMs) have demonstrated to be capable of simulating convective-radiative responses to an imposed large-scale forcing. The CRM-produced cloud and radiative properties have been utilized to study the convective-related processes and their ensemble effects on large-scale circulations. This review summarizes the recent progress on the understanding of convective processes with the use of CRM simulations, including precipitation processes; cloud microphysical and radiative processes; dynamical processes; precipitation efficiency; diurnal variations of tropical oceanic convection; local-scale atmosphere-ocean coupling processes; and tropical convective-radiative equilibrium states. Two different ongoing applications of CRMs to general circulation models (GCMs) are discussed: replacing convection and cloud schemes for studying the interaction between cloud systems and large-scale circulation, and improving the schemes for climate simulations.

Key words: cloud-resolving models (CRMs), convective processes, simulations of convection and clouds

DOI: 10.1007/s00376-008-0202-6

1. Introduction

Cloud systems play an important role in linking atmospheric and hydrological processes and have profound impacts on regional and global climate. The development of convection and clouds relies on environmental conditions. Once formed, they affect the large-scale circulations by the release of latent heat and the transports of momentum, heat, and moisture. Due to the lack of cloud-scale datasets, the cloud-resolving models (CRMs) have been developed to study cloud interactions, convective-stratiform interaction, cloud-radiation interaction, and convective responses to large-scale processes (e.g., Moncrieff and Tao, 1999; Tao, 2003). The CRM-simulated cloud and radiative properties have been used to evaluate and improve the representation of convection, cloud and cloud-radiation interaction for general circulation models (GCMs). With the explosive increase of computational power, CRMs have been directly applied in each grid box of GCMs to replace the convection and cloud schemes.

This purpose of this report is to review the recent progress on the understanding of convective-related processes using the CRM simulations. The framework of CRMs will be briefly described in section 2. The physical processes responsible for producing surface precipitation are examined in section 3. In section 4, the effects of radiative and cloud microphysical processes on the simulations of cloud systems are presented. The mechanism responsible for the development and movement of tropical cloud clusters is discussed in section 5. The analysis of vorticity vectors and their tendencies associated with tropical convection is given in section 6. The precipitation efficiencies of simulated cloud systems are discussed in section 7. The dominant physical processes that control the diurnal variations of tropical convection are quantitatively identified with the surface rainfall equation in section 8. The role of surface precipitation in the ocean mixing

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*Corresponding author: Xiaoqing WU, wuxq@iastate.edu process is examined using a coupled ocean-atmosphere CRM in section 9. The physical processes controlling the convective-radiative equilibrium states are discussed in section 10. Finally, summary and remarks are given in section 11.

2. Cloud-resolving models

Unlike general circulation models, CRMs cover a small domain but have fine horizontal and vertical resolutions that resolve convection and clouds. The non-hydrostatic governing equations with the anelastic approximation include prognostic equations of potential temperature, specific humidity, mixing ratios of five cloud hydrometeors (e.g., Tao and Simpson, 1993). The model also contains solar and thermal infrared radiation parameterization schemes (e.g., Chou et al., 1991; Chou and Suarez, 1994; Chou et al., 1998), cloud microphysics parameterization schemes (e.g., Rutledge and Hobbs, 1983, 1984; Lin et al., 1983; Tao et al., 1989; Krueger et al., 1995), and sub-grid scale turbulence closure (e.g., Klemp and Wilhelmson, 1978).

Environment has an important impact on convective development. Convection in turn modifies environment through momentum, heat, and moisture transports and latent heat release. Environment and convection interact in a nonlinear way (e.g., Chao, 1961, 1962). Due to a small domain in the CRM (e.g., 768 km in a two-dimensional frame), the large-scale circulation cannot be simulated. Thus, observed large-scale forcing is obtained from the field experiments and imposed in the CRM. There are two ways to include large-scale forcing in the temperature and moisture equations of CRMs. The horizontally uniform and vertically varying vertical velocity can be imposed (e.g., Tao and Simpson, 1993), or the horizontally uniform total (horizontal and vertical) advection of the heat and moisture can be imposed (e.g., Grabowski et al., 1996b; Wu et al., 1998). A comparison study by Li et al. (1999) indicated that the bias in temperature and moisture simulated by the model with the imposed vertical velocity is smaller than that with the imposed total advection of heat and moisture.

Three-dimensional (3D) CRM simulations have been carried out less frequently than two-dimensional (2D) simulations. Despite the limitation of 2D framework in representing cloud-scale circulation and structure (e.g., Moncrieff and Miller, 1976), the 2D CRM is able to simulate the convective line in terms of vertical transports of mass, sensible heat, and moisture (e.g., Tao and Soong, 1986; Tao et al., 1987; Grabowski et al., 1998).

CRM simulations of cloud systems during several field experiments are evaluated against observations. The ensemble effects of convection and clouds are compared favorably with the observations in terms of surface precipitation, cloud and radiative properties, and surface heat fluxes during Phase III of the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE) (e.g., Tao and Soong, 1986; Lipps and Hemler, 1986; Krueger, 1988; Grabowski et al., 1996b; Xu and Randall, 1996) and the Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) (e.g., Wang et al., 1996; Wu et al., 1998; Das et al., 1999; Li et al., 1999; Johnson et al., 2002). The validated CRM simulations allow in-depth analysis of physical processes responsible for the development of convection and clouds.

3. Precipitation processes

Surface rainfall rate is one of the most important parameters in meteorology and hydrology, and has significant economic and social impacts. However, the accurate prediction of the surface rainfall rate is difficult because it is the product of multi-scale dynamic, thermodynamic, cloud microphysical and radiative processes, and their interactions (e.g., Li et al., 2006). While the observational data cannot provide enough information to calculate budgets associated with precipitation processes, the CRM simulations can offer cloud-scale properties to examine the energy and water sources which contribute to surface precipitation. The analysis of the phase difference between the mean moist available potential energy and perturbation kinetic energy identified that latent heating and radiative processes are major processes that feed the development of convection and clouds (Li et al., 2002b). The examination of the equation of surface rainfall which is derived by combining the equations of water vapor and cloud water quantified the roles of moisture, condensate and surface evaporation (e.g., Gao et al., 2005a; Zhou et al., 2006; Cui and Li, 2006). Using the CRM simulations of TOGA COARE cloud systems, it is found that moisture convergence and surface evaporation are the largest terms that determine the surface rainfall rate. The phase change of condensates contributes significantly to the surface rainfall rate (Gao et al., 2005a). Large precipitation appears in deep convective clouds due to the consumption of water hydrometeors whereas small precipitation occurs in anvil clouds because of the gain of ice hydrometeors (Zhou et al., 2006). Large surface evaporation occurs in non-precipitation areas, but evaporation is negligible in precipitation areas. Water vapor is transported to precipitation areas from non-precipitation areas through the horizontal convergence term (Cui and Li, 2006).

4. Radiative and microphysical processes

The radiative process affects the development of convection and clouds. The simulation with the varying single scattering albedo and asymmetry factor produces a strong solar radiation absorption by ice clouds in the upper troposphere (Li et al., 1999). The experiment excluding the precipitation-radiation interaction displays a significant cooling and drying bias (Li et al., 2005). The radiative effects of subgrid cloud distributions are crucial for getting the domain-averaged radiation budgets at the top of the atmosphere and the surface to simultaneously agree with observations (Wu and Moncrieff, 2001a). The CRM realization explicitly represents cumulus convection including its mesoscale organization, and produces vertical and horizontal distributions of cloud condensate (ice and liquid water) that interact much more realistically with radiation than the GCM-parameterized clouds.

The microphysical processes play an important role in the simulations of cloud systems. The short-term (less than 1 day) CRM simulations show that the ice phase is crucial for the development of light precipitation associated with stratiform clouds over the trailing region of cloud systems (e.g., Yoshizaki, 1986; Nicholls, 1987; Fovell and Ogura, 1988; Tao and Simpson, 1989a; McCumber et al., 1991; Tao et al., 1991; Wu and Moncrieff, 1996). The effects of cloud microphysics on temperature and moisture profiles are statistically significant in the long-term (more than 1 week) CRM simulations (e.g., Grabowski et al., 1999). The simulations of cloud radiative properties can be improved by modifying the ice fall speed based on the aircraft observations (Wu et al., 1999). The cloud systems simulated without ice microphysics have less extensive stratiform clouds, fast propagation speeds, and shorter life cycles than those simulated with ice microphysics (Grabowski and Moncrieff, 2001; Grabowski, 2003). The exclusion of the depositional growth of snow in the 10-day simulation of TOGA COARE cloud systems causes an anomalous growth of cloud ice, i.e., more than 20% increase of fractional cloud cover and unrealistically large cloud ice mixing ratio (Li et al., 2005). Comparing with the experiment with ice hydrometeors, the experiment without ice hydrometeors produces a larger amount of cloud water and a smaller surface rain rate due to the exclusion of vapor deposition processes, and a colder and moister state due to the smaller heating rate and smaller consumption of vapor (Gao et al., 2006d).

To discuss the interaction between ice and water clouds, a cloud ratio is defined as the ratio of the ice water path (IWP) to the liquid water path (LWP) by Sui and Li (2005). Using the CRM simulations of TOGA COARE cloud systems, it is found that the tendency of the cloud ratio is mainly controlled by the processes related to vapor condensation and deposition during the genesis and decay stages of cloud systems, whereas the tendency is determined by the conversion between water and ice clouds through the melting of graupel and accretion of cloud water by precipitation ice during the mature stage. The growth of graupel by the accretion of cloud water enhances rain water through the melting during a weak-forcing period, whereas the large deposition rate of vapor associated with the large upper-tropospheric upward motion causes the growth of snow from the conversion of cloud ice and the enhancement of graupel from the accretion of snow during a strong-forcing period (Li, 2006). In raining stratiform regions, IWP and LWP have similar magnitudes. The contribution from the collection process to the growth of rain water is slightly more than that from the melting process, and surface rainfall rate is higher than the rain water-related microphysical rate (Cui et al., 2007). In convective regions, IWP is much smaller than LWP, the collection process is dominant in producing rain water, and the surface rain rate is lower than the rain water-related microphysical rate. In non-raining stratiform regions, IWP is much larger than LWP, and the melting process is important in maintaining the rain water budget. The cloud microphysical budgets over convective and stratiform regions may vary under different climate regimes and depend on partition methods (Lang et al., 2003).

5. Tropical cloud clusters

Observational studies using satellite measurements reveal that westward-moving cloud clusters are embedded within the eastward-moving super cloud cluster (e.g., Nakazawa, 1988; Lau et al., 1991; Sui and Lau, 1992). Numerical models including CRMs have been employed to investigate the physical processes controlling the formation, development, and propagation of cloud clusters and super cloud clusters (e.g., Lau et al., 1989; Numaguti and Hayashi, 1991; Chao and Lin, 1994; Yano et al., 1995). The westward movement of cloud clusters in the satellite images is the reflection of the horizontal advection of anvil clouds driven by the mean flow and the creation of new cells to the west of the old clouds within a convectively active phase of the intraseasonal oscillation during TOGA COARE (Wu and LeMone, 1999). The new cloud clusters are generated at the leading edge of a propagating cold pool. The condensational heating associated with the constituent cloud clusters initiates an overall tropospheric-deep gravity wave. The cumulative cluster-induced wave effects lead to the development of new cloud clusters (Peng et al., 2001). Two eastward-moving cloud clusters merge into westward-moving cloud clusters under the environment of vertical wind shear. Merged clouds display notable growth in the eastern edge, indicating that merging processes enhance convection (Ping et al., 2008) and surface rainfall (Tao and Simpson, 1984, 1989b). The studies of cloud interaction and mergers and the comparison between the simulations and observations and between the different CRMs are reviewed by Tao (2003).

6. Dynamic processes

Potential vorticity and helicity are the most important dynamic and thermodynamic variables for studying the genesis and development of weather systems (e.g., Emanuel, 1979; Cao and Cho, 1995; Gao et al., 2002; Lilly, 1986; Droegemeier and Lazarus, 1993). However, they cannot be diagnosed using 2D CRM simulations. Recognizing this limitation, convective (CVV), moist (MVV), and dynamic (DVV) vorticity vectors are defined as the cross product of absolute vorticity vector (Gao et al., 2004) and moist potential temperature gradient, specific humidity gradient, and wind vector (Gao et al., 2005b), respectively. These vorticity vectors are used to analyze 2D and 3D CRM simulations. The vertical components of CVV/MVV in both 2D and 3D frameworks, representing the interaction between horizontal vorticity and horizontal moist potential temperature/specific humidity gradient, highly correlate with the cloud hydrometeors (Gao et al., 2007b). However, the horizontal component of 3D DVV has higher correlation with cloud hydrometeors than the vertical component (Gao, 2007), whereas the vertical component of the 2D DVV has higher correlation (Gao et al., 2005b). The difference is caused by the fact that dominant items in horizontal components of 3D DVV are excluded in the 2D framework.

7. Precipitation efficiency

Precipitation efficiency is an important physical parameter in both vapor and cloud budgets (Sui et al., 2007a). Precipitation efficiency is defined as the ratio of surface rainfall rate to the sum of vapor convergence and surface evaporation rates which is referred to as large-scale precipitation efficiency (LSPE) (e.g., Braham et al., 1952; Heymsfield and Schotz, 1985; Doswell et al., 1996) or the ratio of surface rainfall rate to the sum of vapor condensation and deposition rates which is referred to as cloud-microphysics precipitation efficiency (CMPE) (e.g., Lipps and Hemler, 1986). While CMPE is only affected by cloud microphysical processes and LSPE is related with vapor and cloud processes, both LSPE and CMPE are statistically equivalent since the total moisture source (surface evaporation and vertically integrated moisture convergence) is converted into hydrometeors through vapor condensation and deposition rates (Sui et al., 2005). The precipitation efficiency that includes all moisture and hydrometeor sources associated with rainfall processes range from 0 to 100% (Sui et al., 2007b). Since individual clouds can vary considerably across a large convective system, the precipitation efficiency should be understood as a time average over the life cycle of a precipitation-producing weather system. The estimate of LSPE is 44% and the average of CMPE is between 30%–45%, which varies among the CRM simulations of TOGA COARE, GATE, SCSMEX, and ARM cloud systems (Li et al., 2002a; Tao et al., 2004). The precipitation efficiency is insensitive to environmental moisture, but decreases with the increase of middle-tropospheric wind shear. The condensate convergence (divergence) enhances (reduces) precipitation efficiency.

8. Diurnal variation of tropical oceanic convection

The diurnal variation of tropical oceanic convection is one of most important components in tropical variability and plays a crucial role in regulating hydrological and energy cycles (e.g., Tao and Moncrieff, 2003; Sui et al., 2007a). The dominant diurnal signal is the nocturnal peak in precipitation that occurs in the early morning. Earlier studies suggested that the enhancement of nocturnal rainfall could be due to IR cooling (Kraus, 1963) or the secondary circulation forced by the differences of radiative heating between cloudy and clear-sky regions (Gray and Jacobson, 1977). Some modeling studies later concluded that the nocturnal rainfall maximum is due to the direct solar radiation-cloud interactions (Xu and Randall, 1995) or direct interaction between radiation and convection (Liu and Moncrieff, 1998). Readers are referred to Randall et al. (1991) for a review of relevant studies. An observational analysis by Sui et al. (1997), however, found that the nocturnal rainfall peak is related to the destabilization by radiative cooling and enhanced available precipitable water due to falling temperature during nighttime. These factors favoring maximum nocturnal surface precipitation are consistent with Tao et al. (1996) who found the nocturnal rainfall peak to be associated with higher relative humidity, and are supported by numerical experiments which showed that the condensation rates associated with the diurnal variations are mainly contributed by falling temperatures during the night (Sui et al., 1998; Li, 2004). The application of the surface rainfall equation and heat budget to the diurnal analysis reveals that the infrared radiative cooling after sunset and advective cooling associated with imposed large-scale ascending motion destabilizes the atmosphere and releases convective available potential energy to energize nocturnal convective development (Gao and Li, 2008). The cold temperature enhances condensation and deposition processes (Gao et al., 2006a) from the consumption of the local water vapor, forming the nocturnal rainfall peak.

9. Coupled atmosphere-ocean CRMs

A 2D coupled atmosphere-ocean CRM has been developed to study the effect of fresh water flux and small-scale perturbations on the ocean mixed layer (Li et al., 2000). The coupled model consists of a CRM and an ocean circulation mixed-layer model developed by Adamec et al. (1981) with the mixing scheme of Niiler and Kraus (1977). When the effects of fresh water flux and salinity were included in the coupled model, differences in the zonal-mean mixed-layer temperature and salinity between one-dimensional (1D) and 2D experiments were about 0.4°C and 0.3 PSU, respectively. The mean salinity difference was larger than the mean temperature difference in terms of their contributions to the mean density difference. For the precipitable water budget, maximum magnitudes of the sum of condensation and atmospheric moisture convergence are much larger (2–6 times) than maximum magnitudes of surface evaporation flux (Gao et al., 2006c). In the ocean mixed-layer thermal budget, surface thermal forcing and the sum of ocean thermal entrainment rate and thermal advections have similar maximum magnitudes regardless of the timeframes in which the analyzed data are averaged.

The impact studies of the ocean surface fluxes on the convective development during TOGA COARE and GATE reveal that the exclusion of surface fluxes reduces 12-hour total surface rainfall amount by 20% (Wang et al., 1996) and that the surface fluxes from clear-sky regions are the dominant water-vapor source for the development of tropical convection (Wang et al., 2003).

A 1D ocean model, forced by the CRM surface heat fluxes and wind stress and the prescribed oceanic advection of temperature and salinity or the observed surface fluxes during TOGA COARE, is able to produce the long-term evolution and diurnal variation of the sea surface temperature (Wu and Moncrieff, 2001a; Li et al., 1998). This suggests the important role of accurate representation of cloud-scale and mesoscale processes in the atmosphere-ocean coupling over the western Pacific.

10. Tropical convective-radiative equilibrium states

Tropical climate is essentially determined by the nonlinear interactions of multiscale physical processes including the large-scale and cloud dynamics, cloud microphysics, radiative and surface processes, turbulence, and ocean. The convective-radiative equilibrium studies with the CRMs help to improve the understanding of these controlling processes (Nakajima and Matsuno, 1988; Tao, 2007). The simulations reach a cold and dry equilibrium state (Lau et al., 1993; Sui et al., 1994; Tompkins and Craig, 1998) or a warm and humid state (Grabowski et al., 1996a). The equilibrium states are insensitive to the initial conditions whereas they are sensitive to the minimum surface speed prescribed in the calculation of surface fluxes (Tao et al., 1999). The equilibrium thermodynamic states depend on the surface evaporation, where surface wind plays a central role. Small surface evaporation associated with weak surface winds produces a cold and dry equilibrium state whereas large evaporation associated with strong surface winds causes a warm and humid equilibrium state (Tao et al., 1999; Tompkins, 2000). The vertical wind shear, minimum surface wind speed in the calculations of surface fluxes, and radiative heating determine thermodynamic quasi-equilibrium states (Shie et al., 2003). The condensation and associated latent heat determine the local moisture loss and thermal gain for strong convection, whereas the vertically advective moistening and cooling cause the local moisture gain and thermal loss for weak convection, which forms a tropical heat/water recycling mechanism (Gao et al., 2006b). The simulation with a time-invariant solar zenith angle produces a colder and drier equilibrium state than does the simulation with a diurnally varied solar zenith angle since the former simulation produces less solar heating, more condensation, and consumes more moisture than the latter simulation does (Gao et al., 2007a). The simulation without ice radiative effects produces a colder and drier equilibrium state than the simulations with ice radiative effects regardless of ice microphysical effects (Ping et al., 2007).

The equilibrium simulations can be used to investigate the relative importance of SST and large-scale dynamics (forcing) on the energy budgets at the top of the atmosphere (TOA) and at the surface (Lau et al., 1994; Wu and Moncrieff, 1999). SST variation has large impacts on the water vapor feedback and small impacts on the cloud feedback, TOA radiation budget, and surface energy budget under a given large-scale state, while the variation of large-scale forcing has a large effect on the cloud feedback, TOA radiation budget, and surface energy budget and small effects on the water vapor feedback under a constant SST. Both the variations of SST and large-scale dynamics are positively correlated with surface precipitation.

The inclusion of the interactive radiation calculations leads to a significant modification of the large-scale circulation and causes a large impact on convection in both intensity and horizontal scale in quasi-equilibrium cloud-resolving simulations with a large domain size of 4000 km and a large-scale SST gradient (Grabowski et al., 2000). The simulation with a diurnally-varied SST generates a colder equilibrium state than does the simulation with a time-invariant SST because the former simulation produces a colder temperature through less latent heating and more IR cooling than the latter simulation does (Gao et al., 2007a). Ice microphysics affects radiative-convective-oceanic quasi-equilibrium states. A quasi-equilibrium state with a larger ice fall speed achieves a quasi-equilibrium state characterized by a colder and drier atmosphere, less cloudiness, stronger convection and precipitation, and warmer SST, whereas a quasi-equilibrium state with a smaller ice fall speed has a warmer and moister atmosphere, more cloudiness, weaker convection and precipitation, and colder SST (Wu, 2002).

11. Summary and remarks

The cloud-resolving modeling studies have been reviewed by Moncrieff and Tao (1999), Tao (2003), Tao and Moncrieff (2003), Tao (2007), and Sui et al. (2007a). This report mainly reviews the recent progress on the understanding of convection and clouds using the CRM simulations. The CRMs, developed from the traditional cloud-scale numerical model, include physical processes that are important for modeling cloud systems. The ensemble means of precipitation, cloud, and radiative properties simulated by the CRMs are in general agreement with available observations. The successful simulations allow diagnostic analyses of convective-related processes. The quantitative analysis of surface rainfall equation shows that the rainfall is largely affected by the cloud microphysical sources and sinks, and that the nocturnal peak of rainfall is caused by the falling temperature due to the IR cooling. The simulations of cloud and radiative properties are sensitive to the representation of ice microphysical and radiative processes such as the ice fall speed, single scattering albedo and asymmetry factor. The interaction between cloud-scale processes and the large-scale dynamics and vertical wind shear explains the movement of tropical super cloud cluster and embedded cloud clusters. Convective, moist, and dynamic vorticity vectors are highly correlated with convection and can be applied to analyze dynamic processes in the development of 2D and 3D CRM-simulated cloud systems. The analysis of coupled atmosphere-ocean CRM simulations reveals the strong impacts of small-scale coupling processes on the upper-ocean stratification. The CRM experiments demonstrate that the cloud-radiation interaction, ice microphysical processes, sea surface temperature, vertical shear of horizontal wind, dynamic processes, and surface processes all play roles in reaching certain convective-radiative equilibrium states.

Cloud-resolving models have reasonably simulated thermodynamic, cloud, and rainfall processes despite the uncertainties in the representation of cloud microphysical processes. As computational powers increase dramatically, 2D CRMs can be applied to replace the convection, and cloud schemes in GCMs, which allows the interaction between the CRM-simulated cloud systems and the large-scale dynamics. The approach is referred to as the Cloud Resolving Convection Parameterization (CRCP) (Grabowski and Smolarkiewicz, 1999; Grabowski, 2001) or the superparameterization (Khairoutdinov and Randall, 2001). The comparison between the CRCP and the cloud-resolving simulation in a 2D nonrotating atmosphere with the presence of SST gradients shows that large-scale thermodynamic states and circulations are reasonably simulated in the CRCP. These include precipitation patterns in the tropics and extra-tropical storm tracks, the Inter-Tropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), and the South Atlantic Convergence Zone. An annual cycle simulation produces a Madden-Julian Oscillation (MJO) with a slow propagation over the warm water over the Indian Ocean and western Pacific and a fast movement east of the date line (Randall et al., 2003). A 500-day integration using the NCAR Community Atmosphere Model (CAM) with the superparameterization simulates the mean states, including precipitation, precipitable water, radiative fluxes at the top-of-atmosphere (TOA), cloud radiative forcing, and fractional cover for high clouds in both winter and summer seasons. The simulation also produced more realistic intraseasonal variability (Khairoutdinov et al., 2005).

Satoh et al. (2005) and Tomita et al. (2005) took a further step to conduct a global cloud-resolving simulation using an icosahedral grid technique. The new model is referred to as Nonhydrostatic Icosahedral Atmospheric Model (NICAM), which includes a simple two-category cloud microphysics scheme (Grabowski et al., 1998), a radiation parameterization scheme (Nakajima et al., 2000), and the Meller-Yamada level-2 subgrid-scale turbulence closure and surface flux scheme (Louis et al., 1982). Satoh et al. started a 60-day integration with a horizontal resolution of 14 km, then integrated the model for another 30 days with a grid mesh of 7 km, and finally used the data on the twentieth day of 7-km run as the initial conditions to integrate another 10 days with a horizontal resolution of 3.5 km. The global CRM is able to simulate many interesting features including multi-scale cloud structures, ITCZ, MJO-like wave propagation, and diurnal rainfall variations.

While the CRCP (or superparameterization) and global CRM show encouraging results in the simulations of cloud systems, large-scale circulations and their interactions, the application of CRM simulations to improve the parameterizations of subgrid-scale convection, cloud and radiation in GCMs is and will be a practical and necessary step to improve the global climate simulations especially fully coupled atmosphere-ocean GCM simulations. Progress has been made on this end of CRM research. For example, CRM-simulated cloud-scale properties have shown great value to examine the uncertainties in the parameterizations of subgrid-scale processes (e.g., Wu and Moncrieff, 2001a,b; Wu and Liang, 2005a; Wu and Guimond, 2006; Wu et al., 2007a), and to improve the representation of convective momentum transports in the convection scheme and subgrid cloud distributions in the radiation calculation (e.g., Zhang and Wu, 2003; Liang and Wu, 2005). The improved parameterization schemes have demonstrated positive impacts on the global climate simulations in the GCMs (e.g., Wu et al., 2003; Wu and Liang, 2005b; Wu et al., 2007b; Song et al., 2007). Recently, a fully coupled GCM with the CRM-improved convection scheme successfully simulates both the intraseasonal MJO and the interannual El Niño-Southern Oscillation (ENSO), and reproduces the evolution of 1997/98 El Niño-type events (Wu et al., 2007c).

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