Chapter 2
Numerical Model Description

Abstract To deal with the cloud systems in the diverse scales, various numerical simulation tools are used in this study. Two distinct modeling frameworks, cloud-resolving model and general circulation model, are employed for different cases on the basis of their own features and limitations. The combination of those two frameworks is also explored and evaluated in this study.

2.1 Mesoscale Weather Research and Forecast (WRF) Model

The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed to serve both atmospheric research and operational forecasting needs. It has a fully compressible Euler non-hydrostatic dynamics core. Arakawa C-grid staggering is used for horizontal grid, and vertical grid stretching is permitted. The representation of the microphysical processes in WRF model is essential in determining the cloud structure and development. Two types of microphysical schemes are commonly adopted to describe the size dependence of particles in cloud-resolving models, i.e., the spectral bin microphysics and bulk microphysics.

2.1.1 Spectral Bin Cloud Microphysics

With the utilization of several tens of bins to describe the number and mass distributions of hydrometeors and aerosols, spectral bin microphysics explicitly represents the physical processes on the cloud-resolving scale. A fast version of bin microphysics scheme based on Khain et al. (2004) (hereafter referred to as SBM) has been incorporated into the WRF model (Lynn et al. 2005; Khain et al. 2009; Fan et al. 2012). The fast version of SBM retains the advantages of the full SBM in

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Khain et al. (2005) and produces cloud microphysical and dynamical structure as well as precipitation similar to the full SBM (Khain et al. 2009). SBM uses four size distribution spectra to represent hydrometeors and CCN in the model, including water drops (cloud and rain), low-density ice (ice and snow), high-density ice (graupel and hail), as well as CCN. Each spectrum is composed of 33 mass bins and the relationship between adjacent bins is determined by the function $m_k = 2^* m_{k-1}$.

In the SBM, supersaturation is explicitly predicted at each time step, and the critical radius of CCN ($r_{N\text{crit}}$) is calculated according to the Köhler theory using the value of supersaturation. At each time step, CCN with radius greater than $r_{N\text{crit}}$ is removed from the CCN spectrum and the mass of the activated droplets is added to the cloud spectrum. The size of the activated cloud droplet is calculated under the assumption of equilibrium over the activated droplets, if the radius of the original CCN particle (r_N) is less than 0.03 μm. For large CCN particles with radius greater than 0.03 μm, the mass of water condensation on the particle is parameterized as $m_w = K(4/3)\pi r_N^3 \rho_w$, where $K = 5$ is used in this study (Khain et al. 2000).

Since supersaturation is explicitly predicted in the SBM by solving the equation for supersaturations with respect to water and ice, the diffusion growth/evaporation rate of liquid drops is directly calculated based on the supersaturation in each grid cell. The associated numerical equations are taken from Pruppacher and Klett (1997) and fully discussed by Khain et al. (2005). To better resolve the condensation/evaporation processes in the SBM, sub-timestep iteration is employed and the condensation/evaporation rate is calculated over each sub-time step Δt_{diff}. In the SBM simulation, we set $\Delta t = 4^*\Delta t_{\text{diff.}}$ To avoid artificial broadening in the droplet spectrum as a result of diffusional growth and collisions, the remapping scheme are updated to conserve three moments of the hydrometeor size distributions (i.e., concentration, mass, and radar reflectivity), in contrast to the commonly used scheme of Kovetz and Olund (1969) that conserves only concentration and mass during the remapping (Khain et al. 2008). However, because of large computational resources demanded by the bin microphysics, the bulk microphysics represents a more practical choice for long-term simulations in regional and global climate models.

2.1.2 Bulk Cloud Microphysics—Morrison Scheme

By definition, the size distribution of the cloud hydrometeors in bulk microphysics is determined by the bulk properties of hydrometeors, such as number concentration and mass mixing ratio. The shape of each hydrometeor spectrum is prescribed by a certain type of distribution function, such as the Gamma or Marshall–Palmer function. Empirical parameterizations are needed in the bulk microphysics to resolve subgrid processes in relatively coarse resolution regional and global scale simulations.

A two-moment bulk microphysics with prognostic cloud number concentrations developed by Morrison and co-authors (Morrison et al. 2005, 2007; Solomon et al.

2009) is presently available for application under the framework of WRF (hereafter referred to as 'Bulk-OR'). There are two options in Bulk-OR to calculate the aerosol activation rate. One simple treatment is to parameterize the fraction of activated aerosols by the updraft velocity and assume the simple power-law CCN spectra using two empirical parameters (Fan et al. 2012). A more sophisticated treatment considers a wider range of governing parameters (Abdul-Razzak et al. 1998). In the latter parameterization, each mode of the aerosol spectrum is represented by a single lognormal size distribution. In Bulk-OR, all three parameters (the geometric mean radius, the total number concentration of aerosols, and the geometric standard deviation) associated with the lognormal size distribution are prescribed for each distribution function. There is no degree of freedom in the aerosol spectra, and the amount of aerosols that serve as CCN to form cloud droplets remains invariant in the simulation.

To overcome this deficiency, two prognostic variables of aerosols, i.e., the aerosol number concentration and mass mixing ratio, are introduced into the bulk scheme in the present work (hereafter referred to as Bulk-2M). During the activation process, activated aerosols to form cloud droplets are removed from the aerosol spectra and added to the cloud droplet spectra. The aerosol number and mass concentration are fixed at the lateral boundaries of the domain, to represent the external source of aerosols. By predicting both the number and mass concentration of aerosols, the total aerosol amount and the geometric mean radius of the aerosol spectra are time-dependent, because of removal of aerosols to form cloud droplets or addition of aerosols from the boundary sources. Advective and convective transports of aerosols are accomplished by the dynamical core of the model. The regeneration of aerosols due to evaporation of cloud droplets and raindrops is not included in the current scheme. The fraction of activated aerosols at each time step follows the parameterization developed by Abdul-Razzak et al. (1998).

In the Morrison scheme, the supersaturation is not calculated explicitly and a simplified liquid saturation adjustment strategy is utilized following the equation from Dudhia (1989). The default autoconversion scheme used in the Morrison scheme is a two-moment parameterization developed by Khairoutdinov and Kogan (2000) (hereafter referred to as KK2000). The cloudy grid cells are maintained at 100 % relative humidity. If the air is sub-saturated, cloud/rain water is evaporated continuously until saturation is reached within a time step, or if the air is supersaturated, vapor condensation removes the supersaturation within that time step. The autoconversion rate is derived by fitting the results of large eddy simulations of marine boundary layer clouds that used explicit bin microphysics with analytical functions.

2.1.3 Bulk Cloud Microphysics in the CR-WRF

Li et al. (2008, 2009) has implemented a two-moment bulk microphysical scheme with a three-moment aerosol approach into the WRF model (hereafter referred as

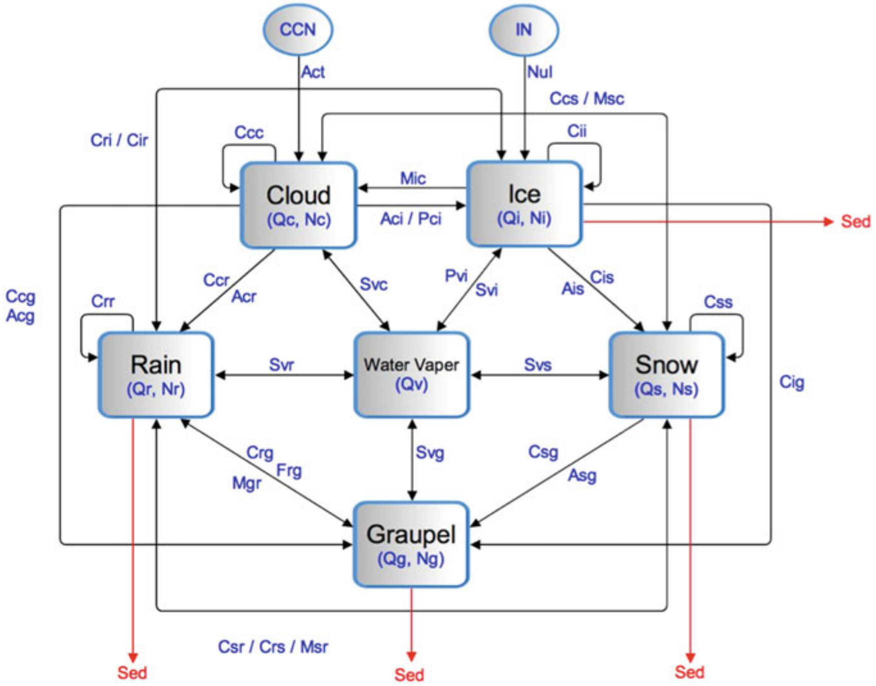

Fig. 2.1 Overview of the two-moment bulk microphysical scheme (TAMU scheme) implemented in the WRF model

CR-WRF). A description of the bulk microphysical processes in CR-WRF pertinent to this present work is summarized in the Fig. 2.1. Briefly, the number concentration and mass mixing ratio of five hydrometeors, including cloud, rain, ice, snow, and graupel, are explicitly predicted in the scheme with the assumption of gamma size distribution. Thirty-four microphysical processes are considered in the scheme, including seven autoconversion parameterization options for the warm rain processes and three types of heterogeneous ice nucleation. In contrast to treating the number concentration of cloud droplets or cloud condensation nuclei (CCN) to be constant in many other two-moment bulk microphysical schemes, three new prognostic variables, i.e., number concentration, surface area, and mass mixing ratio of aerosols, are implemented in this scheme. The process of aerosol activation into cloud droplet is modeled using the classic Köhler theory and the cloud number concentration is directly predicted from aerosol concentration and ambient relative humidity. Under the assumption of a log-normal size distribution of aerosols, the model approach with 48 bins is used to depict the aerosol spectrum in the scheme. The performances of this microphysical scheme under different conditions have been evaluated and an inter-comparison with other available microphysical schemes in the WRF V2.2.1 has been reported previously (Li et al. 2008, 2009).

One important feature of the microphysics in CR-WRF is to employ the new Kessler-type autoconversion scheme derived by Liu and Daum (2004) and Liu et al. (2004), which suggests a strong dependence of the autoconversion rate on the relative dispersion of the cloud droplet size distribution in addition to liquid water content and droplet concentration. Therefore, by incorporating the relative dispersion of the cloud droplet size distribution in this scheme, the coarse assumption inherent in the traditional Kessler-type parameterizations, such as a fixed collision kernel, can be eliminated.

2.2 Global Climate Model

Mesoscale cloud-resolving models with explicit cloud microphysics and aerosol representation are able to perform physically realistic simulations but unable to provide feedbacks to the large-scale circulation. Global climate models (GCM) are commonly used to investigate the responses of large-scale systems from different atmospheric forcings. The Community Earth System Model (CESM) developed by the National Center of Atmospheric Research (NCAR) is a coupled climate model with five separate models simultaneously simulating the Earth's atmosphere, ocean, land, land-ice, and sea-ice, plus one central coupler component. In this study, we mainly use the atmosphere component of CESM Version 1.0, i.e., the Community Atmosphere Model (CAM5) Version 5. This new version of the CAM 5.0 incorporates a number of enhancements to the physics package.

However, the representation of the microphysical processes of convective clouds in GCM is rather unrealistic. Since the vertical velocity and latent heating within deep convective cloud (DCC) systems are crudely diagnosed in the traditional convective parameterizations, the pathways of aerosols to interact with DCC and convective precipitation are excluded in the physics and dynamics of GCMs. Therefore, GCMs can only investigate the aerosol-indirect effects for stratiform/cirrus clouds, but are unsuitable for convective clouds associated with monsoon systems and storm track. There are possible solutions to tackle this dilemma. In this study, we introduce a hierarchical modeling approach with the combination of the models with different scales, i.e., to upscale aerosol forcings calculated from the cloud-resolving model results to the global simulations. A detailed discussion of this method will be presented in Chap. 5.

2.3 Multiscale Aerosol-Climate Modeling Framework

To overcome the deficiencies inherent in the traditional GCMs, the multiscale modeling framework (MMF) was introduced by Khairoutdinov and Randall (2001), which embeds a two-dimensional version of the cloud-resolving System for Atmospheric Modeling (SAM) at each grid column of a host NCAR CAM to resolve the subgrid variability in cloud dynamics and cloud microphysics and replace conventional parameterizations for moist convection and large-scale condensation. As an extension of the MMF, an updated aerosol-climate model (PNNL-MMF) was developed through upgrading the host GCM to CAM version 5, using an explicit-cloud parameterized-pollutant (ECPP) approach to link the cloud processing of aerosols on the large-scale grid with the cloud/precipitation statistics in the cloud-resolving model, and incorporating a two-moment microphysical scheme to replace the one-moment microphysics which was unable to simulate the interaction between aerosol particles and hydrometeors. More descriptions and evaluations of PNNL-MMF can be found in Wang et al. (2011a, b).

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