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Effects of precipitation physics algorithms on a simulated climate in a general circulation model

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ABSTRACT

The purpose of this study is to investigate the effects of precipitation physics in a general circulation model (GCM) on a simulated climate. Experiments are performed under the single column model (SCM) framework to examine basic features and under the general circulation model framework to investigate the impact on seasonal simulation. The SCM simulation shows that convection processes in the model have a considerable influence on the change in vertical thermodynamic structure, resulting in a change in precipitation, whereas in the GCM framework stratiform precipitation physics play a distinct role in changing the atmospheric structure. The GCM experiments also show that the overall reduction of precipitation in simulations with prognostic stratiform precipitation physics is highly related to changes in cloudiness and corresponding changes in radiative flux, which in turn leads to the reduction of convective activities.

1. Introduction

Clouds are important elements affecting the climate system. In particular, accurate parameterization of clouds and their radiative properties is essential in order to produce realistic illustrations of the current climate and credible predictions of possible future climates. However, the interactions between clouds and radiation, and between clouds and hydrological processes are inadequately understood (Arakawa, 2004). Previous studies have revealed that the difference in the models' depictions of cloud–radiation feedback processes can lead to unrealistic patterns of surface heating and cooling that could alter large-scale atmospheric circulation (e.g., Cess et al., 1990; Weare et al., 1995).

Many efforts have been made to improve the cloud–radiation interaction in general circulation models (GCMs); these including improving the cloudiness parameterization itself, and producing a better representation of cloud microphysical processes related to the cloud-radiative properties in a GCM. For cloudiness parameterization, the diagnostic method in which cloudiness is a function of relative humidity (e.g., Slingo, 1987), or of both relative humidity and cloud water (e.g., Xu and Randall, 1996), has been widely used in weather prediction and climate models, even though a prognostic cloudiness scheme (e.g., Tiedtke, 1993) is available. Recently, another complex approach using a probabilistic distribution function (PDF) to represent the sub-grid scale variability of conserved variables (e.g., Bony and Emanuel, 2001; Tompkins, 2002) has been designed. As for cloud microphysical processes and their cloud-radiative properties, increased computer power enables us to represent sophisticated grid-resolvable precipitation physics developed within cloud resolving models (CRMs) in GCMs. In the GCM community, the implementation of sophisticated microphysical processes for stratiform precipitation physics[1] is primarily used to create a realistic representation of cloud–radiation feedback (e.g., Fowler et al., 1996; Ghan et al., 1997). In particular, Fowler and Randall (1996) showed that a prognostic equation for the mass of condensates associated with stratiform cloudiness introduces direct coupling between the atmospheric moisture budget and the radiation budget through the amount of interactive clouds and cloud optical properties.

The purpose of this study is to examine the sensitivity of a simulated climate, in terms of cloud–radiation interaction, to different precipitation physics packages implemented in the National Center for Environmental Prediction (NCEP) global spectral model (GSM) (Kanamitsu et al., 2002a). Four experiments are designed with two cloud microphysical processes under two different convective parameterization schemes. To represent stratiform precipitation physics, the Weather Research and Forecasting (WRF) Single-Moment 1-class (WSM1) (Hong et al., 1998)

[1] In this study, the term stratiform precipitation denotes grid-resolvable precipitation obtained by cloud microphysical processes, whereas convective precipitation denotes the parameterized sub-grid scale processes from a cumulus parameterization scheme.

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and 3-class (WSM3) (Hong et al., 2004) microphysics schemes are utilized. Furthermore, the Simplified Arakawa–Schubert (SAS) scheme (Pan and Wu, 1995; Hong and Pan, 1998) and National Center for Atmospheric Research (NCAR) Community Climate Model (CCM) scheme (Zhang and MacFarlane, 1995) are used for convective precipitation processes. These four experiments are performed under the single column model (SCM) framework for a preliminary investigation into the impacts of different precipitation physics on cloud–radiation interaction. Moreover, the GCM framework is used for further investigation into sensitivities of precipitation processes to climate simulation. We acknowledge that there have been numerous studies on the sensitivity of the simulated climate to precipitation physics, as described above; however, we expect that a detailed evaluation of the simulated climate from a cloud–radiation feedback point of view will shed light on the physical mechanisms underlying the sensitivity of the simulated climate to different physics packages. The relative importance of convective and stratiform precipitation physics on radiative properties will also be investigated. In addition, the effect of stratiform precipitation physics on the simulation of large-scale features will be examined.

This paper is organized as follows. The SCM experiments are discussed in Section 2 to investigate the preliminary characteristics of clouds and radiation due to precipitation physics. The results within the GCM framework are explained in Section 3. A conclusion is presented in Section 4.

2. Experimental design

2.1. Models

The three-dimensional model used in this study is based on the NCEP MRF model (Kanamitsu et al., 2002a). The model utilized in the seasonal simulation employs a resolution of T62L28 (triangular truncation at wave number 62 in the horizontal and 28 terrain-following sigma layers in the vertical). Model physics include longwave and shortwave radiation, cloud–radiation interaction, planetary boundary-layer processes, shallow convection, gravity-wave drag, enhanced topography, simple hydrology, and vertical and horizontal diffusions. The physics package resembles a version similar to versions from 2000, but the vertical diffusion package of Hong et al. (2006) is utilized. For precipitation physics, both stratiform precipitation processes and the cumulus parameterization scheme are employed in this model. Parameterization of precipitation physics used for the experiments is explained briefly in Appendix A.

This study also uses an SCM framework. The SCM is widely used as a tool for the development and diagnosis of the physical processes of climate models because of its economical advantages, although it lacks a more complete dynamical feedback mechanism (Randall et al., 1996). The SCM utilized in this study was developed by Byun and Hong (2007), and its physics package is similar to those of the three-dimensional model for climate simulation.

2.2. Experiments

Four experiments are designed within each framework of the SCM and the GCM, which are summarized in Table 1. The parameterization of moist convection is generally considered one of the most important tasks, though it entails great uncertainty in representing the unresolved scales of motion, particularly in GCMs with coarse resolution. Therefore, two different cumulus parameterization schemes (i.e., SAS and CCM schemes) are compared to investigate the sensitivity of the convective precipitation algorithms to cloud–radiation interaction. Furthermore, the influence of stratiform precipitation physics on clouds and radiation is examined by comparing the results from diagnostic and prognostic cloud schemes (i.e., WSM1 and WSM3), together with corresponding representations of stratiform cloudiness. A description of cloudiness parameterization is presented in Appendix B.

In order to provide observational forcing to the SCM experiments, we use intensive flux array (IFA) data in the western equatorial Pacific as part of the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) (Ciesielski et al., 2003). The integration period of SCM experiments is selected from 0000 UTC 20 to 0000 UTC 26 December 1992. Several convective episodes occurred during this 6-day period with varying degrees of rainfall intensity. During this period, the convection was not as well organized as the strong squall line; however, the systems had substantial mesoscale components. The SCM outputs were obtained at 6 h intervals.

The initial atmospheric data for climate simulations are obtained from NCEP/Department of Energy (DOE) Reanalysis II (R2) data (Kanamitsu et al., 2002b). As a surface boundary condition, observed sea surface temperature (SST) data are used with a resolution of 1 degree (Reynolds and Smith, 1994). The 5-member ensemble runs in each experiment are performed with initial data at 24 h intervals starting from 0000 UTC 1 May 1996 for boreal summer (June–July–August). For the evaluations, the observed precipitation and the observed large-scale fields are obtained from the Climate Prediction Center (CPC) Merged Analysis Monthly Precipitation (CMAP) data (Xie and Arkin, 1997) and the NCEP/DOE R2 data, respectively. The International Satellite Cloud Climatology Project (ISCCP) D2 data and special subset of the ISCCP C1 flux data are used to compare cloud-related properties (Rossow and Schiffer, 1999; Iacobellis and Somerville, 2000). The ISCCP D2 data are used for evaluation of the fractional cloud amount simulated by the GCM, while the special subset of the ISCCP C1 flux is compared to the SCM results. The C1 flux data with a resolution of 2.5° horizontally over the western pacific area

Table 1
Summary of experiments designed in the SCM and GCM frameworks.

Expt	Convective precipitation	Large-scale precipitation	Prognostic water substance	Convective cloudiness	Stratiform cloudiness
SAS1	SAS scheme (Hong and Pan, 1998)	Diagnostic cloud (Hong et al., 1998)	qv	Diagnosed from precipitation rate	Diagnosed from RH (Slingo, 1987)
CCM1	CCM scheme (Zhang and MacFarlane, 1995)	Same as SAS1	qv	Same as SAS1	Same as SAS1
SAS3	Same as SAS1	Prognostic cloud (Hong et al., 2004)	qv qc/qi qr/qs	Same as SAS1	Diagnosed from RH and qc/qi (Xu and Randall, 1996)
CCM3	Same as CCM1	Same as SAS3	qv qc/qi qr/qs	Same as SAS1	Same as SAS3