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Tests and improvements of GCM cloud parameterizations using the CCCMA SCM with the SHEBA data set

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Abstract

A GCM cloud microphysics parameterization is tested and improved using the CCCMA single-column model with cloud properties obtained at the Surface Heat Budget of the Arctic Ocean experiment (SHEBA) during the period of November 1997 to September 1998. The ECMWF reanalysis water vapor profile is scaled with rawinsonde data so that the new relative humidity profiles are compatible with rawinsonde data for nudging purposes. This study demonstrates that the treatment of ice nucleation number concentration is the controlling factor of the overestimation of monthly mean ice water path originally produced by this model. The parameterizations of accretion processes are modified to consider the accumulation due to an increase of precipitation flux through a model layer related to accretion processes. The horizontal inhomogeneity effect of cloud liquid water is considered in parameterization of autoconversion process. A new method developed for mixed-phase clouds to determine the water vapor saturation and partitioning of the condensed water into different phases is also tested in this model.

When using a nudging technique with the adjusted ECMWF water vapor profile the model can well simulate the monthly total cloud cover and daily precipitation rate for the SHEBA period. Using the modified cloud microphysics parameterizations including improved treatments for accretion processes, ice nucleation number concentration, and auto-conversion, the monthly mean cloud liquid water path and ice water path are suitably simulated and compare reasonably well to those derived from measurements.

Keywords: Cloud; Microphysics; Parameterization; GCM; Single-column model; SHEBA

1. Introduction

Clouds cover about 60% of the Earth's surface and play an important role in regulating the Earth's radiation budget. In current climate modeling, the lack of understanding of cloud is still a major uncertainty (Houghton et al., 1996). Inter-comparison studies of general circulation model (GCM) simulations (e.g., Randall et al., 1998) indicate that different models simulating polar processes show large discrepancies in the Arctic. Curry and Ebert (1992) and Zhang et al. (1996) have demonstrated the importance of specific cloud macro- and micro-physical properties, including cloud amount, cloud base height, cloud phase, particle size and shape, and cloud ice/water contents, on cloud-radiation and ice-albedo feedback mechanisms. The cloud-radiation feedback (CRF) in the Arctic significantly influences the way heat passes through the Arctic system. Because of the complexity and importance of

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polar cloud radiative effects, it is necessary to gain an insight into them through a combination of modeling and observational studies.

The difficulties associated with simulating cloud radiative effects in GCM studies exist because of the currently inadequate understanding of cloud processes including the related dynamic, thermodynamic and microphysics processes. The microphysics processes are particularly important because the factors determining cloud optical properties are directly related to these processes. It is crucial to improve parameterizations of microphysics processes in GCMs to ensure reasonable atmospheric optical parameters for the simulation of radiative energy budget.

Due to the complexity of GCMs, it is difficult to isolate specific processes and study them in GCM simulations. The single-column model (SCM) has been promoted as a useful testbed for cloud parameterizations (Randall et al., 1996), but providing suitable boundary conditions to SCM is extremely challenging (Zhang and Lin, 1997; Mace and Ackerman, 1996; Randall et al., 1996).

The Surface Heat Budget of the Arctic Ocean (SHEBA) project is motivated by the large discrepancies among simulations by global climate models of the present and future climate in the Arctic and by uncertainty about the impact of the Arctic on climate change (Moritz et al., 1996). The period of the SHEBA experiments is from 1997 to 1999 at the North Pole SHEBA ice station, which include rawinsonde, lidar, radar, meteorological surface and a microwave radiometer observations, etc. Accompanied by ECMWF provided hourly column output of the water vapor and temperature forcing data, this integrated observation data set is well suited for testing GCM cloud parameterizations through SCM simulations in the Arctic region.

In this study, we applied a recent version of the Canadian Centre for Climate Modeling and Analysis (CCCMA) single-column model (CSCM) (Lohmann et al., 1999) to the SHEBA year to test and improve GCM cloud parameterization in the Arctic region. The CSCM annual cycle simulation is carried out using the ECMWF forcing (Beesley et al., 2000) with a nudging technique. We describe this model and the data used along with nudging techniques in Section 2. In Section 3, we present the problem in nudging using ECMWF reanalysis water vapor profile and discuss our modification of the data to alleviate this problem. The test and improvement of cloud microphysics parameterization using SHEBA data are shown in Section 4. We discuss the effect of a new partitioning method for water vapor in mixed-phase clouds, as derived from in-situ measurements in Section 5. The conclusions are given in Section 6.

2. Descriptions of model and data and nudging technique

2.1. Model description

The CCCMA single-column model (CSCM) used in this study is adapted from the second-generation CCCMA GCM (McFarlane et al., 1993). It predicts horizontal wind components, temperature, water vapor and total condensed water. The turbulence scheme contains a prognostic equation for the turbulent kinetic energy (TKE) (Abdella and McFarlane, 1997). Other second-order quantities are determined diagnostically through a parameterization of the third-order moments based on a convective mass-flux argument. Cumulus clouds are represented by a bulk model including the effects of entrainment and detrainment on the updraft and downdraft convective mass fluxes (Zhang and McFarlane, 1995). The radiation code is based on two-stream solutions of the radiative transfer equation with six spectral intervals in the infrared spectrum (Morcrette, 1989) and two in the solar spectrum (Fouquart and Bonnel, 1980). Gaseous absorption due to water vapor, CO_2, O_3, CH_4, N_2O, and CFCs is included.

Two kinds of cloud schemes are available as options in the CSCM. One is an explicit cloud scheme; the other is a statistical cloud scheme. The explicit cloud scheme is used in this study, which is described in detail by Lohmann and Roeckner (1996). It has prognostic variables for liquid water content (q_l) and ice water content (q_i) and uses an explicit approach for condensation and cloud cover based on Sundqvist (1978). In explicit cloud scheme, cloud fraction (A) is a diagnostic function of relative humidity (Sundqvist et al., 1989).

$$A = 1-\sqrt{1-A_0} \tag{1}$$

$$A_0 = (\mathrm{Rh}-\mathrm{Rh}_0)/(1-\mathrm{Rh}_0) \tag{2}$$

$$\mathrm{Rh}_0 = \mathrm{Rh}_{top} + \left(\mathrm{Rh}_{sfc}-\mathrm{Rh}_{top}\right)\exp\left[1-\left(\frac{p_{sfc}}{p}\right)^4\right] \tag{3}$$

where p_{sfc} and p are the air pressure at surface and in atmosphere, respectively. Rh is the grid-mean relative humidity; Rh_0 is a threshold specified as a function of height based on the work of Xu and Krueger (1991). It decreases from 0.95 near the surface to 0.6 at top of the atmosphere.