Development of a Hybrid Cloud Parameterization for General Circulation Models

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Introduction

We have developed a cloud package with state-of-the-art physical schemes that can parameterize low-level stratus or stratocumulus, penetrative cumulus, and high-level cirrus. Such parameterizations will improve cloud simulations in general circulation models (GCMs). The principal tool in this development comprises the physically based Arakawa-Schubert scheme for convective clouds (Arakawa and Schubert 1974) and the Sundqvist scheme (Sundqvist 1988) for layered, nonconvective clouds. The term "hybrid" stems from Molinari and Dudek (1992) and addresses the fact that the generation of high-altitude layered clouds can be associated with preexisting convective clouds. Overall, the cloud parameterization package developed here should better determine cloud heating and drying effects in the thermodynamic budget, realistic precipitation patterns, cloud coverage and liquid/ice water content for radiation purposes, and the cloud-induced transport and turbulent diffusion for atmospheric trace gases.

Schemes

The Arakawa-Schubert scheme employs a one-dimensional steady-state entraining cloud model with basic microphysics to represent the clouds. A spectrum of sub-ensembles of clouds is allowed to form simultaneously and modify the environment through compensating downward motion, detrainment, and evaporation of cloud water. Cloud-cloud interaction is considered in a way that the development of one sub-ensemble cloud can affect the growth of other sub-ensembles through its stabilizing effect on the large-scale environment. The exchange processes between the planetary boundary layer and the free atmosphere are also included. The Arakawa-Schubert scheme uses a quasi-equilibrium approximation to close the parameterization, which requires that clouds stabilize the atmosphere as the large-scale motion generates moist convective instability.

The Sundqvist scheme has been considered to be the most efficient and yet physically based parameterization of layered clouds (Cotton and Anthes 1989). This scheme prognostically calculates the liquid water content and diagnostically determines the cloud coverage. We have recently developed an extension of the Sundqvist scheme (Kristjánsson and Kao 1993) to include the ice phase. Since the layered clouds are closely tied to the turbulent diffusion process, the Sundqvist scheme is being improved in this aspect. The detrainment of convective cloud water determined by the Arakawa-Schubert scheme is connected to the large-scale liquid water content prognostically calculated by the Sundqvist scheme to ensure that the anvil clouds can be simulated.

Results

The effects of introducing the hybrid cloud parameterization in the Los Alamos GCM (Kao et al. 1992) are investigated. Since the Sundqvist scheme can be applied to any convection scheme, the results based upon the combination of the Sundqvist and the Arakawa-Schubert schemes (SUN+AS) will be compared with those derived from two other combinations; namely, the Sundqvist plus the Kuo schemes (SUN+KUO) (Kuo 1974) and the Sundqvist plus the moist adiabatic adjustment schemes (SUN+MAA) (Manabe et al. 1965). In all three schemes, the stratiform condensation will be treated as described in Sundqvist (1988); that is, stratiform condensation takes place as long as the relative humidity is above 85%. For humidities between 85% and 100%, an assumption is made on the partitioning of moisture between the cloudy and cloud-free parts of a grid box.

Three 1-year-cycle simulations using seasonally varying boundary conditions for the three cases described above have been conducted. Selected results for January averages are discussed as follows.

Figure 1 shows the zonally averaged values of vertically integrated cloud water content in units of kg m^{-2}. The value of 0.08 in the ordinate is from Njoku and Swanson (1983), representing the averaged value of ocean areas between 60°N and 60°S based upon SMMR-microwave analysis. In SUN+AS, the maxima are associated with the storm tracks in both hemispheres. Its global average is in good agreement with the observed value. SUN+KUO apparently underestimates the ocean average without distinct meridional variations. The values in SUN+MAA are two to three times larger than the other two cases because of extensive low clouds the MAA scheme produces.

Figure 2 shows the zonal averages of cloud coverage along with the observation from the International Satellite Cloud Climatology Project (ISCCP). All three cases over-estimate the observations in high latitudes, probably because of the discrepancies in defining clouds between satellite measurements and model calculations. Over the tropics, SUN+AS has the best agreement, while SUN+MAA and SUN+KUO over- and underestimate the ISCCP data, respectively. SUN+KUO simulates the meridional variations between 50°N and 50°S. SUN+AS overestimates the cloudiness over subtropical regions.

For other atmospheric fields, both SUN+AS and SUN+KUO significantly reduce the model cold bias in the mid and upper tropical troposphere and the cold bias in the winter hemisphere. In all three cases, the maximum westerlies in the northern hemisphere (NH) troposphere are shifted

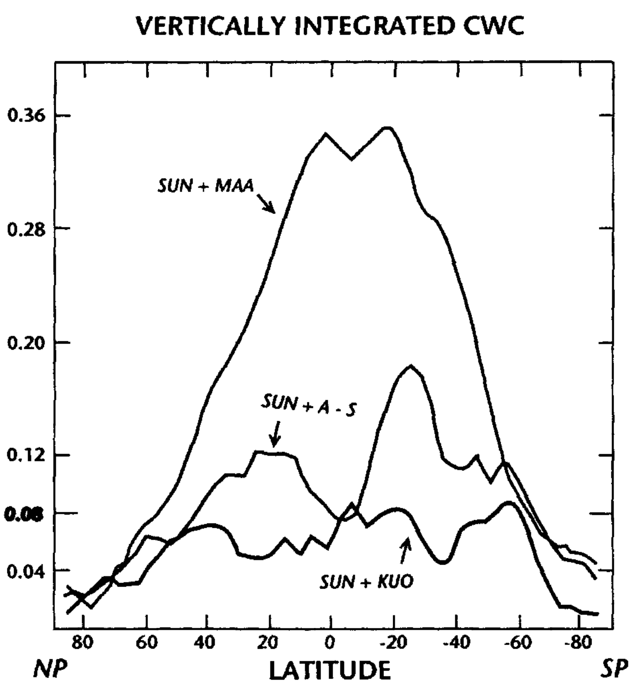

Figure 1. Zonal averaged values of vertically, integrated cloud water content simulated by the three cases.

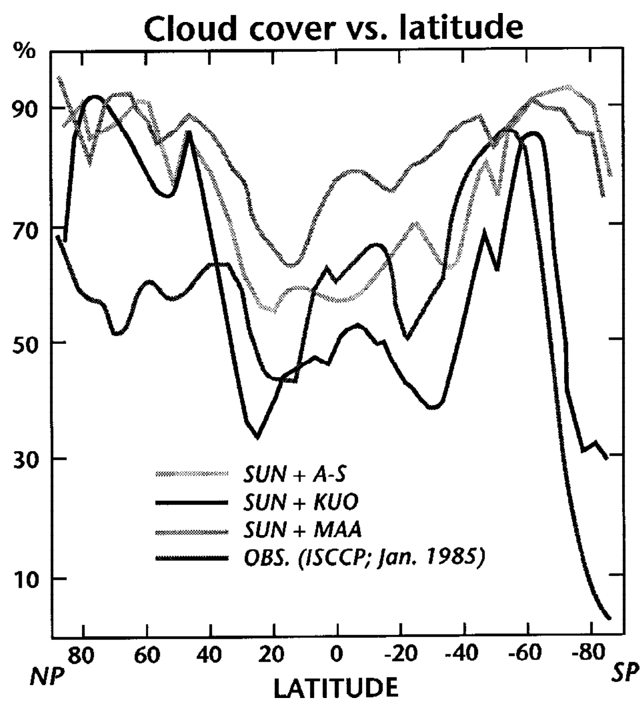

Figure 2. Same as Figure 1, except for cloud cover.

poleward compared with observations, and the easterlies near the tropical tropopause are too strong. The westerly jets simulated by SUN+AS are close to the observed. All three cases tend to overestimate the observed precipitation, but provide a fair simulation of the precipitation pattern.

Concluding Remarks

A physically based cloud parameterization for both convective and nonconvective cloud properties has been incorporated in the Los Alamos GCM. The cloud package is based upon the Sundqvist scheme that prognostically determines cloud water for layered clouds and the Arakawa-Schubert scheme to parameterize cumulus convection. Investigated by comparing with other two combinations (SUN+KUO and SUN+MAA) SUN+AS proved to be superior.

To test the effects of SUN+AS fully, version 2 of the Community Climate Model (CCM2), newly released by the National Center for Atmospheric Research, will be used, especially for a better understanding of cloud/radiation interaction.

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