Diagnostic Analysis of Cloud Radiative Properties

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Introduction

A current dilemma of climate modeling is that general circulation model (GCM) results are extremely sensitive to parameterizations of certain poorly understood physical processes, most notably cloud-radiation interactions. As a result, models with different plausible parameterizations give very different results. Yet, we have no firm basis for knowing which parameterization is more nearly "correct."

It is true that parameterizations are not the only shortcoming of GCMs. Our current ability to create models that will adequately simulate today's climate and predict its evolution is limited by several factors, not just by one. Some of these factors are technical, such as a lack of computer power. Nevertheless, the most critical need is for an improved physical understanding of the key physical processes. Until these processes are much better understood and until this understanding is incorporated in our models, the model results will always be subject to major uncertainties. Reducing these uncertainties so that we can have confidence in the reliability and accuracy of climate forecasts requires focused research on climate processes.

Of the many physical processes involved in climate simulations, feedback from cloud-radiation interactions is currently thought to be the largest single source of uncertainty. For this reason, the Committee on Earth and Environmental Sciences continues to rank the role of clouds as the highest science priority for the U.S. Global Change Research Program. As an example of the importance of cloud-radiation feedbacks, it is noteworthy that the sensitivity of model-simulated climates to changes in atmospheric carbon dioxide concentration has undergone major fluctuations in recent years. The equilibrium global average surface temperature change in response to a carbon dioxide doubling, based on GCM results from models developed in the mid-1970s, was typically between 2°C and 3°C. By the middle to late 1980s, the range of typical GCM sensitivities was between 4°C and 5°C. Nearly all of the increase in sensitivity could be traced to cloud-radiation interactions. More recently, several GCMs incorporating more complex cloud algorithms, including the negative feedbacks thought to be inherent in some cloud microphysical processes, have shown reduced sensitivity to changing greenhouse gas concentrations (IPCC 1992; Senior and Mitchell 1993).

The Atmospheric Radiation Measurement Program and Single-Column Models

The Atmospheric Radiation Measurement (ARM) Program is an imaginative effort to accelerate the improvement of GCM parameterizations. Its major thrust is to provide much of the badly needed empirical foundation for such parameterizations. ARM emphasizes clouds and the interaction between clouds and radiation. Although this area is the highest in scientific priority, it is among the least well founded observationally.

The observations being made during ARM will provide invaluable information for the development of improved parameterizations. These data will include simultaneous measurements of cloud properties and radiation budget components. Such measurements will permit GCM parameterizations to be validated using actual physical conditions rather than hypothetical ones.

Our project is centered around a computationally efficient and economical one-dimensional (vertical) model, resembling a single column of a GCM grid, applied to the ARM experimental configuration. The model contains a full set of modern GCM parameterizations of subgrid physical processes.

The fundamental equations for the single-column model (SCM) are the thermodynamic energy equation and the conservation equation for water vapor (Iacobellis and Somerville 1991a, 1991b). These equations include terms representing the transport of heat and moisture due to horizontal and vertical advection. Because it is one-dimensional, the model does not produce velocity fields. Instead, for this study, the advective components of the heat and moisture budget are evaluated using four-dimensional analyses of observational data, such as those produced operationally for numerical weather prediction purposes.

Model Description

The model closely resembles a single column in a contemporary GCM. The atmosphere within the column is divided into layers, and the fluxes of heat and moisture are determined for each of these layers. Like a GCM, the model includes parameterizations of solar and terrestrial radiation, shallow convection, deep cumulus convection, diffusion, distribution of surface fluxes, and cloud prediction. This atmospheric component of the model is coupled to either a simple land surface treatment (for the Southern Great Plains Cloud and Radiation Testbed [CART] site) or an interactive ocean mixed layer model (for the future Western Tropical Pacific site). Unlike a GCM, the coupled model is not global; instead, it is applied at a specific location.

The model is integrated in time after being initialized with temperature and humidity profiles determined from observational data. This initialization procedure is invoked only at the beginning of the first time step. At every time step, including the first, input to the model consists of horizontal advection of heat and moisture which are specified observationally from operational numerical weather prediction analyses. Theses analyses, based on four-dimensional data assimilation techniques, provide dynamically consistent wind fields and horizontal gradients of temperature and moisture.

The principal output of the coupled model is time-dependent vertical profiles of temperature and humidity. Additionally, the evolution of many diagnostic variables is produced. These variables include convective rainfall, surface fluxes of latent and sensible heat, net incoming solar radiation, and cloud amount and height. It is important to realize that this is a diagnostic model rather than a prognostic model. Its primary purpose is to simulate the various processes and interactions which occur within the model domain, so as to evaluate and improve the parameterizations within the model.

Cloud Parameterization Experiments

We have performed numerical experiments designed to better understand the sensitivity of model results to choices in “tuneable” or “adjustable” parameters. Thus far, our work has concentrated on determining the sensitivity of radiatively important quantities such as cloud amount and net surface shortwave radiation to choices of parameters in cloud parameterizations.

The SCM incorporates a treatment of cloud optical properties adopted by the second-generation GCM of the Canadian Climate Centre (McFarlane et al. 1992), in which optical properties are based on cloud liquid water contents (cf. Stephens 1978). Our cloud liquid water prediction algorithms at present are adaptations of those of Sundqvist et al. (1989) and Smith (1990). Alternatively, the model can incorporate the cloud prediction parameterization of Slingo (1987), which does not include cloud liquid water as a prognostic variable. In this case, cloud optical properties are parameterized on temperature and pressure following Betts and Harshvardhan (1987), Platt and Harshvardhan (1988), and Somerville and Remer (1984).

The model integrations in this study used the solar radiation parameterization of Fouquart and Bonnel (1980) and the longwave parameterization of Morcrette (1990). As ARM observations become more complete, we plan to use the SCM to test cloud-radiation parameterizations based on the stochastic radiative transfer approach of Malvagi et al. (1993).

The European Centre for Medium-Range Weather Forecasts’ Operational Analysis (2.5° x 2.5° and 16 vertical levels) has been used to supply the horizontal convergences of heat, moisture, and momentum needed by the SCM at a location as close as possible to the SGP site. We have selected 16 test cases to use in an initial examination of the model cloud parameterizations. These test cases, within the period from January 1, 1992, to June 30, 1993, vary in range from 5 to 13 days and were selected based (loosely) on the criteria of an increase and subsequent decrease in the relative humidity on timescales of about 3-6 days.

Experiment Procedure

The SCM is run for each of the 16 test cases using control values of the adjustable parameters. The model is then rerun for each of the 16 test cases altering only one of the adjustable parameters. This results in 16 x N_p sensitivity runs, where N_p is the number of adjustable parameters. For each adjustable parameter, we calculate a sensitivity parameter $f_{10\%,X}$ averaged over the 16 test cases, where $f_{10\%,X}$ is the expected change in quantity X for a 10% change in the adjustable parameter. This procedure is repeated for each of the three cloud parameterizations. Results are discussed below for daily averaged cloud amount (X=CLD) and daily averaged net surface shortwave radiation (X=NSW).

Results

The results of the sensitivity experiments, together with a brief description of each of the adjustable parameters, are shown in Table 1. These results indicate that, of the parameters tested, the average daily cloud amount and net surface shortwave are most sensitive to changes in the parameters U_{oo} and c_o from the Sundqvist scheme; C_T and V_F from the Smith routine; and $RH_{H,crit}$, $RH_{M,crit}$ and $RH_{L,crit}$ from the Slingo parameterization.

The parameters c_o (Sundqvist et al.) and C_T (Smith) both represent the time scale at which cloud droplets are converted to precipitation (m_r and C_W are also closely related). However, differences in the two cloud liquid water parameterizations make direct comparisons difficult. For instance, the Sundqvist parameterization uses c_o for both liquid and frozen precipitation, while the Smith routine uses C_T only for liquid precipitation and employs a separate relation for the formation of frozen precipitation.

These model results indicate that average daily cloud amount is not sensitive to changes in RH_c (Smith scheme) while there appears to be significant sensitivity of the NSW to changes in RH_c. At first, this may appear to be a contradiction. However, further analysis indicates that changes in RH_c, while not having an effect on the average daily cloud amount (cloud cover), do affect the vertical distribution and/or total vertical cloud thickness that, in turn, affects the net shortwave radiation at the surface.

These sensitivity studies have relied on only 16 test cases with no separation of convective and nonconvective events. Additionally, the resulting sensitivities are difficult to interpret until the uncertainties in the adjustable parameters can be determined. As a consequence, the results presented here are very preliminary. However, we feel that the techniques described here can lead to an improved understanding of current model parameterizations and assist in the development of new parameterizations.

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Table 1. The adjustable parameters studied in the sensitivity experiments. Shown is a brief description of the parameter, the control value and the model calculated sensitivities. As an example of how to interpret the sensitivity results, a 10% increase in $RH_{H,crit}$ results in a decrease in the average daily cloud amount of 0.062 (i.e., from 58.2% cloudy to 52% cloudy) and an increase in the net surface shortwave of 4.30 W m^{-2}.

Adjustable Parameters of Sundqvist et al. (1989)

Parameter	Description	Control Value	f10%,CLD	f10%,NSW
c_o	characteristic time for conversion of cloud droplets into raindrops (sec^{-1})	$1.0x10^{-4}$	-0.014	+2.61
m_r	threshold value for cloud water (kg/kg)	$3.0x10^{-4}$	+0.014	-1.45
C_2	parameter used to simulate enhanced release of precipitation in clouds containing a mixture of droplets and ice crystals (Bergeron-Findeisen mechanism) ($K^{-1/2}$)	0.5	-0.008	+1.06
T	characteristic time scale for convection (seconds)	3600	+0.002	-0.27
U_{oo}	threshold value of relative humidity used to determine fractional cloud amount	0.75	-0.036	+4.09

Adjustable Parameters of Smith (1990)

Parameter	Description	Control Value	f10%,CLD	f10%,NSW
C_T	characteristic time for conversion of cloud droplets into raindrops (sec^{-1})	$1.0x10^{-4}$	-0.007	+2.37
C_W	threshold value for cloud water (kg/kg)	$8.0x10^{-4}$	-0.001	+0.34
C_A	factor for increased conversion of cloud droplets to rain due to precipitation falling into layer from above (m^2kg^{-1})	1.0	+0.003	-1.01
V_F	fallout speed for frozen precipitation (m sec^{-1})	1.0	-0.011	+2.61
C_{EV}	time constant for evaporation or sublimation of precipitation (sec^{-1})	$2.0x10^{-5}$	0.0	-0.40
RH_C	threshold value of relative humidity at which point cloud formation begins	0.85	0.0	+1.76

Adjustable Parameters of Slingo (1987)

Parameter	Description	Control Value	f10%,CLD	f10%,NSW
b	empirical constant used to calculate convective cloud cover from convective precipitation amount	0.245	+0.006	-0.94
C_{crit}	critical convective cloud cover for formation of cirrus anvils	0.3	-0.007	+0.62
$RH_{H,crit}$	critical relative humidity for formation of extratropical and frontal high clouds (cirrus)	0.8	-0.062	+4.30
$RH_{M,crit}$	critical relative humidity for formation of mid-level clouds	0.8	-0.035	+3.72
$RH_{L,crit}$	critical relative humidity for formation of low-level clouds	0.8	-0.006	+2.04

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