Treatment of Cloud Radiative Effects in General Circulation Models

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We participate in the Atmospheric Radiation Measurement (ARM) Program with two objectives: 1) to improve the general circulation model (GCM) cloud/radiation treatment with a focus on cloud overlapping and the cloud optical properties and 2) to study the effects of cloud/radiation-climate interaction on climate simulations. This paper summarizes the project progress since the second ARM Science Team meeting October 26-30, 1991, in Denver, Colorado. Four graduate students participated in the research.

GCM Radiation Model Development

During this period, we completed the radiation model-measurement comparison using the Albany site data. The measurement data include

- the total direct and diffuse solar radiation reaching the surface (15-minute intervals) for the periods 10/86, (4, 5, 7, 10) 10/87, and 10/91 through 10/92
- the longwave radiation reaching the surface for the periods 10/91-6/92 (15-minute intervals)
- the meteorological data at the surface (hourly data) and in the upper air (6 am and 6 pm) by the National Weather Service. The meteorological data consist of temperature, humidity, wind, and cloud cover and ceiling height for the same periods as the solar radiation.

Using these data as inputs, we evaluated the longwave and solar radiative codes by comparing the calculated radiative fluxes reaching the surface with measurements for both clear and cloudy sky conditions. These codes were used in the general circulation models CCM1 (Wang et al. 1991 and 1992) and the Global ENvironmental and Ecological Simulation of Interactive Systems (GENESIS) for climate simulations. Both GCMs were developed at the National Center for Atmospheric Research. The GENESIS includes the diurnal cycle and much improved physics (clouds, moisture transport, convection, etc.) and surface models for soil and snow/ice.

Figure 1 shows the comparison of longwave and solar radiation for clear and cloudy sky. Note that the cases for longwave radiation are restricted to the time of the day when radiosonde data are available. Note also that the cases of cloudy sky are limited to one layer of cloud either at low level (< 3 km) or at the middle level (between 3 and 6 km), which is determined through examining the humidity profile. For clear sky, the model calculations are in good agreement with measurements for longwave radiation, and the contribution of the observed trace gases of CH_4, N_2O, CFC-11, and CFC-12 is 2 to 3 Wm^{-2}.

The GCM radiation parameterization calculates systematically higher values for solar radiation. Our sensitivity calculations indicate that the effects of column ozone amount and surface albedo are on the order of 10 to 20 Wm^{-2}. The likely cause for the larger values is related to the omission of aerosols in the flux calculations, as well as the measurement uncertainty.

Large differences are found in the comparison for the cases of cloudy sky, and the differences are particularly large for solar radiation. These differences can be attributed to the radiation model's internally assigned cloud albedo and emissivity and, thus, a lack of interactive cloud optical properties. For the latter, work is already under way to use observations such as the First ISCCP Regional Experiment

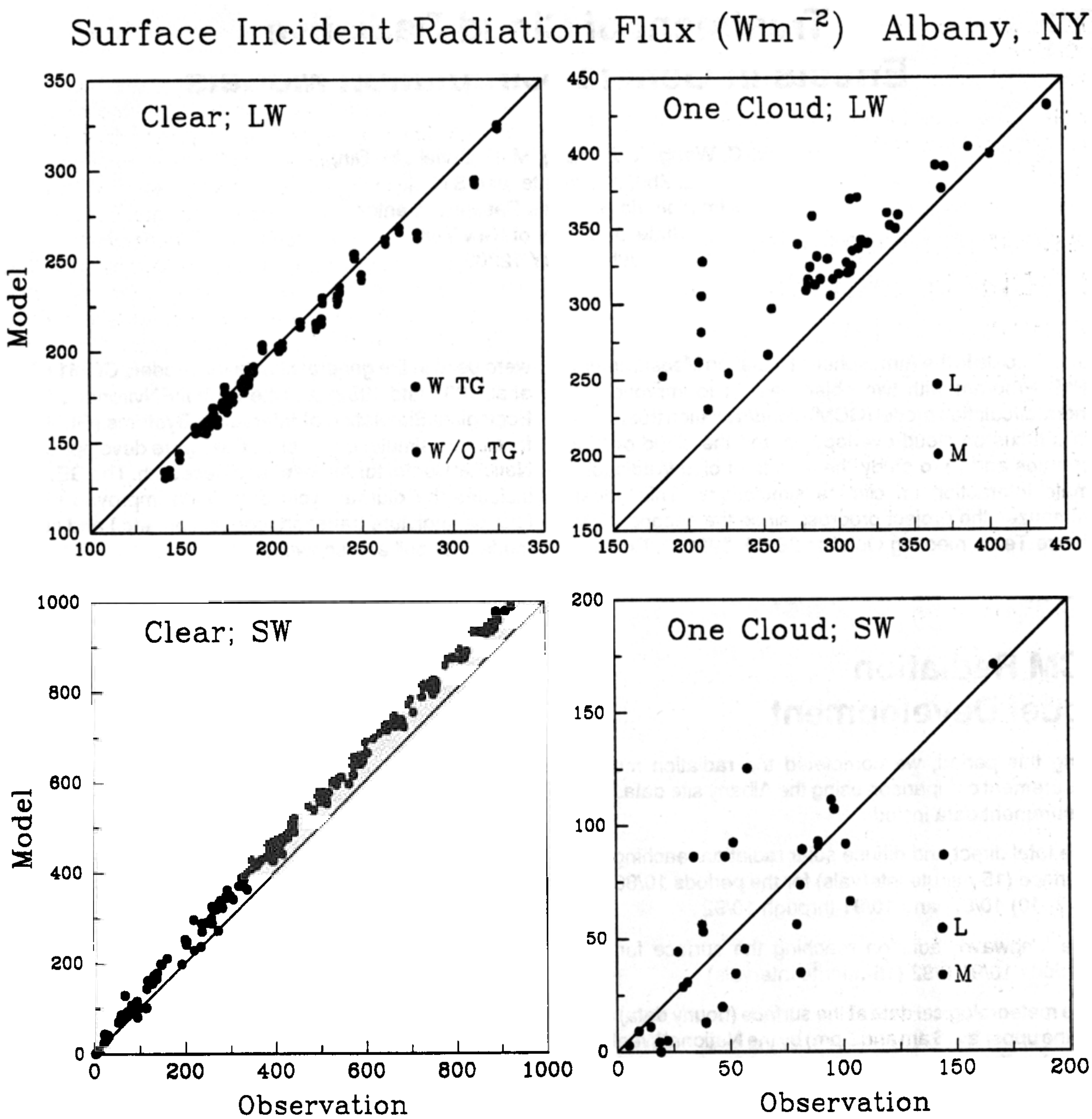

Figure 1. GCM radiation model-observation comparison of the downward radiation fluxes reaching the surface at Albany for clear (with and without trace gases, TG) and cloudy (Low or Middle level cloud) sky conditions. Note that cloudy sky calculations include the trace gases.

(FIRE) and International Satellite Cloud Climatology Project (ISCCP) data to develop radiative parameterizations for cirrus and stratiform clouds with interactive microphysics.

We plan to continue the research using the data from the Southern Great Plains CART site, which are now becoming available.

Resolution Dependence of GCM Cloud-Radiation Parameterization

A semi-prognostic climate model has been developed to study the resolution dependence of physical parameterizations used in GCMs. The climatic model, consisting of the basic physical parameterizations from GENESIS, reads in the three-dimensional atmospheric state for the specified region and computes a consistent set of diagnostic quantities (such as cloudiness, precipitation or surface radiation quantities) and instantaneous local time tendencies (such as radiation or condensation heating rates within the atmosphere).

We have tested the semi-prognostic model using the standard radiosonde network around the Southern Great Plains CART site. The model was run for grid size of 60 km, 120 km, 180 km, 240 km, 360 km, and 720 km. For each grid size, the horizontally averaged basic state quantities are first calculated and used as inputs to the model to calculate the diagnostic quantities and local time tendencies. Comparison of the averages obtained using different horizontal resolutions will allow an assessment of the dependence of the results as the horizontal resolution changes. If the model physics are unchanged across a range of resolutions, the only source of differences in the final averages for the region will be the horizontal resolution of the calculations. In particular, since the semi-prognostic approach allows no dynamical interactions within the model, the effect of changes in horizontal resolution on the physical parameterizations can be isolated from changes in the dynamics of the model.

Figure 2 shows the total cloudiness and net upward longwave radiation evaluated from the semi-prognostic model. For the 60-km grid resolution (upper panels), the horizontal distribution of cloud cover (upper left panel) varies from 100% to 0, with corresponding net longwave radiation (upper right panel) from 0 to 110 Wm^{-2} over the region. Most of the change in surface radiation budget corresponds to cloudy versus clear areas. Figure 2 also shows the resolution dependence of the fractional cloud cover (lower left panel) and the longwave radiation (lower right panel). The fractional cloudiness varies from 0.3 on the 60-km grid to no clouds for the 720-km grid. This result implies that for a very large-scale model, the cloud parameterization would diagnose no clouds over the region. As horizontal resolution increases, the diagnosed fractional cloud cover also increases, indicating the cloud parameterization contains a strong dependence on horizontal resolution. The resulting longwave radiation dependence on the resolution follows the similar change in cloudiness and varies from 72 to 92 Wm^{-2} as the horizontal resolution changes from 60 to 720 km.

We plan to conduct more detailed study using Southern Great Plains CART site data and calibrate the radiation calculations with measurements.

GCM Simulations

Atmospheric Ozone

The radiation model-measurement comparisons reported in the first section of this paper indicate that the atmospheric ozone can substantially affect the solar radiation reaching the surface, with subsequent effect on climate simulations. Currently, the ozone climatology used in GENESIS is the data corresponding to the 1970s and, more importantly, does not account for the longitudinal variations. We have used a combination of the satellite data from Total Ozone Mapping Spectrometer (TOMS) and Stratospheric Aerosol and Gas Experiment (SAGES) and the ozonesonde station data to update the GENESIS model ozone climatology.

Comparison of the ozone column between the two climatologies indicates that large differences exist over the middle- and high-latitude continental regions during winter. To make a preliminary evaluation of the effect of the updated ozone climatology on the climate simulations, we run perpetual January and July simulations.

The differences in the latitudinal-longitude surface temperature between the old and the updated ozone climatologies are shown in Figure 3. The difference can be as large as 6° to 8°C over North America and Central

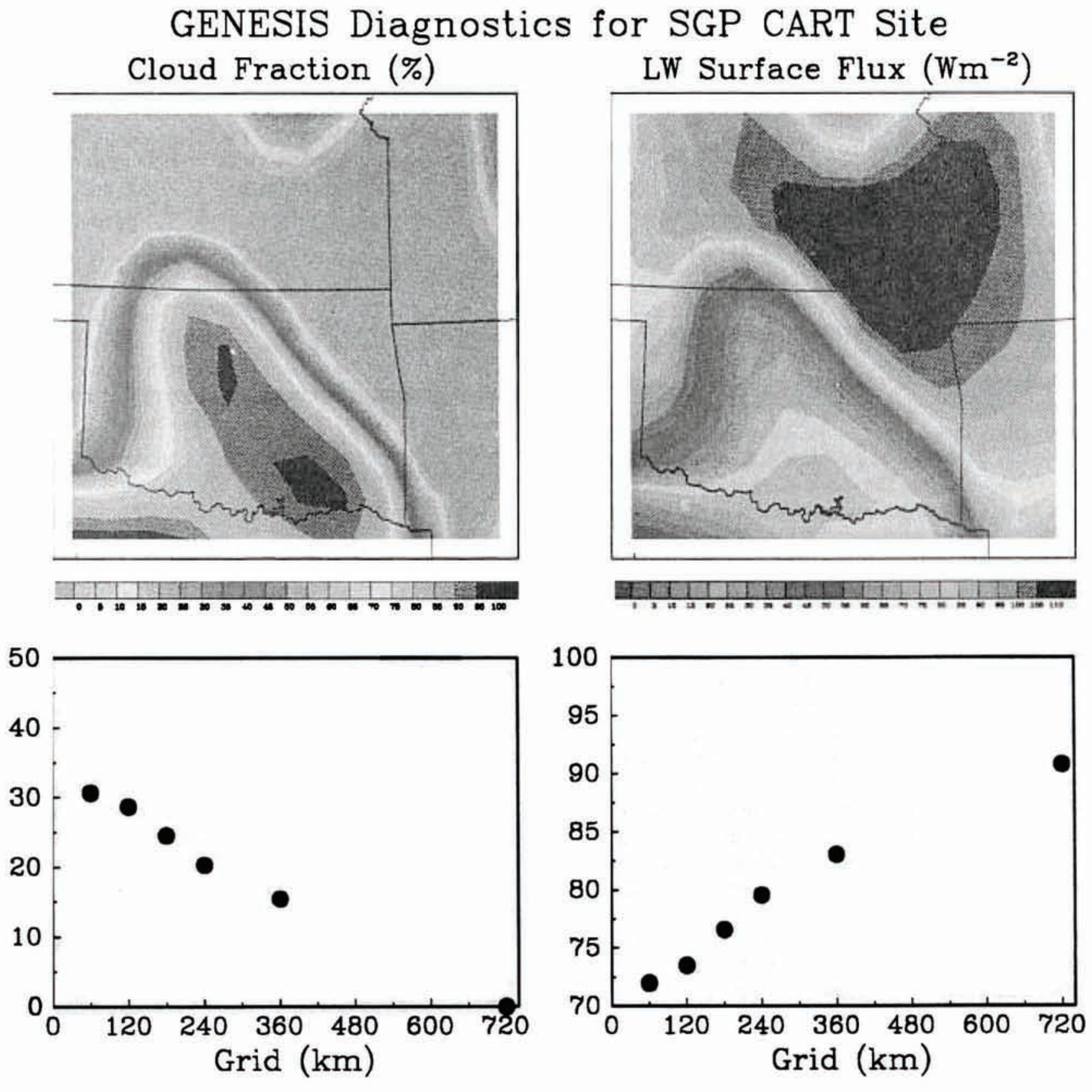

Figure 2. The total fractional cloudiness (top left panel) and the net upward longwave radiation flux at surface (top right panel) diagnosed at the Southern Great Plains CART site for 12 GMT 12 June 1985 on a 60-km grid. The diagnosis is conducted using the GENESIS which includes the Slingo and Slingo (1991) cloud parameterization. Most of the cloudiness within the region is middle clouds, with some vertical overlapping with low clouds in the southeastern corner of the domain. The two lower panels are the domain-averaged cloudiness and net longwave radiation fluxes as a function of horizontal resolution of the computation grid.

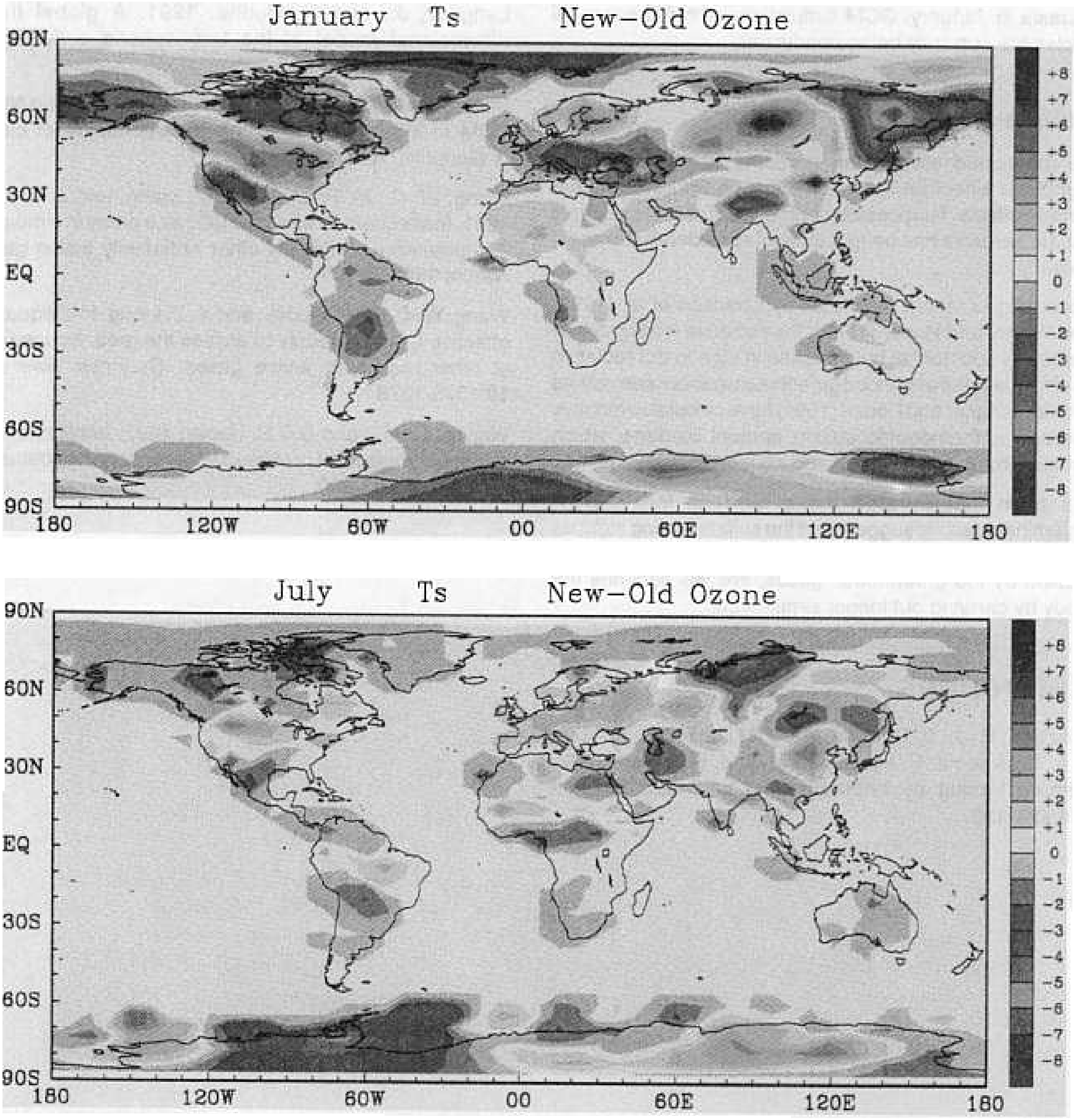

Figure 3. Effect of atmospheric ozone on the January and July surface air temperature as simulated from GENESIS. The new ozone climatology is based on the TOMS, SAGES, and ozonesonde station data, while the old climatology is zonal mean and, thus, does not account for the longitudinal variation. Perpetual January and July experiments were conducted here.

Eurasia in January. GCM simulations with full seasonal cycles are currently being conducted.

Sulfate Aerosols

As mentioned earlier, the aerosols can also have a significant effect on the solar radiation with subsequent climatic effects. The possible cooling effect of anthropogenic sulfate aerosols has been a topic of considerable interest recently.

According to recent estimates by Charlson et al. (1992) and Wigley and Raper (1992), the radiative forcing due to aerosol is substantial but opposite in sign to the radiative forcing due to the enhanced greenhouse gas concentrations to date. Langner and Rodhe (1991) have calculated monthly average anthropogenic sulfate aerosol burdens, which exhibit strong geographical and seasonal variations.

We have incorporated these burdens into CCM1. Preliminary results suggest that the sulfate forcing induces regional climate responses markedly different from those caused by the greenhouse gases. We will continue the study by carrying out longer simulations.

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