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 focus on cloud overlapping and the cloud optical properties and 2) to study the effects of cloud/radiation-climate interaction on climate simulations.

This report summarizes project progress from March 1993 to March 1994. During this period, four graduate students continue to participate in the research.

Effect of Aerosols on the Clear Sky Solar Radiation

As reported in the *Proceedings of the Third Atmospheric Radiation Measurement (ARM) Science Team Meeting*, the GCM radiation parameterization calculates systematically higher values for solar radiation reaching the surface. Our sensitivity calculations indicate that the effects of column ozone and surface albedo are small and the likely cause for the difference is the omission of aerosols.

We have investigated the aerosol effect on the clear sky solar radiative flux using measurements at Albany, New York, for the period January through September 1992. The measurements include radiosonde data of temperature and relative humidity; the hourly downward solar radiative flux reaching the surface; and the daily total column ozone from the total ozone mapping/spectrometer (TOMS).

For the aerosols, we used the total optical depth derived from Multifilter Rotating Shadowband Radiometer measurements taken by Michalsky and Harrison[(a)]. Values for single scattering albedo and asymmetry factor are taken to be 0.965; 0.680 for UV and visible regions and 0.855; 0.540 for the near-IR region (D'Almeida et al. 1991). Because of a lack of information on the vertical distribution, we assume that all aerosols are located within the boundary layer.

Figure 1 shows the comparison of clear-sky solar downward flux reaching the surface between the measurements and

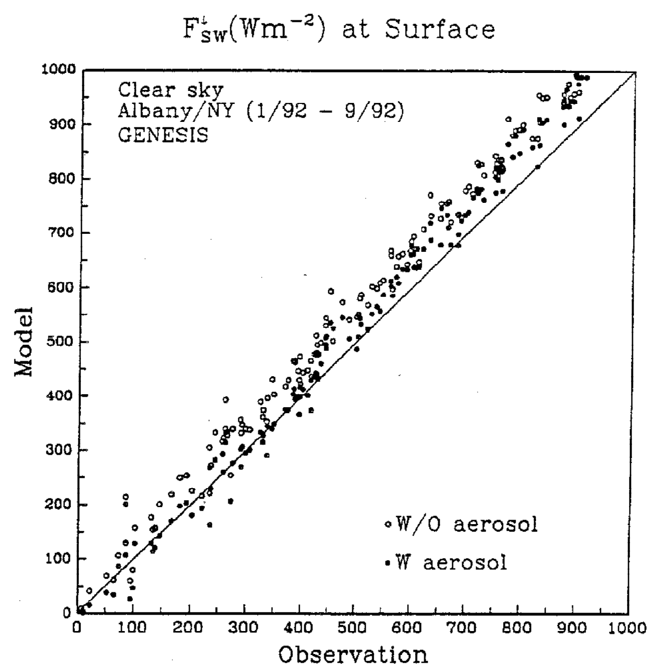

Figure 1. Clear-sky downward solar fluxes reaching the surface calculated using GENESIS compared with observations at Albany, New York, for the period January-September 1992. Open circles represent model calculations without observed aerosol loadings and solid circles represent model calculations with observed aerosol loadings.

(a) Personal communication.

calculations using the solar radiation code of the National Center for Atmospheric Research/Global ENvironmental and Ecological Simulation of Interactive Systems (NCAR/GENESIS) global climate model. Clearly, the agreement is much better when aerosols are included; the difference between the means is reduced from 73 Wm^{-2} (13.6%) without aerosols to 37 Wm^{-2} (7.5%) with aerosols. These results suggest that aerosols will have substantial effect on the solar radiation and need to be included when the model calculations are compared with measurements.

Resolution Dependence of GCM Cloud-Radiation Treatment

We continue the preparation of a regional climate model to study the resolution dependence of GCM parameterizations for cloud-radiation. For this purpose, we have adopted the mesoscale model 5 (MM5), which is a fully compressible nonhydrostatic model (Dudhia 1993).

The model allows the use of multiple nested grids, which can provide high resolution nonhydrostatic grids within a regional scale hydrostatic modeling system. The model uses a terrain-following coordinate and a map scale factor similar to the MM4 hydrostatic modeling system, except with separate predictive equations for the three-dimensional pressure distribution and vertical momentum. Time-splitting is used to separate the fast acoustic waves from the slower low-frequency meteorological waves. The model provides a choice of cumulus parameterizations at coarser resolutions and explicit forecast equations for cloud and rainwater at finer resolutions. The model allows the simulation of fine scale atmospheric phenomena using realistic and changing large scale environmental conditions.

A 23-level hydrostatic version of MM5 is used for our study. The model domain is centered over the Southern Great Plains Cloud and Radiation Testbed (SGP/CART) region with three levels of nesting: a coarse mesh of 45 km, an inner mesh of 15 km, and a fine mesh of 5 km (see Figure 2). The high resolution Blackadar boundary layer parameterization is used. On the outer mesh, a Kuo type convective parameterization is used, while on the two inner meshes the explicit cloud and rainwater prediction equations are used.

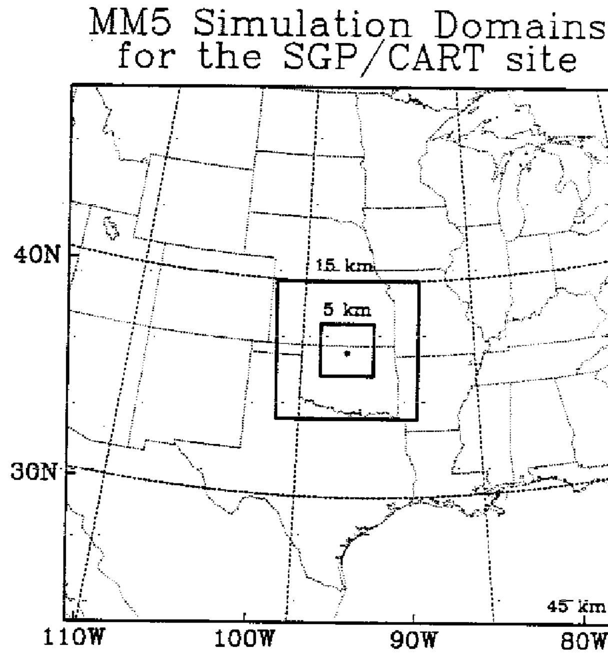

Figure 2. The domains used for the MM5 experiments. The outer region used a 45-km mesh, the second inner nest used a 15 km-mesh and the third inner nest used a 5-km mesh. The location of the ARM SGP/CART central facility is marked with an asterisk.

The radiation parameterizations in the basic model provide only input to a surface energy budget equation, with no direct atmospheric heating being computed. (Note that we intend to incorporate the GENESIS radiation codes into MM5 so that identical schemes in both models will allow consistent diagnosis of model simulations.) The simulations are initialized with boundary conditions from National Meteorological Center analyses mapped onto the MM5 grids.

We conducted a 12-hour MM5 simulation starting 12 GMT October 15, 1993, over the SGP/CART site. Low clouds and drizzle were observed at the central facility for the entire period. A mesoscale region of low cloudiness is seen over western Oklahoma and Kansas at 12 GMT. This region moves slowly northeastward during the 12-hour period and gradually expands.

The simulated atmospheric state on the 15-km grid was used to diagnostically calculate the cloud and radiation fields using the physical parameterizations from GENESIS. Figure 3 shows the cloud and radiation field at 18 GMT and illustrates the inhomogeneities which can be found over a region this size (720 km by 720 km, similar to R15 horizontal resolution in a GCM).

The mesoscale model is used to develop realistic mesoscale detail, especially in the cloud fields. These cloud fields can then interact with the radiation parameterizations in a spatial scale dependent manner (see discussion below). The other fields illustrate the effect of these cloudiness features on the surface and top of atmosphere radiation budgets, i.e., reducing the incoming solar radiation at the surface in cloudy regions and also reducing the net downward longwave flux in these same regions. Since these clouds are primarily low, they produce a weak effect only on the top of the atmosphere longwave flux.

To study the horizontal resolution dependence of the cloud-radiation interaction, we average the basic atmospheric state quantities onto coarser horizontal grids. Note that the cloudiness can be evaluated in two separate ways. In the first, referred to as *area-averaged clouds,* the clouds are evaluated on the finest possible resolution (15 km in this case) and then horizontally averaged, along with all the other thermodynamic variables (T and q), to all other resolutions; this procedure yields relatively small change in total cloud cover as resolution changes. The second technique, referred to as *diagnosed clouds,* averages all thermodynamic quantities except cloudiness; the clouds are instead evaluated on each separate resolution grid, which therefore is sensitive to the region used for averaging. This second approach more closely follows the way a GCM evaluates cloudiness, in that the model only sees the resolution of the grid, it contains no direct information about sub-grid scale structures.

Figure 4 shows the cloud cover at 18 GMT calculated using three cloud vertical overlapping treatments, the maximum, minimum and random schemes; the latter is generally used in GCMs. As expected, minimum overlap calculates the largest cloud cover, while the maximum overlap yields the smallest value.

As also shown in the figure, the total cloud using the *area-averaged-clouds* approach is relatively unchanged across horizontal resolution for the three overlapping schemes. For random overlap, the net longwave flux at the surface is highest at finer resolutions and decreases by approximately 7 Wm^{-2} at the lowest resolution. The downward solar flux shows a similar reduction of 5 Wm^{-2} from highest to lowest horizontal resolution.

On the other hand, the total clouds using the *diagnosed-clouds* approach show a completely different cloud structure, ranging from covering approximately 38% of the region (for the random overlap assumption) on the 15-km grid to having no clouds for the coarsest resolution. As the total cloud amount is reduced with increasing horizontal resolution, the associated longwave and solar radiation fluxes also show a strong resolution dependence, increasing by 24 and 90 Wm^{-2}, respectively.

Effect of O_3 on Climate Simulations

The atmospheric O_3 climatology used in the GENESIS is updated and its effect on simulation of present climate is examined. The new O_3 climatology includes two improvements: the use of measurements from satellite (TOMS and Stratospheric Aerosol and Gas Experiment [SAGE]) and ground-based instruments of recent years and the consideration of longitudinal variations. The difference in the GENESIS simulated global, annual mean surface air temperature between the new and old O_3 climatologies is calculated to be very small. However, differences in the seasonal and longitudinal distribution are quite large, as shown in Figure 5 for January.

The new O_3 yields a warmer surface air temperature for most regions and the warming effect is particularly large in the areas centered around (60E; 60N) and (130W; 60N) where the temperature can be higher by as much as 4 to 5°C. The magnitude of these warmings exceeds the model interannual variability, thus implying that atmospheric O_3 can have substantial influences on the solar and longwave radiation and, thus, on regional climate. The new O_3 data also improve the surface temperature simulations over Russia where substantial cold bias (about 10°C) existed with the old O_3 data. Large differences are also found in the stratospheric temperatures. Details of the GENESIS simulations are documented in Wang et al. (in press).

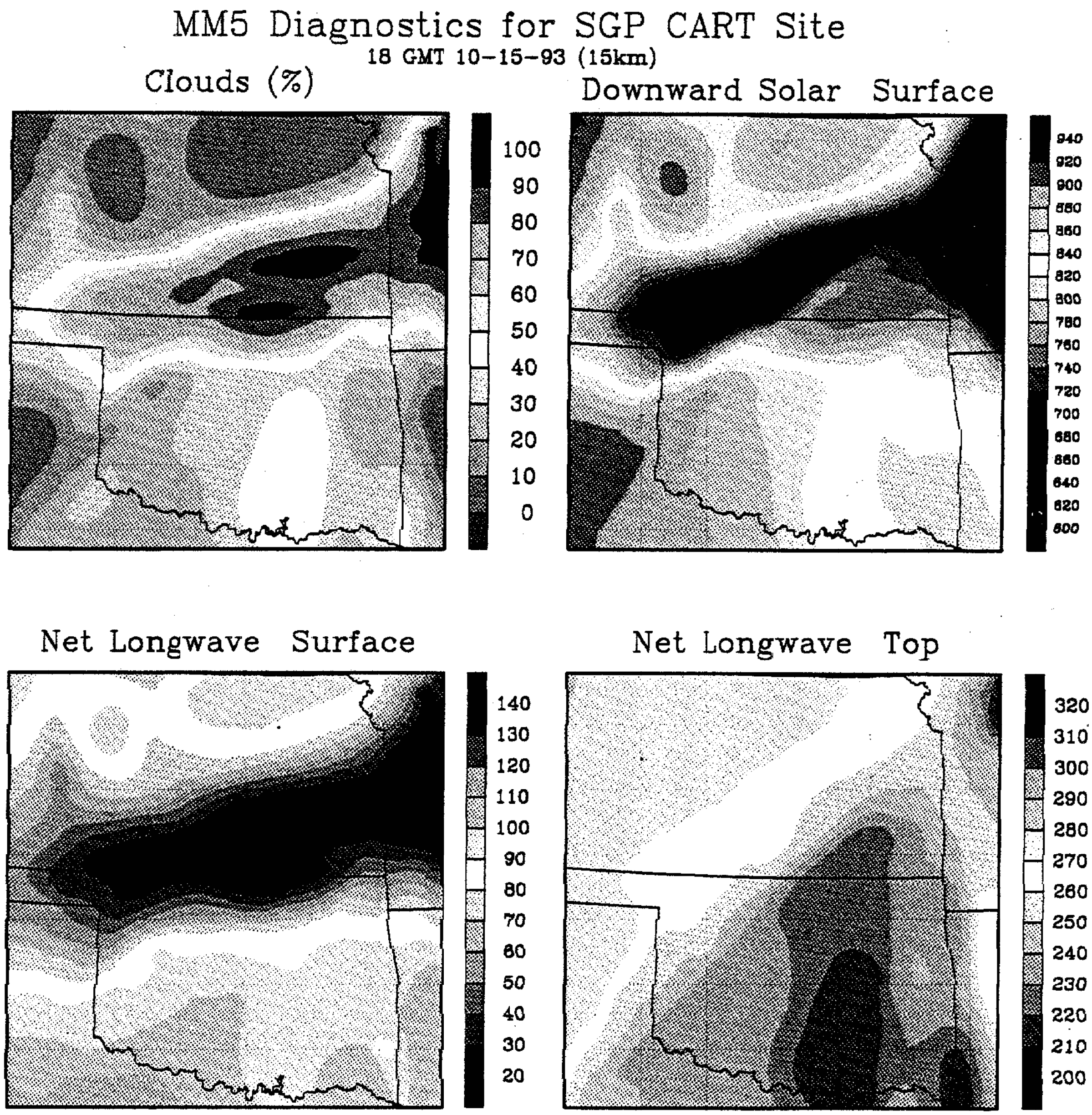

Figure 3. Diagnostics at 18 GMT from a 12-hour MM5 simulation over the SGP/CART region beginning 12 GMT 15 October 1993. The calculations are shown on the 15-km grid. The cloud cover and the solar and longwave radiation fluxes are calculated diagnostically from the MM5 simulation using the GENESIS radiation parameterizations. Substantial spatial variability is observed in the simulation domain.

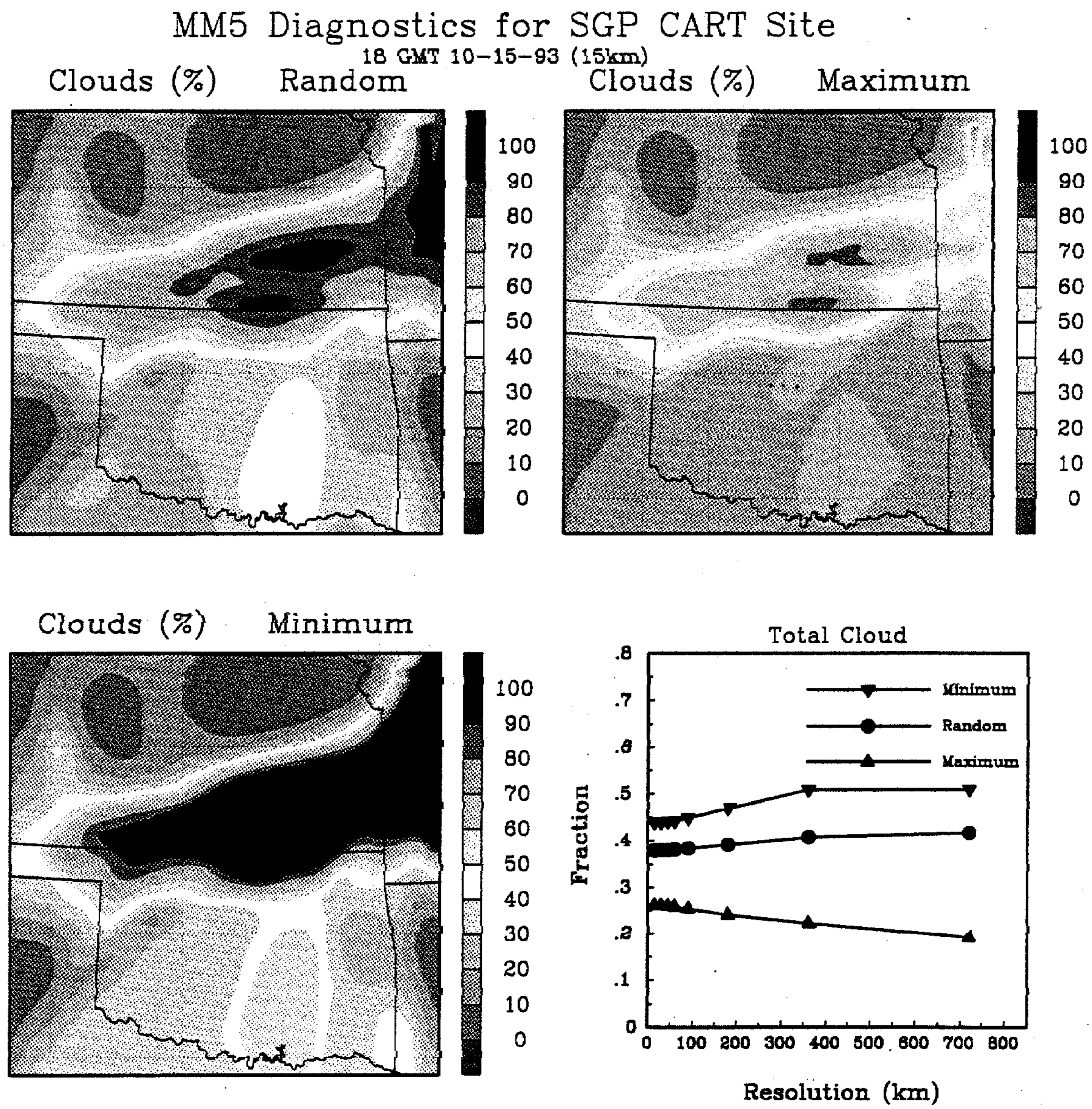

Figure 4. Total cloud cover diagnostically calculated using three cloud vertical overlapping algorithms, minimum cloud overlap, random cloud overlap, and maximum cloud overlap. Also shown is the area-averaged clouds as a function of the computation grid horizontal resolution.

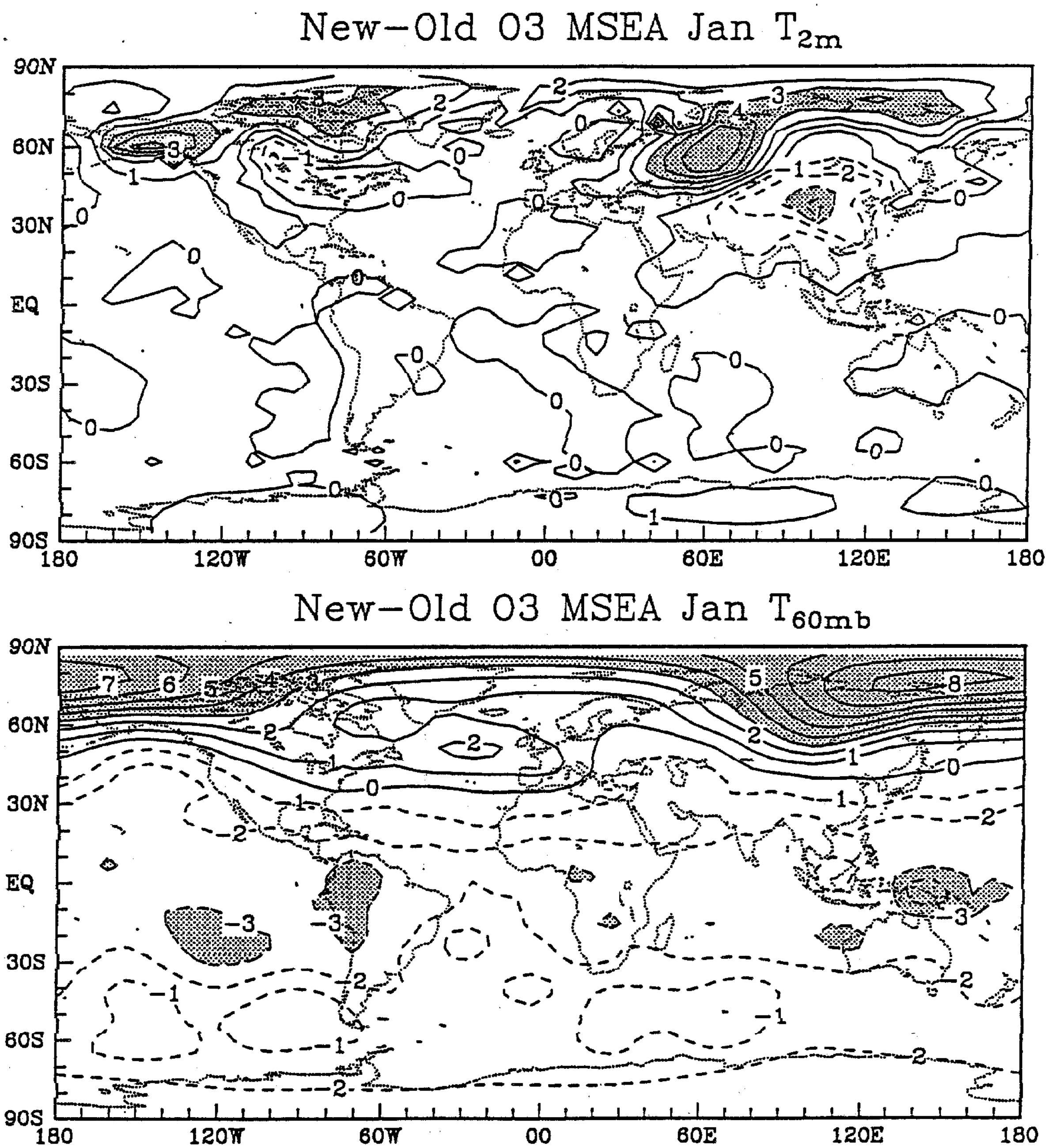

Figure 5. Effect of atmospheric ozone on the simulated temperature difference (°C) at a) surface and b) 60-mb level between new and old ozone climatologies simulated from GENESIS. The new ozone climatology is based on the TOMS, SAGES, and ozonesonde station data, while the old climatology is zonal mean and, thus, does not account for the longitudinal variation.

Plans for Next Year

During the past year, we have made significant progress—in particular, the development of the regional climate model for studying the spatial variability of clouds and radiation within the SGP/CART site and its effects associated with the treatment of cloud vertical overlapping. For the next year, we plan to incorporate the GENESIS radiation parameterization into MM5 so that consistent radiation is used for diagnosing the model simulations. The available SGP/CART measured radiation and cloud fields will allow us to validate the MM5 regional simulation and to further refine the cloud/radiation parameterization for use in GENESIS. We plan also to examine to what extent the GENESIS climate simulation is affected by the improved radiation/cloud treatments.

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