A Cloud Resolving Model as a Cloud Parameterization in the NCAR Community Climate System Model: Preliminary Results

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Abstract. Preliminary results of a short climate simulation with a 2-D cloud resolving model (CRM) installed into each grid column of an NCAR Community Climate System Model (CCSM) are presented. The CRM replaces the conventional convective and stratiform cloud parameterizations, and allows for explicit computation of the global cloud fraction distribution for radiation computations. The extreme computational cost of the combined CCSM/CRM model has thus far limited us to a two-month long climate simulation (December-January) using 2.8° x 2.8° resolution. The simulated geographical distributions of the total rainfall, precipitable water, cloud cover, and Earth radiation budget, for the month of January, look very reasonable.

1. Introduction

It is widely agreed that feedbacks involving clouds are among the most uncertain aspects of simulations of anthropogenic climate change. Climate models include parameterizations of both convective clouds, which produce strong vertical transports and precipitation, and stratiform clouds, which produce comparable amounts of precipitation and are also radiatively important. Cloud-resolving models (CRMs) are high-resolution models with large domains, capable of simulating the statistics of a cloud field. CRMs are being used to evaluate the realism of convective and stratiform cloud parameterizations.

Recently, Dr. W. Grabowski of National Center for Atmospheric Research (NCAR) has performed idealized simulations of the general circulation using a simplified general circulation model (GCM) with a globally uniform sea surface temperature, no continents, prescribed radiative cooling, etc. [*Grabowski and Smolarkiewicz*, 1999; *Grabowski*, 2001]. He embedded a two-dimensional (2-D) CRM within each column of the GCM, to serve as a Cloud-Resolving Convection Parameterization. The cloud models in different GCM grid columns interact with each other via the large-scale dynamics, as is also the case with conventional cloud parameterizations. This is a very exciting approach, because it enables studies of the role of clouds in the atmospheric general circulation with much more realism and in much more detail than would be possible with conventional parameterizations.

In this paper, we present the preliminary results of our short climate simulation with a 2-D CRM installed in a realistic GCM. To our knowledge, the present study is the first attempt to apply a CRM as a cloud parameterization to simulate the Earth climate system using a global climate model with realistic surface boundary conditions and interactive radiation.

2. The model and experiment design

The GCM is the atmospheric component of the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM), also known as CCM3 [*Kiehl et al.* 1998, *Hack et al.* 1998]. We used the version with the semi-Lagrangian dynamical core [*Williamson and Olson* 1994]. The CRM is an anelastic version of a Large-Eddy Simulation (LES) model of *Khairoutdinov and Kogan* [1999]. At Colorado State University, the model was modified to run on massively parallel distributed-memory computers using the Message Passing Interface (MPI) protocol. Besides the wind components, the prognostic variables include the liquid water/ice moist static energy, the total non-precipitating water, and the total precipitating water. The partitioning between the liquid and ice phases is assumed to be a function of temperature only, with the hydrometeor conversion rates expressed following *Lin et al.* [1983]. The subgrid-scale model employs the so-called 1.5-order closure, with the option to use a simple Smagorinsky-type scheme. A staggered Arakawa C-type grid with periodic lateral boundaries is adopted for the finite difference representation of the model equations. The advection of momentum is computed with the second-order finite differences in the flux form with the kinetic energy conservation. The time integration of the equations of motion is done using the third-order Adams-Bashforth scheme. The three-dimensional positive definite and monotonic scheme of *Smolarkiewicz and Grabowski* [1990] is employed to transport all scalars.

A copy of the CRM was embedded in each grid column of the CCSM, replacing the moist convection and large-scale condensation (stratiform) parameterizations. Since the CRM can explicitly compute the cloud fraction for radiation computations, the diagnostic cloud fraction parameterization was also removed. The CCSM ran using the 2.8°x2.8° horizontal grid resolution; therefore, 8192 CRM copies have been applied. Significant memory and CPU expense constrained the use of CRM to the 2-D geometry, much smaller domain and coarser grid resolution than typically found in cloud ensemble simulations. The CRM grid had 24 levels in the vertical located at the same heights as the 24 lowest levels of the CCSM's 26-level grid, so that no vertical interpolation of CRM output into the CCSM grid was needed. Horizontally, the CRM domain was aligned in the west-east direction and had 64 grid points at 4 km spacing.

In a preliminary study, we tested the sensitivity of the CRM results to the domain geometry, size and resolution by conducting several 18-day long CRM runs using the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) Phase III data [the dataset is described, e.g., by *Xu and Randall* 1996]. The model was forced by the horizontal advective tendencies, large-scale vertical velocity and radiative heating derived from observations. The surface latent and sensible heat fluxes were computed rather than prescribed. Here, we present the results from four such runs. Compared to the control domain -- the 2-D 64x24 grid-points -- the same as the one described above, two
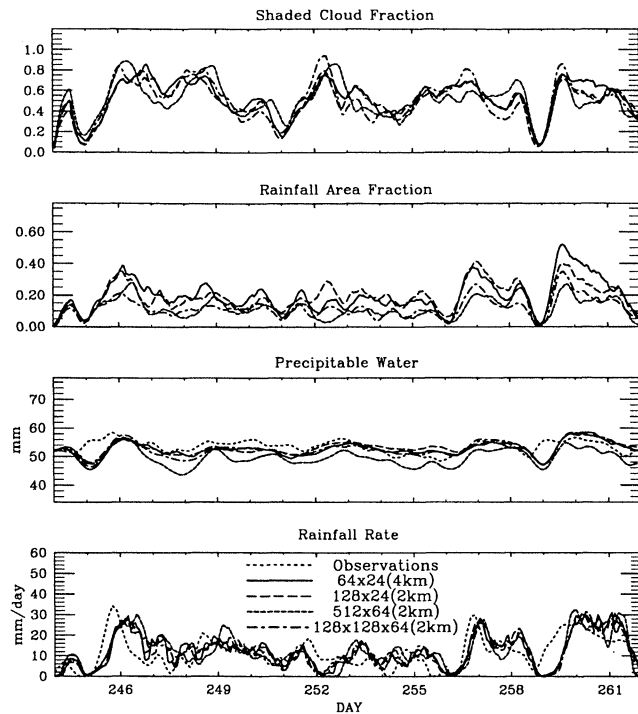
Figure 1. Twelve-hour running mean time-series of various quantities as simulated by the CRM forced with the GATE Phase III data using four different domain configurations (see the text).

domains -- the 3-D 128 x 128 x 64 and 2-D 512 x 64 grid-points -- had significantly higher number (64 vs. 24) of vertical levels and hence much higher vertical resolution, while one domain - the 2-D 128 x 24 grid-points -- had the same vertical size and vertical resolution as the control run. In all three cases the horizontal resolution was doubled (2 km vs. 4 km) relative to the control case.

Figure 1 compares the time series of the shaded cloud fraction, surface rainfall area fraction, precipitable water and total precipitation rate. Note that the time series were smoothed by application of a 12-hour running mean because of rather noisy output (especially of the rainfall rate) of the small-domain runs. One can see that neither the geometry nor the domain's size nor resolution within the described range introduce any clear bias in the results. Even though the rainfall area fraction tends to decrease as the domain size increases, the thermodynamically important total precipitation rate and radiatively important cloud cover and precipitable water seem to behave in a very consistent and similar manner. We conclude, therefore, that despite its smallness and poor resolution, the CRM domain used in the combined CCSM/CRM model produces sufficiently accurate results in terms of cloud statistics.

The strategy for the coupling between the CCSM and the CRM generally follows the procedure outlined by Grabowski in the papers cited above. The CRM is subcycling with its own timestep (20 sec) within a CCSM timestep interval (1 hour) forced (as with conventional convection parameterizations) by large-scale tendencies applied homogeneously at a given level. At the end of the CCSM timestep, the CRM produces the horizontally averaged fields as its output which is then used by the CCSM to compute the tendencies due to subgrid-scale processes. It should be stressed that CRM is not initialized at the beginning of a new CCSM timestep, but rather is continuously running throughout the whole simulation, so that only the large-scale forcing is being updated. Thus, unlike a typical convective parameterization, the

CRM parameterization has a "memory" that goes well beyond the host model's timestep.

The CCSM/CRM model is very expensive to run -- about 180 times as expensive as the atmospheric component of the CCSM itself. A simulated day with the CCSM/CRM takes about 1 wall-clock hour on 64 processors of NCAR's 375-MHz IBM SP, while the CCSM itself simulates about half an year per wall-clock hour on the same number of processors. Due to limited computational resources, we have been able to perform only a two-month December-January simulation with prescribed climatological sea surface temperatures. For the same reason, no tuning of the combined model was done to make globally averaged radiative fluxes balance at the model top. The first month of simulation was ignored to allow the model to spin-up, while the month of January was used to compute the monthly-mean statistics. A similar two-month run was performed using the standard CCSM configuration.

3. Results

Plate 1 shows the geographical distribution of simulated precipitation and the vertically integrated water vapor (precipitable water) for January for the CCSM/CRM and standard CCSM simulations along with the corresponding observations. In general, the observed pattern of precipitation is well reproduced by the CCSM/CRM in both extra-tropical storm tracks and tropics. The geographical pattern of precipitable water is also well reproduced, although with a moist bias compared to the NVAP [Randel et al. 1996] data. The Inter-Tropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), and the South Atlantic Convergence Zone (SACZ) are all well simulated. The precipitation minima in the eastern parts of the oceans are also well defined. There are apparent biases such as, for example, a too vigorous SPCZ extending too far south, and ITCZ in the Indian Ocean extending too far north, and absence of a precipitation zone along the southeast corner of Australia. However, some of the biases of the CCSM/CRM can also be found in the standard CCSM results.

As mentioned above, a CRM used as a cloud parameterization allows one to directly compute the vertical distribution of clouds within a GCM's grid column. Plate 2 shows the simulated geographical distribution of the total cloud cover for the month of January. Overall, the geographical pattern is in reasonable agreement with the observed distribution of clouds. There are well pronounced minima along the subtropical subsidence areas, especially over Australia and northern Africa; a large amount of cloudiness over the tropical Warm Pool and along the tropical convergence zones, associated with the detrainment from deep convective towers; and overcast along the Southern Ocean storm track. The model tends to underestimate the cloud amount in the subtropics due to the rather coarse spatial resolution of the CRM to adequately resolve the boundary layer clouds.

Figure 2 shows the zonally averaged precipitation rate, precipitable water, and radiation characteristics at the top of the atmosphere. The zonal-mean precipitation rate is generally consistent with the Xie and Arkin [1996] climatology, especially for the Northern Hemisphere (NH). Among the major deficiencies here are the simulated precipitation not having a maximum just south of the equator, and a tendency for the tropical precipitation to extend too far south, although the latter is also seen in the standard model result. However, the subtropical minimum and the midlatitude storm-track precipitation seem to agree very well with observations. The zonally averaged precipitable water shows a strong
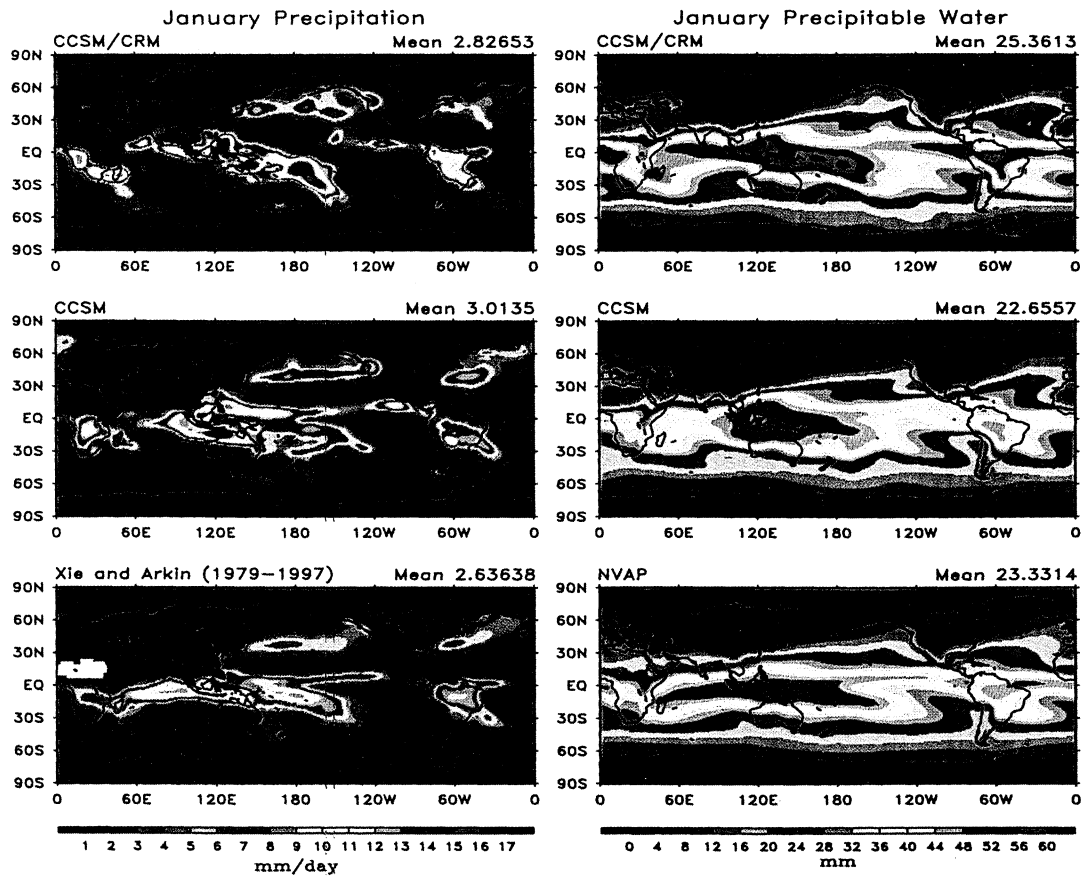
January Precipitation

January Precipitable Water

Plate 1. January precipitation rate and precipitable water, as simulated with the CCSM/CRM (upper panels), standard CCSM (middle), and as observed (bottom).
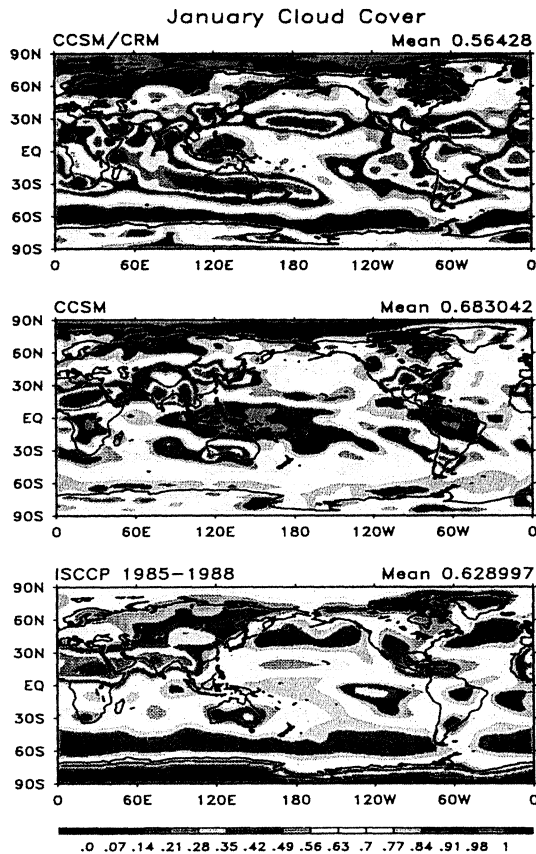
January Cloud Cover

Plate 2. Simulations of the cloud fraction with the CCSM/CSM (upper panel), standard CCSM (middle), and as observed (bottom) for January.

moist bias in the tropics and a moderate moist bias in the Southern Hemisphere (SH). In contrast, the NH precipitable water resembles NVAP data very well. The zonally averaged outgoing long-wave radiation (OLR) and the absorbed solar radiation (ASP) fluxes show surprisingly good agreement with the Earth Radiation Budget Experiment (ERBE) data, considering that no tuning of CRM microphysics was done. The effects of clouds on the top-of-
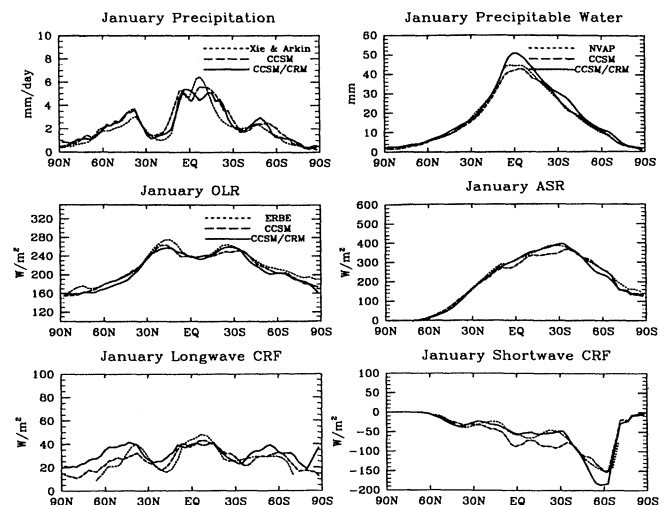

Figure 2. Zonal means of observed and simulated precipitation rate, precipitable water, outgoing longwave (OLR), and absorbed solar radiation (ASR), longwave cloud radiative forcing (CRF), and shortwave CRF. The simulations were performed with the CCSM/CRM and the standard CCSM.

atmosphere radiation agree surprisingly well with ERBE, as seen in the plots of the zonally averaged longwave (LWCF) and short-wave (SWCF) cloud forcing (note that the ERBE cloud forcing is not defined beyond 70° north and south). The LWCF, defined as a difference between the clear-sky and the all-sky OLR, shows three distinct local maxima - one in the tropics and one in the middle latitudes of each hemisphere associated with the extratropical storm tracks. The SWCF, defined as a difference between the the all-sky and clear-sky ASR, has a rather significant bias in the SH extratropical storm track; however, we note that this field is very sensitive to such uncertain microphysics parameters as the cloud drop and ice crystal effective radii, which are prescribed in the SCCM.

4. Concluding remarks

This paper reports our early experiences with the application of a cloud resolving model as a "super parameterization" in the CCSM's atmosphere model. The CRM explicitly resolves the bulk of vertical transports by clouds. It also explicitly computes the grid-box averaged cloud amount for the radiative computations.

The results presented here are very preliminary, but they are quite encouraging, especially considering that the combined model was not tuned in any way. Some of the deficiencies of the simulation may be due to spurious interactions of the CRM with the GCM's surface and boundary layer parameterizations; the latter was still used here because of the CRM's rather poor horizontal resolution. In the future experiments, we plan to remove the boundary-layer parameterization, so that almost all the CCSM's subgrid-scale atmospheric transport is done by the CRM. We also plan to perform all the radiation transfer computations directly within the CRM framework. This will add about 20% to the computational cost of the model.

As already mentioned, the CCSM/CRM is very expensive to run. Indeed, it would take about two weeks to simulate one year, or 4 years to simulate a century on 64 dedicated processors of the 375-MHz IBM SP. We note, however, that such performance is comparable to the performance of a typical GCM of the early 1970s running on the fastest computers of those years. The impressive progress in the massively parallel computing technology promises much better performance in the near future.

The hybrid CCSM/CRM model represents the best that we can do in the early 21st century, given the state-of-the-art computers available today. It is still an idealized and imperfect model of real cloud processes, but it is certainly much more realistic than any conventional parameterization currently available. Much can be learned by studying how such a "super parameterization" performs in climate simulations. We can learn about the detailed physical processes, including the role of cloud microphysical processes, through which clouds feed back on climate change, as simulated by the CCSM/CRM. We can also learn how well the conventional cloud parameterizations work in the climate change applications by comparison with climate change simulations performed by the CCSM/CRM.

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