Global Consequences of Interactions between Clouds and Radiation at Scales Unresolved by Global Climate Models

J. N. S. Cole,[1] H. W. Barker,[2] D. A. Randall,[3] M. F. Khairoutdinov,[3] and E. E. Clothiaux[1]

Horizontal grid-spacings in conventional atmospheric general circulation models (GCMs) are typically between 100 km and 500 km. Hence, many processes are unresolved and must be parametrized in terms of resolved variables. Development of satisfactory parametrizations of mean-field (or domain-average) cloud and radiative processes has been frustratingly slow. Moreover, the importance of interactions between cloud and radiation at scales unresolved by conventional GCMs is unknown. In this study, the native cloud parameterization of a GCM was replaced, in each GCM grid column, by a two-dimensional cloud system-resolving model (CSRM). The CSRMs used a horizontal grid-spacing of 4 km. They were employed to assess the relative importance of accurate domain-average radiative flux profiles and interactions between cloud and radiation at unresolved scales. It is shown here that, for a simulation spanning one season, the unresolved interactions are at least as important as accurate domain-averages.

1. Introduction

Four-dimensional atmospheric general circulation models (GCMs) are important tools for testing hypotheses regarding the nature of Earth's climate, including how it might respond to external forcings such as increasing greenhouse gas concentrations *Houghton et al.* [1996]. The atmospheric component of GCMs discretize the Earth-atmosphere system into columns with horizontal grid-spacings typically $\sim$ 250 km. This leaves many processes and fluctuations unresolved and in need of parametrization. It is widely recognized that representations of unresolved, or subgrid-scale, cloud and radiative processes are sources of much uncertainty surrounding GCM-based predictions of near-future climatic change *Morcrette and Jakob* [1997]. Radiation parametrizations use profiles of cloud water mass *Tiedtke* [1993], layer cloud fraction, temperature, and humidity at scales resolved by GCMs, as well as additional assumptions, such as those related to cloud overlap, to determine cloud optical properties for computation of flux profiles averaged horizontally over each grid cell *Barker et al.* [2003].

A tacit assumption behind global modelling, so fundamental and entrenched that it resembles an axiom, is: parametrizations of subgrid-scale processes that yield unbiased estimates of domain-averages are both necessary and sufficient for satisfactory simulation of climate and climatic change. While most are likely to agree that accurate domain averages are necessary, it is not at all obvious that they are sufficient. The main point of this study is to assess the relative importance of achieving accurate domain-average flux profiles and neglecting unresolved cloud-radiation interactions.

For at least two reasons, conventional GCMs cannot be used for this study. First, GCMs supply inadequate information about unresolved clouds, and what is supplied is highly parametrized. In particular, no information is provided about the vertical overlap of fractional cloud and horizontal fluctuations of cloud water content *Wu and Moncrieff* [2001]. Second, and more importantly, conventional GCMs do not explicitly portray unresolved interactions between clouds and radiation.

For this study, a 2D Cloud System-Resolving Model (CSRM) is employed in each GCM column *Grabowski* [2001], *Khairoutdinov and Randall* [2001], *Khairoutdinov et al.* [2004]. This method has become known as the Multi-scale Modelling Framework (MMF). While this seminal version of the MMF has limitations *Randall et al.* [2003], it provides information about cloud structure that is needed for radiative transfer calculations, and affords a representation of cloud-radiation interactions that is superior to that in conventional GCMs.

2. Experimental design

The GCM used for this study is the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM - version 1.8) *Blackmon et al.* [2001]. For these experiments, the CAM was run using T42 horizontal resolution ($\sim$2.8° grid-spacing) with 26 layers reaching up to 3.5 hPa, used the semi-Lagrangian dynamical core *Williamson and Olson* [1994], and used a timestep of 1 hour. The CAM's conventional 1D cloud parametrization *Zhang et al.* [2003] was replaced, however, with a 2D CSRM *Khairoutdinov and Randall* [2003]. In other words, a CSRM was embedded in each of the CAM's 8192 columns.

Each copy of the CSRM has 64 columns with 4 km horizontal grid-spacing, and 24 layers. The CSRM solves the non-hydrostatic dynamical equations with the anelastic approximation, using a timestep of 20 s. Each CSRM was forced by large-scale tendencies updated every CAM time step, and provided horizontally averaged tendencies back to the CAM. The CSRM prognostic thermodynamic variables included liquid/ice water moist static energy, total non-precipitating water, and total precipitating water. Mixing ratios for cloud liquid, ice, rain, snow, and graupel were diagnosed as functions of temperature *Khairoutdinov and Randall* [2003]. Hydrometeor conversion rates and terminal velocities were computed using a bulk microphysics parametrization *Khairoutdinov and Randall* [2003].

The CSRM shortwave and longwave radiation parametrizations (cloud optical properties and radiative transfer) were those of the CAM *Briegleb* [1992]; *Ramanathan and Downey*

[1]The Pennsylvania State University, University Park, PA, USA
[2]Meteorological Service of Canada, Downsview, ON, Canada
[3]Colorado State University, Fort Collins, CO, USA

0094-8276/04/$5.00

[1986]. Surface properties were assumed to be constant across each CSRM domain. Solar radiative fluxes were computed using a two-stream approximation, while an emissivity approach was used for the longwave.

The radiative parameterizations were used in two configurations. The independent column approximation (ICA) was employed to compute the radiative heating rates for each of the 64 CSRM columns. The ICA uses the CSRM fields directly so it makes no assumptions about cloud overlap and horizontal variability. Accurate domain-average flux profiles were computed by averaging ICA results across the CSRM domain *Barker et al.* [2003]. Domain-averages were also computed by the CAM's 1D radiation parameterization, which uses profiles of cloud fraction, cloud water, ice cloud amount, water vapor, and temperature, in conjunction with assumptions of maximum-random overlap of homogeneous clouds *Collins* [2001], obtained by averaging across the CSRM domain for each vertical layer.

To explore the relative importance of accurate domain-average radiative flux profiles and unresolved cloud-radiation interactions, four experiments were conducted. In all experiments, radiation calculations were performed using, or based on, CSRM data sampled every 15 min. Four such calculations were performed every CAM time step, and the average of these was passed back to the CAM.

- Experiment 1 is the control simulation with the CSRMs experiencing local cloud-radiation interactions through column-by-column ICA heating rate calculations and the CAM receiving domain-mean radiative heating rate profiles obtained by averaging the CSRM column-by-column ICA results.

- Experiment 2 eliminates local cloud-radiation interactions by providing each CSRM column with domain-mean radiative heating rate profiles as computed using ICA, with the CAM still receiving ICA domain-mean radiative heating rates. That is, each CSRM column receives the same heating rate profile as the CAM.

- Experiment 3 is similar to experiment 2 except the domain-average heating rates for the CSRM and CAM are computed using the CAM's 1D radiation parameterization, which assumes clouds to be plane-parallel, homogeneous and to follow the maximum-random overlap rule.

- Experiment 4 is a combination of experiments 1 and 3; the CSRM receives local (i.e., ICA as in experiment 1) radiative heating rates, while the CAM receives radiative heating rates computed using its 1D radiation parameterization.

To summarize, experiment 1 is the control simulation, experiments 2 and 3 test the impact of accurate domain-averaged radiative heating rates without local cloud-radiation interactions in the CSRMs, and experiment 4 tests the impact of the CSRMs receiving local radiative heating rates while the CAM receives inaccurate radiative heating rates.

All simulations started on September 1 and finished on March 1. September through November was a spin-up period; the results presented here are averages for the period December through February. This means that our experiments address only the fast response of the climate system, i.e., the atmospheric portion of the hydrologic cycle. The view taken here is that if clouds are insensitive to the differences between these four experiments, there is little reason to expect slower climatic variables to respond much. Conversely, if clouds respond quickly and differently in these experiments, presumably the slower components of the system will too. Therefore, results presented in the following section focus on the response of clouds in terms of their properties and radiative effects. Cloud and radiation fields are presented here at the resolution of the GCM but as discussed above they were computed using the CSRM fields.

3. Results

For this study, a CSRM grid-cell was defined as cloudy if its cloud water mixing ratio exceeded 10^{-6} kg/kg, and a GCM grid-cell was deemed to be cloudy if it had at least one cloudy CSRM cell. The upper left plot in Fig. 1 shows time/zonal-averages of total vertically-projected cloud fractions below 700 hPa (low cloud), between 700 hPa and 400 hPa (middle cloud), and above 400 hPa (high cloud) for experiment 1. The three other plots in Fig. 1 show differences between the three experiments and experiment 1 for low, middle, and high cloud. Cloud fraction can be partitioned into cloud frequency of occurrence and mean cloud amount when present. Latitude-height plots of mean cloud amount when present for the four experiments are shown in Fig. 2. The most striking feature of Figs. 1 and 2 is that, regardless of cloud altitude, cloud fractions in experiment 2 resemble closely those in experiment 3, while those in experiment 1 resemble those in experiment 4.

At almost all latitudes, high cloud fractions are enhanced for experiments 2 and 3 relative to experiment 1; as much

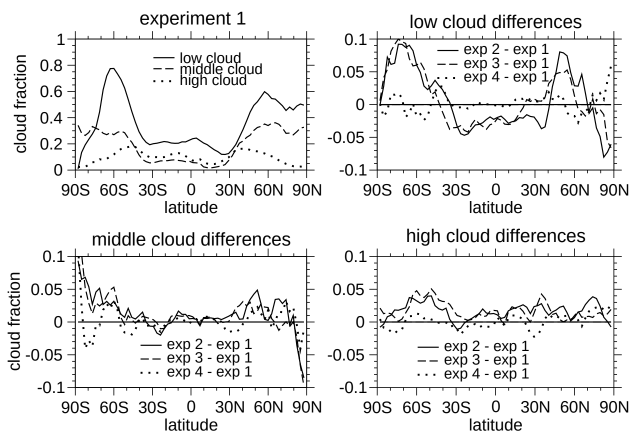

Figure 1. (upper left plot) Time/zonal-average low, middle, and high cloud fractions for the control simulation (experiment 1). (other plots) As in top left plot except these are for differences between cloud fractions for experiments 2, 3, and 4 and the control.

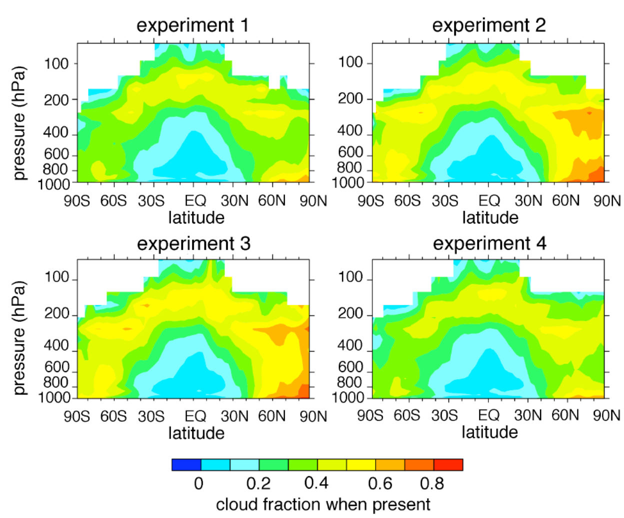

Figure 2. Latitude-height cross sections of mean cloud amount when clouds are present for the four experiments.

as by ~25% in the vicinity of 60°S. This is due in part to the increased high cloud amount when cloud develops without local cloud-radiation interactions. Small-scale structure in the radiative cooling, which is present in experiment 1 but not in experiments 2 and 3, promote small-scale convective motions that mix dry air into the cloud layer, thus tending to reduce the cloud amount. This small-scale interaction between dynamics and radiation favors the reduced high-cloud amount in experiment 1, relative to experiments 2 and 3. This is an example of the importance of local interactions between radiative heating and cloud dynamics (e.g., *Starr and Cox* [1985]).

Outside the tropics, middle and low cloud fractions for experiments 2 and 3 again exceed those for experiment 1. Notable are low cloud fractions near 70°S and 50°N, where increases are on the order of 0.1. Within the tropics, between 30°S and 30°N, low cloud fractions generated in experiment 4 are similar to experiment 1, while low cloud fractions are reduced by ~15% for experiments 2 and 3 relative to experiment 1. These reductions are due largely to decreased amounts of marine stratocumulus clouds off the west coasts of continents (not shown). In experiment 2 and 3 local cloud-radiation interactions are removed and so these results are consistent with the ideas of *Lilly* [1968] who emphasized the importance of concentrated cloud-top radiative cooling and its local interactions with cloud dynamics for the maintenance of marine stratocumulus clouds.

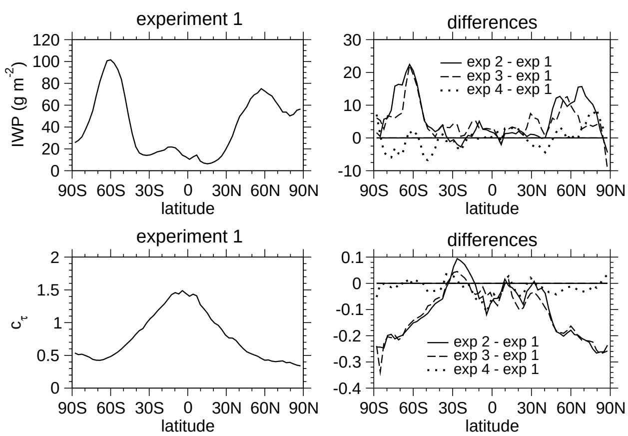

Figure 3. Plots in the left column show time/zonal-average values of cloud ice water path (IWP) and coefficient of variation for cloud visible optical depth (c_τ) for the control simulation (experiment 1). Plots in the right column correspond to those in the left column and show differences between experiments 2, 3, and 4 and the control experiment.

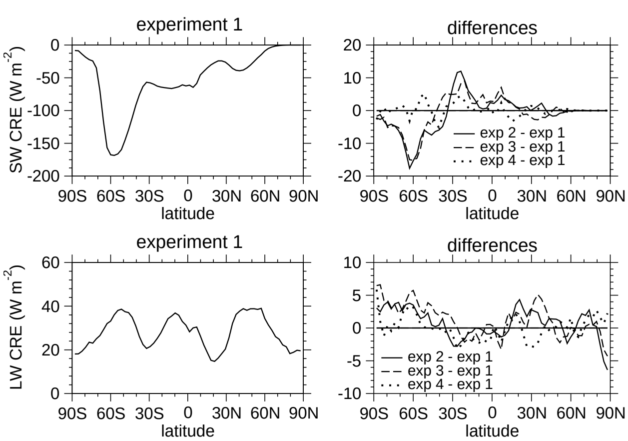

Figure 4. As in Fig. 3 except this shows results for top of atmosphere cloud radiative effects (CRE) (a.k.a. cloud radiative forcing) for shortwave (SW) and longwave (LW) fluxes.

Taken together, Figs. 1 and 2 suggest that errors in domain-average radiative heating rates by a typical GCM radiation algorithm have less impact on cloud amount than does neglect of unresolved (local) cloud-radiation interactions. It should be noted, however, that in a conventional GCM, even cloud fraction, in addition to overlap and variability, would be parametrized, and the resulting feedbacks would surely have an impact that exceeds that shown here. As mentioned earlier, cloud fractions in all four simulations came directly from the CSRM data.

Figure 3 shows time/zonal-average values for experiment 1 of cloud ice water path (IWP) and coefficient of variation for visible cloud optical depth τ, which is defined as $c_\tau = \sigma_\tau / < \tau >$ where $< \tau >$ is the mean of τ and σ_τ is its standard deviation (computed using all cloudy CSRM columns inside a GCM column). Zonal/time averages were computed using vertically-projected total cloud fraction as a weighting factor. Also shown are differences between experiments 2, 3, and 4 and experiment 1. Poleward of about 45° latitude, values of IWP for experiments 2 and 3 exceed those of experiments 1 and 4 by 10 g m^{-2} to 20 g m^{-2} or about 15% to 25%. This increase in IWP is in general agreement with the results of *Petch and Gray* [2001] for stand-alone CSRM experiments for tropical oceanic conditions.

Differences in cloud liquid water paths (not shown) are generally smaller and more erratic than those for IWP, and there is less correlation between errors for experiments 2 and 3. Presumably this means either that errors in domain-averages fluxes and omission of cloud-radiation interactions are fairly comparable for liquid clouds, or that both have little impact. Differences in c_τ are much clearer: again, experiment 4 resembles experiment 1 while experiments 2 and 3 exhibit much smaller values of c_τ poleward of about 40° latitude, commensurate with their larger values of IWP. In fact, for experiments 2 and 3, c_τ at high latitudes was reduced to only about 0.25 on average, meaning that these clouds were very uniform. Evidently, in these regions local cloud-radiation interactions lead to the development of clouds that are more variable and broken, and less extensive.

Figure 4 shows time/zonal-averages of shortwave (SW) and longwave (LW) cloud radiative effects (CREs) at the top of the atmosphere *Ramanathan et al.* [1989] for experiment 1. It also shows differences between the other experiments and experiment 1. Since the CRE is the difference between all-sky and clear-sky radiative fluxes, it is a convenient diagnostic measure that brings together the overall impact of changes to cloud properties discussed so far. As expected, experiments 2 and 3 track each other well and differ from experiment 1 by as much as -16 W m^{-2} for SW CRE near 60°S. These enhanced values of all-sky albedo for experiments 2 and 3 stem from increases in cloud amount (see Figs. 1 and 2), increases in cloud IWP (see Fig. 3), and decreases in the horizontal variability of the cloud (see Fig. 3), all of which conspire to increase cloud albedo *Carlin et al.* [2002]. Equatorward of 30° latitude, SW CREs for experiments 2 and 3 are more positive than for experiment 1. This is due to reductions in low cloud fraction relative to experiment 1, as shown in Fig. 1, as well as slight reductions in LWP (not shown).

Differences in LW CRE at the TOA can be produced most easily in the tropics due to the warm surface and cold high clouds. These differences are much smaller than their SW counterparts however, because differences among all experiments for high cloud properties in the tropics are relatively small. The largest differences in LW CRE are between experiments 1 and 2 and occur over Antarctica and near 30° N. These are due to large differences in ice cloud fractions as well as IWP.

4. Concluding Remarks

The GCM community accepts that to achieve successful simulations of global climate and climatic change, it is necessary that subgrid-scale parametrization schemes yield unbiased estimates of domain-averages. This by itself is a tall order given the coarse-grain portrayal of Earth by GCMs. Rarely is it asked, however, whether accurate domain averages are sufficient for successful climate modelling. In this study, a GCM's conventional cloud fraction and cloud-overlap parametrizations were replaced with cloud system-resolving models and the independent column approximation for radiative transfer. This provided the opportunity to investigate whether unresolved interactions between clouds and radiation are important for successful GCM simulations. Our results show that they are.

This finding raises the bar for conventional parametrizations: not only must they yield unbiased domain-averaged radiation fluxes (which almost all parametrizations fail to do *Barker et al.* [2003]; *Stephens et al.* [2004]), they must also represent local interactions among parametrized processes. This is a tremendous challenge because it implies that in conventional GCMs the parametrizations of cloud amount, radiative transfer, and cloud-scale dynamics must be coupled, and their equations solved simultaneously.

These closing remarks do not imply that climate simulations made by conventional GCMs are fundamentally wrong. At the same time, however, we would not be surprised if important details of the predictions were to be altered by the inclusion of unresolved interactions between parametrized processes.

Acknowledgments. We thank T. Ackerman, S. Krueger and R. Pincus for helpful discussions. This work was supported by the US-DOE ARM programme (grant number DE-FG02-02ER63370 to Colorado State University, grant number DE-FG02-90ER61071 to The Pennsylvania State University and grant number DE-FG02-03ER63521 to the Meteorological Service of Canada), the Canadian Foundation for Climate and Atmospheric Sciences, the Meteorological Service of Canada, and the Natural Sciences and Engineering Research Council.

References

Barker, H. W., et al. (2003), Assessing 1D atmospheric solar radiative transfer models: Interpretation and handling of unresolved clouds, *J. Climate*, *16*, 2676–2699.

Blackmon, M., et al. (2001), The Community Climate System Model, *Mon. Wea. Rev.*, *82*, 2357–2376.

Briegleb, B. P. (1992), Delta-eddington approximation for solar radiation in the NCAR community climate model, *J. Geophys. Res.*, *97*(D7), 7603–7612.

Carlin, B., Q. Fu, U. Lohmann, G. G. Mace, K. Sassen, and J. M. Comstock (2002), High-cloud horizontal inhomogeneity and solar albedo bias, *J. Climate*, *15*, 2321–2339.

Collins, W. D. (2001), Parameterization of generalized cloud overlap for radiative calculations in general circulation models, *J. Atmos. Sci.*, *58*, 3224–3242.

Grabowski, W. W. (2001), Coupling cloud processes with the large-scale dynamics using the cloud-resolving convection parameterization (CRCP), *J. Atmos. Sci.*, *58*, 978–997.

Houghton, J. T., L. G. M. Filho, B. A. Callender, N. Harris, A. Kattenberg, and K. Maskell (Eds.) (1996), *Intergovernmental Panel on Climate Change (IPCC). Climate Change 1995: The Science of Climate Change*, Cambridge University Press, New York.

Khairoutdinov, M. F., and D. A. Randall (2001), A cloud resolving model as a cloud parameterization in the NCAR Community Climate System Model: Preliminary results, *Geophys. Res. Lett.*, *18*, 3617–3620.

Khairoutdinov, M. F., and D. A. Randall (2003), Cloud resolving modeling of the ARM summer 1997 IOP: Model formualation, results, uncertainties, and sensitivities, *J. Atmos. Sci.*, *60*, 607–625.

Khairoutdinov, M. F., D. A. Randall, and C. DeMotte (2004), Simulations of the atmospheric general circulation using a cloud-resolving model as a super-parameterization of physical processes, *J. Atmos. Sci.*, submitted.

Lilly, D. K. (1968), Models of cloud-topped mixed layers under a strong inversion, *Q. J. Royal Meteor. Soc.*, *94*, 292–309.

Morcrette, J.-J., and C. Jakob (1997), The response of the ECMWF model to changes in the cloud overlap assumption, *Mon. Wea. Rev.*, *128*, 1701–1732.

Petch, J. C., and M. E. B. Gray (2001), Sensitivity studies using a cloud-resolving model simulation of the tropical west pacific, *Q. J. R. Meteorol. Soc.*, *127*, 2287–2306.

Ramanathan, V., and P. A. Downey (1986), A nonisothermal emissivity and absorptivity formulation for water vapor, *J. Geophys. Res.*, *91*, 8649–8666.

Ramanathan, V., R. D. Cess, E. F. Harrison, P. Minnis, B. R. E. Barkstrom, E. Ahmad, and D. H. D. (1989), Cloud-radiative forcing and climate: Results from the earth radiation budget experiment, *Science*, *243*, 57–63.

Randall, D. A., M. F. Khairoutdinov, A. Arakawa, and W. W. Grabowski (2003), Breaking the cloud-parameterization deadlock, *Bull. Amer. Meteor. Soc.*, *84*, 1547–1564.

Starr, D. O., and S. K. Cox (1985), Cirrus clouds. Part II: Numerical experiments on the formation and maintenance of cirrus, *J. Atmos. Sci.*, *42*(23), 2682–2694.

Stephens, G. L., N. B. Wood, and P. M. Gabriel (2004), An assessment of the parameterization of subgrid-scale cloud effects on radiative transfer. Part I: Vertical overlap, *J. Atmos. Sci.*, *61*, 715–732.

Tiedtke, M. (1993), Representation of clouds in large-scale models, *Mon. Wea. Rev.*, *121*, 3040–3061.

Williamson, D. L., and J. G. Olson (1994), Climate simulations with a semi-lagrangian version of the NCAR community climate model, *Mon. Wea. Rev.*, *122*, 1594–1610.

Wu, X., and M. W. Moncrieff (2001), Long-term behavior of cloud systems in TOGA COARE and their interactions with radiative and surface processes. Part III: Effects on the energy budget and sst, *J. Atmos. Sci.*, *58*, 1155–1168.

Zhang, M., W. Lin, C. S. Bretherton, J. J. Hack, and P. Rasch (2003), A modified formulation of fractional stratiform condensation rate in the NCAR community atmospheric model CAM2, *J. Geophys. Res.*, *D1*(108), 4035, doi: 10.1029/2002JD002523.

Dr. Howard Barker, Meteorological Service of Canada, Cloud Physics and Severe Weather Research Division, 4905 Dufferin St. Downsview, ON, Canada, M3H 5T4. (howard.barker@ec.gc.ca)