GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L02809, doi:10.1029/2004GL021024, 2005

A new approach for 3D cloud-resolving simulations of large-scale atmospheric circulation

Zhiming Kuang, Peter N. Blossey, and Christopher S. Bretherton

Department of Atmospheric Sciences, University of Washington, Seattle, Washington, USA

Received 15 July 2004; revised 10 December 2004; accepted 16 December 2004; published 27 January 2005.

[1] We present a computationally efficient new method for simulating the interactions of large-scale atmospheric circulations with deep convection in a 3D cloud-resolving model. This is accomplished by reducing the scale difference between the large-scale and convective circulations. Our method, Diabatic Acceleration and REscaling (DARE), consists of accelerating all diabatic processes, reducing the planetary radius and increasing its rotation rate. A second useful interpretation of this rescaling, Reduced Acceleration in the VErtical (RAVE) is also presented briefly. The DARE/RAVE approach is expected to be useful for a wide range of problems involving interactions between large-scale circulation, deep convection, and associated cloud and radiation processes, whose investigation has long been plagued by deficiencies in cumulus/cloud parameterizations. Initial results from a near-global scale equatorial β-plane simulation using the DARE approach are briefly presented.

Citation: Kuang, Z., P. N. Blossey, and C. S. Bretherton (2005), A new approach for 3D cloud-resolving simulations of large-scale atmospheric circulation, *Geophys. Res. Lett.*, *32*, L02809, doi:10.1029/2004GL021024.

1. Introduction

[2] Cumulus convection and the associated cloud processes are of fundamental importance to atmospheric circulation, especially in the tropics. Models for large-scale circulation rely on parameterizations to represent the effects of these processes. However, despite decades of intense research and significant progress, deficiencies in cumulus/cloud parameterizations continue to plague studies of atmospheric circulation [*Randall et al.*, 2003]. Given the extreme complexity involved, satisfactory parameterizations may not be available for many more decades to come and in fact may not be achievable in the end. At the same time, cumulus/cloud-resolving models (CRMs) have been increasingly used to study cumulus convection in limited domains. While these models still parameterize microphysical processes, they resolve at least the largest cumulus scale motions and represent a much more direct approach than conventional parameterizations. Unfortunately, as the dominant scale for cumulus motions is typically of the order of the boundary layer depth (a couple of kilometers), resolving the 3D large-scale atmospheric circulation down to the cumulus scale, as in a global CRM, requires a computing capacity that is also decades away. Research involving the interaction between large-scale circulation and cumulus/cloud processes is thus in a situation where no satisfactory tools appear available in the near future.

[3] As an attempt to break this ‘‘deadlock’’, Grabowski proposed the Cloud Resolving Convection Parameterization (CRCP) approach, where a CRM is embedded in every grid cell of a large-scale model, such as a general circulation model (GCM), and replaces the conventional parameterizations of convective and cloud processes [*Grabowski*, 2001]. Relative to a global CRM, the computational cost is reduced by using either a 2D or 3D CRM that expands a small portion of a GCM grid cell as a ‘‘sample’’ of the cell. This approach is very attractive as it circumvents the extremely difficult cumulus parameterization problem and is feasible with the current computing capabilities. Initial results using this approach, also called superparameterization, are quite encouraging [*Khairoutdinov and Randall*, 2001]. However, CRCP inherits the artificial scale separation from conventional parameterizations. Namely, the CRMs in different GCM grid cells are independent of each other. While this has some computational advantage in terms of parallelization, it does not allow cloud systems formed in one grid cell to directly propagate into adjacent cells. For this reason, CRCP simulations are unable to represent the coupling between convection and wave dynamics as simulated by the CRM [*Grabowski*, 2001] and do not converge to a global CRM as the resolution of the GCM is refined.

[4] Arakawa outlined an approach to address these limitations [*Randall et al.*, 2003]. His approach may be viewed as a sparse net of 2D CRMs augmented by a GCM. The reduction of computational cost here comes from using two orthogonal 2D CRMs to represent the 3D cloud processes. While this approach has much appeal, it is limited by the extent to which 2D CRMs can simulate 3D cloud processes. It is well known that the 2D geometry tends to exaggerate wave-mean flow interactions and excite artificial oscillations in the mean flow [*Held et al.*, 1993]. This was also seen in the CRCP simulations [*Grabowski*, 2001]. Even when these oscillations are suppressed by constraining the mean flow, the long term behavior of a 2D CRM still differs substantially from that of a 3D CRM, because of the effect of the 2D geometry on downdrafts and convective organization [*Tompkins*, 2000].

2. The DARE Approach

[5] In this paper, we present a Diabatic Acceleration and REscaling (DARE) approach which allows computationally efficient 3D cloud-resolving simulations of the interaction of large-scale atmospheric circulation with deep convection. Distinct from existing approaches, the DARE approach reduces the computational cost by *reducing the scale difference between the large-scale circulation and deep*

0094-8276/05/2004GL021024$05.00

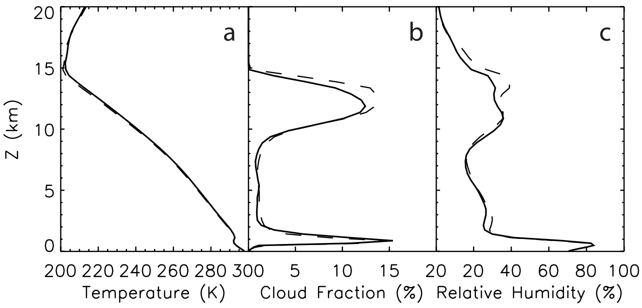

Figure 1. RCE profiles of (a) temperature, (b) cloud fraction, and (c) relative humidity from the control experiment (solid) and the DARE approach (dashed).

cumulus convection, since this wide scale difference is precisely what makes cloud-resolving simulations of large-scale atmospheric circulation so computationally expensive. In DARE, we reduce the scales of the large-scale circulation by increasing the Earth's rotation rate by a factor of γ and reducing the Earth's size by the same factor (REscaling). This reduces both the spatial and temporal scales of the large-scale circulation (i.e., the deformation radius and the Rossby adjustment time) by γ, as in *Smolarkiewicz et al.* [1998]. In order to correctly represent the interaction between the rescaled large-scale circulation and deep convection, the response time of deep convection needs to be shortened by the same proportion. This is accomplished by increasing the radiative fluxes, surface heat/moisture/momentum fluxes, the speed of all microphysical processes, and the precipitation fall velocities by the same factor γ (Diabatic Acceleration). We shall refer to γ as the DARE factor. As γ approaches unity, the DARE simulation converges smoothly to a global CRM.

[6] The usefulness of DARE depends on two assumptions. The first assumption is that DARE convection is able to (a) reproduce the response to large-scale forcing and (b) not drastically change the simulated large-scale atmospheric state (such as temperature, moisture, clouds, and horizontal winds). This assumption is tested in the next section. The second assumption is that interaction between large-scale circulation and deep cumulus convection is approximately unchanged when the separation between the two scales is reduced, provided that the two scales remain well separated. This is somewhat analogous to the assumption that the behavior of turbulence tends to become independent of the Reynolds number provided that the Reynolds number is sufficiently high. Given the substantial scale difference between the large-scale circulation (thousands of kilometers) and the cumulus-scale motions (a few kilometers) in the atmosphere, the two scales remain well separated with a γ of order 10, which provides a reduction in computational cost on the order of 1000.

[7] While the experiments to be presented in this paper are implemented in terms of Diabatic Acceleration and REscaling, it can be shown that the DARE approach is equivalent to changing the vertical momentum equation into:

$$\gamma^2 \frac{Dw}{Dt} = -\frac{\partial p'}{\rho \partial z} + B \tag{1}$$

where D/Dt denotes material derivative, and B is buoyancy. All the other equations remain unchanged from the standard ones. With $\gamma > 1$, this amounts to reducing the vertical acceleration. This interpretation, named Reduced Acceleration in the VErtical (RAVE), offers additional insights to the present approach and its biases and limitations, and is currently being explored. The results will be presented in a future paper.

3. Evaluation of the DARE Approach

[8] To evaluate the usefulness of the DARE approach, we shall compare results from the DARE approach with those from the normal CRM approach. The CRM used in this study is the System for Atmospheric Modeling (SAM), a new version of the Colorado State University Large Eddy Simulation/Cloud Resolving Model [*Khairoutdinov and Randall*, 2003]. The readers are referred to that paper for details about the model.

[9] First, we conducted a radiative-convective equilibrium (RCE) experiment with the normal (or control) CRM settings over a 301 K-ocean surface, with interactive radiation and surface fluxes, and zero mean wind. The domain is 192 × 192 grid points with a 3 km resolution and doubly periodic in the horizontal. The vertical resolution varies from 75 m near the surface to 500 m in the bulk troposphere, with the domain top at 32 km. The experiment is repeated using the DARE approach with a DARE factor of 4. All else remains the same except that a domain of 48 × 48 grid points is used (i.e., the domain is smaller by the DARE factor in both horizontal directions). A DARE factor of 4 is used mainly because for large DARE factors, a DARE simulation with a reasonable number of gridpoints would require comparison with a prohibitively large control simulation. In both cases, convection self-organizes into a convective and a non-convective region. The resulting patterns of convective organization are remarkably similar in the two cases (not shown). Figure 1 shows that the DARE approach reproduces the domain averaged RCE temperature, cloud fraction and relative humidity profiles from the normal CRM quite well. The inversion near 1 km is well-captured in all three fields. Since stronger and more updrafts are needed to accommodate the diabatic acceleration, cloud fraction and relative humidity in the upper troposphere are slightly higher in the DARE approach. However, given the uncertainties in the microphysics parameterization, which can easily give rise to differences of this or larger magnitude, the agreement in Figure 1 should be viewed as evidence that the diabatic acceleration does not drastically change the simulated mean atmospheric state.

[10] To evaluate whether the response of a normal CRM to large-scale forcing is reproduced by diabatically accelerated convection subject to the rescaled large-scale forcing, we imposed periodic large-scale lifting in both experiments starting from the end of the RCE simulations. The shape of the large-scale lifting used is similar to that of the weak forcing case in Figure 1a of *Xu et al.* [1992], which is typical of tropical synoptic disturbances. The forcing varies with time t as $[1 - \cos(2\pi t/T)]/2$. In the normal CRM, the period T is 3 days and the peak vertical velocity is 3 cm/s, while both are rescaled in the DARE approach (the period is reduced and the vertical velocity increased by a factor of γ). The responses of the domain averaged outgoing longwave radiation (OLR) and precipitation are shown in Figures 2a and 2b, respectively. The times of the DARE simulation

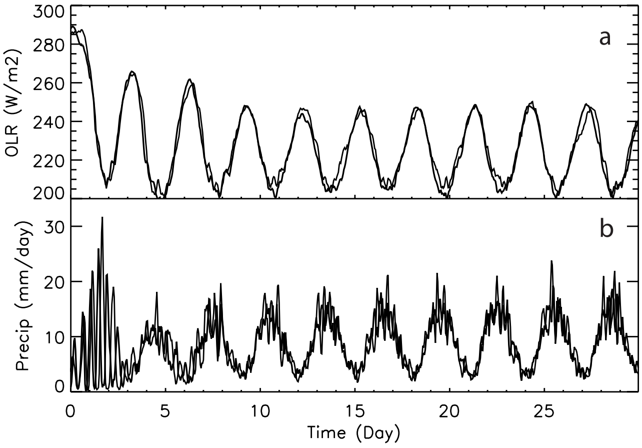

Figure 2. Hourly averaged responses of domain averaged OLR and precipitation to an imposed 3-day periodic large scale lifting in the control (thick) and the DARE (thin) simulations. All variables, including time, from the DARE simulation have been scaled back for the comparison.

have been scaled back for comparison. The excellent agreement between the two experiments confirms that diabatically accelerated convection with rescaled large-scale forcing indeed reproduces the response of natural convection.

[11] We have now demonstrated that *a DARE simulation can mimic the behavior of a normal CRM simulation* γ *times wider in both horizontal directions and* γ *times longer in time*. While the cases considered here do not include large-scale dynamics, its addition is not expected to alter this conclusion because the equations for large-scale hydrostatic motions are unaltered by the rescaling (i.e., $Dw/Dt = 0$ in equation (1)).

4. An Equatorial β-Plane Simulation

[12] We now present some initial results from an equatorial β-plane simulation with a DARE factor of 10, and demonstrate that the DARE approach can produce very physical circulations that share many of the features of those on the Earth. In particular, we wish to show that DARE is a useful approach for problems such as the position of the ITCZ, convectively-coupled waves and the Madden-Julian Oscillation (MJO), studies of which have been particularly plagued by uncertainties in cumulus parameterization. Detailed discussions of these specific problems, however, will be deferred to later publications.

[13] For this experiment, we use a 4 km horizontal resolution, which is marginal in resolving deep convection. The vertical grid size ranges from 125 m near the surface to 800 m in the upper troposphere, with the domain top at ~29 km. The domain has 512 grid points zonally with periodic boundary conditions, and 288 grid points meridionally bounded by solid walls. This may be viewed as a miniature version of a full-sized equatorial β-plane that extends 5760 km (~52°) on each side of the equator and covers about half of the equatorial circle. A 15 meter mixed layer ocean was used with no imposed ocean heat flux. In the figures and discussions to follow, all quantities are scaled back to facilitate discussion. The model was run for 375 days (37.5 model days) and output twice a day. The results presented in Figures 3, 4, and 5 are based on data from the last 300 days. It is important to remember that these initial results are presented as a proof of concept, and their dependence on numerics, resolution, as well as microphysics, radiation, and subgrid-scale parameterizations will be examined in future studies.

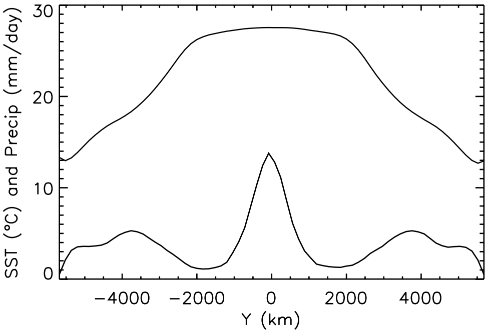

Figure 3. Latitudinal distributions of the time mean zonal mean SST (thick) and precipitation (thin).

[14] The zonally averaged SST and precipitation are shown in Figure 3. The SST distribution has a slight maximum on the equator, and decreases by ~0.3°C from the equator to 10°N/S. A single ITCZ forms on the equator, with a maximum precipitation rate of 14 mm/day. In a separate fixed-SST experiment where the SST distribution is essentially flat within 10°N/S (the decrease from the equator to 10°N/S is ~0.1°C), the single ITCZ is replaced by two weaker ones at 7°N/S.

[15] The zonally averaged zonal wind fields feature equatorial easterlies and westerly jets at ~28°N/S near 200 hPa with surface westerly maxima displaced slightly poleward

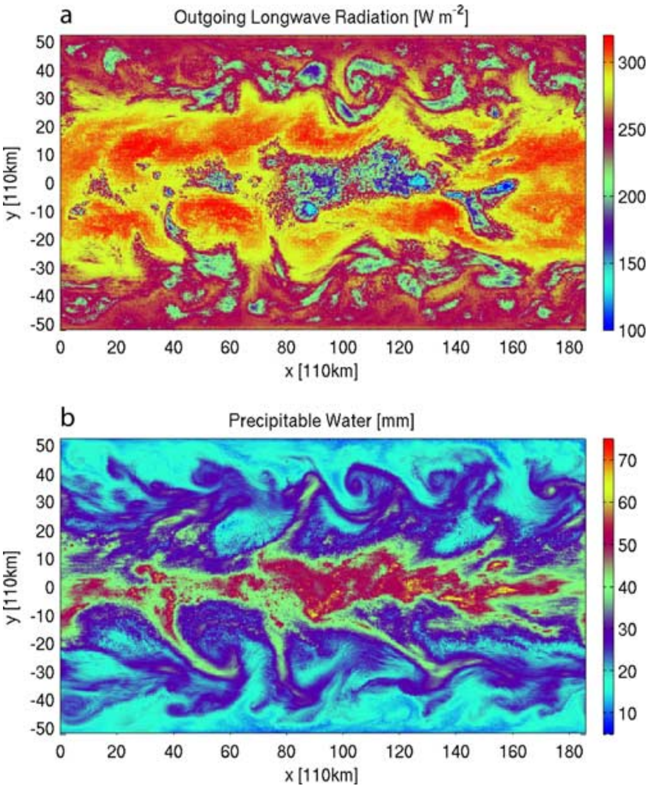

Figure 4. Examples of the simulated (a) OLR and (b) precipitable water fields, averaged over half a day (0.05 model days).

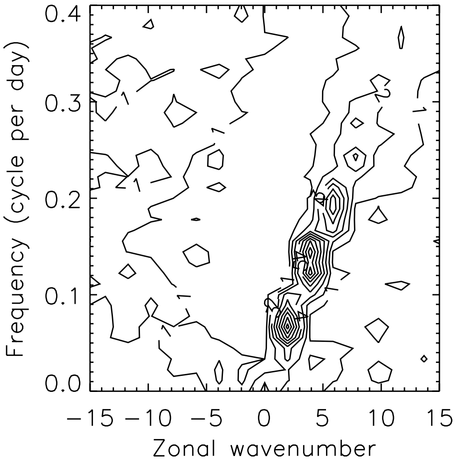

Figure 5. Symmetric OLR power divided by the background power, constructed following *Wheeler and Kiladis* [1999] except with a temporal window of 45 instead of 96 days. The contour interval is 1. The zonal wavenumber is scaled back to that of the Earth so the lowest wavenumber is ~2.

(not shown), similar to that from a GCM study on a water-covered Earth using a moist convective adjustment scheme [*Hess et al.*, 1993]. The simulated OLR and precipitable water fields (Figure 4) resemble those observed for the terrestrial atmosphere, including tropical cloud systems, extratropical eddies and their associated frontal cloud systems.

[16] In the single ITCZ case, Kelvin waves dominate the spectrum of convectively-coupled waves (Figure 5). (In the experiment where a double ITCZ formed, n = 0 mixed Rossby-gravity waves are evident). The phase speed of the simulated Kelvin waves is ~16 m/s, in line with observations. While not shown here, spatial patterns of the OLR and the dynamical fields and their phase relations have a forced Kelvin-Rossby wave structure, as in the observations [e.g., *Wheeler and Kiladis*, 1999]. The vertical structures also agree well with composites using radiosonde data (but not those using reanalysis data) [*Straub and Kiladis*, 2003].

[17] There is no evidence for zonally propagating intraseasonal oscillations, or MJOs, in this simulation, in contrast to previous studies with a similar experimental setup but using parameterized convection [*Raymond*, 2001]. The zonally averaged equatorial precipitation, OLR, SST, etc., however, do exhibit significant variations with a period of ~90 days (not shown). The relevance of this variation to MJO when zonal asymmetry is introduced is currently being investigated.

5. Summary

[18] Based on the above results, we conclude that the DARE approach provides a valuable tool for studying the interaction between deep convection and large-scale circulation. One important advantage over parameterizations (including CRCP) is that DARE allows natural scale interaction between cumulus motions and the large-scale circulation, even though the scale separation between the two has been reduced.

[19] As our approach does not modify the large-scale hydrostatic motions, when Dw/Dt = 0 in equation (1), it should work not only for an equatorial β-plane but also for global dynamics with spherical geometry. We have not yet tried to use DARE/RAVE over a land surface or to include topography, though we see no reason why this should not be possible. Furthermore, coupling a DARE/RAVE atmosphere with an eddy-resolving ocean appears an attractive way of modeling the coupled atmosphere-ocean system. Thus, while we have emphasized in this paper such problems as convectively coupled waves, the ITCZ, and the MJO, our approach is expected to be useful in a wide range of problems involving the interaction between deep convection/cloud processes and large scale circulation, including climate change simulations and numerical weather prediction. For example, problems such as cloud/water vapor feedbacks, which have been long plagued by parameterization issues, can be expected to benefit from the 3D cloud-resolving studies enabled by the DARE/RAVE approach. The comparative advantages of our approach versus Arakawa's proposal depend on whether the 3D DARE/RAVE simulation performs better than the 2D CRM approach. Finally, it is important to point out that our approach and Arakawa's approach are not at all mutually exclusive. We should be able to combine the two (which does not appear to present any difficulties), and enjoy the benefits of both.

[20] **Acknowledgments.** We thank M. Khairoutdinov for making SAM available. Kuang was supported by a NOAA Global and Climate Change postdoctoral fellowship.

References

Grabowski, W. W. (2001), Coupling cloud processes with the large-scale dynamics using the cloud-resolving convection parameterization (CRCP), *J. Atmos. Sci.*, *58*(9), 978–997.

Held, I. M., R. S. Hemler, and V. Ramaswamy (1993), Radiative convective equilibrium with explicit 2-dimensional moist convection, *J. Atmos. Sci.*, *50*(23), 3909–3927.

Hess, P. G., D. S. Battisti, and P. J. Rasch (1993), Maintenance of the intertropical convergence zones and the large-scale tropical circulation on a water-covered Earth, *J. Atmos. Sci.*, *50*(5), 691–713.

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.*, *28*(18), 3617–3620.

Khairoutdinov, M. F., and D. A. Randall (2003), Cloud resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties, and sensitivities, *J. Atmos. Sci.*, *60*(4), 607–625.

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski (2003), Breaking the cloud parameterization deadlock, *Bull. Am. Meteorol. Soc.*, *84*(11), 1547–1564.

Raymond, D. J. (2001), A new model of the Madden-Julian oscillation, *J. Atmos. Sci.*, *58*(18), 2807–2819.

Smolarkiewicz, P. K., V. Grubisic, L. G. Margolin, and A. A. Wyszogrodzki (1998), Forward-in-time differencing for fluids: Nonhydrostatic modeling of fluid motions on a sphere, paper presented at 1998 ECMWF Seminar on Recent Developments in Numerical Methods for Atmospheric Modelling, Eur. Cent. for Medium-Range Weather Forecasts, Reading, U. K.

Straub, K. H., and G. N. Kiladis (2003), The observed structure of convectively coupled Kelvin waves: Comparison with simple models of coupled wave instability, *J. Atmos. Sci.*, *60*(14), 1655–1668.

Tompkins, A. M. (2000), The impact of dimensionality on long-term cloud-resolving model simulations, *Mon. Weather Rev.*, *128*(5), 1521–1535.

Wheeler, M., and G. N. Kiladis (1999), Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber-frequency domain, *J. Atmos. Sci.*, *56*(3), 374–399.

Xu, K. M., A. Arakawa, and S. K. Krueger (1992), The macroscopic behavior of cumulus ensembles simulated by a cumulus ensemble model, *J. Atmos. Sci.*, *49*(24), 2402–2420.

P. N. Blossey, C. S. Bretherton, and Z. Kuang, Department of Atmospheric Sciences, University of Washington, Seattle, WA 98195-1640, USA. (kzm@atmos.washington.edu)