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Large-scale organization of moist convection in idealized aquaplanet simulations

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SUMMARY

This paper discusses results from idealized simulations using a non-hydrostatic general circulation model with Cloud-Resolving Convection Parameterization (CRCP, the 'super parameterization') pertinent to the large-scale organization of tropical convection. The essence of tropical dynamics is the intricate balance between large-scale processes—such as radiative transfer, large-scale waves, monsoons, Hadley and Walker circulations—and the convective dynamics. Traditional approaches to this problem consider either large-scale models using convection parameterization or cloud-resolving models in which large-scale effects are prescribed. The CRCP merges the two approaches. It uses a 2D cloud-resolving model to represent the impact of cloud-scale processes—such as convective motions, precipitation formation and fallout, interaction of clouds with radiative and surface processes—in every column of a large-scale or global model. The global CRCP model is applied to the idealized problem of a rotating constant-SST aquaplanet in convective–radiative equilibrium. The aquaplanet has the size and rate of rotation of the Earth. The global CRCP simulations feature pronounced large-scale organization of convection within the equatorial waveguide. Prominent equatorial 'super cloud clusters' spontaneously develop in CRCP global simulations and bear a strong resemblance to the Madden–Julian Oscillation observed in the terrestrial tropics. Model results suggest that convective transport of zonal momentum, supposedly due to the impact of organized convection, plays a significant role in the large-scale organization of tropical deep convection. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: moist convection; equatorial waveguide; global modelling; subgrid-scale models

1. INTRODUCTION

Tropics cover a significant part of the Earth's surface and play an important role in the Earth's climate system. Yet the dynamics of the tropical atmosphere are poorly understood when compared to the dynamics of the middle latitudes. This is because in the tropics—unlike in the middle latitudes where rotational effects dominate—the large-scale dynamics depend critically on the diabatic processes through which the atmosphere exchanges energy with the

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underlying surface and space aloft. Among various diabatic energy transfer mechanisms, moist convection plays an essential role. Most of the energy available to drive tropical circulations originates as latent heat associated with the evaporation from the ocean surface. This latent heat is released within updraft cores of convective clouds. In turn, convective processes affect the exchange of heat, water and momentum between the atmosphere and the ocean and have a strong impact on solar and terrestrial radiative fluxes. Modelling all these processes requires a horizontal grid spacing of ~ 1 km over horizontal areas of $\mathcal{O}(10^8)\ \mathrm{km}^2$. Thus, it is not surprising that representing tropical moist convection in large-scale and climate models is one of the most fundamental and outstanding problems in atmospheric CFD.

The paradigm described above is typical in many areas of CFD. For instance, engineering reactive flows involve many decades of spatial scales separating the large-scale flow from the dissipation scales (the Kolmogorov and Batchelor microscales). Since these dissipative processes are essential for the volume-averaged rates of chemical reactions, an adequate representation of the microscale processes and associated chemical reactions is vital. One possible approach, the linear eddy model [13], a simple 1D analogue of turbulent stirring and molecular diffusion, appears particularly effective when applied inside every gridbox of the resolved large-scale flow to represent subgrid-scale turbulent mixing and chemical reactions [22]. The computational approach applied herein bears conceptual similarity to the idea of the linear eddy model.

Convective–radiative quasi-equilibrium, a balance between radiative processes and moist convection, is a simple paradigm for the dynamics of the tropical atmosphere. Because absorption of solar (short-wave) radiation is small in the atmosphere, radiative processes destabilize the troposphere as a result of the emission of terrestrial (long-wave) radiation. Moist convection, on the other hand, stabilizes the column through the release of latent heat of condensation and vertical redistribution of energy due to convective motions. Deep convection, spanning the entire depth of the troposphere, is a key factor in the energy and water budgets in the tropics.

Tropical deep convection is observed to be organized on a hierarchy of scales ranging from a single cumulus (a few kilometres) up to intraseasonal oscillations (thousands of kilometres). At intermediate scales, referred to as the mesoscale (say, 50–500km), deep convection is often organized into mesoscale convective systems. These systems are long-lived, coherent ensembles of deep convection and attendant clouds organized in two primary regimes: (i) a leading, typically multicellular convective region consisting of strong cumulonimbus and (ii) a stratiform region with an accompanying mesoscale circulation (see Reference [26] for a review, also Reference [12] and references therein). The mid- to upper-tropospheric stratiform region may lead or trail the system or even extend in both directions depending on the vertical shear of the horizontal wind. For the most part, the vertical windshear controls the organization of deep convection into mesoscale convective systems. The dynamics of these systems are fairly well understood, in great part because of the importance of similar systems outside the tropics, such as summertime convective systems over the central United States. An outstanding feature of organized convection is its impact on the horizontal momentum field (e.g. Reference [23]). This issue, however, is seldom considered in traditional convection parameterizations.

Intraseasonal oscillations, on the other hand, are associated with global-scale patterns. The most spectacular example is the so-called Madden–Julian Oscillation (MJO, Reference [19] and references therein). MJO is a large-scale perturbation (zonal wavenumber 1–2) of surface pressure, cloudiness, precipitation, and winds discovered by Madden and Julian in the early seventies by a careful analysis of tropical sounding data, and subsequently confirmed by satellite observations of tropical cloudiness (e.g. Reference [24]). Since its discovery, MJO has drawn considerable interest from both the weather forecasting and climate communities. MJO dominates the intraseasonal variability in the tropics, but it does impact the extratropics as well. Moreover, its role in longer-timescale climate variations, such as the famous El Niño Southern Oscillation (ENSO), remains unclear. MJO affects convection and surface winds only over the warm waters of the Indian Ocean and the tropical western Pacific, whereas the upper-tropospheric winds show the global impact. MJO propagates west-to-east with typical speeds between 5 and $10\,\mathrm{m\,s^{-1}}$, i.e. it circumnavigates the Earth in several tens of days. Besides MJO, a rich variety of equatorially-trapped convectively-coupled waves (such as Rossby, Kelvin, mixed Rossby-gravity, etc.) affect the large-scale organization of convection in the tropics (cf. References [31, 32]).

A wide range of physical processes, such as cloud dynamics and microphysics, gravity wave dynamics, radiative transfer, equatorial waveguide dynamics, and atmosphere–ocean interaction, are likely involved in the organization process. However, despite vigorous research in the past few decades, this multi-scale organization and, more generally, the coupling of convection with large-scale tropical dynamics, remains enigmatic. In particular, there is no generally accepted theory that accounts for tropical intraseasonal oscillations and MJO. The major impediment is the vast range of interacting scales involved. In numerical modelling, the spectrum of scales can be truncated by using convective parameterization, which is how the coupling between convection and large-scale dynamics has traditionally been examined (e.g. References [2–4, 11, 15, 16, 25]). However, the results are compromised by their sensitivity to the particular parameterization scheme employed [2, 17, 20, 27].

This paper illustrates application of a novel computational approach to the problem of coupling moist convection and large-scale dynamics. A simple dynamical system is considered: a rotating planet, with the same size and rotation as Earth, covered with the ocean (an aquaplanet), and having a uniform sea surface temperature (SST) with a value similar to the tropical ocean on Earth. In such a set-up, complications of land masses (responsible for monsoon circulations and topographically generated large-scale waves) as well as zonal and meridional SST gradients (which drive the Hadley and Walker circulations and are responsible for the baroclinic effects essential for extratropical weather systems) are all ignored.

The new approach, referred to as the Cloud-Resolving Convection Parameterization (CRCP, the 'super parameterization'; [6, 9]), is summarized in the next section. Application of CRCP to the rotating constant-SST aquaplanet is presented in Section 3. The emphasis is to demonstrate model results which address issues beyond the scope of traditional approaches, such as the role of convective momentum transport by organized convection [23]. Final remarks in Section 4 conclude the paper.

2. CRCP

CRCP involves applying a two-dimensional (2D) cloud-resolving model in each column of a three-dimensional (3D) large-scale or global model ([6, 9]; see also Reference [14] for a discussion of the application of this technique to a climate model). In the spirit of classical convection parameterization, which assumes scale separation between convection and large-scale flow, the cloud-resolving models from neighbouring columns interact only through the large-scale dynamics. Thus, CRCP involves many two-dimensional cloud-resolving models interacting in a manner consistent with the large-scale dynamics.

CRCP stems from earlier numerical studies of moist tropical convection driven by observed large-scale conditions over a period of $\mathcal{O}(10)$ days (for a discussion, see References [7, 8, 33]). There, the authors have demonstrated that a 2D computational framework oriented along the E–W direction results in tropical cloud systems whose integral effects (including effects on surface and radiative processes) reproduce both observations and 3D model results. Thus, using a 2D cloud-scale model inside each column of the 3D large-scale model should be capable of directly representing the interaction between moist convection and large-scale flow, convection organization, and the effects of convection on surface and radiative processes. However, limitations of the CRCP associated with the assumed scale separation between large-scale and cloud-scale dynamics (a cornerstone of all convection parameterization schemes) have to be kept in mind (cf. Section 3 in Reference [6]). CRCP results in a reduction of the computational effort required for a hypothetical cloud-resolving model of 3D large-scale tropical dynamics by 2–3 orders of magnitude. However, CRCP is very expensive when compared to traditional convection parameterizations and the cost of running a large-scale model featuring CRCP is almost entirely due to cloud-resolving calculations (see also a discussion in Reference [14]).

The physical motivation behind the coupling formalism of the large-scale and cloud-scale models, and the details of the coupling mechanism, have been discussed in detail in References [6] and [9]. The coupling follows a traditional approach to convection parameterization in which large-scale dynamics provides the so-called large-scale forcing for convection, and convection feeds back the so-called convective response (e.g. Section 2 in Reference [7]). The underlying philosophy is as follows: because temperature and moisture budgets are essential for the convective heating and moistening that drive the large-scale dynamics, all thermodynamic fields should be coupled instantaneously (via proper averaging procedures). In contrast, insofar as the kinematics is concerned, the large-scale flow is assumed to organize cloud-scale convection while the cloud-scale flow should exert a drag on the large-scale flow. In effect, the cloud-scale and large-scale E–W or N–S flows (depending upon the orientation of 2D CRCP domains) may be coupled simply by relaxing one to each other on a finite time-scale (based on gravity wave arguments; the time-scale of 1 h is assumed in all simulations discussed in this paper). Thus, from a mathematical perspective, the two models are coupled differently for the thermodynamic and kinematic dependent variables. It should be mentioned that the role of large-scale flow in convection organization is seldom considered in traditional convection parameterization schemes.

An important aspect of CRCP is its ideal suitability for high-performance computing on distributed memory architectures. Because cloud-resolving models communicate with each other only through the large-scale flow, cloud-scale computations inside each column of the large-scale model proceed independently from each other. This means that the timing of the entire system scales linearly with the number of processors, and the only deviation from the perfect scaling is associated with the overhead due to the large-scale model. Such scaling extends up to the point when the number of processors equals the number of columns in the large-scale model. In contrast, classical approaches for parallel computations used in fluid dynamics codes designed for atmospheric applications (such as domain decomposition in the horizontal plane, e.g. Reference [1]) scale only when the number of model columns is much larger than the number of processors.

3. CONVECTION ORGANIZATION ON A ROTATING AQUAPLANET IN CONVECTIVE-RADIATIVE QUASI-EQUILIBRIUM

To illustrate the interactions between large-scale and cloud-scale dynamics in the context of global-scale flows, we consider an idealized problem of convective–radiative equilibrium on a rotating constant-SST aquaplanet with the size and rate of rotation of the Earth. Preliminary results of this investigation were reported in Reference [6]. The global model is the anelastic non-hydrostatic two-time-level non-oscillatory forward-in-time Eulerian/semi-Lagrangian Navier–Stokes solver in spherical geometry [30]. The global model has low resolution in the E–W and N–S directions (32×16), uses 51 levels in the vertical with a uniform gridlength of 0.5 km, and applies a time step of 12 min. Some tests were also performed with higher spatial resolution to verify that results from low-resolution simulations are robust (not shown).

The 2D CRCP models in each column of the global model have horizontal periodic domains of 200 km with a 2-km gridlength. We take advantage of the fact that the horizontal domain of CRCP periodic models inside each column of the global model can be selected arbitrarily. The choice herein represents a compromise between the computational cost (which increases almost linearly with the number of columns in the CRCP model domain) and the horizontal extent of the domain used in cloud-resolving simulations of tropical convection driven by observed large-scale conditions (typically in the range of 500–1000 km, e.g. References [7, 33]). The vertical grid is the same as in the global model and the time step is 0.5 min.

The globally uniform SST is assumed at 30°C (303.16 K) and the effects of radiative processes on the atmosphere are prescribed by applying a typical tropical cooling rate profile. The cooling rate is 1.5 K per day below 12 km, linearly decreases from 1.5 K per day to zero between 12 and 15 km, and is zero above 15 km. Free-slip boundary conditions are applied at the surface (i.e. no surface friction). The lack of surface friction has to be kept in mind when comparing the strength of surface winds in the global model with the MJO observations. Typical tropical moisture and temperature profiles are used to initiate the simulation. The atmosphere is assumed initially at rest.

Three CRCP global simulations are discussed in this paper. The first simulation is the same as that discussed in Section 4 of Reference [6]. In this simulation, the CRCP domains are aligned in the zonal direction which implies that only the E–W global momentum is coupled to the 2D cloud-resolving model momentum field. We will refer to this simulation as EW. As discussed in Reference [6], this simulation features a spontaneous development of large-scale coherent structures in the surface precipitation and zonal winds, which strongly resemble MJO. In the second simulation, the CRCP domains are aligned in the meridional direction, which allows the coupling of only the N–S momenta between the global model and CRCP domains. We will refer to this simulation as NS. In the simulation NS, convection can only influence the large-scale zonal momentum through the thermodynamic effect (i.e. latent heating) and the impact of convective transport of the zonal momentum (e.g. Reference [23]) is eliminated. Both EW and NS are run for 80 days. The differences in the large-scale convection organization between these simulations highlight the role of convective transport of the zonal momentum.

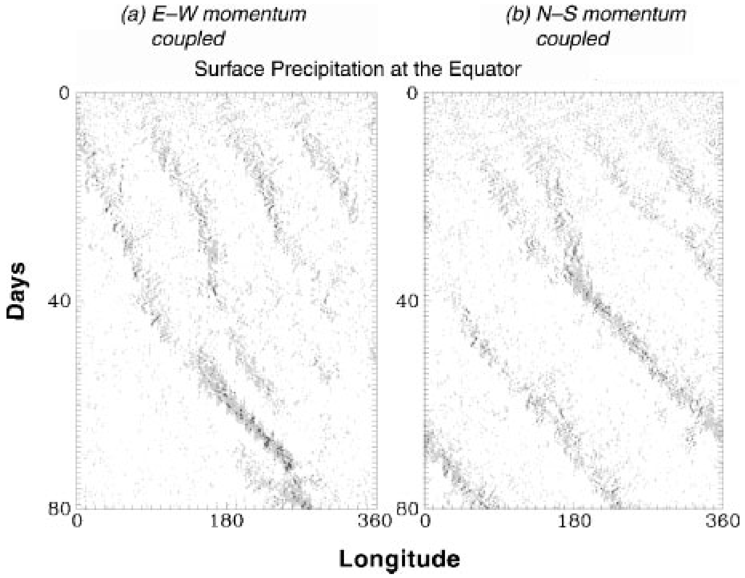

Figure 1. Hovmöller diagrams of the surface precipitation at the equator for (a) simulation EW and (b) simulation NS. Precipitation intensities larger than 0.2 and 5 mm h^{-1} are shown using light and dark shading, respectively.

To illustrate that the differences between EW and NS are robust, a third simulation is performed. It is restarted at day 50 from the simulation NS, but it has CRCP domains aligned E–W. The third simulation is run for 70 days (i.e. up to day 120) and it will be referred to as EW1.

As illustrated in Figure 14 in Reference [6], convection outside the equatorial waveguide lacks large-scale organization throughout the entire simulation EW. The same is true for NS and EW1. Inside the waveguide, on the other hand, large-scale organization spontaneously develops. This is illustrated in Figure 1, which shows data from the equatorial waveguide for the simulations EW and NS. The figure uses Hovmöller (time–space) diagrams, convenient for displaying time evolution of the 1D data. Zonal distributions of surface precipitation at a given latitude are obtained by combining cloud-scale data from CRCP domains located in a one-gridbox-wide zonal belt at this latitude. The Hovmöller diagrams shown in Figure 1 represent averages of the surface precipitation distributions from two zonal belts adjacent to the equator (the global model does not have gridpoints located exactly at the equator). Both simulations demonstrate the formation of large-scale perturbations (identified as equatorially-trapped waves, cf. Reference [6]) which are coupled to convection and have a strong impact on the surface precipitation. A solitary coherent structure spontaneously develops in the simulation EW around day 50. It propagates toward the east with a speed of around 9 m s^{-1}. In NS, on the other hand, wavenumber two perturbations persist. They are weaker and less organized than the solitary perturbation present in EW.

Figure 2 documents the spatial structure of the MJO-like coherent structures propagating along the equatorial waveguide in simulations EW and NS. These structures seem similar to classical solutions of heat-induced tropical circulation (e.g. Reference [5]). The strong westerly

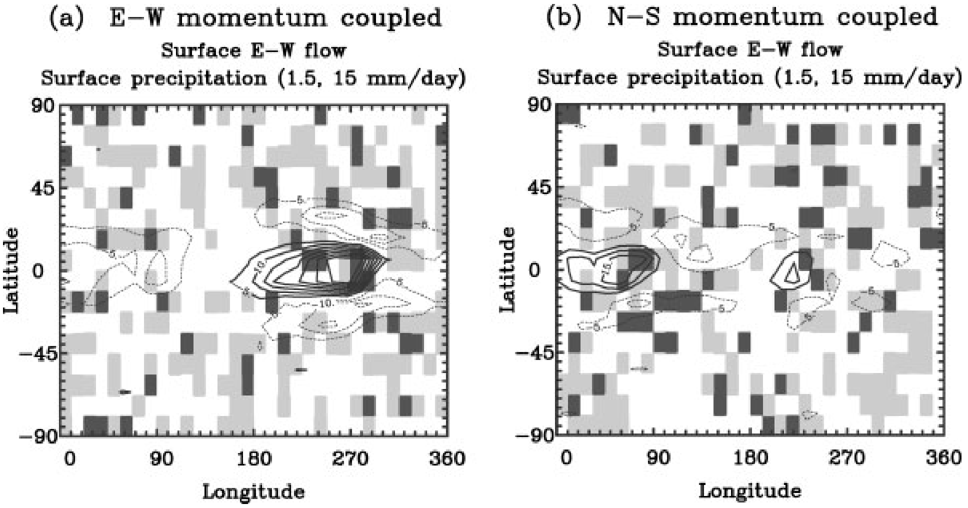

Figure 2. Snapshots, at day 80, of the surface zonal velocity (solid and dashed contours for positive and negative values, respectively; contour interval of 5 m s^{-1}) and the surface precipitation (averaged from CRCP model domains) using a grey scale (precipitation intensity larger than 1.5 and 15 mm per day shown using light and dark shading, respectively). Data for simulations (a) EW and (b) NS.

surface winds to the west of deep convection are traditionally referred to as westerly wind bursts (WWB) and are well known to follow strong convective periods associated with the passage of MJO (cf. Figure 16 in Reference [18]). The coherence of the MJO-like structures can be better appreciated by watching animations in which snapshots as in Figure 2 from subsequent time levels are used. These animations clearly show the slow eastward propagation of the MJO-like structures (in agreement with the data shown in Figure 1) and lack of large-scale organization of convection away from the equator.

The simulation EW features a strong WWB (maximum surface winds over 35 m s^{-1}), whereas considerably weaker WWBs are present in the simulation NS. This may be partly because a solitary coherent structure is present in Figure 2a, whereas two coexist in Figure 2b. We will use the maximum surface westerly winds associated with WWB to measure coherence of the MJO in the idealized aquaplanet simulations.

Figure 3 illustrates convection organization in the simulation EW1, i.e. the one restarted from NS at day 50 and run till day 120 using E–W orientation of CRCP domains. The period between days 50 and 80 can be used to compare EW1 to NS. In general, shortly after initiating EW1 (around day 60), the coherence of the MJO-like feature increases dramatically and a solitary structure replaces the wavenumber two perturbation present in NS. EW1 is extended beyond 80 days to show that the MJO-like coherent structure persists. Its faster propagation speed in the last 40 days of the simulation can be attributed to the significant mean westerly flow which gradually develops within the equatorial waveguide.

The above discussion is supported by an analysis of the maximum westerly winds at the surface shown in Figure 4. The mean surface E–W flow at a given latitude has been subtracted to avoid complications associated with slightly different evolutions of the mean flow near the equator. As mentioned before, we use the strength of the WWB to measure the coherence

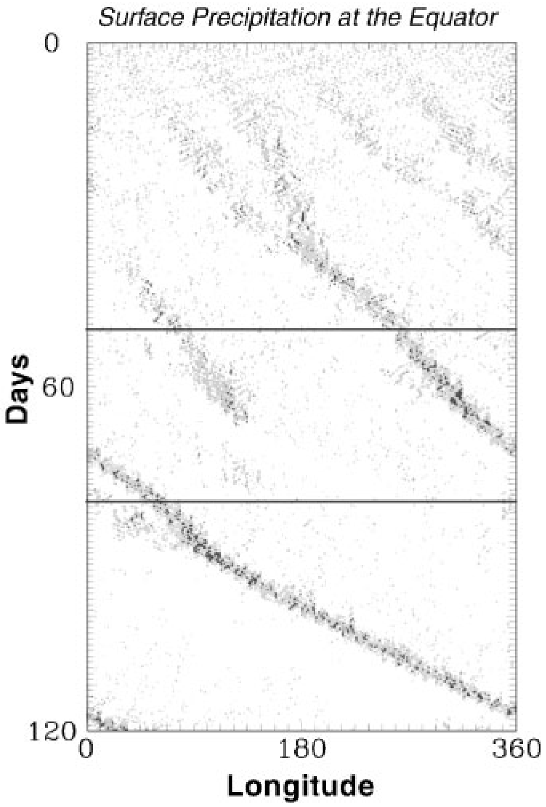

Figure 3. Similar to Figure 1, but using the data from simulation NS up to day 50, and from simulation EW1 from day 50 to 120. The horizontal lines circumscribe the period between days 50 and 80.

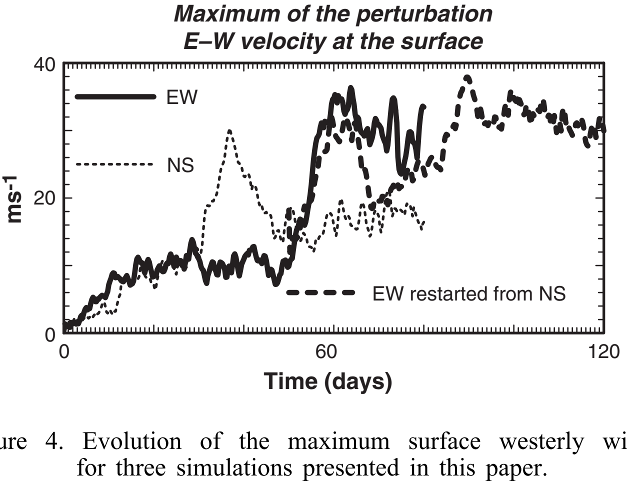

Figure 4. Evolution of the maximum surface westerly winds for three simulations presented in this paper.

of the MJO. Formation of the solitary structure in EW around day 60 results in the dramatic increase of the WWB strength. Simulation NS, on the other hand, features rather weak WWBs (which agrees with the results shown in Figure 3), except for a brief period around day 40. However, EW1, restarted at day 50 of NS, leads to a rapid development of a strong WWB, which persists (with a brief break around day 70) throughout the rest of the simulation.

In summary, CRCP global simulations discussed herein suggest that convective transport of the zonal momentum does have an impact on the strength of the large-scale flow associated with the westerly wind burst which follows the deep convection phase of MJO. This is presumably due to the presence of organized convection and its impact on the horizontal momentum field (e.g. Reference [23] and references therein). The roles of convection organization in mesoscale convective systems, and convective momentum transport by these systems in large-scale convection organization, have recently been illustrated in idealized 2D $(x-z)$ non-rotating simulations using a planetary-scale (20 000km) horizontal domain [10]. However, this is the first time such a statement is made based on an approach in which cloud-scale processes are locally resolved using CRCP, as opposed to being parameterized, in the context of the global 3D dynamics.

4. CONCLUDING REMARKS

This paper illustrates application of the Cloud-Resolving Convection Parameterization (CRCP, the 'super parameterization') to the problem of large-scale organization of convection in the tropics, or, generally, to the problem of coupling between cloud processes and the large-scale tropical dynamics. CRCP has the potential for quantifying various aspects of cloud dynamics and microphysics in the context of large-scale dynamics and climate, which so far have been considered using very simplistic approaches. Although the ultimate goal is to develop a 'cloud-resolving global model', resolutions so fine that they would allow resolving uniformly individual clouds, or even cloud clusters, are unlikely to be achieved in atmospheric general circulation models for decades. As a result, global models featuring CRCP, possibly with small 3D CRCP domains in the future, will remain a useful research tool for years to come. A pilot application of the 'super parameterization' to modelling Earth's climate using the NCAR Community Climate System Model was recently presented in Reference [14].

One of the outstanding issues with respect to climate modelling is the impact of clouds on radiative transfer (e.g. Reference [17]). Traditional climate models rely on sophisticated cloud parameterization schemes to model transfer of solar and terrestrial radiation. The representation of horizontal and vertical distribution of clouds, and of cloud overlapping, seem to be the key problems. Moreover, the role of cloud microphysical processes, which determine sizes and shapes of cloud particles (an important consideration in radiative transfer), is very difficult to address when cloud dynamics are parameterized. CRCP is a natural approach to this problem. It does resolve cloud dynamics (although using a 2D geometry) and couples cloud-scale processes in a natural way. Because cloud-scale dynamics are resolved, realistic vertical and horizontal distributions of cloud fields are available for radiative transfer calculations. Moreover, CRCP is capable of reproducing temporal evolutions of clouds and cloud fields, which is probably an important factor in the coupling between cloud-scale and large-scale dynamics (cf. Section 4 in Reference [10]). The CRCP approach has been extended to include radiative transfer in the way it is done in traditional cloud-resolving models (e.g. Reference [33]). As opposed to the results discussed in Reference [17], interactive radiation has a minor impact on the large-scale organization of convection discussed in this paper. This will be discussed in detail in forthcoming publications.

Moist convection is not the only example of the impact of small-scale and mesoscale processes on large-scale dynamics. For instance, the role of vertically propagating gravity waves, forced by the interaction of the stratified flow with the surface topography, has long been postulated as an important factor controlling the strength of the upper atmospheric circulation. Although 3D effects are no doubt important for gravity wave generation and propagation, quantifying the role of gravity wave drag in the maintenance of large-scale circulation using the 2D CRCP approach would be a significant accomplishment. Such an approach is feasible using present-day computer resources considering that the CRCP calculations would have to be performed only in a small subset of the global model columns, i.e. only those featuring surface topography. We plan to perform such simulations in the future.

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