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# CRCP: a Cloud Resolving Convection Parameterization for modeling the tropical convecting atmosphere ☆

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## Abstract

A new computational approach, CRCP, is proposed in which both the large-scale (LS) tropical dynamics and cloud-scale (CS) dynamics are captured explicitly. The leading idea is to represent subgrid scales of the LS model by imbedding a 2D CS model in each column of the 3D LS model – the approach tailored for distributed memory architectures. The overall philosophy underlying CRCP is the reinvestment of efforts from large-eddy simulation to elaborate yet ‘embarrassingly parallel’ turbulence models. Similar as in the traditional ‘convection parameterization’, the LS model provides ‘ambient forcings’ for the CS model imbedded inside each LS column, and the CS model feeds back a ‘convective response’ for every column of the LS model. Furthermore, availability of the cloud-scale data allows for explicit coupling of moist convection with radiative and surface processes. Following our experience with cloud-resolving modeling of the tropical convection, the CS model is oriented along the E–W direction inside each LS model column. A simple strategy for the coupling the LS and CS models derives from physical understanding of interactions between LS flow and moist tropical convection. Theoretical considerations are illustrated with an example of application to observational data from the Phase III of the Global Atmospheric Research Programme Atlantic Tropical Experiment (GATE). ©1999 Elsevier Science B.V. All rights reserved.

*Keywords:* Tropical atmospheric dynamics; Moist convection; Convection parameterization

## 1. Introduction

Tropics cover a significant part of the Earth surface and play an important role in the Earth climate system. Yet dynamics of the tropical atmosphere is 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 (LS) dynamics depends critically on the diabatic processes through which the atmosphere exchanges energy with the 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 the 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 exchange of heat, water and momentum between the atmosphere and the ocean and have a strong impact on solar and terrestrial radiative fluxes. Modeling all these processes using state-of-the art computers is still impractical. It requires horizontal grid spacing of ∼1 km, to

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represent adequately convective cloud dynamics over horizontal areas of $\mathcal{O}(10^8)\,\mathrm{km}^2$. Thus, it is not surprising that representing tropical moist convection in LS 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 LS 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 [1], a simple 1D analog of the turbulent stirring and molecular diffusion, appears particularly effective when applied inside every gridbox of the resolved LS flow to represent subgrid-scale turbulent mixing and chemical reactions [2]. The approach we advocate in this paper bears some conceptual similarity to the idea of the linear eddy model.

CRCP stems from our earlier numerical studies of moist tropical convection driven by observed LS conditions over a period of $\mathcal{O}(10)$ days (for a discussion, see [3–5]). 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 the observations and 3D model results. Thus, using a 2D cloud-scale (CS) model inside each column of the 3D LS model should be capable to directly represent the interaction between moist convection and the LS flow, convection organization, and the effects of convection on surface and radiative processes. Most important, CRCP amounts to 2–3 orders of magnitude reduction of the computational effort required for a hypothetical cloud-resolving model of the 3D LS tropical dynamics.

The convection parameterization problem has a long history in the atmospheric literature (cf. [6] for reviews). CRCP is an alternate parameterization scheme, and it is subject to similar criticisms as those applied to traditional parameterization techniques. For example, in order to justify our scheme, scale separation between the LS and CS dynamics must be assumed. Furthermore, the interaction between the LS and CS dynamics must be representable in terms of the LS control of the convection and convective feedback onto the LS dynamics (cf. [7]). As these assumptions are controversial [8], CRCP cannot be the ultimate tool to study interactions between LS dynamics and convection in the tropics. On the other hand, CRCP does represent a significant advancement when compared to existing convection parameterization schemes. Traditional schemes represent cloud dynamics and thermodynamics in a simplistic way by neglecting convection organization and convection interaction with radiative and surface processes (cf. [7,9]).

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 LS flow, CS computations inside each column of the LS model proceed independently from each other. It means that the timing of the entire system should scale linearly with the number of processors, and the only deviation from the perfect scaling will be that associated with the overhead due to the LS model. In fact, our earlier experience with massively parallel computations (cf. [10] and the references therein) played an important role in designing CRCP. The overall philosophy underlying CRCP is the reinvestment of efforts from large-eddy simulation to elaborate yet ‘embarrassingly parallel’ turbulence models.

The next section discusses the physical rationale behind CRCP and outlines the model equations. Section 3 reviews the results of simulations of a 3D tropical convection, where CRCP is compared with a direct approach with fully resolved cloud and mesoscale dynamics.

## 2. CRCP approach

### 2.1. Rationale

The strategy underlying CRCP is to consider two distinct flow models coupled with each other in a particular way. The first model is a 3D LS flow model, considered within a framework of either equatorial $\beta$-plane dynamics or global dynamics. The LS model uses horizontal grid length of $\sim$100 km to adequately represent LS dynamics associated with, e.g., equatorially trapped tropical disturbances. The second model is a 2D CS model formulated on the $x$–$z$ plane aligned along the E–W direction[1] and imbedded in each column of the LS model. The CS model uses the same vertical grid as the LS model, but it uses sufficiently small length of the horizontal grid to resolve moist convective dynamics (say $\sim$1 km). The CS model is periodic in the horizontal, an assumption important for the energy conservation (see [3] for a discussion).

The physical motivation behind the coupling formalism of the LS and CS models has been discussed in detail in [3]. The underlying philosophy is as follows: because temperature and moisture budgets are essential for the convective heating and moistening appreciated by the LS dynamics, all thermodynamic fields should be coupled instantaneously (via proper averaging procedures). In contrast, insofar as the kinematics is concerned, the LS flow merely supposes to organize CS convection while the CS flow should exert a drag on the LS flow. In effect, the CS and LS E–W flows may be coupled simply by relaxing one to each other on a finite time-scale (based on gravity wave arguments). Thus, from the mathematical perspective, the two models are coupled differently for the thermodynamic and kinematic dependent variables.

### 2.2. Governing equations

The LS model employs inviscid anelastic equations of motion. For the equatorial $\beta$-plane dynamics, they can be written compactly as

$$\frac{\mathcal{D}\boldsymbol{U}}{\mathcal{D}t} = -\nabla\Pi - \boldsymbol{f}\times\boldsymbol{U} + \boldsymbol{k}gB + \boldsymbol{i}F_{\mathrm{CS}}^{U} + D_{\boldsymbol{U}} \tag{1}$$

$$\nabla\cdot(\rho_0\boldsymbol{U}) = 0 \tag{2}$$

$$\frac{\mathcal{D}\Psi_i}{\mathcal{D}t} = F_{\mathrm{CS}}^{\Psi_i} + D_{\Psi_i} \quad i = 1, N \tag{3}$$

Here, $\boldsymbol{U} = (U, V, W)$ is the LS flow in E–W, N–S, and the vertical direction, respectively; $\mathcal{D}/\mathcal{D}t \equiv \partial/\partial t + \boldsymbol{U}\cdot\nabla$; $\Pi$ is the pressure perturbation with respect to a geostrophically balanced ambient state, normalized by the anelastic reference density $\rho_0$; $\boldsymbol{f} = (0, 2\Omega, 2\Omega Y/R)$ is the $\beta$-plane Coriolis parameter with $\Omega$ and $R$ denoting the Earth angular velocity and radius, respectively; $\boldsymbol{i}$ and $\boldsymbol{k}$ are unit vectors in the E–W and vertical directions, respectively; the buoyancy $B$ depends on the $N$ thermodynamic scalars $\Psi_i$ (i.e., the potential temperature and the water substance mixing ratios such as water vapor, cloud water, rain water, ice, etc.), and $g$ is the gravitational acceleration. The $F_{\mathrm{CS}}$-terms on the rhs of Eqs. (1) and (3) represent the CS model feedback, while the $D$-terms represent dissipative wave-absorbing devices applied in the vicinity of the model boundaries. Note, that the LS model does not include explicit representations of surface fluxes, radiative transfer, phase changes, latent heating, or precipitation fallout. These are included in the CS model and their effects transferred to the LS model via $F_{\mathrm{CS}}$ terms (for a discussion see Section 2 of [3]).

The governing anelastic equations of the CS model are written as follows:

$$\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = -\nabla'\pi + \boldsymbol{k}gb + \boldsymbol{i}f_{\mathrm{LS}}^{u} + d_{\boldsymbol{u}} \tag{4}$$

$$\nabla'\cdot(\rho_0\boldsymbol{u}) = 0 \tag{5}$$

$$\frac{\mathrm{d}\psi_i}{\mathrm{d}t} = s_{\psi_i} + f_{\mathrm{LS}}^{\psi_i} + d_{\psi_i} \quad i = 1, N \tag{6}$$

where the lower case symbols have the same meaning as the respective upper case symbols in Eqs. (1)–(3). For example, $\boldsymbol{u} = (u, w)$ is the CS flow in E–W and vertical direction, respectively; $\mathrm{d}/\mathrm{d}t \equiv \partial/\partial t + \boldsymbol{u}\cdot\nabla'$ with $\nabla' \equiv (\partial/\partial x, \partial/\partial z)$; etc. The $f_{\mathrm{LS}}$-terms represent the LS forcing exerted on the CS model. The $s_{\psi_i}$-terms denote sinks/sources of the thermodynamic scalars associated with physical processes included in CS model, such as phase changes of the water substance, latent heating, precipitation fallout, surface fluxes of water and temperature[2], tempera-

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[1] A more general CS model, formulated on a ribbon aligned with vertically-varying LS horizontal flow, may be considered in future studies.

[2] The N–S flow from the LS model is considered when calculating surface fluxes.

ture tendency due to radiative flux divergence, etc. [11–13]. In particular, cloud microphysical processes are represented using a simple yet robust scheme of Grabowski [13]. The $d$-terms appearing in the prognostic equations symbolize viscous forcings due to the subgrid-scale turbulence (optional) and gravity-wave absorbers.

### 2.3. Model coupling terms

As far as thermodynamic fields are concerned, the $F_{\mathrm{CS}}$-terms in the LS model equations (1)–(3) are derived from the CS fields:

$$F_{\mathrm{CS}}^{\Psi_i} = \left\langle \frac{\mathrm{d}\psi_i}{\mathrm{d}t} \right\rangle \tag{7}$$

where the $\langle .. \rangle$ denotes the horizontal averaging of a CS dependent variable, i.e.,

$$\Phi(X, Y, Z, t) \equiv \langle \phi(x, z, t)|_{(X,Y)} \rangle = \frac{1}{L}\int_{-L/2}^{L/2} \phi(\xi, z, t)|_{(X,Y)}\, \mathrm{d}\xi \tag{8}$$

where $L$ is the extent of the horizontal domain used in each CS model and $Z \equiv z$. Decomposing the model variables into the LS and CS components, and employing the scale separation arguments, leads to the representation the LS forcing terms $f_{\mathrm{LS}}$ in the CS model equations (4)–(6) in terms of the advective tendencies from the LS model

$$f_{\mathrm{LS}}^{\psi_i} = -\boldsymbol{U} \cdot \nabla\Psi_i; \tag{9}$$

see [3] for a discussion.

In both models, the E–W momenta are relaxed to each other as follows:

$$F_{\mathrm{CS}}^{U} = -\frac{U - \langle u \rangle}{\tau_m} \tag{10}$$

$$f_{\mathrm{LS}}^{u} = -\frac{\langle u \rangle - U}{\tau_m} \tag{11}$$

where $\tau_m$ is the time scale of the kinematic coupling. In the experiments reported in this paper, $\tau_m = 1\,\mathrm{h}$ is assumed (related to the propagation of a heat-source induced gravity wave over the CS model domain).

The above-outlined model coupling assures that, at any given level, the thermodynamic fields of the LS column exactly match the horizontal average of the CS fields

$$\Psi(X, Y, Z, t) = \langle \psi(x, z, t)|_{(X,Y)} \rangle, \tag{12}$$

which is important for temperature and moisture budgets. In contrast, at any instance, the E–W flows match only approximately

$$U(X, Y, Z, t) \approx \langle u(x, z, t)|_{(X,Y)} \rangle, \tag{13}$$

with relatively small flow-matching discrepancies ($\sim 0.5\,\mathrm{m\,s^{-1}}$), as illustrated a posteriori by the results in the next section.

### 2.4. Numerical aspects

Both the LS and CS models employ the Eulerian variant of the two-time-level, nonhydrostatic anelastic fluid model EULAG of Smolarkiewicz and Margolin [14]. The moist precipitating thermodynamics is applied following Grabowski [13]. For all prognostic variables, both models use the nonoscillatory forward-in-time (NFT) approach of Smolarkiewicz and Margolin [15], built on the transport algorithm MPDATA reviewed recently in [16]. For a thorough discussion of algorithmic details the interested reader is referred to [14,16], and references therein. The time stepping of the entire system (1)–(6) is imbedded into the NFT formalism and it proceeds in three distinct steps:

*Step* 1. The advective tendencies for momenta and thermodynamic variables in the LS model are derived. The tendencies for thermodynamic fields form the LS forcing terms (9) for the CS model. The E–W momentum forcing (11) is calculated as well.

*Step* 2. The forced evolution of the cloud field (in response to the LS forcing, and to the radiative and surface processes) is calculated in parallel using the CS model inside each column of the LS model. As a result, new time level thermodynamic fields are obtained for each CS model. Usually, a smaller time step ($\delta t$) has to be used in the CS models than in the LS model ($\Delta t$). Thus, the CS models perform several $\delta t$ time steps, in order to reach the time level $t + \Delta t$ to which the LS model will be updated after completing Step 3 below.

*Step* 3. LS thermodynamic fields are updated according to Eq. (7) by horizontal averaging of the CS fields for each column of the LS model. Updated buoyancy is applied to the vertical momentum equation (1) of the LS model, and the E–W momentum forcing for the LS model (10) is applied to the $U$ – Eq. (1). Derivation of the LS pressure gradient and its application to the LS momenta completes the time step $\Delta t$ of the entire system.

The free-slip impermeable upper and lower boundaries are common in both models. Weak gravity wave absorbers are employed in upper portion of both models to minimize wave reflection from the rigid boundary and to mimic an infinite vertical extent of the fluid. The lateral boundaries are periodic in CS models, but can be either periodic, rigid, or open, optionally in each direction of the LS model.

## 3. Application to the GATE data

CRCP has been successfully compared with 2D cloud-resolving simulations [13] of the LS circulation driven by a gradient of the underlying sea surface temperature. The primary purpose of such an exercise was to verify the ‘reflexivity’ of the two-model relation, i.e., to assure that CRCP and the LS/CS model coupling *do work* for 2D flows. Here, we apply CRCP to the GATE[3] Phase III data ([17] and references therein).

Our results can be compared directly with 3D cloud-resolving simulations discussed in [5]. In those simulations, the Clark–Hall cloud model [18] was driven by prescribing the observed LS forcing for the temperature and moisture and relaxing LS horizontal winds to observed profiles, in order to generate realizations of cloud systems consistent with LS estimates of moisture and temperature budgets. In order to directly resolve CS dynamics, a relatively small horizontal domain of $400 \times 400\,\mathrm{km}^2$ was applied in the 3D cloud-resolving simulation with a 2 km horizontal grid length.

The LS model was configured in the following way: the domain was $400\,\mathrm{km}\times 400\,\mathrm{km}$ in the horizontal directions with 40 km horizontal grid length, and 25 km in the vertical direction with 1/3 km grid length. The domain was periodic in both horizontal directions. To be consistent with the 3D cloud resolving simulation of [5], the Coriolis term was omitted, i.e., $f$ was set to zero in Eq. (1). Model time step $\Delta t$ was 60 s. A gravity wave absorber was applied in the uppermost 8 km of the model domain. The LS model was forced by the observed data following [5].

The CS models inside each column of the LS model used a 2D domain with 40 km in the horizontal and 25 km in vertical, with the corresponding grid lengths 1 and 1/3 km. The model time step $\delta t$ was 15 s. As in the LS model, gravity wave absorber was applied in the uppermost 8 km of the domain. Surface heat fluxes were calculated using a bulk approach with transfer coefficients dependent upon the near-surface stability (cf., [3]).

The entire model system was initialized using an observed sounding on 00GMT 1 September and run for the 7-day period, following [5]. The LS flow and forcings for the temperature and moisture are shown in Fig. 1 of [5] for the entire 7-day period. Below we present selected results from our simulation, and compare them to those reported in [5].

Temperature and moisture fields evolve similarly in the CRCP and the cloud-resolving simulations during the entire course of the experiment. Fig. 1 shows the evolution of the deviations of the simulated thermodynamic profiles (temperature, moisture, and relative humidity) from the observed values; the corresponding results for the cloud-resolving model are shown in Fig. 6 of [5]. Overall, the deviation profiles evolve similarly in both simulations. Some differences are worth noting: our results agree better with observations for upper tropospheric relative humidity, but larger deviations for the temperature during the day 4 are apparent.

The differences between the simulated and observed profiles of the LS flow are shown in Fig. 2(a,b). The model predicted flow is typically within $1\,\mathrm{m\,s}^{-1}$ of the observed flow. The rms deviations between the $U$ and $\langle u\rangle$ E–W flows in the LS and CS models are shown in Fig. 2(c). Except for the first 12 h of the

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[3] Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment (GATE) was conducted in the tropical eastern Atlantic in summer 1974.

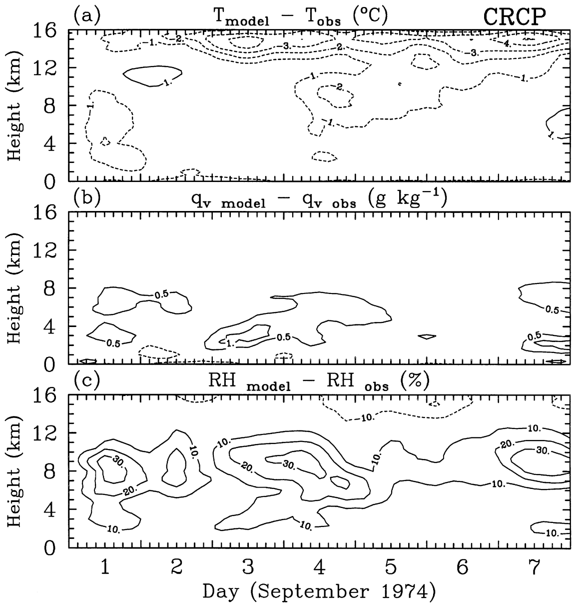

Fig. 1. Time evolution of the difference profiles between results of the experiment using CRCP approach and the observations for (a) the domain-averaged temperature field, (b) the domain-averaged water vapor mixing ratio, and (c) the domain-averaged relative humidity. Contour intervals are 1 K in (a), $0.5\,\mathrm{g\,kg^{-1}}$ in (b), and 10% in (c).

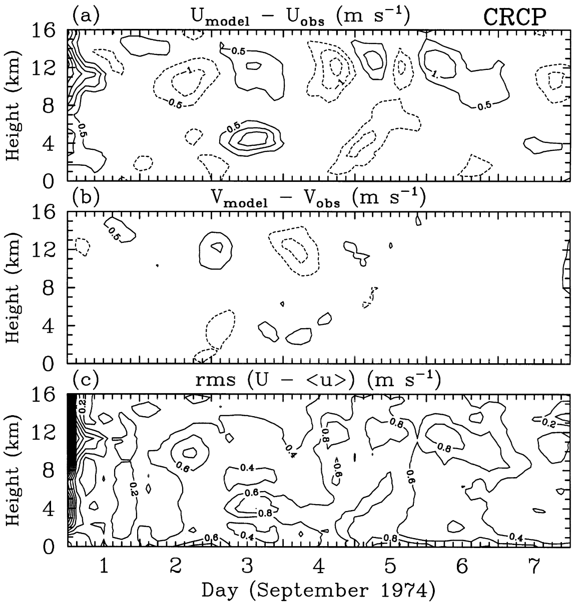

Fig. 2. Time evolution of the difference profiles between results of the experiment using CRCP approach and the observations (a) and (b) for the LS domain-averaged: (a) E–W and (b) N–S velocity components, and (c) the evolution of the difference profiles between LS and the CS model E–W velocity. Contour intervals are $0.5\,\mathrm{m\,s^{-1}}$ in (a) and (b), and $0.2\,\mathrm{m\,s^{-1}}$ in (c).

simulation (model spinup stage)[4], these deviations are small usually below a few tenths of $\mathrm{m\,s^{-1}}$ (recall the assertion following Eq. (13)).

Fig. 3 shows the Hovmöller $(X, t)$ diagrams of the N–S averaged surface precipitation for the entire 7-day period, for both the CRCP and the cloud-resolving simulations. Despite the apparent differences in the E–W resolution, the patterns of surface precipitation (associated with the nonsquall cloud clusters on 2 and 5 September, and the squall line on 4 September, see [5] for a discussion) are similar. The time evolution of the domain-averaged surface precipitation (Fig. 4) resembles that for the cloud-resolving simulation with the $0.06\,\mathrm{mm\,h^{-1}}$ 6-day mean rms deviation between the instantaneous and 3-hour average surface precipitation. In general, this measure highlights the difference between the 2D and 3D cloud resolving simulations [5] characterized, respectively, by high and low rms deviations. The small rms value in the present simulation documents that CRCP captures the 3D character of the convecting atmosphere.

Insofar as the clouds are concerned, the results of the two simulations exhibit similar features (the different microphysical parameterizations used here and in [5] preclude a better agreement). For instance, in both cases the upper-tropospheric anvil clouds dominate, and cover upto 80% of the horizontal extent of the domain during strong convection periods. This agreement is encouraging considering the importance of clouds in the radiative transfer. For illustration, Fig. 5 shows the probability density functions (pdfs) for the distribution of the total condensate path (vertical integral of the total condensate concentration) for the two simulations. Their similarity is apparent.

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[4] The large initial deviations can be substantially reduced by means of a more consistent flow initialization. Here, to assess the 'self-adaptability' of the model coupling procedure, we prescribed the LS wind profiles in the LS model, while assuming no flow inside the CS models.

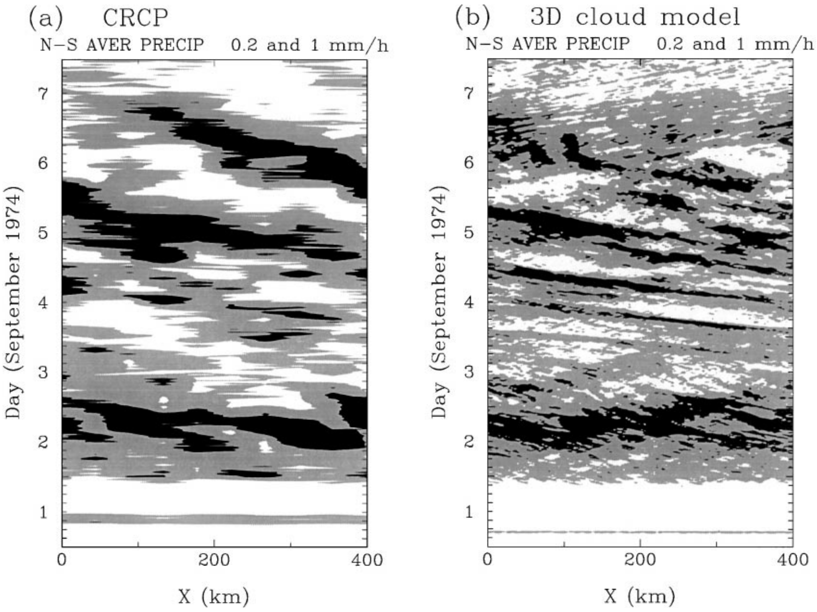

Fig. 3. Hovmöller ($X$–$t$) diagrams of the N–S (or $y$) averaged surface precipitation rate from (a) the experiment using CRCP approach and (b) the experiment using the 3D cloud resolving model. Precipitation intensity larger than 0.2 and $1\,\mathrm{mm\,h^{-1}}$ is shown using light and dark shading, respectively.

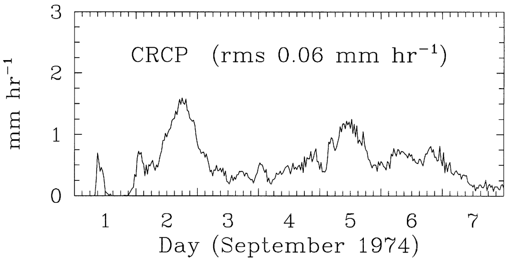

Fig. 4. Evolution of the domain-average surface precipitation rate (plotted with the rate of $2\,\mathrm{h^{-1}}$) for experiment using CRCP approach. The rms difference between the instantaneous surface precipitation rate and the 3-hour running mean averaged over 6-day period (days 2 to 7) is shown in the panel.

## 4. Concluding remarks

We propose a modeling approach in which both the LS dynamics and the CS dynamics are allowed to interact explicitly. Such an interaction plays a fundamental role in the tropical dynamics, yet it cannot be resolved with the present computational technology. The approach advocated here, CRCP, resolves LS dynamics in three spatial dimensions using averaged thermodynamic fields, predicted by a 2D cloud-resolving model imbedded inside each column of the LS model. The 2D cloud-resolving model can be thought of as a sophisticated subgrid-scale representation of the flow fields due to presence of convective clouds, organization of convection, and the interaction of convection with surface and radiative processes.

Because of the inherent incompatibility between the 2D and 3D frameworks, coupling the LS model with the CS model requires special attention. Our strategy is based on physical arguments, which dictate accounting for the effects of the LS flow on moist convection due to the LS advective tendencies of temperature and moisture as well as the LS vertical shear of the horizontal flow. Both of them were shown to be the dominant factors in LS–CS interactions. Our coupling formalism allows the two effects to be incorporated effectively into the CS model.

We believe that the CRCP approach carries substantial promise as far as the representation of convection

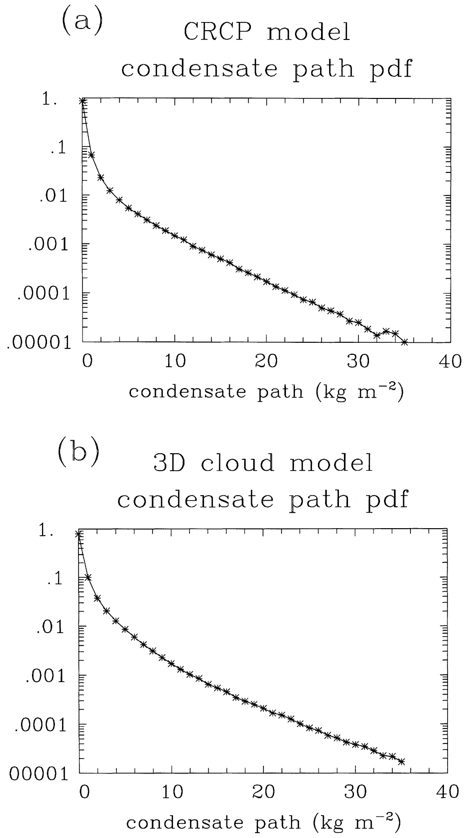

Fig. 5. Pdfs of the condensate path calculated for the 7-day experiments using (a) the CRCP approach and (b) the 3D cloud resolving model.

in LS models is concerned. At the moment, it appears the only feasible way to explicitly include elements of cloud dynamics, and its effects on radiative and surface processes, into LS models of tropical dynamics and climate. It remains to be seen, however, if the CRCP approach is suitable to represent mid-latitude convective systems for which 3D effects associated with the Earth rotation are essential.

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