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Development of a toy column model and its application in testing cumulus convection parameterizations

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Abstract A single-column model is constructed based on parameterizations inherited from the Finite-volume/Spectral Atmospheric Model F/SAMIL and tested in simulations of tropical convective systems. Two representative convection schemes are compared in terms of their performances on precipitation types, individual physical tendencies, and temperature and moisture fields. The main difference between the two selected schemes is in their representation of entraining/detraining process. The Tiedtke scheme assumes bulk entrainment, while the Zhang–McFarlane scheme parameterizes entrainment/detrainment rates under the spectrum concept. Large-scale forcing and verification data are taken from the GATE phase III field campaign, during which abundant convective events were observed. Given the same triggering function and closure assumption, results show that entrainment/detrainment representation remains the dominant factor on the simulation of cumulus mass flux and of temperature and moisture fields. By analyzing sources and sinks of heat and moisture, this study reveals how parameterization components compensate for each other and make model results insensitive to parameterization changes in certain fields, thus suggesting the need to treat parameterizations as systems rather than individual components.

Keywords Single-column model (SCM) · TCM · GATE · Cumulus convection · F/SAMIL

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1 Introduction

Parameterization testing in general circulation models (GCMs) is a vital task in the process of model development. The easiest and most widely used approach is by application of climate simulations, the results of which can be directly compared with multiple observation or reanalysis datasets. However, one disadvantage is that it can be very difficult to attribute particular deficiencies of the simulations to particular aspects of the model's formulation. This is because various feedbacks, such as the interplay between dynamics and physics, are mingled together during the model integration. In this sense, climate simulation is similar to model evaluation but far from ideal for parameterization testing. The purpose of any parameterization is essentially to compute certain "tendencies", the accuracy of which is mostly concerned. Therefore, a parameterization can be tested by evaluating its ability to reproduce observed tendencies for a given large-scale situation [1]. Lord [2] pioneered such an approach, the so-called semi-prognostic test, in which a particular parameterization or a suite of parameterizations is exercised in the framework of a single atmospheric column. "Semi-prognostic" means that the atmospheric state is not advanced in terms of the computed tendencies but specified by observations at each time step. One may imagine such a treatment as a hard nudging relaxation process, which plays a role in preventing errors from accumulating step by step. However, the lack of feedback from one time step to the next makes it difficult to detect parameterization deficiencies that arise directly from such feedbacks. This promotes the "single-column modeling" approach first addressed by Betts and Miller [3]. The clear differentiation is to use computed physical tendencies along with prescribed large-scale forcings to advance the model. Implicitly, the "semi-prognostic" approach focuses more on particular parameterizations, while the "single-column modeling" approach emphasizes the integral performance of a suite of parameterizations, in particular interactions between various parameterization components. Because of these merits, single-column models (SCMs) were widely developed and applied in parameterization testing and improving in the literature [4–9]. In particular, Xie and Zhang [10] and Xie et al. [11–14] published a series of papers exploring SCM performance using site observations. In addition, SCMs are useful tools in exploring scientific issues such as radiative–convective equilibrium [15] and the interactions between convection and gravity waves [16, 17].

In this study, a single-column model is developed, with most of the parameterizations inherited from those of the Finite-volume/Spectral Atmospheric Model IAP/LASG (F/SAMIL) [18, 19]. For ease of use, the model is deliberately designed to be independent of the host model, and in this sense, it is named the toy column model (TCM). The constructed model is then used in sensitivity studies of SCM simulations to convection schemes, with the goal of contrasting and exploring their performances in simulating precipitation types, individual physical tendencies, and thermodynamic fields.

2 Model design

2.1 Model framework

Since TCM can be thought of as a single column taken from a global climate model, the governing equations of moments and thermodynamics are the same as those in a climate model, which are written as:

$$\frac{\partial u}{\partial t} = -\vec{V}_h \cdot \nabla u - \omega\frac{\partial u}{\partial p} + f(v - v_g) - \frac{\partial\overline{\omega' u'}}{\partial p}, \quad (1)$$

$$\frac{\partial v}{\partial t} = -\vec{V}_h \cdot \nabla v - \omega\frac{\partial v}{\partial p} - f(u - u_g) - \frac{\partial\overline{\omega' v'}}{\partial p}, \quad (2)$$

$$\frac{\partial T}{\partial t} = -\vec{V}_h \cdot \nabla T - \omega\frac{\partial T}{\partial p} - \omega\frac{\partial T}{\partial p} + \omega\frac{R_d T}{C_p P} + Q_1, \quad (3)$$

$$\frac{\partial q_v}{\partial t} = -\vec{V}_h \cdot \nabla q_v - \omega\frac{\partial q_v}{\partial p} - \frac{C_p}{L}Q_2, \quad (4)$$

where $\vec{V}_h$ is the horizontal wind vectors of u and v, ω is the vertical velocity, u_g and v_g are the zonal and meridional geostrophic winds, T represents temperature, q_v represents water vapor, f is the Coriolis parameter, C_p is the specific heat and L is the latent heat of evaporation, and Q_1 and Q_2 represent the apparent heating source and moisture sink, respectively, as defined in Yanai et al. [20]. Prime denotes unresolvable motions within a grid cell. The rightmost terms in Eq. (14) are usually parameterized by individual physical process or a suite of processes, the solving of which is the kernel of the TCM. Rather than through a set of rules known as "large-scale dynamics" representing column interactions in climate models, horizontal temperature and moisture advective tendencies, in addition to vertical velocity, are prescribed as inputs to drive the model. Specifically, the model uses an Eulerian vertical advection scheme coupled to a leapfrog time-differencing scheme associated with an Asselin filter. Surface sensible and latent heat fluxes are calculated according to the following equations:

$$SH = \rho_A V^* C_p C_H \Delta\theta, \quad (5)$$

$$LH = \rho_A V^* L C_H \Delta q, \quad (6)$$

where ρ_A is the atmospheric surface density, V^* is a typical surface wind speed, C_H is the drag coefficient, and $\Delta\theta$ and Δq denote the difference between surface layer and the lowest model level for potential temperature and water vapor, respectively.

The nudging relaxation module for prognostic variables such as u, v, T, and q_v is available in the TCM but switched off in this study.

2.2 Physical parameterizations

The TCM shares almost the same physical parameterizations as those in F/SAMIL. The convection scheme is based on a bulk mass-flux framework developed by Tiedtke [21], in which three types of convection: penetrative convection in connection with large-scale convergent flow, shallow convection in suppressed conditions, and middle-level convection, are uniformly treated. The boundary layer turbulent process is parameterized by a "non-local" first-order closure scheme, which determines the eddy-diffusivity profile based on the diagnosed boundary-layer height and turbulent velocity scale [22]. The "Rapid Radiative Transfer Method for GCMs" package is used to represent radiative transfer processes [23]. The stratiform precipitation scheme in TCM is different from that in F/SAMIL, which consists of prognostic equations for vapor, liquid, and ice phase [24].

In addition to the above schemes that are considered default in TCM, alternative schemes are also available. For example, the Zhang and McFarlane's [25] deep convection scheme is implemented in the model along with a separated shallow convection scheme proposed by Hack [26].

3 Results and analysis

3.1 Case introduction

The "Global Atmospheric Research Program's Atlantic Tropical Experiment" (GATE phase III) field campaign