SP-CAM coupling

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Introduction

The SP-CAM is a "super-parameterized" general circulation model (GCM) in which a cloud-resolving model (CRM) is used to compute the physical sources and sinks of temperature and moisture. One copy of the CRM runs in each grid column of the GCM.

In the SP-CAM, the GCM is the Community Atmosphere Model (CAM; Collins et al., 2006; http://www.cesm.ucar.edu/models/atm-cam/), while the CRM is the System for Atmospheric Modeling (SAM) developed by Marat Khairoutdinov (Khairoutdinov and Randall, 2003; http://rossby.msrc.sunysb.edu/~marat/SAM.html).

The bibliography lists publications that present results from the SP-CAM.

This document explains the coupling of the embedded CRM with the GCM, as implemented in the SP-CAM. Fig. 1 illustrates the basic idea. The GCM provides advective

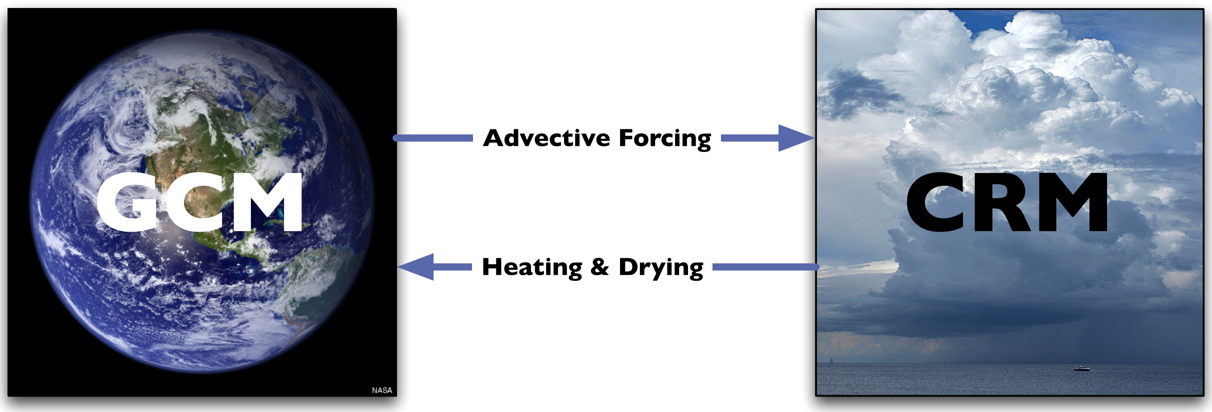

Fig. 1: Schematic illustrating the coupling of the GCM and the CRM, in the SP-CAM.

forcing to the CRM, much as in a GCSS or ARM case study based on field data, while the CRM provides heating and drying as feedback to the GCM, much as a conventional parameterization would do.

The GCM's time step is typically tens of minutes, while the CRM's time step is just a few seconds. It is assumed (or required) that the GCM's time step is an integer multiple of the CRM's time step. The CRM "sub-cycles" through a sequence of its short time steps, in order to determine the physical tendencies for one of the longer GCM time steps. We take enough CRM time steps to span the longer GCM time step.

The CRM runs continuously throughout a simulation; it is not restarted between GCM time steps.

Forcing and feedback

Let q be a generic scalar variable that is defined in both the GCM and CRM. We define $\widetilde{q_G^{n+1}}$ as a provisional GCM value of q that includes all non-CRM effects (mainly advective effects):

$$\widetilde{q_G^{n+1}} \equiv q_G^n + B_G \Delta t_G ,$$

so that

$$B_G = \frac{\widetilde{q_G^{n+1}} - q_G^n}{\Delta t_G} . \tag{1}$$

Here B_G is the adiabatic tendency of q due to non-CRM effects, as computed by the GCM; the subscript G denotes a GCM value; the superscripts n and $n+1$ denote successive GCM time steps; and Δt_G is the GCM time step. The tilda on $\widetilde{q_G^{n+1}}$ denotes a provisional value. Eq. (1) represents a "partial time step," before accounting for the diabatic tendency of q that is computed by the CRM.

The CRM variables, denoted by q_C, are updated using CRM time steps of size Δt_{CRM}:

$$\frac{q_C^{m+1} - q_C^m}{\Delta t_{CRM}} = B_C + \left(\frac{\widetilde{q_G^{n+1}} - \langle q_C \rangle^n}{\Delta t_G} \right) + S_C . \tag{2}$$

Here the superscripts m and $m+1$ denote successive CRM time steps. The term B_C represents the adiabatic tendency of q_C due to advection on the CRM's grid. Pointy brackets denote a horizontal average over the CRM's domain. The quantity $\langle q_C \rangle^n$ is the domain average of q_C at the beginning of the GCM time step. The term $\left(\frac{\widetilde{q_G^{n+1}} - \langle q_C \rangle^n}{\Delta t_G} \right)$ represents the "advective forcing" of the CRM; it is the mechanism through which the GCM's advective tendencies are felt by the CRM. The effect of this term is to relax the domain-average of q_C towards $\widetilde{q_G^{n+1}}$. The advective forcing is independent of time as the CRM sub-cycles through one GCM time step, and it is also independent of horizontal position on the CRM's grid. The source of q due to the CRM physics is denoted by S_C; it has no counterpart in Eq. (1) because the physics is computed only in the CRM.

We take enough CRM time steps to span the longer GCM time step, arriving at GCM time level $n+1$. We then let the CRM feed back on the GCM. To accomplish this, the GCM variables are updated using

$$\begin{aligned}\frac{q_G^{n+1}-q_G^n}{\Delta t_G} &= B_G + \frac{\langle q_C\rangle^{n+1}-\widetilde{q_G^{n+1}}}{\Delta t_G} \\ &= B_G + \frac{\langle q_C\rangle^{n+1}-\left(q_G^n + B_G\Delta t_G\right)}{\Delta t_G} \\ &= \frac{\langle q_C\rangle^{n+1}-q_G^n}{\Delta t_G}\,.\end{aligned} \tag{3}$$

Here $\langle q_C\rangle^{n+1}$ represents the horizontal average of q_C at GCM time level $n+1$, i.e., at the end of the sequence of CRM time steps based on (2).

It follows from (3) that

$$q_G^{n+1} = \langle q_C\rangle^{n+1} \tag{4}$$

Of course, we can also write

$$q_G^n = \langle q_C\rangle^n\,. \tag{5}$$

This means that, at both the beginning and end of the time step, the GCM value of q is guaranteed to agree with the horizontal average of the CRM values. As a result, it is impossible for the GCM and the CRM to drift apart over time.

Using (5) to replace $\langle q_C\rangle^n$ in (2), and then using (1), we see that the CRM variables evolve according to

$$\frac{q_C^{m+1}-q_C^m}{\Delta t_{CRM}} = B_C + B_G + S_C\,. \tag{6}$$

This re-statement of (2) makes it clear that the CRM feels the GCM advection as a simple additive term. If we horizontally average (6) over the CRM's grid, we get

$$\frac{\langle q_C\rangle^{m+1}-\langle q_C\rangle^m}{\Delta t_{CRM}} = \langle B_C\rangle + B_G + \langle S_C\rangle\,. \tag{7}$$

Of course, $\langle B_C \rangle$ involves only vertical transports, because of the CRM's periodic boundary conditions. From (4), (5), and (7), we see that

$$\frac{q_G^{n+1} - q_G^n}{\Delta t_G} = B_G + \overline{\langle B_C + S_C \rangle}, \tag{8}$$

where the overbar on the right-hand side represents an average over the GCM time step. The interpretation of (8) is simple and clear.

The main point of this section is that the integration procedure represented by (1-3) leads to the result (8), and so guarantees consistency between the GCM fields and the CRM fields, as they both evolve during a simulation.

Vertical structure

The CRM uses the anelastic system with the height coordinate. The GCM uses the quasi-hydrostatic system with the sigma-pressure coordinate. The heights of the GCM layer centers and edges evolve with time and also vary geographically, while those of the CRM do not.

For each GCM grid column, the time-varying GCM sounding is used as the "reference sounding" for the CRM. When the CRM is called by the GCM, it receives as input the provisional temperature and vapor profiles that have been updated by the GCM dynamics, as well as the height and pressure profiles. The CRM adjusts its vertical grid to agree with the GCM's, assuming that the reference-state pressures at mid- and interface-levels are the same as the GCM's. The CRM computes the reference-state air density from hydrostatic balance.

Because the GCM grid heights are slightly different from those on the previous GCM time step, there is a small spike at the beginning of each CRM subcycle; because the step-by-step changes in grid height in the GCM are rather small, the spike does not significantly affect the CRM results.

The vertical integral of water vapor in the CRM at the beginning of a sequence of CRM time steps is not the same as it was when CRM finished computing at the end of the preceding sequence. This discrepancy is eliminated at the end of CRM call, however, because it is automatically corrected by the prescribed large-scale forcing. As a result, the vertical integral of total water in the CRM at the end of the GCM time step always equals the vertical integral of total water in the of GCM after the provisional dynamics step. The same is true for the frozen static energy.

A complication is that the precipitation water in CRM is not passed back to the GCM; some of it is left in the CRM grid, hanging in the air. As a result, precipitation hanging in the air at the end of the GCM time step is not accounted for by the GCM. It is conserved by the CRM though, and can eventually reach the surface and be outputted as rainfall, or evaporate and thus return back to the GCM's grid as vapor.

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References and Bibliography

Benedict, J. J., and D. A. Randall, 2007: An analysis of the MJO based on TRMM rainfall data. *J. Atmos. Sci.*, **64**, 2332-2354.

Benedict, J. J., 2009: *Analysis of the Structure of the Madden-Julian Oscillation in Coupled and Uncoupled Versions of the Superparameterized Community Atmosphere Model.* Ph.D. Thesis, Colorado State University.

Benedict, J. J., and D. A. Randall, 2009: MJO Structure in the Superparameterized CAM. *J. Climate,* **66**, 3277-3296.

Cole, J. N. S., H. W. Barker, W. O'Hirok, E. E. Clothiaux, M. F. Khairoutdinov, and D. A. Randall, 2005: Atmospheric radiative transfer through global arrays of 2D clouds. *Geophys. Res. Lett.*, **32**, L19817, doi:10.1029/2005GL023329.

Collins, W. D., C. M. Bitz, M. L. Blackmon, G. B. Bonan, C. S. Bretherton, J. A. Carton, P. Chang, S. C. Doney, J. J. Hack, T. B. Henderson, J. T. Kiehl, W. G. Large, D. S. McKenna, B. D. Santer, and R. D. Smith, 2006: The Community Climate System Model Version 3 (CCSM3). *J. Climate*, **19**, 2122-2143.

DeMott, C., D. A. Randall, and M. Khairoutdinov, 2010: Implied ocean heat transports in the standard and super-parameterized Community Atmosphere Models. *J. Climate,* **23**, 1908-1928.

Khairoutdinov, M., and D. A. Randall, 2003: Cloud-resolving modeling of ARM Summer 1997 IOP: Model formulation, results, uncertainties and sensitivities. *J. Atmos. Sci.,* **60**, 607-625.

Khairoutdinov, M., D. A. Randall, and C. DeMott, 2005: Simulation of the atmospheric general circulation using a cloud-resolving model as a super-parameterization of physical processes. *J. Atmos. Sci.*, **62**, 2136-2154.

Khairoutdinov, M., C. A. DeMott, and D. A. Randall, 2008: Evaluation of the simulated interannual and subseasonal variability in an AMIP-style simulation using the CSU Multiscale Modeling Framework. *J. Climate,* **21***,* 413 - 431.

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

Stan, C., M. Khairoutdinov, C. A. DeMott, V. Krishnamurthy, D. M. Straus, D. A. Randall, J. L. Kinter, III, and J. Shukla, 2010: An ocean-atmosphere climate simulation with an embedded cloud resolving model. *Geophys. Res. Lett.*, **37**, L01702, doi:

10.1029/2009GL040822.

Tao, W.-K., J. Chern, R. Atlas, D. A. Randall, X. Lin, M. Khairoutdinov, J.-L. Li, D. E. Waliser, A. Hou, C. Peters-Lidard, W. Lau, and J. Simpson, 2009: A multi-scale modeling system: Developments, applications, and critical issues. *Bull. Amer. Meteor. Soc.,* **90***,* 515-534.

Thayer-Calder, K., and D. A. Randall, 2009: The Role of Convective Moistening in the Formation and Progression of the MJO. *J. Climate*, **66**, 3297-3312.