An enhanced convection-wind-evaporation feedback in a superparameterization GCM (SP-GCM) depiction of the Asian summer monsoon

Zhengzhao Luo[1] and Graeme L. Stephens[1]

Received 1 November 2005; revised 20 January 2006; accepted 10 February 2006; published 22 March 2006.

[1] Both the Colorado State University (CSU) and Goddard superparameterization GCM (SP-GCM) simulate a superactive Asian summer monsoon with unrealistically enhanced levels of precipitation. The underlying physical mechanism for this monsoon bias in the CSU SP-GCM is shown to involve an enhanced convection-wind-evaporation feedback. The feedback process is studied using two experiments with different fixed specifications of surface evaporation. A regional analysis of an area that exhibits excessive precipitation offers a glimpse of the transient nature of the feedback. Finally, we discuss the broader relevance of the feedback study to climate modeling.
Citation: Luo, Z., and G. L. Stephens (2006), An enhanced convection-wind-evaporation feedback in a superparameterization GCM (SP-GCM) depiction of the Asian summer monsoon, *Geophys. Res. Lett.*, *33*, L06707, doi:10.1029/2005GL025060.

1. Introduction

[2] Global Climate Modeling community has witnessed a number of new modeling tools over the past several years. One of the most noteworthy is the superparameterization GCM or SP-GCM [*Grabowski*, 2001; *Khairoutdinov and Randall*, 2001]. The idea of SP-GCM is to replace the conventional, single-column physics parameterization with a cloud-resolving model (CRM), which employs a first-principle approach to representing the dynamics and physics of cloud-scale processes with the exception of cloud microphysics. In SP-GCM, every grid (typically covering several hundred kilometers) has a copy of the CRM; it runs continuously and interacts with the large-scale dynamics through a "forcing-feedback" coupling mechanism between the host GCM and the CRM.

[3] *Khairoutdinov et al.* [2005] evaluated the Colorado State University (CSU) SP-GCM simulation against a suite of satellite and ground-based observations of selected benchmark climate parameters. The SP-GCM shows several improvements, especially in the areas of high-level cloudiness, the diurnal cycle of precipitation and convective intraseasonal variability. The model also exhibits large biases, notably producing a significant overestimate in boreal summer precipitation over Southeast Asia and West Pacific, a region affected by the world's strongest monsoon [see *Khairoutdinov et al.*, 2005, Figure 3]. This monsoon bias is not just unique to the CSU SP-GCM; the newly-developed Goddard SP-GCM, which uses totally different CRM and host GCM, also shows a similar bias (Tao, personal communication 2005), indicating that some common, inherent deficiency might be responsible for the bias. The nature of bias has not been understood, although some connection with the configurations of the 2-D CRM is suggested [*Khairoutdinov et al.*, 2005]. We show in this letter that while there may be such a connection, the underlying physical mechanism for the bias involves an excessively strong convection-wind-evaporation feedback. The transient nature of the feedback is examined and the implication and relevance of this study to global climate modeling in general is discussed.

2. CSU MMF and Experiment Design

[4] The SP-GCM idea was first proposed and implemented in an idealized case (aqua planet) by *Grabowski* [2001]. *Khairoutdinov and Randall* [2001] took this approach one step further by developing the first full-blown SP-GCM based on the CSU CRM and the NCAR Community Atmospheric Model (CAM), hence it is referred to as SP-CAM hereafter. The newest version of the CAM, namely CAM3, is used in this study. The CAM is configured to run at T42 horizontal resolution ($2.8° \times 2.8°$) with 26 vertical levels using semi-Lagrangian dynamical core; the time step is an hour. The CRM used is a 2-D version, which has 64 grids aligned in the west-east direction with the horizontal grid spacing of 4 km. Twenty-four vertical levels are collocated with those of the CAM3. The CRM time step is 20 s. SP-CAM is computationally 200 times more expensive than the standard CAM [*Randall et al.*, 2003], which severely limits possibilities of conducting long-term runs with parallel experiments. Since the focus of this study is on the model bias in the simulation of the Asian summer monsoon, we only run the model for the month of July with the monthly mean climatological SST. To avoid the model spin-up problem, we start it from an atmospheric/land surface state which has been spun up through a previous 10-month SP-CAM climatological run (provided by Steven Gahn and Roger Marchand at the Pacific Northwest National Lab). A parallel standard CAM run is performed in a similar way by simply turning off the CRM option and turning on the conventional parameterization.

3. Convection-Wind-Evaporation Feedback in the Model

[5] The convection-wind-evaporation feedback is not new and was introduced by *Emanuel* [1987] and *Neelin et*

[1]Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, USA.

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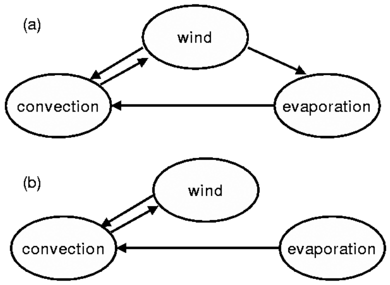

Figure 1. Schematic diagram showing the convection-wind-evaporation feedback in (a) the SP-CAM control run and (b) the experiments. Each arrow indicates a direct cause-effect relationship.

al. [1987] to explain the mechanism of the Madden-Julian Oscillation (MJO). Latent heat released from convection forces anomalously strong winds, which increase surface evaporation; the enhanced evaporation and surface wind then feed back to fuel the convection by converging moisture feeding the convective region. The impact of this feedback on the mean state of the surface climate is significant and robust in GCMs [e.g., *Zhang*, 1996]. Moreover, *Behera et al.* [1999] found that such a feedback mechanism explains the intensified monsoon observed over India and Southeast Asia during 1994.

[6] Figure 1a shows schematically how this feedback mechanism works in GCMs. Convection and wind constitute a two-way relationship, feeding back on each other directly. The relationship between wind and evaporation is formulated as one way (i.e., wind affects evaporation) via the bulk aerodynamic formula evaluated in GCM grids, although evaporation indirectly affects wind through its influence on convection. The link between evaporation and convection is also treated to a large extent as one way in both CAM and SP-CAM. In the real world, however, gusty wind produced by convection has an effect on evaporation, but in the model, surface evaporation only responds to the model large-scale wind. Evaporation calculated in the CRM instead of in the GCM is under plan for a future version of the SP-CAM; feedbacks are likely to be different when surface exchange between the atmosphere and land, ocean or ice surfaces are treated at the cloud scale. Since episodic evaporation events from gustiness associated with convection was observed in TOGA COARE to be an important contribution to evaporation [*Webster and Lukas*, 1992], including the cloud-scale evaporation is likely to exaggerate the feedback. Figure 1b illustrates the conceptual idea behind the model experiments we perform. We break the convection-wind-evaporation feedback loop by specifying the surface evaporation. Despite the break in the feedback loop, a feedback between convection and wind remains in the model, potentially producing local enhancements of the hydrological cycle in some regions.

[7] The feedback is studied in the SP-CAM and the CAM over a tropical region covering the Indian Ocean and West Pacific that notably comes under the influence of the Asian summer monsoon (30S–30N and 40E–20W). The monthly mean precipitation (P) minus evaporation (E) in this domain is negligibly small (P and E are both 4.8 mm/day for the SP-CAM; for the CAM, P is 4.6 mm/day and E is 4.5 mm/day), suggesting that it behaves to a large extent like a closed system, at least as far as hydrological cycle is concerned. Figure 2 shows the July mean SP-CAM surface wind, evaporation and precipitation (considered a proxy for convection). The geographical distributions of these variables suggest a mutual cooperation among them: stronger surface winds evaporate more moisture from the ocean and these same winds converge this moist air fueling convection. The signature circulation of the Asian summer monsoon is well captured in both SP-CAM (Figure 2) and CAM (not shown), with enormous amounts of cross-equatorial moisture transport over the Indian Ocean. One major difference between the two simulations lies in the West Pacific, where the SP-CAM shows a local maximum in precipitation and evaporation coupled with strong surface convergent winds. A similar situation is also found over the Western Indian and the Bay of Bengal, although with a lesser discrepancy between the models and the observation [see *Khairoutdinov et al.*, 2005, Figure 3]. Figure 2 suggests that the SP-CAM precipitation bias is mostly likely linked to the excessively strong surface wind and the enhanced surface evaporation. This does not mean that the precipitation bias is literally "caused" by the strong surface winds and evaporation. Rather, they constitute a feedback loop through which all three fields get enhanced, as will be shown later.

[8] To demonstrate that the convection-wind-evaporation feedback establishes the superactive monsoon in the SP-CAM, we perform two experiments with the SP-CAM using fixed surface evaporation. Experiment 1 (Exp1) uses the monthly mean evaporation from the SP-CAM control run. This sustains the same moisture supply as the control but cuts off the feedback loop (Figure 1b). Experiment 2 (Exp2) uses the monthly mean evaporation from the CAM control run, which not only breaks the feedback loop but also changes the spatial distribution of evaporation and reduces the domain-mean moisture supply by about 8%. Figure 3 shows the simulated surface wind and precipitation for the control run (upper panel), the two experiments (middle panels) and observation/reanalysis (bottom panel). Note that the "observed" precipitation and surface wind are long-term means (obtained from NOAA CDC) while the model results are for one single month. The intent is not to show an improvement toward reality but to reveal different aspects of the feedback as it operates in the SP-CAM in contrast to CAM. There is a noticeable difference in precipitation between the Exp1 and the control run over the West Pacific "hot spot" (17N–22N and 132E–142E): the magnitude of the former is only about half that of the latter

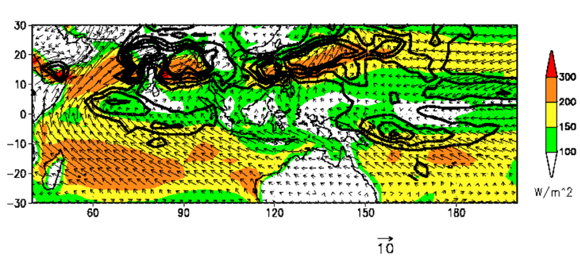

Figure 2. July mean SP-CAM surface winds (vector), precipitation (black contours; 5–25 mm/day in 5 mm/day interval) and surface evaporation (color contours).

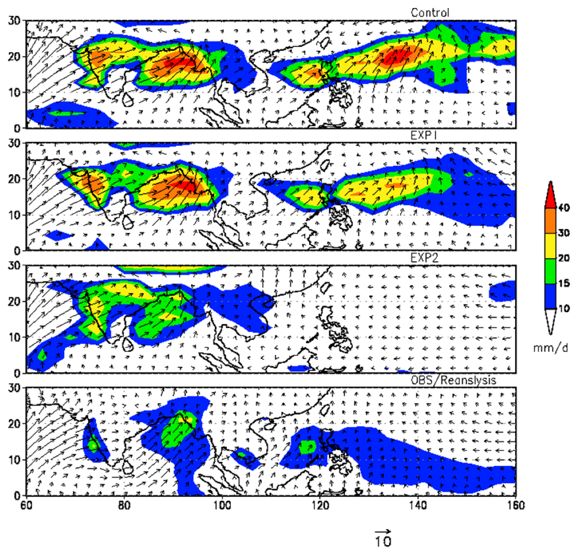

Figure 3. July mean surface winds and precipitation for, from top to bottom, the SP-CAM control run, Exp1, Exp 2, and the observation/reanalysis.

(i.e., 25 mm/day vs. 40 mm/day). Surface winds are also weaker in Exp1 over this region. Since the total moisture supply is identical for both runs, the differences are due to the convection-wind-evaporation feedback. Precipitation over the India and the Bay of Bengal is similar between EXP1 and the control probably as the convection-wind feedback remains in EXP1 and maintains a locally enhanced hydrological cycle in this region. This is difficult to show conclusively with idealized experiment since neither convection nor wind can be as easily perturbed in isolation. However, the fact that strong precipitation coincides with strong surface wind in the EXP1 over the India and the Bay of Bengal is consistent with such a feedback. Precipitation and surface wind patterns of EXP2, however, are more different from the control than is EXP1, highlighting the importance of moisture supply by enhanced evaporation. These two experiments hint at how evaporation affects surface wind and convection and how the convection-wind-evaporation feedback affects the model simulation. We argue that this feedback occurs in the real world and in comparison with observation and reanalysis (Figure 3, bottom), we suggest the strength of the feedback in the real world is most likely weaker than that of the SP-CAM.

[9] To gain further insight into the operation of the convection-wind-evaporation feedback process in the SP-CAM, we examine the time series of the 3-hourly means of several variables over the "hot spot" region. The variables analyzed are precipitation, vertically-integrated moisture convergence, surface wind speed, evaporation, and total column water vapor, and these are shown in Figure 4 as a function of time counted from July 1. Figure 4 shows that a "preparatory" period exists (roughly day 1 to day 5 in duration) during which water vapor builds up through large-scale moisture convergence and local evaporation. This is followed by an "onset" of the monsoon convection, which develops strong convection with the averaged surface rain rate of around 40 mm/day persisting for about two weeks. The moisture balance during the convective stage is, for the most part, maintained between large-scale moistening and convective drying. In both the conventional GCM and SP-GCM, the separation between the large-scale forcing and the subgrid-scale response introduces an intrinsic feedback: large-scale circulation brings in water vapor and induces cooling; moist convection then rains out the condensed moisture and warms the atmosphere through latent heat release and eddy transport. The drying and warming effects of the moist convection, in turn, feed back to the large-scale fields, completing a feedback loop (and one model time step). The convection-wind-evaporation feedback can be thought of as one manifestation of the more general large-scale/subgrid-scale feedback in the model. In light of this, one interesting feature from Figure 4 is that the precipitation and moisture convergence (and evaporation/surface wind, too, to a lesser extent) tend to closely track each other on a very short time scale (~hours) during convection. That is, the CRM responds quickly to the large-scale forcing imposed on by the host GCM's dynamical core, and vice versa. Furthermore, there appears to be a timely cancellation between them such that the net effect on moisture is small at any given time (notice that total column water vapor variation is smaller during the convective stage than the preparatory stage). There is no constraint in the SP-CAM formulation that demands such close coupling, which is different from the conventional cumulus parameterization where typical closure assumptions require that the response be tied to the forcing on some a priori time scale (see *Arakawa* [2004] for a review). This well-timed coupling between large-scale dynamics and subgrid-scale processes can only be understood as an inherent property of the SP-CAM model. It also implies that the underlying feedback process must also occur on a similar, if not shorter, time scale to produce a mutual cooperation and intensification.

[10] A logical question to consider is, why does this convection-wind-evaporation feedback act in a more enhanced way in the SP-CAM than in the standard CAM (and the real world)? Although the reason is not yet entirely understood, there are a number of candidate explanations. One is that under the periodic boundary condition used in the 2-D CRM, convection does not propagate to the neighboring GCM grid but is recycled back into the same grid from the other side (Figure 5). This artificial "trapping" of convection prolongs its lifetime (locally) providing a prolonged opportunity for convection and large-scale dynamics to reinforce each other. The 2-week-long, locally-trapped monsoon convection as depicted in

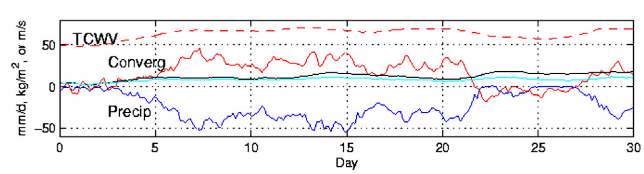

Figure 4. Time series of the 3-h means of the column-integrated moisture source/sink through large-scale convergence (red; in mm/d), evaporation (cyan; in mm/d) and precipitation (blue; in mm/d), and total column water vapor (red dashed; in kg/m^2) and surface wind speed (black; in m/s) for the "hot spot" discussed in the text.

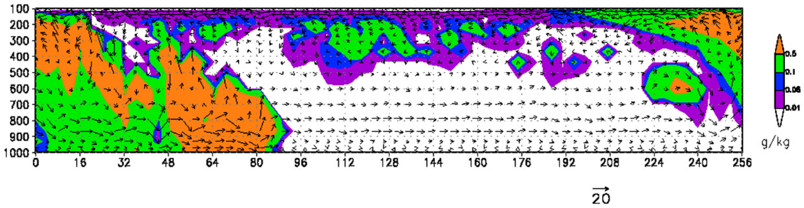

Figure 5. A snapshot of cloud condensates and precipitation from the 2-D CRM used in the SP-CAM at a "hot spot" grid. Also shown are the winds (m/s) with the vertical component amplified by a factor of 10. The horizontal domain is 256 km.

Figure 4 is probably an illustration of this effect. Future development of the SP-GCM with the quasi-3D approach proposed by *Arakawa* [2004], which allows convection to move from one GCM grid to another, will shed more light on how the feedback operates and modulates the monsoon precipitation.

4. Summary and Discussion

[11] The problem of cumulus convection is essential to many important interactions of the physical climate system [*Arakawa*, 2004] and to the feedback mechanisms that modulate it [*Stephens*, 2005]. Representing cumulus convection in global models and accounting for the various interactions that couple to convection has been a long-standing challenge to the modeling community [*Arakawa*, 2004]. The development of the SP-CAM approach represents a new step in addressing this long-standing problem.

[12] This study illustrates how the convection-wind-evaporation feedback, exaggerated in the SP-GCM, produces an excessively active monsoon in the Western Pacific of that model. When the evaporation is fixed and unable to feed back on convection and winds, the monsoon precipitation is diminished by almost 50% over the West Pacific. A regional analysis of an area that exhibits excessive precipitation offers a glimpse of the evolution of the feedback process: a preparatory stage exists during which time large-scale convergence and surface evaporation build up the water vapor locally, followed by a convective stage where the feedback drives the model hydrological cycle to an enhanced state and further maintains it in that state for some time. Although the precise reason for the enhanced feedback in the SP-CAM is not determined, it is most likely associated with the way the CRM is implemented in the model with cyclic boundary conditions that sustain convection locally prolonging its influence on the feedback.

[13] Given the seminal role of convection in the climate system, and its role in many different climate feedbacks it is important to test the representation of convection against all possible relevant observations. This paper underscores the complications involved in evaluating the effects of new parameterizations of convection through feedbacks that are triggered by convective processes that lead to significant changes to the model's hydrological cycle. The convection-wind-evaporation feedback mechanism is one recognized as important in most global models and presumably important in the real world. The research described is part of an activity that seeks to assess the SP-CAM against available observations. One advantage of the SP-CAM is it makes model-data comparison of cloud and convection-scale processes more straightforward. In particular, our ongoing research seeks to bring the advanced satellite-borne radar observations of TRMM and CloudSat to evaluate the SP-CAM.

[14] **Acknowledgments.** This work was supported by the NASA Grant NNG04GB97G. We thank Steven Gahn and Roger Marchand at PNNL for providing us with the SP-CAM model code and the restart files. Norm Wood helped set up the SP-CAM experiments. We benefited from conversations with Dave Randall and Marat Khairoutdinov at CSU and W.-K. Tao and J.-D. Chern at NASA Goddard.

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Z. Luo and G. L. Stephens, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523, USA. (luo@atmos.colostate.edu)