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Performance of two cloud-radiation parameterization schemes in the finite volume general circulation model for anomalously wet May and June 2003 over the continental United States and Amazonia

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[1] An objective assessment of the impact of a new cloud scheme, called Microphysics of Clouds with Relaxed Arakawa-Schubert Scheme (McRAS) (together with its radiation modules), on the finite volume general circulation model (fvGCM) was made with a set of ensemble forecasts that invoke performance evaluation over both weather and climate timescales. The performance of McRAS (and its radiation modules) was compared with that of the National Center for Atmospheric Research Community Climate Model (NCAR CCM3) cloud scheme (with its NCAR physics radiation). We specifically chose the boreal summer months of May and June 2003, which were characterized by an anomalously wet eastern half of the continental United States as well as northern regions of Amazonia. The evaluation employed an ensemble of 70 daily 10-day forecasts covering the 61 days of the study period. Each forecast was started from the analyzed initial state of the atmosphere and spun-up soil moisture from the first-day forecasts with the model. Monthly statistics of these forecasts with up to 10-day lead time provided a robust estimate of the behavior of the simulated monthly rainfall anomalies. Patterns of simulated versus observed rainfall, 500-hPa heights, and top-of-the-atmosphere net radiation were recast into regional anomaly correlations. The correlations were compared among the simulations with each of the schemes. The results show that fvGCM with McRAS and its radiation package performed discernibly better than the original fvGCM with CCM3 cloud physics plus its radiation package. The McRAS cloud scheme also showed a reasonably positive response to the observed sea surface temperature on mean monthly rainfall fields at different time leads. This analysis represents a method for helpful systematic evaluation prior to selection of a new scheme in a global model.

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1. Introduction

[2] The decision to replace and/or significantly upgrade an existing physical parameterization scheme, such as cloud physics, in a general circulation model (GCM), with that of a new physically more desirable scheme is always a daunting endeavor because the new scheme may not improve all aspects of the model's simulations. Consequently, the performance of the new scheme must be evaluated on a variety of timescales and space scales through extensive intercomparisons with the old. Since model performance can show discernible variances on weather and climate timescales, performance evaluation on both timescales should be invoked. Moreover, it is well known that some areas of the simulations improve while others get worse; consequently, one often waits until the relatively poor aspects of the simulations are better understood and resolved. A central issue is whether the decision to adopt a new scheme should be solely governed by (1) better representation of the relevant physics and its demonstrated superiority in controlled test bed evaluation scores such as Atmospheric Radiation Measurement–Single Column Model (ARM-SCM) evaluations regardless of the impact on GCM simulations or (2) the positive impact on the GCM simulations as the primary determinant of the intrinsic value of the new scheme. The latter can only be ascertained by quantities such as improvement in skill scores on the key timescales. The second approach guarantees continually improving forecast skill, which is also a pragmatic criterion of model performance for weather and/or climate forecasts [*Phillips et al.*, 2004]. On the other hand, if a parameterization is physically more defensible, i.e., it better represents the physical processes of central importance that were either undermined or poorly represented in the old scheme, the most plausible reasons for less than superior performance of

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the new scheme would be (1) its inability to work in concert with the rest of the physics schemes of the model containing systematic errors and biases of their own that are often intertwined into compensating biases of interacting schemes (via tuning) and/or (2) numerical approximations that could introduce spurious interactions at some specific spatiotemporal scales. Logically, one would argue that the new scheme must await until all the other interacting schemes and numerical inconsistencies have been ironed out to yield even more tangible improvements in the overall performance of the model; however, a major drawback of such an approach is that the scientists who developed the other schemes also need to interact with the developer of the new scheme at a substantial level. Lacking such interactions, it often reduces to an exercise in retuning the model to work optimally with the new scheme. Tuning work is seldom attractive, particularly to those scientists who have the ability to formulate physically much more rigorous and state-of-the-knowledge parameterization schemes. In other words, the model developer views this as an exercise in turning backward and therefore finds little challenge in it; moreover, ad hoc tuning exercises not only are time-consuming, but they also weaken the rigor of a well-formulated solution. As a consequence, the full potential of a physically more representative scheme is seldom realized, while GCMs continue to carry a mixture of sophisticated as well as rudimentary representations of variously tuned parameterizations schemes of often important and significantly interacting physical processes.

[3] A good example of such a combination is our own Microphysics of Clouds with Relaxed Arakawa-Schubert Scheme (McRAS) [*Sud and Walker*, 1999a, 2003]. Whereas thermodynamic processes producing cloud-water substance, deposition and cloud-scale motions are derived from first principles of cloud physics and dynamics, the number density and effective size of cloud ice and/or water droplets, an important input to cloud-radiation interactions, is parameterized on the basis of empirical relations derived from limited observational data [*Sud and Walker*, 1999a]. Thus, despite so much attention to prognostic cloud dynamics and associated condensation physics, its key function of simulating cloud-water and cloud-radiation interaction ends up being ad hoc and empirical. Such types of coupling of complex, nevertheless important, physical processes are commonplace in many models. Therefore one would argue that the best approach to gauge the performance of a new scheme is through its ability to function more realistically within a model's environment with or without the agonizing retuning exercise.

[4] However, modeling experience also dictates that the probability of the superior performance of a new cloud scheme increases remarkably if it is derived from the first principles of physics and has already demonstrated superior performance in stand-alone test bed evaluations such as the ARM-SCM evaluations [*Xie et al.*, 2002, 2004]. Our specific focus here is the cloud physics of the finite volume GCM (fvGCM) of NASA Goddard's Modeling and Data Assimilation Office (GMAO). It uses the NCAR-based CCM3 cloud physics, radiation, and convection. We have reasoned that McRAS might perform better in the fvGCM because (1) it employs several physically derived convective triggers and inhibitors along with parameterized rain evaporation and downdrafts [*Sud and Molod*, 1988; *Sud and Walker*, 1993] and (2) it invokes fully interactive cloud microphysics using well-tested algorithms designed by *Sundqvist et al.* [1989], *Tiedtke* [1993], and *Del Genio et al.* [1996].

[5] The goal then is to evaluate the performance of McRAS vis-à-vis the current cloud scheme in the fvGCM and use McRAS if and only if it performs better. This is a challenging task for midlatitude evaluation particularly when one recognizes that there is very little local summer season climate predictability outside of the tropics [*Palmer and Anderson*, 1994; *Pavan and Doblas-Reyes*, 2000]. On the other hand, the background weather needs to be reliable for simulating realistic clouds and rainfall patterns, because in addition to modulating climate, clouds are a by-product of weather systems. Therefore evaluating clouds in global weather models is an essential next step following SCM evaluation wherein all the forcing fields are prescribed [*Phillips et al.*, 2004]. Since pluses and minuses of a model evaluation matrix can be complex, we devised a methodology which relies on an ensemble approach and evaluates the model performance on both weather and climate timescales [*Xie et al.*, 2004]. Moreover, for cloud parameterization evaluation, we need to focus specially on specific regions and time frames of anomalous circulation and rainfall.

[6] We would like to focus on the simulated weather, but we must keep in mind the Lorenz limit of predictability of weather; in a strategy in which weather forecasts are time averaged to assess the climatic timescale impact, we naturally invoke weather and climate phenomena in evaluating a cloud parameterization. We have devised such a unified method, which tests the impact of a scheme on both on instantaneous weather as well as monthly averaged climate. We also use an objective criterion to discern if the new scheme (one that a developer claims to better represent the key physical processes) is capable of performing discernibly better than the already existing one. The GCM involved in this study is NASA/NCAR finite volume general circulation model (fvGCM) developed at NASA/GSFC (hereafter fv-NCAR GCM). Its hydrodynamics was developed in house [*Lin*, 2004], but it uses NCAR's Community Climate Model (CCM3) physics. Microphysics of Clouds with Relaxed Arakawa-Schubert (McRAS) is the cloud scheme that is to be evaluated against the model's CCM3 cloud scheme. McRAS with Chou and Suarez radiation has shown several promising features in simulating rainfall climatology within the GEOS GCMs [*Sud and Walker*, 1999b, 2003; *Maloney and Hartmann*, 2001; *Maloney*, 2002]. Without tuning the cloud droplet number density as a function of temperature, the model produced some discernible drift in cloud-radiative forcing, but it was significantly mitigated with better empirical assumptions of cloud particulate number density of water and ice clouds following *Del Genio et al.* [1996] and *Ou and Liou* [1995], respectively. We have a 15-year AMIP-type simulation that shows that the rainfall and circulation climatology of the model does not produce excessive drift in its climatology. Several options to test the effects of McRAS were examined; however, the one described in this paper was not only appealing, but also turned out to be useful and revealing. Section 2 of the paper contains descriptions of the fvGCM, as well as of the new schemes of McRAS and Chou radiation. The methodology

Table 1. Parameterization of Clouds, Radiation, and Convection in McRAS and CCM3 as Implemented in the fvGCM

	Item	McRAS	CCM3
1	boundary layer clouds	Relaxed Arakawa-Schubert (RAS) [*Moorthi and Suarez*, 1992] extended to boundary layer convection with clouds when supersaturated [*Sud and Walker*, 2003]	explicit nonlocal convection [*Holtslag and Boville*, 1993]
2	cumulus clouds/moist convection	RAS mass flux scheme [*Moorthi and Suarez*, 1992]; ice-phase physics, *Sud and Walker* [2003]	deep clouds, CAPE-based mass flux scheme [*Zhang and McFarlane*, 1995]; shallow clouds, *Hack* [1994]
3	stratiform clouds	linear relative humidity (RH)/probability distribution function outside the cloud and 100% RH inside the cloud [*Sud and Walker*, 1999a]	cloud fraction is a function of vertical velocity, RH, and stability [*Slingo*, 1987]
4	cloud/precipitation microphysics	*Sundqvist et al.* [1989] and *Tiedtke* [1993] microphysics core [*Sud and Walker*, 1999a] with saturated air mass fraction forming clouds	diagnosed from precipitable water and convective overturning following *Xu and Krueger* [1991]
5	rain evaporation and downdrafts	evaporating raindrops [*Sud and Molod*, 1988] and convective-scale downdrafts [*Sud and Walker*, 1993]	CCM3 upgraded to evaporate falling rain; no downdrafts
6	radiative transfer parameterizations	shortwave, *Chou et al.* [1999]; longwave, *Chou et al.* [1998]	shortwave, *Briegleb* [1992] with some upgrades, plus *Ramanathan and Downey* [1986]
7	cloud-radiation interaction and forcing	prognostic clouds of three types: shallow, midlevel, and deep; maximum overlap within and random overlaps among different types	*Keihl and Ramanathan* [1990]; *Slingo* [1989] overlapping assumptions

of the experiment and the observed data sets used for evaluation of the new schemes are described in section 3. Section 4 contains results of the experiments and describes figures showing the effect of the new schemes, while a summary and discussion is provided in section 5.

2. Model Description

[7] The fv-NCAR GCM uses a finite volume dynamical core developed and extensively evaluated by *Lin and Rood* [1996] and more comprehensively documented by *Lin* [2004]. The radiation and cloud schemes (along with the rest of the physics, including the Community Land Model version 2.0 (CLM2)) in fv-NCAR GCM are from the NCAR CCM3.6.6 community model [*Hurrell et al.*, 1998]. It is well known that different interacting physics complexes are often deeply intertwined into each other. The advantage with the NCAR CCM3 physics is that its different sections are so well encapsulated that the task of implementation and evaluating McRAS, our new cloud scheme, became much easier.

[8] The fv-NCAR GCM is used for weather forecast assessment climate studies and observational data analysis. On an experimental basis, it is extensively used at NASA/GSFC for real-time short- to medium-range forecasting. The initial atmospheric state of the real-time simulations is taken from the NCEP analysis system, with data available at 0000 and 1200 UT. The initial land surface soil moisture states for the GCM's land model are continuously "spun up" from the previous real-time model simulation. This has its drawbacks but it was the next best thing to performing exhaustive soil moisture analysis. For this investigation, the model resolution is 0.5 degrees latitude by 0.625 degrees longitude, with 32 vertical levels covering the atmosphere from the ground surface to an altitude of approximately 55 km. The sea surface temperatures and sea ice boundary conditions are monthly and climatological. However, the current version of the experimental fv-NCAR GCM also can run at a finer horizontal resolution using prescribed sea surface temperatures and sea ice boundary conditions from the NOAA Optimum Interpolation SST Analysis, a weekly data product.

[9] Cloud and radiation physics schemes of McRAS were developed and extensively tested in house have also been implemented into the fv-NCAR GCM. The McRAS cloud scheme tracks the cloud amount through a prognostic cloud mass and water substance calculation in which cloud and precipitation microphysics remains interactive within all cloud types at all times. McRAS was structured around the moist convective core of Relaxed Arakawa-Schubert scheme due to *Moorthi and Suarez* [1992]. The radiation scheme of *Chou and Suarez* [1994] with several updates extensively discussed by *Chou et al.* [1998] and *Chou et al.* [1999] is coupled to McRAS and both were implemented into the fv-NCAR GCM. These two schemes replace the cloud, radiation, and convection schemes of the fv-NCAR GCM to create a separate upgraded version of the GCM called fv-McRAS GCM. The key features of the two schemes are highlighted in Table 1. We assess the influence of this upgrade in this study.

3. Data and Methodology

[10] For comparative evaluation of the cloud schemes, we used the recent period of May and June 2003 that produced highly anomalous and largely convective precipitation over two key regions: (1) the continental United States and (2) tropical South America. Besides being a region of special interest to the authors, the continental United States has extensive available daily rainfall data. The rainfall is generated from water vapor condensation/deposition; its sources are local evaporation and horizontal moisture convergence that in turn is supported by the quasi-stationary synoptic-scale circulation. The months of May and June 2003 experienced a stronger subtropical jet over the southeastern United States, with an associated strengthening of the low-level jet into this region from the Gulf of Mexico. This pattern is in the initial data based on the analysis of observations. The investigation employed separate sets of ensemble forecasts with the fvGCM. A series of 10-day daily forecasts, each started every day at 1200 UT using initial conditions from the analysis of observations, was made for each version of the model. In short, each set of simulations contains seventy daily forecasts (61 days of

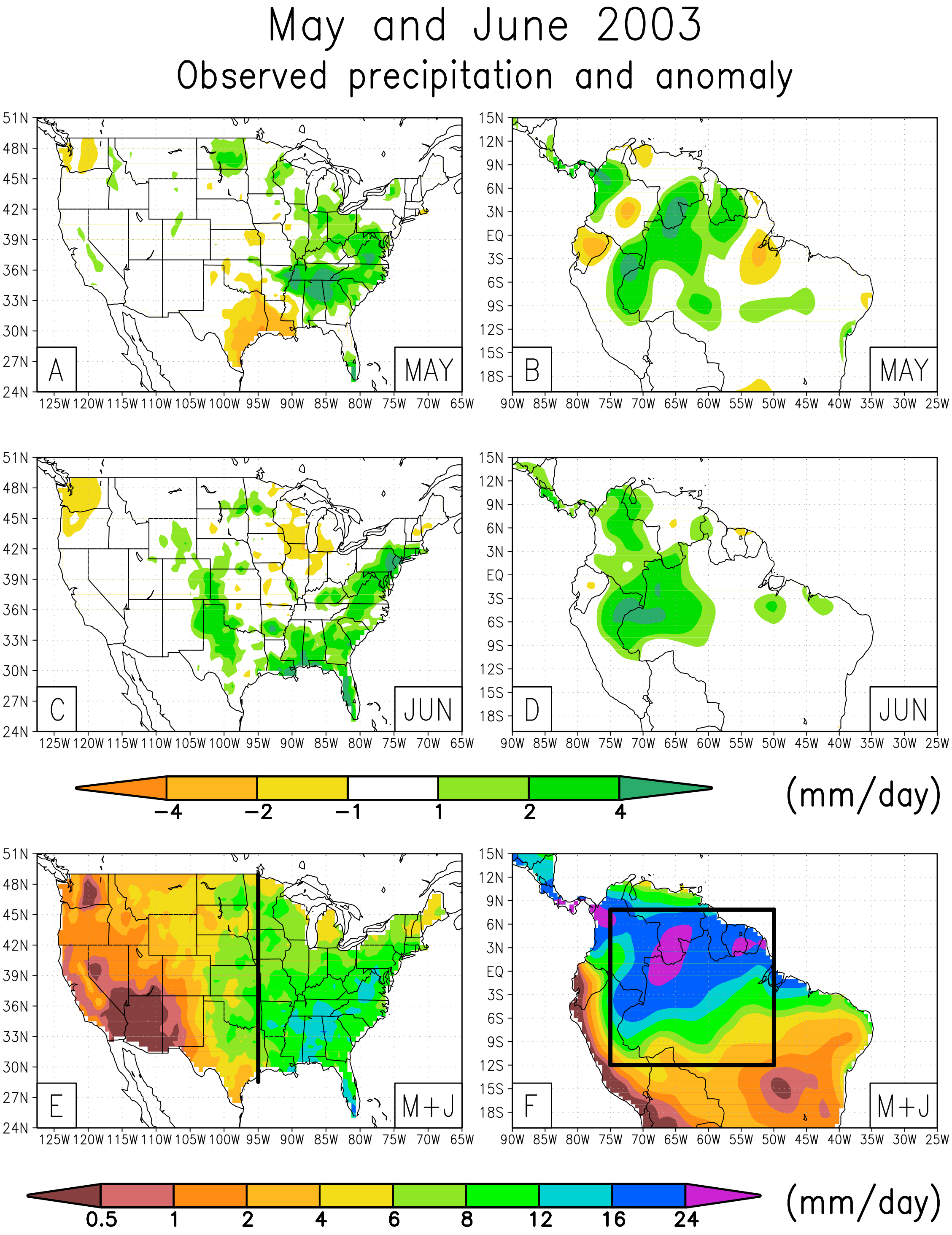

Figure 1. Observed precipitation anomaly (mm/d) for (a and b) May and (c and d) June 2003 over the continental United States (left) and Amazonia (right); (e and f) corresponding May and June averaged precipitation. U.S. data contain monthly averages of daily precipitation values from CPC; Amazonia data are monthly GPCP precipitation analyses. Precipitation climatology over both regions is GPCP data. The solid lines in Figures 1e and 1f demark the "wet anomaly region" separately analyzed for anomaly correlation shown in Figures 4 and 5. Over the United States the "wet anomaly region" is all U.S. land points east of 95°W; over Amazonia the wet region is all land points between 75°W and 50°W and 12°S and 8°N.

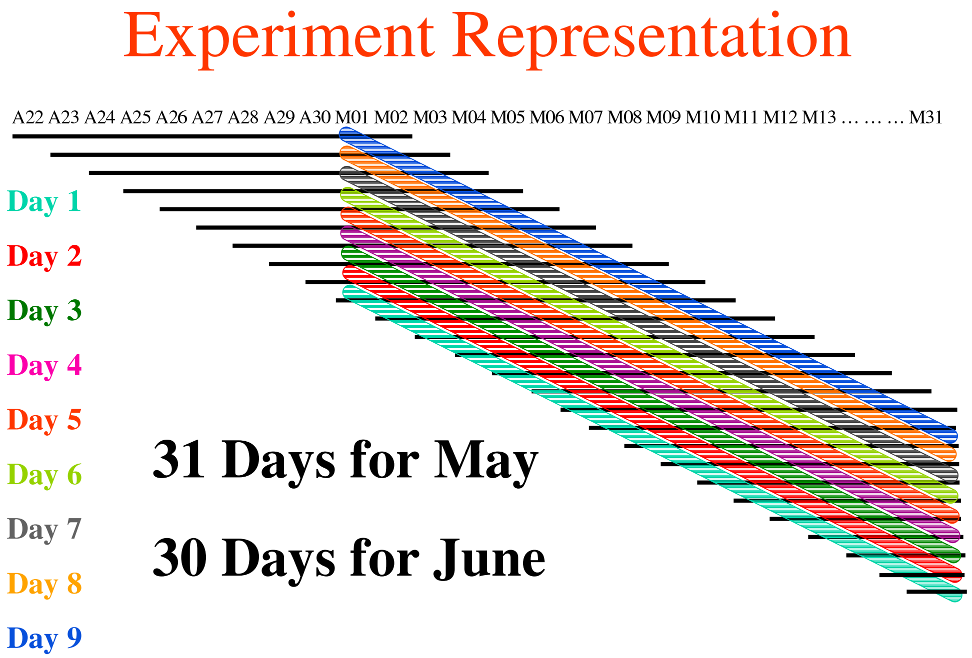

Figure 2. Schematic representation of the 10-day simulations (horizontal black lines) with the ensemble-averaged data used to compute monthly averages with different forecast lead times. The average of the days highlighted in light blue represent the day 1 ensemble for May, the average of the days highlighted in red represent the day 2 ensemble, and so on until day 9. The same procedure was used for June day 1 to day 9 ensembles.

May and June plus 9 days of initial lead time). Monthly averages of daily means from the output of all simulations in a given month yielded monthly simulated fields for the periods of May and June 2003.

[11] The NCEP Climate Prediction Center's daily rainfall data (1200 UT to 1200 UT), which is based on in situ daily rain gauge data from roughly 5000 River Forecast Center stations, is the most comprehensive data source for May and June 2003. The Global Precipitation Climatology Project (GPCP) [*Huffman et al.*, 1997] is another source of monthly precipitation data for May and June 2003 as well as monthly long-term climatology. On the basis of records dating back to 1895, all-time high rainfall records were set in several eastern states during months of May and June 2003. Overall, most of the eastern half of the United States was much wetter than normal, while areas of the western half of the continent were relatively drier (Figures 1a and 1c). Similarly, northern Amazonia in South America was anomalously wet (Figures 1b and 1d).

[12] In addition to the circulation and rainfall forecasts of ensemble means with 1- to 9-day lead time, we also examined how monthly forecasts degrade with lead time varying from 1 to 9 days. This provides an objective measure of the behavior of the model forecast skills on monthly timescales. In this way, nine monthly forecasts were produced with the data for each month by averaging the rainfall for the entire month using the identical lead times. This can be viewed as nine ensembles of 31 (30) forecasts for May (June) with each monthly average containing 1- through 9-day lead time. As an example, the ninth-day forecast from the run initialized at 1200 UT, 22 April, is from the 24-hour period: 1200 UT, 30 April, to 1200 UT, 1 May. The 1-day forecast of the same period (1200 UT, 30 April, to 1200 UT, 1 May) is drawn from the simulation initialized at 1200 UT, 30 April. Figure 2 shows how an nth day forecasts are collected to provide an n-day lead ensemble-averaged (also known as monthly average) forecast of each member of the ensemble.

[13] Both versions of the GCM were run separately in the above experimental mode; the first version of the fvGCM using the NCAR CCM3 physics (fv-NCAR GCM), and the other version using the McRAS cloud scheme and Chou and Suarez radiation (fv-McRAS GCM). A third set of ensemble simulations were generated with fv-McRAS GCM employing weekly observed sea surface temperatures (SSTs) from the NOAA SST Analysis [*Reynolds et al.*, 2002] in place of monthly climatological SSTs, and will be referred to as fv-McRAS SST. The daily simulation for each case was initialized at 1200 UT and was integrated out to 240 hours (10 days). Starting at 1200 UT is consistent with daily precipitation data aggregated from 1200 UT to 1200 UT by the Climate Prediction Center (CPC). A mask was applied over the data to focus the analysis over only the continental United States as well as the relatively wet window on the eastern part of Figure 1e. A similar strategy was used for Amazonia: The analysis produces data for whole region of tropical Amazonia versus the wet window (Figure 1f). Comparisons of key fields with that of the observations are used to delineate the forecast skills of the two model versions for the three cases.

4. Results

4.1. Rainfall Differences

[14] Figure 3 shows monthly precipitation differences for May and June 2003 for each of the three cases (fv-NCAR

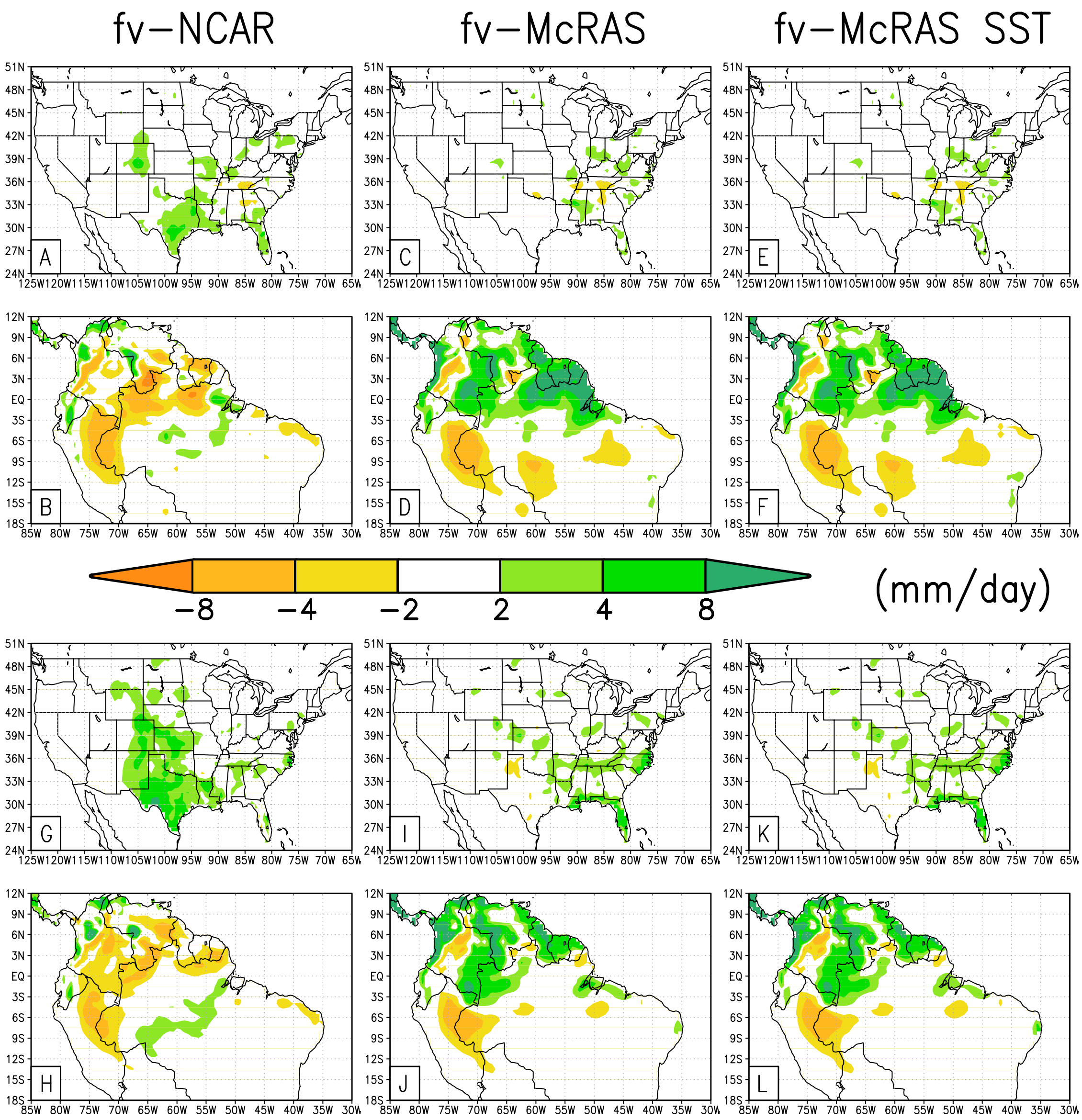

Figure 3. (a–f) May and (g–l) June 2003 monthly averaged day 1 differences with respect to observations for the three cases: first and third rows for over the United States and second and fourth rows for over Amazonia. The left column is for the fv-NCAR GCM simulations, the middle column is for the fv-McRAS GCM simulations, and the right column is for the fv-McRAS SST simulations. The 2003 observations over the United States are monthly averages of daily values from CPC; the 2003 observations over Amazonia are from the monthly GPCP precipitation analysis.

GCM, fv-McRAS GCM, and fv-McRAS SST) with 1-day lead time of the daily forecasts for both the United States and Amazonia. In the first day monthly means, all the model simulations showed a tendency to produce more rainfall than the observed for the United States (Figures 3a, 3c, 3e, 3g, 3i, and 3k), especially along the Gulf Coast and Front Range. This may be expected if the initial vertical structures of the relative humidity and moist static energy in the model are discernibly different from the analyzed. In other words, the difference in the preferred modes of vertical structures of humidity in the model and in situ data would be a source of rainfall anomalies during the initial adjustment period of a day or so. The positively biased regions would produce increased rainfall while the negatively biased regions cannot produce negative rain. This would naturally lead to biases in a nonlinear system invoking Heavyside functionals (on/off triggers) such as used in precipitation parameterization. The overall influence of such a spatiotemporal summation will be to increase in rainfall. To circumvent such problems, a whole body of literature emerged on Incremental Analysis Updates (IAU) to limit sudden shocks in the simulated rainfall field [e.g., *Pleim and Xiu*, 2003], but this only holds if the data assimilation model characteristics are same as that of the GCM being initialized. The secondary influence of larger rainfall is on the soil moisture; that is, it produces wetter soils. Even though all three cases tended to be wetter than the observed, the fv-NCAR GCM simulation, especially over the Front Range and Texas, produced discernibly larger

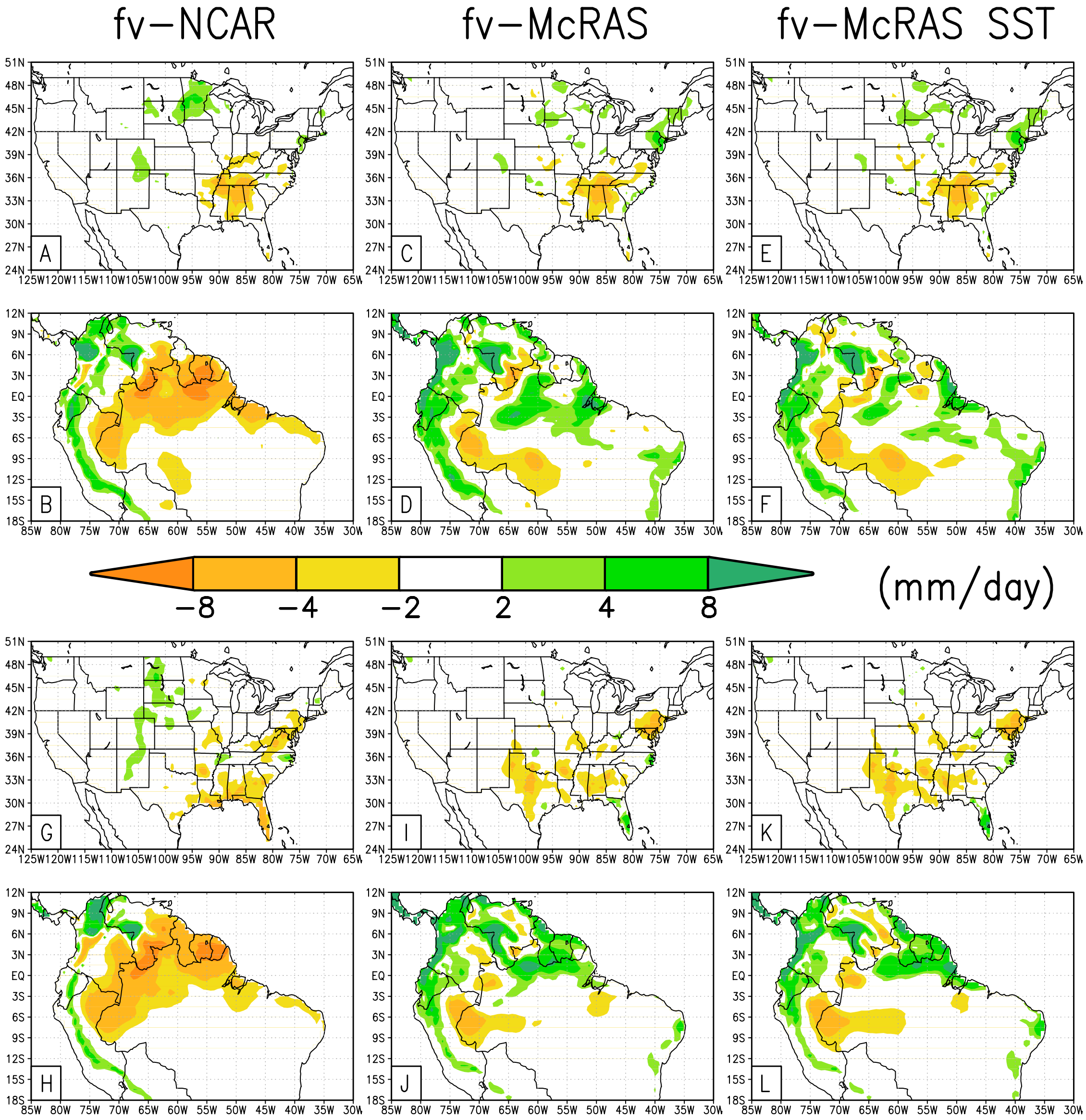

Figure 4. Same as Figure 3, only for the May and June 2003 monthly averaged day 4 differences.

biases (Figures 3a and 3g). On the other hand, over Amazonia, the fv-NCAR GCM tends to be drier than the observed (Figures 3b and 3h), which implies dry biases of the future soil moisture that can lead to a positive feedback effect on the rainfall. The dry bias of the fv-NCAR GCM is so large that it overwhelms the wetting tendency due to initialization effects of a relatively bias-free model; in comparison, the model produced more precipitation in Amazonia than observed in both the fv-McRAS GCM with or without observed SST (Figures 3i–3l). The fv-McRAS SST (employing observed SST) simulation biases are very similar to those of the fv-McRAS GCM (employing climatological SST), which suggest that the rainfall biases are not caused by the SST, whether realistic or climatological, but are a feature of the respective cloud schemes. The relatively minor influence of SSTs on day 1 is an expected result because the SST anomalies cannot make a significant impact on either the evolution of precipitation or the circulation in the very first day.

[15] Figures 4 and 5 show the corresponding plots for the monthly averages with 4-day and 8-day forecast lead time. Over the continental United States, the general trend is for models to be drier than the observed, particularly over Alabama and Georgia for lead periods of 3–6 days (not shown). However, a systematic dry bias develops in May in the central southeastern United States in the fv-NCAR GCM (Figures 4a and 5a) that grows with lead time even with 4-day to 8-day leads, while the corresponding biases in the fv-McRAS GCM are less intense. The dry bias even reduces for a couple of days after day 5 (not shown). Over Amazonia, fv-NCAR GCM starts with a dry tongue that keeps getting drier with lead time (Figures 4b, 4h, 5b, and 5h). The particular way of initializing soil moisture may have some role in this outcome because of the influence of soil moisture feedback from the operational version of the model. Increasing biases with lead time imply systematically developing trends over longer timescales (even up to 8 or 9 day lead time). Biases that are similar regardless of

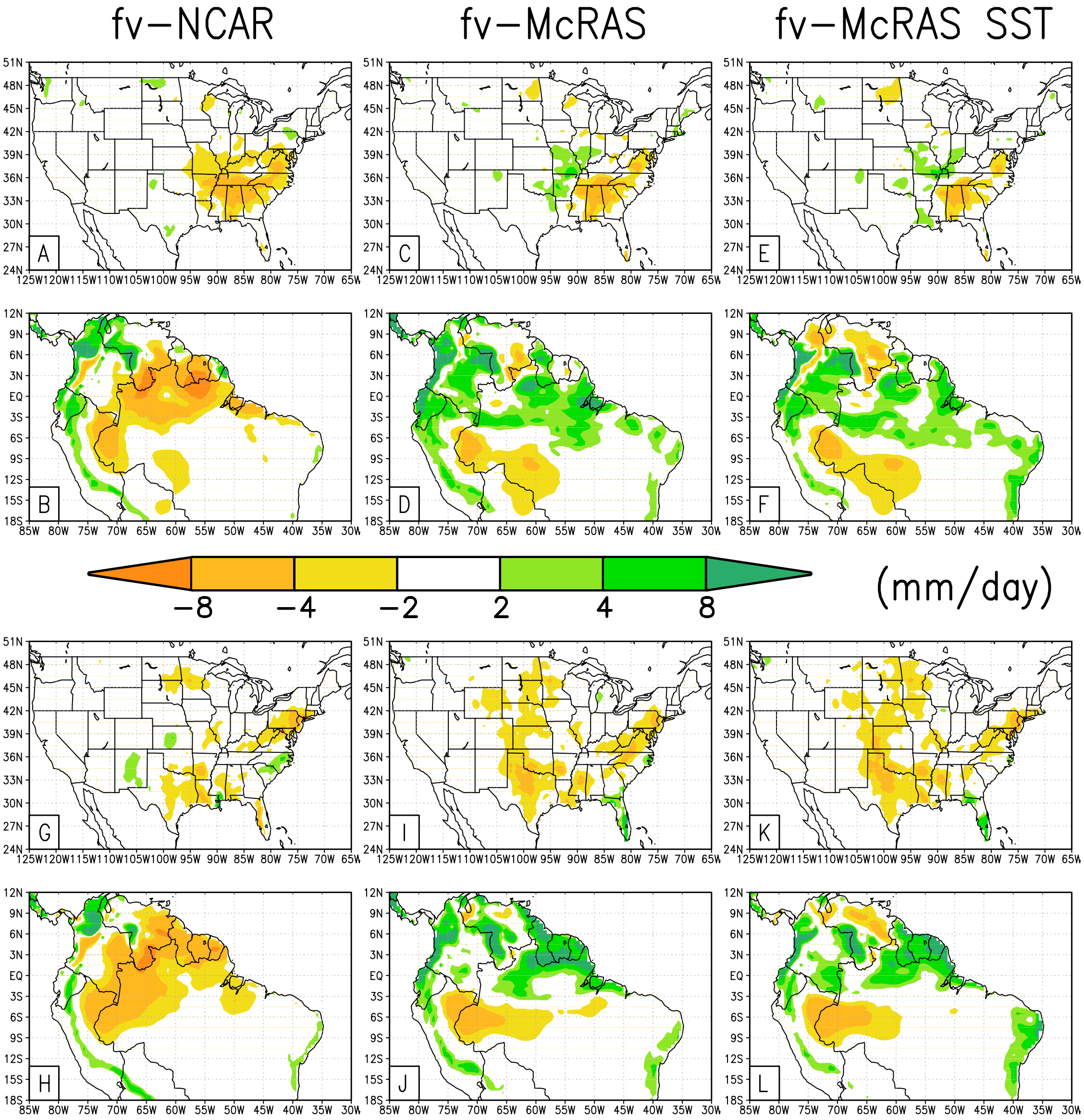

Figure 5. Same as Figure 3, only for the May and June 2003 monthly averaged day 8 differences.

the forecast lead time, however, suggest that they do not exert a positive feedback effect on the parameterized precipitation. One can see that fv-McRAS GCM starts out wet in the northern regions (Figures 3f and 3l) and that the wet biases get reduced with lead time of 2+ days (Figures 4f, 4l, 5f, and 5l), while the rainfall difference patterns that have some correspondence with observations persist throughout. In this way, the rainfall difference pattern of the fv-McRAS GCM shows better correspondence with that of the observations while the fv-NCAR GCM virtually misses out on the wet anomalies. All cases produce wetter than observed rainfall over the Andes (reaffirming well-known problems with orographic precipitation). The fv-McRAS SST simulated rainfall anomaly patterns over the tropical Atlantic that are intimately related to local SST anomalies, but that area is not the present focus. However, the magnitude of overall drying is considerably less for fv-McRAS GCM simulations than those of fv-NCAR GCM, particularly for the northeast and southeast United States as well as for Amazonia. Over Amazonia, in the 1-day lead monthly forecasts for June (Figure 3h), the fv-NCAR GCM simulates better rainfall patterns as compared to those of May (Figure 3b), while the fv-McRAS GCM gets drier over the United States (Figures 4j and 5j), particularly after lead time of 4 days (can be see in the 8 day lead time forecast too). We shall see that even though the fv-McRAS GCM did better initially, its forecasts for June over the United States got somewhat worse as compared to fv-NCAR GCM, particularly with the 8-day lead time. On the other hand, fv-McRAS GCM maintained comparatively better rainfall patterns over Amazonia vis-à-vis the fv-NCAR GCM that showed a dry tongue very similar to the May simulations. On the basis of these results and without additional objective analysis, it is not evident as to which parameterization is likely to perform better. Overall, Amazonia results favor the fv-McRAS GCM, while the continental U.S. results give the appearance of a toss-up, except for the

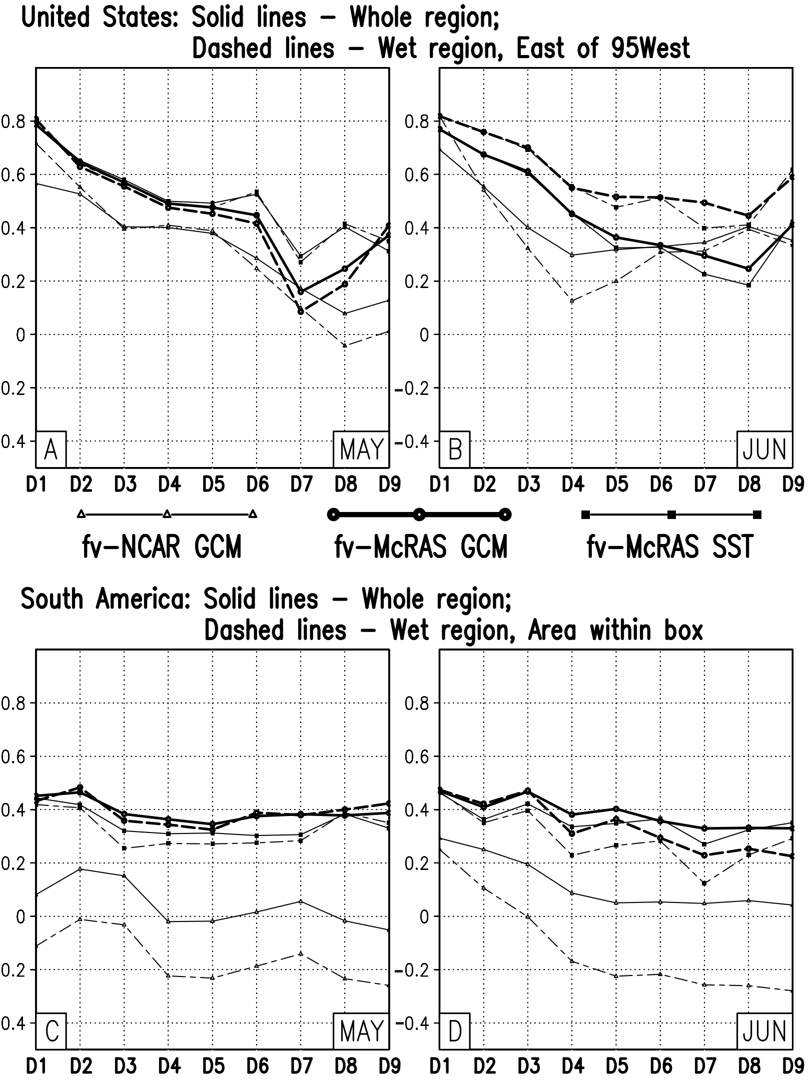

Figure 6. Anomaly correlation of precipitation (a and b) for over the United States and (c and d) for over Amazonia for the three cases: May 2003 (Figures 6a and 6c) and June 2003 (Figures 6b and 6d). Solid lines are for the entire region (continental United States, land only; or South American region shown in Figure 1, land only); dashed lines are for the masked wet anomaly regions shown in Figures 1e and 1f (continental United States east of 95°W, land only; or Amazonia region between 75°W and 50°W and 12°S and 8°N, land only). The three cases are denoted as follows: fv-NCAR GCM, thin lines with triangles; fv-McRAS GCM, thick lines with open circles; fv-McRAS SST, thin lines with solid squares.

shorter lead times of the order of 5 days, where the fv-McRAS GCM appears to perform consistently better.

4.2. Rainfall Anomaly Correlations

[16] The toss-up issue outlined in the last section is addressed with the help of anomaly correlation. The anomaly correlation (AC) has been used in a number of model evaluations [e.g., *Hollingsworth et al.*, 1980; *Kalnay et al.*, 1990]. The AC does a good job of delineating the linear association between two fields [*Stensrud and Wandishin*, 2000], while eliminating biases and errors associated with the space scale [*Murphy and Epstein*, 1989]. *Hollingsworth et al.* [1980] suggested that for "useful" medium-range forecasts an AC value of 0.6 should be used as a lower limit, although that is a tough standard for rainfall anomalies. As one of the primary jobs of a cloud scheme in weather and climate forecasting models is to accurately simulate rainfall anomalies, and since the monthly rainfall is highly variable, we chose by design to focus on two regions: (1) the continental United States and (2) Amazonia in South America. Both regions had significant rainfall anomalies during May and June of 2003 and are worthy choices for a cloud scheme. For details on how the AC was calculated; see Appendix A.

[17] The fv-McRAS GCM simulation produces better rainfall anomaly correlations over the United States for nearly all days of lead time as compared to the fv-NCAR GCM (Figures 6a and 6b). Particularly with respect to the wet anomaly region (dashed lines) east of 95°W (as shown in Figure 1e), the results show similar outcome as for the entire region (solid lines). The fv-McRAS correlations are discernibly better particularly the first 5–6 days (a period

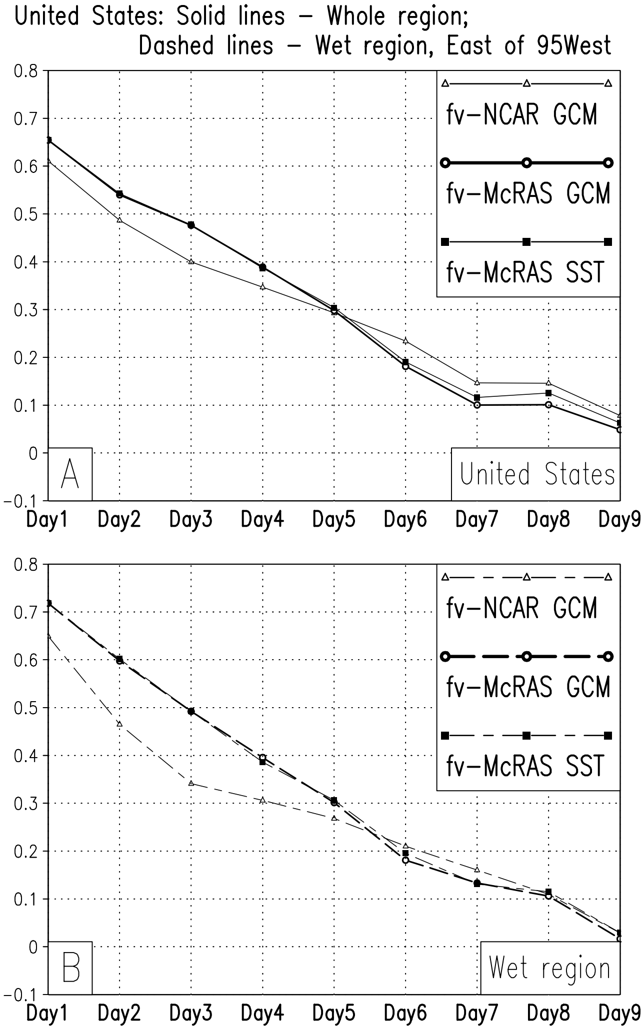

Figure 7. Sixty-one-day average of the daily precipitation correlation coefficient for the three cases (a) over the continental United States and (b) over the wet anomaly region east of 95°W only. The lines for the three cases are denoted as in Figure 6.

within Lorenz's predictability limits). The anomaly correlations for Amazonia (Figures 6c and 6d) also are distinctly better for the fv-McRAS GCM simulations as compared to fv-NCAR GCM, for both May and June 2003. When focusing on the wet anomaly region of the central Amazon (as shown in Figure 1f), the AC values are slightly lower for all three models as compared to those of the entire region, but the fv-McRAS GCM still performs better. This should be expected because the wet regions over Amazonia and the United States had larger precipitation anomalies that imply discernible significance because of the well-known large natural variability of precipitation. Realistic SST data (the fv-McRAS SST case) does not make much difference to these correlations with shorter lead times, but for the longer lead periods, the AC improves, clearly over the continental United States in May. The well-maintained differences (between the two models) in these correlations over Amazonia as well as continental United States suggest the beneficial influence of the new cloud parameterization scheme, McRAS, particularly the moist convective modules that can have a large influence on the rainfall on a short timescale and maintain it for each ensemble of 31 (30) days of May (June) 2003.

[18] In order to determine whether the performance of fv-McRAS GCM was related to the choice of the specific way of determining the anomaly correlation, i.e., via use of monthly ensemble averages, we calculated the correlation coefficient on the daily time series at each grid point and then aerially averaged it for each lead of the nine periods. However, this analysis could only be performed over the United States because daily observed rainfall data was not available for Amazonia. Despite some differences at the level of fine details, this analysis also produced a very similar outcome (Figure 7). For the first 5 days of forecast lead time, fv-McRAS GCM performed better, while the employment of more realistic SSTs forcing had very little influence on the outcome. Indeed, if SST has little influence (given the 10-day forecasts), what other forcing could be involved? We have not addressed this question; presumably the answer could be found in the variations of large-scale circulation patterns maintained by natural variability of climate due to remote forcing as well as the soil moisture initial conditions. However, these are conjectures because an in-depth study to discern this is outside the purview of the present focus.

[19] Since these results are consistent with another set of simulations (not shown) in which the surface albedos became erroneous because of time step inconsistency between the surface albedo data sets and radiation physics, we can safely infer that the primary source for the current outcome is more realistic cloud condensation and precipitation microphysics and its associated condensation-evaporation heating fields, a result that also bears out in ARM-CART SCM evaluations with the particular version of NCAR cloud scheme and earlier tropical evaluations [*Maloney and Hartmann*, 2001]. We therefore interpret the difference in ACs between the fv-McRAS GCM and fv-NCAR GCM to be a consequence of a more realistic cloud scheme, whereas the reduction of ACs with increasing lead time as a natural response to deteriorating in situ circulation on which clouds and cloud physics processes very much depend. In this way, we affirm that the new cloud scheme, McRAS, performs consistently better over the wet regions. Moreover, observed sea surface temperatures can be expected to nudge the circulation for a better simulation, but not within the first few days. Indeed, that did occur to some extent: the forecast with larger lead time (5 days or more) gave somewhat better (definitely not worse) ACs as compared to the one using climatological SST forcing. Beyond the 6-day lead time, the simulated precipitation ACs are low, but they are generally better for the fv-McRAS SST case.

[20] Over Amazonia, a tropical region with very robust trade winds and circulation features, the rainfall anomalies can be affected by changes in Tropical Intraseasonal Oscillations (TIOs) along with the Hadley and Walker circulations in response to tropical SSTs and easterly waves at roughly 5-day intervals. In the data, there was a large east-west rainfall anomaly pattern over the tropical Pacific; naturally, it was well simulated by both models (not shown). Nevertheless, it does not imply a major success because

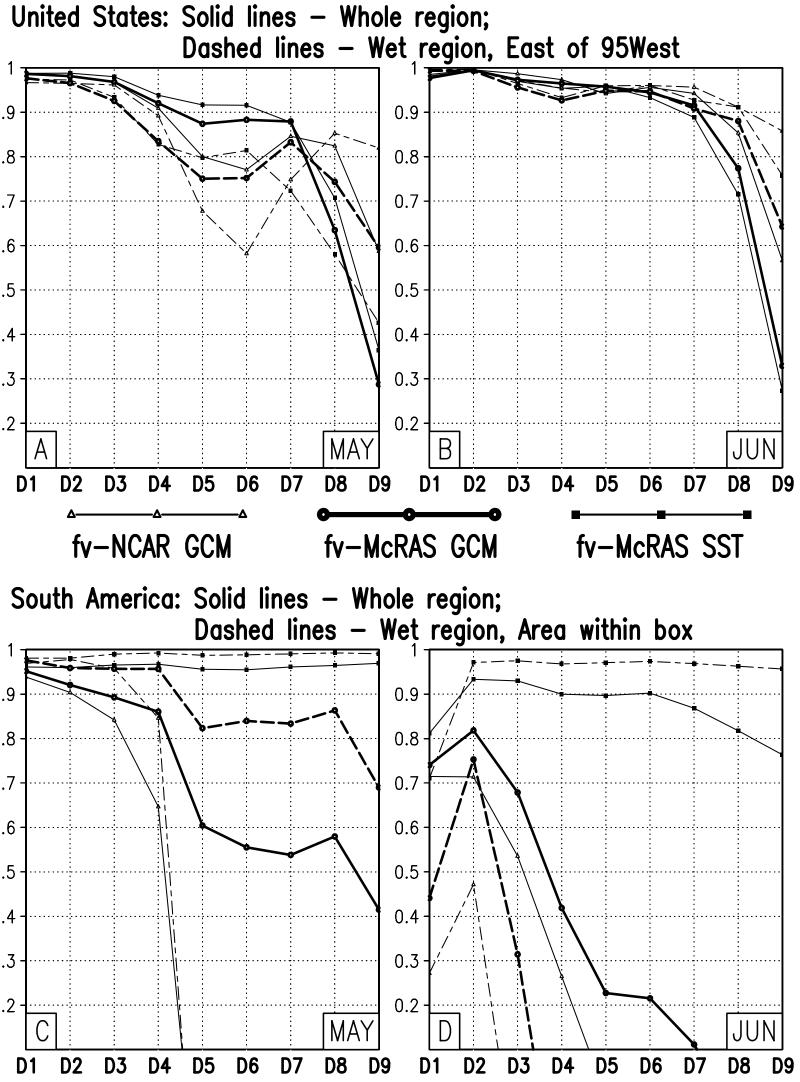

Figure 8. Same as Figure 6, only for anomaly correlation of 500 hPa. Observations for 2003 and climatology are from CDC reanalysis.

most models are able to simulate them. However, we focus on the Amazonia with a window on the wet regions (for reasons discussed earlier), which are somewhat far away from the SST anomaly region. Here, the fv-McRAS GCM simulations show a better performance for the entire period as compared to the fv-NCAR GCM simulations. The steady anomaly correlation is a response to robust tropical winds that don't change all that much with time. On the other hand, the well-maintained difference between the two simulations (fv-McRAS GCM and fv-NCAR GCM) suggests a response to cloud parameterization. Both simulations produce relatively low ACs as compared to the United States because the rainfall anomalies for the region were higher and the inability of the model to simulate them with respect to orographic forcing (note rainfall errors along the Andes) of tropical circulation and precipitation leads to large local errors. However, both models do better over the whole Amazonia as opposed to the chosen wet window. An unexpected result of the Amazonia region is that the observed SSTs actually deteriorate the ACs slightly as compared to climatological SSTs. Naturally, this is not a strong ENSO year with a large shift in tropical SSTs, therefore, a small deterioration representing a small shift in circulation patters in the wrong direction is not much of a surprise. The result is not dependent on the size of the region because it remains robust when viewed for the entire Amazonia or a chosen wet window.

4.3. Heights of 500 hPa and 300 hPa and SLP Correlations

[21] The sea level pressure and 500 hPa and 300 hPa height fields were also examined. For these variables, the observed values used for 2004 are from the NOAA Climate Diagnostic Center's NCEP reanalysis [*Kalnay et al.*, 1996], and the climatology for May and for June are from the same long-term reanalysis. Figure 8 shows the anomaly correlation of the 500-hPa heights over the United States and Amazonia for May and June 2003. The model (for all cases) does notably better in June than it does in May over the United States, when the forecasting skill deteriorates rapidly with time. In May, the use of observed SSTs has improved the AC of the 500-hPa heights through 6–7 days. By days

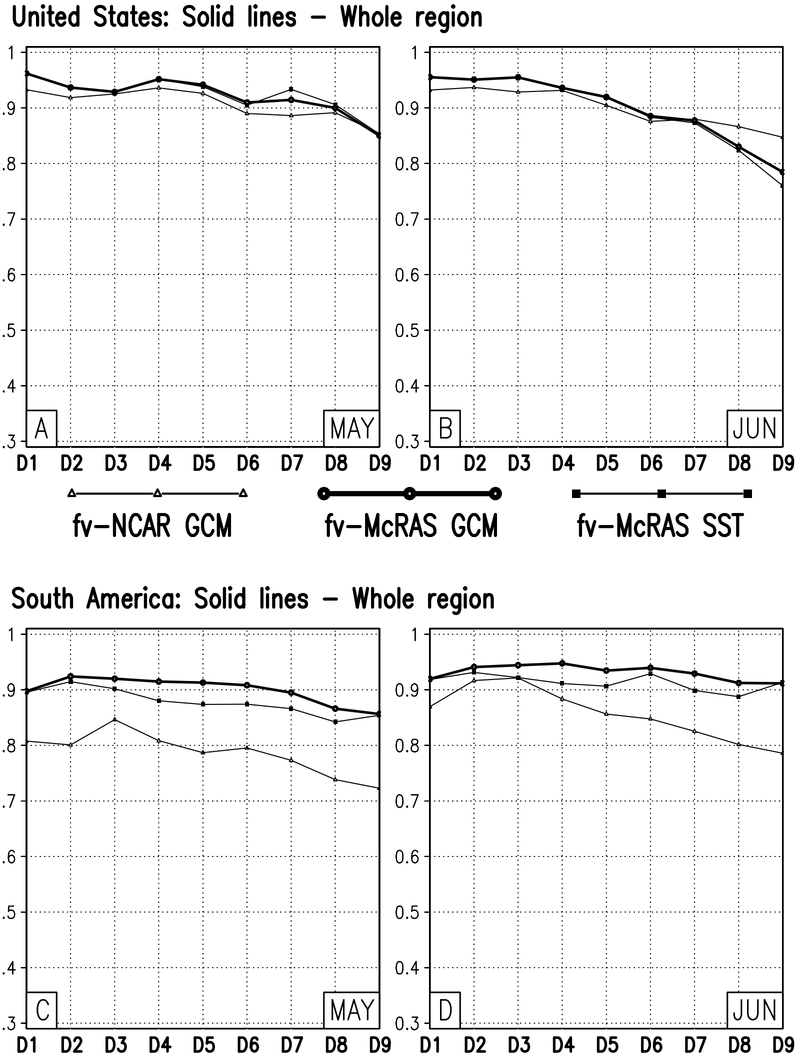

Figure 9. Same as Figure 6, only for correlation coefficient with observed CERES longwave top of the atmosphere (TOA). Lines for the wet anomaly region are not shown.

8 and 9 for both May and June, the fv-NCAR GCM has a slightly higher AC of 500 hPa heights than the other cases. Figures 8c and 8d, over Amazonia, show a large increase in AC with fv-McRAS GCM, as well as an additional benefit from using observed SSTs in fv-McRAS SST case. The fv-NCAR GCM has ACs that rapidly drops below 0 beyond 4 days. The sharp dropoff in AC in these figures from some of the models is related to the large-scale feature of the heights that may be slightly outside the box of interest after several days. The 300 hPa heights and sea level pressure also demonstrate a general improvement in AC skill for these months with fv-McRAS GCM (not shown), with the exception of the AC for sea level pressure for June only over the United States, which shows a higher AC for later day lead time forecasts with fv-NCAR GCM.

4.4. Longwave and Shortwave TOA From CERES Correlations

[22] Figures 9 and 10 show the correlation coefficient between all three cases and monthly observations of longwave at the top of the atmosphere and shortwave at the top of the atmosphere. These observations [*Wielicki et al.*, 1996] are from the CERES instrument as part of both the Terra and Aqua platforms. As CERES has not been aloft for a long period, a suitable climatology of net longwave TOA and net shortwave TOA was not plausible so we look at only what can be compared. Figure 9 shows that the fv-McRAS GCM had a higher correlation for net longwave TOA for all days in May and days 1–7 in June over the United States. The higher correlation with fv-NCAR GCM over the United States for the extended period (days 7+) in June only, as seen previously, continues for this variable as well. Over Amazonia, Figures 9c and 9d show that the improvement in correlation with fv-McRAS GCM is larger than over the United States. In Figure 10, the correlation skill found with respect to the net shortwave TOA over both the United States and Amazonia is significantly higher in the fv-McRAS GCM case than with fv-NCAR GCM. In addition to the improvement previously noted with fv-McRAS, the better cloud-radiation interaction has led to an improved simulation of the TOA radiation compared to the fv-NCAR GCM case. Again, the use of observed SSTs do not improve

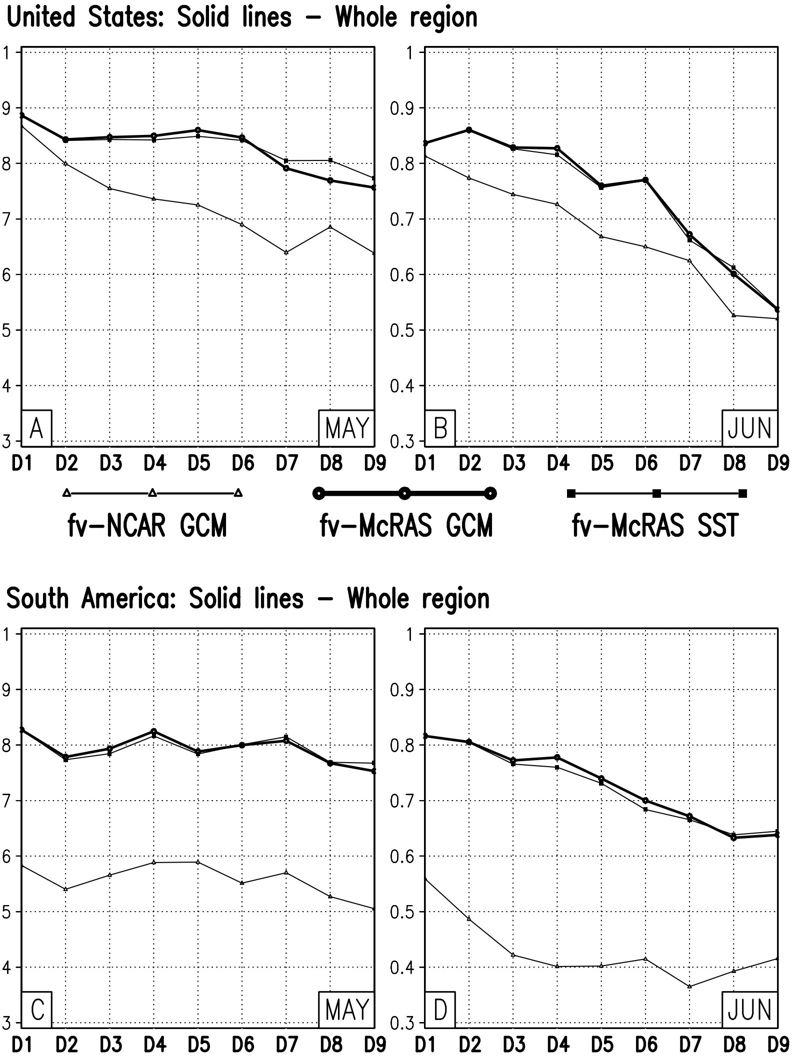

Figure 10. Same as Figure 9, only for correlation coefficient with observed CERES shortwave top of the atmosphere (TOA).

the simulations much on the relatively short length of the simulations.

5. Summary

[23] In model development work, one of the difficult decisions is the strategy for evaluation of a new physics scheme for objective guidance to replace the corresponding old scheme. The work must begin with assessment of representation of physical processes from first principles. If the scheme reveals good prospects on the basis of first principles of processes represented in the scheme, it should be assessed on a standard evaluation platform, such as the ARM-CART SCM mode. Having been satisfied on the above score, the evaluation in the GCM is the natural next step. However, midlatitude summer climate predictions are often inaccurate [*Blender et al.*, 2003], so evaluating convection for North American spring and summer months where we have data and daily rainfall is problematic. We devised the strategy for weather-cum-climate evaluation to circumvent the problems associated with such evaluations. In cloud work, one naturally looks for wet periods to evaluate the performance of the scheme in order to assess its ability to simulate them realistically. McRAS, our new cloud scheme, interacting with radiation schemes developed at Goddard by M.-D. Chou and M. J. Suarez, was a candidate for replacing the standard cloud and radiation schemes in the fvGCM. We plan to conduct similar exercises with GEOS 5 GCM. We chose the anomalously wet periods of May and June 2003 to determine if the new schemes can outperform the old. Since climate models can drift because of systematic biases, we chose a combination methodology involving both weather and climate timescales in which 10-day forecasts, made once everyday, were used to generate monthly precipitation anomaly data for the anomalously wet eastern United States and Amazonia. Monthly averages of precipitation, cloud-radiation forcing, and upper air geopotential heights were compared with analysis of observations.

[24] Two parallel sets of simulations of daily 10-day forecasts were made with the fv-NCAR GCM (finite volume hydrodynamics with CCM3 physics) and then a corresponding set of simulations were generated with fv-

McRAS GCM (with new cloud scheme, McRAS, and radiation scheme). Each 10-day forecast started from observed initial conditions and spun-up soil moisture based on the first day of the 10-day forecasts for the months of May and June 2003 that produced highly anomalous rainfall over the eastern United States and northern Amazonia. The fv-McRAS GCM simulations showed a better daily forecast of precipitation as compared to fv-NCAR GCM. However, the medium-range precipitation forecast biases were similar for both cases, which may also be related to initial condition biases or land hydrology, rather than deficiencies in the cloud schemes. A third parallel set of simulations was made with fv-McRAS GCM using observed as opposed to climatological SSTs, which had a small positive impact on the longer (6–9 day) forecasting skill. The correspondence among the rainfall and the SST anomalies was expected to help discern the model's response to SST if indeed such a response exists. In the test, the fv-McRAS showed only a minimal SST response. This implies that even on 7- to 10-day timescale, the direct effect of SST anomalies was not very strong and whatever long-term effect influencing the circulation is already included through the initial conditions.

[25] In both regions and on most of the correlations with respect to observations, McRAS performed better than the standard cloud scheme of the fvGCM. This makes the decision of replacing the current scheme with McRAS a little more straightforward. However, if there are two schemes that perform relatively similarly, such a decision can be truly hard. In such cases, performance over the region of interest, or the quality of forecast or a certain feature (for example, simulating TIO for tropical forecasting) might have to be factored into the decision making process. However, objectivity in making such decisions is paramount to systematic model development. Such objectivity is hard to strategize and execute; consequently, model development work often suffers from subjective decisions about making a change to the new scheme. Using positive and negative impacts of the change on the monthly simulation with modelers striving for a better version of the scheme can be an unending exercise. On the other hand, well-designed evaluations are so worthwhile that they can turn model module selection into an objective process. We submit that our current evaluation is a good example of such a strategy for cloud parameterization evaluation.

6. Discussion

[26] In our extensive evaluation of the two cloud-radiation schemes on weather and monthly climate timescales, McRAS with its radiation package, has fared better in both rainfall and cloud-radiation forcing simulation accuracies than the corresponding fvGCM cloud-radiation scheme taken from the NCAR-CCM. However, biases in both the schemes are so large that none of them is really far better than the other. Both schemes still can benefit from cloud model development. Recently, *Zhang and Mu* [2005] showed how the CCM3 convection due to *Zhang and McFarlane* [1995] improved as a consequence of moving the cloud base above the planetary boundary layer and using a relative humidity threshold for the onset of convection as opposed to using Convective Available Potential Energy (CAPE) starting from the boundary layer. This suggests that a scheme must be examined through the physics of its algorithms as opposed to its ability to make a better simulation because accuracy of its simulation can change very significantly and so easily. A more complex scheme, such as McRAS, has more degrees of freedom and therefore it runs the risk of giving a poor performance in a certain location at a certain time wherein its biases happen to reinforce each other. Therefore evaluators have to be cautious in arriving at general conclusions. Regardless of the outcome of intercomparison, both schemes do quite poorly over Amazonia and over topography and could benefit enormously from research and development work on moist convection. Indeed, one also wonders if any cloud scheme with similar biases is ready for useful simulation of changes in the global hydrologic cycle in response to realistic changes in anthropogenic forcings of the present time. This assessment needs to be confirmed for other cloud schemes, however.

[27] Even though many cloud-radiation interaction biases emanate from cloud physics deficiencies, cloud-radiative forcing in models is still a major problem; however, cloud optical properties are often adjusted in a tuning framework to get the best possible radiative forcing of the column atmosphere. In the fv-McRAS GCM simulations, the cloud-radiative forcings are based on a *McFarquhar* [2001] scheme, which uses zonal departures of simulations vis-à-vis data from analysis of observations. It is evident that an objective assessment of a new parameterization is better assessable in this evaluation instead of a comparison of straight climate simulations, wherein model drifts and biases interact significantly with the parameterizations reducing the value of intercomparison.

[28] Regardless of the extensive use of daily 10-day forecasts with two cloud physics schemes and one realistic SST data set, the overall outcome is an evaluation of midlatitude warm-season rainfall prediction. This evaluation does not guarantee winter season precipitation forecast success. However, we have examined the rainfall climatology in the winter hemisphere too; its subjective assessment does not show any remarkable improvements. Therefore we can assume that an evaluation of the convective parameterization, representing summer season rainfall, has enough signatures to affirm the superiority of McRAS for upgrading the cloud scheme of the fvGCM. Clearly, tuning of a scheme to work in concert with other schemes of the GCM can influence the outcome, but in the present case, the NCAR cloud scheme has been tuned to get the best performance in the operational NCAR physics scheme of the fvGCM; while McRAS has not been tuned as extensively. Most of the benefits of McRAS are in near-term rainfall amounts and those are related to accuracy of moist convection.

[29] This weather and climate mode of evaluation also helps to ascertain the climate and weather related influences of a scheme. It is vital for developing a climate model because clouds not only are central to climate change, but also are dependent on weather and its dynamics. Consequently, a meaningful cloud evaluation requires accurate background weather. Indeed, through interactive feedback, an improved weather and precipitation forecasts are an expected outcome of a model with better physics (such as invoked by a cloud scheme).

Appendix A: Anomaly Correlations

[30] The anomaly correlations for both the continental United States and Amazonia regions were computed to quantify the results of our simulation for each of the three cases. The following standard relation provides a single anomaly correlation of a generic φ fields (AC_φ) for the monthly ensemble with daily data generated at specific lead times of 1–9 days in our evaluation. It is defined as follows:

$$AC_\varphi = \frac{\sum_{i,j}\left[(\varphi_O - \overline{\varphi_C})(\varphi_M - \overline{\varphi_C})\right]}{\sigma_O \sigma_M}$$

where φ represents a given field, the overbar represents the (C) climatology (long-term mean), O represents the 2003 monthly observations field, and i,j is for each land point in the continental United States or each land point in Amazonia. The anomaly in the observations (observed 2003 values minus observed climatology) was multiplied by the simulated anomaly (simulated 2003 values for each case minus observed climatology) for each grid point and summed up over all land points of the United States. The sum was divided by the standard deviation (σ) of the observation (O) anomaly times the standard deviation of the simulated model (M) anomaly. For this paper, the observed climatology was used in the calculation of both the observed and the model simulated anomalies. The observed climatology was used because a corresponding long-term model climatology was not available at such a high resolution. Separate tests using a model climatology at a lower resolution and regridded to the high resolution showed that the impact of the definition of model anomaly made negligible impact on the results (not shown). Furthermore, the correlation with respect to observations is a more stringent test, because large regional biases generated by the model simulation cannot cancel out.

[31] The correlation coefficient, sometimes referred to as the Pearson product moment correlation coefficient, was used to produce the correlation values in Figures 7, 9, and 10. For some of the fields, the climatology was unavailable; in such cases, the spatial mean was used in its place to extract the spatial pattern to obtain pattern correlation. The corresponding relation is

$$r = \frac{\sum\left[(\varphi_O - \overline{\varphi_O})(\varphi_M - \overline{\varphi_M})\right]}{\sigma_O \sigma_M}$$

The other symbols have the same meaning.

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