Role of convection triggers in the simulation of the diurnal cycle of precipitation over the United States Great Plains in a general circulation model

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[1] Recent comparisons of a number of general circulation models (GCMs) have shown that most of them have deficiencies in the simulation of the diurnal cycle of warm season precipitation. The deficiencies are particularly pronounced over the United States Great Plains where the models generally fail to capture the nocturnal rainfall maximum found in the observations. By using the National Centers for Environmental Prediction's Global Forecasting System (NCEP GFS) GCM, which is unusual in that it produces a realistic nocturnal rainfall signal over the Great Plains, this study examines the nature and realism of the mechanisms responsible for the nocturnal rain in the GCM. A series of sensitivity experiments highlight the importance of triggers implemented in the convection scheme. Specifically, the convection trigger function that the cloud base (defined as the level of free convection) must be within 150 hPa depth from the convection starting level (which crudely represents an upper limit of convective inhibition) plays a key role on the realistic simulation of the diurnal phase of convection. On the basis of this trigger, the nighttime elevation of the convection starting level (defined as the maximum level of moist static energy from the surface) above the boundary layer inversion provides the condition favorable for the development of nocturnal precipitation over the Great Plains. The results are discussed in terms of their implications for improving our understanding and parameterizations of the physical processes that generate nocturnal rain in this and other regions with large diurnal cycles.

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1. Introduction

[2] Observed precipitation shows a strong diurnal variation over the continental United States during the warm season [e.g., *Wallace*, 1975; *Higgins et al.*, 1997; *Dai et al.*, 1999]. For example, more than 40% of the total precipitation in the southeastern United States and the Rocky Mountains is concentrated in the daytime hours between 1400 to 1900 LST (local solar time). During these hours, the chance of precipitation is more than three times larger than during the nighttime hours. The amplitude and time of the maximum in the diurnal cycle of precipitation also exhibit wide geographical variations. Precipitation has a late afternoon maximum over the southeastern United States and over the Rockies, while it has a nocturnal maximum over the Great Plains.

[3] Several mechanisms have been proposed to explain the nocturnal precipitation signal over the Great Plains. *Riley et al.* [1987] discuss the role of mountain-initiated storm systems (including mesoscale convective systems) that tend to move eastward from the Rocky Mountains into the Plains. The rainfall associated with these systems tends to occur over the Great Plains anywhere from late evening through midnight [*Nesbitt and Zipser*, 2003]. *Carbone et al.* [2002] found that the propagation speed of major convective episodes over this region is close to that of gravity waves. Other studies highlight the importance of subcontinental-scale regulation of diurnal convection, such as that associated with the Great Plains low-level jet [e.g., *Helfand and Schubert*, 1995; *Ghan et al.*, 1996; *Higgins et al.*, 1997; *Schubert et al.*, 1998], and thermally driven atmospheric tides [*Dai and Deser*, 1999; *Dai et al.*, 1999].

[4] Most current global and regional climate models show deficiencies in reproducing the nocturnal precipitation signal over the Great Plains [e.g., *Ghan et al.*, 1996; *Dai et al.*, 1999; *Zhang*, 2003; *Collier and Bowman*, 2004],

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reflecting our incomplete understanding for the underlying mechanisms. Recently, *Lee et al.* [2007a, 2007b] examined the fidelity of three GCMs in their simulation of the warm season diurnal cycle of precipitation over the continental United States. The key results of those studies are the following:

[5] 1. The models exhibited substantial differences in their simulations of the diurnal cycle of precipitation, particularly in the phase of the diurnal maximum.

[6] 2. Large-scale biases in the amplitude and phase of the diurnal cycle of precipitation were not substantially improved by an increase in the horizontal resolution (tested up to about 50 km resolution) of the models. In fact, the differences among the models were found to be in general much larger than those resulting from the change in resolution in a single model.

[7] 3. The differences in the moist physics parameterizations, particularly the cumulus convection scheme and its coupling with the boundary layer processes, are the primary causes for the model differences. This is the case, despite the fact that the deep convection schemes of all three models examined are fundamentally based on *Arakawa and Schubert*'s [1974] buoyancy closure, indicating that differences in the implementation of the schemes (e.g., convection triggers, the coupling with the boundary layer) are important.

[8] In their comparison of the three GCMs, only one of the global models, the National Centers for Environmental Prediction's Global Forecasting System (NCEP GFS), produced a realistic nocturnal rainfall signal over the Great Plains. It was found that the nocturnal precipitation signals simulated by the GFS model are quite robust with respect to changes in the initial state and horizontal resolution of the model [*Lee et al.*, 2007b]. In this study we attempt to understand the mechanisms that drive the diurnal cycle of Great Plains precipitation in the GFS model, with the broader goal of improving our understanding and parameterization of the mechanisms that drive the diurnal cycle in nature. We hypothesize that diurnal cycle is particularly sensitive to the implementation of ad hoc convection trigger functions that are meant to be simple surrogates for nature's more complex large-scale controls on the diurnal cycle discussed above. We determine the dominant forcing of the diurnal cycle through a set of sensitivity experiments that isolate the role of various individual convection triggers implemented in the GFS model. In the next section, we give a brief description of the GFS model, focusing in particular on the convection trigger functions.

2. Model and Sensitivity Experiments

[9] The NCEP GFS is a global spectral model described in detail by *Wu et al.* [1997] and the references therein. The version of GFS used in this study has a relatively coarse T62 truncation or about 200 km horizontal grid spacing compared to the operational model. However, the model has a relatively fine resolution in vertical, with 64 sigma levels, which are concentrated in the planetary boundary layer (there are 15 levels below the 0.8 sigma level). This resolution seems to be more than adequate for simulating the vertical structure of the model state variables, including reasonable simulations of the diurnal variations in the planetary boundary layer (section 5). We focus our attention here on the convection scheme and its trigger conditions and how they might influence the simulation of the diurnal cycle of precipitation.

[10] The NCEP GFS employs a simplified version of the Arakawa-Schubert (SAS) scheme for the deep cumulus convection developed by *Pan and Wu* [1995]. This scheme uses the cloud work function (CWF) to determine the strength of convection. The CWF is the vertically integrated buoyancy of the parcel that is lifted from the convection starting (origination) level, and it is basically the same as the convective available potential energy (CAPE) but it includes dilution of the lifted parcel by environmental air. Both quantities represent the convective instability of the column at a grid point. As in other simplified versions of *Arakawa and Schubert* [1974], the SAS scheme relaxes the CWF to a critical value over a fixed timescale (relaxation timescale) [*Moorthi and Suarez*, 1992]. Thus, in order to trigger convection, the magnitude of the CWF at given time must exceed this critical value (critical CWF).

[11] Several conditions for triggering convection are identified to be specific to the GFS model, and might be relevant for driving nocturnal precipitation over the Great Plains. One that would be particularly relevant is the dependency of the CWF in the GFS model on the large-scale vertical motion. The critical CWF is a function of the vertical motion at the cloud base (currently, defined as the level of free convection or LFC), by which it is allowed to approach to zero as the large-scale rising motion becomes strong. Considering that the current GCMs including the NCEP GFS simulate the nocturnal low-level jet and moisture fluxes over the Great Plains reasonably well [*Helfand and Schubert*, 1995; *Ghan et al.*, 1996; *Lee et al.*, 2007b], enhanced upward motion at night could be associated with the convergence driven by the low-level jet. This process can therefore effectively decrease the critical CWF and provide a more favorable condition for triggering nocturnal convection. A second condition involves a state-dependent relaxation timescale, which controls the convection strength. The SAS scheme relaxes the CWF with a timescale of 20–60 min, depending on the vertical motion at the cloud base. This modification is intended to induce stronger convection in the presence of large-scale upward motion. Strictly speaking, the relaxation timescale is related to the closure assumption that determines the intensity of convection, and so it is different from the trigger functions that are involved in the decision about whether the convection scheme should operate or not. However, as a result of their dependence on the large-scale vertical motion, both the critical CWF and the relaxation timescale of the SAS scheme act to enhance the coupling between the large-scale circulation and local convection.

[12] The concept of convection triggers that depend on the grid-scale vertical motion is widely used in mesoscale models, although there are differences in the details of their implementation [*Fritsch and Chappell*, 1980; *Kain and Fritsch*, 1992; *Rogers and Fritsch*, 1996]. As an example, *Kain and Fritsch* [1992] incorporated a perturbation to the parcel temperature that is proportional to the magnitude of vertical motion at the lifting condensation level (LCL), and the scheme triggers convection when the temperature of the parcel is higher than the environmental value.

Table 1. A Summary of the Control and Sensitivity Experiments

Run	Description
CTRL	control run with the standard SAS scheme
EXP1	same as CTRL but with the fixed critical CWF in time (independent to the vertical motion)
EXP2	same as CTRL but with the fixed relaxation timescale (30 min)
EXP3	same as CTRL but the convection starting level is always fixed at the first model level
EXP4	same as CTRL but the LFC must be located within 500 hPa depth of the convection starting level (from 150 hPa in the standard)

[13] The third trigger condition involves the origination level of deep convection in the vertical. *Lee et al.* [2007b] showed in a different model, that the convection starting level can substantially influence the phase of diurnal convection. The current SAS scheme defines the starting level of convection as the level of maximum moist static energy within a depth of 300 hPa from the surface. This can effectively elevate the starting level of convection during the nighttime when the radiation cooling develops a nocturnal inversion in the boundary layer. The fourth trigger condition in the SAS scheme is that the LFC must be located within 150 hPa depth of the convection starting level, which crudely represents an upper limit of convective inhibition (CIN). This is analogues to the "lifting depth trigger" in *Kain and Fritsch*'s [1992] parameterization. Shallower depth generally tends to suppress convection, as it activates convection only when the depth between the parcel origination level and the LFC is less than the specified value. This critical value varies widely among the models, with a range of 50–250 hPa, although the simulated precipitation characteristics change significantly with the choice of this parameter [*Kain and Fritsch*, 1992; *Yang and Arritt*, 2002]. With such a trigger in the SAS scheme, the nighttime elevation of the convection starting level may help to satisfy the 150mb limit, and trigger nocturnal convection more easily.

[14] We next describe the results from a set of sensitivity experiments designed to examine which among the aforementioned convection triggers affects more critically the generation of nocturnal precipitation over the Great Plains. The idea is to disable the convection triggers one by one to isolate the key process in the model. Table 1 summarizes the control and the four sensitivity experiments. For these runs the NCEP GFS was forced by the observed climatological mean (an average of 1983–2002), but weekly varying, sea surface temperatures (SSTs). Each experiment consists of an ensemble of five runs started from different atmospheric and land initial states: these consist of 1 May states taken from the NCEP-DOE (Department of Energy) Reanalysis-2 [*Kanamitsu et al.*, 2002] for five arbitrary years (1984, 1988, 1990, 1992, and 1993). While there is evidence that initial differences in soil moisture may produce a substantial impact on the simulated rainfall in specific regions [*Koster et al.*, 2004], we found that any impacts on the diurnal cycle of rainfall tend to be confined to the seasonal mean and the amplitude of the diurnal cycle, with little impact on the phase. After one month spin-up, the amplitude and phase of the diurnal cycle of precipitation was computed for the three summer months of June-August, on the basis of the method described in *Lee et al.* [2007a]. In order to validate the model simulations, we compare the results to the observed 2° latitude by 2.5° longitude hourly precipitation data set (HPD) developed by *Higgins et al.* [1996]. We also validate the model simulations with the vertical sounding observations at the Southern Great Plains from the Atmospheric Radiation Measurement (ARM) Program, which were processed by *Zhang and Lin* [1997] and *Zhang et al.* [2001] for single-column tests of the numerical models.

3. Sensitivity to the Convection Triggers

[15] Figure 1 compares the amplitude and the phase of the maximum of the diurnal cycle of precipitation from the five experiments and those from the observations. The observations show large amplitudes in the diurnal cycle over the southeastern United States, downstream of the Rockies and the adjacent Great Plains. Regarding the phase, the observations show late afternoon or evening peaks in most regions over the United States (1600–2000 LST), except for the nighttime peaks over the eastern slopes of the Rockies and the adjacent Plains where peak hours tend to change systematically toward the east from late afternoon to nighttime hours (105–90°W). The control simulation with the standard SAS scheme (CTRL) is quite reasonable in reproducing large-scale coherent patterns of the phase of the maximum, as described in detail by *Lee et al.* [2007b]. The model shows good correspondence with the observations in the nighttime maxima over the Great Plains. Over the rest of the continent, the model exhibits a precipitation maximum in the afternoon or evening, which is consistent with the observations, although the peak times are in general a few hours earlier than in the observations. Even though the model simulates slightly larger than observed amplitudes of the diurnal cycle over most of the land regions, the simulated amplitudes are in good agreement with the observations, with relatively stronger amplitudes in the southern and eastern United States and the Great Plains. The eastward progression of the times of maximum in the eastern slope of the Rockies and the adjacent Plains are less systematic in the simulation. This deficiency appears to be the result of the relatively coarse resolution of the model [*Lee et al.*, 2007a]. Similar deficiencies can be found over Baja California, where the current resolution of the model is not adequate to resolve the complicated terrain.

[16] We see from Figure 1 that the EXP1 (fixed CWF run) and EXP2 (fixed relaxation timescale run) simulations are not qualitatively different from the control simulation, both in terms of the amplitude and phase of the diurnal cycle. On the other hand, EXP3 (the convection starting level is fixed to be the first model level) and EXP4 (with a loosened criterion for the LFC condition) show significant shifts in the phase over the Great Plains from the control simulation. Precipitation peaks in the morning (0800–1200 LST) in EXP3, and in the early afternoon (1200–1600 LST) in EXP4, compared with the nighttime maximum in the control run. Also, the evening peaks in the CTRL over

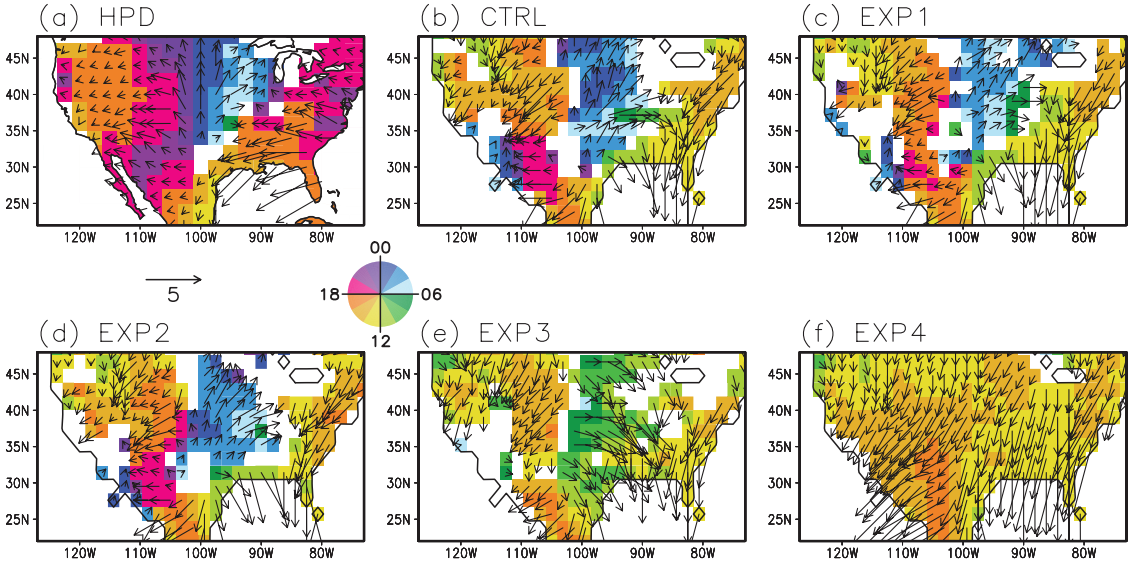

Figure 1. Amplitude and maximum phase of the diurnal cycle of precipitation in (a) the observations (HPD, 1983–2002) and (b–f) the model simulations (ensemble means). Length of arrow in each grid point indicates the amplitude (mm d^{-1}), whereas the arrow direction indicates the maximum phase in LST (local solar time). The maximum phases are also indicated in color shading. Only grid points in land and significant at the 10% level are shown. The land-sea boundary that was used in the model is indicated in Figures 1b–1f.

the North American monsoon region (southern Arizona–New Mexico and northwestern Mexico) shift to early afternoon maxima in these two runs. Other regions show little sensitivity to the changes in the convection triggers.

[17] Over most locations, the EXP3 and EXP4 experiments produce daytime precipitation maxima. In particular, EXP4 shows an early afternoon (1200–1600 LST) preference for the precipitation maxima, with little geographical variation. These characteristics are consistent with the results from another GCM that uses the near-ground level for starting convection and does not incorporate the LFC condition for triggering convection [*Lee et al.*, 2007b]. We further examine in Figure 2 the time series of the seasonal mean (June-August mean) hourly precipitation averaged over the Great Plains (100–95°W, 35–45°N). Here we do not present the results from EXP1 and EXP2 because they are very similar to that from CTRL. The ensemble mean of the CTRL follows the observed diurnal variations reasonably well (Figure 2a), not only for the phase but also for the amplitude. All ensemble runs of the CTRL are consistent with the ensemble mean in capturing the nocturnal maximum, consistent with a rather small ensemble spread. In contrast, the ensemble mean of the EXP3 (Figure 2b) shows a daytime peak in the diurnal variation, which is out of phase with the observations. The ensemble spread in both the amplitude and phase of the precipitation diurnal cycle is much bigger in EXP3. It is interesting that one ensemble member is rather insensitive to the modification (close to CTRL runs) showing a strong early morning maximum. The reason for this is unclear. We did not find any systematic relationship between the initial soil moisture anomaly and the ensemble spread in the phase, although this should be tested further in larger ensembles. On the other hand, all ensemble runs in EXP4 (Figure 2c) show clear diurnal maxima in the afternoon, with a very little ensemble spread.

4. Nocturnal Precipitation Mechanism in the Model

[18] The results from the sensitivity experiments suggest that the nocturnal precipitation in the control experiment is particularly sensitive to changes in the convection starting level and the LFC condition in the SAS scheme. We next look in more detail at the mechanisms by which the standard SAS scheme produces the nocturnal rainfall over the Great Plains. Figure 3a compares the seasonal mean diurnal time series of total precipitation (the sum of convective and stratiform precipitation) with convective precipitation over the Great Plains in the control simulation. More than 70–80% of the total precipitation is made up of convective precipitation, indicating that nocturnal rainfall is mostly generated by the convection scheme in the model. We further examined the diurnal variation of CAPE in the region. In our definition, CAPE is the maximum energy that can be achieved for a given moist static energy profile, for which we integrate the undiluted buoyancy of the lifted parcel from the level of maximum moist static energy (searching between the surface and the 700 hPa level) to the neutral buoyancy level. Note that the diurnal variation of convective precipitation is completely out of phase with that of CAPE (compare Figure 3b) in the Great Plains. CAPE reaches its maximum value during the day as the PBL heats up, and decreases to its minimum during the night, as one would expect as a result of radiative cooling at the ground and in the PBL. The out-of-phase relationship between convective precipitation and CAPE is quite intriguing because, to determine the intensity of convective precipitation in the model, the SAS scheme depends heavily on the

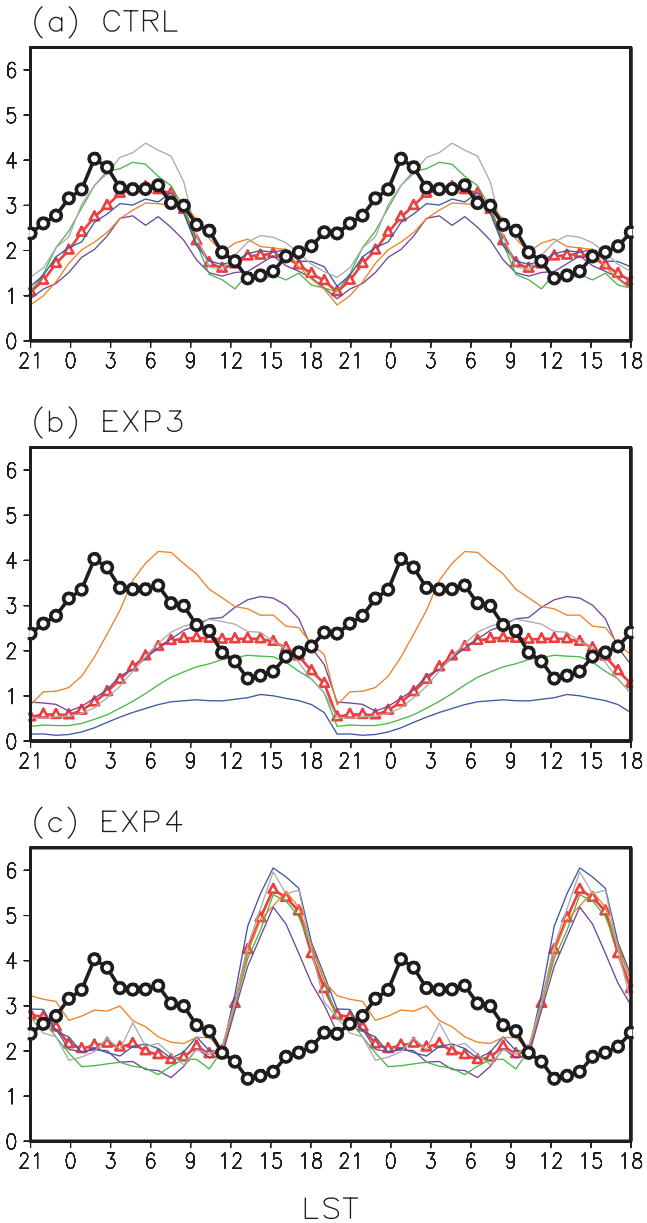

Figure 2. Summer mean (JJA) diurnal cycle of precipitation over the Great Plains (100–95°W, 35–45°N) simulated in (a) CTRL, (b) EXP3, and (c) EXP4. Ensemble mean is denoted by thick solid line with open triangles (in red), and individual ensemble run is denoted by thin solid line. The HPD observation is also indicated in thick solid line with open circles (in black). The time series are repeated twice for 48 h, and the precipitation unit is mm d^{-1}.

CWF, which is qualitatively similar to CAPE. We found that the CWF is not defined during most of the daytime in the Great Plains because the deep convection is not triggered.

[19] The reason for this is illustrated in Figure 4. Here, we show the time evolution of several variables that represent the evolution of convection at a specific grid point (90°W, 35°N) in the Great Plains. During this 4-d period, the model produced a very regular nocturnal rainfall signal, coming almost entirely from the model convection scheme (Figure 4a). Consistent with Figure 3, CAPE (Figure 4b) shows a diurnal variation that is quite opposite in phase to that of precipitation. In Figure 4b, we also show the diurnal variation of the CWF that is actually obtained during the GFS model integration. The diurnal variation of precipitation intensity corresponds well to the variation in the CWF, consistent with the model formulation. Indeed, the discrepancy between the CWF and CAPE is simply the result of whether or not the convection was actually triggered. Otherwise, the CWF would display a similar diurnal variation as the CAPE. Note that during most of the daytime (1200–0000 UTC) the CWF is defined to be zero, while the CAPE reaches to its diurnal maximum. This is because the convection trigger condition that the LFC must be located within 150 hPa depth from the convection starting level is not satisfied during the day. Figure 4c shows that the convective cloud base (i.e., LFC in the GFS) and cloud top (neutral buoyancy level) are mostly undefined during the day, indicating no trigger of deep convection. During the nighttime, when the convection is triggered, the LFC is usually located near the 750 hPa level. The magnitude of the CWF is comparable to that of CAPE during this time. As such, the reason that deep convection is triggered only in the nighttime by the LFC criterion must be tied to the day/night differences in the vertical structure of the PBL. Figure 4d shows the time evolution of moist static energy (h) at 975 hPa (closest level to the ground) and 850 hPa levels. Both variables exhibit similar diurnal variations, with the

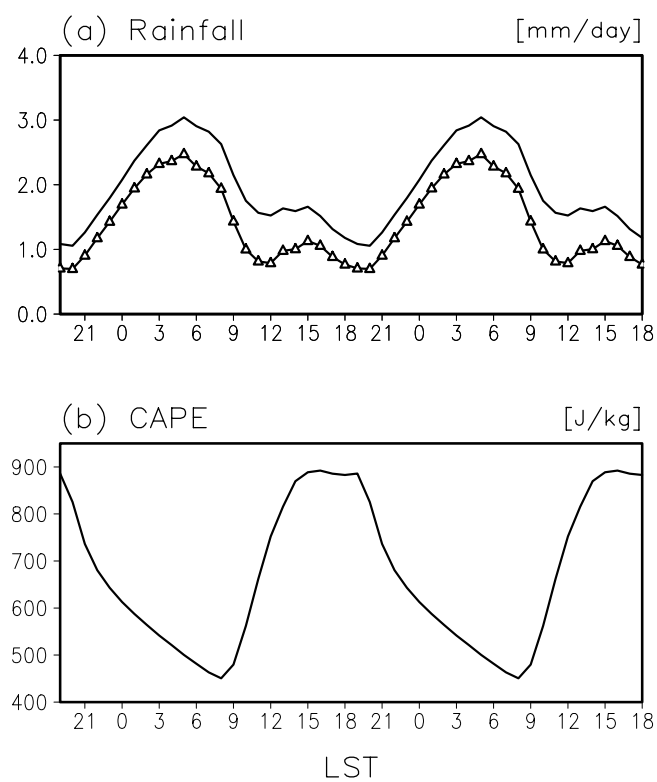

Figure 3. (a) Summer mean (JJA) diurnal cycles of total (solid line) and convective precipitation (solid line with triangles) in the Great Plains (100–95°W, 35–45°N) in the CTRL run (ensemble mean). The unit is mm d^{-1}. (b) Summer mean diurnal cycle of CAPE over the same area. The unit is J kg^{-1}.

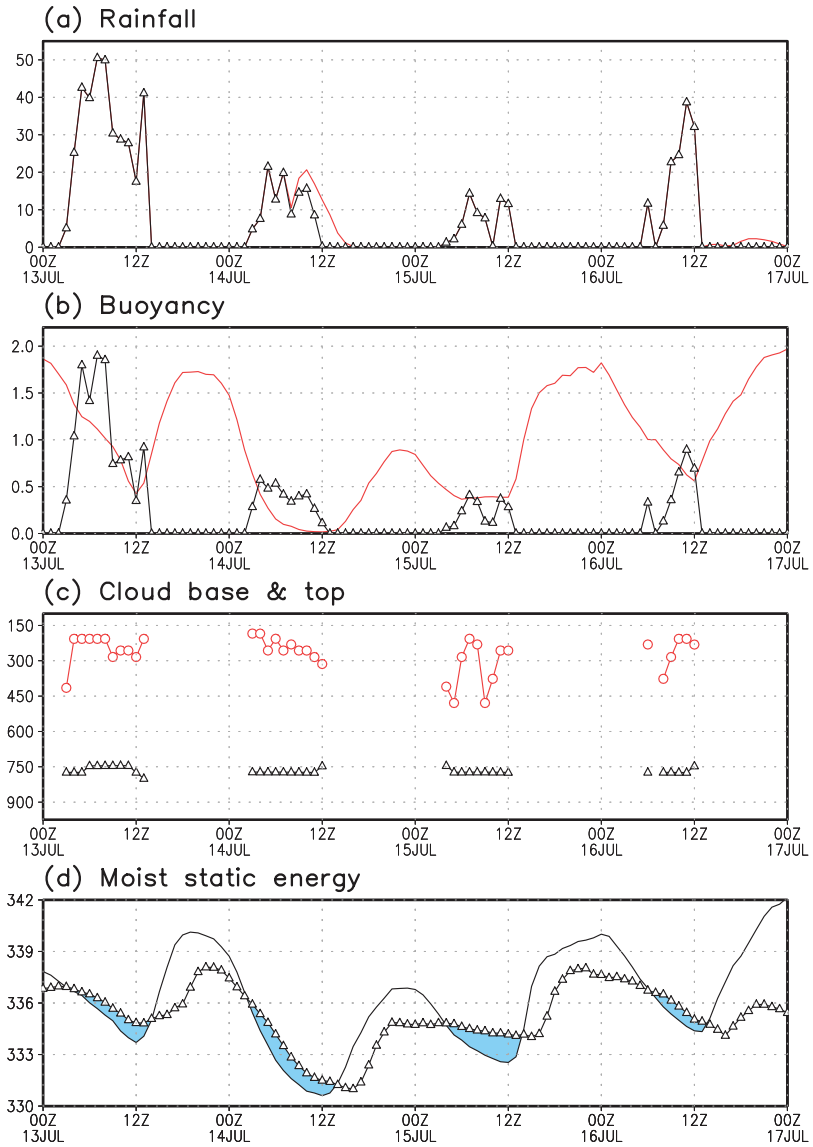

Figure 4. Time series of (a) total (solid line) and convective precipitations (solid line with triangles), (b) CAPE (solid line) and CWF (solid line with triangles), (c) cloud base (solid line with triangles) and top pressures (solid line with circles), and (d) moist static energy at 975 hPa (solid line) and 850 hPa (solid line with triangles) at 90°W and 35°N, simulated from one of the CTRL runs. In Figure 4d, shaded area (in blue) indicates the nocturnal inversion. The units are mm d^{-1} in Figure 4a, kJ kg^{-1} in Figure 4b, hPa in Figure 4c, and J in Figure 4d, and time is indicated in GMT (6 h ahead of LST).

maximum during the day and the minimum during the night, according to the surface heating and cooling. However, because of the nocturnal inversion of the PBL, *h* at 850 hPa becomes larger than *h* at the ground during the night. Since the current SAS scheme defines the level of maximum *h* as the convection starting level, the nighttime inversion can effectively elevate the convection starting level above the inversion layer so that the LFC criterion can be easily met to trigger convection. During the daytime, on the other hand, the convection starting level is usually the lowest model level. As the PBL grows with surface heating, the LFC also becomes higher, having a maximum elevation during late afternoon. As a result, the LFC criterion would hardly ever be met especially during afternoon time and this suppresses the afternoon convection substantially, although the CWF (or CAPE) during the daytime is likely higher than during the nighttime. This behavior of the model is described conceptually in Figure 5. The mechanism is consistent with the results from our sensitivity experiments. Although precipitation during the daytime is larger than during nighttime in EXP3 (see Figure 2b), the ensemble mean of daytime precipitation is comparable to that of CTRL (Figure 2a), and much weaker than that of EXP4 (Figure 2c). This is caused by large convective inhibition during the daytime (suppressed convection). Nocturnal convection is even more suppressed when the parcel is lifted from the first model layer in EXP3, because the CWF tends to decrease by accumulating negative buoyancy from the ground to the LFC level. In addition, the LFC can be further lifted because of the colder

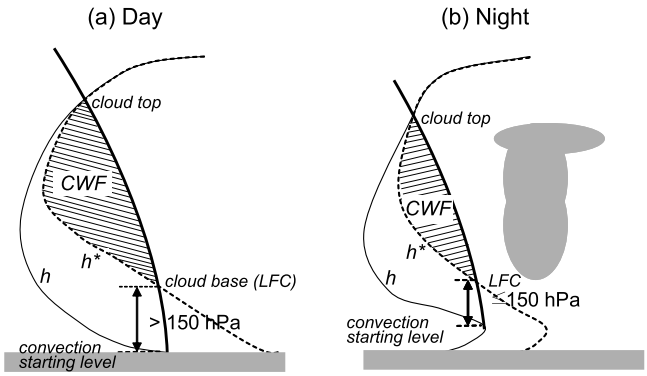

Figure 5. Schematics for (a) daytime and (b) nighttime profiles of moist static energy (h), saturated moist static energy (h*), and CWF in the model.

initial states of the parcel that originated from the surface, which can easily exceed the allowed depth for the LFC. In EXP4, there is essentially no inhibition of deep convection by the LFC criterion, because the threshold depth is so large. Therefore the diurnal variation of precipitation tends to have a sharp peak during the daytime, as a result of being proportional to the positive buoyancy of the CWF above the LFC (shaded area in Figure 5).

5. Validation With the ARM Soundings

[20] We next examine the degree to which the nocturnal precipitation produced by the model is realistic by comparing the simulations with the ARM sounding observations at the Southern Great Plains. For the comparison, we selected the 1995 summer Intensive Observing Period (IOP) extending from 0000 UTC 18 July to 0000 UTC 5 August. Figure 6a shows the height-time distribution of the maximum h (h_{max}) minus saturated h of the environment (h*) during the IOP. The plot of $h_{max}-h^*$ indicates the vertical profile of convective buoyancy of the lifted parcel that conserves h during the pseudoadiabatic ascent: its vertical integration is equivalent to CAPE. In a convectively unstable case, the lifted parcel reaches the LFC where the buoyancy changes its sign from negative to positive, and eventually extends to the neutral buoyancy level (NBL) where $h_{max}-h^*$ equals zero in the upper troposphere. The vertical integral of negative buoyancy from the level of h_{max} to the LFC is regarded as the convective inhibition (CIN). We choose h_{max} as the maximum h between surface and the 700 hPa level, consistent with the SAS scheme. In Figure 6a, we masked out the values below the level of h_{max}, which corresponds to the inversion layer of the moist static energy during the nighttime. Figure 6b shows the observed surface precipitation during the same period. During this IOP, there is a distinct period of diurnal variation in precipitation from 20 to 27 July when the precipitation events developed mostly during the local nighttime hours (0000–1200 UTC). This period was followed by dry days until 1 August, and then followed by continuous wet days, presumably influenced by a large-scale synoptic disturbance. Note that, although there is a very regular diurnal variation in $h_{max}-h^*$ for the entire IOP, this does not necessarily produce regular diurnal variation in precipitation. There appears to be a synoptic timescale variation in CAPE and CIN that modulates the variation of precipitation,

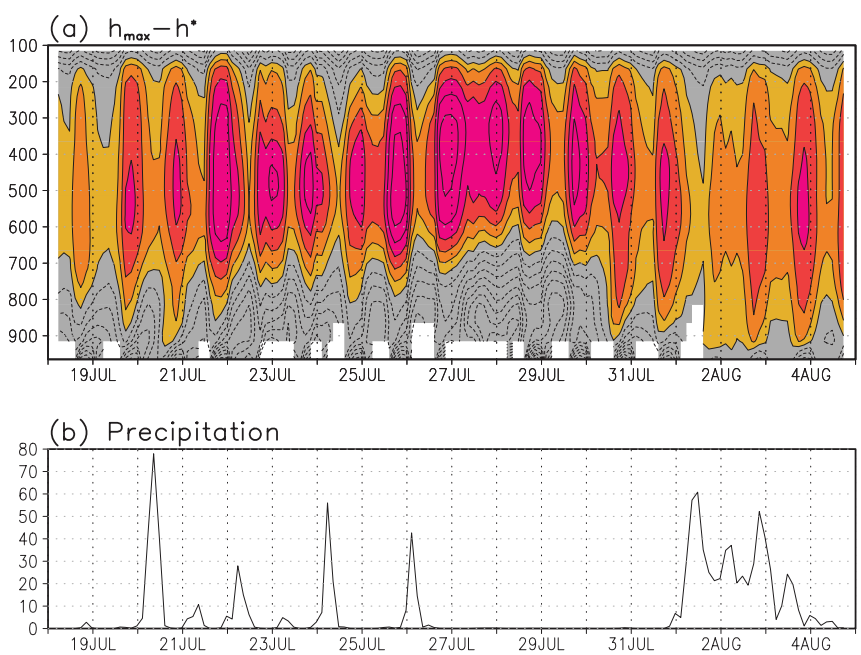

Figure 6. (a) Time-height (pressure in hPa) distribution of the maximum moist static energy (h_{max}) minus saturated moist static energy (h*) of the environment at the Southern Great Plains (97.49°W, 36.61°N) during 0000 UTC 18 July to 0000 UTC 5 August 1995 obtained from the ARM sounding observations. h_{max} is the maximum value of moist static energy between surface and 700 hPa level. The contour interval is 5 kJ kg^{-1}, and the values below the level of h_{max} are masked out. (b) Surface precipitation (mm d^{-1}).

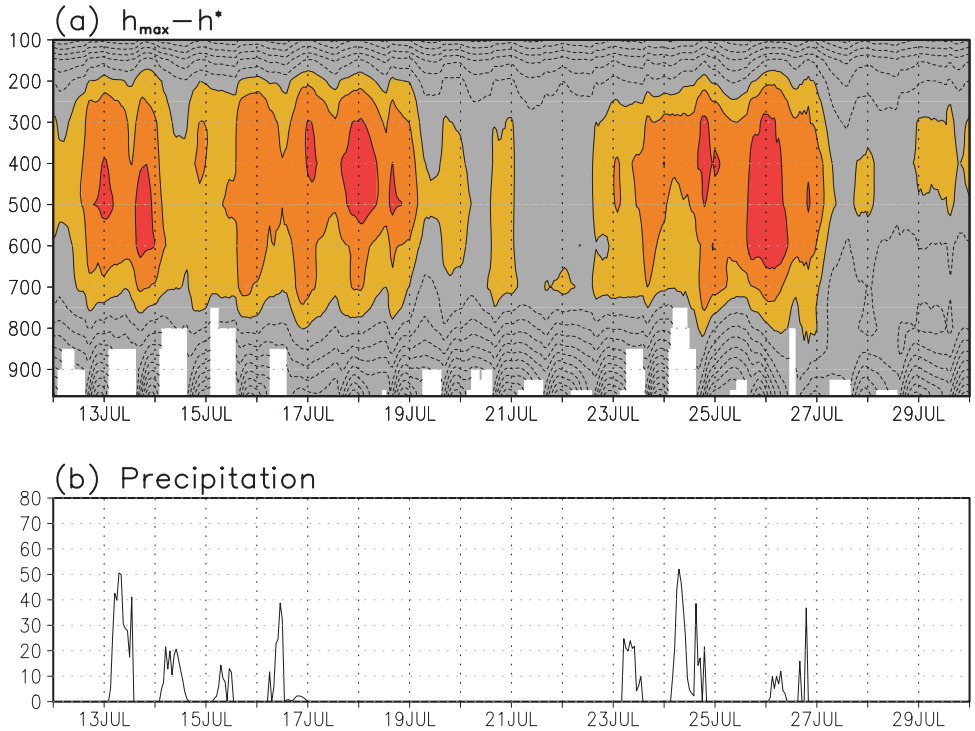

Figure 7. Same as Figure 6 but the model simulation at 90°W, 35°N in the Great Plains during 0000 UTC 12 July to 0000 UTC 30 July from one of the CTRL runs.

such that the CIN is largest during the dry period of 27–30 August and smallest during the wet period of 1–5 August. During the diurnally precipitating period (20–27 July) the magnitude of CIN is still large, especially during the time when the nocturnal precipitation develops. The LFC is generally located near the 700–750 hPa level during this precipitating time. Figure 7 shows the $h_{max}-h^*$ profile and precipitation simulated by the model at the Great Plains. The model simulation is qualitatively consistent with the ARM observations with large negative buoyancy below the LFC during the daytime. The LFC is in general located near the 700–750 hPa, which is in good agreement with the observations. The large CIN and high LFC seems to be caused by the general dryness in the PBL over the Great Plains. This is in contrast with the more humid environment in the southeastern United States (Figure 8), where the LFC is located near the 850 hPa level.

[21] We note that while there exist some qualitative similarities, the inversion of moist static energy in the nocturnal boundary layer over the Great Plains is weaker in the ARM soundings than in the model simulation. It is unclear whether this is the result of averaging several sounding profiles from sites with different surface elevation for the ARM results, or whether the GFS model tends to exaggerate this feature because of an overall dry bias in the boundary layer in this region.

6. Summary

[22] The mechanism by which the NCEP GFS model generates a realistic diurnal cycle in precipitation over the Great Plains was investigated by running a set of sensitivity experiments designed to assess the impact of several convection triggers implemented in the SAS scheme. It was found that the simulated amplitude and phase of the diurnal cycle of precipitation is insensitive to modifications in the convection scheme that disabled the dependency of the cloud work function and the relaxation timescale on the grid-scale vertical motion. On the other hand, it was found that the simulated diurnal cycle in precipitation is sensitive to the choice of the convection starting level and the model-specific LFC condition ($\leq$150 hPa from the convection starting level). When the convection starting level was set to be the model level closest to the ground, rather than the level of maximum moist static energy (as defined in the SAS scheme), the simulated nocturnal precipitation disappears over the Great Plains and the peak in the precipitation is shifted to the daytime. A similar sensitivity was obtained when the LFC condition was relaxed substantially (set to $\leq$500 hPa from the convection starting level) in the model.

[23] Further analysis indicates that the convection trigger associated with the LFC condition, which crudely represents an upper limit of convective inhibition, produced a significant impact on the phase of the diurnal convection. In particular, the nighttime elevation of the convection starting level above the nocturnal inversion layer provides a favorable condition for the nocturnal development of precipitation over the Great Plains. On the other hand, daytime convection appears to be largely suppressed as the convection starting level is closer to the ground and consequently, the convective inhibition (i.e., the depth of the LFC from the convection starting level) becomes larger, although the potential convective instability of the column is much larger during the day than at night. This mechanism appears to be effective in the inland regions such as the Great Plains

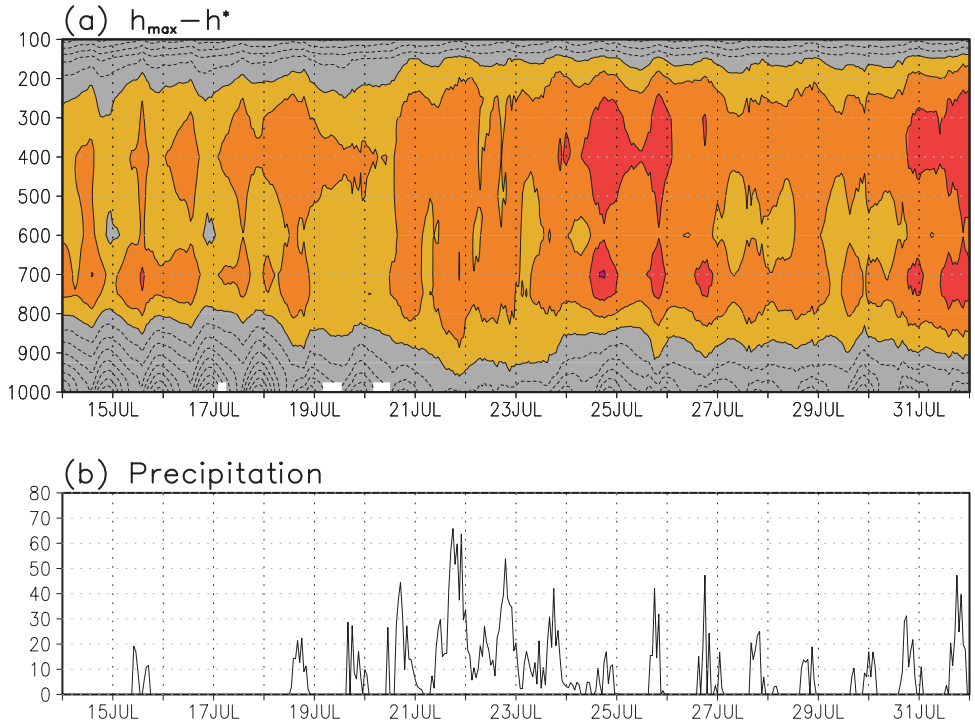

Figure 8. Same as Figure 7 but at 90°W, 35°N in the southeastern United States during 0000 UTC 14 July to 0000 UTC 1 August.

where the relatively dry PBL air causes an elevation of the LFC and large convective inhibition. This feature is qualitatively consistent with the ARM sounding observations over the Great Plains.

[24] The results of our analysis of the NCEP GFS model behavior has implications for how to improve the simulation of the diurnal cycle of deep convection and precipitation processes in AGCMs. First, it is clear that the definition of the starting level of deep convection is important. The elevation of the convection starting level above the nocturnal inversion layer in the NCEP GFS has an analogy to the approach of *Zhang* [2003] who eliminated the boundary layer tendency in his buoyancy closure. This can effectively increase the CWF and possibly enhance nocturnal precipitation, by eliminating the large amount of negative buoyancy near the ground. From another perspective, the model can be considered to be more prone to the destabilization process associated with the nocturnal low-level jets and moisture transports over the Great Plains, which seems to be important in the observed nocturnal rainfall events [*Ghan et al.*, 1996; *Helfand and Schubert*, 1995; *Higgins et al.*, 1997; *Schubert et al.*, 1998].

[25] Second, more work is required to understand and model the triggering processes of deep convection. Simple buoyancy closure schemes that initiate deep convection whenever convectively unstable (i.e., positive CAPE) clearly do not work properly in certain circumstances. For example, when the ambient air is quite dry, the LFC forms in higher altitudes and therefore a large amount of thermal and/or mechanical lifting is required to overcome the negative buoyancy levels below LFC and to trigger convection. Daytime convection cannot be triggered without this destabilization process, even when the potential for deep convection is large (i.e., larger CAPE) during day. This explains why the daytime convection is predominant in many current global models that do not implement ad hoc conditions for inhibiting convection. This is consistent with the findings of *Xie et al.* [2004], who implemented a convection trigger function that utilizes the dynamical tendency of CAPE caused by large-scale advection. This ad hoc condition has led to considerable improvements in the simulation of precipitation, by reducing the model bias of too-frequent diurnal convection during the daytime.

[26] Regarding the implementation of convection triggering functions, a more generalized framework seems to be required, and some approaches implemented in mesoscale models are worth testing in AGCMs. For example, many of the mesoscale models parameterize subgrid-scale perturbations of temperature and vertical velocity for triggering deep convection [e.g., *Fritsch and Chappell*, 1980; *Kain and Fritsch*, 1992; *Rogers and Fritsch*, 1996]. In this context, *Rogers and Fritsch* [1996] provided a useful framework that can be applied to a wide variety of environments, ranging from well-mixed, free convective boundary layers to stably stratified, nocturnal boundary layers. Their formulations conceptually include various factors, such as the effects of surface heterogeneity (i.e., subgrid-scale variations in surface type and elevation), surface heating, and large-scale convergent motion, all of which seem to be quite relevant for simulating the nocturnal convection over the Great Plains.

[27] Finally, it should be noted that a GCM with a 200 km resolution is incapable of resolving some of the important real world physical mechanisms for producing the nocturnal precipitation maximum. In reality, nocturnal precipitation over the Great Plains is frequently produced by organized

mesoscale convective systems that can propagate long distances [*McAnelly and Cotton*, 1989; *Cotton et al.*, 1989; *Carbone et al.*, 2002; *Nesbitt and Zipser*, 2003]. A full assessment of these mechanisms and the fundamental limitations imposed by the column-wise parameterizations for deep convection will require GCM simulations at resolutions comparable to if not higher than that of current mesoscale models.

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