On the Effect of Relative Timing of Diurnal and Large-Scale Forcing on Summer Extreme Rainfall Characteristics over the Central United States

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ABSTRACT

Impacts of diurnal radiative forcing on flow and rainfall patterns during summer flood and drought conditions (1993 and 1988, respectively) in the central United States were investigated using a regional climate model. The modeling approach, which included evaluation of sensitivity to modification in the solar hour, enabled evaluation of the impact *on an event-by-event basis.* The effect of the solar hour forward shift of 12 h on boundary layer wind speed over north-central Texas, which is often related to rainfall in the central United States through northward moisture advection, followed almost exactly the shift in solar hour. Domain-averaged daily rainfall in the central United States simulated with 12-h solar shift frequently showed in the flood year a backward or forward time shift of ∼12 h in the timing of its peak, an increase or decrease of rainfall rate, and on a few occasions noticeable formation of short-lived rainfall events. This pattern suggests relatively high sensitivity to the timing of the diurnal radiative forcing with respect to the large-scale perturbations. In contrast, in the drought year 12-h solar shifted simulations these modifications were weaker. The climatological domain-average diurnal cycle of rainfall showed for the flood year a well-defined 12-h shift when comparing the control and perturbed simulations. In contrast, in the drought year such a shift was not well defined.

1. Introduction

A large amount of the summer rainfall over the central United States is related to diurnal variation of radiative forcing at the surface (e.g., Wallace 1975; Fritsch et al. 1986; Dai et al. 1999). Development of the daytime convective boundary layer (CBL) commonly provides conducive thermodynamical conditions for deep convection. Mesoscale diurnally forced systems, such as nocturnal low-level jets and thermally induced slope circulations in the high plains, provide an environment that is favorable for development and sustenance of convection in various portions of the central United States. A large portion of the summer rainfall in the central United States is contributed by mesoscale convective systems (MCSs), whose evolution is linked to diurnal forcing (e.g., Maddox 1983; Fritsch et al. 1986). While the above diurnal processes are important in triggering convective systems, the diurnal variation of the CBL also affects the thermodynamic background conditions associated with large-scale perturbations. It is worth pointing out additional situations in which large-scale perturbations interact with the diurnal forcing to affect rainfall. Ekman pumping associated with precipitating cyclones is modulated diurnally (with peak induced vertical velocity likely in the afternoon) and should affect correspondingly the precipitation distribution. Likewise, frontal systems are modulated in response to diurnal changes in the boundary layer, with consequences for rainfall. Some factors that produce frontal modification include diurnal variations in boundary layer turbulence (e.g., Becker et al. 1997), daytime cloud shading effects (e.g., Segal et al. 1993; Koch et al. 1995), and variations of daytime evapotranspiration (Koch et al. 1997).

Considering the processes described above it is of interest to quantify how the rainfall pattern of a given summer is affected by the timing of diurnally forced atmospheric processes relative to large-scale perturbations crossing the domain of interest. Of particular interest is the contribution by diurnal forcing during extreme summer rainfall periods, as these situations are dominated by large-scale anomalies. Various studies have evaluated the diurnal effect on the average rainfall observationally, based on climatological analysis. *In contrast to these studies, we ask how important is the effect of diurnal timing of passage of large-scale perturbations in a given domain on rainfall patterns as identified on an event-by-event basis.* This question is the focus of the present note.

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Statistically, large-scale transient perturbations (including cyclones, short synoptic waves, and fronts) appear to cross the central United States randomly during the day and night. The timing of the interference between ''diurnal'' and ''large-scale perturbation'' forcing may be important in determining the rainfall associated with the large-scale systems. From observational analysis, it is impossible to quantify the importance of this timing for *individual* rainfall days. It can be estimated only climatologically for the total effect of all events assuming there is a large sample of events. In order to evaluate the importance of the timing of diurnal radiative forcing for rainfall induced by an individual large-scale perturbation in a given region, a hypothetical shift in the diurnal forcing cycle should be applied. Such evaluation can be carried out only by a modeling study that compares a control simulation with a simulation in which the solar cycle is shifted. When a shift of 12 h in the solar time is imposed (e.g., midnight is turned into noon) the timing of the diurnal forcing may be ideal to interact with the large-scale perturbation and produce a rainfall event that otherwise does not exist (i.e., appropriate timing of the diurnal forcing is needed in order to trigger the rainfall event). Likewise when a rainfall event exists, the shift of the diurnal forcing is likely to affect the characteristics of the event. (As evaluated later, the shift in solar time is likely to affect at most only secondarily the regional-scale characteristics of the large-scale perturbation.)

Three options could be considered for the modeling application. (i) Global model seasonal simulation. A disadvantage of this approach is that the transient large-scale waves in the control simulation would likely not be reproduced in the 12-h shifted solar cycle simulation, due to the cumulative effect of the difference in the diurnal forcing on long-term predictability. Thus, the impact of diurnal forcing on a given rainfall event cannot be isolated through global model simulations. (ii) A second approach is to use a regional model in a short-term prediction mode (e.g., 48 h) forced by observed initial and lateral boundary conditions. A sequence of such simulations covering the period of interest would provide the rainfall fields for the control simulations. However in such simulations when the solar hour is shifted forward by 12 h the initial condition in the lower atmosphere would be, at least for part of the period, severely out of balance with the radiative forcing. (iii) Regional climate models forced by observed meteorological variables as lateral boundary conditions would likely maintain the observed large-scale transient perturbation crossing the domain of interest in both the control and the solar hour shifted simulations. This type of simulation produces *long-term* rainfall fields in reasonable agreement with observations (e.g., Giorgi et al. 1996; Pan et al. 2000, 2001). However, it is not expected that a regional climate model will reproduce the observed short period details of rainfall spells. Note that in this approach the model forcing for most of the simulation period is by lateral boundary conditions only, and the continuous cycle of simulations provides inertia to the evolving meteorological fields in the interior of the domain. Given the above arguments, a regional climate model simulation as outlined in (iii) provides the most appropriate choice for our study objectives, and it was adopted as described in section 2b.

It is the purpose of this note to evaluate the importance of the diurnal timing of large-scale systems during the flood of 1993 and the drought of 1988 in the central United States, primarily on rainfall events. These extreme weather situations were characterized by pronounced anomalies in the large-scale weather patterns over the central United States as summarized in section 2. Results focusing on the central United States are presented in section 3.

2. Meteorological conditions and methodology of evaluation

a. Brief background of the meteorological conditions during the 1993 flood and the 1988 drought

Various studies have evaluated the meteorological conditions during the 1993 flood in the central United States. Trenberth and Guillemot (1996) found that the extreme rainfall conditions were the result of a warm sea surface temperature (SST) anomaly in the tropical Pacific. This anomaly was accompanied by a large-scale quasi-stationary wave anomaly over the United States. Numerical modeling by Helfand and Schubert (1995), Paegle et al. (1996), and Giorgi et al. (1996) pointed out the role of the diurnally forced Great Plains low-level jet (LLJ) in supporting enhanced precipitation. Observational studies (e.g., Mo et al. 1995; Arritt et al. 1997) confirmed the contribution of the LLJ to extreme rainfall in the 1993 flood.

During the first half of the summer of 1988 a high pressure system persisted throughout the troposphere for most of the period over the central United States. Consequently the jet stream and associated storm tracks shifted well north of their climatological position (e.g., Trenberth and Guillemot 1996). Severe drought conditions developed in this region. Temporary retreats of the high pressure system enabled large-scale perturbations to produce occasionally some rainfall over the area.

b. Methodology of evaluation

The second-generation Regional Climate Model (RegCM2), whose formulation is given in detail in Giorgi et al. (1993), was adopted in the present study. The boundary layer formulation includes the nonlocal eddy diffusion formulation of Holtslag et al. (1990). RegCM2 incorporates the second generation Community Climate Model (CCM2) radiation package (Briegleb 1992) and Biosphere–Atmosphere Transfer Scheme (BATS) ver-

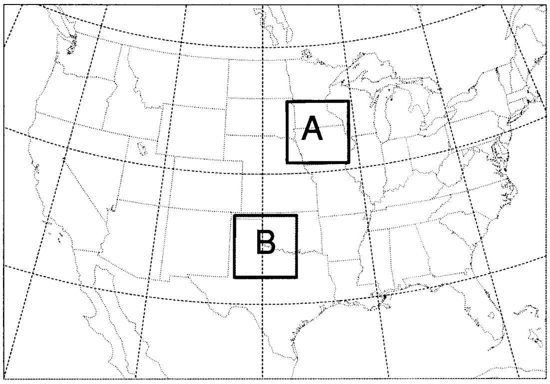

FIG. 1. The simulation domain and two subdomains (A and B), which are used in the presentation of the results.

sion 1E (Dickinson et al. 1992) surface package. The present simulations used the Grell convection scheme (Grell et al. 1995). This mass flux scheme is a simplified version of the Arakawa and Schubert (1974) convection scheme that assumes a single updraft and downdraft.

We adopted the following approach in examining the diurnal effect. A control simulation (initialized at 0000 UTC) was carried out for the summer months of 1993 and 1988 when flood/drought conditions prevailed. Each simulation was repeated with the solar time shifted forward by 12 h, hereafter referred to as the ''solar shifted'' simulation. This produced a corresponding time lag in the diurnal thermal forcing along with modifications in the spatially averaged boundary layer wind speed and precipitation fields in the domains of interest (domains A and B shown in Fig. 1). These modifications are evaluated in comparison with the control simulation.

The domain of simulation was 5200 $\times$ 3850 km^2 encompassing the continental United States, portions of neighboring oceans, and parts of Canada and Mexico. The model horizontal grid spacing was 52 km. Soil moisture and vegetation coverage characteristics were provided based on seasonal classifications. The initial and lateral boundary conditions were derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis. The lateral boundary conditions were updated at 6-h intervals and were imposed within a 16-gridpoint nudging zone adjacent to each lateral boundary, in which the weighting of the reanalysis data was reduced linearly with distance from the boundary.

The east, west, and south boundaries of the model are almost entirely over water surfaces (Fig. 1). In such locations diurnal radiative influences on meteorological fields are very mild so that inconsistencies in the lateral boundary conditions induced as a result of the solar hour shift are minimized. The northern boundary is located mostly over land so that some interference in the lower-atmosphere lateral boundary conditions may be caused there by the solar shift. These inconsistencies are mitigated to some extent because the lateral boundary forcing is reduced in the standard version of the RegCM2 for the lower layers (through decreased nudging in these layers).

3. Results

To evaluate the realism of the comparisons between the control simulation and the solar shifted simulation we examine the time sequence of difference in the geopotential fields between the two simulations. Such comparisons are meaningful if the large-scale perturbations are nearly identical in both cases, and merely differ by perturbations related to the effect of difference in the diurnal solar cycle (i.e., no temporal or magnitude change in the general characteristic of the large-scale perturbation is induced in the solar hour shifted simulation). The diurnal effect will be most noticeable in the lower atmosphere. Therefore we averaged 850-hPa geopotential height fields in the subdomain A, and present the time sequence for both simulations in the years 1993 and 1988 (Fig. 2). Similar features of the time sequences in both the control and the solar hour shifted cases are simulated for both years. The small differences between the two simulations are attributed to effects emerging

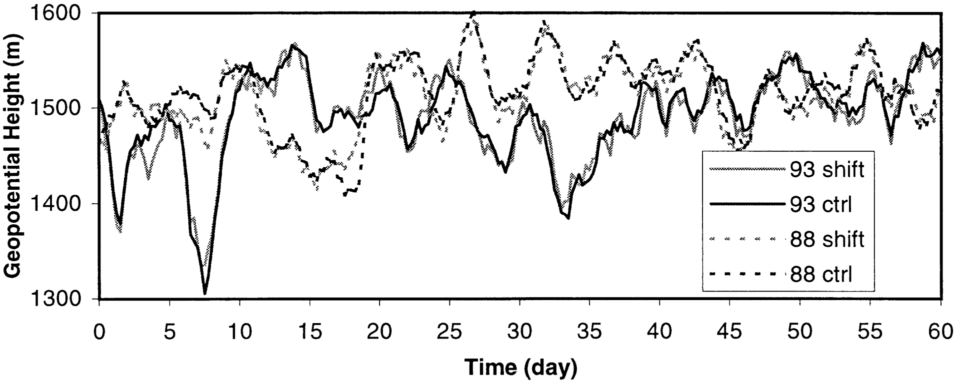

FIG. 2. Time sequence of simulated averaged geopotential height at 850 hPa in area A during the 1993 flood and the 1988 drought, for the control and the solar shifted simulations.

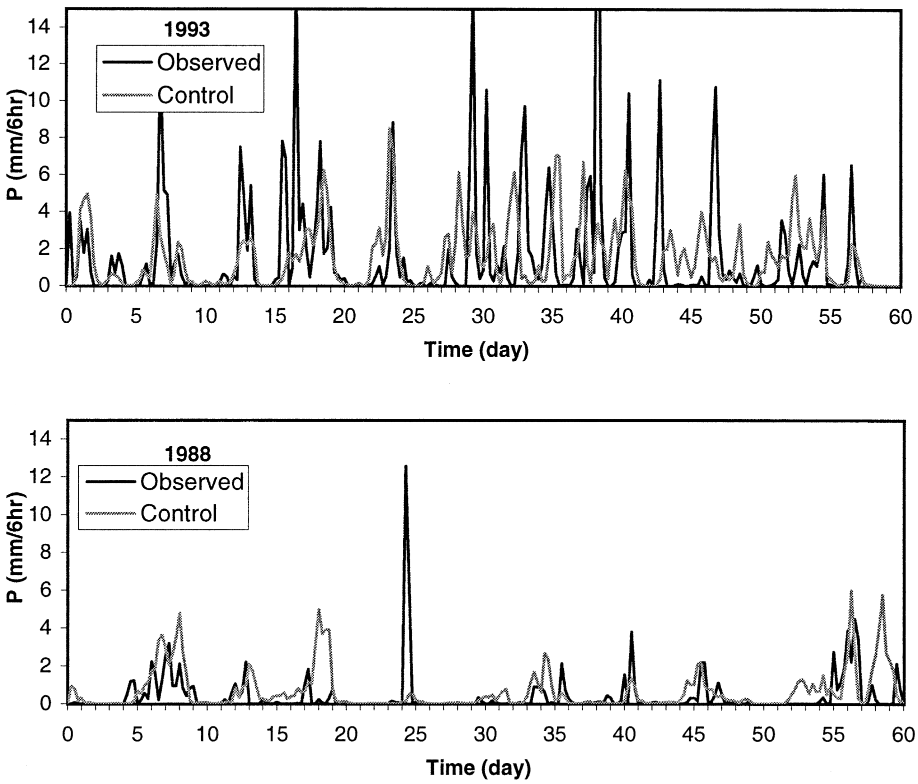

FIG. 3. Time sequences of simulated and observed domain-averaged 6-hourly rainfall rate, *P*, in area A during the 1993 flood and the 1988 drought [observational source: Higgins et al. (1996)].

from the difference in the solar cycle. This pattern is simulated as well for the 500-hPa geopotential field (not shown). The small difference in geopotential height indicates that the large-scale synoptic environment at model lateral boundaries is not strongly affected by the prescribed solar cycle shift [the root-mean-square (rms) difference is 12 m for 1993 and 18 m in 1988]. This result supports the use of lateral boundary conditions that are driven by a solar cycle differing from the one used inside the model domain as adopted in the solar shifted simulation.

As pointed out in the introduction it is not anticipated that regional climate models can resolve the short period details of rainy spells. However, the observed rainfall patterns associated with flood/drought years should be simulated, and should overlap to a large extent periods of observed rainfall activity. Effectively, lack of forcing by initial conditions (in contrast to operational short period model prediction) would likely cause modifications in the details of simulated rainfall events compared with the observed ones. Figure 3 presents the control and observed 6-h rainfall temporal variations averaged in the domain A for 1993 and 1988. In both years the simulated rainfall tended to coincide only with the general pattern of the observed rain spells in agreement with prediction skill anticipated from a regional climate model. This suggests that the evaluation presented later provides only general estimation of the actual effect of the diurnal radiative cycle on rainfall for the observed flood (drought) conditions of 1993 (1988). However in a broader context, this evaluation can be viewed also as a model quantification of the diurnal forcing effect as obtained by simulated flood (drought) conditions resembling those in 1993 (1988).

a. Simulated effect of solar cycle shift for the flood of 1993

Control and solar shifted simulations were carried out for the period 1 June–30 July 1993 (corresponding to days 0–60 in the figures). As anticipated, the solar shifted simulation produced a 12-h shift in the diurnal evolution of the boundary layer depth (not shown). Likewise in the solar shifted simulation the areal-averaged wind speed in subdomain B shown in Fig. 1 indicates a persistent 12-h shift in the diurnal alternation of the wind speed in the boundary layer (at $\sigma = 0.95$; ~500 m above surface), in part as a response to the time alteration in formation of the nocturnal LLJ (Fig. 4). In all periods in which the background flow was relatively intense (or relatively weak), the corresponding flow was maintained in the solar shifted simulation. The illustrated wind speed pattern suggests that northward moisture transport through this area is altered temporally in the solar shifted simulation in a similar manner. In re-

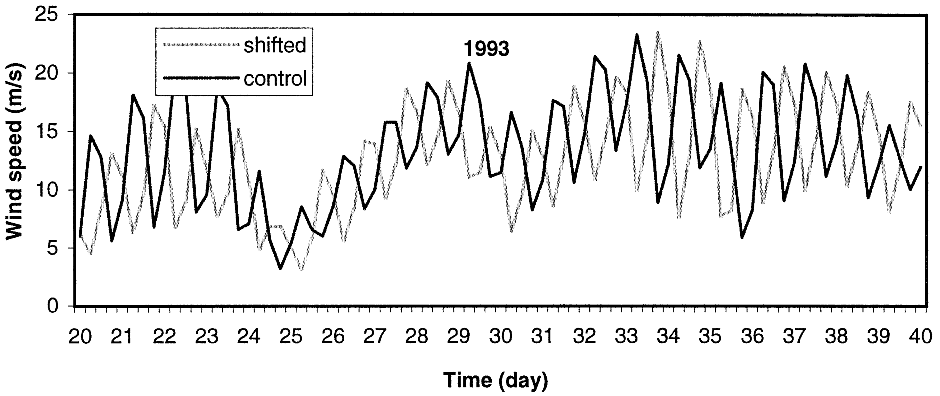

FIG. 4. Simulated domain-averaged wind speed at model level $\sigma = 0.95$ in area B during the 1993 flood period, for the control simulation and the solar shifted simulation.

sponse some temporal alteration of moist processes in the central United States is likely.

Figure 5 presents the time sequence of area-averaged 6-h rainfall rates in subdomain A, for the control simulation and the 12-h solar hour shifted simulation. As stated in the introduction there are various diurnal forced atmospheric processes in the central United States affecting the rainfall. The results presented in Fig. 5 suggest the aggregate effect of these diurnal processes on rainfall while interacting with the large-scale forcing. Effectively the results indicate the importance of diurnal timing of passages of large-scale perturbations over domain A for the temporal variation of rainfall in this domain. The following is evident upon examining the time series. (i) In general in the solar shifted simulation there was a time shift (randomly backward or forward with characteristic time difference ~12 h) in the rainfall peaks with some modification in their magnitudes. The random nature of these shifts is reflected by corresponding small lag-correlation coefficients between the two rainfall time series (in the range of 0.24–0.43 for the ±6 h and ±12 h time lags). (ii) On a few occasions (e.g., on the 4th and 24th days, for the 12-h solar shifted simulation) new intense, short-lived rainfall events were simulated. Computing the average rainfall in domain A for the simulated period suggested slight difference between the solar shifted and control simulations [0.02 mm $(6\ \text{h})^{-1}$]. This difference was almost unaffected when area A was quadrupled.

To quantify the impact of the solar cycle shift on the rainfall we applied a simplified index for the simulated period. The index reflects normalization of the average rainfall difference between the two simulations by the average rainfall for both simulations, defined as

$$I = \frac{\sum_{i=1}^{N} |r_{ci} - r_{si}|}{\sum_{i=1}^{N} 0.5(r_{ci} + r_{si})}, \qquad (1)$$

where $N = 240$ is the number of 6-h samples (corresponding to the 60-day simulation period), and r_{ci} and r_{si} refer to the 6-h rainfall rate in the control and shifted simulations, correspondingly. Note that if r_{ci} is (for example) at noon, then r_{si} will be at midnight. The periods in which $r_{ci} = r_{si} = 0$ were excluded. The value of I (ranging from 0 to 2) reflects quantitatively the sensitivity of rainfall to the relative timing of the large-scale forcing and the diurnal forcing. When $I = 0$ (i.e., $r_{ci} = r_{si}$ for all i), the timing of the large-scale forcing with respect to the diurnal forcing has no importance. When $I = 2$ (i.e., $r_{si} = 0$ or $r_{ci} = 0$ for all i), the rainfall is entirely sensitive to the timing of the large-scale forcing in the investigated domain. For the 1993 flood period $I = 0.76$. This value suggests that in the simulated period the shift in the solar cycle generated perturbation in the rainfall is 0.76 of the period-averaged rainfall. It implies that the timing of large-scale perturbation occurrence relative to the diurnal radiative cycle had a noticeable effect on rainfall event characteristics in area A.

Figure 6 provides the 60-day mean diurnal variation of rainfall averaged over subdomain A in the control simulation and in the solar shifted simulation. The diurnal wave in the observed rainfall pattern, which was derived using Higgins et al. (1996) rainfall data, is reflected in the control simulation although with more of an idealized sinusoidal variation than observed. In the solar shifted simulation the phase of the diurnal wave pattern for the averaged rainfall was effectively reversed. Applying Eq. (1) to the diurnal composite precipitation wave at 3-h resolution ($N = 8$) yields $I \cong 0.32$, compared with $I = 0.76$ computed previously from the time sequence of rainfall presented in Fig. 5 ($N = 240$). Thus the simulated diurnal forcing effect on rainfall during the 1993 flood period as obtained by event-by-event computation is ~2.5 times larger than that obtained by diurnal averaging.

b. *Simulated effect of solar cycle shift for the drought of 1988*

Control and solar shifted simulations were carried out for the period 15 May–14 July 1988 (corresponding to

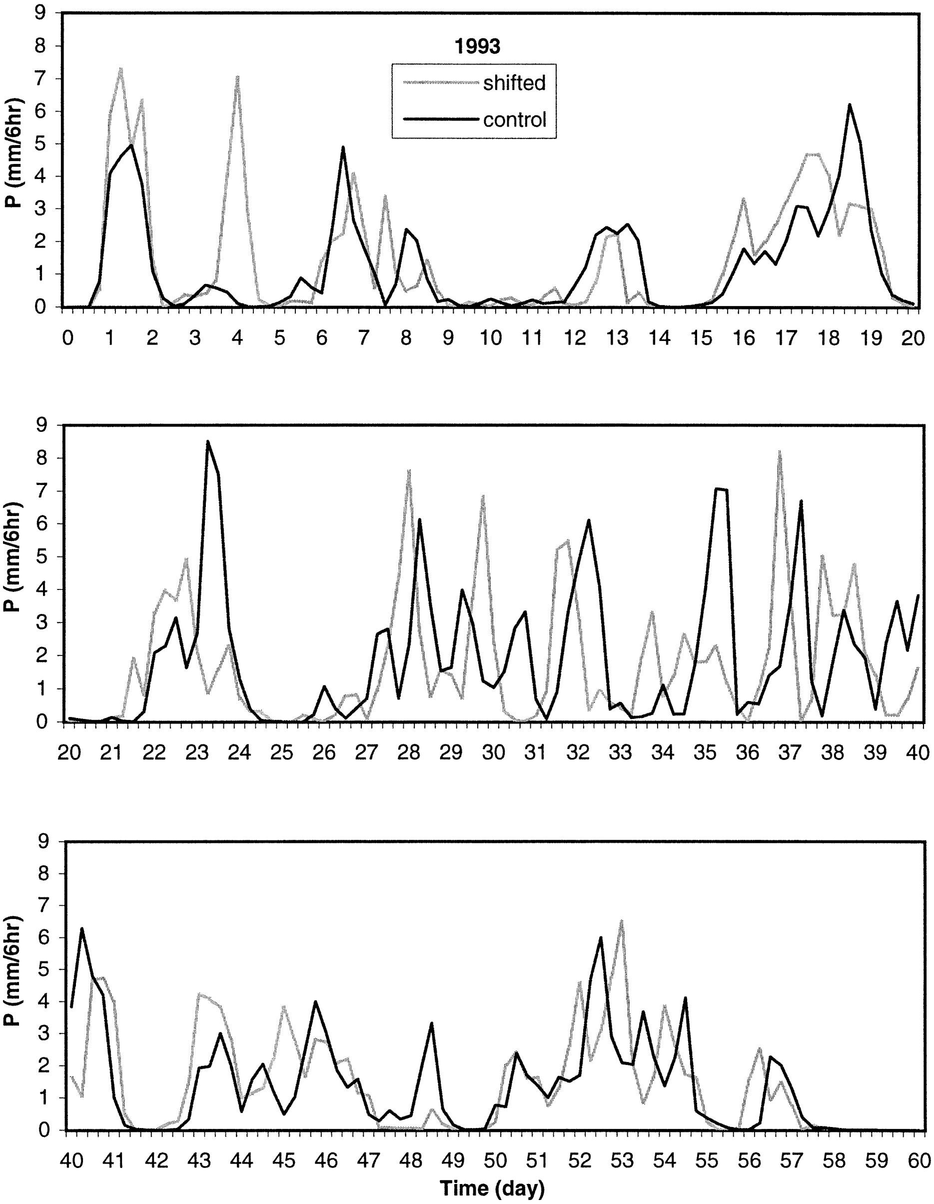

FIG. 5. Simulated domain-averaged 6-hourly rainfall rate, *P,* in area A during the 1993 flood period for the control simulation and the solar shifted simulation.

days 0–60 in the figures), and results are presented in a similar manner as for 1993. The areal average wind speed at model level $\sigma = 0.95$ in subdomain B showed diurnal variations that were well defined in both the control and the solar shifted simulations (Fig. 7). An expected 12-h time lag is evident, as in the 1993 simulation.

Figure 8 depicts the domain-averaged 6-h rainfall rates for domain A. The differences between the control and the solar shifted simulation are reflected by the alterations of rainfall peaks or intensification of rainfall (mostly in favor of the solar shifted simulation). The computed area-average rainfall difference (solar shifted minus control) for the simulated period was 0.13 mm $(6\ h)^{-1}$, which is higher than in 1993. As in 1993 the difference was only slightly changed when area A was quadrupled. For the 1988 simulation $I = 0.58$, which is somewhat lower than the corresponding value in 1993, implying that in 1988 the timing of large-scale perturbations within the diurnal cycle had less influence on rainfall modification compared with 1993.

The diurnal variation of the averaged rainfall during the drought of 1988 in domain A (Fig. 9) shows a double-peaked wave pattern with a smaller amplitude compared with the 1993 case. The diurnal rainfall variation pattern in the control simulation shows a rainfall peak

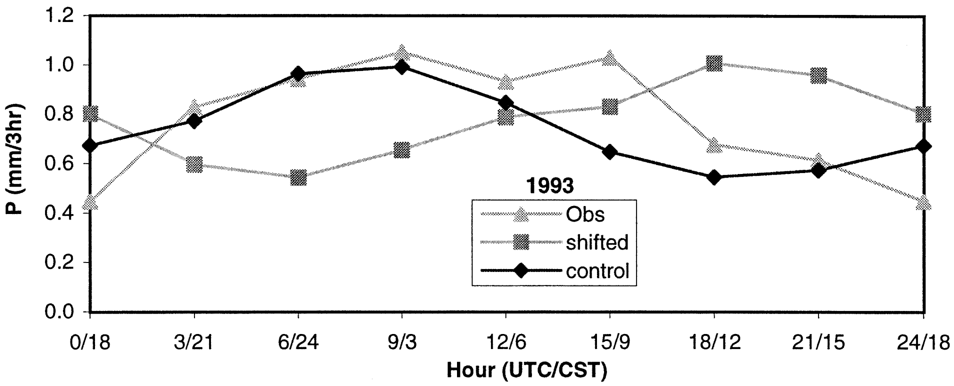

FIG. 6. The 60-day mean diurnal variation of the domain-averaged 3-hourly rainfall rate, *P,* in area A during the flood of 1993 as observed and in the control and 12-h solar shifted simulations [the hour is specified in both UTC and central standard time (CST)].

in early morning, which is in agreement with the corresponding observed pattern. However, the diurnal amplitude in the control simulation is smaller than observed, and there is no indication of the secondary peak in the afternoon. In the solar shifted simulation the expected shift generally occurs in that rainfall amounts are higher in the second 12-h period than in the first 12-h period, which is opposite to the distribution in the control simulation. The diurnal wave is distorted and relatively flat in both simulations, which indicates large contribution of the large-scale perturbations to the rainfall. Using Eq. (1) in a similar manner to the 1993 case for the diurnal average precipitation shown in Fig. 9 yields $I = 0.17$, which is much smaller than the I value derived for the time sequence of precipitation presented in Fig. 8.

4. Discussion

Summer rainfall in the central United States is affected by the coupling of large-scale perturbations and diurnal atmospheric processes in the region. The diurnal processes respond to the 24-h radiative cycle and include among others daytime CBL convection, low-level jets, outflow boundaries, and MCSs, while the large-scale perturbations include, for example, cyclones and frontal boundaries. The latter have random temporal occurrence with respect to the diurnal cycle, but are modulated in relation to their precipitation activity by diurnal variations of boundary layer thermodynamics and turbulence.

While observational analysis enables climatological evaluation of diurnal variation of rainfall, numerical modeling provides an effective option to evaluate event by event the importance of the timing of interactions between large-scale perturbations and diurnal processes on rainfall characteristics. The regional climate modeling approach adopted in the present note provides the best choice to evaluate the importance of a series of individual diurnal cycle related effects on rainfall. Even though the prediction skill of such long-term simulations is limited in resolving short-time details of observed rainfall events, meaningful physical insight can be obtained.

Results presented in this note suggest that the diurnal timing of transient large-scale perturbations is important in determining the characteristics of rainfall episodes in extreme years of summer rainfall in the central Midwest. The diurnal cycle forcing had a greater effect on simulated rainfall in the flood period of 1993 than in the

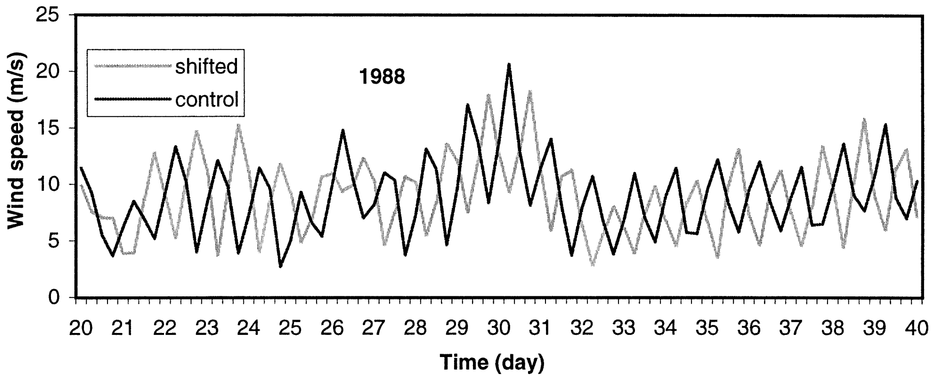

FIG. 7. As in Fig. 4 except for the drought of 1988.

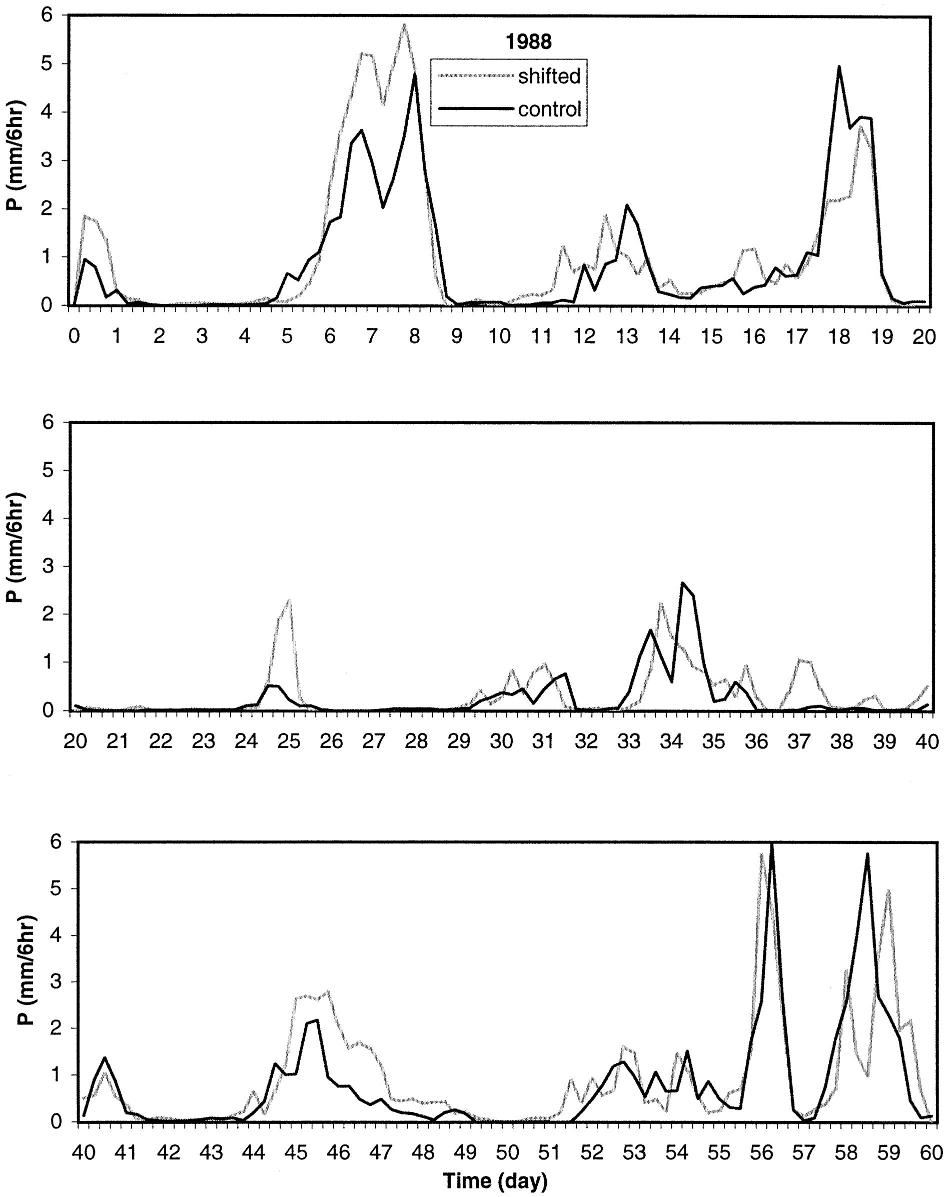

FIG. 8. As in Fig. 5 except for the drought of 1988.

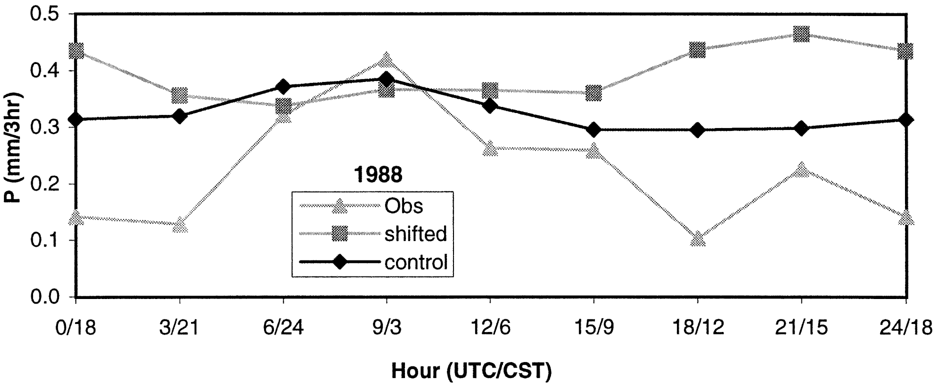

FIG. 9. As in Fig. 6 except for the drought of 1988.

drought period of 1988. Examining in both years the rainfall episodes event by event suggests a variety of modifications in the solar shifted simulations. Some events were shifted in time (typically ~12 h), which suggests an influence of the solar hour shift on the development of diurnally varying features such as the CBL or the LLJ. Infrequently new intense rainfall events were generated when the solar cycle was shifted (and when generated they were short lived). In an additional evaluation, the diurnal forcing contribution to rainfall in an event-by-event analysis was shown to be about 3 times larger than that suggested by analysis of the average diurnal rainfall cycle of the simulated period.

It should be pointed out that the present study provided only one simulated realization of diurnal forcing effects for each year. Further substantiation of the results could be achieved by adopting ensemble simulations with members reflecting, for example, perturbations in the initial or lateral boundary conditions (e.g., Giorgi and Bi 2000). Then various pairs of control and shifted solar cycle simulations and their aggregate difference could be evaluated, further enriching our present findings. Additionally, in the present note a 12-h solar cycle shift was adopted. This shift is likely to produce the most noticeable effect on simulated rainfall compared with less extreme (i.e., <12 h) solar cycle shifts. Likewise in the present study illustration of extreme summer rainfall features (flood and drought) was considered. It is suggested that ''normal'' summers would generate intermediate patterns of rainfall variation in response to solar cycle shift. Evaluation of these aspects could be considered in future studies.

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