# A Multidecadal Variation in Summer Season Diurnal Rainfall in the Central United States*

QI HU

*Climate and Bio-Atmospheric Sciences Group, School of Natural Resource Sciences, University of Nebraska at Lincoln, Lincoln, Nebraska*

6 September 2001 and 24 July 2002

ABSTRACT

Recent studies have identified two sources alternating their dominant roles in the interannual summer rainfall variations in the central United States. One is the ENSO cycle in the tropical Pacific, and the other is the interannual variability in the intensity of the southerly flow from the Gulf of Mexico. The ENSO cycle affected the rainfall variation through an atmospheric teleconnection, which was particularly strong in 1871–1916 and 1948–78. When the teleconnection weakened in 1917–47 and 1979–2002, the southerly flow from the Gulf of Mexico invigorated its effect on the interannual rainfall variation. Because the effect of the two sources could result in different rainfall processes in the central United States, their alternation should have built similar variation into the region's summer season diurnal rainfall pattern.

An hourly rainfall dataset was used to examine this hypothesis. Results showed a multidecadal variation in the diurnal rainfall pattern. In the decades when the southerly flow dominated the rainfall variation, the diurnal pattern had large rainfall in late night/morning hours with a sharp rainfall peak in the midnight hour. In the decades when the southerly flow effect weakened, a different diurnal pattern emerged, with small late night/morning hour rainfall and a broad plateau of rainfall in the late night/early morning hours. This diurnal pattern change was happening simultaneously with variations of the southerly moisture flux and moisture convergence in the central United States. These coherent variations show that the summer season diurnal rainfall pattern varied at a multidecadal scale consistent with the alternation frequency of the two sources. In addition to showing the variation in the diurnal rainfall pattern, results of this study provide the knowledge for understanding the climate of extreme events, particularly heavy rainfall and floods, in the central United States.

## 1. Introduction

Recent studies have shown that the total rainfall of June, July, and August (hereafter referred to as summer rainfall) in the central United States (the area in 37.5°–45.0°N, 90°–105°W) has significant interannual variations, and they have been influenced by two major sources. One is the El Niño–Southern Oscillation (ENSO) cycle, which influenced the summer rainfall through a teleconnection, and the other is the interannual variability of the intensity of the southerly flow from the Gulf of Mexico and coupling of the variability with the central U.S. rainfall development (Hu and Feng 2001a,b, hereafter HF01a,b, respectively). In addition, these two sources have alternated their dominance in the rainfall variation over the last century. As seen in the four epochs shown in Fig. 1a, the ENSO teleconnection effect was significantly strong and persistent from 1871 to 1916, but languished from 1917 to 1948, was reinforced in 1949–78, and weakened again in the recent decades beginning in the late 1970s. Figure 1b shows that when the ENSO effect weakened, the southerly flow from the Gulf of Mexico enhanced its role in the rainfall variation, a change that also was demonstrated in Fig. 2. Coherent changes of the sea surface temperature in the North Pacific and atmospheric circulation in North America were additional results associated with the alternation of the two sources (see HF01a,b). These results depicted a multidecadal alternation of the sources influencing the interannual summer rainfall variation in the central United States.

Because the two sources affected rainfall development in very different ways (HF01a,b), their alternation could have left a signature in the central U.S. diurnal rainfall pattern. Because differences in the diurnal rain-

* University of Nebraska Agricultural Research Division Contribution Number 13278.

*Corresponding author address:* Dr. Qi Hu, School of Natural Resource Sciences, 237 L. W. Chase Hall, University of Nebraska at Lincoln, Lincoln, NE 68583-0728.
E-mail: qhu2@unl.edu

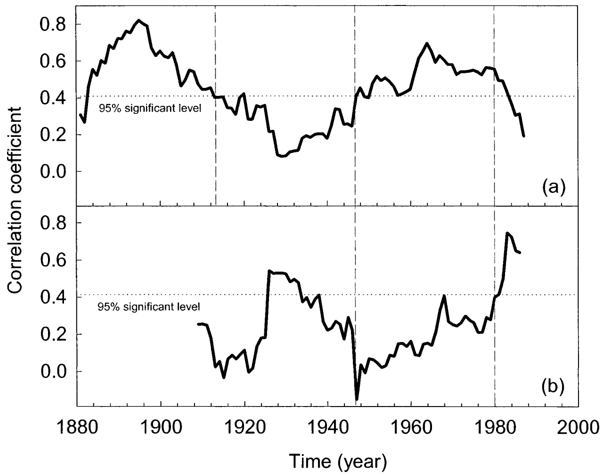


FIG. 1. (a) The 21-yr moving correlation of boreal summer SST in the Niño-3.4 and Niño-4 regions [(5°N–5°S, 120°–170°W) and (5°N–5°S, 150°W–160°E), respectively] vs central U.S. summer rainfall, and (b) 21-yr moving correlation of the central U.S. summer rainfall vs the southerly wind intensity from the Gulf of Mexico. The dotted line in (a) and (b) is the 95% significance level, based on the Student's *t* test distribution for the null hypothesis of no association. The vertical dashed lines separate different epochs (see text for details).

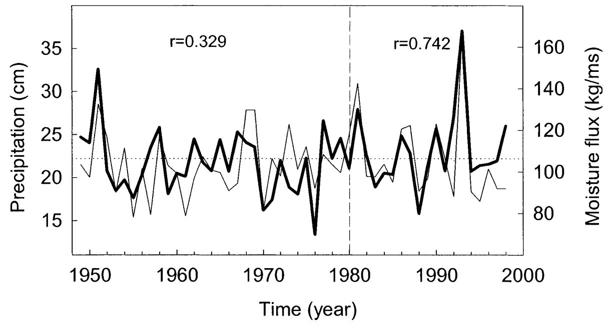


FIG. 2. Variations of vertically integrated moisture flux in the entrance region of the southerly flow (thin line) and summer rainfall in the central United States derived from hourly data (thick line). Correlation coefficients of the variations in the two epochs divided by the vertical dashed line are labeled. The horizontal dotted line is the average of the flux over the period.

fall pattern can affect local and regional hydrological cycles and thus climate, it is important to examine if such changes occurred in the diurnal rainfall pattern. The objective of this study is to address the question of how multidecadal alternation of the aforementioned sources influenced the central U.S. diurnal rainfall pattern. In the epochs when the southerly flow effect was strong, the nocturnal feature of the southerly flow would influence the rainfall so that the diurnal pattern shows more rainfall in the late night/morning hours. On the other hand, when the ENSO effect was strong, a different diurnal pattern could emerge. The reasoning behind this hypothesis is as follows: the southerly flow carried moisture from the Gulf of Mexico to the central United States and played a catalyst role in the region's rainfall development (Bonner and Paegle 1970). Therefore, more rainfall could develop in nighttime and early morning hours when the southerly flow was strongest, owing to decoupling of the flow from surface friction after the surface cooled off and turbulence weakened in late night/early morning hours (Holton 1967; Bonner and Paegle 1970; Mo et al. 1997). But in the epoch when the southerly flow weakened and the ENSO effect was enhanced, the nighttime rainfall could decrease, yielding a different diurnal rainfall pattern. So, the diurnal rainfall pattern in the central United States would vary between the epochs.

This hypothesis was examined in this study. The data used in the analysis are discussed in the next section. Major results are presented in section 3, showing different diurnal rainfall patterns in the recent two epochs (whose data were available to this analysis). Implications of the results to weather and climate in the central United States are discussed in section 4.

## 2. Data and methods

Two datasets are used in this study: the hourly precipitation dataset for the contiguous United States (Higgins et al. 1996), and the 6-hourly National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset for North America (Kalnay et al. 1996). The hourly rainfall dataset was developed based on data from 2500 stations covering the period 1948–98. The station data were quality controlled at the National Weather Service Techniques Development Laboratory and interpolated, using a modified Cressman scheme, to a gridded mesh of resolution 2.0° latitude × 2.5° longitude in the contiguous United States. Higgins et al. (1996) discussed the details of these methods, related assumptions, and quality and reliability of the data. This hourly dataset was different in several ways from the monthly dataset of Dai et al. (1997), which was used in our previous studies (HF01a,b). 1) Except for the major airport stations, whose hourly data were used in calculating the rainfall in the monthly dataset, the majority of the hourly stations' data were not included in deriving the monthly data, so the data source used in the two datasets were different. This difference resulted in some minor differences in rainfall variations of the two datasets, but the overall variations of the two were consistent, as can be seen from comparisons of the thick line in Fig. 2 of this article with Fig. 1c in HF01a. 2) Because the monthly data filtered out the diurnal variation, the interannual and multidecadal variations described by the monthly data in HF01a,b, were not affected by the diurnal variation, nor could they significantly affect diurnal rainfall variation in the hourly data because of the conditions noted in 1). Because the hourly rainfall dataset is, to a large degree, independent of the monthly rainfall dataset used in HF01a,b, results from analysis of this hourly

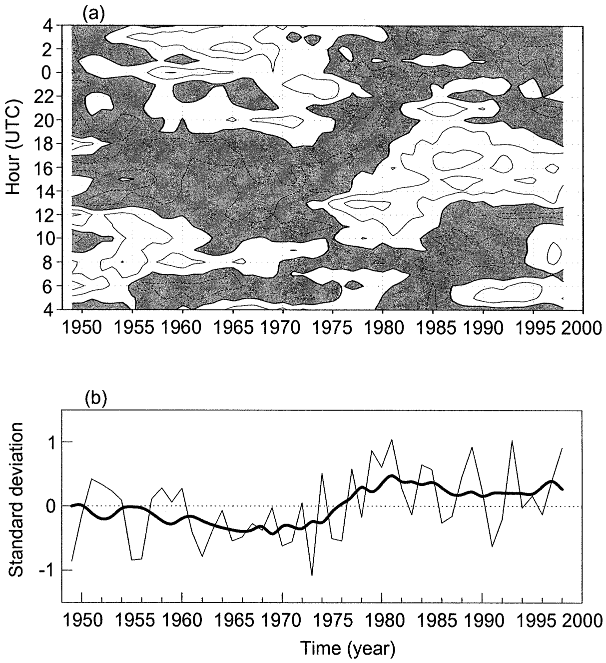


FIG. 3. (a) Variation of $f'$. Contour interval is 0.4, and negative anomalies are shaded. (b) Variation of $f'$ averaged over the hours from 0600 to 1700 UTC (see text for details).

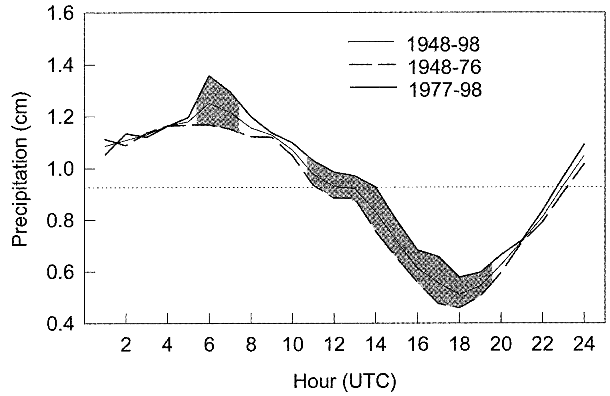


FIG. 4. Diurnal rainfall pattern averaged over 1948–98 (thin solid line), and the two epochs: 1948–76 (dashed line), and 1977–98 (thick solid line). The shaded area shows that the change of hourly rainfall from 1948–76 (dashed line) to 1977–98 (thick solid line) is above the 95% significance level. The dotted line shows average summer season hourly rainfall.

dataset will not only reveal summer season diurnal rainfall variation in the central United States, but also be an independent test of the multidecadal alternation of the two sources affecting the rainfall.

To evaluate diurnal rainfall pattern changes, we used the ratio $f(t) = [p(t) - P]/P$, where $p(t)$ is the rainfall amount of hour $t$ and $P =$ (average daily rainfall of *each summer*)/24, which was normalized by 24 in order to have a scale relevant to $p(t)$. Because a large (small) rainfall in hour $t$ would yield a large (small) $f$, this ratio describes the change of hourly rainfall contribution to daily rainfall and, hence, changes of the contribution and the diurnal rainfall pattern. We determined $f$ by first computing average daily rainfall from 1 June to 31 August and $P$ in the period 1948–98. Then, we computed $f(t)$ for each hour from the above expression and obtained 24 time series, each of which had 51 values. Finally, we obtained the time series of $f'(t)$ for every hour after removing the means and dividing by the standard deviation of each $f(t)$ series, and used $f'(t)$ to examine variations of the diurnal rainfall pattern.

To examine the relationship of variations in hourly rainfall and the moisture flux and divergence, we calculated the vertically integrated moisture flux and divergence in the central United States from the 6-hourly NCEP–NCAR reanalysis data from 1948 to 1998. To avoid the possible loss of mass balance resulting from interpolation of data between coordinates (see Trenberth 1991), the moisture flux and divergence were integrated in the original sigma coordinates of the reanalysis model. The integrated values at the Gaussian grids in the spectral domain of the model were transformed to the physical domain to obtain the flux and divergence.

## 3. Diurnal rainfall change in the late 1970s

The $f'$ series for each hour of the day in the 51 summers from 1948 to 1998 are shown in Fig. 3a. A positive (negative) value at a particular hour indicates increase (decrease) of contribution to daily rainfall from that hourly rainfall. The diagram is drawn such that the ordinates run from the local late night/morning hours (0400–1700 UTC) to local afternoon/evening hours (1800–0300 UTC). Figure 3a shows a change in the hourly contribution to daily rainfall in the late 1970s, particularly in the late night/morning hours. From 1948 to the late 1970s, the rainfall in the late night/morning hours contributed less to the total daily rainfall than it did in the decades after the late 1970s. This change is shown more clearly in Fig. 3b by the contribution averaged over the late night/morning hours. A significance test using the Student's $t$ test method yielded a value of 4.42 for the difference of $f'$ between 1948–76 and 1977–98, which is much larger than the critical value 2.02. The difference is over 95% significant.

The change in hourly rainfall contributions resulted in a change in the diurnal rainfall pattern. As shown in Fig. 4, the diurnal pattern has significantly more rainfall in the late night/morning hours in the decades since 1976 than in the years from 1948 to 1976 (except for the 2 hours of 0800–1000 UTC). In recent decades, the significant increase of the late night/morning hour rainfall created a single sharp rainfall peak at the local midnight hour (0600 UTC). In contrast, the relatively weak rainfall in the late night/morning hours from 1948 to 1976 corresponded to a plateau of rainfall from 0300–0900 UTC in the diurnal pattern, and the relatively flat variation in the hourly rainfall also showed multiple smaller peaks in the hours between 0900 and 1300 UTC.

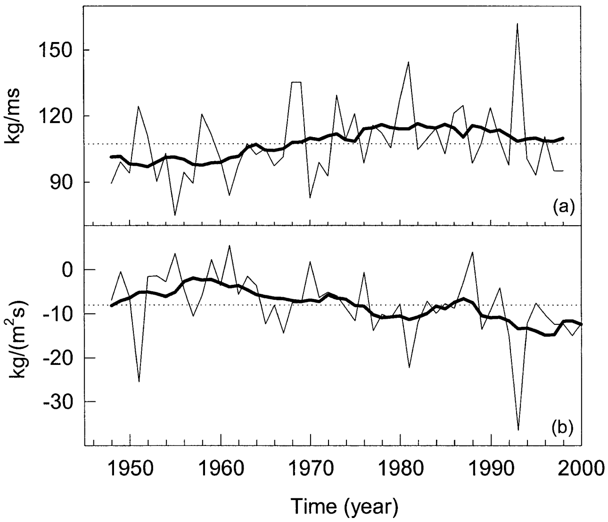


FIG. 5. Variations in (a) vertically integrated meridional moisture flux in the entrance region from the Gulf of Mexico to the central United States and (b) domain-averaged moisture divergence in the atmospheric column of the central United States (thin solid line). Both the flux and divergence are the sum of the values at 0600 and 1200 UTC. The thick solid line in (a) and (b) is the nine-point running mean of the annual variation, and the dotted line is the average of the period from 1948 to 1998.

Compared to the changes in the late night/morning hours, the diurnal rainfall pattern in Fig. 4 shows little change in the afternoon/evening hours (1900–0400 UTC) before and after the late 1970s. The hourly rainfall increased slightly in 1900–2400 UTC and changed little in 0100–0400 UTC. These small changes also corresponded to weak variations in hourly rainfall contribution from those hours to the daily rainfall. As shown in Fig. 3, while the contribution showed some decrease in recent decades compared to that before the late 1970s, it was rather sporadic and occurred mainly because of the much larger and more consistent contribution to the daily rainfall from the late night/morning hours. The small variation in the afternoon/evening hours indicated that the change in intensity and contribution to daily rainfall from the late night/morning hours resulted in a significant difference in diurnal rainfall pattern before and after the late 1970s.

Comparing the two diurnal rainfall patterns in Fig. 4, we also found that the daily rainfall and, hence, the summer rainfall in the central United States increased significantly in the decades after the 1970s, a result consistent with several previous studies (e.g., Karl et al. 1996; Hu et al. 1998). Moreover, this increase resulted nearly solely from the increase of the late night/morning hour rainfall, showing a dramatic change of the circulation and rainfall development in those hours before and after the late 1970s.

To address the question of what could have caused such change, we examined moisture flux associated with the southerly flow from the Gulf of Mexico and moisture convergence in the central United States. Figure 5a shows the vertically integrated meridional moisture flux, $\overline{vq}$, through the region 25°–35°N, 90°–105°W, often referred to as the entrance region of moisture flow from the Gulf of Mexico to the central United States (e.g., Helfand and Schubert 1995), and Fig. 5b shows the integrated moisture convergence in the central United States. The flux and convergence values were the sum of their respective values at 0600 and 1200 UTC from the 6-hourly NCEP–NCAR reanalysis data. These values did not include the flux and convergence at 1800 UTC, which was at the end of the late night/morning period (Fig. 4). The flux and convergence at that hour would barely affect the moisture budget and rainfall in the late night/morning period. Also, we only showed $\overline{vq}$ in the moisture flux because it was, in general, at least twice as large as the zonal moisture flux, $\overline{uq}$, and was the primary moisture supply to the central United States.

Figure 5a shows an increase of $\overline{vq}$ in the late night/morning hours from below the flux average of 1948–98 before the late 1970s to above the average after the late 1970s. This increase of the late night/morning hour moisture flux provided abundant moisture to the central United States and created a potential to increase rainfall in those hours. Concurrently with the increase of southerly moisture flux, Fig. 5b shows an increase of moisture convergence in the vertical column in the central United States. This increasing convergence in association with the decreasing thermodynamic stability in the atmosphere after the late 1970s (see Fig. 9 in HF01a) effectively converted the increasing moisture to more rainfall in the late night/morning hours. On the other hand, from 1948 to the late 1970s, the meridional moisture flux was weak and the rainfall decreased in the late night/morning hours. These variations in meridional moisture flux and moisture convergence could explain the enhancement of late night/morning hour rainfall in the recent decades and the difference of the diurnal rainfall pattern before and after the late 1970s.

Because the variations in the meridional moisture flux and moisture convergence were aspects of the multidecadal variations of the sources affecting the interannual summer rainfall variations in the central United States (HF01a,b), their coherent change with the region's diurnal rainfall pattern supported our hypothesis that different diurnal rainfall patterns existed in different epochs of the multidecadal variation, and the notion that the diurnal rainfall pattern in the central United States varied as a part of the multidecadal variation. Because these coherent changes were identified from two nearly independent datasets, the variation in the diurnal rainfall also served as an additional support of the previously identified multidecadal alternation in the two sources affecting the summer rainfall in the central United States.

## 4. Concluding remarks

Recent studies have revealed multidecadal alternations of two sources influencing the interannual summer rainfall variation in the central United States. One is the ENSO cycle, which influenced the summer rainfall through teleconnection, and the other is the interannual variability of the intensity of the southerly flow from the Gulf of Mexico. Because the two sources affected rainfall development in very different ways, they could yield unique diurnal rainfall patterns when they dominated the rainfall variation, so their alternation could result in an associated multidecadal variation of the diurnal rainfall pattern in the central United States.

Using an hourly rainfall dataset independent of the monthly rainfall data used in the previous studies, we examined this hypothesis. Our results showed a significant change of the summer diurnal rainfall pattern in the central United States in the late 1970s when an ENSO-dominant epoch (1948–76) gave way to the recent epoch (1977–2000) with strengthening southerly flow effect on the rainfall variation. In the recent epoch, the diurnal rainfall pattern showed a substantial increase of late night/morning hour rainfall with a single large rainfall peak around the midnight hour. This diurnal pattern was quite different from that in the epoch 1948–76, which showed rather weak rainfall in the late night/morning hours. The diurnal pattern also lacked a clear single rainfall peak as in the recent epoch but had a plateau of hourly rainfall in the late night hours before midnight. Associated with this rainfall pattern change were changes in the late night/morning hour southerly moisture flux and moisture convergence in the central United States. The moisture flux increased in the recent epoch after 1976. The simultaneous increase of moisture convergence in the central United States could explain the late night/morning hour rainfall increase, its contribution to the total daily rainfall, and the diurnal rainfall pattern change.

The coherent changes of the diurnal rainfall pattern and the meridional moisture flux and moisture convergence after 1976 described a consistent circulation and rainfall change in the region. In the recent decades after the late 1970s, the strengthening southerly flow from the Gulf of Mexico dominated the rainfall variations in the central United States and produced a large late night/morning hour rainfall with a single large peak at the midnight hour. In the previous epoch from 1948 to the late 1970s, when the southerly flow effect weakened, teleconnection processes associated with ENSO affected the region's rainfall and resulted in weak late night/morning hour rainfall and a different diurnal rainfall pattern. In association with the multidecadal alternation of these two sources, the diurnal rainfall pattern in the central United States varied with a similar multidecadal scale. Of course, additional data will need to be developed and analysis must be continued to further confirm this multidecadal variation in the diurnal rainfall pattern in the central United States.

The multidecadal variation of the diurnal rainfall pattern has implications in understanding variations of the region's hydrological processes and climate. For example, this study showed that wet summers in the central United States were often observed when the summer diurnal rainfall pattern showed large late night/morning hour rainfall, a result not only explaining the increasing number of wet summers in recent decades when the strengthening southerly flow effect favored late night/morning hour rainfall, but also indicating that a phase lock of circulation anomalies with late night/morning hour rainfall development could raise heavy rainfall and flood potential in the region. By disclosing the variation of the diurnal rainfall pattern, this study provides additional knowledge for understanding the climate of extreme events, particularly heavy rainfall and floods, in the central United States.

*Acknowledgments.* The author thanks Dr. S. Feng for performing calculations in this work and for useful discussions, Dr. A. Dai at NCAR for communications on data issues, and Dr. K. Hubbard of UNL for useful comments. Thanks also go to the editor, Dr. Francis Zwiers, and two anonymous reviewers whose comments and suggestions led to improvements of this manuscript. This work was partially supported by NOAA GCIP Grant NA06GP0226 to the University of Nebraska at Lincoln, and by USDA Cooperative Research Project NEB-40-008.

## REFERENCES

Bonner, W. D., and J. Paegle, 1970: Diurnal variations in boundary layer winds over the south central United States in summer. *Mon. Wea. Rev.,* **98,** 735–744.

Dai, A., I. Y. Fung, and A. D. Del Genio, 1997: Surface observed global precipitation variations during 1900–88. *J. Climate,* **10,** 2943–2962.

Helfand, H. M., and S. D. Schubert, 1995: Climatology of the simulated Great Plains low-level jet and its contribution to the continental moisture budget of the United States. *J. Climate,* **8,** 784–806.

Higgins, R. W., J. E. Janowiak, and Y. Yao, 1996: *A Gridded Hourly Precipitation Database for the United States (1963–1993).* NCEP/CPC Atlas No. 1, 47 pp. [Available form NCEP/CPC, W/NP52, Washington, DC 20233.]

Holton, J. R., 1967: The diurnal boundary layer wind oscillation above sloping terrain. *Tellus,* **19,** 199–205.

Hu, Q., and S. Feng, 2001a: Climatic role of the southerly flow from the Gulf of Mexico in interannual variation in summer rainfall in the central United States. *J. Climate,* **14,** 3156–3170.

——, and ——, 2001b: Variations of teleconnection of ENSO and interannual variation in summer rainfall in the central United States. *J. Climate,* **14,** 2469–2480.

——, C. M. Woodruff, and S. E. Mudrick, 1998: Interdecadal variation of annual precipitation in the central United States. *Bull. Amer. Meteor. Soc.,* **79,** 221–229.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Karl, T. R., R. K. Knight, D. R. Easterling, and R. G. Quayle, 1996: Indices of climate change for the United States. *Bull. Amer. Meteor. Soc.,* **77,** 279–292.

Mo, K., J. Nogués-Paegle, and R. W. Higgins, 1997: Atmospheric processes associated with summer floods and droughts in the central United States. *J. Climate,* **10,** 3028–3046.

Trenberth, K. E., 1991: Climate diagnostics from global analyses: Conservation of mass in ECMWF analyses. *J. Climate,* **4,** 707–722.