GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 3, PAGES 341-344, FEBRUARY 1, 1999

Recent Changes in the Diurnal Cycle of Precipitation Over the United States

Aiguo Dai

National Center for Atmospheric Research, Boulder, Colorado

Abstract. Hourly precipitation data from 1963 to 1993 of the contiguous United States were analyzed for secular trends in the diurnal cycle of precipitation. During the period the winter daytime and nighttime precipitation frequencies and the diurnal amplitude of precipitation frequency increased by ~30−47% over the Southwest, while the winter precipitation frequencies and the diurnal amplitude of precipitation intensity decreased by similar amounts over the Northwest. During this period, summer afternoon precipitation frequency increased by ~30−60% in the Southwest and decreased by ~15−30% in the Southeast.

Introduction

Precipitation has increased by ~10% across the contiguous United States since 1910 and the increase is reflected primarily in the heavy and extreme daily precipitation events [*Karl and Knight*, 1998]. There is also evidence suggesting that from 1963 to 1993 the frequency of precipitation events increased in the southern U. S. in winter and decreased in the Pacific Northwest from November to January [*Trenberth*, 1998]. Precipitation has a large diurnal cycle over many parts of the U. S., especially during the warm seasons [*Wallace*, 1975; *Higgins et al.*, 1996; *Dai et al.*, 1998a]. For example, in summer on average it is more than twice likely to have precipitation from about 3PM to 6PM in the afternoon than any other times over the Rocky Mountains and the Southeast [*Dai et al.*, 1998a]. The diurnal cycle of precipitation has significant effects on the surface hydrology and the surface air temperature range [*Dai et al.*, 1998b], and is closely related to the diurnal cycles of atmospheric moist convection and cloudiness. For example, an increase of the summer afternoon maximum of precipitation could strongly suggest enhanced moist convection. Changes in the daytime and nighttime frequencies of precipitation events could imply changes in daytime and nighttime cloudiness, which has very different effects on surface radiation. Therefore, it is of interest to analyze hourly precipitation for any secular changes in the diurnal cycle of precipitation over the U.S.

Here we have analyzed hourly precipitation data from 1963 to 1993 for the contiguous U. S. We attempt to address the following questions: 1). are there any changes in the amplitude and phase of the diurnal cycle of precipitation during this period? 2). are there any trends in the daytime and nighttime frequency, intensity and amount of precipitation? and 3). are there any changes in summer afternoon precipitation (frequency, intensity and amount)?

Paper number 1998GL900318.
0094-8276/99/1998GL900318$05.00

Data

The hourly precipitation data used here are from [*Higgins et al.*, 1996] in the form of a gridded (2.5^o long. by 2.0^o lat.) dataset derived from quality-controlled station records from about 2,500 U.S. stations. It covers the period from 1 January 1963 to 31 December 1993. More details can be found in [*Higgins et al.*, 1996]. The dataset has been applied in a number of climate studies (e.g. *Trenberth,* 1998; *Dai et al.,* 1998a). In the U. S., Fischer and Porter recording rain gauges were introduced in the early 1960s to gradually replace unshielded universal recording gauges, which had a smaller undercatch bias and higher reporting accuracy than the Fischer and Porter gauges. This gauge change could potentially induce spurious changes in the precipitation records (mostly for winter season). However, an assessment by Dai et al.(1997) suggest that the inhomogeneity errors in the station records of precipitation are likely to be small during the recent decades at most of the U.S. stations. Furthermore, systematic biases resulting from undercatch and other factors should have a much smaller effect on the amplitude of the diurnal cycle of precipitation than on the mean precipitation amount.

At each grid box and for each hour, we computed the seasonal averages of precipitation frequency (the percentage of hours having precipitation during the season), intensity (the rate when precipitation occurs), and amount (the product of the frequency, intensity and the number of days for the season) for each year. Trace precipitation with a (gridded) rate less than 0.1 mm/hr is excluded in the calculation. We then computed the amplitude (defined here as the difference between the daily maximum and mean) and phase T_{max} (the local solar time or LST when the maximum occurs) from the seasonally averaged hourly data for each year. The linear trends and their statistical significance (based on a two−tailed t test) of the amplitude and phase were calculated for the 1963−1993 period using linear regression [*Woodward and Gray*, 1993]. More discussions on the methods of analyzing the diurnal cycle of precipitation can be found in [*Dai et al.*, 1998a].

The daytime (6AM−6PM) and nighttime (6PM−6AM LST) averages of the seasonally averaged hourly precipitation frequency, intensity and amount were also computed for each year. For the summer (June−August) season, afternoon to evening (2PM−8PM LST, referred to as afternoon thereafter) averages of the three quantities were also computed for each year. The linear trends of the daytime, nighttime, and afternoon averages were then computed in the same way as for the amplitude and phase.

Results

Fig. 1 shows that from 1963 to 1993 there were some increases (4~16% of the 1963-93 mean amplitude per decade)

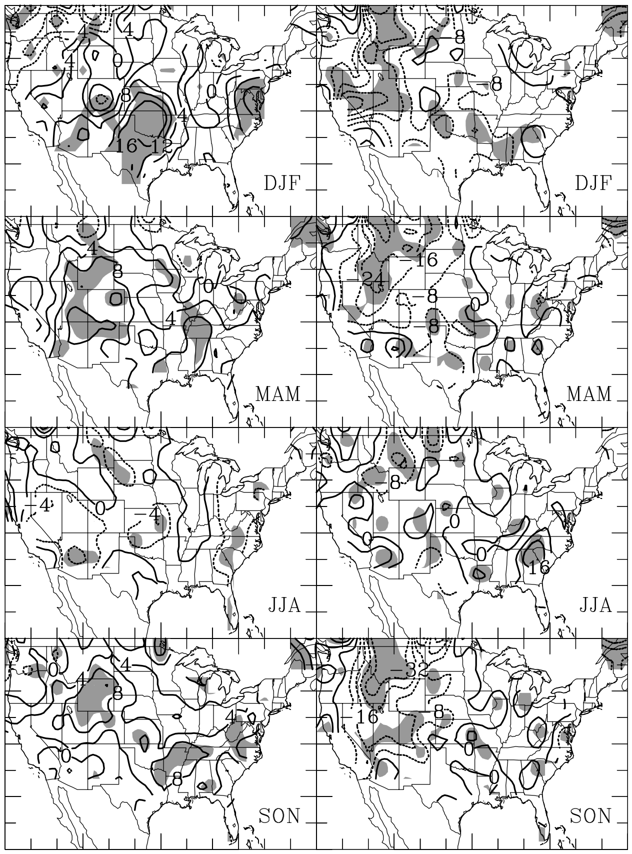

Figure 1. Seasonal (1963-93) trends of the amplitude expressed as percent of the mean amplitude per decade for the frequency (*left column*) and intensity (*right column*) of precipitation events. Dashed contours have negative values. Shading indicates statistical significance at the 10% level based on a two-tailed t test (same in figures 2 and 3).

in the diurnal amplitude of precipitation frequency over most of the U.S. (especially over Texas, Oklahoma and Kansas in winter) during all but summer seasons, although the trends are generally not very significant statistically, partly due to the relatively short sample length (31 years). One exception to the increasing trends is the northwestern U.S. during winter (thus a large part is snow) where the amplitude of precipitation frequency decreased slightly (−4∼−8%/decade). On the other hand, the diurnal amplitude of precipitation intensity decreased (−8∼−32% /decade) over most of the Rockies and the region east of the Rockies during all but summer seasons. The trends in summer are small over most of the U.S. for both the frequency and intensity amplitudes. The amplitude of precipitation amount (not shown) decreased over the northern Rockies (−8∼−32%/decade) during all but summer seasons, and changed little (0∼8%/decade) elsewhere. The trends of T_{max} of the precipitation frequency, intensity and amount are small (−0.8∼0.8 hr/decade) and statistically insignificant.

Fig. 2 shows that in winter both the daytime and nighttime precipitation frequencies decreased by about 10 to 20%/decade over the Pacific Northwest and increased by a similar amount over the southwestern U.S. In spring, there are some increases (5−10%/decade) in both the daytime and nighttime precipitation frequencies over western U.S. The changes in the daytime frequency are generally small (−5∼5%/decade) in summer and autumn, while there are some increases in the nighttime frequency over the central U.S. in summer and autumn. The daytime and nighttime precipitation amounts (not shown) exhibited changes similar to Fig. 2, while the plots for the intensity (not shown) are noiser than Fig. 2.

During summer, afternoon precipitation frequency (Fig. 3) increased by about 5−20%/decade over most of the U.S. (especially in the Southwest, South Dakoda, Minnesota and Wisconsin) except for the Southeast and a region centered in northern Nevada where the afternoon frequency decreased (about −5∼−15%/decade). There were some increases (10∼20%/decade) over the Southwest and slight decreases (−5∼−10%/decade) over the the northern Rockies in the afternoon precipitation intensity, while the intensity changes are small east of about 100°W. The summer afternoon precipitation amount increased (about 2∼6 mm/decade) over the central U.S., while it decreased slightly (about −2∼−4 mm/decade) over the Southeast. The decrease in the summer precipitation frequency over the Southeast is also evident in the daytime and nighttime averages (cf. Fig. 2), while the decrease in the precipitation amount over the Southeast is mostly seen in the nighttime average.

The above linear trends at many individual grid boxes are statistically insignificant. However, if averaged over a larger

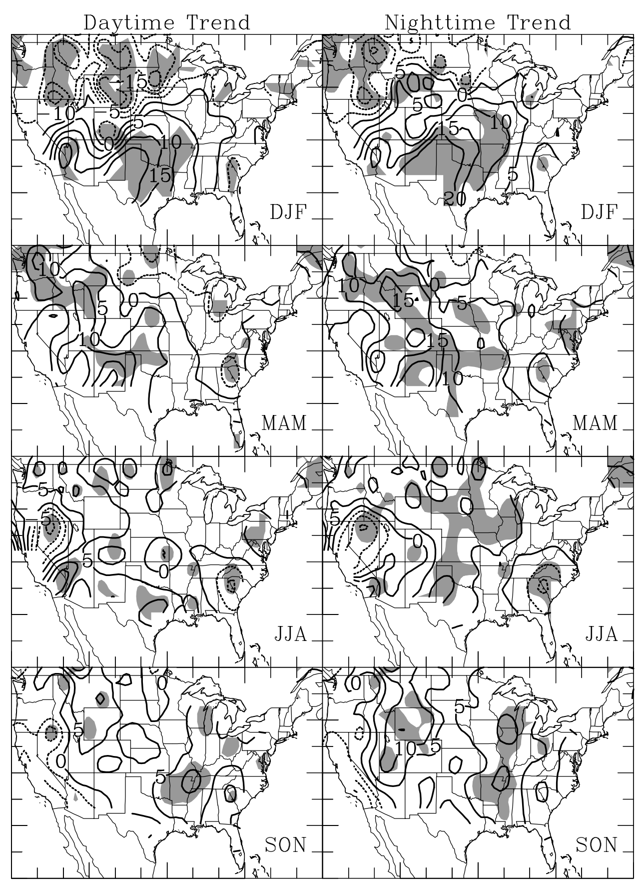

Figure 2. Seasonal trends expressed as percent of the mean frequency per decade of the daytime (6AM−6PM, *left column*) and nighttime (6PM−6AM, *right column*) precipitation frequencies.

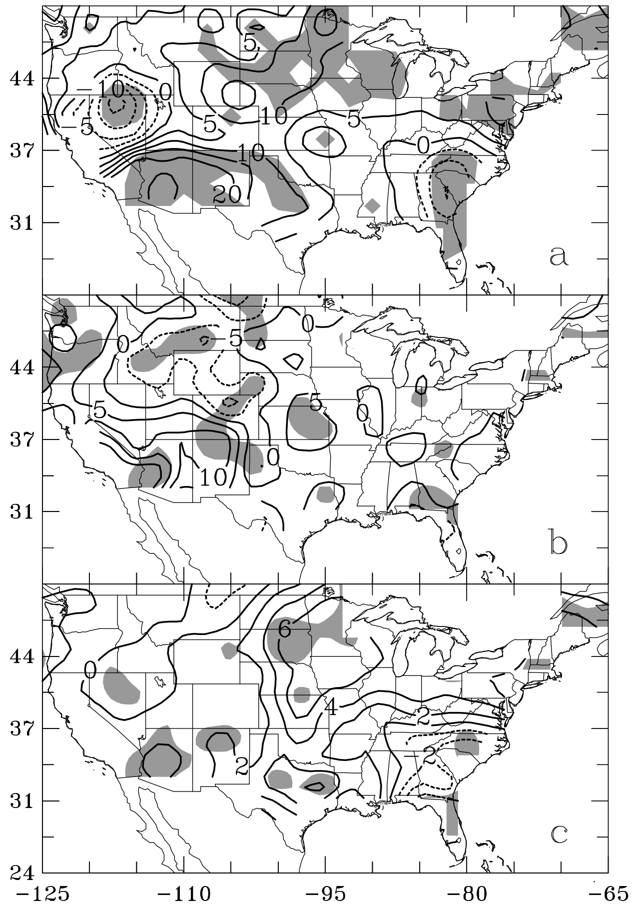

Figure 3. Trends of JJA afternoon (2PM−8PM) precipitation frequency (*a*, % of the mean frequency per decade), intensity (*b*, % of the mean intensity per decade), and amount (*c*, mm/decade).

area having similar changes, the statistical significance of the trends increases substantially as the interannual variations being reduced. For example, when the DJF trends of the daytime and nighttime frequencies (cf. Fig. 2) and the DJF trends of the amplitudes (cf. Fig. 1) are averaged over the Northwest and Southwest (Fig. 4), they become highly significant, both practically (10∼15%/decade, negative for the Northwest curves and positive for the Southwest) and statistically (attained significance level p=0.14−4.93%). Fig. 4 also shows that the decreases in the precipitation frequencies and the amplitude of precipitation intensity over the Northwest occurred after the late 1970s. Even after averaging over the two regions, there are still large multi-year variations in the frequencies and the amplitudes that are often associated with the El Niño−Southern Oscillation (ENSO) events (the correlation coefficients between the Southern Oscillation Index (SOI) and the curves of Fig. 4 are about −0.50 for the Southwest but insignificant for the Northwest). Despite these large variations, the secular trends are evident.

Discussion

It should be emphasized that while the measurement errors in the rain-gauge records should have a much smaller effect on the estimated diurnal cycle of precipitation than on the mean precipitation amount, it is still possible that some of the changes reported here may have resulted from the errors. Nevertheless, the above results suggest that from 1963 to 1993 the daytime and nighttime precipitation frequencies and the diurnal amplitude of precipitation frequency increased by ∼30−47% (of the 1963−93 mean values) over the Southwest in winter, while the precipitation frequencies and the diurnal amplitude of the precipitation intensity decreased by similar amounts over the Northwest in winter (Fig. 4). During the same period, summer afternoon precipitation frequency increased by ∼30−60% in the Southwest and 15−30% over South Dakota, Minnesota and Wisconsin, and decreased by ∼15−30% over the Southeast. Changes are generally smaller in other seasons, especially in summer.

Since precipitation occurs with clouds, the changes in the frequency of precipitation events have direct implications for cloudiness trends. Station records of cloud cover suggest that there has been a tendency toward increased cloudiness over the contiguous U.S. since the middle of the 20th century [*Karl and Steurer*, 1990]. However, the station cloud data have inhomogeneity problems due to changes in observational practices [*Karl and Steurer*, 1990] and the cloud

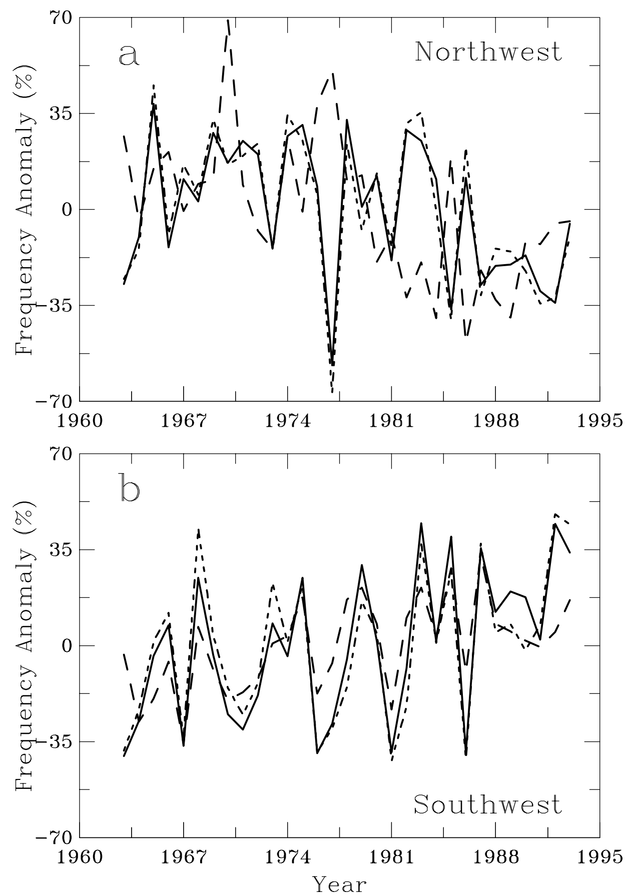

Figure 4. Anomalies (expressed as percent of the mean) of DJF daytime (*short-broken line*) and nighttime (*solid line*) precipitation frequencies averaged over the Northwest (106°−124°W, 41°−49°N, *upper panel*) and the Southwest (91°−109°W, 31°−41°N, *lower panel*). Also shown (*long-broken line*) are the anomalies (as percent of the mean amplitude) of the diurnal amplitude of precipitation intensity (*upper panel*) and frequency (*lower panel*) averaged over the regions.

trends have been interpreted cautiously. Our results provide another piece of independent evidence suggesting that there have been increases over the Southwest and decreases over the Northwest in both the daytime and nighttime cloudiness during winter since the early 1960s. Unfortunately, we do not have the regional changes of cloudiness from station cloud data to compare with the precipitation frequency trends. The changes in the summer afternoon precipitation frequency also suggest that summer afternoon convection seems to have increased over the Southwest and the northern central U.S. and decreased slightly in the Southeast.

ENSO events have large impacts on the diurnal cycle of precipitation over the U.S., especially over the Southwest, which is expected from the large influences of ENSO on U.S. precipitation (e.g., *Ropelewski and Halpert, 1989; Dai et al., 1997*). Our results (Fig. 4) seem to be consistent with *Cayan et al.*(1998) who find that high precipitation and streamflow events are more (less) frequent than average over the Southwest (Northwest) during El Niño years. However, it is unclear whether the secular changes of Fig 4 are due to the decadal, low-frequency variations in ENSO (Dai et al., 1998c), or related to the observed warming during the period [*Karl et al.*, 1995].

Acknowledgments. I thank Higgins et al. for making the hourly precipitation data available and an anonymous reviewer for sharing his/her knowledge of the rain gauges at U.S. stations. The author is supported by a NOAA Postdoctoral Program in Climate and Global Change fellowship, administered by the University Corporation for Atmospheric Research. NCAR is sponsored by the National Science Foundation.

References

Cayan, D. R., K. T. Redmond, and L. Riddle, Accentuation of ENSO effects on extreme hydrologic events over the western United States. Submitted to *J. Clim.*, 1998.

Dai, A., I. Y. Fung, and A. D. Del Genio, Surface observed global land precipitation variations during 1900-1988. *J. Clim.* **10**, 2943-2962, 1997.

Dai, A., F. Giorgi, and K. E. Trenberth, Observed and model simulated precipitation diurnal cycle over the contiguous United States. *J. Geophys. Res.*, in press, 1998a.

Dai, A., K. E. Trenberth, and T. R. Karl, Effects of clouds, soil moisture, precipitation and water vapor on diurnal temperature range, *J. Climate*, in press, 1998b.

Dai, A., K. E. Trenberth, and T. R. Karl, Global variations in droughts and wet spells: 1900-1995. *Geophys. Res. Lett.* **25**, 3367-3370, 1998c.

Higgins, R. W., J. E. Janowiak, and Y.-P. Yao, A gridded hourly precipitation data base for the United States (1963-1993), *NCEP/Climate Prediction Center Atlas No. 1*, U.S. Dept. of Commerce, Washington, D.C., 47pp., 1996.

Karl, T. R. and P. M. Steurer, Increased cloudiness in the United States during the first half of the twentieth century: fact or fiction? *Geophys. Res. Lett.* **17**, 1925-1928, 1990.

Karl T. R. and R. W. Knight, Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Am. Met. Soc.* **79**, 231-241, 1998.

Karl, T. R., et al., Indices of climate change for the United States. *Bull. Am. Met. Soc.* **77**, 279-292, 1995.

Ropelewski, C. F. and M.S. Halpert, Precipitation patterns associated with the high index phase of the Southern Oscillation, *J. Clim.* **2**, 268-284, 1989.

Trenberth, K. E., Atmospheric moisture residence times and cycling: implications for rainfall rates and climate change. *Climatic Change*, **39**, 667-694, 1998.

Wallace, J.M., 1975, Diurnal variations in precipitation and thunderstorm frequency over the conterminous United States, *Mon. Wea. Rev.* **103**, 406-419, 1975.

Woodward, W. A. and H. L. Gray, Global warming and the problem of testing for trend in time series data. *J. Clim.* **6** 953-962, 1993.

A. Dai National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307. (e-mail: adai@ucar.edu;)

(Received September 23, 1998; revised October 27, 1998; accepted December 10, 1998.)