GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 9, PAGES 1081-1084, MAY 1, 1995

Seasonality of precipitation along a meridian in the western United States

Balaji Rajagopalan, Upmanu Lall

Utah Water Research, Utah State University Lab.

Abstract. We investigate seasonality of daily precipitation along a meridian in the Western U.S. using a nonparametric technique. The occurrence of daily precipitation is treated as a nonhomogeneous Poisson process and the time varying intensity function is estimated for every calendar day using a kernel estimator. The technique is fully data adaptive. We apply this technique to selected long record stations along a meridional transect spanning from Tucson, AZ to Priest River ID. Differences in the seasonality of precipitation occurrence and magnitude are revealed as a function of latitude and topographic factors. A monotonic trend in the seasonality of precipitation over the length of record is also observed.

Introduction

Seasonality in hydroclimatic variables is usually related to the unequal heating of the earth's surface over the year, particularly as one moves to higher latitudes. Precipitation is an important hydrologic variable since it is a primary input into surface hydrologic models. The timing and duration of the seasons of high precipitation at a site is important since they indicate the form (rain or snow) of precipitation as well as the nature of the input signal for the surface hydrologic system.

Here we were interested in how the seasonality of rainfall varies by latitude along a transect in the western U.S. (approx. longitude 112°W). Long record precipitation stations which had essentially complete records were selected from latitude 48°17' N to latitude 32°15' N . We were interested in daily precipitation because of its use for agriculture, crop management and forest management. The attributes of interest considered are precipitation magnitude and relative frequency of occurrence.

Stochastic precipitation models as well as other hydrologic models often deal with the nonstationarity in precipitation and other climatic inputs by dividing the year into a number of seasons and then fitting model parameters independently for each season. The leading terms (one or two) of a Fourier series representation of the precipitation data are commonly used to identify seasonality, for time varying parameter description and for delineating seasons.

Paper number 95GL01100
0094-8534/95/95GL-01100$03.00

An attractive alternative to Fourier series methods is provided in this paper. We focus first on the rate of occurrence of precipitation as a function of Julian calendar day (1 to 365 or 366) within the year. A kernel estimator is used to estimate the rate of rainfall occurrence of precipitation by calendar day, by smoothing a binary (1 or 0) indicator sequence that represents precipitation occurrence on a given day in the historical record. This rate is interpretable as the time varying rate parameter of a nonhomogeneous Poisson process. Variation in precipitation magnitude over a 90 day moving window is also investigated.

An interesting trend in seasonality is exhibited by the stations we analyzed. There appears to be a consistent shift in the seasons identified on the basis of precipitation rate. The calendar dates associated with the highest and the lowest precipitation rates for a given year appear to move forward each year of the record.

Methodology

Precipitation is an intermittent process. For understanding climatic variations it is often useful to consider adaptive representations that allow a smooth, continuous time interpretation of precipitation. The Poisson process has been used to describe rainfall occurrence as a point process [*Waymire and Gupta* , 1981; *Cox and Isham,* 1980]. For a stationary point process, the number of events (e.g., the events are occurrence of wet days) n(T) occurring in a duration T is a random variable with a Poisson distribution with mean λ T:

$$p(n(T)=k)=\frac{(\lambda T)^k}{k!}e^{-(\lambda T)}k=0,1,2.... \quad (1)$$

where λ is called the rate or intensity parameter. The changing intensity over the year can be described by a nonhomogeneous Poisson process (same as Equation (1) with a time varying rate parameter , i.e. $\lambda(\tau)$, $\tau =$ 1,..,365 or 366). This time varying rate parameter is a useful indicator of precipitation seasonality at a site.

Kernel intensity estimators [see *Diggle,* 1985; *Solow,* 1991] can be used to estimate $\lambda(\tau)$ from the record, through an optimal, weighted moving average of the rate of rainfall occurrence over time. To form such an estimate, we need to define an appropriate weight function, a span over which to average and a criterion for

Table 1. Data Sets Analyzed

Station	Lat.	Long.	Elev.	Record
Priest River, ID (PRR)	48°21' N	116°50' W	2380	1911-1992
Sandpoint, ID [SNP]	48°17' N	116°34' W	2100	1910-1992
Laketown, UT [LAK]	41°49' N	111°19' W	5980	1948-1992
Logan, UT [LOG]	41°45' N	111°48' W	4790	1928-1992
Woodruff, UT [WOD]	41°32' N	111°09' W	6320	1948-1992
Silverlake, UT [SIL]	40°36' N	111°35' W	8740	1948-1992
Snake Creek, UT [SNC]	40°33' N	111°30' W	6010	1928-1992
Heber, UT [HEB]	40°30' N	111°25' W	5630	1928-1992
Spanish Fork, UT [SPF]	40°05' N	111°36' W	4720	1932-1992
Alton, UT [ALT]	37°26' N	112°29' W	7040	1929-1992
Miami, AZ [MIA]	33°24' N	110°53' W	3560	1914-1992
Tucson, AZ [TUS]	32°15' N	110°57' W	2440	1901-1992

Data from EarthInfo CD ROM; Elevation in ft. above MSL

choosing the weight function and span in an optimal way. For brevity, our presentation here is restricted to a description of the estimation process used.

Daily precipitation data from twelve sites (Table 1) in Arizona, Utah and Idaho were used.

Estimation procedure

We considered the estimation of $\lambda(\tau)$, for each calendar day τ(1,2,..,365 or 366), for each year of record y. The average across years of the estimates of $\lambda(\tau)$ provides a measure of the typical seasonality at the site.

The kernel estimator used for $\lambda_y(\tau)$, the rate on calendar day τ, in year y is,

$$\hat{\lambda}_y(\tau) = \frac{1}{h_y}\sum_{i=1}^{n_y} K\left(\frac{\tau - \tau_{i,y}}{h_y}\right) \qquad (2)$$

In Equation (2), τ is the calendar day on which the estimate is desired, $\tau_{i,y}$ is the index of a calendar day on which there was rain in year y; K(.) is a kernel function which is taken to be a positive function that integrates to unity, is symmetric and has finite variance; h_y is a bandwidth or "scale" parameter (for year y) of the kernel function, that controls the smoothness of $\hat{\lambda}_y(\tau)$ and n_y is the number of rainy days in year y.

The estimator in Equation (2) is very similar to a kernel density estimator [see *Silverman,* 1986; *Scott,* 1992]. The choice of a kernel function is considered secondary [*Silverman,* 1986; *Scott,* 1992] to the choice of the bandwidth in terms of the Mean Square Error (MSE) of the resulting estimate $\hat{\lambda}_y(\tau)$. [*Diggle and Marron,* 1988] show the equivalence between density and intensity estimation and that the same bandwidth is optimal in both cases under a MSE criterion. We used the plug in estimator due to [*Sheather and Jones,* 1991] to pick the bandwidth h_y. Thsi procedure minimizes the Average Integrated MSE of a kernel density estimate.

We used the Epanechnikov kernel, given as:

$$K(x) = 0.75(1 - x^2) \qquad |x| \leq 1 \qquad (3)$$

where $x = \frac{\tau - \tau_{i,y}}{h_y}$

Periodic boundaries are used for the estimation by (a) recognizing that dates from the end of one year can be within a bandwidth hy of dates in the beginning of the next year, and (b) using data from year (y-1) or (y+1) for estimates on days within such a bandwidth in year y. The bandwidths h_y selected ranged from 30 to 120 days.

Weighted average precipitation for each calendar day of each year in the historical record is also estimated using the Epanechnikov kernel with a bandwidth of 90 days.

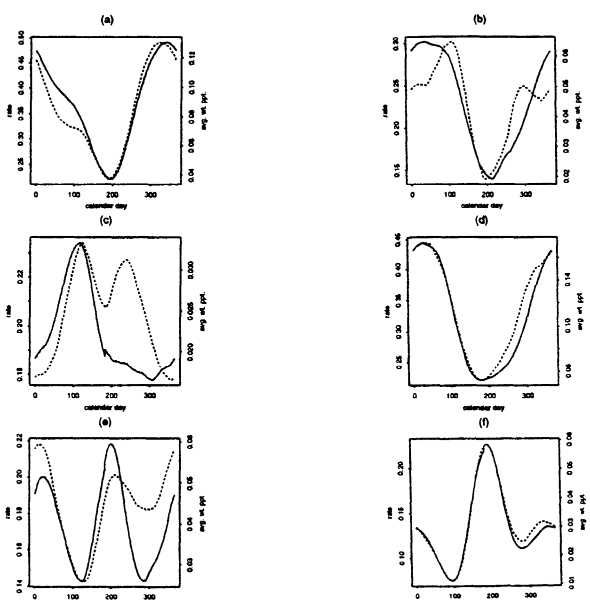

Figure 1. Average daily rate (solid line) and average weighted precipitation (dotted line) for each calendar day, at (a) Priest River, ID, (b) Logan, UT, (c) Woodruff, UT, (d)Silverlake, UT, (e) Alton, UT, and (f) Tucson, AZ.

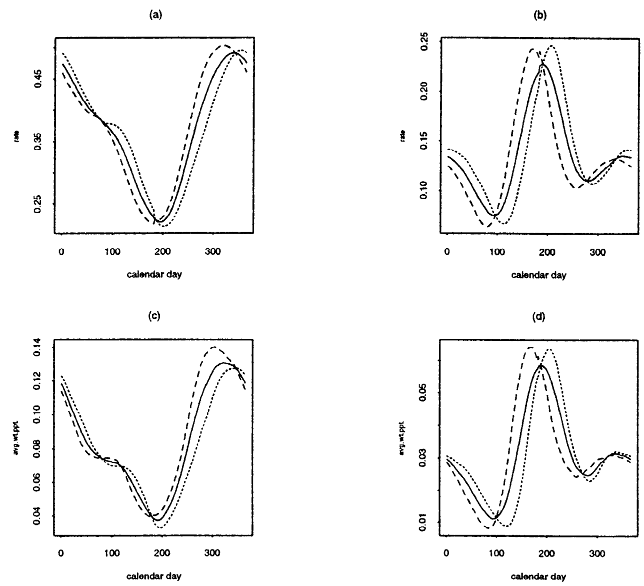

Figure 2. Average daily rate (a) and (b) and average weighted precipitation (c) and (d) from the entire historical record (solid line), from the historical record before 1950 (dotted line) and from the historical record after 1950 (dashed line), at Priest River, ID, and Tucson, AZ, respectively.

Results

The average rate across years and the average weighted precipitation for each calendar day, were estimated as described above for each station. Here, we present illustrative plots of average rate and average weighted precipitation for six stations PRI, LOG, WOD, SIL, ALT, TUS in Figures 1a through 1f, respectively. The following observations were made:

1. The average daily rate and the average weighted precipitation fluctuate similarly at each of the stations (see Figures 1a through 1f). The average daily rate appears to better describe the fundamental mode of the annual precipitation cycle. The high variability in daily precipitation amounts does not lead to a smooth picture of the annual cycle.

2. Stations in the north end of the meridional transect (namely, SNP, PRR, LAK, LOG, SIL,SNC, HEB and SPF) have similar shapes for the rate and precipitation curves, Figures 1a,b and d show these curves for stations PRR, LOG and SIL. Peak rates at these stations occur during October-March. A similar trend is seen in the precipitation amount. Station WOD is interesting (see Figure 1c). It's peak rate is during March-May. However, it has two periods (March-May and July-September) with higher than average precipitation. This station lies in a rain shadow region with respect to the large scale atmospheric flow, and experiences convective summer/fall precipitation on a few days, as well as weak general precipitation in the spring.

3. Stations near the southern end of the meridional transect (namely, ALT, MIA and TUS) have similar rate and weighted precipitation patterns. Figures 1e and f illustrate the curves for stations ALT and TUS respectively. Peak rates at these stations occur during April-August, and November-December. The "wet" seasons in the north appear to correspond to "dry" seasons in the South and vice versa. This observation corresponds to the largely zonal flow driven winter/spring precipitation in the north, as opposed to the largely convective summer precipitation in the South [*Ropelewski and Halpert,* 1986; 1987].

Seasonality trends over this century

[*Thomson,* 1995] found significant changes in the timing of seasons since around 1940 in the Northern hemisphere by analyzing the 1651-1991 Central England temperature record, and other long temperature series. The peak temperature occurs later in the year as one moves to higher latitudes in the Northern hemisphere reflecting the delay in transport of heat. Thomson's thesis is that in an atmosphere enriched by Carbon Dioxide, the radiative component of the heat balance in the Northern hemisphere relative to transport from other regions is more efficient, and the trend may be a sign of global warming. He is able to relate the trend in CO_2 to a trend in the phase of the annual cycle more conclusively than in the amplitude of the annual cycle. However, considerable variety is found in the extent of the change in phase depending on location.

Consequently, it was of interest to examine changes in the seasonality of precipitation, as reflected by the estimated rate and weighted amount. We estimate the average rate for the periods before and after 1950 (a time approximately in the middle of the data sets) at two stations with long records (PRR and TUS), and show them in Figures 2a, and 2b respectively. It can be

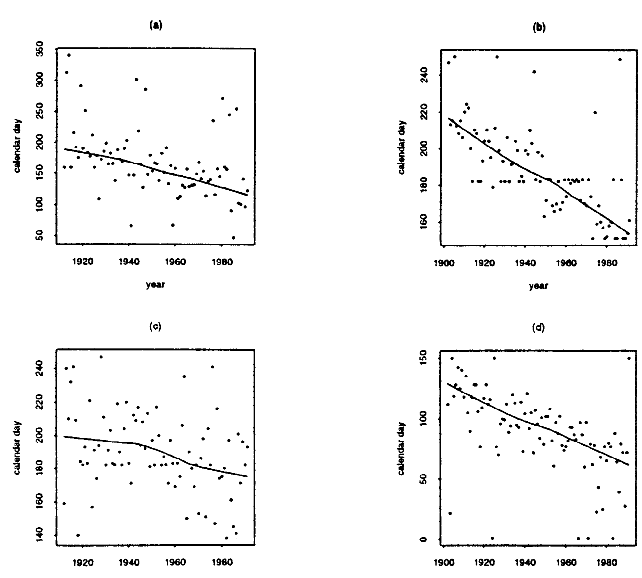

Figure 3. Calendar date of maximum (a) and (b) and minimum (c) and (d) estimated average daily rate in each year (dots), along with a LOWESS smooth of the date (thick line), at Priest River, ID and Tucson, AZ, respectively.

seen that the average rate after 1950 is shifted to the left (i.e., the peaks and valleys are shifted left) relative to the average rate before 1950. Similar observations can be made from the analysis of the average weighted precipitation amounts, shown in Figures 2c and 2d.

We also analyzed the records to see how this shift was occurring over time, i.e., is it a sudden or continuous trend. The calendar day in each year on which the estimated rate was maximum and the date on which it was a minimum were selected. These dates are plotted for two stations PRR and TUS (the northern and the southern extremes of our data set), in Figures 3a and 3b for the maximum rate and Figures 3c and 3d for the minimum rates. The line in these figures is a nonparametric smooth fitted by LOWESS [*Cleveland,* 1979]. One can see that the date for both the maximum and minimum rates has a decreasing trend with year. The nonparametric Mann-Kendall test [*Gilbert,* 1987] for monotonic trend showed that these trends were significant (p-values in all cases were of the order of 10^{-10}). Robust estimates of the linear trend, the Sen slopes [see *Gilbert,* 1987] range from -0.33 to -1 days per year. Similar results are obtained for average weighted precipitation. It is curious that these trends are roughly constant over the whole record. This differs from the observations of [*Thomson,* 1995], where a somewhat abrupt increase in the phase slope of temperature data is observed around 1940.

Closure

The nonparametric methods focusing on the estimation of the rate of precipitation occurrence presented here were shown to be useful for identifying seasonal variations in precipitation occurrence as a function of latitude and also for variations in seasonality across years. For the data sets we analyzed, remarkable differences were seen in the timing and duration of the precipitation seasons along the meridional transect selected west of the Rockies. An interesting trend in the seasonality across the sites was also identified. If this trend is related to global warming it has important implications for the form of precipitation in these areas, and also for crop water requirements in the growing season. Further investigation of such trends and their relationship to atmospheric circulation is warranted.

Acknowledgments. Partial support of this work by the U.S. Forest Service under contract notes, INT-915550-RJVA and INT-92660-RJVA, Amend. 1 is acknowledged. The principal investigator of the project is D.S. Bowles.

References

Cleveland, W.S, Robust locally weighted regression and smoothing scatter plots, *J. Amer. Statist. Assoc., 74,* 829-836, 1979.

Cox, D.R. and V. Isham, *Point Processes*, Chapman and Hall, London, 1980.

Diggle, P.J, A kernel method for smoothing point-process data, *Applied Statistics, 34,* 138-147, 1985.

Diggle, P.J. and J.S. Marron, Equivalence of smoothing parameters selectors in density and intensity estimation, *J. Amer. Statist. Assoc.*, 83, 793-800, 1988.

Gilbert, R.O, *Statistical methods for environmental pollution monitoring*, Van Nostrand Reinhold Company, New York, 1987.

Ropelewski, C.F. and M.S. Halpert, North American precipitation and temperature patterns associated with the El Nio/Southern Oscillation (ENSO), *Mon. Wea. Rev., 114,* 2352-2362, 1986.

Ropelewski, C.F. and M.S. Halpert, Global and regional scale precipitation patterns associated with the El Nio/southern oscillation, *Mon. Wea. Rev., 115,* 1606-1626, 1987.

Scott, D.W., *Multivariate density estimation: Theory, Practice and Visualization*, Wiley series in probability and mathematical statistics, John Wiley and Sons, New York, 1992.

Sheather, S.J. and M.C. Jones, A reliable data-based bandwidth selection method for kernel density estimation, *J. Roy. Stat. Soc., B. 53,* 683-690, 1991.

Silverman, B.W., *Density estimation for statistics and data analysis*, Chapman and Hall, New York, 1986.

Solow, A.R., The nonparametric analysis of point process data: the freezing history of lake Konstanz, *J. Clim., 4,* 116-119, 1991.

Thomson, D. J., The Seasons, Global Temperature, Precession, and CO2, *Science*, in press, 1995.

Waymire, E. and V.K. Gupta, The mathematical structure of rainfall representations, 2, A review of the theory of point processes, *Water Resour. Res., 17(5),* 1273-1286, 1981.

B. Rajagopalan and U. Lall,Utah Water Research Lab., Utah State University, Logan, UT 84322-8200.

(received February 10, 1995; accepted March 7, 1995.)