GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L22815, doi:10.1029/2007GL031889, 2007



# Weekly precipitation cycles? Lack of evidence from United States surface stations

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Received 31 August 2007; revised 5 October 2007; accepted 23 October 2007; published 30 November 2007.

[1] Previous work has inferred a relationship between human activity and the occurrence and amount of precipitation through examining possible weekly cycles in precipitation. Daily precipitation records for 219 surface observing stations in the United States for the 42-year period 1951–1992 are investigated for weekly cycles in precipitation. Results indicate that neither the occurrence nor amount of precipitation significantly depends upon the day of the week. **Citation:** Schultz, D. M., S. Mikkonen, A. Laaksonen, and M. B. Richman (2007), Weekly precipitation cycles? Lack of evidence from United States surface stations, *Geophys. Res. Lett.*, *34*, L22815, doi:10.1029/2007GL031889.

## 1. Introduction

[2] Anthropogenic effects on the earth's weather and climate include urban heat islands, atmospheric pollution, and global climate change [e.g., *Albrecht*, 1989; *Rosenfeld*, 2000; *Rosenfeld et al.*, 2007]. One hypothesized effect is that, by supplying additional cloud condensation and ice nuclei, pollution downwind from urban centers would increase precipitation occurrence, precipitation amount, or both. Research since the late 1980s, however, suggests anthropogenic aerosols may decrease precipitation occurrence and amount because pollution particles cause the same amount of cloud water to be distributed among more droplets, hence the droplets are smaller and less likely to grow to precipitation-sized particles. The hypothesized result is that precipitation is less likely to occur. Previous research [e.g., *Schultz*, 1998; *Jin et al.*, 2005; T. L. Bell et al., Midweek increase in U.S. summer rain and storm heights suggests air pollution invigorates rainstorms, submitted to *Journal of Geophysical Research*, 2007, hereinafter referred to as Bell et al., submitted manuscript, 2007] has focused on whether such a precipitation increase might be detected by looking for a signal related to the seven-day week (Monday, Tuesday, …, Sunday).

[3] In the 1890s to 1920s, the weekend reduction of smoke and hot gases from English factories was believed to be responsible for 13% less rainfall on Sunday than the average of all other days [*Ashworth*, 1929, 1933]. In the 1960s, various authors debated whether Tuesdays, Thursdays, or Saturdays, if any day of the week, were the wettest in London, England [*Walshaw*, 1963; *Hartley-Russell*, 1964; *Dixon*, 1964; *Scorer*, 1964; *Walshaw and Rodgers*, 1964; *Craddock*, 1965; *Nicholson*, 1965, 1969; *Walters*, 1969]. Ultimately, no consensus was reached, in part owing to the different observing stations, time periods, and methodologies employed by these authors, as well as the lack of statistical testing. Later research found that weekday precipitation was significantly higher than weekend precipitation at five French cities [*Dettwiller*, 1968] and at Melbourne, Australia [*Simmonds and Kaval*, 1986], although *Bäumer and Vogel* [2007] found that precipitation amount and occurrence was maximum on Saturday and minimum on Monday at 12 German stations. In contrast, no statistically significant signal was found between weekday and weekend precipitation at Vienna, Austria [*Cehak*, 1982], at five Midwestern US cities [*Horsley and Diebolt*, 1995], and at 92 stations in the United Kingdom [*Wilby and Tomlinson*, 2000].

[4] *Cerveny and Balling* [1998] used satellite-derived precipitation estimates from the Microwave Sounding Unit (MSU) aboard the TIROS-N satellites over a large oceanic area off the east coast of the United States. Their study region was composed of 12 2.5° × 2.5° latitude–longitude grid boxes between 27.5°N and 42.5°N and within 5° longitude of eastern North America for 1 January 1979 to 31 March 1995. They found a seven-day cycle of precipitation amount with Saturday precipitation averaging 22% higher than Monday precipitation. They also found a seven-day cycle in surface carbon monoxide and ozone concentrations in a three and a half year data set from Sable Island in the North Atlantic Ocean. Combining the two gases into a single variable yielded a weekly cycle with a minimum on Monday and a maximum on Thursday. They concluded [*Cerveny and Balling*, 1998, p. 561], "Although our statistical findings limit the identification of cause–effect relationships, we advance the hypothesis that the thermal influence of pollution-derived aerosols on storms my drive these weekly climate cycles." Because of the potential problems in estimating precipitation from MSU data [*Spencer*, 1993], as well as questionable causal links between their data sets, questions arise as to *Cerveny and Balling*'s [1998] results. Specifically, why cycles in ozone and carbon monoxide concentrations on Sable Island, which are not aerosols nor necessarily related to the concentration of anthropogenic aerosols, should relate to satellite-derived precipitation amounts over the coastal Atlantic Ocean and tropical cyclone intensity is not clear. Indeed, *DeLisi et al.* [2001] examined the weekly surface precipitation records from seven coastal cities in the northeastern United States between 1973 and 1992 and found no such weekly cycles.

[5] A more recent study by Bell et al. (submitted manuscript, 2007) found weekly cycles in summertime rainfall area and intensity estimated from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager. Specifi-

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0094-8276/07/2007GL031889$05.00

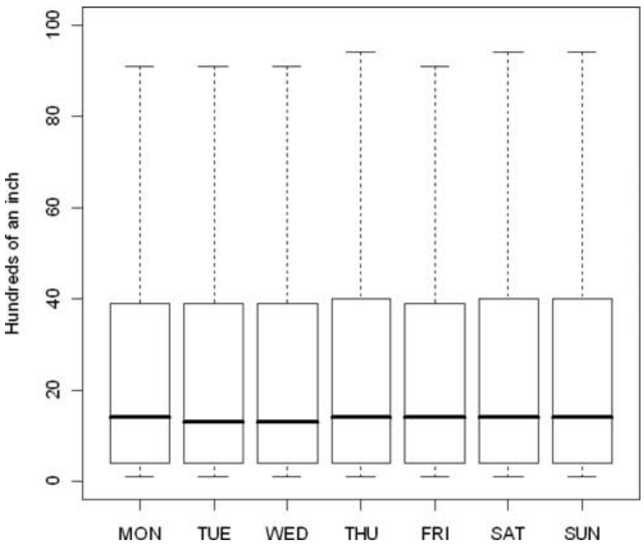


**Figure 1.** Boxplots of the full data for all 219 stations, including the median, interquartile range, and range. Outliers, observations higher than 1.5 times the box length, are omitted.

cally, the southeast United States showed a peak in precipitation rate on Tuesday and a minimum on Sunday. In contrast, the coastal Atlantic Ocean showed the opposite cycle, which Bell et al. (submitted manuscript, 2007) suggested was indicative of compensating subsidence over the oceans from the enhanced precipitation over land. Precipitation gauge data over the southeast United States analyzed by Bell et al. (submitted manuscript, 2007) maximized on Thursday and minimized on Sunday, similar to that from the satellite-based precipitation. The southwest United States did not show any significant weekly cycles, and the analysis was not performed anywhere in the United States north of 40°N.

[6] Although these studies in the past have produced disagreement and controversy, we hope to address this issue by employing a large number of stations over a large region with long time series of continuous precipitation measurements. The purpose of this paper is to explore the effect of day of the week on precipitation occurrence and amount for 222 stations across the entire United States for a 42-year period.

## 2. Data and Methodology

[7] Precipitation observations for a 24-h period from 222 stations across the United States (including Alaska and Hawaii) are derived from the Daily Weather Observations data set (TD-3220), archived by the National Climatic Data Center and the National Center for Atmospheric Research. The day of the week was noted for each precipitation event (trace, 0.01 inch, and greater) for each station during the 42-year period 1951–1992, then the number of events for each of the seven days of the week at each station was determined. The total number of precipitation events over all seven days at each station was also determined. Three stations had a statistically significant underreporting bias on the weekends (as per the $\chi^2$ test) and were eliminated from the data set, leaving 219 stations for testing. All results are tested using suitable statistical methods, described later in the paper.

## 3. Does Precipitation Amount Vary During the Week?

[8] The first test is to examine whether precipitation amount varies as a function of day of the week. Our null hypothesis is that there is no significant difference between precipitation amount as a function of day of the week. The precipitation amounts at each station for each day of the week are ranked, excluding days with nonmeasurable precipitation (zero and trace). The mean, standard deviation, median, and interquartile range of the ranked precipitation amounts for each day of the week at each station are calculated.

[9] Taken as a whole, the full data set does not show a weekly cycle (Figure 1), as determined by the Wilcoxon Rank Sum and Signed Rank tests (R Development Core Team, http://www.R-project.org). For each of the 219 stations, none of the means for each day of the week exceeds one standard deviation of any of the other six days, and none of the medians exceeds the interquartile range of any of the other six days. For example, the station that bears the highest range in medians from the driest day of the week to the wettest day of the week (0.12 inches) is Dallas/Forth Worth, Texas. Even stations nearest to the western North Atlantic Ocean region selected by *Cerveny and Balling* [1998] do not exhibit statistically significant weekly cycles, in agreement with *DeLisi et al.* [2001]. These results are not changed when different minimum thresholds in precipitation amount (i.e., trace, every 0.01-inch amount from 0.01 to 0.15 inch, 0.20, and 0.25 inch, as well as the mean value for nonzero precipitation amounts, 0.32 inch) are tested. Furthermore, we did not find significant differences in the amount of rain at any of the stations for just the summer months (June, July, August), contradicting the results of Bell et al. (submitted manuscript, 2007). Thus, we conclude that the precipitation amount does not show any preference for any day of the week for any station.

## 4. Does Precipitation Occurrence Vary During the Week?

[10] The second test is to see if precipitation occurrence varies as a function of the day of the week. Our null hypothesis is that there is no significant difference between precipitation occurrence (trace and greater) as a function of day of the week. Ideally, we would expect that $\frac{1}{7}$ (14.3%) of all precipitation events at a given station would occur on any given day of the week. At each station, the difference between the actual number of events on any given day of the week and $\frac{1}{7}$ of the total number of precipitation events is computed. These seven values are tested using the $\chi^2$ test to see if they deviate significantly from the ideal uniform (flat) distribution [*Wilks*, 1995]. Only one station is significantly different from the ideal distribution at the 90% confidence level: Coeur D'Alene, Idaho. Considering that we would expect to reject the null hypothesis by chance for 22 stations at the 90% level, these data are not inconsistent with the null hypothesis, providing evidence that precipitation occurrence does not vary as a function of the day of the week.

[11] Furthermore, we tested all stations for significant differences in summertime precipitation occurrence. Five stations had weak statistically significant differences. Interestingly, all five stations had Monday as the common day that was significantly different from the other days. Specifically, Monday had fewer than the expected number of precipitation events at Tampa, Florida, and Atlanta, Georgia, whereas Monday had greater than the expected number of precipitation events at Bangor, Maine; Mount Washington, New Hampshire; and Amherst, Texas. Given that we would expect to reject the null hypothesis by chance for 22 stations at the 90% level, these data are not inconsistent with the null hypothesis, providing evidence that precipitation occurrence does not vary as a function of the day of the week in the summer, in contrast to the results of Bell et al. (submitted manuscript, 2007).

## 5. Testing With Nonlinear Mixed Models

[12] Finally, the full data is analyzed with a nonlinear mixed model structure [*McCulloch and Searle*, 2001] where location, month and year were parameterised and are given an additional variance component (i.e., location have effect $\beta_l$ for the probability of rain and magnitude of precipitation and the variance of the effect is $\sigma_l$, month have effect $\beta_m$ with variance component $\sigma_m$, and year have effect $\beta_y$ with variance component $\sigma_y$).

[13] Modelling the (co-)variances of the variables reduces the bias of the estimates and prevents autocorrelation of the residuals. Successful modeling of variances and covariances of the observations provides valid statistical inference for the fixed effects $\beta$ of the mixed model. Parameterization of location and time removes their effect from the weekday parameters, which improves the accuracy of comparison between weekdays and weekends.

[14] The model for a single observation is given by

$$g(y_{ilym}) = \beta_{wd}x_{wd} + (\beta_l + u_l)x_l + (\beta_y + u_y)x_y + (\beta_m + u_m)x_m + \varepsilon_{ilym}, \quad (1)$$

where $g$ is a nonlinear link function depending on $y_{ilym}$, which is either a binary variable (rain or no rain) or the amount of precipitation, $\beta_i$ are the fixed effects of weekday, location, year and month respectively, $u_i$ are the random effects of location, year, and month respectively caused by the additional variance component, and $\varepsilon_{ilym}$ is the error term. Random effects of year and month are location specific. Random effects are assumed to follow a normal distribution with an expected value of zero and variance $\sigma_j$, denoted by $u_j \sim N(0, \sigma_j)$.

[15] A multivariate mixed regression model with logarithmic link function is constructed for the amount of rain, and a mixed analysis of covariance model with logit-link function is constructed for the binary rain variable (rain or no rain). We assume the response variables to have a random variation within locations, years, and months, which is taken into account with the mixed model structure.

[16] The pair-wise differences between days in the model are tested with the LSMEANS option [*SAS Institute, Inc.*, 2004] and with Tukey's student range test. The tests are constructed such that the weekday estimate for Sunday (or Saturday+Sunday in those test runs where the days are combined as weekend) is set to ground level and the other days are compared to that. The results from both of the tests are similar: neither of them find significant differences between weekends and weekdays in the amount or occurrence of rain. The tests are made for the whole data set from 219 stations and for each station separately. To avoid type II errors (false negative results) in the analysis, the results of the LSMEANS and Tukey's tests are confirmed with a permutation test included in the R environment [*Giraudoux*, 2007] (R Development Core Team, http://www.R-project.org).

## 6. Autocorrelation Analysis

[17] A reviewer of this paper suggested that we employ spectral or harmonic analyses, as *Cerveny and Balling* [1998] did in their study. These two techniques would imply some kind of cyclostationary process. Actually, the techniques we have applied in our manuscript are more powerful than spectral or harmonic analyses because they do not assume a smoothly varying, seven-day cycle, nor should we necessarily expect one. Any existing seven-day cycle would be detected with the statistical tests already in the paper. Consequently, spectral and harmonic analyses are unnecessary.

[18] Nevertheless, further testing of our data set looking for cyclic structures from autocorrelation functions or partial autocorrelation functions did not produce any positive results for any of the stations (tested all together and each station separately). We also tried to fit a seasonal Autoregressive Integrated Moving Average model with seven-day cyclic structure to the data, but the output from this model did not differ significantly from that of the null model (i.e., the model did not find weekly cycles). Thus, we find no significant autocorrelation beyond a weak 1-day persistence, which is easily explainable from synoptic reasoning due to the persistence of rainfall from one day to the next. Both of these new approaches are more sophisticated than spectral or harmonic analysis.

## 7. Conclusion

[19] In the present study, we used a number of different statistical techniques and found no statistically significant weekly cycles in precipitation amount or occurrence at 219 land-based stations across the United States. Using only the summertime data also produced no statistically significant results. These results are consistent with the results of *DeLisi et al.* [2001] who used three different statistical techniques and found no statistically significant weekly precipitation cycles at seven coastal cities in the northeastern United States.

[20] The number of studies looking for weekly cycles in clouds and precipitation continues to grow, yet new results sometimes confirm and sometimes contradict previous studies. For example, *Cerveny and Balling* [1998] and *Bäumer and Vogel* [2007] found that precipitation amount was maximum on Saturday and was minimum on Monday. In contrast, Bell et al. (submitted manuscript, 2007) found that TRMM-derived summertime precipitation rates maximized on Tuesday over the southeast US and minimized on Sunday, whereas summertime gauge data maximized on Thursday and minimized on Sunday (Bell et al., submitted

manuscript, 2007). By comparison, cloud characteristics also can exhibit weekly cycles: *Jin et al.* [2005] found that water-cloud effective radius peaked on Wednesday and liquid water path peaked on Friday, Saturday, and Sunday.

[21] Why our negative results (as well as those of *DeLisi et al.* [2001]) should differ from the other studies is cause for concern. Of comparable concern is how to reconcile the rain-gauge data with various satellite approaches, which do not measure precipitation directly, but instead infer the precipitation from brightness temperatures that are sensitive to some of the cloud microphysical characteristics that are believed to be changed by anthropogenic effects. For example, *Spencer* [1993, p. 1304] states, ‘‘based upon theory and what little is known about the relative frequencies of occurrence of rain- and cloud water, the MSU channel 1 Tb variations are probably dominated by cloud water variations, the direct contribution to rainwater being small.’’ Similarly, Bell et al. (submitted manuscript, 2007) state, ‘‘the 85-GHz signal is largely determined by the size and amount of ice aloft, .... It is therefore possible that the weekly cycle in TRMM rain estimates may be partially due to changes in the ice aloft that are not necessarily accompanied by such large changes in rainfall amounts at the surface.’’ Consequently, we question whether the satellite-derived precipitation schemes are capable of fully discerning the indirect aerosol effect. Clearly, reconciling these approaches remains a significant challenge for understanding the role of humans on clouds and precipitation.

[22] **Acknowledgments.** The data for this study comes from the World Weather Disc, provided by Cliff Mass and Mark Albright. We thank the following individuals for their encouragement, advice, and contributions to this work: Harold Brooks, Charles Doswell III, Kimberly Elmore, Robert Maddox, Allan Murphy, Douglas Worsnop, and two reviewers. This work was begun in 1996 while Schultz was a National Research Council Postdoctoral Fellow at the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory in Norman, Oklahoma, USA. Partial funding for Schultz during 1998–2006 was provided by NOAA/Office of Oceanic and Atmospheric Research under NOAA–University of Oklahoma Cooperative Agreement NA17RJ1227, U.S. Department of Commerce.

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