Day-of-Week Variation of Rainfall and PM_{10} in Death Valley National Park

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Abstract

Evidence for a significant weekly cycle in Death Valley precipitation over the past forty years (1971–2010) was demonstrated using analysis of variance (ANOVA), chi-squared analysis, and difference of means (student's t-test) testing. Since 1971, 23.5% more precipitation occurred during the Wednesday to Friday (weekday) period than the Saturday to Monday (weekend) period. The absolute difference in total precipitation between the weekday and weekend group was 215 mm for the entire period. This difference represents almost four years of annual precipitation in Death Valley. While there were only 2.5% more precipitation days in the weekday group, mean precipitation intensity during the weekday period was 20.4% higher than the weekend group (2.80 mm d^{-1} versus 2.33 mm d^{-1}). Results stratified by warm season (April–September) and cold season (October–March) showed a similar pattern, but the positive weekday anomaly was considerably stronger in the warm season, with 61.7% more weekday than weekend precipitation observed over the forty-year study period. The observed day-of-week variability in Death Valley precipitation coincided with statistically significant weekly cycles in PM_{10} concentrations, which supports the view that anthropogenic emissions influence precipitation even in extremely arid regions such as Death Valley.

Introduction

Overview of Weekend vs. Weekday Comparisons

Over the past few decades, there has been an impressive array of research on the impacts of anthropogenic activities on local- to global-scale weather and climate. Beyond the widely discussed role of atmospheric carbon dioxide on the global climate system, many studies have elucidated anthropogenic effects on urban climate, such as the urban heat island; climate change owed to land-cover change, such as that occurring in the Amazon Basin; and weekly cycles of atmospheric pollution, which have been reported in almost every geographic region on earth. The allure of studies focused on weekly cycles may stem from the fact that the human week is a distinct temporal signal that has no known natural analogue in environmental research (Cerveny and Balling 1998). Accordingly, many believe meteorological variables that exhibit day-of-week (DOW) variability offer irrefutable evidence of human influence on climate given the uniqueness of this cycle in nature.

A weekly cycle in temperature has been demonstrated in countless studies spanning multiple decades in both urban and rural locations throughout diverse geographic regions and across local to global scales (e.g., Mitchell 1961, Lawrence 1971, Gordon 1994, Simmonds and Keay 1997, Forster et al. 2003, and You et al. 2009). However, evidence for a weekly cycle in precipitation is more difficult to assess, given the spatial discontinuities and high variance of precipitation over even small geographic distances. Ashworth (1929) demonstrated that Sundays generally had less rainfall in the factory town of Rochdale, United Kingdom, a result that likely marked the beginning of research on DOW variability in precipitation. Later, research on anthropogenic precipitation modification was greatly stimulated by the controversial "La Porte Anomaly," a finding by Changnon (1968) of significantly higher precipitation amounts downwind of Chicago in the small town of La Porte, Indiana. In part inspired by the scientific discussion generated by the La Porte research, a large urban climate field campaign called METROMEX examined St. Louis, Missouri, in great detail and produced many significant articles on urban climatology, including several on anthropogenic influences on precipitation (Huff and Changnon 1972, Huff and Vogel 1978). Since METROMEX, DOW precipitation variability has been documented in a variety of cities across the globe (e.g., Cehak 1982, Simmonds and Kaval 1986, Bäumer and Vogel 2007, Svoma and Balling 2009, and Marani 2010), lending support to the existence of a weekly cycle. However, debates about the veracity of DOW precipitation variability increased following a set of contradictory studies in North America.

Using satellite-derived rainfall estimates, Cerveny and Balling (1998) found that Saturday precipitation was 22% higher than Monday precipitation off the coast of North America. They showed that the weekly cycle in precipitation is mirrored by the cycles of CO and O_3, suggesting that pollution may be responsible for the observed DOW variability. Their study is unique in that it demonstrates the potential of a regional- to global-scale DOW cycle in precipitation. On the other hand, DeLisi, Cope, and Franklin (2001) did not observe any statistically significant weekly cycle for seven cities along or near the east coast of the United States from the northern mid-Atlantic region to northern New England. Bell et al. (2008) also found a weekend positive anomaly in eastern North America, bolstering the conclusions reached by Cerveny and Balling (1998). However, in a study of 219 weather stations in the United States, Schultz et al. (2007) concluded that precipitation amount and frequency do not exhibit any statistically significant DOW dependence and questioned the statistical cogency of previous research on the topic. Marani (2010) suggested that the divergence of research on DOW precipitation variability is a product of varying methodologies and statistical techniques, among other factors. Nevertheless, Marani (2010) reported statistically significant DOW variability in precipitation amount, though not total precipitation days, at three locations Marghera, Italy; Philadelphia, Pennsylvania; and Portland, Maine for the period 1990–2006, with no clear DOW signal evident before 1989.

While DOW precipitation variability and potential anthropogenic influence on precipitation have been examined in many regions with contradictory results, studies performed in arid regions are comparatively rare. Some notable exceptions include the work of Diem and Brown (2003), which observed that precipitation downwind of Phoenix, Arizona, might be related to anthropogenic activity. Shepherd (2006) continued research in this area and found that suburb locations downwind of Phoenix experienced a 12 to 14% increase in precipitation in the period 1950–2003, compared with the pre-urban period of 1895–1949. Results from Shepherd (2006) regarding an anthropogenic influence on precipitation downwind of Riyadh, Saudi Arabia, were less conclusive. However, neither study specifically sought to identify evidence for a weekly cycle in precipitation. On the other hand, Shutters and Balling (2006) explicitly identified weekly periodicities in numerous meteorological and air-pollution variables in Phoenix, including minimum temperature, wind speeds, haze events, and PM_{10} concentration, but the precipitation findings were somewhat inconclusive, perhaps due to the relatively short study period of less than nine years. Nevertheless, Shutters and Balling (2006) observed a very high correlation of $r = 0.92$ between precipitation and sulfur aerosols in Phoenix, which supports the existence of an anthropogenic impact on Phoenix precipitation. More recently, Svoma and Balling (2009) identified an inverse relationship between $PM_{2.5}$ and DOW precipitation amount in Phoenix, with the highest (lowest) precipitation totals during winter observed on Monday (Thursday). They asserted that human activity, specifically the generation of $PM_{2.5}$, is "having a statistically significant recognizable impact on local-area precipitation patterns" (Svoma and Balling 2009, 320).

Study Purpose

In this study, DOW variability in Death Valley precipitation is examined for the period 1971–2010. Death Valley is one of the driest places in North America, with just 55–60 mm of average annual precipitation, ranging from a maximum annual total of 121 mm recorded in 2005 to no measurable precipitation in 1929 and 1953. Roof and Callagan (2003) noted that precipitation increased in Death Valley by 35% since the 1960s, with less summer rainfall but an increase in total precipitation days. The motivation for this study stems from Death Valley's location downwind of numerous major cities (Figure 1), each with distinct DOW variability in atmospheric pollution (e.g., Marr and Harley 2002, and Blanchard and Tanenbaum 2003) that could modulate precipitation patterns in this arid

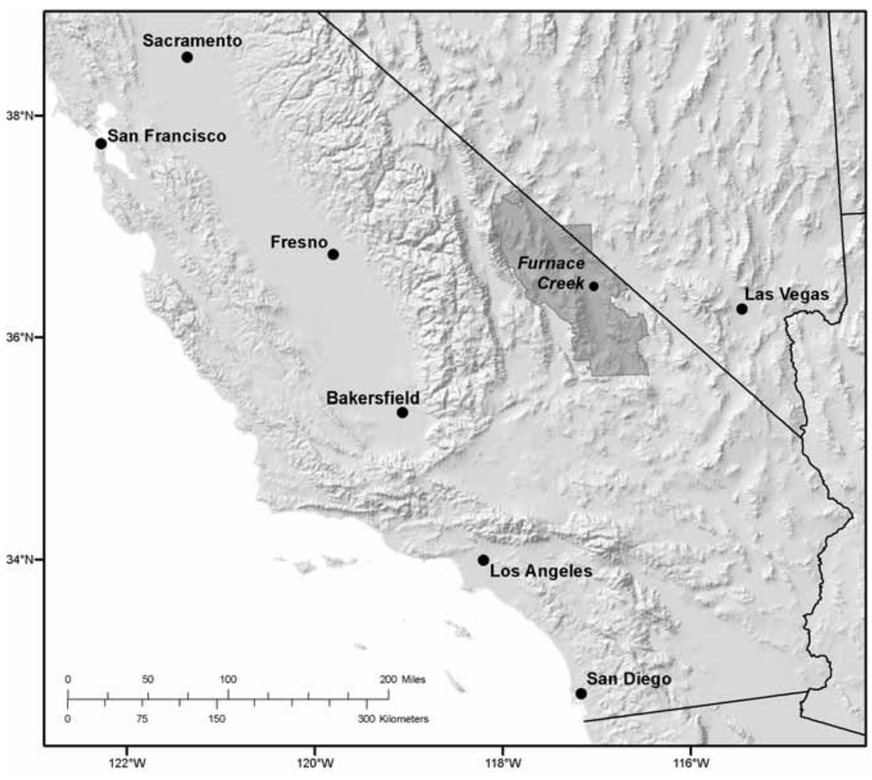

Figure 1.—Map of southern California, with Death Valley indicated by the dark shading.

region. In general, urban ozone levels tend to peak on weekends (e.g., Atkinson-Palombo, Miller, and Balling 2006; and Murphy et al. 2007), but other atmospheric pollutants typically experience mid-week peaks, including the main pollutant of interest here, PM_{10} (aerosol particulate matter with a diameter <10 µm). Because Death Valley is located downwind of many sources of PM_{10}, a pollutant closely linked to anthropogenic activities due to its composition of smoke and dust from industrial sources as well as automobile emissions (Choi et al. 2008), it is hypothesized that Death Valley should likewise experience a statistically significant DOW PM_{10} variability. While the research literature suggests that aerosols may act to either suppress or enhance precipitation (e.g., Rosenfeld 2006, Bell et al. 2008, and Svoma and Balling 2009) depending on a host of factors, including time of day and year, prevailing synoptic conditions, and so forth, it seems that aerosols may suppress precipitation from shallow clouds, but enhance convective precipitation, though even this generalization is subject to numerous caveats. Nevertheless, the working hypothesis, informed by results from Nicholson (1965), Simmonds and Kaval (1986), Simmonds and Keay (1997), Cerveny and Balling (1998), and Miller (2007), among others, is that precipitation amount and intensity will be higher on days with higher levels of atmospheric pollution. Accordingly, in this study, DOW variability in Death Valley PM_{10} and precipitation will be analyzed to test the hypothesis of enhanced rainfall totals due to upwind anthropogenic emissions.

Data and Methods

Data

Daily precipitation data for the official weather station in Death Valley National Park (DVNP) for the period 1971–2010 were obtained from the Utah Climate Center's online (http://climate.usu.edu) data repository. In the forty-year study period, missing data were negligible, with only sixty-seven days unavailable, the majority from two missing months, December 1984 and December 1994. An unfortunate but common problem for climate research in the remotest regions of the western United States is the paucity of meteorological records. In this case, there is not another long-term weather station near the Furnace Creek location. As such, this study will present results from just one weather station, which is an obvious but unavoidable limitation of long-term studies of Death Valley climate (Roof and Callagan 2003).

While the DVNP record extends back to 1911, there were several factors that made the use of the 1971–2010 period preferable. Perhaps most importantly, the daily data in DVNP before 1948 have been shown to contain many potential errors (e.g., Roof and Callagan 2003). Moreover, in 1961, the DVNP weather station relocated approximately 8 km south from the Cow Creek Park Service Headquarters location to its current location at Furnace Creek. Given the potential discontinuity or homogeneity issue this could pose (e.g., Alexandersson 1986), the decision was made to only consider data from the current location. Though 1971–2010 is the focus of this current study, the 1961–2010 period was also examined to see if the results differed. Regardless of the time period, the data showed the same basic weekly cycle in precipitation. Accordingly, the shorter record was selected due to its correspondence with the period of greatest urban expansion in California and implementation of the Clean Air Act of 1970, which has generally resulted in improved air quality throughout the state, though improvements vary by geographic location and specific pollutants (Carle 2006). With a precipitation dataset that corresponds entirely to the period of stricter air-pollution regulations, it is possible to examine what effect, if any, improving air quality has had on the existence of weekly cycles of precipitation in DVNP.

Daily PM_{10} data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network for the period 2000–2010 were used to examine possible weekly cycles in atmospheric pollution in DVNP. The IMPROVE station for Death Valley is also located in Furnace Creek, providing a close match with the official precipitation gauge for the park. While PM_{10} data in Death Valley were available from 1993–2010, the decision to use only data after summer 2000 was made because this date marks the transition when the Wednesday–Saturday observation schedule switched to a once-every-third-day schedule that allows for monitoring of each weekday in the eleven-year dataset between 2000 and 2010. While the precipitation and PM_{10} data do not completely overlap, the eleven-year record in the pollution data should be sufficient to detect weekly cycles. Moreover, the data show that weekly cycles in PM_{10} were fairly consistent from year to year, suggesting that the baseline established for the period 2000–2010 can be reasonably assumed to parallel years unavailable in the PM_{10} record. While there is conflicting evidence as to whether PM_{10} enhances or suppresses precipitation and on what scale, it is an appropriate indicator of human influence within the lower troposphere that can plausibly act as a mechanism to increase cloud condensation nuclei (CCN) into the atmosphere, thereby potentially influencing precipitation amount, frequency, and intensity.

Methods

Three main precipitation variables were examined, precipitation amount (mm), precipitation days, and precipitation intensity (mm/event). In testing the null hypothesis of no significant difference between variables by DOW, analysis of variance (ANOVA), chi-squared analysis, and difference of means (student's t-test) were each used, where appropriate. For the majority of the analyses, the days were grouped into weekday (Wednesday–Friday) and weekend (Saturday–Monday) categories and then subjected to the student's t-test to examine the significance of the weekday-weekend differences. Forster and Solomon (2003) suggested this weekday-weekend grouping to ensure a near-equal amount of days and argued specifically for Monday in the weekend category due to its timing right after the weekend reduction in urban activity. Given the change from frontal-induced precipitation in winter to a more convective pattern in summer, the results were also grouped by season, with April–September labeled "warm season," while October–March were considered "cold season." Following the recommendation of Gordon (1994), a one-tailed test for the meteorological and pollution variables is justified, given the *a priori* understanding that anthropogenic activity is higher during the week; therefore, there is strong theoretical reasoning to suspect that precipitation would also be highest during this time. In all cases, the significance level is 10%, unless noted otherwise.

Results

The DOW variability in total precipitation amount for the entire study period of 1971–2010 in DVNP is shown in Figure 2. The data clearly show a distinct weekly cycle with mid-week precipitation amounts significantly higher than those observed during the weekend period. Combined Wednesday and Thursday precipitation accounted for 771 mm (31.8%) of the forty-year total, while Saturday and Sunday combined for just 599 mm (24.7%); the difference between the two groupings was statistically significant ($p = 0.076$). The difference between the weekday (Wednesday–Friday) and weekend (Saturday–Monday) grouping was also statistically significant ($p = 0.084$) with total weekday precipitation 216 mm (23.5%) higher than that observed in the weekend (Saturday–Monday) grouping.

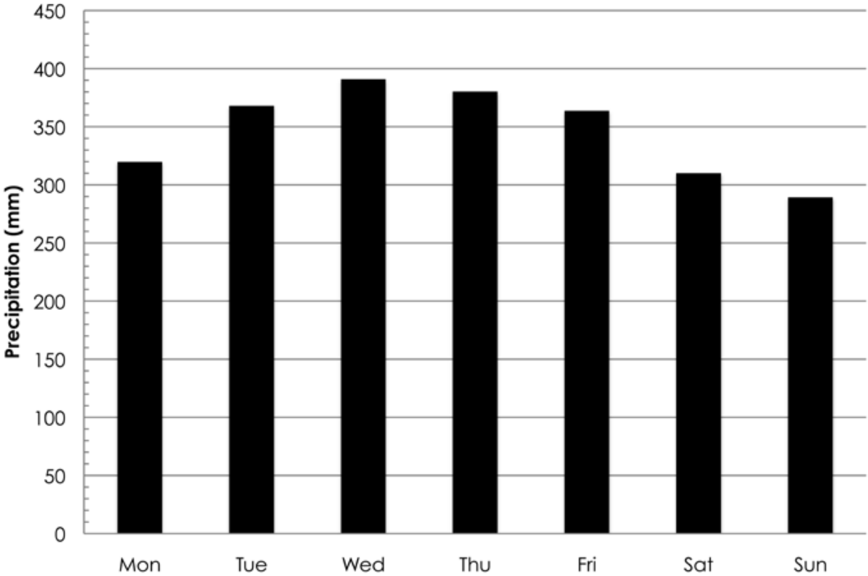

Figure 2.—Total precipitation in Death Valley (Furnace Creek) by day-of-week, 1971–2010.

To demonstrate that the same general pattern of wetter (drier) weekdays (weekends) is not simply an artifact of the time period investigated, the forty-year record was also split into two twenty-year periods, 1971–1990 and 1991–2010. As indicated in Table 1, the 1971–1990 period featured a weekday anomaly of 36.6% in total precipitation amount, while the later period 1991–2010 had a 10.7% weekday anomaly. Accordingly, there is strong support for a long-term preference for higher precipitation amounts in Death Valley during the mid-week. This is also evidenced in Figure 3, which shows the temporal evolution of weekday and weekend cumulative (since 1971) precipitation. Beginning in 1978, cumulative Wednesday to Friday precipitation exceeded Saturday to Monday precipitation through the end of the study period. Figure 3 also demonstrates what was evident in Table 1, specifically that the weekday positive precipitation anomaly has decreased slightly in the period 2003–2010. Nevertheless, Figures 2 and 3, and Table 1, each indicate that weekday precipitation amounts significantly exceeded weekend values throughout the study period.

Table 1. Death Valley (Furnace Creek) precipitation statistics for weekdays (Wednesday–Friday) and weekends (Saturday–Monday) during 1971–1990 and 1991–2010.

	1971– 1990		
	Precipitation (mm)	Precipitation Days	Intensity (mm/event)
Wed–Fri	618	216	2.86
Sat–Mon	452	207	2.19
Difference	165	9	0.67
%	36.6%	4.3%	30.9%

	1991– 2010		
	Precipitation (mm)	Precipitation Days	Intensity (mm/event)
Wed–Fri	517	189	2.74
Sat–Mon	467	188	2.48
Difference	50	1	0.25
%	10.7%	0.5%	10.2%

Further evidence for the existence of a weekly cycle in Death Valley precipitation is revealed in the analysis of cold-season (October-March) and warm-season (April–September) precipitation shown in Table 2. The positive weekday anomaly is far more pronounced in the warm-season with 61.7% (p <0.05) more weekday than weekend precipitation observed over the forty-year study period. While weekday cold-season precipitation totaled 6.8% more than weekend precipitation, the difference was not statistically significant. However, it is worth noting that during the cold-season, Wednesday precipitation amounted to 16.8% of the total, while Saturday precipitation was just 11.9%, a difference that was statistically significant.

The frequency of observed precipitation days did not exhibit a strong DOW dependence, with a chi-squared analysis failing to reveal significant differences in the number of days with precipitation by DOW. The total rain days in the weekend and weekday groupings was reasonably similar in both time periods investigated (Table 1) and in both halves of the year (Table 2). In addition, there was no clear indication of significant differences in the number

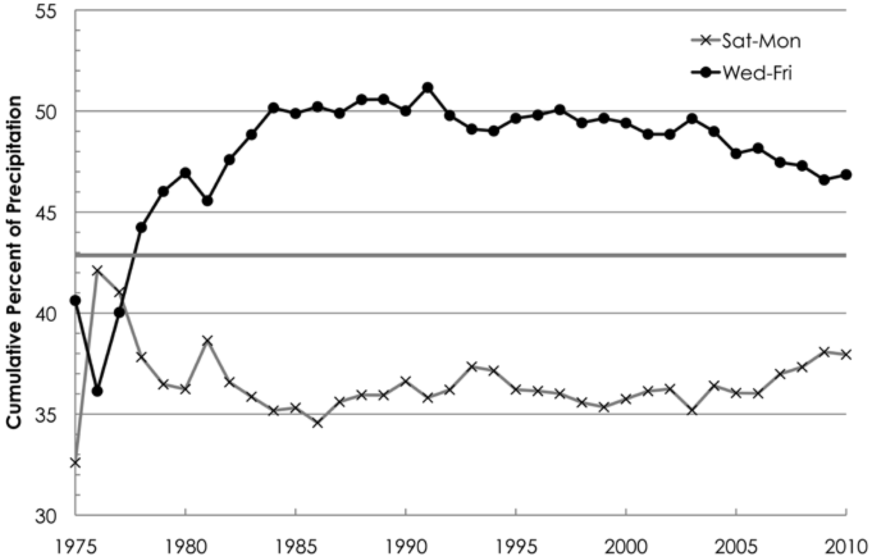

Figure 3.—Cumulative precipitation percent since 1971 for weekdays (Wednesday–Friday) and weekends (Saturday–Monday) in Death Valley (Furnace Creek). The solid grey line at 42.857% is displayed to show departures from a homogenous day-of-week precipitation distribution.

of days above various thresholds (1 mm, 5 mm, 10 mm, 25 mm, etc.). Nevertheless, it is interesting that Sunday had the fewest precipitation days, with 123 (12.9% of the total), while Tuesday had the most precipitation days, with 156 (16.3% of the total). Overall, the weekday grouping contained only ten more precipitation days than the weekend grouping in the entire forty-year study, an insignificant 2.5% difference. Given that precipitation frequency was essentially statistically homogenous throughout the week, but precipitation amounts demonstrated significant DOW variability, it is not surprising that precipitation intensity showed pronounced DOW differences.

As illustrated in Figure 4, precipitation intensity for the entire study period exhibited a marked mid-week peak, with a weekday grouping average of 2.80 mm/rain event compared to 2.33 mm/rain event, a 20.4% intensity increase during Wednesday to Friday compared to the Saturday to Monday period. Among individual days, Wednesday experienced the highest precipitation intensity at 2.92 mm/event, which was 27% higher than Saturday precipitation events. Results stratified by the two time periods demonstrate that the weekday positive precipitation anomaly persisted throughout the study period, but the phenomenon was considerably stronger in the 1971–1990 period. Overall, the data show that weekdays experienced 30.9% and 10.2% higher precipitation intensities than weekends in 1971–1990 and 1991–2010, respectively. A possible explanation for the observed positive weekday anomalies is the DOW variability in DVNP PM_{10}.

Table 2. Death Valley (Furnace Creek) precipitation statistics for weekdays (Wednesday–Friday) and weekends (Saturday–Monday) during the "cold season" (October–March) and "warm season" (April–September).

	Cold Season (October–March)		
	Precipitation (mm)	Precipitation Days	Intensity (mm/event)
Wed–Fri	759	248	3.06
Sat–Mon	711	264	2.69
Difference	49	-16	0.37
%	6.8%	-6.1%	13.7%

	Warm Season (April–September)		
	Precipitation (mm)	Precipitation Days	Intensity (mm/event)
Wed–Fri	297	125	2.38
Sat–Mon	184	105	1.75
Difference	113	20	0.63
%	61.7%	19.0%	35.8%

Despite being located between 200–350 km from the urban areas of California's Central Valley, approximately 300 km from the Los Angeles metropolitan region, and over 450 km from the San Francisco Bay area, a distinct weekly cycle in PM_{10} concentration that is extremely unlikely to be a result of local sources was found in Death Valley as illustrated in Figure 5. For the entire eleven-year record, weekday (Wednesday–Friday) PM_{10} levels were 33.7% higher ($p < 0.05$) than those observed on weekends. Superimposed on Figure 5 are the forty-year precipitation intensity values from Figure 4 to demonstrate the strong correlation between average precipitation intensity and PM_{10} levels. It is interesting to note that the three highest PM_{10} days, also correspond to the three highest precipitation intensity days. Given the lack of significant DOW variation

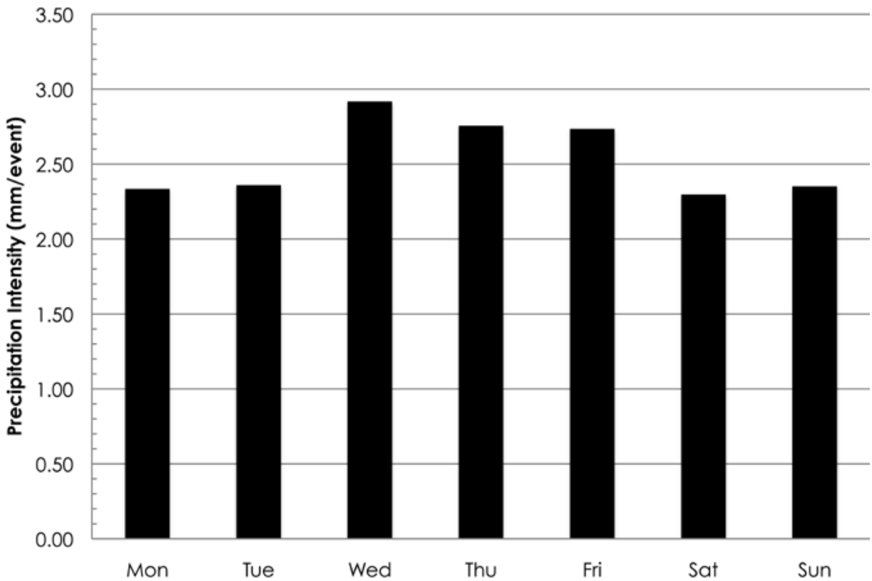

Figure 4.—Precipitation intensity (mm/rain event) in Death Valley (Furnace Creek) by day-of-week for 1971–2010.

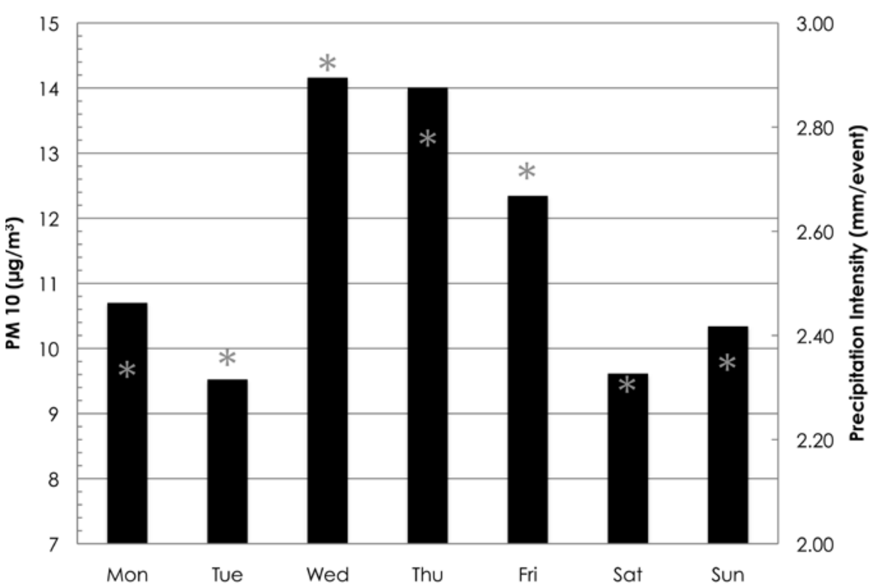

Figure 5.—Average PM_{10} concentration at Death Valley (Furnace Creek) by day-of-week for 2000–2010, with the precipitation intensities from Figure 4 indicated by the asterisks.

in precipitation days, this suggests that atmospheric pollution in Death Valley acts to enhance precipitation, not necessarily cause it. Notably, overall PM_{10} concentrations in DVNP were over two times as high in the warm season compared to the cold season; between April and September, average PM_{10} concentrations were 15.99 μg/m^3, compared to 7.60 μg/m^3 in the colder half of the year. This result is possibly related to the observation that DOW precipitation variability was much stronger in the warm season. Nevertheless, in both halves of the year, PM_{10} levels exhibited statistically significant DOW variation that mirrored DOW precipitation cycles. In the cold half of the year, October–March, the weekday PM_{10} averaged 13.50 μg/m^3, compared to 10.09 μg/m^3 among the weekend grouping, a statistically significant (p <0.05) difference of 33.7%. During the warm half of the year, weekday PM_{10} was 18.74 μg/m^3 versus 13.51 μg/m^3 for weekends, a 38.7% difference (p <0.05). The DOW PM_{10} variation by season reveals that weekdays during the cold season contain the same PM_{10} levels as weekends in the warm season. Overall, both warm and cold season PM_{10} levels exhibit strong DOW dependence, with higher pollution levels during the mid-week than the weekend, which lends credibility to the contention that elevated precipitation amounts and intensities during the mid-week are related to anthropogenic activities far upwind of Death Valley.

Discussion

The working hypothesis in this study was that atmospheric pollution generated upwind of Death Valley in cities such as Los Angeles, Bakersfield, Fresno, and the San Francisco Bay area would lead to a weekly cycle in PM_{10} in DVNP, which would in turn help produce a distinct weekly cycle in precipitation. With regard to a weekly cycle in PM_{10}, the data show that weekday levels of PM_{10} are 30–40% higher than those observed on weekends. The weekly cycles in PM_{10} even for a remote region like DVNP are not uncommon, but the magnitude of the weekly range is considerably higher than non-arid values reported elsewhere. For instance, Bell et al. (2008) noted that PM_{10} weekly cycle amplitudes were ± 10%, which is consistent with results from Barmet et al. (2009), who found a 10–15% difference between DOW maximum and minimum PM_{10} concentrations. Closer to Death Valley, Miller (2007) found a DOW cycle in Las Vegas, Nevada PM_{10} with more than double the PM_{10} concentration on weekdays compared to weekends at two urban stations. Overall, the results presented here are reasonably consistent with previous research on DOW variability in PM_{10}.

With respect to DOW precipitation variability, Svoma and Balling (2009) observed a Monday maximum in winter Phoenix precipitation that was approximately 30% greater than the Saturday minimum. Simmonds and Keay (1997) found weekday-weekend differences in Melbourne, Australia, generally less than 15%. Similarly, Cerveny and Balling (1998) concluded Saturday precipitation was 22% higher than Monday precipitation along the east coast of North America. In general, where DOW statistically significant differences in precipitation amount or intensity are reported, they are commonly in the 10–30% range. As such, the 23.5% weekday positive anomaly found here for Death Valley is quite consistent with previous research on DOW precipitation variability.

The finding that DOWV was greatest during the summer months is also not surprising, given the difference in atmospheric circulation during the cold and warm season. During winter, precipitation tends to occur in association with low-pressure systems and frontal lifting, leading to a much more active atmosphere. Moreover, fronts create a wind shift when they pass through an area and can significantly alter the local pollution field. Because each storm carves out a unique path in the atmosphere, the dispersion of pollution in association with low-pressure systems would tend to minimize enhancement in one particular area. As summarized by Oke (1982) and Arnfield (2003), anthropogenic effects on climate are often much stronger during the warm season. Though not a DOW study, Diem and Brown (2003) found evidence for precipitation enhancement downwind of Phoenix, Arizona, during the summer monsoon season. Therefore, the more robust results found in the warm season are consistent with basic meteorological principles and previous research. Furthermore, that DOW variability was more pronounced in the 1971–1990 period is likely related to improvements in air quality throughout California following passage of the Clean Air Act of 1970. However, the relatively short PM_{10} record spanning from 2000 to 2010 does not allow for a more definitive conclusion.

Clearly, the above analysis indicates that there is a solid statistical relationship between DOW cycles in PM_{10} and precipitation in DVNP. Previous research suggests it is highly likely that pollutants play an important role in producing DOW variability or urban enhancement in meteorological parameters (e.g., Lowry 1977; Vogel and Huff 1978; Khemani, Momin, and Naik 1987; Simmonds and Keay 1997; Cerveny and Balling 1998; Diem and Brown 2003; Rosenfield 2006; Shepherd 2006; Svoma and Balling 2009; and Marani 2010). While

Marani (2010) correctly notes that research on DOW precipitation variability has been unequivocal, his study suggests that differences in methodology, data sets, study locations, and time periods may account for the divergence of results. In reporting significant DOW precipitation variability in three cities, Marani (2010) reiterated the general conclusions reached by Rosenfeld (2006), specifically that aerosols are likely not capable of producing consistently higher precipitation frequencies, but they can promote high rainfall intensities. Indeed, that is the main conclusion reached in this study; rainfall intensities were consistently higher on days with higher PM_{10} levels, but precipitation frequencies were not.

Conclusions

Using forty years of daily precipitation data from Death Valley National Park, significant DOW variability in precipitation amount and intensity was observed. Notably, more robust results were found in the warm season and in the earlier period (1971–1990) of the study. While it is always important to note that correlation does not imply causation and equally important to consider the limitations of a study based on a single weather station, the DOW variability found in the forty-year dataset is nevertheless impressive. The weekly cycle in precipitation presented here is consistent with previous research and adds to a growing body of literature on DOW variability in local to regional climate. The results from this study suggest that human activity hundreds of kilometers upwind of Death Valley exerts a statistically significant impact on local precipitation, with PM_{10} appearing to enhance precipitation intensities. However, whether particulate matter generally enhances or suppresses precipitation, and under what synoptic conditions such effects may occur, is far from a settled question. Accordingly, a broader study focusing on the entire Mojave Desert region to examine the possibility of a region-wide DOW precipitation signal is recommended.

References

Alexandersson, H. 1986. A homogeneity test applied to precipitation data. *Journal of Climatology* 6:661–675.

Arnfield, J. A. 2003. Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology* 23:1–26.

Ashworth, J. R. 1929. The influence of smoke and hot gases from factory chimneys on rainfall. *Quarterly Journal of the Royal Meteorological Society* 55:341–350.

Atkinson-Palombo, C., J. A. Miller, and R. C. Balling. 2006. Quantifying the ozone "weekend effect" at various locations in Phoenix, Arizona. *Atmospheric Environment* 40:7644–7658.

Barmet, P., T. Kuster, A. Muhlbauer, and U. Lohmann. 2009. Weekly cycle in particulate matter versus weekly cycle in precipitation over Switzerland. *Journal of Geophysical Research* 114: doi:10.1029.2008JD011192.

Bäumer, D., and B. Vogel. 2007. An unexpected pattern of distinct weekly periodicities in climatological variables in Germany. *Geophysical Research Letters* 34: doi:10.1029/2006GL028559.

Bell, T. L., D. Rosenfeld, K.-M. Kim, J.-M. Yoo, M.-I. Lee, and M. Hahnenberger. 2008. Midweek increase in U.S. summer rain and storm heights suggests air pollution invigorates rainstorms. *Journal of Geophysical Research* 113: doi:10.1029/2007JD008623.

Blanchard, C. L., and S. J. Tanenbaum. 2003. Differences between weekday and weekend air pollutant levels in southern California. *Journal of the Air & Waste Management Association* 53:816–828.

Carle, D. 2006. *Introduction to Air in California. (California Natural History Guides)*. Berkeley: University of California Press.

Cehak, K. 1982. Note on the dependence of precipitation on the day of the week in a medium industrialized city. *Archives for Meteorology, Geophysics, and Bioclimatology* 30:247–251.

Cerveny, R. S., and R. C. Balling. 1998. Weekly cycles of air pollutants, precipitation and tropical cyclones in the coastal NW Atlantic region. *Nature* 394:561–563.

Changnon, S. A. 1968. The LaPorte weather anomaly—fact or fiction? *Bulletin of the American Meteorological Society* 49:4–11.

DeLisi, M. P., A. M. Cope, and J. K. Franklin. 2001. Weekly precipitation cycles along the northeast corridor. *Weather and Forecasting* 16:343–353.

Diem, J. E., and D. P. Brown. 2003. Anthropogenic impacts on summer precipitation in Central Arizona, U.S.A. *The Professional Geographer* 55:343–355.

Forster, P. M. D., and S. Solomon. 2003. Observations of a "weekend effect" in diurnal temperature range. *Proceedings of the National Academy of Sciences* 100:11225–11230.

Gordon, A. H. 1994. Weekdays warmer than weekends? Nature 367:325–326.

Huff, F. A., and S. A. Changnon. 1972. Climatological assessment of urban effects on precipitation at St. Louis. *Journal of Applied Meteorology* 11:823–842.

Huff, F. A., and J. L. Vogel. 1978. Urban, Topographic and Diurnal Effects on Rainfall in the St. Louis Region. *Journal of Applied Meteorology* 17:565–577.
Khemani, L. T., G. A. Momin, and M. S. Naik. 1987. Influence of atmospheric pollutants on cloud microphysics and rainfall. *Boundary Layer Meteorology* 41:367–380.
Lawrence, E. N. 1971. Urban climate and day of the week. *Atmospheric Environment* 5:935–948.
Lowry, W. P. 1977. Empirical estimation of urban effects on climate: a problem analysis. *Journal of Applied Meteorology* 16:129–135.
Marani, M. 2010. The detection of weekly preferential occurrences with an application to rainfall. *Journal of Climate* 23:2379–2387.
Marr, L. C., and R. A. Harley. 2002. Spectral analysis of weekday–weekend differences in ambient ozone, nitrogen oxide, and non-methane hydrocarbon time series in California. *Atmospheric Environment* 36:2327–2335.
Miller, J. A. 2007. Local and regional climate change in the Mojave Desert, USA. Ph.D. dissertation, Department of Geography, Arizona State University.
Mitchell, J. M. 1961. The temperature of cities. *Weatherwise* 14:224–229.
Murphy, J. G., D. A. Day, P. A. Cleary, P. J. Wooldridge, D. B. Millet, A. H. Goldstein, and R. C. Cohen. 2007. The weekend effect within and downwind of Sacramento ? Part 1: Observations of ozone, nitrogen oxides, and VOC reactivity. *Atmospheric Chemistry and Physics* 7:5327–5339.
Nicholson, G. 1965. Wet Thursdays again. *Weather* 20:322–323.
Oke, T. R. 1982. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society* 108:1–24.
Roof, S., and C. Callagan. 2003. The climate of Death Valley, California. *Bulletin of the American Meteorological Society* 84:1725–1739.
Rosenfeld, D. 2006. Aerosol-cloud interactions control of Earth radiation and latent heat release budgets. *Space Science Reviews* 125:149–157.
Schultz, D. M., S. Mikkonen, A. Laaksonen, and M. B. Richman. 2007. Weekly precipitation cycles? Lack of evidence from United States surface stations. *Geophysical Research Letters* 34: doi:10.1029/2007GL031889.
Shepherd, J. M. 2006. Evidence of urban-induced precipitation variability in arid climate regimes. *Journal of Arid Environments* 67:607–628.

Shutters, S. T., and R. C. Balling. 2006. Weekly periodicity of environmental variables in Phoenix, Arizona. *Atmospheric Environment* 40:304–310.

Simmonds, I., and J. Kaval. 1986. Day-of-the-week variation of rainfall and maximum temperature in Melbourne, Australia. *Archives for Meteorology, Geophysics, and Bioclimatology* 31:1589–1603.

Simmonds, I., and K. Keay. 1997. Weekly cycle of meteorological variation in Melbourne and the role of pollution and anthropogenic heat release. *Atmospheric Environment* 31:1589–1603.

Svoma, B. M., and R. C. Balling. 2009. An anthropogenic signal in Phoenix, Arizona winter precipitation. *Theoretical and Applied Climatology* 98:315–321.

You, Q., S. Kang, W.-A. Fiügel, A. Sanchez-Lorenzo, Y. Yan, Y. Xu, and J. Huang. 2009. Does a weekend effect in diurnal temperature range exist in the eastern and central Tibetan Plateau? *Environmental Research Letters* 4:1–7.