J10.3 AN ANTHROPOGENIC SIGNAL IN PHOENIX, ARIZONA WINTER PRECIPITATION

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Abstract

Many other investigators have shown pronounced weekly cycles in atmospheric composition, particularly in large urban settings. A substantial body of literature shows that the varying concentrations of fine atmospheric aerosols ($PM_{2.5}$) impact precipitation processes; generally, higher concentrations of these aerosols tend to depress winter precipitation especially in short-lived, shallow, and orographic clouds. Phoenix, Arizona has a large population relying heavily on motor vehicles as the primary means of transportation. This results in a strong weekly cycle of $PM_{2.5}$ concentrations with a maximum on Wednesday and Thursday and a distinctive minimum on the weekend. To determine any influence on rainfall, we analyze daily precipitation records from 116 stations in the Phoenix area and find a strong weekly cycle in winter precipitation frequencies with maximum values on Sunday and minimum values on Thursday. The weekly cycle in precipitation frequency strengthens slightly moving eastward (downwind) across the metropolitan area as well as with increasing proximity to the metropolitan area. These results strongly suggest that human activity is influencing winter precipitation primarily by the suppressing effect of $PM_{2.5}$.

Keywords: Urban climate, human influences, winter precipitation, Phoenix

1. INTRODUCTION

Anthropogenic impacts on Earth's weather and climate have been studied extensively in recent years (IPCC 2007). These impacts vary in scale and include global and regional climate change, urban heat islands, and local air pollution. Recognizing that the human population will continue to grow, particularly in urban areas, many climate scientists have focused their attention on the local and regional climate impacts of urban activities.

It has frequently been hypothesized that anthropogenic air pollution may have an effect on precipitation. Aerosols produced in urban centers affect downwind precipitation by introducing cloud condensation nuclei into the atmosphere (Borys et al. 2003; Lohmann and Feichter 2005; Jin et al. 2005; Khain et al. 2005; Rosenfeld and Givati 2006; Rosenfeld et al. 2007; Van den Heever and Cotton 2007). The introduction of fine aerosols results in large amounts of small cloud droplets/ice particles which suppress drop/particle growth thus increasing the time required for drops/particles to attain the mass necessary to fall as precipitation (Rosenfeld and Givati 2006). This effect is very noticeable in short-lived, shallow and particularly orographic clouds (Rosenfeld and Givati 2006) and in some cases precipitation can be completely suppressed (Rosenfeld 2000). Coarse aerosols on the other hand can act as giant cloud condensation nuclei and thus have the ability to enhance precipitation (Rosenfeld and Givati 2006). Borys et al. (2003) found that small aerosols, sulfates in particular, significantly slowed orographic snowfall rates in the Colorado Rocky Mountains. Givati and Rosenfeld (2004; 2005) attributed orographic precipitation suppression in California and Israel to fine aerosols. Rosenfeld et al. (2007) found similar results for mountainous areas in parts of China. Rosenfeld and Givati (2006) found winter orographic precipitation suppression downwind of several urban centers in the western United States, including the Phoenix metropolitan area. This was mainly attributed to elevated and increasing/stable levels of fine aerosols ($PM_{2.5}$) and possibly to decreasing levels of coarse aerosols (PM_{10} – $PM_{2.5}$). Shutters and Balling (2006) found very high correlations ($r > 0.92$)

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*Corresponding author. Tel.: + 1 480 694 1189. *Address: 2750 S. Morrow St. Tempe, Arizona 85282* between precipitation and sulfur/sulfate aerosols in the Phoenix area but hesitated on drawing any conclusions from this result.

Sulfate aerosols have been found to be mainly in the $PM_{2.5}$ category (Wang et al. 2006) and a study done in the urban areas of the mid-Atlantic United States found sulfate aerosols to be the main contributor to $PM_{2.5}$ mass and found vehicle emissions to be the largest source of $PM_{2.5}$ mass (Kim and Hopke 2005). Furthermore, Hopke et al. (2006) found sulfate aerosols and traffic to be highly correlated (r >0.9) in Phoenix and Lewis et al. (2003) found vehicle emissions and secondary sulfates to be the most prominent sources for $PM_{2.5}$ mass in the Phoenix area.

The Phoenix metropolitan area is one of the fastest growing urban centers in the United States. Currently lacking a well-developed mass transit system, commuters rely heavily on automobile transportation. In addition, the current growth in the city is typical of urban sprawl, therefore, commuters travel great distances daily to their places of employment. Furthermore, Phoenix population grows substantially in the winter season given the influx of visitors from colder climates.

Winter season in the Phoenix area is characterized by a near-consistent upper-level westerly wind pattern with relatively infrequent but widespread precipitation events. The rough topography in and around Phoenix increases the spatial complexity of these precipitation events; detecting a human signal using resulting spatial patterns in precipitation (e.g., suppression of downwind rainfall) would be difficult. However, evidence of significant weekly precipitation cycles in this environment would be very suggestive of true anthropogenic influence.

Weekly cycles in atmospheric variables are often cited as evidence of anthropogenic influences on those variables. Recent research has focused on the identification of weekly precipitation cycles. Schultz et al. (2007) examined 219 surface stations across the United States and found no evidence of precipitation total and frequency variation by day of the week. Bell et al. (2008), however, found a significant midweek increase in summer rainfall over the southeast United States. Bäumer and Vogel (2007) found weekly precipitation cycles for 12 stations in Germany. Bäumer and Vogel seemed to suggest that these cycles occurred in both rural and urban locations and therefore the weekly aerosol cycle may influence precipitation on larger scales. Gong et al. (2007) found weekly cycles of PM_{10} aerosols as well as the frequency of light precipitation in China. The minimum of light precipitation events occurred on Wednesday which coincided with the PM_{10} maximum. Gong et al. suggested that this weekly cycle in precipitation was due to the weekly cycle in aerosols.

Significant weekly cycles in both $PM_{2.5}$ and PM_{10} have been found in Phoenix through fitting seven day sinusoidal waves to daily particulate matter data with the maxima occurring on Thursday and Wednesday respectively (Bell et al. 2008). Furthermore, traffic flows in Phoenix follow a significant weekly cycle with a maximum occurring on Wednesday and a minimum on Sunday (Shutters and Balling 2006). Shutters and Balling (2006) studied pollution variables in the Phoenix metropolitan area and found significant day of the week differences in PM_{10}, sulfate, and elemental sulfur aerosols.

Orographic barriers lead to the creation of gravity waves which influence the location and intensity of downwind precipitation (Bruintjes et al. 1994). Therefore, even the low elevation valley where Phoenix is located is influenced by orographic processes due to the topography within and surrounding the metropolitan area which impact cloud longevity over the valley. Thus, we hypothesize that the pronounced weekly cycle in traffic and therefore $PM_{2.5}$ in Phoenix produces an inverse weekly cycle in winter precipitation, which is mainly generated from shallow clouds influenced by these orographic processes.

2. DAILY PRECIPITATION DATA

Daily precipitation data for 291 stations in and around the Phoenix metropolitan area were provided to us by the Flood Control District of Maricopa County (see Fig. 1); the data extend from 1980 to 2007. This dense yet widespread network of automated rain gauges provides us with a unique opportunity to examine the spatial variability of weekly precipitation cycles in the area. We limited our analyses to the winter events occurring during the period November 1st to March 31st.

For each station, we determined the total amount of precipitation and the frequency of precipitation events by day of the week. If a station had fewer than 210 days with at least 1 mm of precipitation, the station was eliminated from further analysis. This criterion reduced the network to 116 stations; we altered the cut-off and found that our results were largely insensitive to realistic cut-off decisions.

3. ANALYSES AND RESULTS

We combined the precipitation frequencies and amounts for all 116 stations by day of week and immediately identified a strong weekly cycle in the frequencies and a more complex weekly pattern for the amounts (see Figs. 2 and 3). The frequency graph shows a clear maximum on Monday, with relatively high values on Sunday and Tuesday, and a minimum on Thursday, with a relatively low value on Wednesday as well. The plot of daily amounts certainly shows a strong maximum on Monday, but any weekly "cycle" is not nearly as well identified.

A popular, and powerful, statistical tool for analyzing cycles over a fixed fundamental period (in this case, a week) is harmonic analysis. The basic form of the harmonic equation is:

$$f(x) = \bar{X} + \sum_{r=1}^{N/2} A_r \cos(r\theta - \Phi_r)$$

where $f(x)$ is the estimated value in each day, $\bar{X}$ is the average value over the N observations (seven), A_r is the amplitude of the r^th^ harmonic wave (we are interested in the first harmonic wave showing any weekly cycle in the data), r is the frequency or number of times the harmonic wave is repeated over the fundamental period, θ is derived as $2\pi x/N$ where x represents the intervals through the fundamental period, and Φ_r is the phase angle of the r^{th} harmonic often reinterpreted as the time of maximum. The basic form is expanded to:

$$f(x) = \bar{X} + \sum_{r=1}^{N/2} \left[a_r \sin(2\pi rx/P) + b_r \cos(2\pi rx/P) \right]$$

where the Fourier coefficients, a_r and b_r, are calculated as:

$$a_r = \sum_{x=1}^{N} \frac{2}{N} \left[f(x) \sin(2\pi rx/P) \right]$$

and

$$b_r = \sum_{x=1}^{N} \frac{2}{N} \left[f(x) \cos(2\pi rx/P) \right]$$

The amplitude, A_r, is calculated as $(a_r{}^2 + b_r{}^2)^{0.5}$, the standardized amplitude is calculated as $A_r/2\bar{X}$, the phase angle, Φ_r, equals $\tan^{-1}(a_r/b_r)$, and the portion of variance explained by the r^{th} harmonic wave, V_r, is determined as $A_r^2/2s^2$ where s is the standard deviation of the N values. A useful parameter may be generated when the standardized amplitude is multiplied by two and added to one. For example, a standardized amplitude of 0.10 implies that the probability of occurrence in the peak period is 1.20 times the mean value.

We used harmonic analysis to quantify the patterns shown in Figs. 2 and 3, and found in the case of frequencies, that the first harmonic explained 86.0 percent of the variance in the weekly data (p□< 0.01). Here, statistical significance was established by taking the square root of the explained variance and assessing the root as a Pearson Product Moment Correlation Coefficient with five (n-2) degrees of freedom. The standardized amplitude was 0.04 and the time of maximum was near midnight between Sunday and Monday. For precipitation amounts, the variance explained by the first harmonic wave was 0.24 which is not statistically significant even at the p□= 0.05 level of confidence (standardized amplitude was 0.03 and time of maximum was Monday afternoon).

Having determined that a significant weekly cycle exists for Phoenix area winter season precipitation frequencies, we next conducted a separate harmonic analysis for each of the 116 stations in the network. As seen in Fig. 4, the amount of variance explained by the first harmonic at each of the 116 stations varied from 0.02 to 0.94, and averages 0.54. The Moran's I statistic quantifies spatial autocorrelation and is a measure of autocorrelation similar in interpretation to the Pearson's Product Moment correlation statistic for independent samples, in that both statistics range between -1.0 and 1.0 depending on the degree and direction of spatial correlation (Moran, 1950). For our 116 station network, the Moran's I was +0.07 for the amount of variance explained by the first harmonic and +0.06 for the standardized amplitudes of the first harmonic fits. Both of these values are positive and significant at the p□□< 0.01 level of confidence showing that the explained variance and standardized amplitude values were similar for stations close to one another and less similar for stations located farther apart. Another useful spatial statistic is the Getis-Ord General G statistic (Getis and Ord 1992) which is a z-score calculated as the difference between the sum of the local sample and the weighted mean of all data points divided by the weighted standard deviation of all data points where positive (negative) values indicate that values higher (lower) than the mean are clustered (Laffan 2002). The Getis-Ord General G statistic showed that the high values of explained variance and standardized amplitude were significantly more clustered ($p < 0.01$) than the low values.

Through simple linear regression, both explained variance and standardized amplitude had a tendency ($p = 0.11$) to increase with decreasing distance from the center of the Phoenix metropolitan area where $PM_{2.5}$ concentrations are the highest (Owen 2006). Through multiple linear regression with latitude and longitude as the independent variables, the explained variance had a tendency ($p = 0.09$) toward higher values in more easterly (downwind) locations. Lastly, we found that almost all stations showed the day of maximum precipitation frequency to be Sunday or Monday while no station had Wednesday or Thursday as the day of maximum frequency.

4. DISCUSSION

The strong weekly cycle found in rainfall frequency in the Phoenix area suggests an anthropogenic influence. Several studies have found that the presence of fine aerosols, typically $PM_{2.5}$, act to suppress precipitation produced by shallow, short lived and particularly orographic clouds (Borys et al. 2003; Givati and Rosenfeld 2004;2005; Rosenfeld and Givati 2006; Rosenfeld et al. 2007). On the other hand, some studies have shown that the delay in rainfall caused by fine aerosols can act to enhance updrafts thus bringing more moisture into the upper levels of the cloud, potentially invigorating the storm (Andrea et al. 2004; Khain et al. 2005; Lynn et al. 2005; Bell et al., 2008). This effect, however, was only seen in areas over land in the summer where large atmospheric instability allows for the growth of convective storms. Larger, particularly hygroscopic, aerosols have been thought to enhance precipitation (Rosenfeld and Givati 2006), but a model study done for subtropical winter conditions concluded that the enhancement of precipitation due to large pollutants is often not enough to offset the suppressing affects of small pollutants (Teller and Levin 2006).

In the Phoenix area, downwind winter orographic precipitation has been found to be suppressed by anthropogenic emissions of $PM_{2.5}$ (Rosenfeld and Givati 2006). In addition, high correlations have also been observed between sulfate aerosols and rainfall (Shutters and Balling 2006) as well as sulfate aerosols and traffic flows in the Phoenix area (Hopke et al. 2006). It is worth noting that studies have found sulfate aerosols to be mainly in the $PM_{2.5}$ category (Kim and Hopke 2005) and that vehicle emissions and secondary sulfates from vehicle emissions are the main contributors to $PM_{2.5}$ mass in Phoenix (Lewis et al. 2003).

Significant weekly cycles in both $PM_{2.5}$ and PM_{10} have been found in Phoenix with the maxima occurring on Thursday and Wednesday respectively (Bell et al. 2008). Furthermore, traffic flows in Phoenix follow a significant weekly cycle and with a maximum occurring on Wednesday and a minimum on Sunday (Shutters and Balling 2006).

These cycles inversely correspond to the cycle in Phoenix area rainfall frequency found in this study. The low frequencies on Wednesday and Thursday seem to be a response to high traffic flows and thus high concentrations of $PM_{2.5}$. Likewise the reverse scenario contributes to high values of rainfall frequency on Sunday and Monday. The apparent clustering of higher explained variance ($p < 0.01$) by the first harmonic over the central Phoenix area ($p = 0.11$) along with a slight tendency for variance explained to increase with eastward progression ($p = 0.09$), which is in response to the dominant westerly wind pattern, provide further evidence to the fact that anthropogenic emissions of $PM_{2.5}$ are the likely cause for this cycle.

5. CONCLUSIONS

We used a high density network of 116 stations in and around the Phoenix metropolitan area and found a significant weekly cycle in winter season daily precipitation frequencies over the period 1980 to 2007. The maximum frequencies occurred on Monday and the minimum occurred on Thursday; this basic pattern was found for nearly all stations in the network. The weekly cycle in winter precipitation is consistent with an ever-growing body of literature suggesting that $PM_{2.5}$ from motor vehicles acts to suppress precipitation formation. The results from our analyses strongly suggest that human activity in Phoenix is having a statistically significant, recognizable impact on local-area precipitation patterns.

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Figures

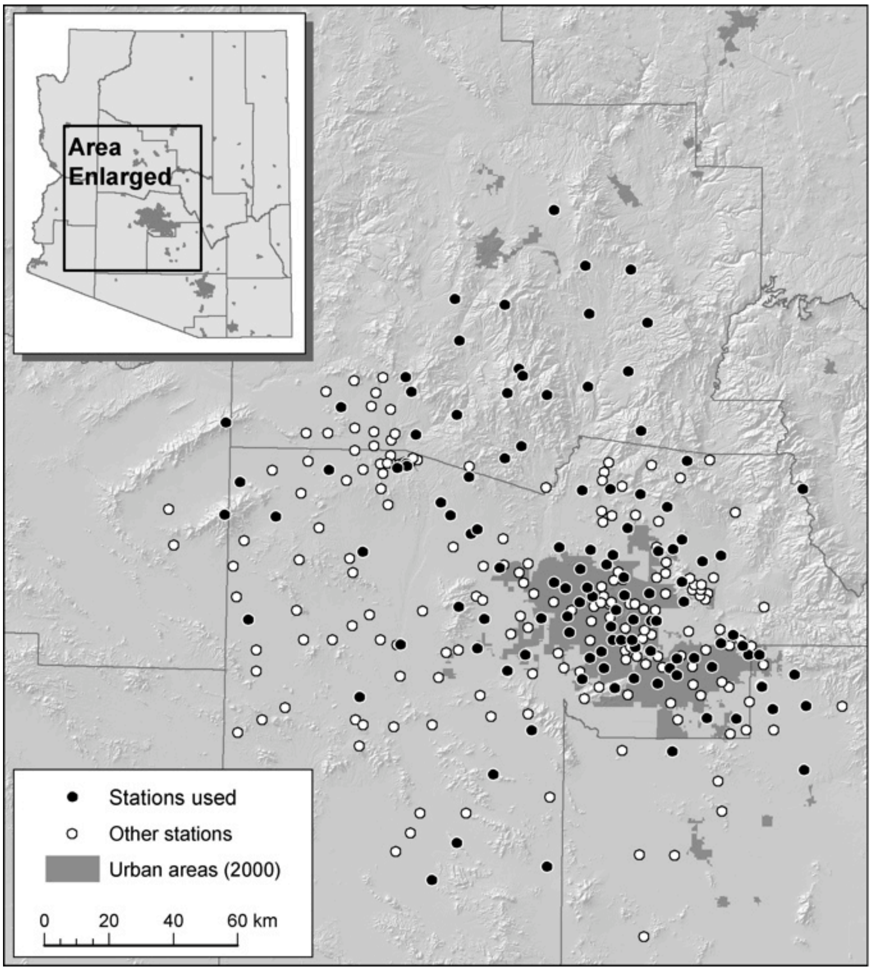

Figure 1: Map of original 291 station network (black circles and white circles) and the final 116 station network (black circles)

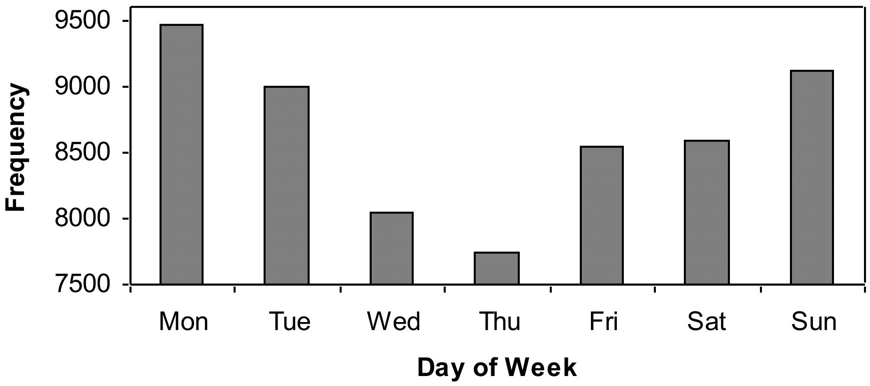

Figure 2: Total frequency of daily winter season events ≥ 1.0 mm by day of the week over the 116 station network; 1980-2007

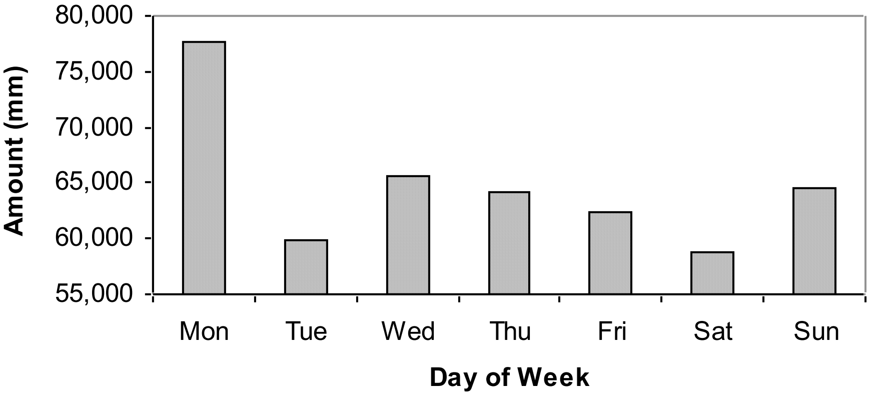

Figure 3: Total amount of precipitation (mm) by day of the week for daily winter season events ≥ 1.0 mm over the 116 station network; 1980-2007

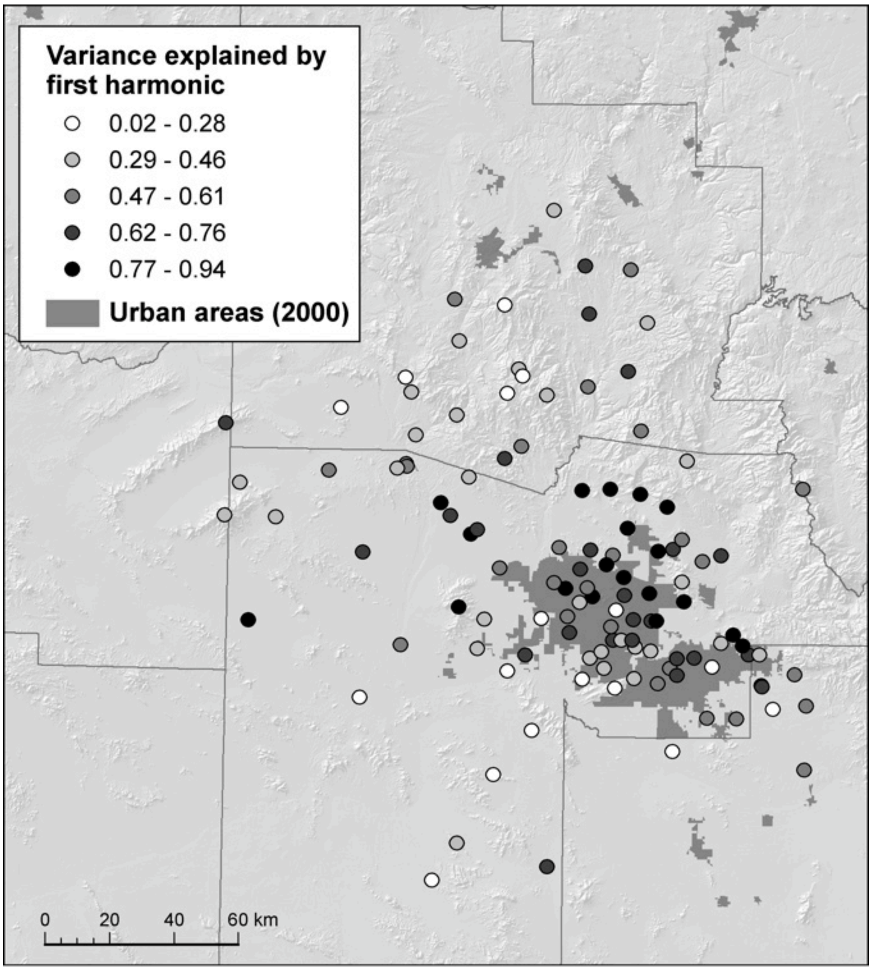

Figure 4: Map of variance explained by the first harmonic for daily precipitation frequencies ranging from 0.02 (whitest circle) to 0.94 (darkest circle)