5.3 EXAMINATION OF THE ARIZONA PRECIPITATION RECORD FOR EVIDENCE OF PRECIPITATION SUPPRESSION BY AIR POLLUTION AEROSOLS

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1. INTRODUCTION

Has air pollution generated from the urbanization and industrialization of the United States during the 20th century had a significant effect on cloud and precipitation characteristics? Air pollution generally results in an increase in the number of small cloud condensation nuclei (CCN), which for a given liquid water content leads to more, smaller cloud droplets (Twomey et al. 1984; Borys et al. 1998). These smaller cloud droplets downwind of urban and industrial areas act to inhibit the efficiency of the precipitation process, resulting in the suppression of the amount of precipitation that reaches the ground (Rosenfeld 1999, 2000; Borys et al. 2000; Borys et al. 2003). Thus, it is important to understand the magnitude and extent of this anthropogenic influence on precipitation.

Givati and Rosenfeld (2004) first attempted to quantify the microphysical effect of air pollution on mesoscale precipitation. They focused on short-lived, shallow clouds (e.g., orographically forced clouds) since pollution is expected to have the greatest effect on precipitation from these types of clouds (Rosenfeld and Woodley 2002). A reduction of 15 – 25% in orographic precipitation was discovered at elevated sites downwind of major coastal urban areas in California and Israel during the 20th century while similar precipitation trends were not observed for more pristine areas. Griffith et al. (2005), Jirak and Cotton (2006), Rosenfeld and Givati (2006), and Rosenfeld et al. (2007) performed related studies for Utah, Colorado, the Western U.S., and China, respectively, and found similar results. At all of these locations, a decreasing trend (~15-30%) in the orographic component of precipitation over the past half century was found downwind of pollution sources (i.e., urban and industrial areas), but not downwind of more pristine locations. Given our physical understanding of the precipitation process, the best explanation of these observations is that the formation of orographic precipitation has been suppressed by pollution aerosols. Following the results of these previous studies, the objective of this study is to investigate the possible effect of air pollution on precipitation in Arizona.

This paper provides a description of the data and methods used to select and compare precipitation stations in Arizona. Results of precipitation trends from these stations are shown for the total annual precipitation and for winter precipitation. Finally, conclusions about the possible effect of air pollution on precipitation in Arizona are presented.

2. DATA AND METHODOLOGY

Arizona is a state comprised of complex terrain with the surface elevation generally increasing from the southwest corner of the state toward the northeast. The regions of interest for this study include the polluted Phoenix basin and surrounding mountainous region (red outlines in Fig. 1) and the more pristine Colorado River basin with higher terrain to its east (green outlines in Fig. 1). The Phoenix metropolitan area has grown significantly over the last several decades from a population of less than a half-million in 1950 to over three million in 2000. The premise behind this study is that orographic precipitation has been affected at elevated locations north and east of the polluted Phoenix basin while orographic precipitation in more pristine parts of the state (e.g., west-central Arizona) has not been significantly affected by air pollution.

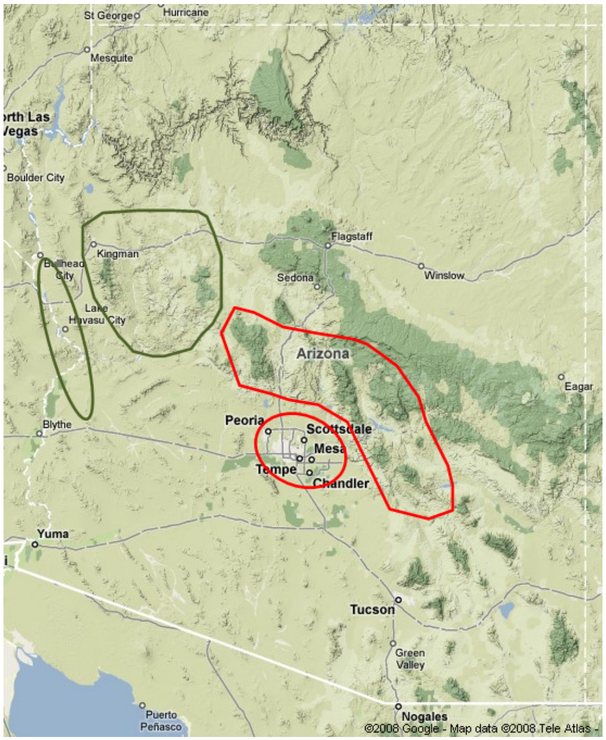

Figure 1. Map of Arizona showing regions of interest for this study. Polluted locations are outlined in red, and pristine locations are outlined in green.

The monthly precipitation data used in this study were obtained from the Western Regional Climate Center. All precipitation stations located in the outlined areas in Figure 1 were included in the study as long as they had at least 50 years of data extending through the

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year 2000 with no more than 10% of the data missing. For every station, each valid month was required to have fewer than six days of data missing, and each valid year (or season) was required to have data from more than half of the months. Consequently, this study included six stations from the Phoenix basin and eleven elevated stations surrounding Phoenix (see Fig. 2 & Table 1) for a total of 66 polluted pairs. In western Arizona, four stations from the Colorado River basin and four nearby elevated stations (see Fig. 3 & Table 1) were examined for a total of 16 pristine pairs.

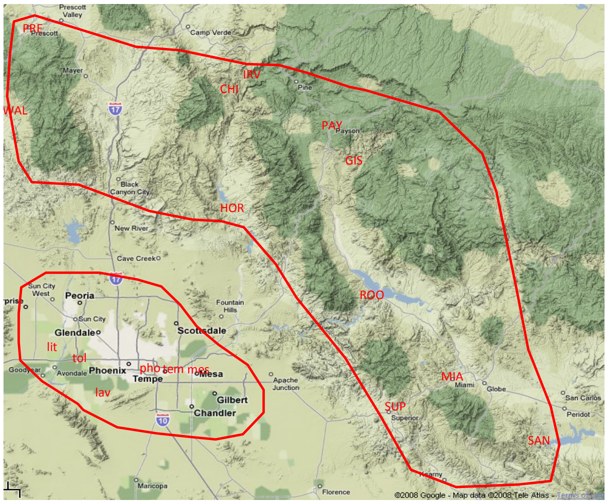

Figure 2. Map of Phoenix area showing polluted precipitation sites included in this study (see Table 1). Low elevation urban sites are labeled with lower-case letters and elevated sites are labeled with upper-case letters.

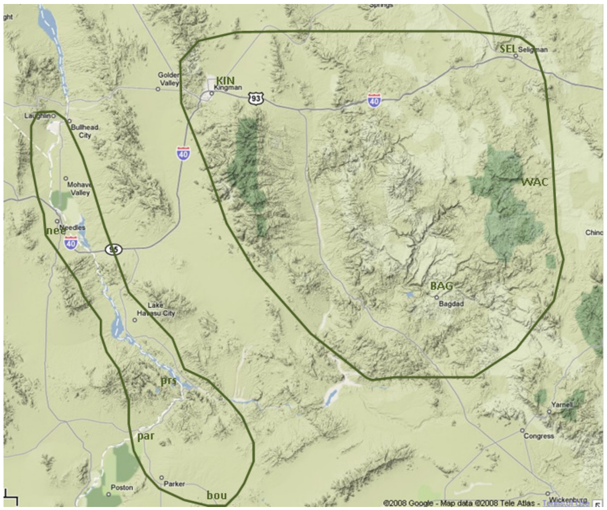

Figure 3. Map of western Arizona showing pristine precipitation sites included in this study (see Table 1). Low elevation sites are labeled with lower-case letters and elevated sites are labeled with upper-case letters.

Table 1. List of polluted and pristine precipitation stations examined in this study, including the station name, abbreviation used in Figs. 2 & 3, years of data used, latitude, longitude, and elevation.

	Station	Map	Years	Lat	Lon	Elevation
Polluted	Laveen 3 SSE	lav	1948-2007	33.337	-112.147	1135
	Litchfield Park	lit	1917-2007	33.499	-112.363	1040
	Mesa	mes	1896-2007	33.411	-111.818	1235
	Phoenix Sky Harbor	pho	1933-2007	33.428	-112.004	1107
	Tempe ASU	tem	1953-2007	33.426	-111.922	1167
	Tolleson 1 E	tol	1951-2007	33.452	-112.243	1025
	Childs	CHI	1915-2005	34.349	-111.698	2650
	Gisela	GIS	1934-2007	34.111	-111.276	2900
	Horseshoe Dam	HOR	1948-2007	33.983	-111.714	2020
	Irving	IRV	1951-2005	34.403	-111.618	3795
	Miami	MIA	1914-2007	33.404	-110.870	3560
	Payson	PAY	1948-2007	34.231	-111.340	4908
	Prescott	PRE	1898-2007	34.571	-112.432	5205
	Roosevelt 1 WNW	ROO	1905-2007	33.673	-111.151	2205
	San Carlos Rsvr	SAN	1900-2007	33.182	-110.526	2532
	Superior	SUP	1920-2006	33.300	-111.097	2860
	Walnut Grove	WAL	1893-2007	34.312	-112.562	3764
Pristine	Bouse	bou	1952-2007	33.943	-114.024	925
	Needles AP, CA	nee	1948-2007	34.768	-114.619	890
	Parker	par	1893-2007	34.155	-114.290	420
	Parker Rsvr, CA	prs	1934-2007	34.290	-114.171	738
	Bagdad	BAG	1925-2007	34.597	-113.174	3955
	Kingman	KIN	1901-2007	35.183	-114.050	3363
	Seligman	SEL	1905-2007	35.332	-113.167	5584
	Walnut Creek	WAC	1915-2007	34.928	-112.810	5090

Arizona has an arid climate with two distinct modes of precipitation. The first mode of precipitation occurs during the North American monsoon in the form of thunderstorms from late June through early September when low-level moisture is advected northward from the Gulf of California. The other mode of precipitation is baroclinically forced as synoptic-scale troughs approach from the west carrying moisture from the Pacific Ocean that generally leads to upslope flow in central and northern Arizona. Since this mode of precipitation primarily occurs in the winter, any precipitation that falls outside of the monsoon season (i.e., October through May) is classified as winter precipitation. Note that April, May, and June are typically the driest months in Arizona. Figure 4 reveals that there is a strong positive correlation between elevation and precipitation in central Arizona. In fact, the station elevation alone can explain a large portion of the variance in precipitation, especially during the monsoon. Overall, monsoon precipitation generally accounts for about one-third of the annual precipitation in the Phoenix area.

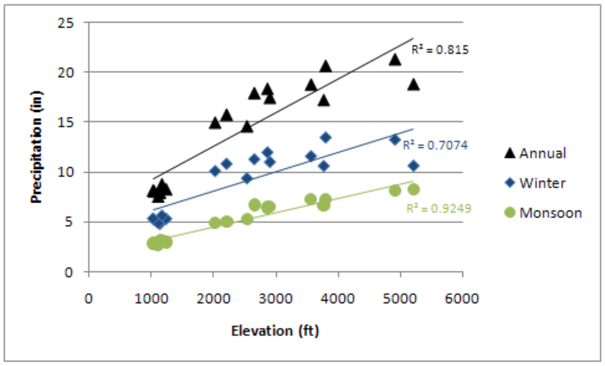

Figure 4. Average annual, winter, and monsoon precipitation for Phoenix-area stations plotted against elevation.

For this study, the variable of interest is the orographic enhancement factor (R_o), which is simply the ratio between the precipitation at a higher elevation station to that of a lower elevation site. In this study, R_o is calculated on an annual basis and also for winter precipitation. Looking at the precipitation ratio of two highly correlated precipitation stations should reduce the influence of any long-term change in precipitation (e.g., a shift in weather patterns) on the overall trend. Each pair of stations in this study has a correlation greater than 0.60 for annual precipitation and 0.70 for winter precipitation. Simple linear least-squares regression is applied to each pair of stations to see if a trend exists in R_o, and a t-test is used to check for statistical significance.

3. RESULTS

Each elevated station is paired with each lower elevation station for both the polluted and pristine regions of Arizona for a total of 66 polluted pairs and 16 pristine pairs. R_o is calculated each year for both annual and winter precipitation for each pair of stations. The data are analyzed to determine whether a statistically significant decreasing trend in R_o exists in the precipitation record. An example of one pair of polluted stations is provided in Fig. 5. The stations at Mesa (Fig. 5a) and Prescott (Fig. 5b) do not individually show a statistically significant trend in winter precipitation since 1900 (i.e., $P>0.05$). However, the ratio of their winter precipitation in Fig. 5d does show a statistically significant decrease over time ($P<<0.05$).

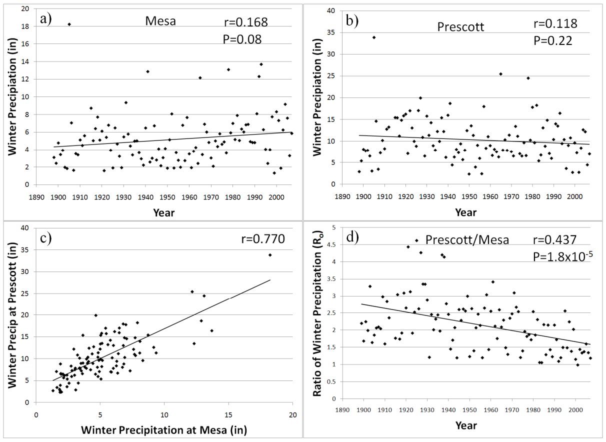

Figure 5. Trends of winter precipitation measured for polluted sites: a) Mesa and b) Prescott. The correlation of precipitation between the stations (c) and R_o (d) are shown. The linear correlation coefficient, r, and the statistical significance corresponding to the t-test, P, are shown in the panels.

With the large number of stations examined in this study, it is not practical to show all of the results in this fashion. Thus, the results are summarized by focusing on the trend of R_o (e.g., Fig. 5d). For each pair of stations, 95% and 99% confidence intervals (CI) are calculated for the slope of R_o and converted to an annual percentage change in R_o. For example, an annual percentage change of -0.5% over 50 years is a 25% change in R_o, which would suggest that for an inch of rain at Mesa, Prescott would now receive 1.5 inches of rain instead of 2 inches that might have been expected fifty years ago. The results of the annual percentage change in winter R_o for Prescott is provided in Fig. 6 as an example. Clearly, the slope of winter R_o is negative for Prescott when compared to all of the lower elevation Phoenix stations at very high statistical significance. The results are summarized for all pairs of stations in a similar way in the following sections.

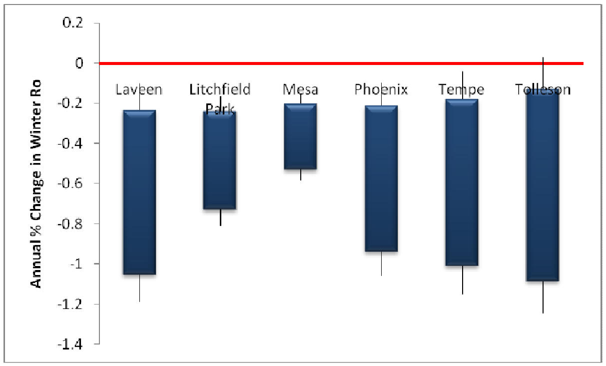

Figure 6. Confidence intervals for the annual percentage of change in winter R_o for Prescott compared to Phoenix stations (bars indicate 95% CI and lines indicate 99% CI).

3.1 *Annual Precipitation*

Figure 7 shows the percentage change in the annual R_o for all 66 polluted pairs. The general picture is that the precipitation ratio has decreased for annual precipitation in the Phoenix area. Not every pair of stations shows a statistically significant decrease in R_o; however, the vast majority (92.4%) at least show a negative trend in R_o (see Table 2). If this negative trend in R_o is due to the suppression of precipitation, then a similar trend should not be evident for the 16 pristine pairs. Figure 8 reveals that a negative overall trend in R_o is not evident for the pristine sites, as only half of the pairs show a negative slope in R_o (Table 2). These results provide support to the idea that air pollution has led to precipitation suppression at elevated locations downwind of the Phoenix metropolitan area over the last half century.

Table 2: Summary of results showing the percentage of polluted and pristine pairs that showed a decreasing R_o at a statistically significant level.

		% with	% with statistically significant decrease in R_o	
		neg. slope	at 95%	at 99%
Annual	polluted	92.4	30.3	12.1
	pristine	50.0	6.25	0.0
Winter	polluted	97.0	56.1	27.3
	pristine	75.0	12.5	6.25

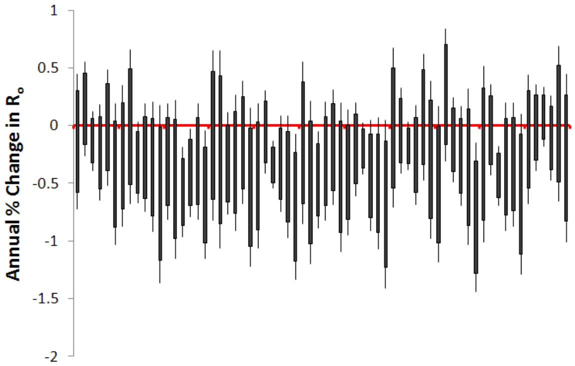

Figure 7. Confidence intervals for the annual percentage of change in annual R_o for the 66 polluted pairs (bars indicate 95% CI and lines indicate 99% CI).

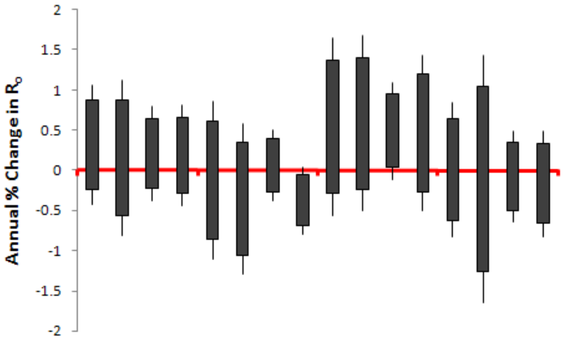

Figure 8. Confidence intervals for the annual percentage of change in annual R_o for the 16 pristine pairs (bars indicate 95% CI and lines indicate 99% CI).

3.2 *Winter Precipitation*

The effect of pollution on precipitation is expected to be more significant for shallow, orographic clouds than for deep convective storms (e.g., monsoon precipitation); thus, examining only winter precipitation should produce stronger evidence of precipitation suppression. In addition, the majority of winter precipitation events in Arizona include a significant upslope component, resulting in pollution being advected from the Phoenix basin to higher terrain. The correlation of winter precipitation is also larger for all pairs of stations compared to the correlation of annual precipitation, indicating better spatial continuity of precipitation in winter storms. Looking at winter R_o for polluted pairs (Fig. 9), there is stronger evidence of a decreasing trend than for annual precipitation. More than half of the polluted pairs show a statistically significant decrease in winter R_o at the 95% confidence level, which is almost double the number for annual R_o (see Table 2). The pristine pairs, on the other hand, do not show a clear trend in winter R_o (see Fig. 10). A stronger signal of decreasing R_o for winter precipitation compared to annual precipitation supports the idea that air pollution may indeed be inhibiting the precipitation process for shallow upslope events, which is in agreement with findings from previous studies.

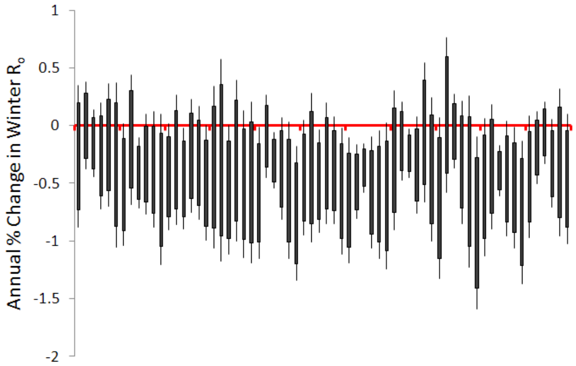

Figure 9. Confidence intervals for the annual percentage of change in winter R_o for the 66 polluted pairs (bars indicate 95% CI and lines indicate 99% CI).

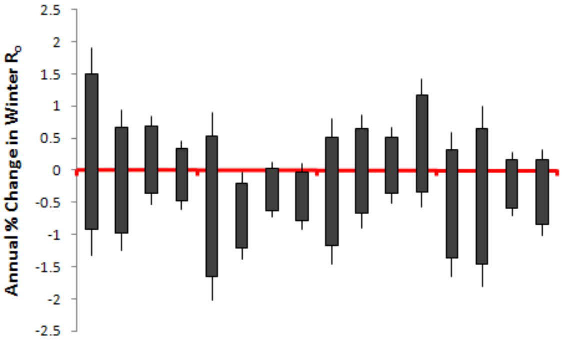

Figure 10. Confidence intervals for the annual percentage of change in winter R_o for the 16 pristine pairs (bars indicate 95% CI and lines indicate 99% CI).

Although there is not an obvious trend in winter R_o for the pristine pairs (Fig. 10), it is worth mentioning that winter R_o reveals a more negative trend (75% show a negative slope; Table 2) than annual R_o. This is likely due to the fact that no truly pristine area exists, as most locations are subject to more air pollution today than fifty years ago. Thus, the "pristine" area chosen for this study would not be expected to be completely void of precipitation suppression. In fact, both of the statistically significant decreases in winter R_o for the pristine pairs came from Kingman, which is only 100 miles southeast of the rapidly developing and growing city of Las Vegas, Nevada.

4. DISCUSSION AND CONCLUSIONS

Monthly precipitation data were analyzed for polluted and pristine areas in Arizona to identify the possibility of precipitation suppression by pollution. The orographic enhancement factor, R_o, was examined for the polluted Phoenix area and a more pristine region in western Arizona to see if there has been a decreasing trend in this ratio over the last fifty years. Overall, R_o showed a predominantly negative trend in the polluted region, but did not reveal a strong trend in the pristine region. Additionally, a stronger decreasing trend of R_o was found when examining only winter precipitation, which is more susceptible to the microphysical effects of air pollution than deep convective storms during the monsoon. This evidence is not necessarily conclusive, but it does support the idea that anthropogenic air pollution has led to the suppression of orographic precipitation downwind of the Phoenix basin over the last half century.

Precipitation suppression for upslope events downwind of Phoenix could have major implications on the water supply for this growing metropolitan area. The Phoenix metropolitan area relies on runoff from the mountains as a source of water; therefore, any reduction of precipitation in this area would be a detriment to the already limited water supply. As the area becomes increasingly populated, water demands will increase along with pollution emissions, making the problem worse. Additional studies, including field observations and modeling, should be performed to get a true handle on the extent of this problem.

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