P1.6 EFFECT OF AIR POLLUTION ON PRECIPITATION ALONG THE FRONT RANGE OF THE ROCKY MOUNTAINS

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1. INTRODUCTION

Air pollution generated in industrial and urban areas can act to suppress precipitation (Rosenfeld 1999, 2000). In fact, large (>1μm) pollution particles, which can actually enhance precipitation, are often effectively removed from pollution emissions (Gavati and Rosenfeld 2004) while the smaller particles get expelled into the atmosphere. Therefore, 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). Consequently, the growth of precipitation is inhibited by this narrow droplet spectrum due to small collection efficiencies and small collection kernels (Warner and Twomey 1967). With the industrialization and urbanization throughout the United States during the 20th century, it is important to understand how the corresponding increase in air pollution has affected precipitation.

The first study to attempt to quantify the microphysical effect of air pollution on mesoscale precipitation was done by Gavati and Rosenfeld (2004). 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 orographic precipitation by 15 – 25% was discovered at elevated sites downwind of major coastal urban areas in California and Israel during the 20th century. Similar precipitation trends for elevated sites downwind of more pristine areas were not observed for these same regions. Consequently, the best explanation for the precipitation reduction downwind of urban areas is the precipitation suppression brought about by the increased number of small particles in the atmosphere from pollution.

Following the interesting and significant results of Gavati and Rosenfeld (2004), the objective of this study is to investigate the effect of air pollution on the precipitation at elevated sites downwind of urban areas along the Front Range of Colorado. Although the geographical features differ from the study of Gavati and Rosenfeld (2004), the same mechanisms are expected to apply for upslope precipitation along the Rocky Mountains. Therefore, one would expect a relative decrease in orographic precipitation downwind (i.e., west) of Denver over the last half-century due to an increasing concentration of small pollution aerosols.

This paper provides a description of the data and methods used to select and compare precipitation stations along the Front Range. Analyses of precipitation trends from these stations are shown for the total annual precipitation and the annual upslope precipitation. Finally, the implications of the findings are discussed with respect to air pollution.

2. DATA AND METHODOLOGY

Two types of data were needed to conduct this study: daily precipitation data and daily wind data. These data were obtained for the stations of interest from the National Climatic Data Center (NCDC) for the years 1950 through 2002. There are numerous precipitation stations along the Front Range of Colorado, but only a few of these stations have continuous precipitation measurements since 1950. As a result, the number of possible combinations of polluted and pristine sites was limited. Additionally, the complex terrain of the Rocky Mountains complicates the situation. Thus, the most straightforward interpretation of results involved picking sites directly downwind (i.e., west) and slightly elevated above urban sites along the Front Range.

Polluted sites were chosen from the Denver metro area and Colorado Springs since these are the largest, most populated urban areas along the Front Range. The pair of polluted sites selected for the Denver area were the Cherry Creek Dam (1721 m) and Morrison (elevated; 1780 m), and the pair of polluted sites selected for Colorado Springs were the Colorado Springs Municipal Airport (1884 m) and Ruxton Park (elevated; 2758 m) (see Fig. 1). The "pristine" sites were difficult to choose since the Front Range has become increasingly populated and developed over the last half century, but the best sites were north of Denver. The sites selected for the pristine area were Greeley (1437 m), Waterdale (elevated; 1594 m), and Estes Park (elevated; 2280 m) (see Fig. 1). These particular pairs of sites were chosen for their similar geographical arrangement and horizontal distance between them.

The only daily wind data available for this study were from Stapleton International Airport in Denver (see Fig. 1). These data were given in terms of the direction for the peak wind gust during the day. Upslope winds were defined as those days when the peak wind was north-northeasterly to south-southeasterly (20°-160°). Thus, any precipitation recorded on a day with upslope winds was considered upslope precipitation. This daily upslope precipitation was summed over the entire year

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and analyzed as annual data. Certainly, this general definition of upslope and the nature of the wind data could lead to overestimation of upslope precipitation for some events and underestimation for other events.

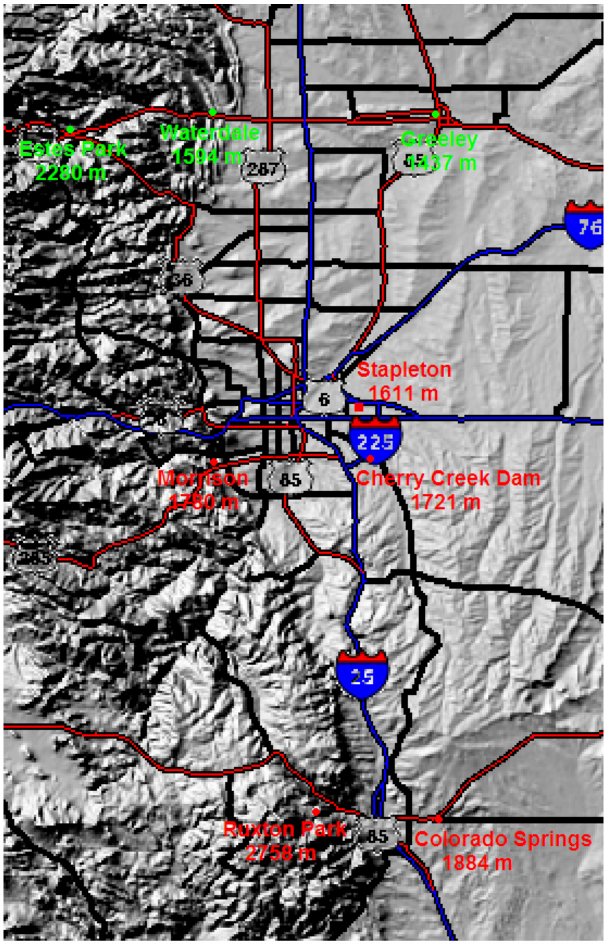

Figure 1. Map of rain and wind gauge locations along Front Range of Colorado. Pristine locations are in green, and polluted locations are in red. Elevations are noted below station names.

3. RESULTS

Ideally, the suppression of precipitation by pollution would be most evident downwind of urban areas for shallow, upslope events. This reduction of precipitation should be apparent when looking at the trend of the orographic enhancement factor (OEF), where the OEF is defined as the ratio between the precipitation in the hills to the precipitation at the lower elevation site (Gavati and Rosenfeld 2004). The OEF is calculated for sites along the Front Range using daily precipitation data for the total annual precipitation and annual upslope precipitation for the last half-century.

3.1 *Total Precipitation – Polluted Sites*

Figure 2 shows the total annual precipitation for the polluted Denver sites over the last 50 years. Neither Cherry Creek nor Morrison shows a statistically significant trend in annual precipitation, as seen by the large P values in Figs. 2a and 2b. Figure 2c shows that the precipitation at these sites is fairly well correlated (large R value). A decreasing trend in the OEF is shown in Fig. 4d, but the trend is not very statistically significant (P=0.10). If this trend in the total annual precipitation is due to the suppression of precipitation in upslope events, then a significant decrease in the OEF should be evident when looking at just upslope precipitation (see Fig. 4).

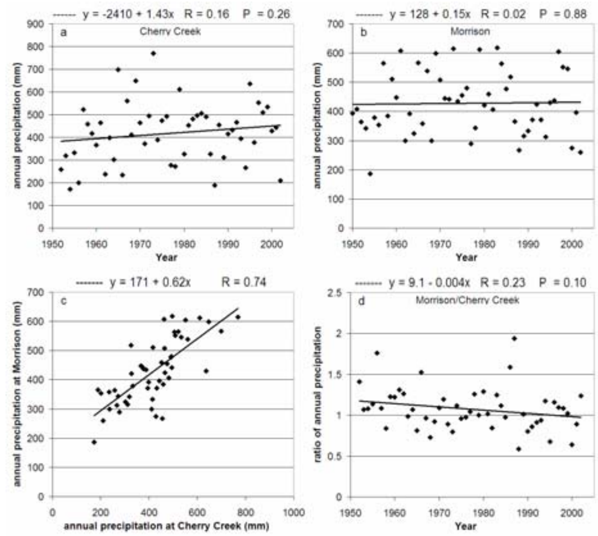

Figure 2. Trends of annual precipitation measured for the Denver polluted sites: a) Cherry Creek and b) Morrison, the elevated site. The correlation between the two stations (c) and their ratio of annual precipitation (d) are also shown. R is the linear correlation coefficient and P is the statistical significance that corresponds to the t-test.

3.2 *Total Precipitation – Pristine Sites*

Figure 3 shows the total annual precipitation for the pristine sites north of the Denver area over the last five

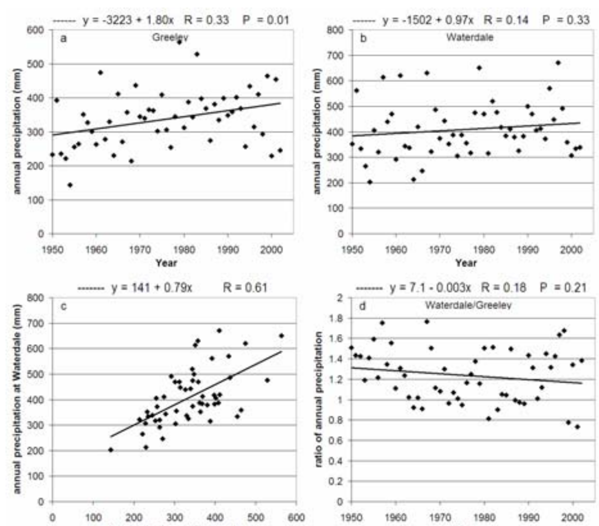

Figure 3. Same as Fig. 2, but for the pristine sites: a) Greeley and b) Waterdale, the elevated site.

decades. Even with the recent drought conditions, Greeley has seen a statistically significant (P=0.01) increase in precipitation over the last 50 years. Waterdale, the elevated site at the foothills, has seen a less significant increase in precipitation. The precipitation ratio of these two stations (see Fig. 3d) reveals a decreasing trend with time, but one that is not statistically significant (P=0.21).

3.3 *Upslope Precipitation – Polluted Sites*

Considering only upslope precipitation should produce the strongest evidence of precipitation suppression since upslope winds carry the pollution up the terrain affecting the formation of clouds and precipitation. The average fraction of annual upslope precipitation for the Denver metro sites is slightly greater than one-third. Cherry Creek has an annual upslope precipitation average of 148 mm, which is 35% of the total annual precipitation average of 418 mm. Morrison has a slightly higher percentage of annual average upslope precipitation (38%), receiving 165 mm of upslope precipitation annually out of 429 mm of total precipitation.

Figure 4 shows the same data as Fig. 2, except only upslope precipitation is considered. Cherry Creek has not experienced a statistically significant trend in upslope precipitation, but Morrison has seen a statistically significant (P=0.04) decrease in upslope precipitation over the past several decades. This alone does not indicate the presence of precipitation suppression by pollution since a change in the general weather pattern could also have led to a reduction in upslope precipitation. The strongest evidence of precipitation reduction is shown in Fig. 4d when looking at the precipitation ratio between Morrison and Cherry Creek. There is strong statistical evidence (P=0.02) that upslope precipitation at Morrison has decreased relative to upslope precipitation at Cherry Creek during the last half century. In fact, the OEF decreased by 30% during this time (ending/starting ratio = 0.953/1.352 = 0.70). The loss of upslope precipitation at Morrison could be explained by precipitation suppression due to pollution, assuming that the concentration of small CCN has increased during this period in the Denver metro area.

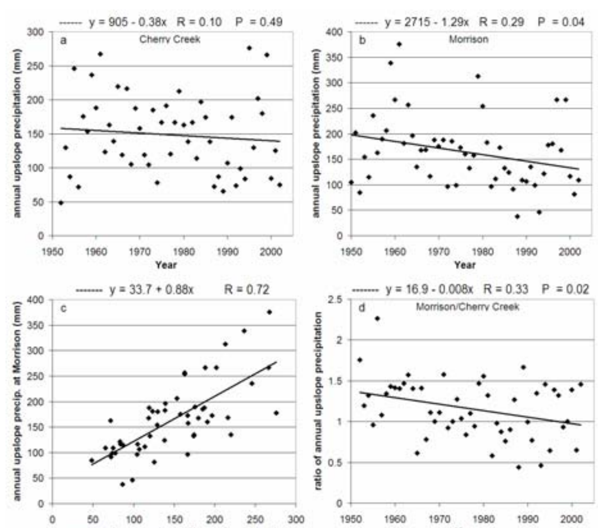

Figure 4. Same as Fig. 2, but considering only upslope precipitation.

Figure 5 shows the precipitation trends for a pair of polluted sites from the Colorado Springs area. The sites by themselves do not show a precipitation trend since 1960. However, there is a statistically significant (P=0.02) decrease in the ratio of upslope precipitation at Ruxton Park to Colorado Springs over this period. The OEF decreased by almost 40% during this time (ending/starting ratio = 1.065/1.737 = 0.61), providing more evidence of precipitation suppression by air pollution along the Front Range.

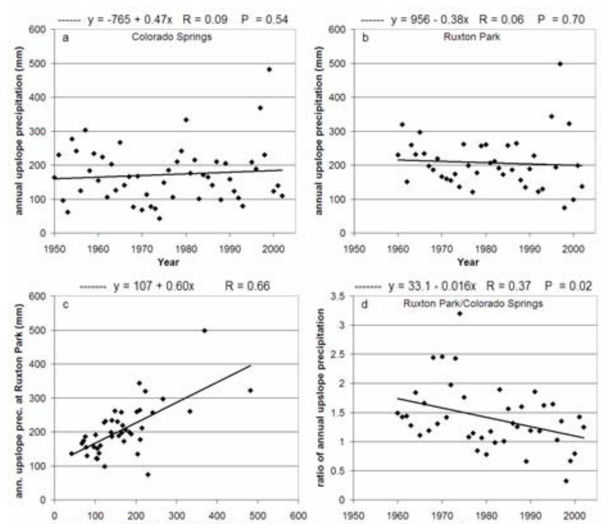

Figure 5. Same as Fig. 4, but for another pair of polluted sites: a) Colorado Springs and b) Ruxton Park, the elevated site.

Figure 6 shows a polluted case from the Gavati and Rosenfeld (2004) study. Clearly, they were dealing with a longer time period and much larger precipitation amounts, especially for their elevated site, which led to significantly larger OEFs. Regardless of the differences between their study and this one, the overall results are similar. Both studies show a statistically significant decrease around 30% in orographic precipitation at an elevated site relative to the upwind urban site.

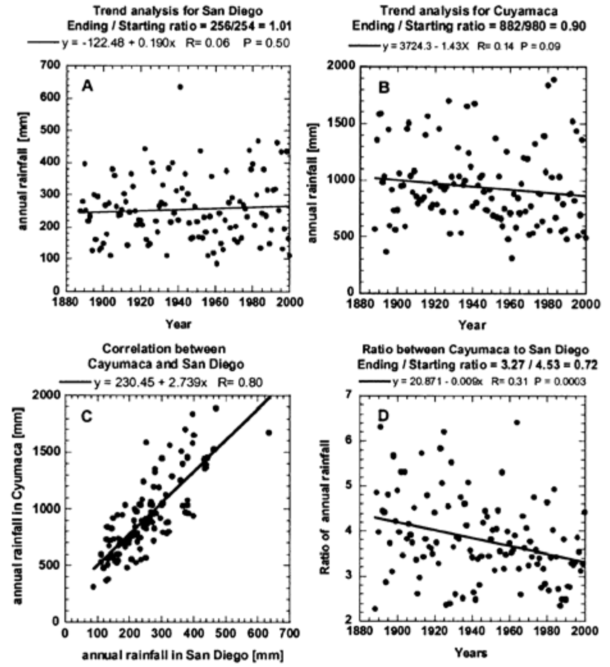

Figure 6. Similar to Fig. 2, but for San Diego and the downwind hilly station of Cuyamaca. [From Gavati and Rosenfeld (2004)]

3.4 *Upslope Precipitation – Pristine Sites*

If air pollution in urban areas is causing precipitation suppression, then the same effects would not be expected in more pristine areas. In other words, there should not be a decrease in the OEF over time for upslope precipitation at Greeley and Waterdale. Of course, it is important to understand that these sites are not truly pristine, but are less polluted than the Denver and Colorado Springs sites. Both Greeley and Waterdale receive more than one-third of their average annual precipitation from upslope events. Greeley receives an annual average of 124 mm (37%) of upslope precipitation while Waterdale receives an annual average of 169 mm (41%) of upslope precipitation.

Figures 7a and 7b reveal that neither Greeley nor Waterdale experienced a trend in upslope precipitation with time. Additionally, there is not a statistically significant (P=0.16) trend in the ratio of their upslope precipitation amounts (see Fig. 7d). The fact that a significant trend is not found in the OEF for a more pristine area provides additional support that precipitation suppression has likely occurred west of Denver and Colorado Springs due to air pollution. As a side note, it is not surprising that the data show a slight decreasing trend in the OEF since this area would not be expected to be completely void of precipitation suppression, as it has also become increasingly urbanized over the past 50 years.

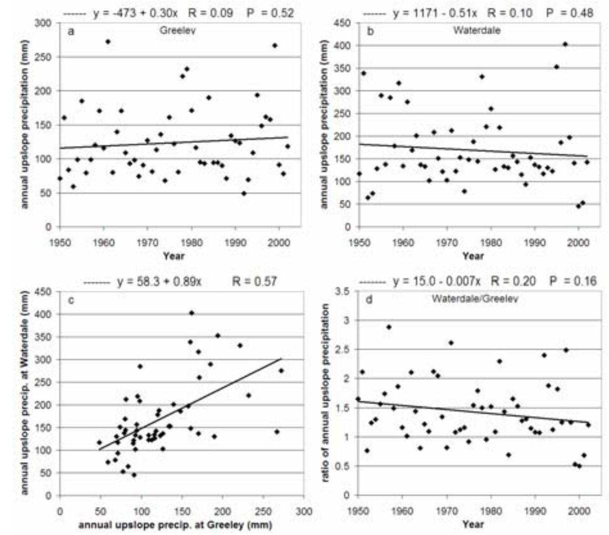

Figure 7. Same as Fig. 3, but considering only upslope precipitation.

Precipitation from another elevated pristine site, Estes Park, is paired with Greeley in Fig. 8. Estes Park does not show a trend in upslope precipitation, nor was a statistically significant (P=0.21) trend evident in the OEF (see Fig. 8d). However, as anticipated from the fact that these locations are not completely pristine, the OEF does reveal a weakly decreasing trend. This evidence provides further support to the possibility of precipitation suppression by air pollution along the Front Range of Colorado.

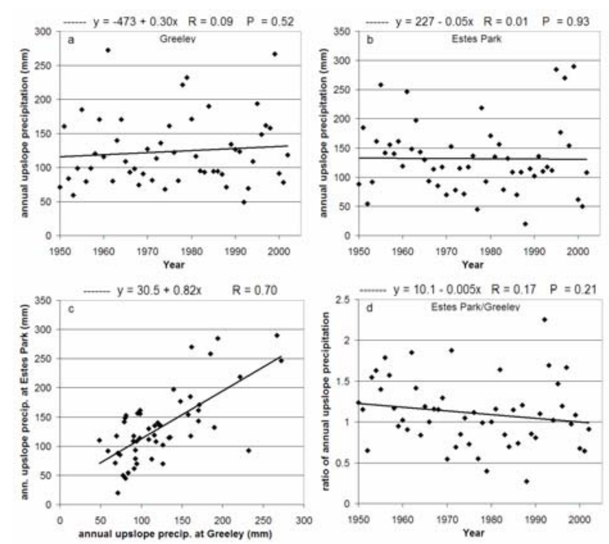

Figure 8. Same as Fig. 3, but for another pair of pristine sites: a) Greeley and b) Estes Park, the elevated site.

4. DISCUSSION AND CONCLUSIONS

Daily precipitation data were analyzed for polluted and pristine areas along the Front Range of Colorado to identify the possibility of precipitation suppression by pollution. No statistically significant trends were found in the OEF for the total annual precipitation. However, decreasing trends of upslope precipitation for elevated sites relative to upwind polluted sites in Denver and Colorado Springs were found without a statistically significant trend for a more pristine area. As this trend has occurred during a period of industrialization and urbanization, it suggests that anthropogenic air pollution has led to the suppression of orographic precipitation west of metropolitan areas along the Front Range over the last half century. Undoubtedly, an even stronger argument could be made if more polluted and pristine sites with long-term precipitation records were available for analysis along the Front Range.

If there truly has been precipitation suppression on the order of 30% for upslope events west of Denver and Colorado Springs, this could have major implications on the water supply for these cities. Continued precipitation suppression at this rate would result in precipitation losses on the order of 1 mm per year to the west of these cities. They rely heavily on snowmelt and runoff from the mountains as a source of water; therefore, any reduction of precipitation in this area would be a detriment to the already depleted water supply. Certainly, this sets up a vicious circle for these areas. As the cities become increasingly populated, water demands increase along with pollution emissions. An increased concentration of pollution aerosols could lead to further precipitation suppression west of the cities, which would lead to less available water. Precipitation suppression by pollution can only make the water shortage worse and must be studied in detail to get a true handle on the extent of this problem.

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