NOTES AND CORRESPONDENCE

Effect of Air Pollution on Precipitation along the Front Range of the Rocky Mountains

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ABSTRACT

Air pollution generated in industrial and urban areas can act to suppress precipitation by creating a narrow cloud droplet spectrum, which inhibits the collision and coalescence process. In fact, precipitation ratios of elevated sites to upwind coastal urban areas have decreased during the twentieth century for locations in California and Israel while pollution emissions have increased. Precipitation suppression by pollution should also be evident in other areas of the world where shallow, orographic clouds produce precipitation. This study investigates the precipitation trends for sites along the Front Range of the Rocky Mountains to determine the effect of air pollution on precipitation in this region. The examination of precipitation trends reveals that the ratio of upslope precipitation for elevated sites west of Denver and Colorado Springs, Colorado, to upwind urban sites has decreased by approximately 30% over the past half-century. Similar precipitation trends were not found for more pristine sites in the region, providing evidence of precipitation suppression by air pollution.

1. Introduction

Air pollution generated in industrial and urban areas can act to suppress precipitation (Rosenfeld 1999, 2000; Borys et al. 2000, 2003). In fact, large (>1 μm) pollution particles, which can actually enhance precipitation, are often effectively removed from pollution emissions (Givati 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 1974; Borys et al. 1998). As a consequence, the growth of precipitation is inhibited by this narrow droplet spectrum because of small collection efficiencies and small collection kernels (Warner and Twomey 1967). With the industrialization and urbanization throughout the United States during the twentieth century, it is important to understand how the corresponding increase in air pollution has affected precipitation.

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The first study to attempt to quantify the microphysical effect of air pollution on mesoscale precipitation was done by Givati and Rosenfeld (2004). They focused on short-lived, shallow clouds (e.g., orographically forced clouds) because pollution is expected to have the greatest effect on precipitation from these types of clouds (Rosenfeld and Woodley 2003). 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 twentieth century. Similar precipitation trends for elevated sites downwind of more pristine areas were not observed for these same regions. 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 Givati 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 and meteorological features differ from the study of Givati and Rosenfeld (2004), the same mechanisms are hypothesized to apply for upslope precipitation along the Rocky Mountains. Assuming that the

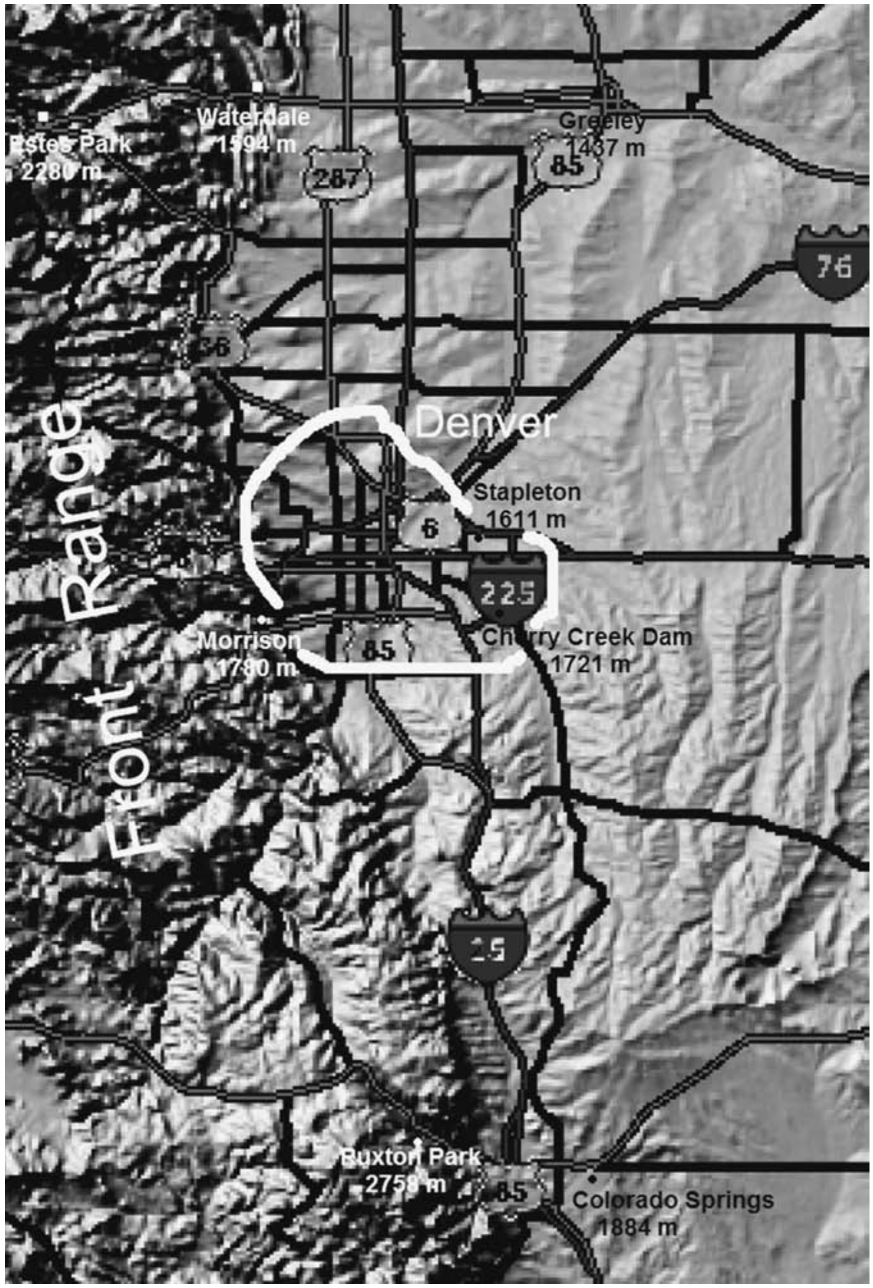

FIG. 1. Map of rain and wind gauge locations along the Front Range of Colorado. Pristine locations are to the north (Greeley, Waterdale, and Estes Park). Polluted locations for Denver (Cherry Creek Dam and Morrison) and Colorado Springs (Colorado Springs Municipal Airport and Ruxton Park) are to the south. The elevated stations are in white, with elevations noted below the station names.

production of small pollution aerosols has increased over time for metropolitan areas along the Front Range, then the increased number of atmospheric aerosols would act to suppress the precipitation process through the creation of a narrow droplet spectrum when advected up the terrain. Therefore, one would expect a relative decrease in orographic precipitation downwind (i.e., west) of Denver over the last half-century because of an increasing concentration of small pollution aerosols.

This paper provides a description of the data and methods used to select and compare precipitation sta-

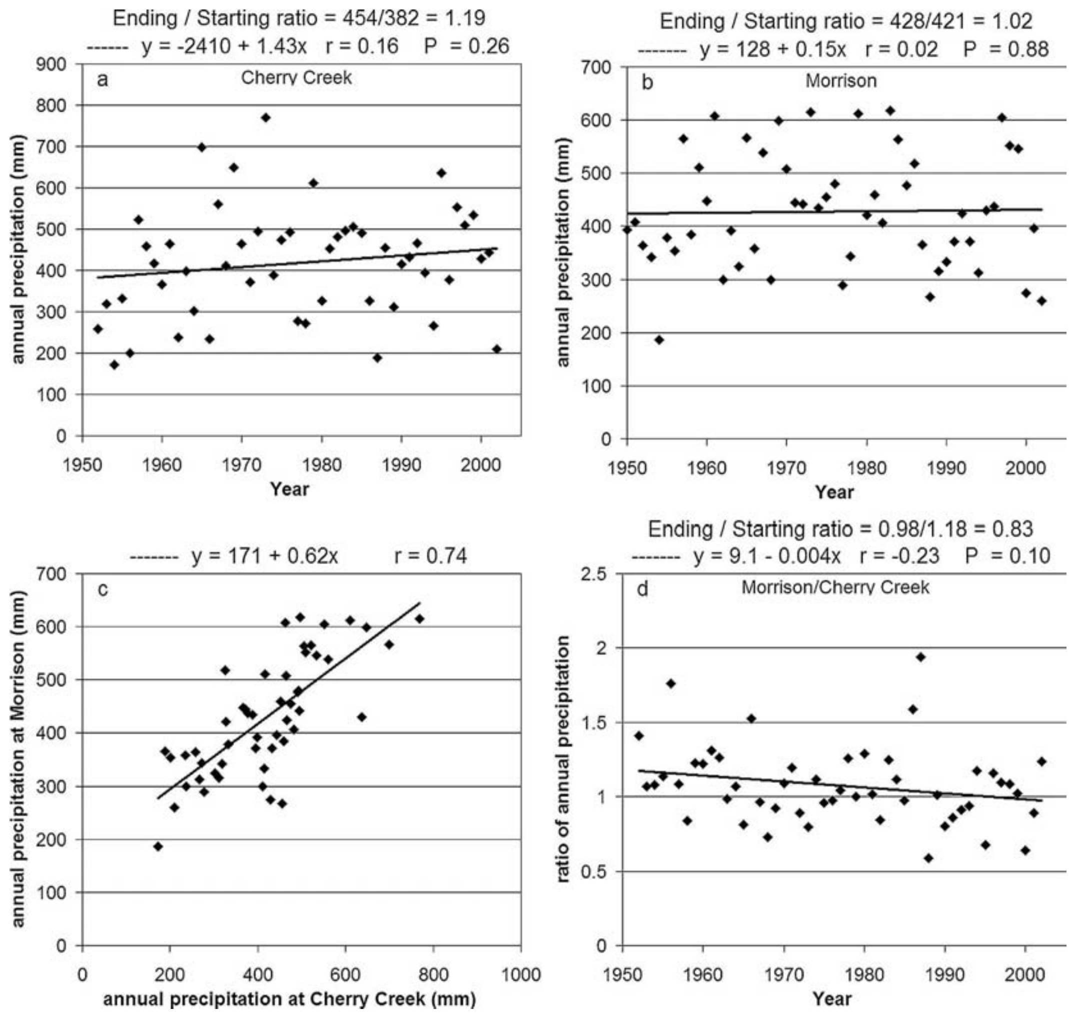

FIG. 2. Trends of annual precipitation measured for the Denver polluted sites: (a) Cherry Creek and (b) Morrison, the elevated site. The (c) correlation between the two stations and (d) their ratio of annual precipitation are also shown. The linear correlation coefficient r and the statistical significance corresponding to the Student's t test P are shown above the panels.

tions along the Front Range. Analyses of precipitation trends from these stations are shown for the total annual precipitation and the annual upslope precipitation. The implications of the findings are discussed with respect to air pollution.

2. Study area, data, and method

The Front Range of the Rocky Mountains extends meridionally across the central portion of northern Colorado with numerous cities being developed right along the eastern slopes. Unlike the locations studied by Givati and Rosenfeld (2004), the location of interest in this study is on the leeward side of a mountain range well removed from its sources of moisture: the Pacific Ocean and the Gulf of Mexico. Thus, the climate is semiarid, with the majority of the precipitation falling during the warm season (i.e., April–September). Because the goal of this study is to determine the effect that urbanization along the Front Range has had on the amount of local precipitation, an emphasis is placed on precipitation events that result from easterly winds carrying low-level moisture and pollution up the terrain.

Two kinds 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 for 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. In

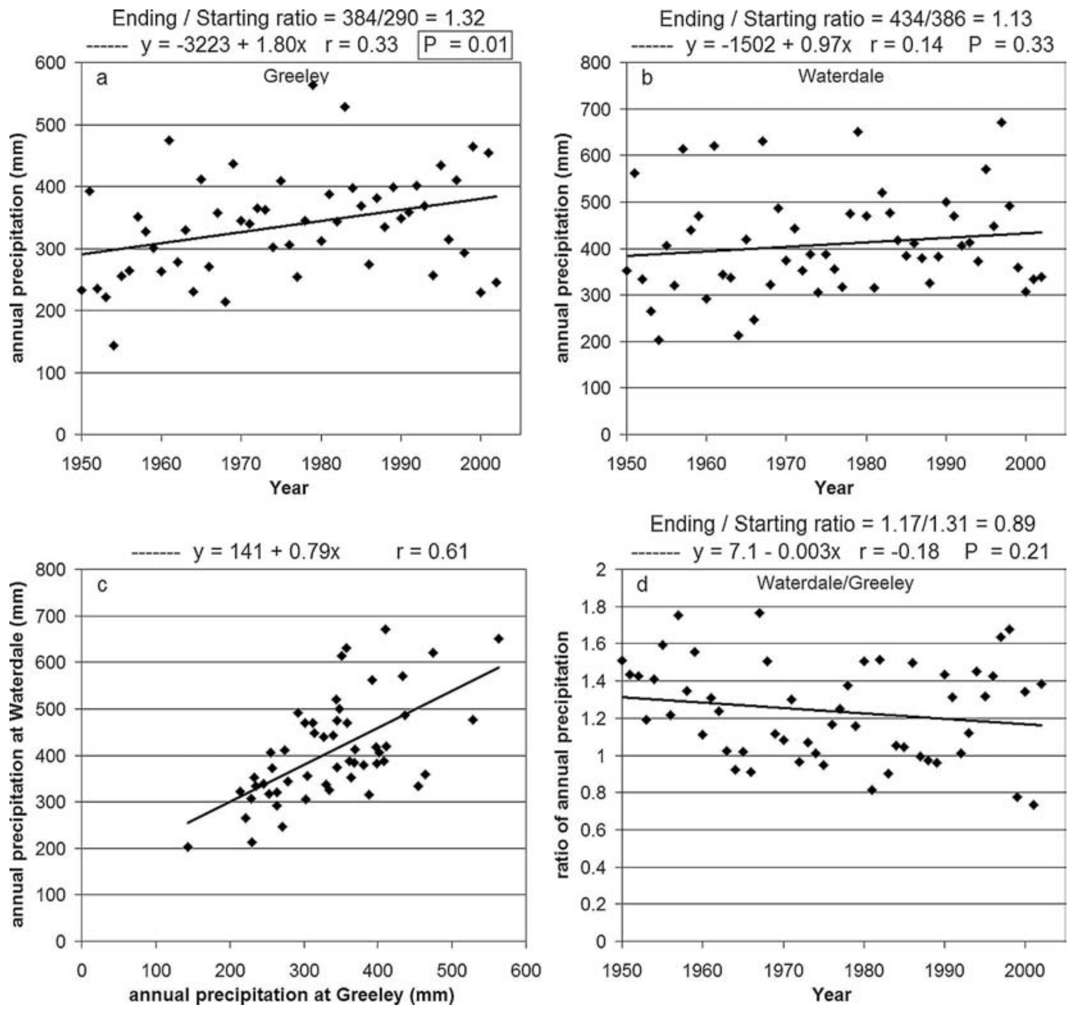

FIG. 3. Same as Fig. 2, but for the pristine sites: (a) Greeley and (b) Waterdale, the elevated site.

addition, the complex terrain of the Rocky Mountains complicates the situation. Thus, the most straightforward interpretation of results involved picking sites directly downwind of (i.e., west) and slightly elevated above urban sites along the Front Range.

Polluted sites were chosen from the Denver metropolitan area and Colorado Springs, Colorado, because these are the largest, most populated urban areas along the Front Range. The population of the Denver metropolitan area has increased from over 500 000 in 1950 to more than 2 million in 2000, and the number of people living in the Colorado Springs metropolitan area has increased from around 75 000 to more than 500 000 over the last 50 yr. 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 because 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), Colorado (see Fig. 1). The population of the Greeley area has grown significantly over the last 50 yr from around 20 000 to over 85 000, but the area is still much less populated than are the Denver and Colorado Springs areas. The particular pairs of sites selected for this study were chosen for their strong correlation of precipitation and similar geographical arrangement. The temperature, moisture, and vertical motion associated with precipitation events are assumed to remain systematically similar for the pairs of sites during the study period.

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

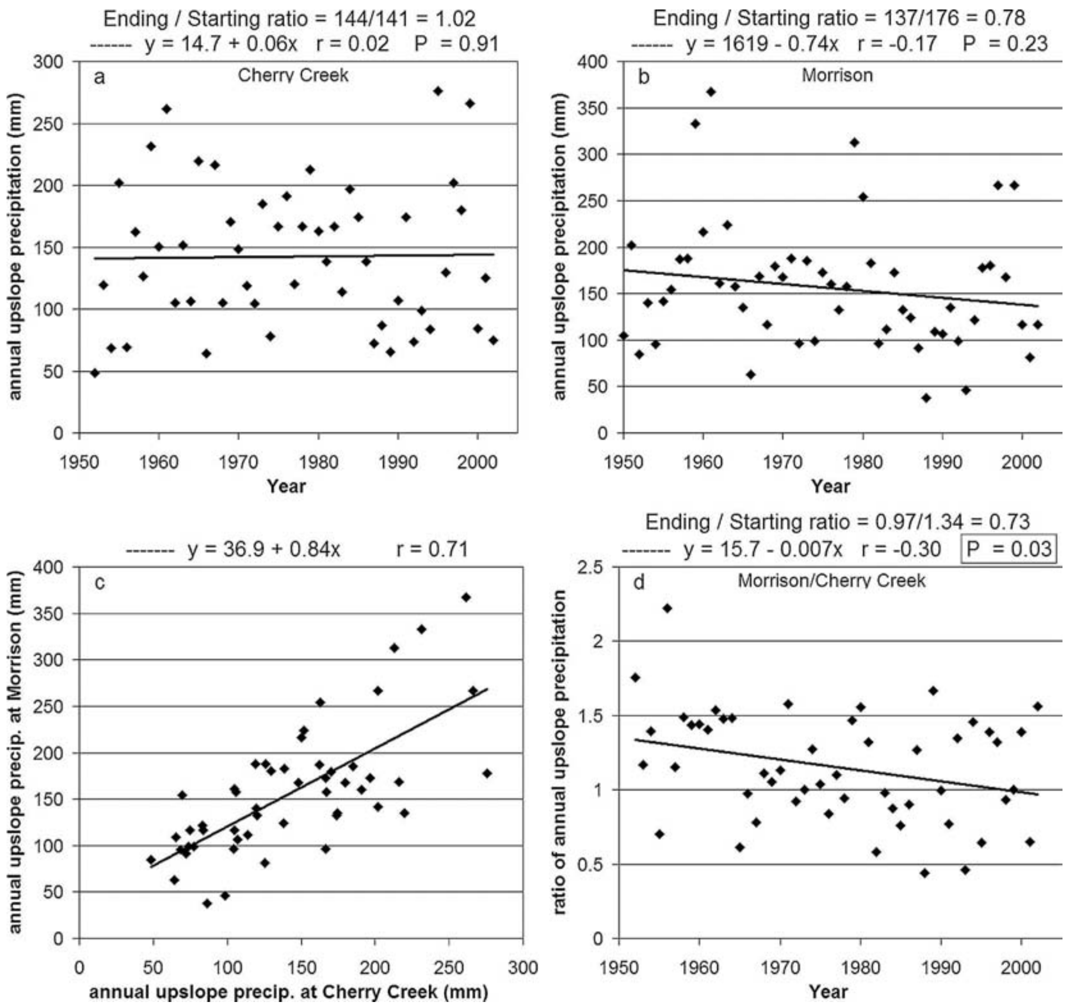

FIG. 4. Same as Fig. 2, but considering only upslope precipitation.

for the peak wind gust during the day. Upslope winds were defined as those days on which the peak wind was from the north-northeast to the south-southeast (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 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.

3. Results

In the ideal case, the suppression of precipitation by pollution would be most evident downwind of urban areas for shallow convective, 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 (Givati and Rosenfeld 2004). The OEF is calculated for sites along the Front Range for the total annual precipitation and annual upslope precipitation during the last half-century.

a. Total precipitation—Polluted sites

Figure 2 shows the total annual precipitation for the polluted Denver sites over the last 50 yr. Neither Cherry Creek nor Morrison shows a statistically significant (i.e., significance level $P < 0.05$) 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 correlation coefficient r value). A decreasing trend in the OEF is shown in Fig. 2d, but the trend is not very statistically signifi-

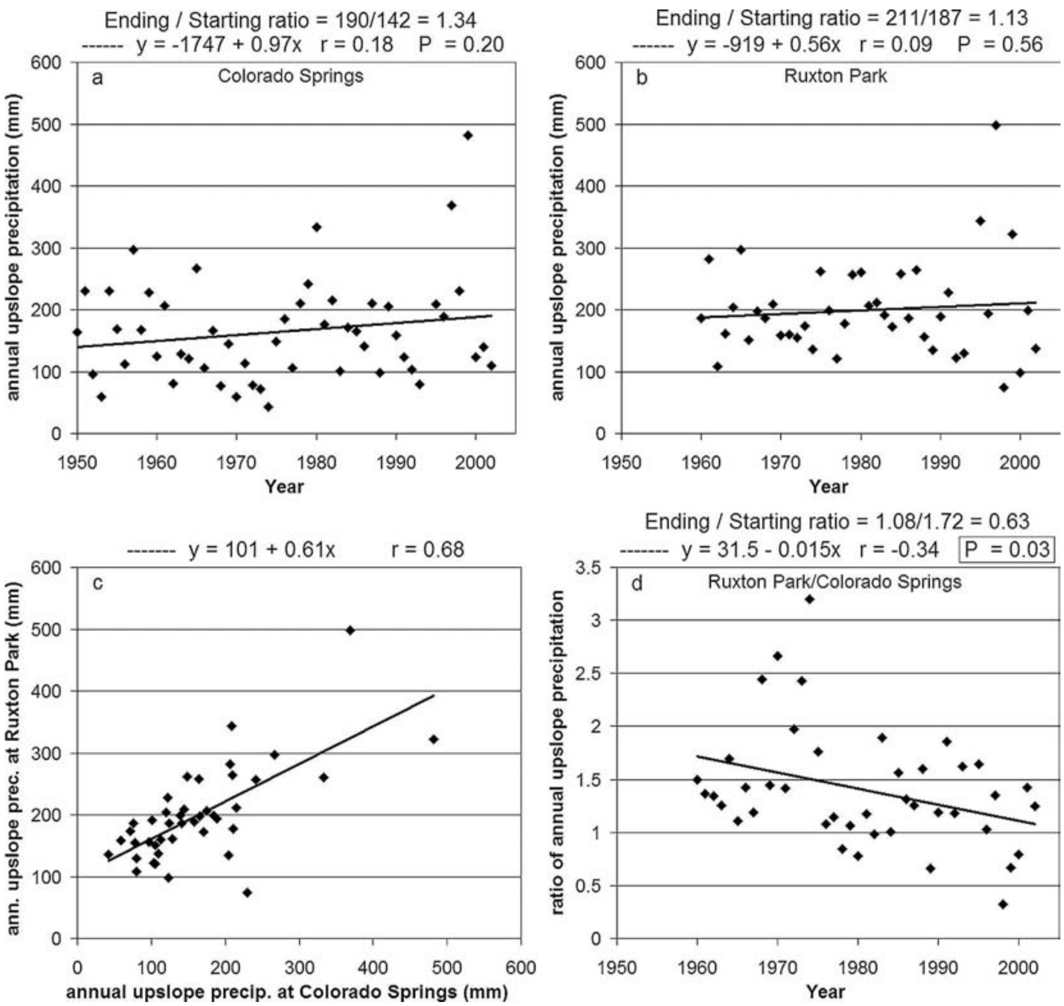

FIG. 5. Same as Fig. 4, but for another pair of polluted sites: (a) Colorado Springs and (b) Ruxton Park, the elevated site.

cant ($P = 0.10$). 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, described below).

b. *Total precipitation—Pristine sites*

Figure 3 shows the total annual precipitation for the pristine sites north of the Denver area over the last five decades. Even with the recent drought conditions, Greeley has seen a statistically significant ($P = 0.01$) increase in precipitation over the last 50 yr. 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 ($P = 0.21$).

c. *Upslope precipitation—Polluted sites*

Considering only upslope precipitation should produce the strongest evidence of precipitation suppression because upslope winds carry the pollution up the terrain that affects the formation of clouds and precipitation. The average fraction of annual upslope precipitation for the Denver metropolitan sites is slightly greater than one-third. Cherry Creek has an annual upslope precipitation average of 142 mm, which is 34% of the total annual precipitation average of 418 mm. Morrison has a slightly higher percentage of annual average upslope precipitation (36%), receiving 156 mm of upslope precipitation annually out of 429 mm of total precipitation.

Figure 4 shows the same data as are in Fig. 2, except only upslope precipitation is considered. Cherry Creek has not experienced a statistically significant trend in

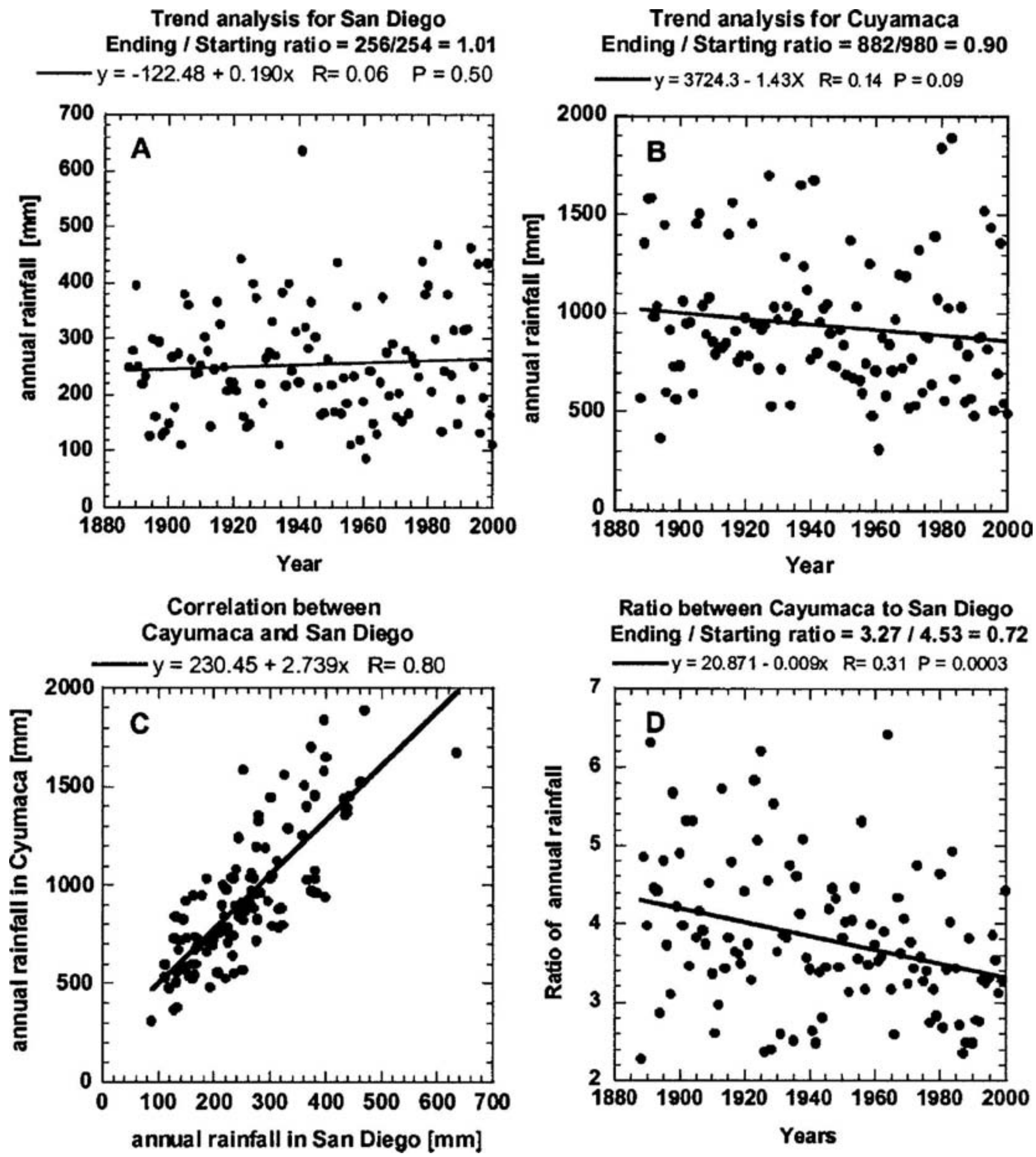

FIG. 6. Similar to Fig. 2, but for San Diego, CA, and the downwind hilly station of Cuyamaca, CA. [From Givati and Rosenfeld (2004).]

upslope precipitation. Morrison has a decreasing trend in upslope precipitation over the past several decades, but one that is not statistically significant ($P = 0.23$). A decreasing trend in upslope precipitation at the elevated site alone does not indicate the presence of precipitation suppression by pollution because a change in the general weather pattern (e.g., physical and thermodynamical parameters) could also lead to a reduction in upslope precipitation over time. The strongest evidence of precipitation reduction is shown in Fig. 4d for the precipitation ratio between the highly correlated stations of Morrison and Cherry Creek, which reveals the precipitation trend with some of the annual variability removed. There is strong statistical evidence ($P = 0.03$) 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 almost 30% during this time (ending/starting ratio = 0.972/1.339 = 0.73). The decrease in the OEF is larger and much more significant for upslope precipitation than for total precipitation, which suggests that airflow over urban areas is affecting the precipitation process at the elevated sites. Therefore, the loss of upslope precipitation at Morrison could be explained by precipita-

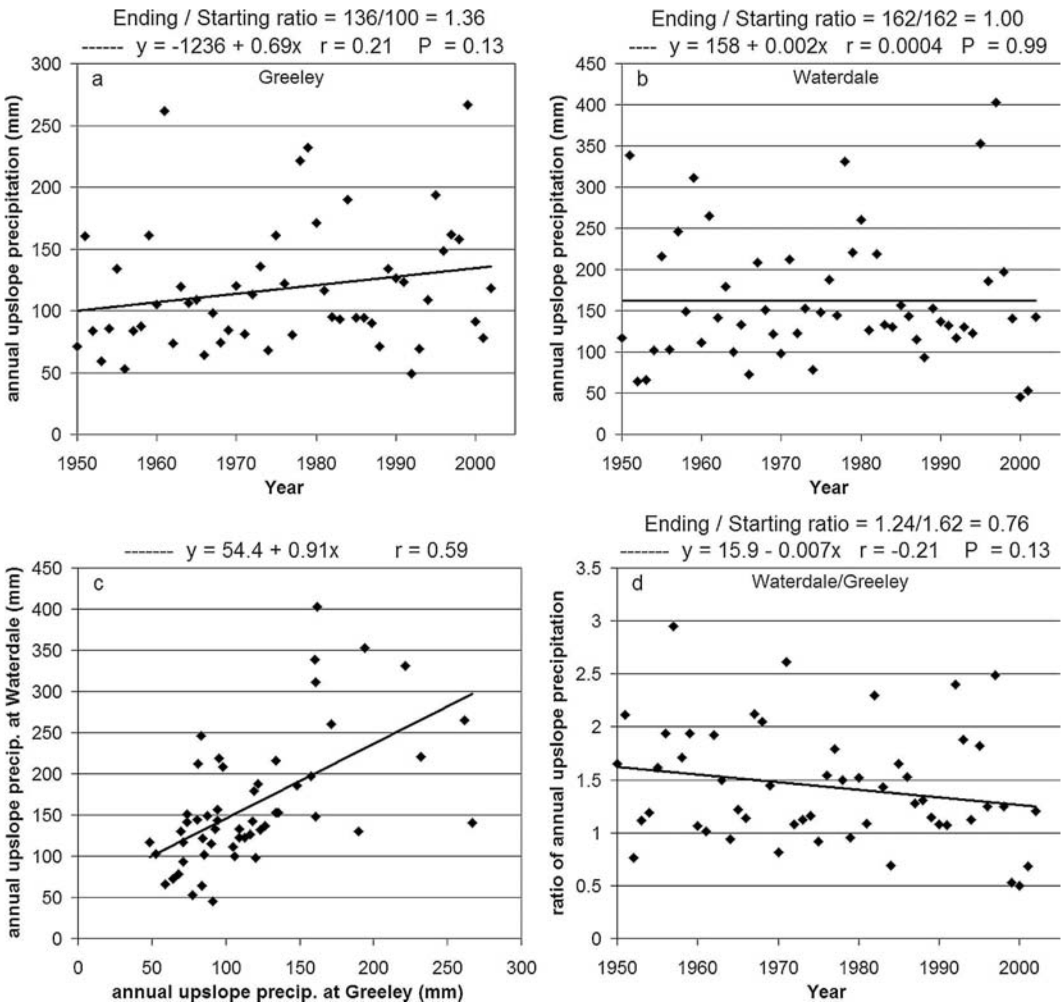

FIG. 7. Same as Fig. 3, but considering only upslope precipitation.

tion suppression resulting from pollution, assuming that the concentration of small CCN has increased during this period in the Denver metropolitan area.

Figure 5 shows the precipitation trends for a pair of polluted sites from the Colorado Springs area. The sites by themselves do not show any appreciable precipitation trend since 1960. However, there is a statistically significant ($P = 0.03$) decrease in the ratio of upslope precipitation at Ruxton Park to that in Colorado Springs over this period (Fig. 5d). The OEF decreased by more than 30% during this time (ending/starting ratio = 1.082/1.719 = 0.63), providing more evidence of precipitation suppression by air pollution along the Front Range.

An example from the Givati and Rosenfeld (2004) study of polluted sites in southern California is shown in Fig. 6 for comparison with the polluted sites along the Front Range in this study. It is clear that they were considering 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 of approximately 30% in orographic precipitation at an elevated site relative to the upwind urban site.

d. 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 statistically significant 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.

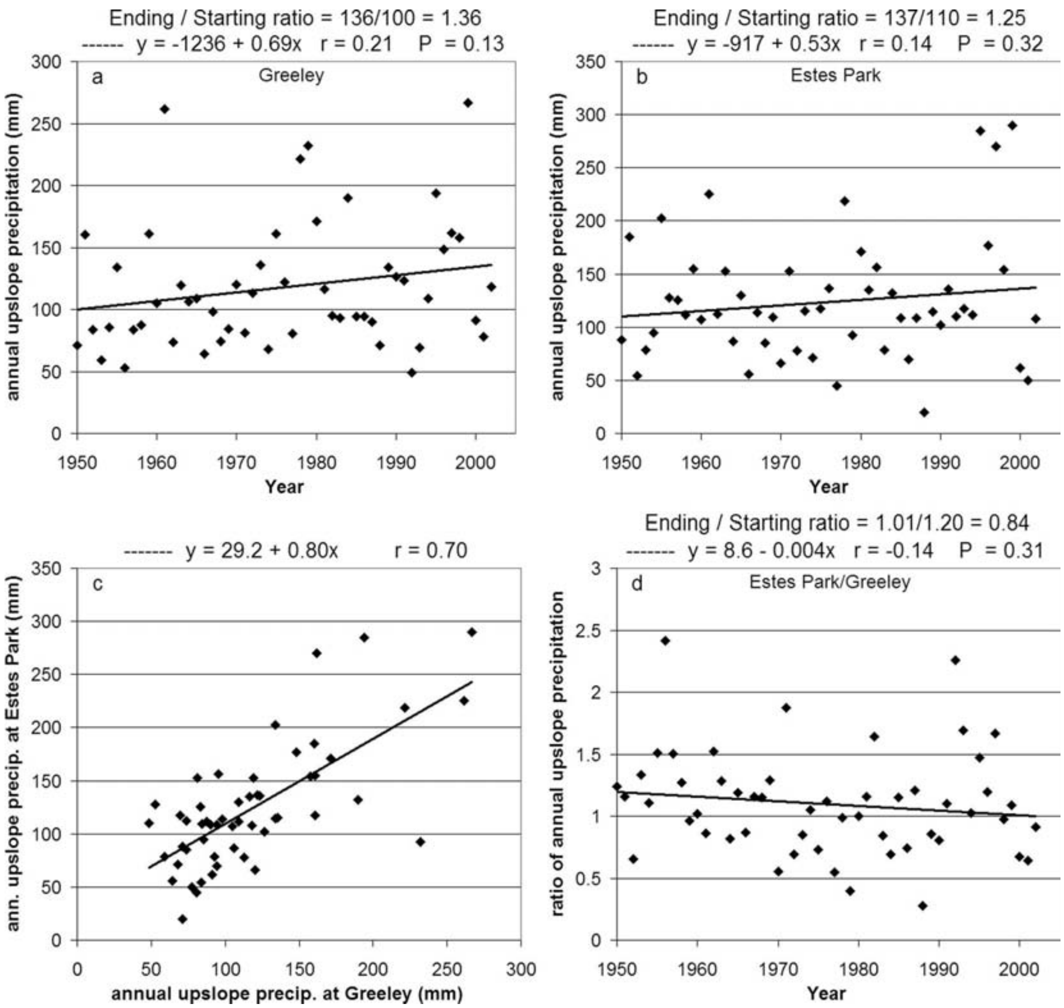

FIG. 8. Same as Fig. 7, but for another pair of pristine sites: (a) Greeley and (b) Estes Park, the elevated site.

Greeley receives an annual average of 118 mm (35%) of upslope precipitation, and Waterdale receives an annual average of 162 mm (40%) of upslope precipitation.

Figures 7a and 7b reveal that neither Greeley nor Waterdale experienced a significant trend in upslope precipitation with time. In addition, there is not a statistically significant ($P = 0.13$) trend in the ratio of their upslope precipitation amounts (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 because of air pollution. As a side note, it is not surprising that the data show a slight decreasing trend in the OEF given that this area would not be expected to be completely void of precipitation suppression, because it has also become increasingly urbanized over the past 50 yr.

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 ($P = 0.31$) trend evident in the OEF (Fig. 8d). Again, 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.

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 (see Table 1). However, decreasing trends of upslope precipitation for elevated sites relative to upwind polluted sites in Denver and Colorado Springs were found with-

TABLE 1. Summary of the trend analysis for the polluted and pristine sites along the Front Range. Significance levels ≤0.05 are in boldface type.

	Station	Location	*P* value	Ending/starting ratio
Total precipitation	Cherry Creek	Polluted	0.26	1.19
	Morrison	Polluted, elevated	0.88	1.02
	Morrison/Cherry Creek	Polluted	0.10	0.83
	Greeley	Pristine	**0.01**	1.32
	Waterdale	Pristine, elevated	0.33	1.13
	Greeley/Waterdale	Pristine	0.21	0.89
Upslope precipitation	Cherry Creek	Polluted	0.91	1.02
	Morrison	Polluted, elevated	0.23	0.78
	Morrison/Cherry Creek	Polluted	**0.03**	0.73
	Colorado Springs	Polluted	0.20	1.34
	Ruxton Park	Polluted, elevated	0.56	1.13
	Ruxton Park/Colorado Springs	Polluted	**0.03**	0.63
	Greeley	Pristine	0.13	1.36
	Waterdale	Pristine, elevated	0.99	1.00
	Greeley/Waterdale	Pristine	0.13	0.76
	Greeley	Pristine	0.13	1.36
	Estes Park	Pristine, elevated	0.32	1.25
	Estes Park/Greeley	Pristine	0.31	0.84

out a statistically significant trend for a more pristine area (see Table 1). Because 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, it could have major future impacts on the water supply for these cities. Continued precipitation suppression at this rate would result in precipitation losses on the order of 1 mm yr^{-1} 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. This possibility certainly 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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