

# IS AIR POLLUTION IMPACTING WINTER OROGRAPHIC PRECIPITATION IN UTAH?

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Abstract. Winter precipitation data from selected locations within the States of Utah and Nevada were analyzed to determine if there were any indications of reductions in mountainous precipitation when compared with upwind valley precipitation. This work followed the approach utilized in a comprehensive study of precipitation in Israel and California that indicated the orographic component of precipitation was declining at precipitation stations at mountain locations which were downwind of major cities. The authors of that study theorized that these reductions were due to the transport of air pollution from the cities into winter storms at these downwind mountainous locations leading to microphysical changes within the affected clouds resulting in reductions in observed precipitation. The work which we performed in Utah and Nevada indicated similar reductions in mountainous precipitation downwind of the Salt Lake City/Provo metropolitan complex. These indicated reductions in precipitation extended downwind of the first mountain barrier into a mountain valley location and into the upwind slope of a second mountain barrier some 80 km downwind. Reductions in precipitation at other mountain stations in Utah and Nevada were not indicated. These stations were located in more rural settings which may suggest that air pollution from major cities may in fact be related to the reductions in precipitation that are indicated downwind of the Salt Lake City/Provo metropolitan complex.

## 1.0 INTRODUCTION

Reports have recently appeared in the literature relating pollution from various cities in coastal or near-coastal environments apparently causing reductions in the orographic component of winter precipitation in mountainous areas downwind of these cities (e.g., Givati and Rosenfeld, 2004). The abstract of that paper is as follows: *“Urban air pollution and industrial air pollution have been shown quantitatively to suppress rain and snow. Here, precipitation losses over topographical barriers downwind of major coastal urban areas in California and in the land of Israel that amount to 15-25% of the annual precipitation are quantified. The suppression occurs mainly in the relatively shallow orographic clouds within the cold air mass of cyclones. The suppression that occurs over the upslope side is coupled with similar percentage enhancement on the much drier downslope side of the hills. The evidence includes significant decreasing trends of the ratio of hill to coast precipitation during the twentieth century in polluted areas in line with the increasing emissions during the same period, whereas no trends are observed in similar nearby pristine areas. The evidence suggests that air-pollution aerosols that are incorporated in orographic clouds slow down cloud-drop coalescence and riming of ice precipitation and*

*hence delay the conversion of cloud water into precipitation. This effect explains the pattern of greatest loss of precipitation at the midlevel of the upwind slopes, smaller losses at the crest, and enhancement at the downslope side of the hills.”*

This paper examines whether this phenomenon might be occurring in Utah even though, due to the location of Utah, the air masses would normally be expected to be continental not maritime in origin. It would be expected that winter storm systems in California and Israel would be of a more maritime nature. Whether or not the apparent air pollution effects would be different in the two types of air masses is unclear. The potential impact of air pollution reductions in precipitation are then considered in the context of whether such reductions would reduce the likelihood of detecting effects of winter cloud seeding programs that North American Weather Consultants (NAWC) has been conducting in Utah. This possibility has been investigated quantitatively in Israel in a paper that has been conditionally accepted for publication in the American Meteorological Society's *Journal of Applied Meteorology*.

## 2. POSSIBLE AIR POLLUTION IMPACTS IN UTAH

NAWC investigated whether the precipitation reduction phenomenon identified by Givati and Rosenfeld was possibly occurring in some mountainous areas of Utah. Data were accumulated for November through March precipitation for several groupings of valley/mountain precipitation observation sites. Data sources were National Weather Service sites or Natural Resources Conservation Service sites. For reference purposes, Figures 1 and 2 provide the locations of all the precipitation sites utilized in preparing comparison plots in this paper. The November through March period was selected to represent the winter period equivalent to the one analyzed by Givati and Rosenfeld. Chronological plots were then prepared of the ratio of November through March precipitation totals at mountain sites versus upwind valley sites for as long a historical period as possible. Most plots are for the period of 1949 through 2004 or 1956 through 2004. Figure 3 provides one of these plots for the Silver Lake Brighton Ski area (~2.7 km in elevation) versus the Salt Lake City International Airport (~1.3 km in elevation). The Brighton ski area is located near the crest of the Wasatch Mountains just east of Salt Lake City. This plot indicates a definite downward trend in this mountain/upwind valley precipitation ratio, similar to what has been reported by Givati and Rosenfeld in California and Israel. A trend line appears on this and other similar figures in this paper which are simple linear regression fits of the data sets. The regression equation and  $r^2$  values are also provided in these plots. Givati and Rosenfeld calculated the magnitude of changes in this type of plot by dividing the ending value of the trend line by the starting value (y intercept) of the trend line. Consequently, the resulting ratio is an average increase or decrease over the time period of the input data. We followed this convention in this paper. The indicated reduction in Figure 3 averages ~24% over the 56 seasons of record. We speculated that the area downwind of Salt Lake City and Provo was the most likely to experience an air pollution effect, if present, because of the large population concentration in the Salt Lake and Utah Valleys.

A plot similar to Figure 3 was prepared for Ely, Nevada (~1.9 km in elevation) versus Berry Creek (a high elevation site, ~2.8 km in elevation, located northeast of Ely) which was thought to be representative of a low pollution environment. That plot is provided in Figure 4. It does not show the same decline as that



Figure 1. Location of Precipitation Stations in the Salt Lake City Vicinity



Figure 2. Location of Other Precipitation Gages

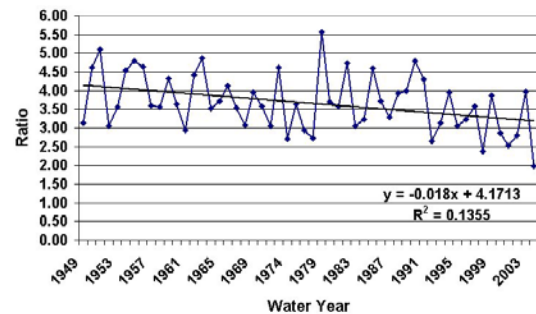


Figure 3. Plot of the Ratio of November-March Precipitation at Silver Lake Brighton vs. Salt Lake City International Airport

observed in Figure 3 for Silver Lake Brighton versus Salt Lake City (in fact an increase with time is indicated), which lends support to the hypothesis advanced by Givati and Rosenfeld that the decline in the orographic precipitation ratio between Silver Lake Brighton and Salt Lake City may be related to air pollution.

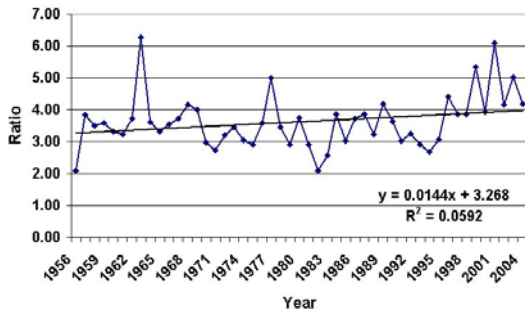


Figure 4. Plot of the Ratio of November-March Precipitation at Berry Creek vs. Ely, Nevada

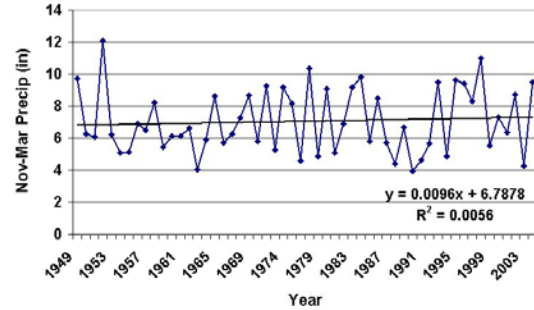


Figure 5. Salt Lake City November-March Precipitation Totals

A question arises when considering Figure 3; is the reduction in the ratio of valley to mountain precipitation due primarily to increases in valley precipitation, decreases in mountain precipitation, or a combination of both? To address this question, two chronological plots were prepared of the November through March precipitation for Salt Lake City (Figure 5) and Silver Lake Brighton (Figure 6). The plot at Salt Lake City (Figure 5) indicates an increase in precipitation over the 56 seasons of record (approximately an average 7% increase, ~1.3 cm, based upon a simple linear regression fit of the data). Figure 6, on the other hand, shows a decrease (an average decrease of ~20%, ~14.2 cm, over the 56 seasons). Incidentally, the reader is reminded that the scales contained in several of the figures contained in this paper are allowed to change (i.e. they are not all constrained to the same scale) due to the rather broad ranges observed in the data sets. Considering the information provided in Figures 3, 5 and 6, it is concluded that there has been an actual decline in the amount of winter precipitation observed at Silver Lake Brighton over a 54 year period but that the drop in the ratios plotted in Figure 3 may be due both to decreases in mountain precipitation and increases in valley precipitation. Figure 7 provides a plot of November through March precipitation for a site at Cottonwood Wier (1.5km in elevation) which is located at the base of the Wasatch Mountains just east of Salt Lake City. This figure indicates an increase in precipitation (~15%, ~3.8 cm, for the 56 seasons) which is higher than that indicated for Salt Lake City in Figure 5. The reasons for these apparent increases in precipitation over time in the Salt Lake Valley are unknown. The work of Givati and Rosenfeld suggests that in those situations where precipitation ratios are declining at mountain

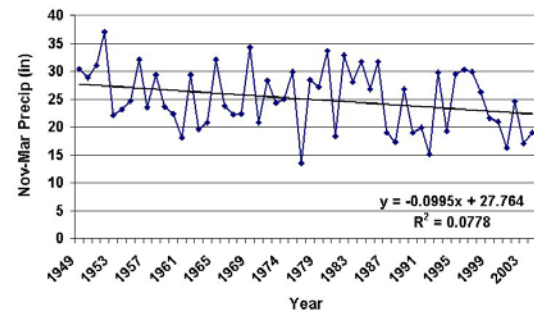


Figure 6. Silver Lake-Brighton November-March Precipitation Totals

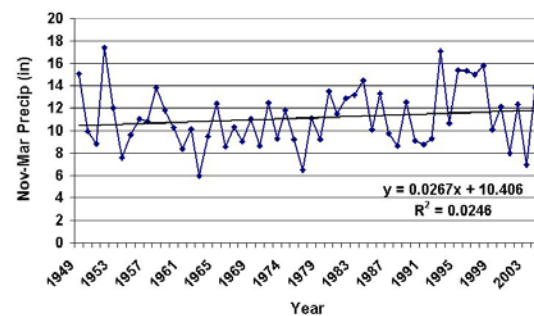


Figure 7. Cottonwood Wier November-March Precipitation Totals

sites downwind of major cities, those sites downwind of the mountains actually experience increases in precipitation. We tested this possibility in Utah by preparing a chronological plot of the November through March precipitation at Heber City (1.7 km in elevation) for the 56 season period (Figure 8). Heber City is located in a mountain valley southeast of Salt Lake City. This plot is similar to Figure 6 for Silver Lake Brighton in indicating a decrease in precipitation with time (an average of approximately a 24% decrease, ~ 5.6 cm decline

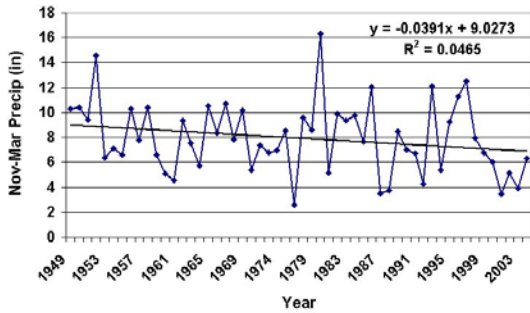


Figure 8. Heber City November-March Precipitation Totals

over the period of record). This finding may be contrary to those of Givati and Rosenfeld for locations in Israel and California where their results indicated increases in precipitation. Heber City is in a downwind mountainous valley setting, however, and is not a true lee barrier site such as those examined by Givati and Rosenfeld.

We decided that we would examine data from precipitation sites that comprise NAWC cloud seeding project target sites for the western Uintas area (the Uintas are an east-west oriented mountain barrier located in northeastern Utah at approximately the same latitude as Salt Lake City) to determine if this reduction in precipitation might extend further downwind of the Salt Lake City/Provo metropolitan complex. We had data compiled for these sites for use in our evaluations of the western Uintas cloud seeding program. Some of these data were estimated from storage gage records that predated the advent of the NRCS SNOTEL data collection system. These estimates consisted of determining the November through March precipitation from the periodic measurements of the amounts of precipitation that had fallen in storage gages normally made when manual snow course observations were taken at these sites. Plots of the precipitation ratios were prepared for Trial Lake (~3.0 km in elevation) and Smith and Morehouse (~2.3 km in elevation) versus Salt Lake City (Figures 9 and 10). Data from water years 1973 and 1976 were not included in these two plots and the two plots that follow due to missing data. These two plots indicate a similar downward trend in the precipitation ratios versus Salt Lake City; approximately a 23% reduction at Trial Lake and a 19% reduction at Smith and Morehouse. Figures 11 and 12 were prepared to examine the possible impact on November through March precipitation at these two sites. There are apparent decreases in precipitation at Trial Lake of approximately 16%, ~9.4 cm

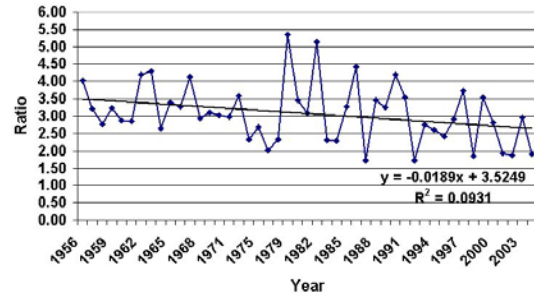


Figure 9. Trial Lake vs. Salt Lake City, November-March Precipitation Ratios

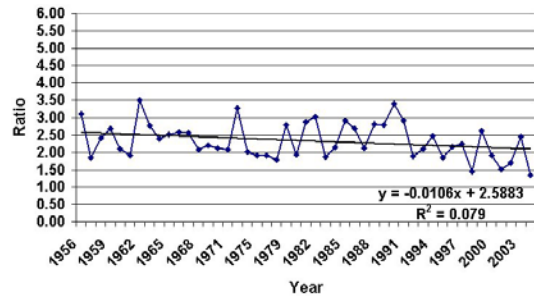


Figure 10. Smith and Morehouse vs. Salt Lake City, November-March Precipitation Ratios

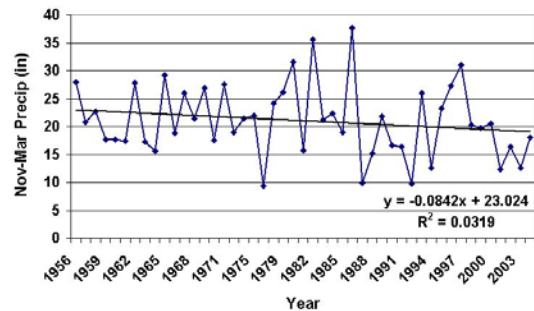


Figure 11. Trial Lake November-March Precipitation Totals

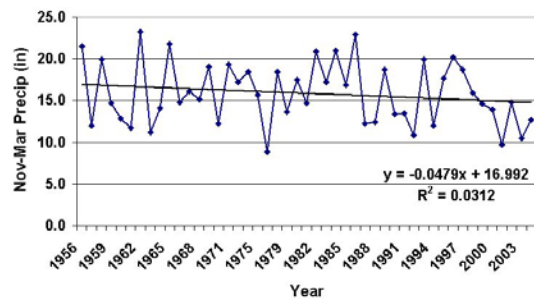


Figure 12. Smith and Morehouse November-March Precipitation Totals

decline from 1949 through 2004 and a 19%, ~5.6 cm decline from 1949 through 2004 at Smith and Morehouse. These results imply that the air

pollution (or perhaps some other unidentified phenomenon) from the Salt Lake City/Provo complex may be affecting downwind mountain precipitation at least to distances of approximately 80 km.

The concept of what locations are “downwind” of the Salt Lake City/Provo complex needs to be understood in the context of the average wind directions in the lower levels of the atmosphere when precipitation is occurring in the Salt Lake City vicinity. These winds during winter storm periods in northern Utah typically go through a natural progression from winds blowing from the southwest towards the northeast in pre-frontal conditions, from west to east under frontal passage conditions and from northwest to southeast in post-frontal conditions. It can be seen that these average wind flow conditions would favor the transport of pollution generated in the Salt Lake Valley towards locations that are northeast through southeast of the Salt Lake Valley and northeast of Utah Valley where the City of Provo is located. The Western Uinta Mountains are certainly within this sector, as illustrated in Figure 13. Parleys Canyon (located east of Salt Lake City) and Provo Canyon (located east of Provo) may in effect “channel” air pollution from the two valleys towards the Western Uintas during winter storm periods. A similar channeling effect may occur up Big Cottonwood Canyon. The Silver Lake Brighton precipitation observation site is located near the top of this canyon.

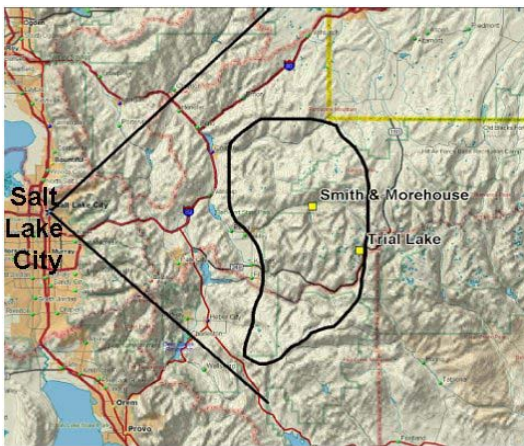


Figure 13. Location of the Western Uintas Target Area Relative to Salt Lake City

Similar plots were prepared for Ogden (a smaller city located north of Salt Lake City) versus two mountainous sites (Little Bear and Ben Lomond Peak) located east of this city. These plots (not shown in this paper) did not exhibit the differences noted downwind of the Salt Lake City/Provo complex.

### 3.0 POSSIBLE IMPACTS ON THE EVALUATIONS OF THE UTAH WINTER CLOUD SEEDING PROGRAMS

The discussion in Section 2.0 was provided both as general interest information as well as background information on a phenomenon that may potentially impact our ability to estimate the effects of some cloud seeding programs that NAWC is conducting in Utah, especially one located downwind of the Salt Lake City complex known as the Western Uintas program. In terms of general interest, sponsors of this cloud seeding program may wish to know about conditions that may be resulting in a reduction in winter precipitation in the prime watershed areas of the Weber and Provo Rivers which provide significant streamflow utilized as agricultural and municipal water supplies. Others in the meteorological community may also find these indications of interest since they apparently extend the observation of decreases in winter precipitation due to atmospheric pollution to an area in a more continental setting than the more maritime settings as examined by Givati and Rosenfeld. The sponsors of the cloud seeding program are also interested in circumstances that may lessen the likelihood of detecting any cloud seeding induced changes in precipitation in the target area during the seeded periods.

The latter situation is of interest to NAWC since our annual reports contain estimates of the potential impacts of the cloud seeding programs. The target/control evaluation procedures that NAWC uses to estimate the seeding effects on programs like the Western Uintas program rely upon establishing relationships between target and control area precipitation observations during an historical period prior to the start of the seeding program. The historical periods used to develop the target/control relationships were taken from the 1970's and 1980's. The potential problem we have is that these relationships may be impacted by the air pollution scenario as discussed above.

The control area sites that NAWC has used in these evaluations, located in northeastern Nevada and southwestern Idaho, are primarily in unpopulated areas which would not be expected to be subject to the apparent air pollution problems as discussed in Section 2.0. On the other hand, it appears that some of the sites in the Western Uintas target area are being negatively impacted by air pollution. The likely result then is that the equations used to evaluate this program may be over-predicting the amount of natural precipitation in the target area during the seeded periods. As a consequence, the evaluations of the program may be indicating less of a seeding effect than that which is actually occurring.

This situation was also considered in the study conducted by Givati and Rosenfeld, since there are operational cloud seeding programs being conducted in Israel and some areas in California (e.g., programs located in the Sierra Nevada Range) that are apparently experiencing these pollution impacts. A quote Givati and Rosenfeld (2004) is as follows: “In this study, we avoided addressing the possible confounding effects of the glaciogenic cloud seeding of the orographic clouds in both Israel and California. If seeding did enhance precipitation, the effects in the absence of seeding may have been larger than indicated in this study.” The authors of this study have addressed this issue in Israel in a separate publication that has been conditionally accepted for publication in the *Journal of Applied Meteorology*. In other words, cloud seeding may potentially be offsetting the negative effects of the apparent negative effects of air pollution on precipitation. For example, if air pollution was reducing November through March precipitation by 10% in the Western Uintas and cloud seeding was increasing precipitation by 10%, then the evaluations that we have been conducting for the target area might indicate no effect even though there actually was a 10% increase due to cloud seeding. And the corollary is that without cloud seeding, the drop in precipitation due to the apparent air pollution effects might be more pronounced.

It is concluded that the impact of this reduction in precipitation may be impacting the detection of effects of cloud seeding in the Western Uintas program. This conclusion is based in part on the fact that we are using the same techniques, equipment, seeding rates,

evaluation methods, etc. on the Western Uintas program as we are on the other winter cloud seeding programs being conducted in other parts of the state of Utah.

Evaluations of those other projects are indicating average precipitation increases of approximately 5-15% (Griffith, *et al*, 1991 and Griffith, *et al*, 1997), while evaluations of the Western Uintas program indicate only slightly positive increases in snow water content to perhaps 10% increases in precipitation. One of the main differences between these other projects in Utah and the Western Uintas project is that the target areas for these other projects are not located immediately downwind of major cities which may serve as air pollution source regions.

To test this hypothesis, we prepared some plots for the central and southern Utah seeding program (which is the largest target area in the Utah seeding programs and also the one where seeding has been conducted for the longest period of time), similar to those provided in Section 2.0 for the areas downwind of Salt Lake City. Figure 14 provides a plot of the November through March precipitation ratio for the NRCS Big Flat site (3.1 km elevation) located in the Tushar Mountains east of Beaver, Utah versus Milford, Utah (1.5 km in elevation) which is an upwind valley site (located west of Beaver). Data for Big Flat partially consisted of interpolated data (prior to 1980) similar to the data at Smith and Morehouse and Trial Lake as discussed previously.

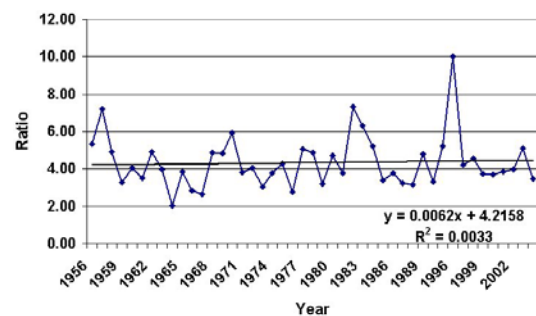


Figure 14. Big Flat vs. Milford, November-March Precipitation Ratios

This plot indicates a slight increase (~7%) in the precipitation ratio, implying no effects of air pollution as might be expected in this rural setting (even though the Big Flat site is downwind of the small city of Beaver). Figure 15 provides the November through March

precipitation plot for Big Flat. This figure indicates an increase in precipitation at this site (~13%, ~5.1 cm increase over the period from 1956 through 2004), consistent with the concept of a possible increase that may be due, in part, to a winter cloud seeding program. Seeding has been conducted to affect this area for most winter seasons, beginning in water year 1974, except for an unseeded period in the mid-1980's.

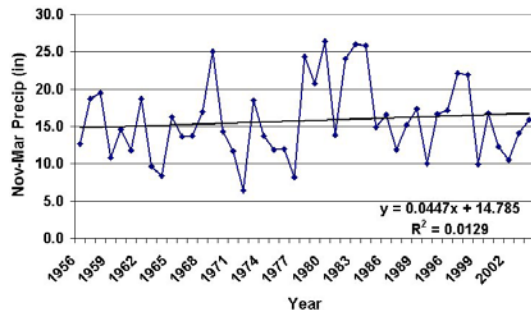


Figure 15. Big Flat November-March Precipitation Ratios

#### 4.0 SUMMARY AND CONCLUSIONS

The information presented in this paper requires some speculation in order to draw any conclusions. With this stated caveat, it appears that the air pollution generated by the greater Salt Lake City/Provo, Utah complex may be interacting with winter (November-March) storm systems in a negative fashion resulting in a reduction of precipitation in mountain and valley locations out to downwind distances of approximately 80 km. Givati and Rosenfeld, 2004 theorize that these negative impacts of air pollution on winter orographic precipitation may be due to very small particles (< 1 micron) that are emitted by diesel engines which then serve as CCN. Surprisingly, for unknown reasons, the November through March precipitation in the Salt Lake Valley (based upon data from the Salt Lake International Airport and Cottonwood Wier) appears to be increasing with time. It is certainly conceivable that these indicated decreases in mountainous locations downwind of the Salt Lake City/Provo complex may be due to another type of pollution or other unidentified phenomenon that may not be related to air pollution. An example of a different source of air pollution produced by coal fired power plants affecting snowfall is documented by Borys, *et al*, 2003 which noted decreases attributed to the production of sulfate aerosols by these plants.

Comparisons of precipitation ratios of mountain sites downwind of the Salt Lake City complex with precipitation records for Salt Lake City show downwind site declines over the past fifty-six years. Similar comparisons (plots) for valley-mountain site pairs in southern Utah and eastern Nevada do not indicate any significant declines in the November through March precipitation ratio plots between upwind valley and mountain locations. This is interpreted to mean that the air pollution effects that appear to be present at sites downwind of Salt Lake City are not present in the more rural areas of southern Utah and eastern Nevada. Plots of the November through March high elevation precipitation at a representative site in southern Utah has also shown an increase over time, which may suggest evidence of a positive effect of cloud seeding in this area. It is therefore concluded that the apparently negative effects of air pollution on winter precipitation at high elevation sites that are within the intended target area of the Western Uintas seeding program may be masking the effects of a cloud seeding program that is being conducted in this area. These indications, if true, have potentially significant implications regarding efforts to estimate the true effects of cloud seeding for precipitation increase in mountainous areas located downwind of cities and industrial areas.

#### 5.0 REFERENCES

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