# AN 'AEROSOL EFFECT' DETECTED IN WINTER OROGRAPHIC CLOUDS BUT AN EFFECT ON PRECIPITATION COULD NOT BE DETERMINED

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**Abstract.** Analyses of a 22-year record (1984/85 - 2005/06) of wintertime (December - February) measurements at Storm Peak Laboratory (SPL) in the northern Colorado Rocky Mountains have shown aerosol particle concentrations were directly related to cloud droplet concentrations, the droplet concentrations were inversely related to mean diameters and the mean diameters were not related to the precipitation rates. A direct relationship between mean diameters and precipitation rates was expected due to snow crystal riming; the measurements were too variable to establish a relationship. Additionally, no significant trends in precipitation rate and snowfall water content were detected; at least a 40-year record is required. Nevertheless, the record defines average wintertime cloud and precipitation properties at SPL.

## 1. INTRODUCTION

At Storm Peak Laboratory (SPL) in the northern Colorado Rocky Mountains during the winters of 1984/85 through 2005/06 (a 22-winter period), cloud and snow physical and chemical measurements were made to determine if expected increasing anthropogenic emissions would increase droplet concentrations, decrease mean droplet diameters and decrease cloud pH and, through the snow crystal riming mechanism, increase snow pH values.

From the first 20 winters, Hindman *et al.* (2006) reported an aerosol effect opposite that expected: significant trends occurred of decreasing cloud droplet concentrations, increasing mean diameters and initially increasing cloud and snow pH values then more recent decreasing values. Decreased condensation nucleus (CN) concentrations, and most likely cloud-condensation nucleus concentrations as well, caused the decrease in droplet concentrations. However, CN concentrations and precipitation rates were not related. Thus, the inverse relationship between aerosol concentration and precipitation rate reported by Borys et al. (2003) for two storms at SPL was not detected in the long-term record.

Two additional winters of data have been collected (winters of 2004/05 and 2005/06) since the Hindman *et al.* paper. The purpose of this paper is to add the new data to the long-term record, repeat the analyses and report that there was no significant trend in either precipitation rates or snowfall water contents in the record. Due to the large variability in precipitation, a 40-year record is required to detect significant trends.

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## 2. MEASUREMENTS

The 2004/05 and 2005/06 cloud droplet, pH, CN, precipitation rate, temperature and wind measurements were collected and analyzed following exactly the procedures detailed by Hindman *et al.* (2006). Please refer to that publication for a description of the instruments and procedures. The temperature and wind measurements, not mentioned in that publication, were made from a 10 m tower attached to SPL using deiced sensors. As with most of the previous measurements, the data were collected for two-week periods during the month of January 2005 and 2006.

Additionally, at a mid-mountain site directly upwind and below SPL, personnel from the Steamboat Ski Patrol made daily snow depth and water equivalent measurements (from which snow water content was derived using standard methods). These measurements were made for an entire ski season (November-April). These data have been included in the long-term record.

The measurements in the long-term record were made during cloud episodes (immersions) at 3-hour intervals during two-week periods in December, January or February. The individual measurements were used to produce seasonal averages and their standard deviations/standard errors (see the Table). Seasonal averages were determined to identify trends in the record.

**Table**

Average values, standard deviations (StDev) and standard errors (StError) from the SPL 22-year winter (December – February) record: number of samples (n), droplet number concentration (N), droplet mean diameter ($D_{bar}$), liquid water content (LWC), cloud pH, condensation nucleus concentration (CN), snowfall water-equivalent precipitation rate (Ppt. Rate), snow pH, air temperature (T) and wind speed and direction.

| Winter | n (699) | N ($cm^{-3}$) | StError | $D_{bar}$ (μm) | StError | LWC ($gm^{-3}$) | StError | Cloud pH | StError | CN ($cm^{-3}$) | StError | Ppt. Rate (mm/h) | StError | Snow pH | StError | T (C) | StError | Speed (m/s) | StError | Direction (degrees) | StError |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1984-85 | 89 | 235 | 15 | 8.5 | 0.3 | 0.092 | 0.008 | 4.13 | 0.06 | 5049 | 337 | 2.20 | 0.30 | 4.46 | 0.050 | -8.5 | 0.3 | 10.4 | 0.4 | 260 | 5 |
| 1985-86 | 31 | 499 | 28 | 7.2 | 0.3 | 0.134 | 0.023 | 3.44 | 0.07 | 3562 | 911 | 1.30 | 0.20 | 4.29 | 0.100 | -9.4 | 0.5 | 8.0 | 0.4 | 287 | 4 |
| 1986-87 | 14 | 306 | 28 | 7.6 | 0.3 | 0.089 | 0.012 | 3.87 | 0.09 | 100 | 0 | 0.22 | 0.31 | | | -9.7 | 0.2 | 5.6 | 0.5 | 294 | 6 |
| 1987-88 | 12 | 303 | 45 | 6.4 | 0.3 | 0.053 | 0.011 | 3.70 | 0.06 | | | 3.90 | 1.50 | | | -9.5 | 0.9 | 7.2 | 0.6 | 254 | 20 |
| 1988-89 | 10 | 261 | 50 | 6.0 | 0.2 | 0.035 | 0.007 | 3.99 | 0.03 | 4710 | 1213 | 4.50 | 5.70 | | | -14.1 | 1.8 | 5.7 | 0.4 | 296 | 7 |
| 1989-90 | | | | | | | | | | | | | | | | | | | | | |
| 1990-91 | 45 | 313 | 24 | 7.9 | 0.3 | 0.098 | 0.013 | 4.32 | 0.07 | 7758 | 616 | 0.85 | 0.30 | 4.30 | 0.100 | -10.9 | 0.2 | 5.5 | 0.5 | 296 | 3 |
| 1991-92 | 34 | 221 | 21 | 6.6 | 0.3 | 0.040 | 0.006 | 4.42 | 0.07 | 1311 | 208 | 0.46 | 0.13 | 5.08 | 0.140 | -13.2 | 0.4 | 5.4 | 0.3 | 297 | 3 |
| 1992-93 | 52 | 220 | 15 | 6.4 | 0.2 | 0.041 | 0.004 | 4.98 | 0.06 | 742 | 69 | 0.86 | 0.15 | 4.99 | 0.059 | -10.5 | 0.4 | 6.3 | 0.3 | 267 | 5 |
| 1993-94 | 71 | 281 | 21 | 7.5 | 0.3 | 0.063 | 0.005 | 4.81 | 0.04 | 1117 | 97 | 1.18 | 0.17 | 5.35 | 0.068 | -11.7 | 0.3 | 6.4 | 0.2 | 303 | 2 |
| 1994-95 | 55 | 212 | 19 | 7.7 | 0.2 | 0.059 | 0.010 | 4.96 | 0.05 | 1483 | 185 | 0.12 | 0.04 | 5.39 | 0.042 | -11.3 | 0.5 | 6.8 | 0.3 | 291 | 4 |
| 1995-96 | | | | | | | | | | | | | | | | | | | | | |
| 1996-97 | 33 | 125 | 14 | 7.1 | 0.5 | 0.038 | 0.004 | 4.42 | 0.14 | 1374 | 230 | 0.50 | 0.18 | 5.15 | 0.130 | -12.4 | 0.6 | 9.1 | 0.4 | 294 | 5 |
| 1997-98 | 57 | 70 | 6 | 9.8 | 0.3 | 0.030 | 0.007 | 4.40 | 0.06 | 718 | 80 | 0.82 | 0.12 | 5.10 | 0.094 | -10.3 | 0.4 | 11.6 | 2.1 | 272 | 6 |
| 1998-99 | 33 | 137 | 24 | 9.7 | 0.5 | 0.039 | 0.009 | 5.56 | 0.13 | 834 | 159 | 3.00 | 0.54 | 6.38 | 0.190 | -9.3 | 0.6 | 8.9 | 0.5 | 269 | 6 |
| 1999-00 | 29 | 206 | 18 | 7.3 | 0.5 | 0.046 | 0.015 | 5.63 | 0.16 | 866 | 154 | 1.54 | 0.49 | 6.13 | 0.130 | -7.1 | 0.7 | 13.5 | 1.0 | 261 | 13 |
| 2000-01 | 30 | 193 | 18 | 10.2 | 0.4 | 0.092 | 0.009 | 4.63 | 0.15 | 1476 | 257 | 0.43 | 0.12 | 4.60 | 0.075 | -8.3 | 0.5 | 8.4 | 0.3 | 277 | 5 |
| 2001-02 | 19 | 108 | 34 | 11.5 | 0.8 | 0.067 | 0.012 | 4.24 | 0.07 | 1174 | 208 | 1.27 | 0.22 | 4.67 | 0.067 | -8.4 | 0.6 | 7.2 | 0.5 | 286 | 7 |
| 2002-03 | 21 | 144 | 21 | 9.6 | 0.6 | 0.068 | 0.012 | 3.83 | 0.07 | 1086 | 151 | 1.90 | 0.40 | 4.44 | 0.110 | -11.1 | 0.6 | 8.0 | 0.6 | 289 | 6 |
| 2003-04 | 4 | 133 | 13 | 6.7 | 0.9 | 0.022 | 0.008 | 3.96 | 0.09 | 1415 | 127 | 0.09 | 0.01 | 4.29 | 0.011 | -8.6 | 1.0 | 4.9 | 0.7 | 309 | 9 |
| 2004-05 | 8 | 160 | 26 | 11.4 | 0.6 | 0.099 | 0.019 | 4.29 | 0.07 | 1916 | 666 | 1.08 | 0.99 | 4.94 | 0.050 | -7.3 | 0.6 | 7.8 | 0.6 | 291 | 6 |
| 2005-06 | 22 | 88 | 12 | 11.0 | 0.6 | 0.059 | 0.012 | 5.47 | 0.07 | 816 | 205 | 2.76 | 1.12 | 5.49 | 0.057 | -11.9 | 0.6 | 7.4 | 0.7 | 281 | 6 |
| Average | | 211 | | 8.3 | | 0.063 | | 4.45 | | 1974 | | 1.45 | | 5.00 | | -10.2 | | 7.7 | | 284 | |
| StDev | | 100 | | 1.8 | | 0.029 | | 0.62 | | 1932 | | 1.25 | | 0.62 | | 1.9 | | 2.2 | | 15 | |
| StError | | 23 | | 0.4 | | 0.007 | | 0.14 | | 455 | | 0.29 | | 0.15 | | 0.4 | | 0.6 | | 4 | |

Measurements were not obtained for two winters during the 22-winter period (1989/90 and 1995/96). The number of measurements was not constant each winter because of the variable durations of the cloud episodes which ranged from a few hours to a few days.

## 3. RESULTS

The average values in the Table, due to the small standard errors, define the wintertime (December – February) cloud and precipitation properties at SPL. For example, the average 1.45 mm/h precipitation rate illustrates that it must snow frequently with substantial duration at SPL to produce the average 2100 mm of wintertime precipitation.

The values in the Table were analyzed producing the following results.

### 3.1 Trends

Upon addition of the winter 2004/05 and 2005/06 data, the cloud droplet concentration, mean diameter and LWC values now produce statistically significant trends of decreasing concentrations and increasing diameters (Figs. 1a and b). Further, the significant LWC trend remains consistent with the decreasing droplet concentrations and increasing mean diameters: an initial decreasing LWC trend in the early years but an increasing trend in the later years as the mean diameters became larger (Fig. 1c).

The statistically significant trends of initially increasing cloud and snow pH values then more recent decreasing values reported from the 20-winter record, upon addition of the winter 2004/05 and 2005/06 data (Figs. 2a and 2b), remain significant but with a reduced correlation coefficients: respectively, from 0.70 to 0.58 and from 0.61 to 0.49.

The addition of the winter 2004/05 and 2005/06 CN and precipitation rate measurements to the record (Figs. 2c and 2d) did not change the marginally significant decreasing trend in CN concentrations but did change the insignificant decreasing trend in precipitation rate to an insignificant increasing trend in recent winters.

### 3.2 Relationships

The series of relationships in the 'aerosol effect' at SPL (Borys *et al.,* 2003) is as follows: aerosol concentrations are directly related to cloud droplet concentrations, the droplet concentrations are inversely related to droplet mean diameters and the droplet mean diameters are directly related to the precipitation rates. The mean diameters and precipitation rates are related through snow crystal riming. So, increasing the aerosol concentra-

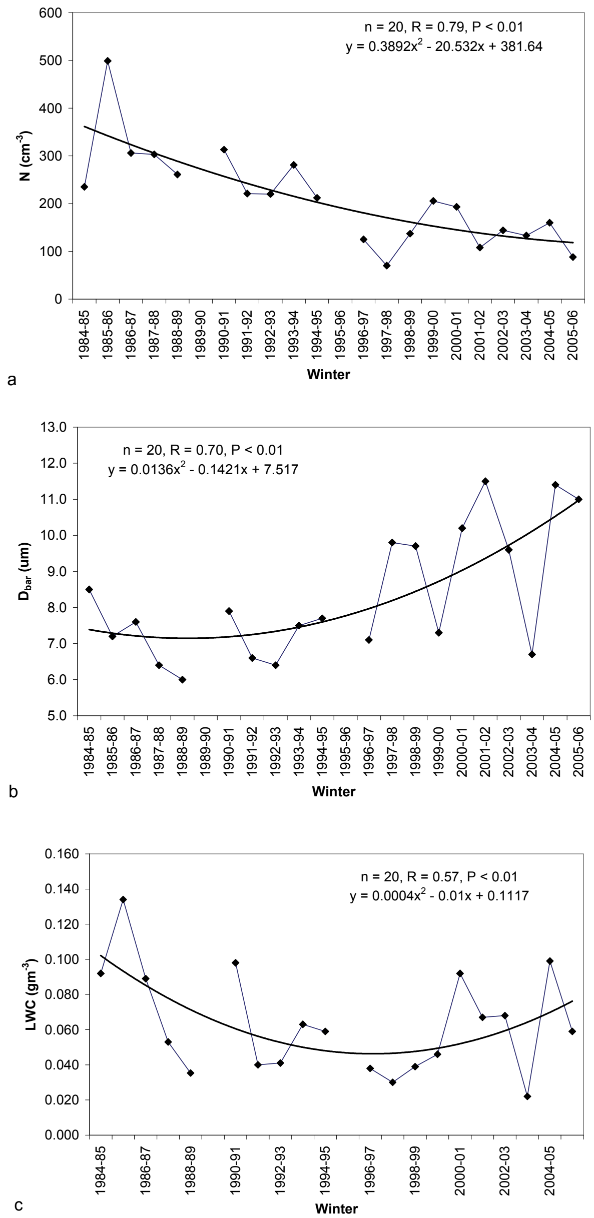


*Fig. 1:* ***a.*** *Cloud droplet concentration (N),* ***b.*** *cloud droplet mean diameter ($D_{bar}$) and* ***c.*** *cloud droplet liquid water content (LWC) as a function of winter. R represents the correlation coefficient and P the significance level. A polynomial-fit was the lowest order that produced the best R value in this figure and in subsequent figures.*

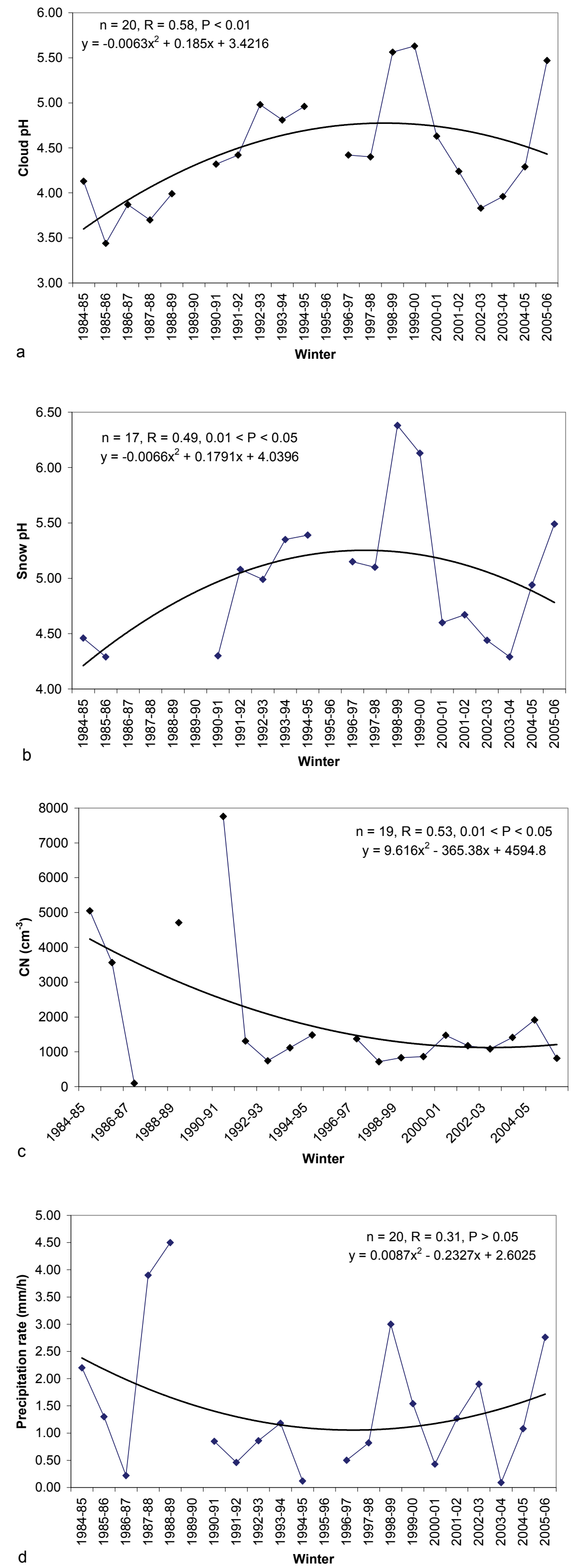


*Fig. 2.* ***a.*** *Cloud droplet pH,* ***b.*** *snow pH,* ***c.*** *interstitial condensation nucleus concentrations (CN) and* ***d.*** *snowfall water-equivalent precipitation rate as a function of year.*

tion is expected to increase droplet concentrations, decrease mean droplet sizes causing decreased crystal riming and decreased precipitation rates, and vice versa.

Addition of the winter 2004/05 and 2005/06 measurements to the long-term record and reanalysis of the relationships produced the following results.

The marginally significant relationship between aerosol concentration (CN concentration, considered the 'surrogate' CCN concentration) and cloud droplet concentration did not change but increased the correlation coefficient slightly from 0.46 to 0.49 (Fig. 3). In support of this relationship, the inverse relationship between cloud pH and CN concentrations became significant at better than the 1% level (Fig. 4). To check the cloud pH-CN relationship, cloud pH was correlated with droplet concentration (Fig. 5). It can be seen that as droplet concentration increased (due to increased aerosol particle concentrations) the cloud pH decreased supporting the Borys *et al.* (2000) finding that the more pollution-derived aerosol particles at SPL, the larger the droplet concentrations and vice versa.

The marginally significant inverse relationship between cloud droplet concentration and mean diameter became statistically significant with an improved correlation coefficient: from 0.48 to 0.63 (Fig. 6). This result is consistent with the fact that keeping LWC constant and increasing the droplet number concentrations decreases the mean droplet diameter and vice versa.

The highly significant relationship between cloud and snow pH values was maintained (Fig. 7) demonstrating the importance of riming to crystal chemical composition.

The statistically insignificant relationship between droplet mean diameter and precipitation rate did not change (Fig. 8).

## 4. DISCUSSION

The 'weak link' in the aerosol effect detected in the long-term record is the lack of a statistically significant relationship between droplet mean diameter and precipitation rate.

The most likely cause is meteorological variability. From first principles, the precipitation rate is

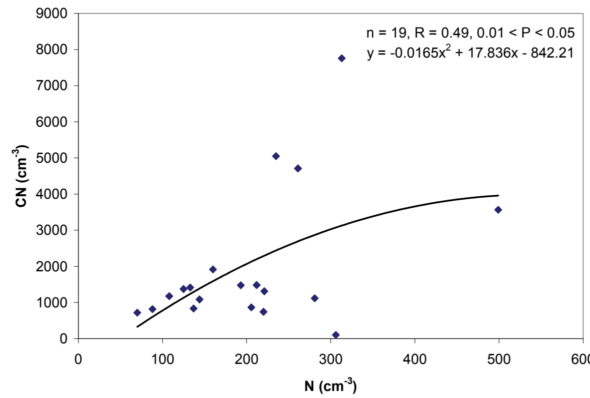


*Fig. 3. Correlation of cloud droplet concentration (N) and interstitial condensation nucleus concentration (CN) from, respectively, Figs. 1a and 2c.*

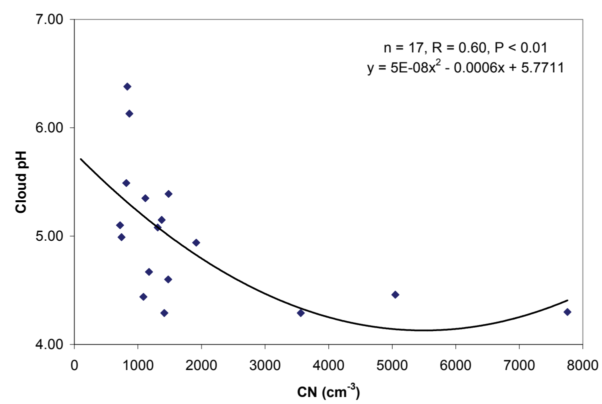


*Fig. 4. Correlation of cloud pH and interstitial condensation nucleus (CN) concentration from, respectively, Figs. 2a and 2c.*

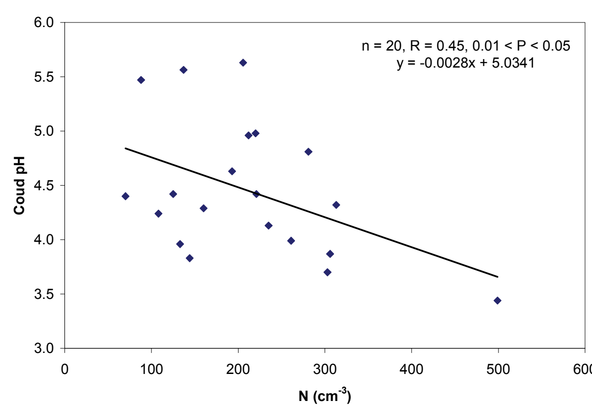


*Fig. 5. Correlation of cloud pH and cloud droplet concentrations (N) from, respectively, Figs. 1a and 2a.*

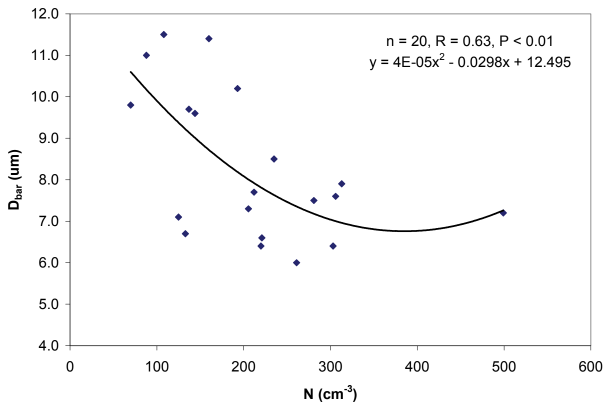


*Fig. 6. Correlation of cloud droplet concentration (N) and mean droplet diameter ($D_{bar}$) from, respectively, Figs. 1a and 1b.*

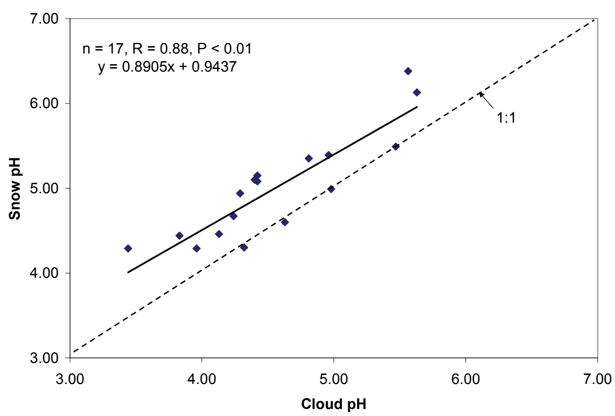


*Fig. 7. Correlation of cloud pH and snow pH values from, respectively, Figs. 2a and 2b.*

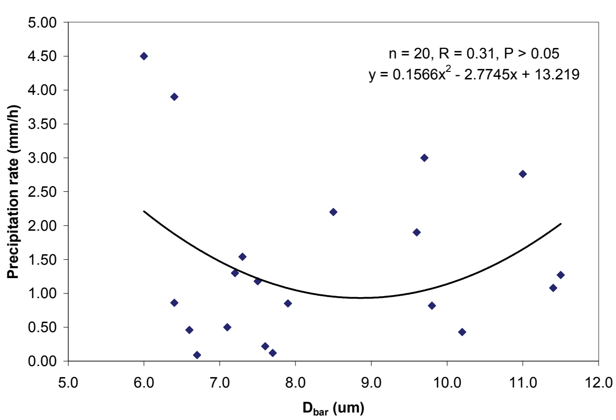


*Fig. 8. Correlation of mean droplet diameter ($D_{bar}$) and snowfall water-equivalent precipitation rate from, respectively, Figs. 1b and 2d.*

related to the following meteorological factors: the depth of the orographically-induced liquid cloud at and above SPL, the absolute humidity (which is determined by cloud-base temperature) and the upslope component of the wind speed. The aerosol particles only modulate these major factors.

The meteorological factors were correlated with precipitation rate in an attempt to estimate the effects of meteorological variability. The cloud depth was not measured due to the lack of a suitable instrument. So, temperature and wind speeds were correlated with precipitation rates. The results are shown in Figs. 9a and 9b. The best fits to the data illustrate an initial increase in the precipitation rates as temperatures and wind speeds increased, then a reduction of temperatures and speeds for the largest rates. These non-linear relationships illustrate the difficulty of extracting meteorological variability from the data in the Table. The variability may be accounted for if the 699 individual measurements summarized in Table are analyzed as independent variables; a project which is not possible at this writing.

There was no significant trend in precipitation rates in the long-term record (Fig. 2d). Additionally, the measurements corresponding to the period of the Ski Patrol snowfall water equivalent measurements (Winter 1987/88 through Winter 2005/06) are shown in Fig. 10. The Ski Patrol measurements are shown in Fig. 11. It can be seen in Figs. 10 and 11, no significant trends in precipitation were identified. The lack of significant trends in the precipitation measurements is due, in part, to the large variability in the values. To determine a significant trend in such variable data at less than the 5% significance level, it would take at least a 40-year record (Snedecor and Cochran, 1956).

From a 50-year record (1950-2000) of precipitation measurements from Steamboat Springs (at the base of the Park Range upon which SPL is located) and Hayden (an 'upwind' station on the plains 20 km to the west), Rosenfeld and Gavati (2006) report a suppression of orographically-induced precipitation due to the 'aerosol effect'.

## 5. CONCLUSIONS

The addition of the 2004/05 and 2005/06 measurements to the SPL long-term record reported by Hindman *et al.* (2006) strengthened some re-

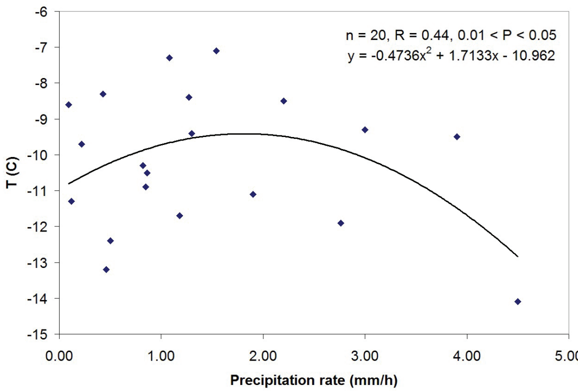


*Fig. 9a. Correlation of the SPL temperature with the precipitation rate from the Table.*

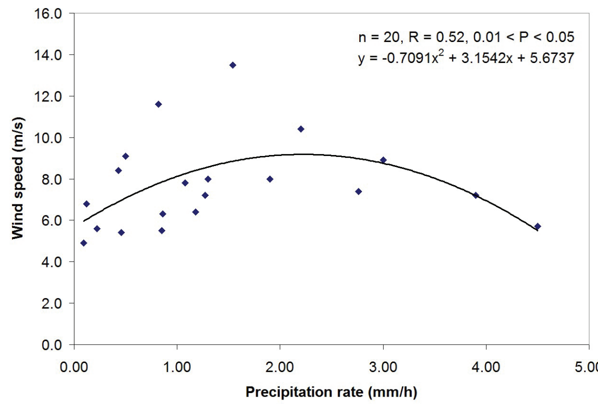


*Fig. 9b. Correlation of SPL wind speed with precipitation rate from the Table.*

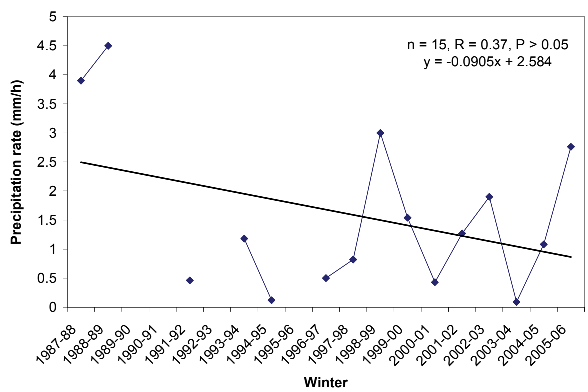


*Fig. 10. Snowfall water-equivalent precipitation rate values that correspond to the period of the Ski Patrol measurements of snow water contents shown in Fig. 11.*

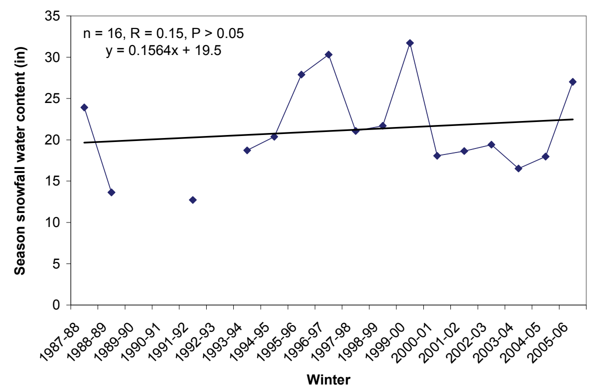


*Fig. 11. The Ski Patrol measurements of snow water contents.*

lationships and weakened others. But, the conclusions remain the same: the variations in CN concentrations (perhaps CCN concentrations as well) were directly related to droplet concentrations, the droplet concentrations were inversely related to droplet mean diameters and the mean diameters were not related to the precipitation rates. Thus, the long-term record supports the 'aerosol effect' for cloud droplets but, due to meteorological variability, no correlation between droplet mean diameter and precipitation rate could be established. Thus, the effect of the aerosol particles on precipitation rates could not be determined.

There was no significant trend in either precipitation rates or snow water contents in the long term -record. To determine a significant trend in such variable data at less than the 5% significance level, it would take at least a 40-year record.

There may be other factors that determine precipitation rate as much as snow crystal riming, eg. snow crystal type, size and concentration. For example, Meter *et al.* (2007) have reported pollution aerosol may be a rich source of ice-forming nuclei; perhaps crystal concentrations increased to offset the apparent reduction in crystal riming at SPL reported by Borys *et al.* (2003) and Rosenfeld and Givati (2006). Crystal collections were made as part of the long-term record following Hindman and Rinker (1967) but these data have not been reduced and analyzed. The average values in the Table, due to the small standard errors, define the wintertime (December

– February) cloud and precipitation properties at SPL.

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