12.3 AN ‘AEROSOL EFFECT’ DETECTED BUT PRECIPITATION NOT AFFECTED

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1. INTRODUCTION

At Storm Peak Laboratory (SPL) in the northern Colorado Rocky Mountains during the winters of 1983/84 through 2005/06 (a 23-wintor record), 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 21 winters of the record, 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, no relationship between CN concentrations and precipitation rates was identified. Thus, the inverse relationship between aerosol concentration and precipitation rate reported by Borys, et al. (2003) for 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 these new data to the 21-winter record and report that, upon the removal of two outlier precipitation rate values, the record now supports the Borys, et al. findings. However, there is no significant trend in either precipitation rates or snowfall water contents in the long-term record. The aerosols may have either increased snow crystal concentrations, offsetting the reduction in riming, or the large variability in seasonal precipitation masked the ‘aerosol effect’.

2. MEASUREMENTS

The 2004/05 and 2005/06 cloud droplet, pH, CN, precipitation rate and temperature measurements were collected and analyzed following exactly the procedures detailed by Hindman, et al. (2006). 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, 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 at 3-hour intervals during cloud immersions during two-week periods in December, January and February. The individual measurements were used to produce seasonal averages and their standard deviations/standard errors (see the Table). Measurements were not obtained for three winters during the 23-year period (W83/84, W89/90 and W95/96).

3. RESULTS

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 21-winter record, upon addition of the winter 2004/05 and 2005/06 data (Figures 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

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(Figures 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 the recent winters. Thus, there is no significant trend in precipitation rate2 in the long-term record.

3.2 *Relationships*

The marginally significant inverse relationship between cloud droplet mean diameter and concentration became statistically significant with an improved correlation coefficient: from 0.48 to 0.63 (Fig 3). 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 statistically insignificant relationship between mean droplet diameter and precipitation rate did not change (Fig. 4a). The two ‘outliers’ were removed (3.9 and 4.5 mm/h) and the best-fit became a first-order (linear) polynomial (Fig. 4b) with an R value of 0.45 ($0.01 < P < 0.05$). Thus, the long-term record, removing the outlying values, now supports the conclusion reached by Borys, et al. (2000) that there is a direct relationship between droplet mean diameter and precipitation rate.

The marginally significant relationship between CN concentration and cloud droplet concentration did not change but increased the correlation coefficient slightly from 0.46 to 0.49 (Fig 5).

The highly significant relationship between cloud and snow pH values was maintained (Fig. 6) and the inverse relationship between cloud pH and CN concentrations became significant at better than the 1% level (Fig. 7). To check the cloud pH-CN relationship, cloud pH was correlated with droplet concentration (Fig. 8). 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.

3.3 *Trends in Precipitation*

There was no significant trend in precipitation rates in the long-term record (Fig. 2d). When the two outlying values, identified in Figure 4a, were removed, an insignificant increasing trend resulted (Fig. 9).

The SPL precipitation rate measurements corresponding to the period of the Ski Patrol snowfall water equivalent measurements (Winter 1987/88 through Winter 2005/06) are shown in Figure 10; the Ski Patrol measurements are shown in Figure 11. It can be seen in the figures, no significant trends in precipitation were identified in either the SPL or the Ski Patrol measurements.

The lack of significant trends may be 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, 1956). Rosenfeld and Gavit (2006) report a statistically significant decrease in winter precipitation at Steamboat from a fifty year record (1950-2000) of precipitation. The decrease was attributed to the ‘aerosol effect’.

4. 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 relationships and weakened others. But, the conclusions remain the same: the variations in CN concentrations (perhaps CCN concentrations as well) were directly related to droplet concentration and the droplet concentrations were inversely related to droplet mean diameters. By eliminating two outlying precipitation-rate values, the long-term record now supports the conclusion reached by Borys, et al. (2000): there is a direct relationship between droplet mean diameter and precipitation rate. Thus, the long-term record supports the ‘aerosol effect’ on precipitation rate reported by Borys, et al. (2003).

There was no significant trend in either precipitation rates or snow water contents in the long term-record. This finding suggests that either the ‘aerosol effect’ may not have affected wintertime precipitation at SPL during the last 23-winters, which is contrary to Rosenfeld and Gavit (2006), or the effect may be important for only a small subset of winter storms at SPL or during periods within storms that are too short (hours) for a seasonal average to detect.

There may be other factors that determine precipitation rate as much as snow crystal riming, eg. snow crystal type, size and concentration. 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. Crystal collections were made as part of the long-term record following Hindman and Rinker (1967) but these data have yet to be reduced and analyzed.

5. REFERENCES

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Borys, et al., 2003: *Geophys. Rsh. Ltrs.*, p. 1538.

Hindman and Rinker, 1967: *J. Appl. Meteor.*, p. 126.
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Mertes, et al., 2007: *Aerosol Sci. Tech.*, p. 848
Rosenfeld and Givati, 2006: *J. Appl. Meteor. Climo.*, p. 903.
Snedecor, 1956: *Statistical Methods*, p. 557.

6. ACKNOWLEDGEMENTS

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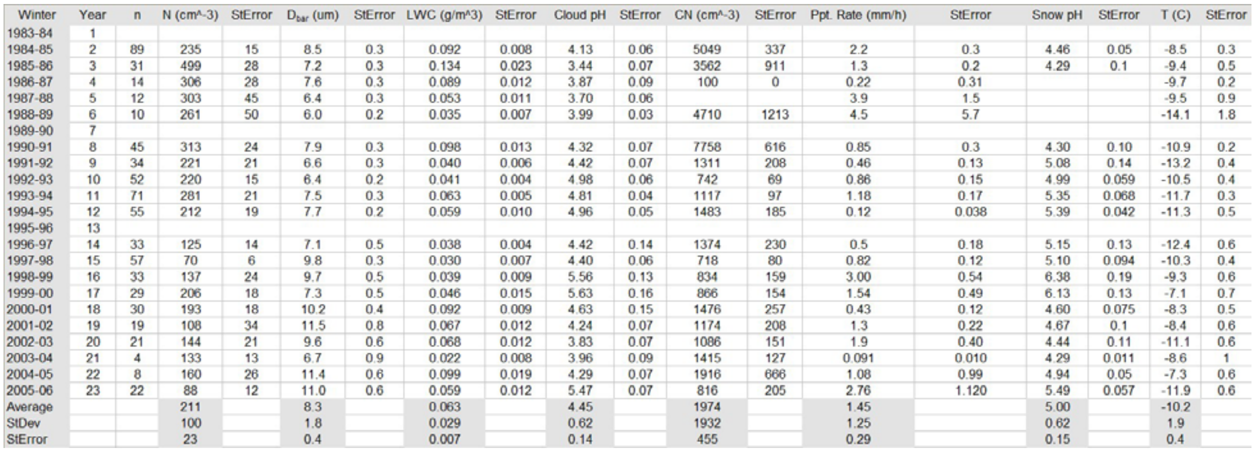
Table

Average values from the SPL 23-winter record:
number of samples (n), droplet number concentration (N), mean diameter (D_{bar}),
liquid water content (LWC), pH, CN, snowfall water-equivalent precipitation, snow pH and air temperature (T)



Winter	Year	n	N (cm^-3)	StError	D_{bar} (um)	StError	LWC (g/m^3)	StError	Cloud pH	StError	CN (cm^-3)	StError	Ppt. Rate (mm/h)	StError	Snow pH	StError	T (C)	StError
1983-84	1																	
1984-85	2	89	235	15	8.5	0.3	0.092	0.008	4.13	0.06	5049	337	2.2	0.3	4.46	0.05	-8.5	0.3
1985-86	3	31	499	28	7.2	0.3	0.134	0.023	3.44	0.07	3562	911	1.3	0.2	4.29	0.1	-9.4	0.5
1986-87	4	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
1987-88	5	12	303	45	6.4	0.3	0.053	0.011	3.70	0.06			3.9	1.5			-9.5	0.9
1988-89	6	10	261	50	6.0	0.2	0.035	0.007	3.99	0.03	4710	1213	4.5	5.7			-14.1	1.8
1989-90	7																	
1990-91	8	45	313	24	7.9	0.3	0.098	0.013	4.32	0.07	7758	616	0.85	0.3	4.30	0.10	-10.9	0.2
1991-92	9	34	221	21	6.6	0.3	0.040	0.006	4.42	0.07	1311	208	0.46	0.13	5.08	0.14	-13.2	0.4
1992-93	10	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
1993-94	11	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
1994-95	12	55	212	19	7.7	0.2	0.059	0.010	4.96	0.05	1483	185	0.12	0.038	5.39	0.042	-11.3	0.5
1995-96	13																	
1996-97	14	33	125	14	7.1	0.5	0.038	0.004	4.42	0.14	1374	230	0.5	0.18	5.15	0.13	-12.4	0.6
1997-98	15	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
1998-99	16	33	137	24	9.7	0.5	0.039	0.009	5.56	0.13	834	159	3.00	0.54	6.38	0.19	-9.3	0.6
1999-00	17	29	206	18	7.3	0.5	0.046	0.015	5.63	0.16	866	154	1.54	0.49	6.13	0.13	-7.1	0.7
2000-01	18	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
2001-02	19	19	108	34	11.5	0.8	0.067	0.012	4.24	0.07	1174	208	1.3	0.22	4.67	0.1	-8.4	0.6
2002-03	20	21	144	21	9.6	0.6	0.068	0.012	3.83	0.07	1086	151	1.9	0.40	4.44	0.11	-11.1	0.6
2003-04	21	4	133	13	6.7	0.9	0.022	0.008	3.96	0.09	1415	127	0.091	0.010	4.29	0.011	-8.6	1
2004-05	22	8	160	26	11.4	0.6	0.099	0.019	4.29	0.07	1916	666	1.08	0.99	4.94	0.05	-7.3	0.6
2005-06	23	22	88	12	11.0	0.6	0.059	0.012	5.47	0.07	816	205	2.76	1.120	5.49	0.057	-11.9	0.6
Average			211		8.3		0.063		4.45		1974		1.45		5.00		-10.2	
StDev			100		1.8		0.029		0.62		1932		1.25		0.62		1.9	
StError			23		0.4		0.007		0.14		455		0.29		0.15		0.4	

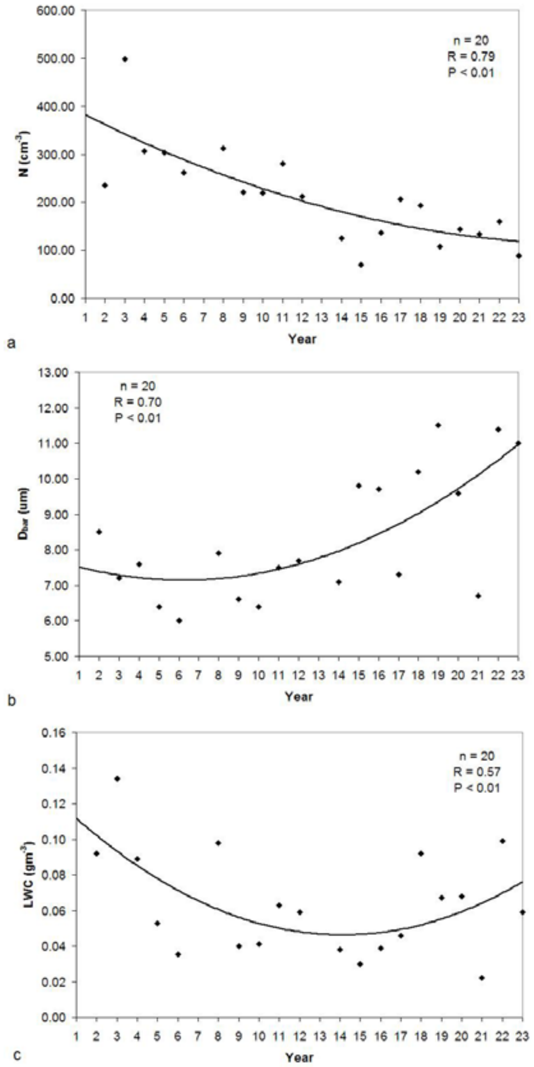


Figure 1: **a**. Cloud droplet concentration (N), **b**. cloud droplet mean diameter (D_{bar}) and **c**. cloud droplet liquid water content (LWC) as a function of year. Year 1 = Winter 1983/84 and Year 23 = Winter 2005/06. R represents the correlation coefficient and P the significance level.

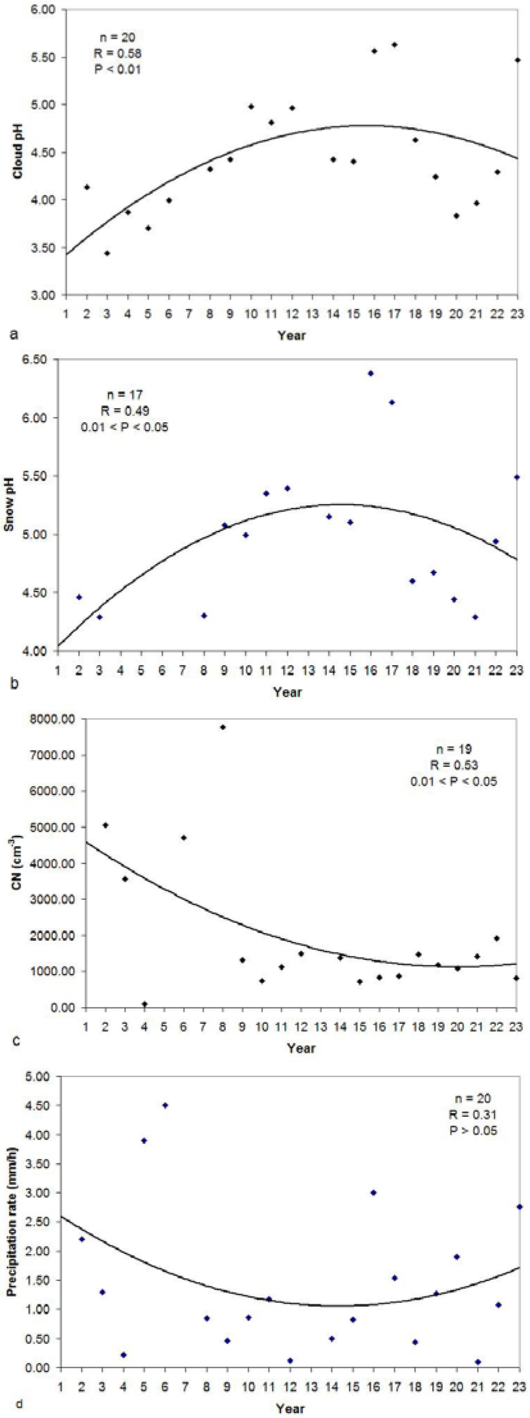


Figure 2. **a**. Cloud droplet pH, **b**. snow pH, **c**. interstitial condensation nucleus concentrations (CN) and **d**. snowfall water-equivalent precipitation rate as a function of year.

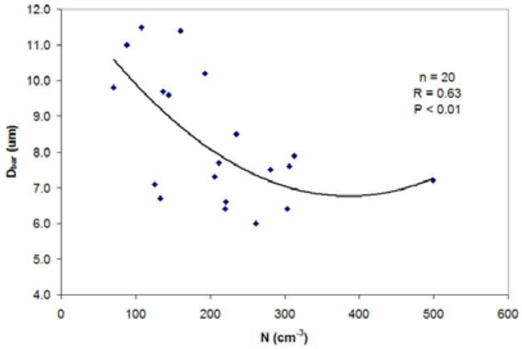


Figure 3: Correlation of cloud droplet concentration (N) and mean droplet diameter (D_{bar}) from, respectively, Figures 1a and 1b.

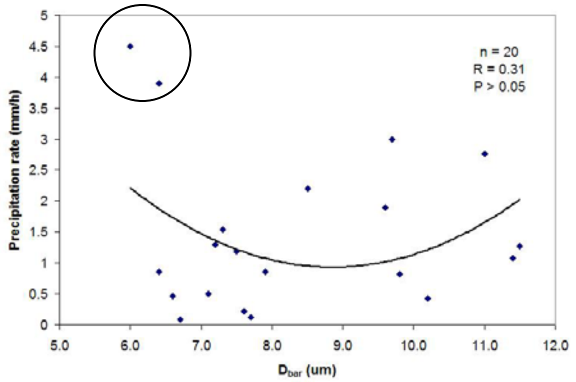


Figure 4a: Correlation of mean droplet diameter (D_{bar}) and snowfall water-equivalent precipitation rate from, respectively, Figures 1b and 2d.

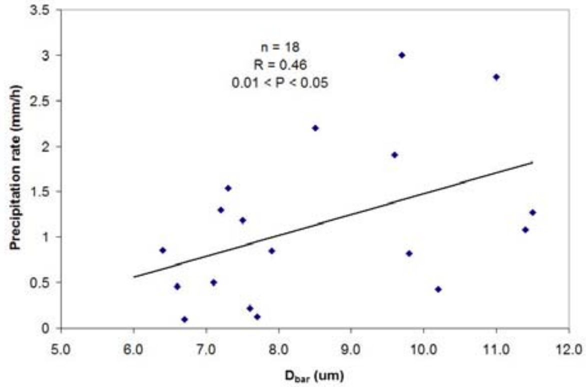


Figure 4b: The circled values in Fig. 4a were deemed outliers and were removed producing this result.

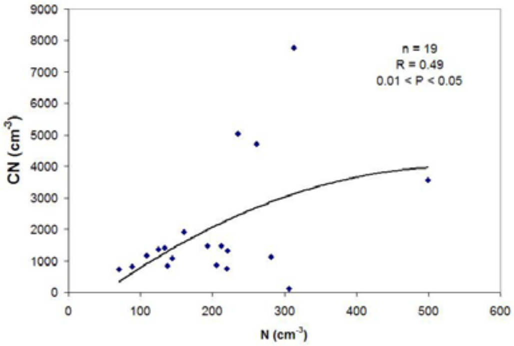


Figure 5. Correlation of cloud droplet concentration (N) and interstitial condensation nucleus concentration (CN) from, respectively, Figures 1a and 2c.

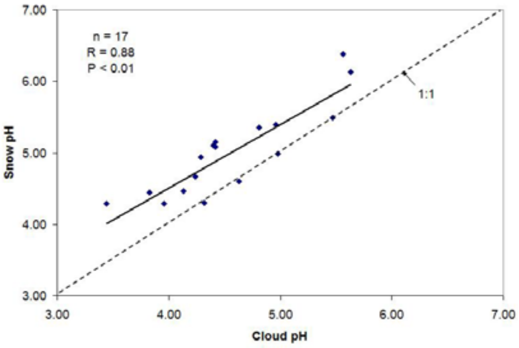


Figure 6. Correlation of cloud pH and snow pH values from, respectively, Figures 2a and 2b.

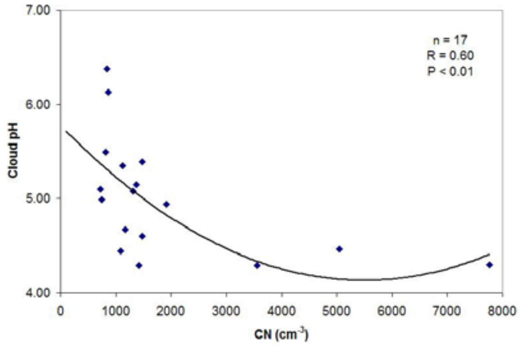


Figure 7. Correlation of cloud pH and interstitial condensation nucleus (CN) concentration from, respectively, Figures 2a and 2c.

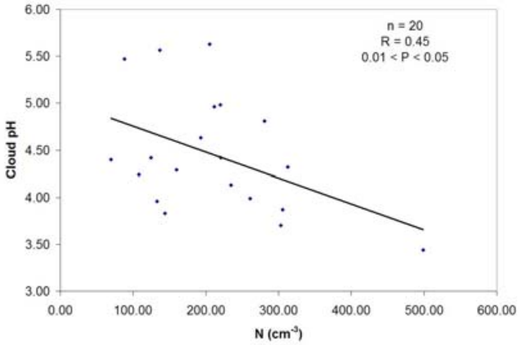


Figure 8. Correlation of cloud pH and cloud droplet concentrations (N) from, respectively, Figures 1a and 2a.

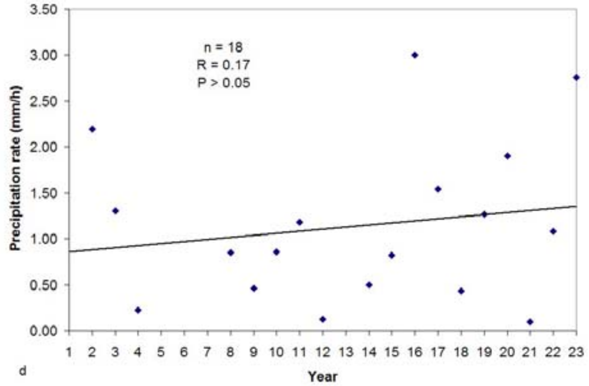


Figure 9. Snowfall water-equivalent precipitation rate as a function of year (Figure 2d again but with the two outliers identified in Fig. 4a removed).

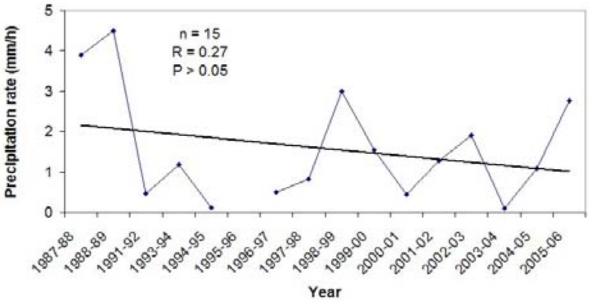


Figure 10. Snowfall water-equivalent precipitation rate values that correspond to the period of the Ski Patrol measurements of snow water contents shown in Figure 11.

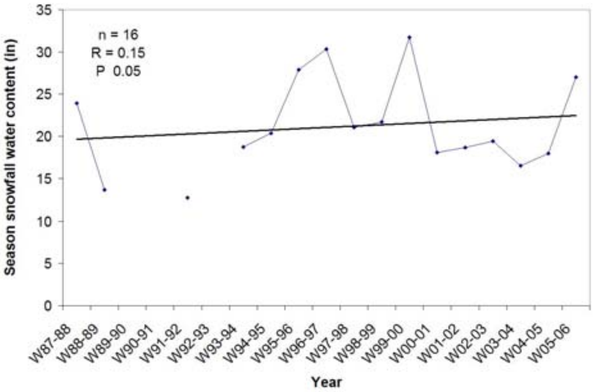


Figure 11. The Ski Patrol measurements of snow water contents.