SNOW VOLUME COMPARISONS FOR ATMOSPHERIC DEPOSITION MONITORING

By

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To evaluate the potential ill-effects of acidic deposition, both pollutant concentrations and precipitation volume must be known to calculate pollutant flux to the soil surface. Monitoring stations for precipitation chemistry in locations dominated by snowfall yield inaccurate data because the techniques used to measure rainfall volume and chemistry are not reliable in snow country.

Acidic precipitation has been measured over wide areas of the Sierra Nevada (Melack et al., 1982; McColl, et al., 1982; California Air Resources Board, 1986; Berg, 1986). Several researchers have reported that snowfall in the Sierra Nevada has low levels of all chemical constituents (Feth et al., 1964; Woo and Berg, 1986). But at higher elevations in the range, 80-95 percent of the annual precipitation typically falls as snow. In an environment where a meter or more of snow water equivalent (SWE) is deposited annually (compared to a few centimeters of rainfall), annual chemical loading is dominated by the high volume of low ionic strength snowfall. At a site in the central Sierra Nevada, snowfall has contributed between 3.5 and 4.3 times as much pollutant load as rainfall (Table 1). Hence, accurate estimates of snowfall amount are especially crucial for determination of pollutant loading in these high snowfall areas.

The accurate measurement of snowfall is not a trivial concern. Two major problems arise from the relatively low density of snowfall. First, with new snow density ranging as low as 40 kg m^{-3} (McGurk, et al., 1988) at the Central Sierra Snow Laboratory (CSSL), a typical snowstorm there can deposit 30-75 cm depth of snow (Smith and Berg, 1982). Precipitation gauges must be of adequate height to retain these large depths of snow. Second, the relatively high surface area-to-mass ratio of falling snow allows it to be readily entrained by wind currents. At even moderate wind speeds, snow can bypass a gauge orifice. Quantification of this "undercatch" has been the subject of numerous studies (e.g., Larson and Peck, 1974; Goodison et al., 1981). Results generally show a near-linear decrease in catch with wind speed increases through 9-10 m s^{-1} (Figure 1). At moderately low wind speeds of 4 m s^{-1}, shielded gauges collect 70-85 percent of the "true" amount but unshielded gauges catch only 45-65 percent (Figure 1). Above 10 m s^{-1} relatively little is known about gauge efficiency, but a significant undercatch is suspected.

Following pioneering research in North America by Pagliuca (1934) on snow gauging techniques and Alter (1937) on gauge shielding, many investigators have tried to improve gauge design, calibration, placement, and wind correction (e.g., Garstka, 1944; Allis et al., 1963; Struzer, 1969; Hamon, 1972; World Meteorological Organization, 1973). Peck (1972) summarized the problem of monitoring snowfall, stating that measurements of snowfall rates and volumes are the least accurate of the meteorological measurements used in hydrologic modeling. Goodison (1978) and Goodison and Metcalfe (1982) did detailed analyses of the ratio of gauge catch to true snowfall, as measured by snow boards, over a period of years using several types of gauges, gauge placements, and types of wind shields. A few studies have evaluated precipitation data from mountainous regions (e.g., Pagliuca, 1934; Garstka, 1944). Problems associated with wind during deposition are increased in rugged, high-altitude regions where gauge placement can significantly alter gauge catch.

A common response to the wind problem has been to install a windscreen and to site the gauge in a forest clearing. In the alpine terrain typical of parts of the southern Sierra Nevada that have low acid-neutralizing capability (Melack et al., 1982), trees are rare and wind speeds are often high. Gauge catch deficiency in such areas is difficult to

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Paper presented at the Western Snow Conference, April 19-21, 1988, Kalispell, MT.

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Table 1. Loading of hydrogen ions (H^+) by rain and snow at the Central Sierra Snow Laboratory (CSSL).

Dates	Precip. Type	Depth (cm H_2O)	pH (by volume)	Concentration (ueq L^{-1})	Loading (meq m^{-2})
7/84-	Rain	11.5	4.7	18.4	2.1
6/85	Snow	106.0	5.2	6.8	7.3
7/85-	Rain	27.9[1]	5.1	8.2	2.3
6/86	Snow	174.8	5.3	4.7	8.3
7/86-	Rain	7.5	4.6	24.0	1.8
6/87	Snow	97.9	5.1	8.0	7.8

[1] 56% of all rainfall occurred during January storms each having pH = 5.3. Values of pHs for summer rains were typically below 4.8.

determine. Even excavation and careful weighing of a large volume of snow (several m^3) has some measurement uncertainty (Farnes et al., 1980). The best alternative for estimating "true" snow deposition volume is to measure the SWE of snow deposited on a snow board adjacent to the gauge.

A snow board is a rectangular board with a protruding vertical rod to allow post-storm location of the board. Snow volume is estimated by measuring the snow depth in several places on the board and by weighing samples collected with a corer of known cross-sectional area. Because the board is at the snow surface prior to snowfall, it does not create extra turbulence, and snow board measurements are often accepted as "ground truth" values of snowfall (Goodison et al., 1981; McGurk, 1986). In windy sites with dry, cold snow, however, both drifting and wind scour can distort the measurements obtained by snow boards (Harris and Carder, 1974).

This paper reports a field study comparing precipitation volume catches using six methods. Four traditional collectors are evaluated. One technique assesses an experimental collector designed for combined snow volume and chemistry assessment, and one method makes use of a precipitation volume/chemistry collector currently used for nationwide atmospheric deposition monitoring. In this case study, two sites were monitored for one field season. Extrapolation of the results to other locations and for longer periods must be made with caution.

DESCRIPTION OF SITES AND INSTRUMENTATION

Two sites were selected that were considered representative of much of the common snow environments in the Sierra Nevada: the mixed conifer/true fir zone of the middle elevations; and the open, windswept expanses of the high elevation southern Sierra. Both the Central Sierra Snow Laboratory (CSSL) and Mammoth Mountain receive large volumes of snowfall, have ready winter access, and a history of snow measurement (Figure 2). At CSSL (39°19'26" N. Lat., 120°22' W. Long.), 1 km east of Soda Springs, California, all measurements were made in a 40 m x 50 m forest clearing at 2100 m msl. Mean annual precipitation is 139 cm (California Cooperative Snow Survey, 1987), of which 120 cm is snow (Smith and Berg, 1982), and mean annual temperature is 2°C. The typical peak depth accumulation is about 3 m of snow that is typically isothermal near 0°C and has a dilute contaminant load (Smith and Berg, 1982; McGurk, 1983; Berg, 1986). At 11 m above the ground surface, average wind speeds in the clearing are low, about 1 m s^{-1} (U.S. Forest Service, 1988). Much of the central and northern Sierra Nevada mountains is similar in these respects to CSSL.

The Mammoth Mountain snow study site (37°88'16" N, 119°01'38" W) is located on the Mammoth Mountain Ski Area, at elevation 2940 m msl. Mean annual accumulation of snow water equivalent at Mammoth is 142 cm (California Cooperative Snow Survey, 1987). In the center of the site is a metal 2.5 m x 9 m platform, raised 5.7 m off the ground. The platform is oriented east-west so that the predominant wind direction is approximately perpendicular to the platform's long axis. The site typically has a peak snow accumulation between 3 and 4 m. The Mammoth site is characterized by high winds, dry snow, and the periodic influence of atmospheric deposition originating in the Great Basin. In these respects, the Mammoth

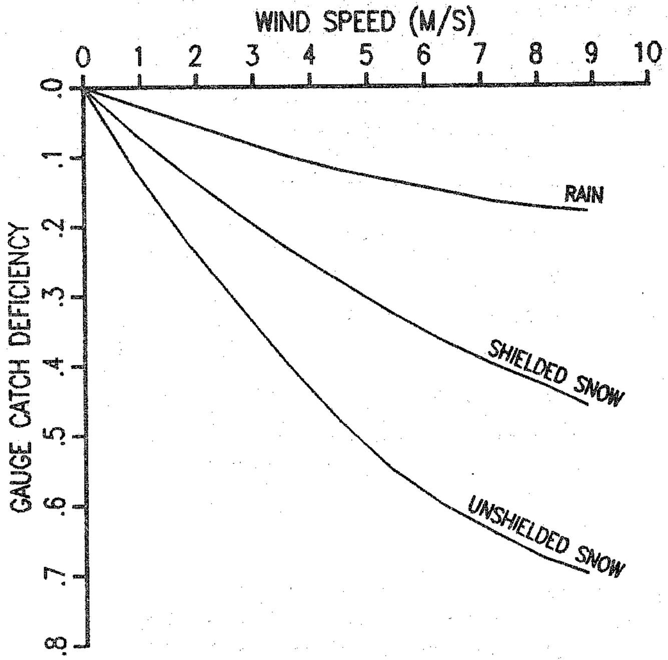

Figure 1. Gauge catch ratios versus wind speed for rain, shielded snow, and unshielded snow (after Larson and Peck, 1974).

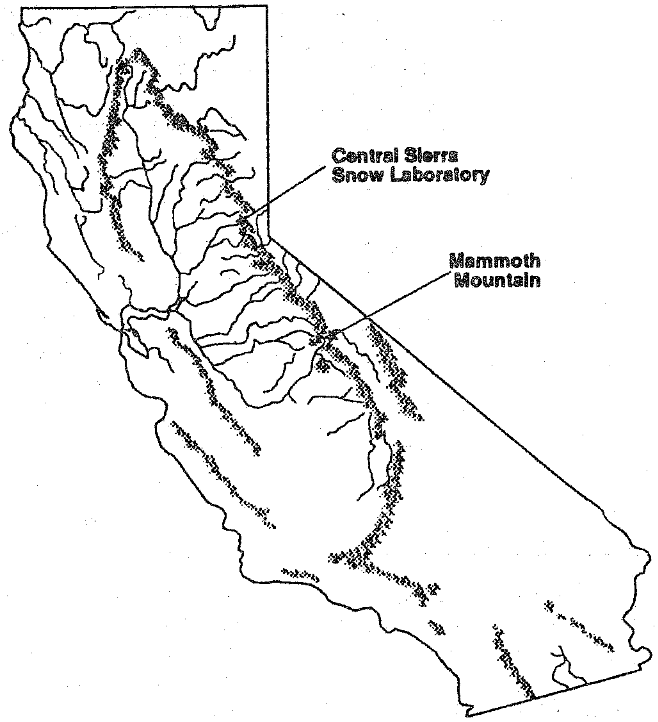

Figure 2. Location map of snow study sites, Central Sierra Snow Laboratory and Mammoth Mountain, California.

site is similar to many other geologically and pedologically sensitive sites in the southern Sierra Nevada.

More than 90% of the annual precipitation falling at CSSL is snow (Smith and Berg, 1982). Rain may occur during winter as well as during summer. Short-term records of precipitation type at Mammoth indicate that 95% or more of the annual precipitation falls as snow (Melack, et al., 1982). Though separated by only a few hundred kilometers, climatically the two sites are very different. The Mammoth site, on an exposed ridge, is unprotected by trees and experiences very high winds both during and following storms. CSSL is 840 m lower than the Mammoth site, is located in a forest clearing, and is protected from the wind.

Both sites were equipped during the winter of 1986-1987 with five snow boards, two Alter-shielded, Belfort high-capacity precipitation gauges (30 cm orifice), two Alter-shielded, experimental snow collectors similar in size and shape to the Belfort gauges (Dawson, 1986), and an unshielded Belfort gauge (30 cm orifice). The CSSL site also had an Aerochemetric atmospheric deposition collector approximately 40 cm tall with a 30-cm orifice. At Mammoth, all gauges were located on the single platform, 5.67 m above the ground surface. At CSSL, three towers were used, and gauge heights varied from 7 to 10 m above the ground surface. Three snow boards were turned daily and two were turned at weekly intervals. Two samples were collected from each board and weighed to estimate SWE. The polyvinyl chloride (PVC) experimental collectors and the Aerochemetric collector were monitored weekly for precipitation volume and trace chemistry. Temperature, humidity (vapor pressure), and wind were also monitored. These climatic factors affect snow density and methods of measuring snow accumulation volumes (McGurk et al., 1988).

The data recording procedures and meteorological instrumentation were identical at both sites. All meteorological variables were monitored at five minute intervals and reduced to 15-minute averages. Data were recorded on Omnidata Easy Logger Field Units. The data recording sensitivity, or "Noise Equivalent Change" (NEC), and an estimate of the recorded data precision were estimated for each instrument used in the study (Table 2). The NEC is the minimum parameter change required to cause a change in the recorded data. Estimated precision is the minimum change that must occur for the difference to be considered significant.

Table 2. Instrumentation, data recording sensitivity, and precision for the instruments used at the Central Sierra Snow Laboratory and Mammoth Mountain snow study sites, 1987 snow season.

Parameter	Instrument		Recorded Data	
	Brand	Model	NEC	Precision
Air Temperature	Vaisala	HMP113V	0.02°C	±0.2°C
Vapor Pressure	Vaisala	HMP113V	5 Pa	±25 Pa
Wind Speed	R.M. Young	Anemometer 3-cup	0.05 m s^{-1}	±0.2 m s^{-1}
Wind Direction	R.M. Young	12002 Microvane	2.5°	±5°
Precipitation	Belfort	6071PR	0.1 cm H_2O	±0.5 cm H_2O
Snow Density	Snowmetric	1 L cutter	---	±3 %

SNOW BOARD AND PIT SAMPLING

During precipitation events, snow accumulation was sampled both once per day from "daily" boards and once per week from "weekly" boards. Snow boards were 0.61 m square, covered with a sheet of linear polyethylene to reduce contamination of snow chemistry samples. If deposition was less than 20 cm, several samples were extracted using a sharpened 5-cm diameter PVC tube. The depth of each sample was noted, and all of the samples were weighed on a digital electronic balance and density and SWE were calculated. This technique was unreliable in very low density snow, or in snow with crusts or ice layers.

Snow pits were dug every other week near the snow boards and were sampled following a protocol described by Perla and Martinelli (1978). Pairs of density profiles or samples were taken in most instances from each snow board or snow pit. For larger snow depositions and for snow pit measurements, a snow density sampler was used that was designed specifically for use in the Sierra Nevada (Dozier et al., 1988). The sampler is a wedge-shaped cutter 20 cm long, 10 cm wide and tapers from 10 cm high at the handle end to 0.1 cm at the sharpened leading edge, giving a 1000 mL volume. A top-loading digital scale allowed the sample to be weighed while in the cutter.

SNOW CHEMISTRY METHODS

Snow was sampled from the PVC tubes, the daily and weekly snow boards, and the snow pits. Field measurements were taken, and detailed laboratory measurements were made at a later date. Only results from the pH measurement of weekly samples from the PVC tubes are reported here.

Sampling Sierran snow without contaminating the sample requires extremely precise techniques. Because hydrogen ion, anion, and cation concentrations are low, touching the inside of a corer or sample container ruins the sample. Because most materials available for collector fabrication are sources of contamination, the collectors were fabricated from polyvinyl chloride. Laboratory studies of liquid stored in the PVC collectors showed no significant contamination. All collector tubes, containers, and spatulas were acid-washed in a 0.1 normal nitric acid solution and rinsed ten times in high-purity deionized water. Field technicians wore disposable plastic gloves while collecting samples, and samples were double-bagged in acid-washed, ziplock bags while being transported. Samples were melted in a 12-to-15°C room and field pH was measured. Staff at both sites used Fisher Accumet digital pH meters with a low ionic-strength electrodes.

RESULTS AND DISCUSSION

Climate Results

Mean daily air temperature, vapor pressure, and wind speed illustrate the differences between the two snow study sites (Figure 3). At Mammoth there was a strong vapor gradient away from the snow surface which, when coupled with high winds, would drive sublimation leading to snowcover cooling and mass loss. Beaty (1975) observed that this occurred at high elevation sites, and Stewart (1982) showed that sublimation could cause up to 25

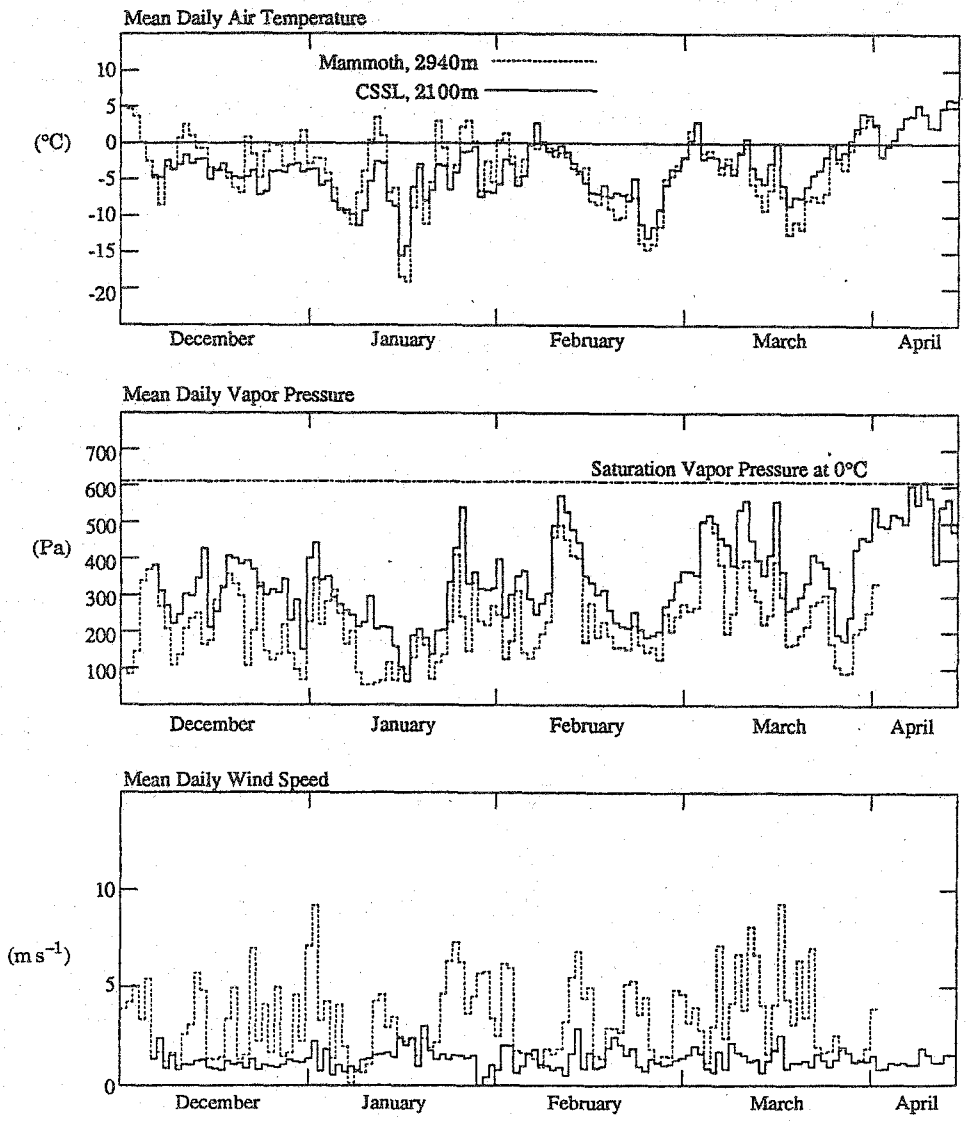

Figure 3. Mean daily air temperature, vapor pressure, and wind speed at the Central Sierra Snow Laboratory and Mammoth Mountain study sites.

percent of the snowcover mass to be lost each year at the Mammoth site. The Mammoth site was appreciably less humid and windier than the CSSL site, and the frequent near-saturation daily averages at CSSL indicate that nighttime saturation and surface condensation were routine. The Mammoth site was warmer during December and January, and then slightly cooler during the rest of the snow season. This finding is surprising due to the elevational difference between the two sites. The pattern of the air temperature and vapor pressure traces suggested that large frontal systems affected both sites similarly.

Monthly climatic averages further illustrate the differences between the two sites (Table 3). Monthly averages have little physical significance, but they allow evaluation of a parameter which is subject to so much stochastic short-term variation. Comparison with long term monthly temperature averages reported by Smith and Berg (1982) indicate that it was about 2°C colder than average at the CSSL site during 1987.

Snow Volume Comparisons

During the 1986-1987 snow season, nearly twice as much precipitation was caught by the high-capacity Belfort gauges at CSSL than at Mammoth (Figure 4). Although the unshielded gauge caught less than the shielded gauges at both sites, the end-of-season difference was not statistically significant. Gauge placement may cause microclimate variations at each gauge. CSSL's two shielded Belforts were approximately 10 m and 17 m from the northwest edge of the forest clearing. The unshielded Belfort was near the center of the 50-m

Table 3. Climate summary for the Central Sierra Snow Laboratory and Mammoth Mountain snow study sites, 1987 snow season.

Air Temperature Summary, Monthly Averages (°C)

	CSSL			Mammoth		
Month	Mean	Max*	Min*	Mean	Max	Min
Dec	-3.9	2.1	-8.5	-1.6	1.3	-4.2
Jan	-6.4	-1.0	-11.0	-4.7	-1.3	-8.3
Feb	-4.9	0.2	-9.4	-5.6	-2.0	-8.7
Mar	-2.5	2.1	-6.8	-3.9	-0.7	-7.0
Apr	3.0	9.9	-3.0	3.0	6.5	-1.2
Seasonal Mean	-2.9	2.7	-7.8	-2.6	0.8	-5.9

Humidity Summary, Monthly Averages (Pa)

	CSSL			Mammoth		
Month	Mean	Max	Min	Mean	Max	Min
Dec	316	409	227	212	292	131
Jan	271	372	187	181	264	104
Feb	312	400	230	231	317	150
Mar	389	479	299	271	350	192
Apr	523	676	389	294	448	219
Seasonal Mean	362	467	266	238	344	159

Wind Speed Summary, Monthly Averages (m s^{-1})

	CSSL			Mammoth		
Month	Mean	Max	Min	Mean	Max	Min
Dec	1.14	2.14	0.23	3.15	6.33	1.03
Jan	1.38	2.64	0.38	3.47	7.20	1.20
Feb	1.38	2.52	0.41	3.07	6.47	0.94
Mar	1.38	2.74	0.34	3.89	7.71	1.35
Apr	1.24	2.41	0.29	2.90	6.45	0.78
Seasonal Mean	1.30	2.49	0.33	3.30	6.83	1.06

* Monthly averages of daily maximum and minimum values.

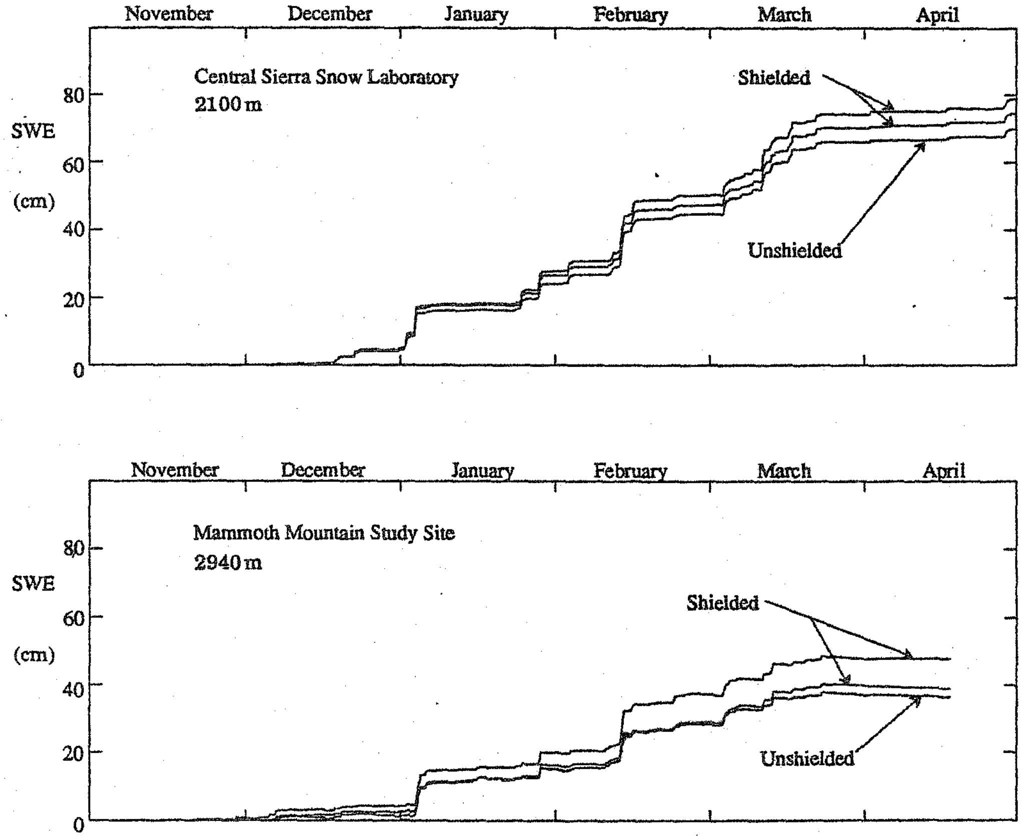

Figure 4. Seasonal accumulation of precipitation for water year 1987 as measured by the Belfort high-capacity precipitation gauges at the Central Sierra Snow Laboratory and Mammoth Mountain study sites.

clearing. At Mammoth, space limitations on the platform resulted in the shielded Belforts being 2-3 m downwind from the shielded PVC tubes. The proximity of the devices may have further modified wind conditions.

Cumulative average weekly totals from the Belforts, the PVC tubes, the Aerochemetric sampler, and the daily and weekly snow boards yielded differing results at each site (Table 4). At CSSL, the totals ranged from 61.5 cm to 72.2 cm, and the snow board values were 6 to 9 cm less than the Belfort and PVC tube means and the Aerochemetric's value. The difference between the snow boards and the other samplers is at least partially due to 0.9 cm of rain and a mixed rain-and-snow storm that totaled 4.7 cm in the Belfort gauges but only 1.3 cm on the daily snow boards. If rain losses are added to the board totals, the values for the four methods in Table 4 are within 10 percent. Melting prior to measurement may also have contributed to the board's low values.

The CSSL Aerochemetric wet/dry sampler's catch was slightly greater than the Belforts and the PVC tubes, but it requires reliable maintenance by on-site technicians for alpine operation. Three problems, however, must be overcome if the device is to be used at an alpine site: wind, freezing of the movable arm, and the shallow bucket depth. Past experience with a similar collector at Mammoth showed that the movable arm could be seriously damaged by high winds and that the "cap" did not prevent snow from being added or removed from the bucket. The bucket is only 40 cm deep, and during large storms, a technician must climb the tower and change buckets if an accurate volume of snow is to be recorded. In an average winter at both Mammoth and CSSL, weekly bucket changes might seriously underestimate SWE between three and six times during the winter.

The snow pit SWEs are not directly comparable to the collector SWEs, but they do provide an indication of accumulated SWE. The pit SWE at CSSL lagged behind the Belfort mean total SWE until mid-February, then matched it for one month before falling behind. The Mammoth pit's SWE was roughly comparable to the SWEs from the Belforts and the tubes until mid-February. The pit SWE was midway between the boards and the collectors for the rest of the season.

The monthly and seasonal wind speeds at Mammoth were approximately three times the CSSL values (Table 3), and this difference may be the cause of the 25 percent undermeasure by Mammoth's Belforts and PVC tubes as compared to the snow boards. No rain was reported at Mammoth during the entire season. Based on a seasonal average wind speed of 3.3 m s^{-1}, a

Table 4. Snow volume comparison for the Central Sierra Snow Laboratory and Mammoth Mountain snow study sites, 1987 snow season (cumulative weekly depth [cm H_2O]).

	Central Sierra Snow Laboratory						Mammoth Mountain				
Date[1]	Belfort Gauge[2]	PVC Tube	Daily Board	Weekly Board	Aero Chem	Snow Pit	Belfort Gauge	PVC Tube	Daily Board	Weekly Board	Snow Pit
861209	--	--	--	--	--	--	2.1	2.5	2.0	2.0	--
861223	4.4	3.8	2.2	3.8	3.8	--	3.2	3.7	2.9	3.2	--
861231	4.3	3.8	2.6	4.5	4.2	--	3.1	3.7	2.9	3.2	--
870106	17.5	16.7	13.9	19.1	16.9	--	13.1	13.4	17.8	17.3	--
870113	17.7	16.9	13.9	19.1	17.2	24	13.3	13.6	17.8	17.3	19
870120	17.7	16.9	13.9	19.1	17.2	--	14.1	14.4	18.7	17.9	--
870127	21.3	20.7	16.9	21.9	21.1	28	14.8	15.6	19.5	19.5	14
870203	29.2	28.5	25.4	29.9	29.2	25	18.4	19.2	24.2	26.8	--
870210	29.6	28.9	25.4	29.9	29.6	--	19.4	20.4	25.4	28.1	--
870217	45.9	44.5	39.7	42.9	47.1	46	31.1	30.4	40.0	42.8	33
870224	47.2	45.7	41.0	44.0	48.3	--	33.4	33.5	42.2	45.4	--
870303	47.4	45.9	41.3	44.0	48.5	46	33.5	33.9	42.8	45.4	37
870310	53.2	52.0	45.3	45.7	54.6	--	38.3	39.4	49.8	50.6	--
870317	63.3	62.3	54.5	58.1	64.7	57	42.1	43.7	52.4	56.6	50
870324	70.1	69.0	60.7	63.9	71.4	--	44.4	47.4	54.7	60.6	--
870331	70.1	69.0	60.7	63.9	71.4	60	43.8	47.6	57.0	62.9	49
870408	70.8	69.7	61.5	63.9	72.2	--	43.8	48.8	57.0	63.8	--

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[1] Week ending.

[2] At each site the values are the means of measurements from two shielded Belfort gauges, two shielded PVC tubes, two or three snow boards turned at daily and weekly intervals, and two adjacent snow pit depth/density profiles.

collector catch deficiency of approximately 23 percent (Figure 1) might be expected (Table 3). Although a seasonal average wind speed is not directly related to wind speeds during storms, there is close correspondence between the actual and the projected deficiency.

Because seasonal accumulations mask short-term variation, weekly bar charts for the two sites were prepared (Figure 5). Weeks with less than 1 cm of precipitation were excluded. At CSSL, the Aerochemetric sampler record is shown along with the Belfort, PVC tube, and weekly board values. The low board values for 17 February and 10 March and both April intervals are in part due to mixed rain and snow or rain events. Although catch variations of several centimeters did occur, the catch by all four methods was quite similar. At

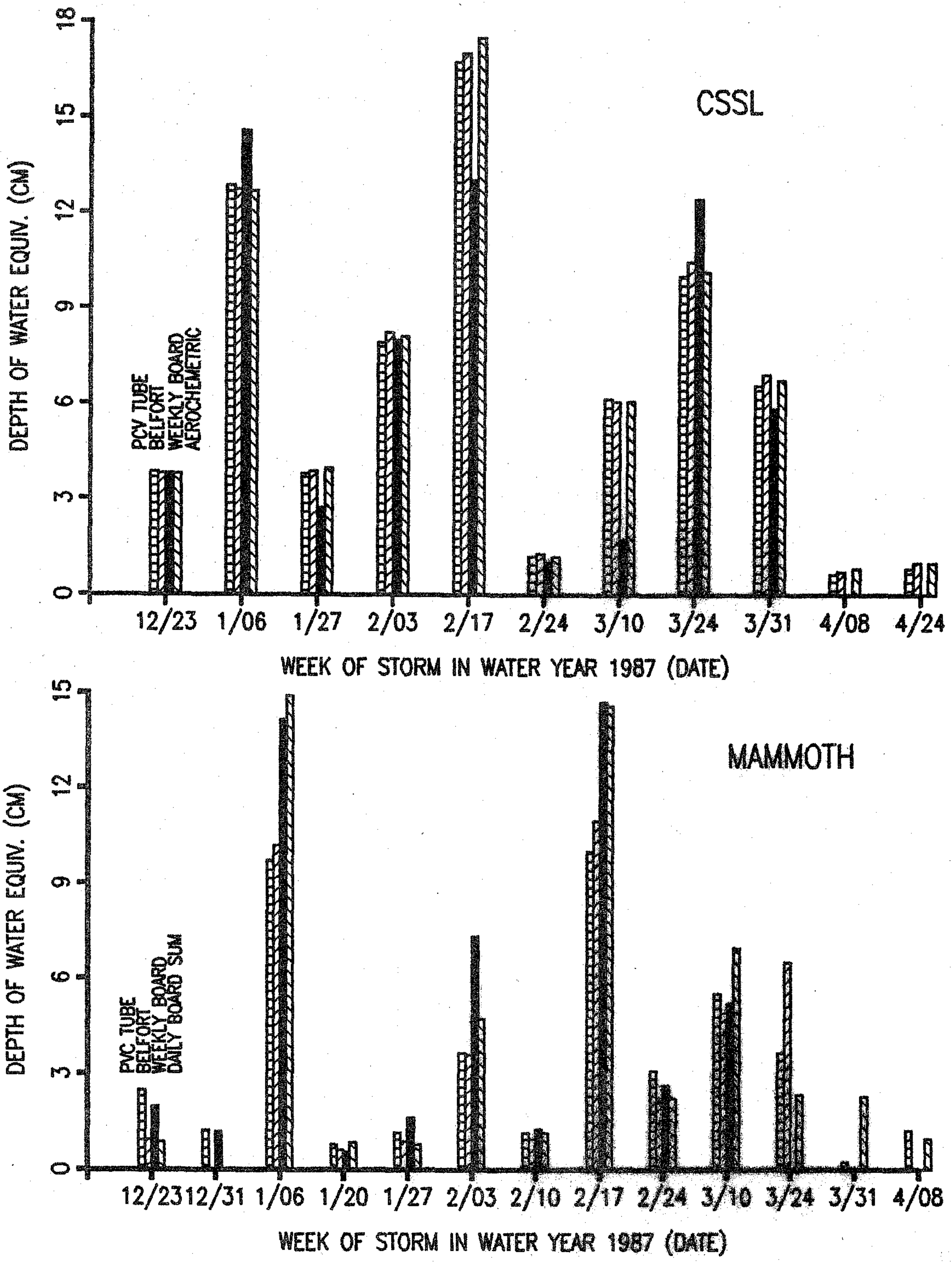

Figure 5. Bar charts of mean weekly precipitation depths for selected weeks of water year 1987 at the Central Sierra Snow Laboratory (Belforts, PVC tubes, weekly snow boards, and Aerochemetric sampler) and Mammoth Mountain (Belforts, tubes, weekly and sum of daily snow boards).

Mammoth, a 30 percent catch deficiency by the Belforts and PVC tubes was apparent during the large storms. The weekly storm totals that were less than 3 cm showed no clear difference between methods.

DEPOSITION AND ESTIMATES OF CHEMICAL LOADING

By combining accurate estimates of precipitation accumulation with the associated chemical constituents at a site, the pollutant load at a site over time can be determined. Hydrogen ion (H^+) concentrations were calculated from volume and pH measurements of weekly samples from the PVC bulk snow collectors at both CSSL and Mammoth (Table 5). Snow samples from the PVC tubes were more acidic (lower pH and high H^+ levels) at CSSL than at Mammoth. Calculated H^+ loading at CSSL, however, was nearly three times the loading at Mammoth due to the combined effects of elevated acidity and greater precipitation volume.

The critical effect of accurate volume estimates is further illustrated by comparison of calculated loadings based on concentrations from the PVC tubes and weekly precipitation volumes measured by the four techniques (Table 6). Differences in calculated loading were small at both sites when comparing the Belfort gauges and the PCV collectors. The loading difference is less than 1% at CSSL but is about 9% at Mammoth. Lightning-caused static electricity caused several problems with the Belfort gauges at Mammoth after March 24. If these measurements are excluded from the Mammoth data set, the difference between calculated H^+ loading for the Belforts and tubes is less than 3%.

Calculated H^+ loading differences between daily and weekly snow boards were also small at both sites. The difference at CSSL was about 3%, and at Mammoth it was about 10%. H^+ loading results at CSSL were within 9% for all methods of estimating SWE over the snow season. At Mammoth, however, nearly a 30% increase in calculated loading if snow board-derived estimates of SWE were used. If loading is based upon Belfort estimates of SWE, CSSL received over three times what Mammoth received. If weekly snow board estimates of SWE are used, however, CSSL received just 1.9 times the H^+ loading calculated for Mammoth.

CONCLUSIONS

The shielded PVC collector and the shielded Belfort had nearly identical weekly catches and seasonal totals at both sites. At the windy Mammoth site, however, both devices undermeasured the seasonal precipitation by about 25 percent as compared to snow board

Table 5. PVC snow tube chemistry summary at the Central Sierra Snow Laboratory and at Mammoth Mountain during the 1987 snow season.

Date[1]	SWE (cm)		pH		H^+ Concentration (μeq L^{-1})		H^+ Loading (μeq m^{-2})	
	CSSL	Mammoth	CSSL	Mammoth	CSSL	Mammoth	CSSL	Mammoth
861209	---[2]	2.5	---	5.63	---	2.3	---	58.5
861223	3.8	1.2	4.88	5.05	13.2	8.9	500.8	106.9
870106	12.9	9.7	5.20	5.30	6.3	5.0	806.3	486.0
870113	0.2	0.2	5.20	5.93	6.3	1.2	12.6	2.3
870120	---	0.8	---	5.32	---	4.8	---	38.7
870127	3.8	1.2	5.35	5.69	4.5	2.1	171.0	24.6
870203	7.9	3.7	5.17	5.30	6.8	5.0	535.6	187.4
870210	0.4	1.1	5.13	5.20	7.3	6.3	29.3	69.4
870217	16.7	10.0	5.30	5.68	5.0	2.1	835.0	209.0
870224	1.2	3.1	4.66	5.47	21.8	3.4	261.0	105.4
870303	0.2	0.4	4.80	5.44	15.7	3.6	31.4	14.5
870310	6.1	5.5	5.21	5.77	6.1	1.7	373.9	94.1
870317	10.0	4.3	5.12	5.87	7.6	1.4	758.0	58.1
870324	6.5	3.6	5.21	5.38	6.2	4.2	401.1	150.1
870331	---	0.3	---	5.65	---	2.2	---	6.7
870408	0.6	1.2	4.99	5.49	10.3	3.2	62.1	38.9
870424	0.8	---	5.15	---	7.0	---	56.1	---
Total:	71.1	48.8	---	---	8.6[3]	3.6[3]	4834.2	1650.6

[1] Week ending. [2] No precipitation recorded. [3] Mean H^+ value.

Table 6. H^+ loading, by instrument, at the Central Sierra Snow Laboratory and Mammoth Mountain snow study sites, 1987 snow season (cumulative weekly deposition [ueq m^{-2}]).

Date[1]	Central Sierra Snow Laboratory				Mammoth Mountain			
	Belfort Gauge[2]	PVC Tube	Daily Board	Weekly Board	Belfort Gauge	PVC Tube	Daily Board	Weekly Board
861223	500.8	500.8	290.0	500.8	98.0	106.9	80.2	106.9
870106	818.8	806.3	731.3	956.3	496.0	486.0	746.5	706.4
870113	12.6	12.6	0.0	0.0	2.3	2.3	0.0	0.0
870120	0.0	0.0	0.0	0.0	38.7	38.7	43.6	29.0
870127	162.0	171.0	135.0	126.0	14.4	24.6	16.4	32.8
870203	535.6	535.6	576.3	542.4	180.4	185.4	235.5	365.7
870210	29.3	29.3	0.0	0.0	63.1	69.4	75.7	82.0
870217	815.0	835.0	715.0	650.0	244.5	209.0	305.1	307.2
870224	282.8	261.0	282.8	239.3	78.2	105.4	74.8	88.4
870303	31.4	31.4	47.1	0.0	3.6	14.5	21.8	0.0
870310	355.5	373.9	245.2	104.2	82.1	94.1	119.7	88.9
870317	765.6	758.0	697.4	939.9	51.3	58.1	35.1	81.0
870324	419.6	401.1	382.5	357.9	95.9	150.1	95.9	166.8
870331	0.0	0.0	0.0	0.0	---[3]	6.7	51.5	51.5
870408	72.5	62.1	82.8	82.8	---[3]	38.9	29.2	29.2
870424	70.1	56.1	56.1	56.1	---[4]	---[4]	---[4]	---[4]
Total:	4871.5	4834.2	4241.5	4555.7	1448.5	1590.1	1931.0	2135.8

[1] Week ending.

[2] At each site values are the means of measurements from two shielded Belfort gauges, two shielded PVC tubes, and two or three snowboards turned at daily and weekly intervals.

[3] Net loss of precipitation in gauge; possible evaporation.

[4] No measurements made.

totals. During weeks with large storms with high winds, the catch deficiency was as high as 30 percent.

Because of local site variations and potential equipment malfunctions, pairs of measuring devices should be installed. With a single precipitation measurement, unusual values associated with malfunctions may not be recognized and corrected. An important statistical benefit of twin collectors is the ability to calculate confidence limits around the mean measurement. Volume and pollutant concentration measurements should be co-located.

At a shielded mid-elevation site such as CSSL, the PVC collector may be required instead of snow boards or pits because when rain or melt occur, both water and contaminants are lost from snow boards. At a higher, windy site such as Mammoth, forest clearings are difficult to find, but midwinter rain is very rare. Weekly snow boards provide the greatest accumulation and pollutant loading information at high, windy sites.

At mid-elevation sites there are advantages and disadvangages to both snow boards or PVC collectors. For accumulations of 20 cm or less, collection of data and samples from a weekly snow board is more convenient than changing PVC tubes. If the weekly snow accumulation is deeper than 20 cm, changing the PVC tube is easier than the excavation and coring techniques required with the weekly snow board. During weeks with no precipitation, the PVC tube must be replaced with a clean tube to avoid sampling dry deposition and other debris when precipitation does occur. Another drawback to the use of a PVC collector is the need for a tower and a windscreen. Towers are required for sites that experience deep snow, and the cost and safety hazard associated with towers is significant.

The Aerochemetric sampler might be adequate for snow sampling at a site such as CSSL except for two factors: low capacity and freezing. During large storms, the shallow buckets overflow before the weekly servicing time. The seasonal accumulation for the Aerochemetric sampler was approximately equivalent to the other devices only because of bucket changes during the large storms by the onsite technicians. Because storms at CSSL are frequently near 0°C, the movable arm occasionally freezes in place and must be manually repaired. Based on past experience at Mammoth, the Aerochemetric seriously undermeasures during windy storms, and the movable arm is easily damaged by strong gusts.

The seasonal accumulation from the less labor-intensive weekly boards was similar to the results from the daily boards. Snow pits are a possible alternative to snow boards at windy alpine sites such as Mammoth. If pits were excavated to ground and samples taken both on 1 March and 1 April, a reasonable estimate of winter pollutant loading might be obtained. Pits would not be acceptable at lower-elevation sites such as CSSL due to both mass and pollutant losses when rain or melt occur.

Correction of precipitation accumulation for the PVC tube based on wind speed is possible, but such a procedure adds considerable uncertainty. A correction coefficient of 1.25 or 1.3 might be correct for Mammoth, but the coefficient should be based on at least two years of calibration data from both tower-mounted and ground collectors. Prediction of a correction coefficient based on site characteristics and meteorological parameters is not yet possible.

Because the unshielded Belfort caught less at both sites, windscreens are recommended for all precipitation collectors. Windscreens, however, cannot overcome the lack of shelter provided by a forest clearing. For precipitation and pollutant monitoring at windy, alpine sites where forest shelter is not available, but that are the most sensitive to pollutant loading, different procedures must be available that will produce accurate data. A well-designed monitoring network should match sampling procedures and equipment to site characteristics.

ACKNOWLEDGEMENTS

Jim Bergman, Randall Osterhuber, and Joe Lipka fabricated and installed the data collection platform at the Central Sierra Snow Laboratory, and collected the data. Staff at Mammoth Mountain Ski Area fabricated and installed the data collection platform at Mammoth Mountain, and Dan Dawson collected the data. Dan Dawson and Danny Marks fabricated the PVC collectors. The California Air Resources Board funded this study.

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