PRECIPITATION AND SNOW WATER EQUIVALENT SENSORS: AN EVALUATION

798-86

By

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INTRODUCTION

The economic importance of California's water resource has helped justify the development, installation, and operation of new ways to measure the water content of the Sierra Nevada snowpack. Although the traditional snow courses are still visited and sampled monthly, they have been supplemented by telemetered sensors that provide more frequent information on snow water equivalent (SWE), precipitation, and temperature. As data collection budgets are declining, information demands are increasing and the need for accurate SWE estimation is ever more crucial. Costs of manual snow measurement are additive because three trips cost three times as much as a single trip. However, once a sensor has been installed, it can be read as frequently as desired with only marginal increases in cost.

The ultimate utility of the snow sensors has been debated since their initial installation. Early prophets suggested that the data could predict flood flows, runoff rates, and drought (Shannon, 1968), and estimate land management effects and eliminate the need for manual snow courses (Farnes, 1978). Although this optimistic future has not been realized, the sensors are widely used. About 100 sets of sensors have been installed in California over 30 years, and information from snow sensors and snow courses serve numerous needs. From April through June, state and Federal agencies use the data to prepare total runoff forecasts. These forecasts aid reservoir operators in balancing their opposing flood control and water supply storage objectives. The sensor data are typically combined with other information in empirically derived regression models to predict snowmelt runoff volumes and river flow rates.

Numerous efforts have been made to evaluate the performance of the snow and precipitation sensors. Suits (1985) compared storm totals registered by the storage gauge and the pillow in the Feather and Tuolumne river basins. He also compared the pillow's total SWE with snow cores taken near the pillows. Snow pillows typically registered more storm precipitation than did storage gauges and the lag in sensing new snow was greater at lower elevations than at higher elevations. However, comparisons of the pillow and the storage gauge were not conclusive because of the lack of wind data and the tendency of precipitation gauges to progressively undermeasure snow as wind speed increases (Linsley et al., 1982). Diurnal variations in manometer readings of as much as 8 cm have been observed during summer, and similar -- although smaller -- fluctuations were observed during winter (Smith and Boyne, 1981). The California Department of Water Resources (1976) concluded that more accurate precipitation values at high elevations were obtained with a snow pillow than with a precipitation gauge. The Department also found no significant problems with lag or overmeasurement when the four-panel stainless steel design was used. Cox et al. (1978) found a correlation coefficient of 0.94 between stainless steel pillows and Federal snow tube measurements for 1135 station-years of record from 12 states. In tests of pillow response using continuous chart recorders, a butyl rubber pillow registered snowfall rates as low as 0.08 cm/hr, and response to new snow occured in 5 minutes or less (Beaumont 1965).

Past tests of the accuracy of snow sensors fall into two categories: comparisons of a storage gauge or Federal snow tube samples with snow pillow readings, and analyses from intensively instrumented sites that are specially constructed and continuously measured and staffed. The former test suffers from a lack of correlative information with which to compare the telemetered data and explain anomalies, as well as from possible overmeasurement by the Federal sampler. The latter test may be biased due to the exceptional attention devoted to the system by the resident staff during installation and operation, a condition not usually encountered in normal, unattended field operation.

To overcome the above shortcomings, I compared the relative storm SWE totals for seven storms in 1984 and 1985 while the snow telemetry system (SNOTEL) at the U.S.D.A. Forest Services's Central Sierra Snow Laboratory (CSSL) was operated in a typical, unattended manner. One goal of the study reported here was to determine if the snow pillow's response

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to snowfall was delayed both at the beginning and the end of a storm. Another goal was to test the performance of the precipitation storage ("missile") gauge, because it is often used in conjunction with the pillow to detect the onset and magnitude of storms. This evaluation seemed timely in an era when increased reliance is being placed on data from automated systems that may receive minimal checking due to increasingly severe shortages of personnel.

The analysis was based on the operation of a single SNOTEL system for two winters at one site. While I believe that the sensor system at CSSL is representative of any of the 550 SNOTEL systems in 12 western states or any of the 100 systems in California, no data exist to support this belief.

METHODS

CSSL is slightly below and west of the crest of the central Sierra Nevada at an elevation of 2100 m. Winters are characterized by deep snowpacks (2 to 5 m) that begin to accumulate in December and last through May. Temperatures range from -20°C to 10°C, and winds in the 75-m diameter forest clearing rarely exceed 3.5 m/s at a 9-m height. Precipitation is frequent during winter, and while snow predominates, rain and mixed snow and rain also occur.

While a round, butyl rubber pillow was the original design, the U.S.D.A. Soil Conservation Service's (SCS) pillow at CSSL is a four-panel stainless steel pillow. Each panel is 1.2 x 1.5 m, and the fluid in the cavity is a mixture of ethylene glycol and methanol. The CSSL pillow is connected to a 51-cm capacity Robinson-Halpern pressure transducer that converts the pressure due to the weight of the snow to an analog voltage. Readings are taken every 15-16 minutes, and the transducer's analog signal is digitized and stored in solid-state memory. The system's transmitter is polled twice daily by the SCS master station. The VHF radio signals are reflected by ionized meteor trails, and the data are stored by a central computer system (Barton and Burke, 1977). The analog voltages are converted to depth of water with an algebraic equation. Voltages corresponding to air temperature and accumulated water in a precipitation storage gauge are included with SWE in the transmission and reduction process.

A 20-cm orifice Belfort dual-traverse rain gauge with an Alter wind screen is located on a 9-m tower in the clearing at CSSL. The Belfort gauge is equipped with a linear voltage displacement transducer (LVDT) as well as an 8-day chart drive. Air temperature is sensed by a YSI thermistor in an aspirated shelter. The SNOTEL missile gauge and snow pillow are within 10 m of the Belfort gauge and the thermistor, as are nine meltpans located at the soil surface and plumbed to individual tipping buckets. The meltpan outflow is recorded by an Esterline Angus chart recorder. All other data are recorded by a Monitor Labs 9350 datalogger (ML) that calculates and stores hourly averages (meteorological data) or prints instantaneous readings (SNOTEL) on paper tape. Stored data are transferred to diskette and later transmitted to the Pacific Southwest Forest and Range Experiment Station in Berkeley for reduction and analysis.

The SNOTEL transmitter is housed in the basement of the CSSL garage and obtains 12 v dc from a trickle charger plugged into line current. An interconnection with the ML signals the ML to scan the four SNOTEL channels while the SNOTEL system reads and stores the three sensor voltages. Snow pillow, missile gauge, air temperature, and the energizing voltage are printed onto paper tape by the ML, and the data are keypunched at Berkeley. Because the ML is occupied for 20 seconds of each minute scanning the meteorological instruments, and the SNOTEL signals last only for 5 seconds, only one or two SNOTEL scans are typically recorded per hour. Occasionally several hours pass before the ML records a valid SNOTEL scan. Both the meteorological and the SNOTEL data are subject to extensive error checking by both computer programs and manual inspection.

SNOTEL data were collected from January to May in 1984, and January to April in 1985. To compare storm catch and response lags among sensors, four storms from 1984 and three storms from 1985 were selected. All storms deposited more than 5 cm SWE, and five of the seven storms deposited only snow. Two of the 1985 storms had less than 0.25 cm of rain mixed with snow at the beginning of the storms.

The SNOTEL system was designed to produce an energizing voltage of 7.5 v dc, but voltage fluctuations were suspected. Energizing voltages for each month were sorted into seven arbitrary classes between approximately 7.0 and 7.6 v dc. Observed deviations were reduced by using the rating equations to assess depth variations that resulted from power supply fluctuations.

The Belfort, pillow, and missile sensor voltages recorded by the ML were converted to depths of water by rating equations. Hourly accumulated values were obtained by subtracting the reading for the initial hour of a storm from the depth readings during the rest of the storm. The hourly depths were plotted to display the accumulation of precipitation for each of the three sensors. Hourly average air temperature was also plotted to allow evaluation of potential temperature effects.

Twenty-four hour accumulations were tabulated using 0800 hours as the start and stop point. The first day of the storm sequence included precipitation from midnight to 0800, and the final total included changes from 0800 to midnight. The intervals typically had precipitation during the first 4 or 5 days, and none during the last 2 days. The post-storm intervals were included so that temperature or snow loading effects could be assessed. The daily total tabulations included the pillow, missile gauge, both LVDT and strip chart values from the Belfort gauge, and SWE values from a pair of snow boards. Daily, at 0800 and 1600 hours, and 20-cm cores were collected from the boards, melted, measured volumetrically, and converted to areal depth. Depth and SWE values from snow boards have been considered to be "ground truth" in past precipitation gauge comparisons (Goodison and McKay, 1978). This is because deposition on the boards is very similar to deposition on the snowpack, while capture of snow particles in an elevated rain gauge orifice is quite dissimilar to deposition of particles on a snow surface.

Because the storm intervals were often preceded and followed by warm and sunny conditions, meltpan outflows were tabulated for each day on a midnight-to-midnight basis. CSSL's meltpans accurately measure outflow, but the pan walls are only 20 cm tall, and the contributing area is unknown and possibly changing. Hence, the conversion of outflow volume to areal depth of melt is uncertain. Based on estimates of maximum melt depths for each of the storm periods (U.S. Army Corps of Engineers, 1956) and maximum observed period outflows, a rough technique was devised to convert bucket tips to areal depths. The depth estimates should be considered as trends rather than absolute values.

RESULTS AND DISCUSSION

Voltage-to-Depth Conversions

The accuracy of a pressure transducer is affected by the stability of the input voltage and ambient temperature. Both the SNOTEL sensors and the Belfort's LVDT receive their voltages from power supplies designed to produce a constant input to the sensor. Variations in sensor output are thereby attributed to changes in pressure or linear displacement due to storm deposition. Because power supply voltage controls are affected by temperature, some output variation is virtually unavoidable. The Belfort's empirical conversion equation compensates for this problem by incorporating both the input and output voltages as variables. The SNOTEL equations use only the sensor output:

$$SWE = 2.54\ [(20\ V_p) - A] \qquad (1)$$

$$DEP = 2.54\ [(30\ V_m) - B) \qquad (2)$$

where SWE is the snow water equivalent of the snowpack and DEP is the accumulated precipitation, both in cm. V_p and V_m are transducer output voltages from the pillow and missile gauge, and A and B are offset values that the SCS determines about October 1 of each year. The offset values incorporate factors such as the glycol charge in the missile gauge and the weight of the layer of soil on the snow pillow.

At CSSL, voltages from the SNOTEL sensors are typically between 1.5 v and 4.5 v, and in 1984 the value of A was 9.5 and B was 46.2 v. In April, 1984, 60 percent of the energizing voltages were between 7.510 and 7.515 v, but 14 percent were less than 7.500 v. Changes in the energizing voltage are transferred directly to the output voltage from the sensors, and thereby to the depth of water. For example, by varying the missile gauge output from 3.500 v to 3.515 v, the SWE changes from 149.3 cm to 150.5 cm. Due to the pillow's smaller multiplier and its lower voltage range (1.5 - 2.5 v), the 15 mv change at 2.0 v changes the SWE less, from 77.5 to 78.2. Although these deviations are not extreme, at least once during 4 of the 9 months in the study, sensor output exceded 7.520 v or was less than 7.300 v, a much more significant deviation (Table 1). Because the SNOTEL equipment has a transmission capacity well in excess of what is being used currently, the energizing voltage could be included if the system's software is changed.

Daily Storm Depths

Daily precipitation depths and storm totals were similar for many of the storms (Table 2). The Belfort gauge is represented twice in Table 2 to show the difference between two recording systems attached to the same measuring device. All storm totals but those for February 1985 are within 0.3 cm of each other, but the 0800 totals diverge more. Timing inaccuracies due to chart reduction are the probable cause of the daily variations.

Table 1

Proportional Distribution of Energizing Voltages from the SNOTEL System at the Central Sierra Snow Laboratory near Soda Springs, California.

Year & Month	N	<7.300	7.300–7.450	7.451–7.500	7.501–7.505	7.506–7.510	7.511–7.515	7.516–7.520	>7.520
		Volts, dc							
1984									
Jan.	466	0.0	0.0	0.013	0.105	0.176	0.590	0.116	0.0
Feb.	445	.0	.0	.139	.092	.724	.043	.002	.0
Mar.	677	.0	.0	.056	.055	.620	.185	.084	.0
Apr.	684	.002	.002	.073	.076	.180	.596	.070	.001
May.	597	.0	.0	.151	.034	.144	.601	.070	.0
1985									
Jan.	432	.0	.0	.051	.005	.127	.766	.046	.005
Feb.	579	.002	.0	.119	.005	.090	.558	.226	.0
Mar.	707	.001	.0	.108	.001	.134	.342	.413	.0
Apr.	565	.002	.0	.331	.018	.019	.580	.048	.002

Table 2

Daily Precipitation (cm) Measured at 0800 hours at the Central Sierra Snow Laboratory near Soda Springs, California.

Storm Date		Board	Belfort (LVDT)	Belfort (Chart)	Pillow	Missile
Feb. 1984	13[3]	0.5	0.3	0.3	.3	.6
Depth=2.0 m	14	5.4	3.6	↓	5.0	3.7
	15	1.3	2.0		1.8	2.2
	16	4.8	4.4		5.9	3.7
	17	0.7	0.8	10.4[1]	2.0	5.1
	18	.0	0.0	.0	0.4	2.2
	19	.0	0.0	.0	0.2	-1.0
Total ($\bar{x}$=12.8, s=2.0)[2]		12.7	10.0	10.7	15.2	14.2
Mar. 1984	13[3]	0.0	0.6	.8	0.3	0.6
Depth=1.9 m	14[3]	5.5	4.9	4.7	4.1	4.2
	15	2.6	3.0	3.1	2.0	4.3
	16	1.5	1.0	0.8	2.1	1.9
	17	2.7	2.5	2.5	2.8	3.1
	18	.0	-.1	.0	0.9	0.1
	19	.0	.1	.0	0.1	0.0
Total ($\bar{x}$=12.6, s=2.0)		12.2	11.9	11.9	12.6	14.4
Apr. 1984	7	.0	0.2	0.0	0.0	0.0
Depth=1.4 m	8	1.4	1.4	1.9	-0.6	1.6
	9	1.4	1.4	1.0	-0.1	2.3
	10	2.0	1.7	1.8	1.8	2.6
	11	2.0	1.3	1.0	2.0	2.0
	12	.0	.0	.0	0.0	-.6
	13	.0	.0	.0	.0	.0
Total ($\bar{x}$=6.7, s=1.2)[4]		6.8	6.0	5.7	3.2	8.4
Apr. 1984	17	0.4	0.4	0.4	-1.5	-.3
Depth=0.8 m	18	0.6	0.5	0.6	-2.0	.9
	19	2.6	2.3	2.4	-.7	1.5
	20	1.9	2.0	1.8	2.2	3.9
	21	.0	.0	.0	.6	.3
	22	.0	.2	.0	.4	.2
Total ($\bar{x}$=5.4, s=0.2)[4]		5.5	5.3	5.2	-0.2	5.7
Feb. 1985	7	0.7	0.6	0.7	-.6	-1.7
Depth=1.6 m	8	12.0	9.1	9.5	12.0	.4
	9	2.8	2.0	2.1	5.6	12.7
	10	.0	.0	.0	.8	4.9
	11	.0	.1	.0	-.1	-2.1
	12	.0	.0	.0	-.5	-1.0
Total ($\bar{x}$=14.2, s=2.3)		15.5	11.8	12.3	17.5	14.1
Mar. 1985	4	0.6	0.4	.6	-.6	-1.7
Depth=2.3 m	5	1.7	1.5	1.2	1.8	2.7
	6	3.8	3.7	3.8	3.6	2.3
	7	3.8	2.4	3.3	4.1	2.6
	8	.0	0.4	.3	1.1	4.3
	9	.0	-.2	.0	-.1	.4
Total ($\bar{x}$=9.6, s=0.3)		9.9	9.3	9.2	9.9	9.7
Mar. 1985	24	.0	.0	.3	-.4	.3
Depth=2.2 m	25	1.6	1.3	1.1	1.1	.5
	26	0.3	0.4	0.4	-.1	-.8
	27	9.5	6.2	6.4	7.2	2.1
	28	4.9	4.0	3.7	5.4	.5
	29	0.1	.2	0.2	.8	10.3
	30	.0	.0	.0	1.3	1.5
Total ($\bar{x}$=12.6, s=1.1)		16.4	12.0	12.1	15.2	14.4

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[1] Clock stopped; final total for 4 days is reported.

[2] Totals in LVDT, pillow, and missile columns are differences between first and last depths and may not equal the sums of daily depths.

[3] Mixed rain and snow are reported.

[4] Pillow total is not included in mean and standard deviation.

The pillow totals for the April 1984 storms are much less than the other storm totals. Because the snowpack depth was declining before and after the storm, liquid water loss was the likely cause of the small loss or minimal increase in the pillow's SWE during the storms. Liquid water drains slowly out of the snowpack for a few days after surface input ceases, and temperatures did go above 0°C during the April storms. The meltpan record showed that large volumes of water were being released from the snowpack during April 1984 (Table 3). The estimate of loss during the early April storm appears high, but the late April estimate of a 5.6 cm outflow closely matches the pillow's loss of 0.2 cm over a storm that averaged 5.4 cm of precipitation.

Table 3

Estimated Average Areal Outflows from Meltpans at the Central Sierra Snow Laboratory near Soda Springs, California, During Storm Intervals in 1984 and 1985, by Date.

1984								1985					
Feb.	cm	Mar.	cm	Apr.	cm	Apr.	cm	Feb.	cm	Mar.	cm	Mar.	cm
13	0.2	13	0.4	7	2.2	17	1.8	7	0.1	4	0.1	24	0.3
14	.1	14	.3	8	.7	18	.5	8	.0	5	.1	25	.1
15	.1	15	.2	9	.5	19	.2	9	.1	6	.1	26	.1
16	.1	16	.2	10	.2	20	.1	10	.0	7	.1	27	.1
17	.1	17	.1	11	.5	21	.1	11	.1	8	.1	28	.1
18	.1	18	.3	12	.6	22	1.9	12	.1	9	.2	29	.1
19	.1	19	.2	13	.6							30	.4
Total	.8		1.7		7.3		5.6		.4		.7		1.2

The daily differences in storm depths can be seen more clearly when presented in histogram form (Figure 1). The missile gauge appears to register late in the February 1984 storm, but the data in Table 2 show a -1.0 cm adjustment on February 19. This change indicates that temperature or energizing voltage fluctuations may have been responsible. Visual observations as well as the record from the Belfort gauge and the snow board indicate that no snow fell. Minor loading on the pillow continued to occur for 2 days after snowfall ceased.

Pillow loading also continued after the March 1984 storm. The histograms for the April 1984 storms are inexact in that the SWE losses are shown as zero gains rather than as reverse bars protruding below the axis during the first 3 days of both events.

The missile gauge also showed a very late response for the 1985 events. The pillow failed to show the 0.7 cm of precipitation that fell during the first day of the February storm, but on February 8 the pillow and the snow board totals agreed. The missile gauge registered 90 percent of the total storm depth of 14.1 cm on February 9 alone.

On the basis of storm totals, catch for the seven storms can be ranked (Table 4). The pillow depths used in the ranking have the estimated meltpan outflow for the April 1984 storms added to the Table 1 storm totals. In five of the seven storms, the pillow registered the highest SWE. The Belfort gauge registered the lowest for all seven storms. In 1984, the snow board was consistently in the middle of the ranking, but the missile gauge took that position in 1985. The windiness of the February 1985 storm may account for one of these changes in position. The storm totals from the missile gauge and snow board storm in early March 1985 were equal (0.1 cm different before rounding), but the snow board depth exceeded

Table 4

Precipitation Sensors Ranked by Catch for Seven Storms at the Central Sierra Snow Laboratory near Soda Springs, California.

Date	Lowest --				Highest
Feb. 13, 1984	Chart	LVDT	Board	Missile	Pillow
Mar. 13, 1984	Chart	LVDT	Board	Pillow	Missile
Apr. 7, 1984[1]	Chart	LVDT	Board	Missile	Pillow
Apr. 17, 1984[1]	Chart	LVDT	Board	Missile	Pillow
Feb. 7, 1985	LVDT	Chart	Missile	Board	Pillow
Mar. 4, 1985	LVDT	Chart	Missile	Board	Pillow
Mar. 24, 1985	LVDT	Chart	Missile	Pillow	Board

[1] Melt amounts were added in before catches were ranked.

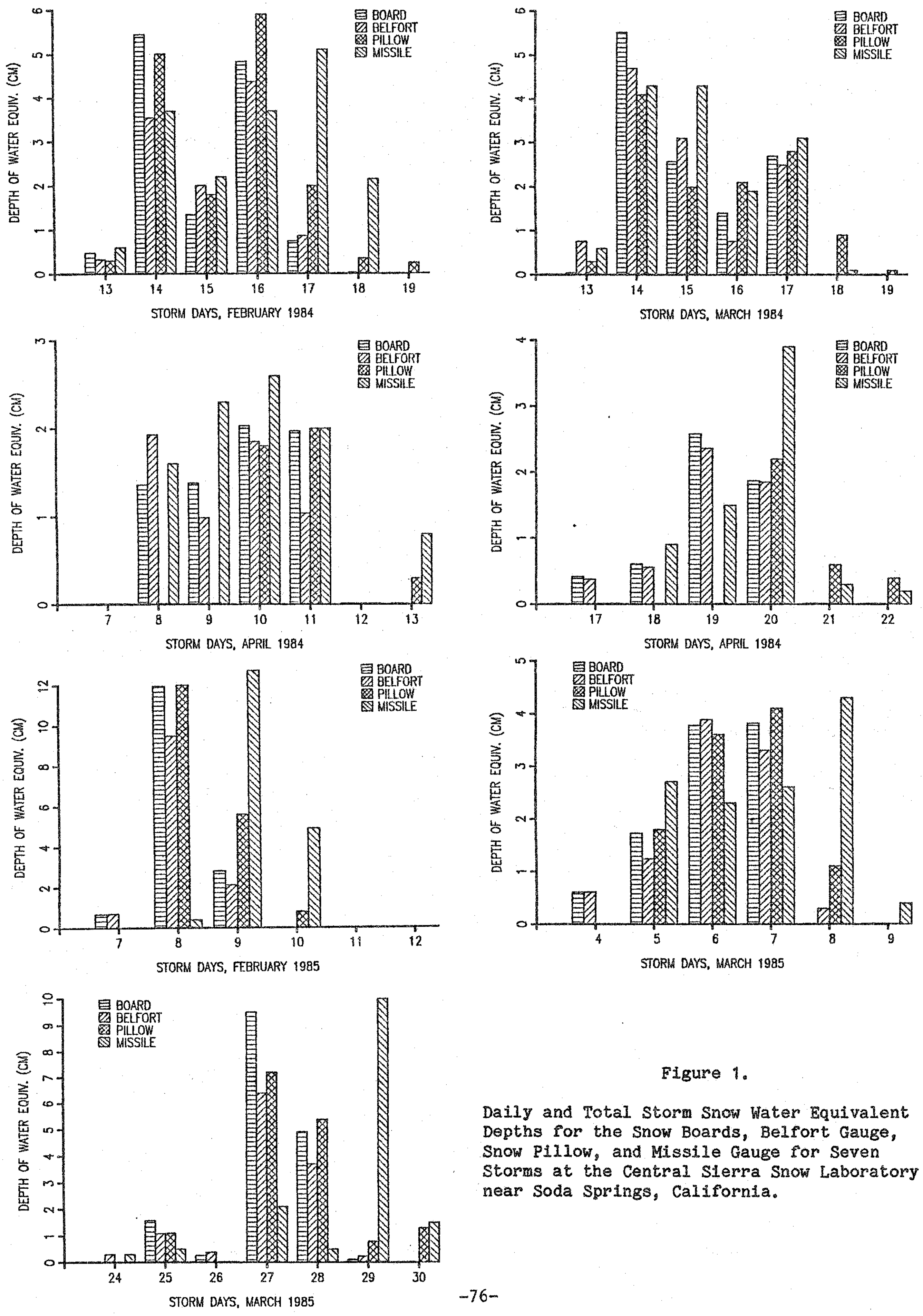
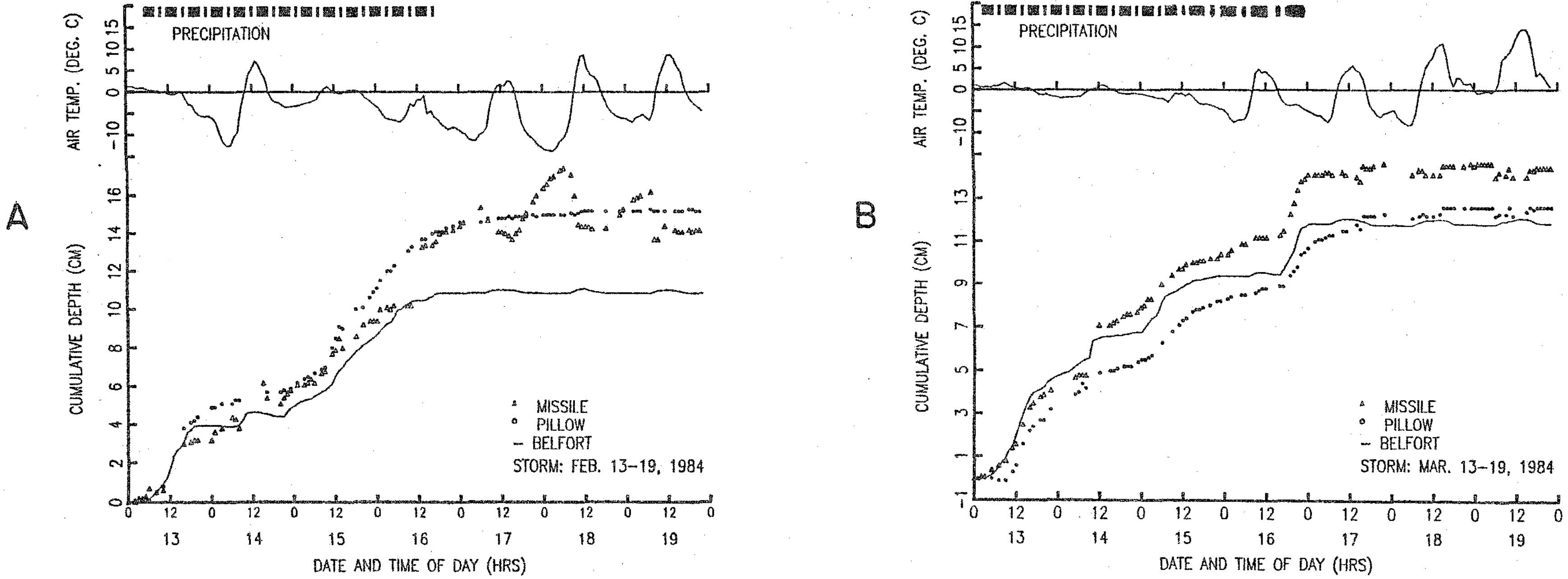


Figure 1.

Daily and Total Storm Snow Water Equivalent Depths for the Snow Boards, Belfort Gauge, Snow Pillow, and Missile Gauge for Seven Storms at the Central Sierra Snow Laboratory near Soda Springs, California.



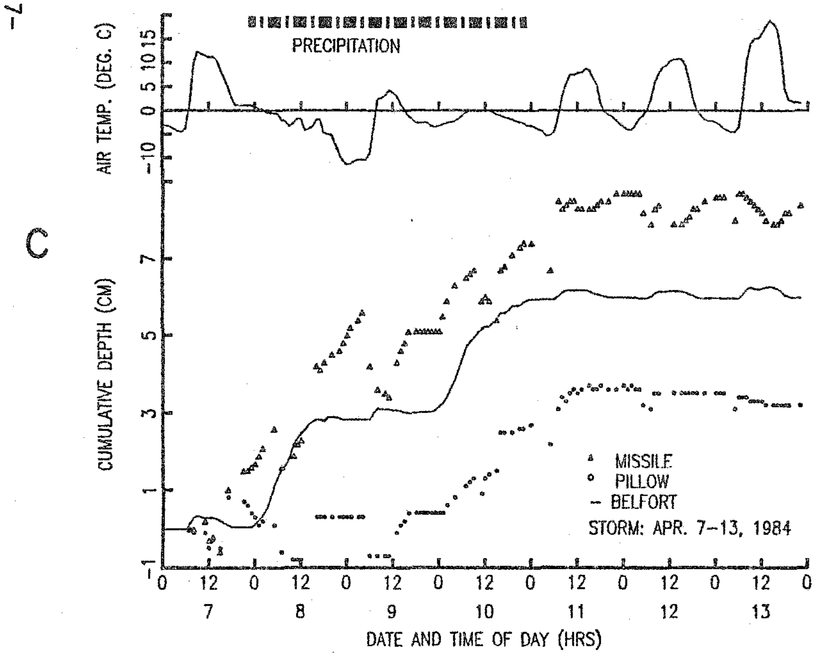


Figure 2.

Air Temperature, Duration of Precipitation, and Accumulated Snow Water Equivalent Depths for the Belfort Gauge, the Snow Pillow, and the Missile Gauge at the Central Sierra Snow Laboratory near Soda Springs, California: (A) Feb. 13-19, 1984, (B) Mar. 13-19, 1984, (C) Apr. 7-13, 1984, (D) Apr. 17-22, 1984, (E) Feb. 7-12, 1985, (F) Mar. 4-9, 1985, (G) Mar. 24-30, 1985.

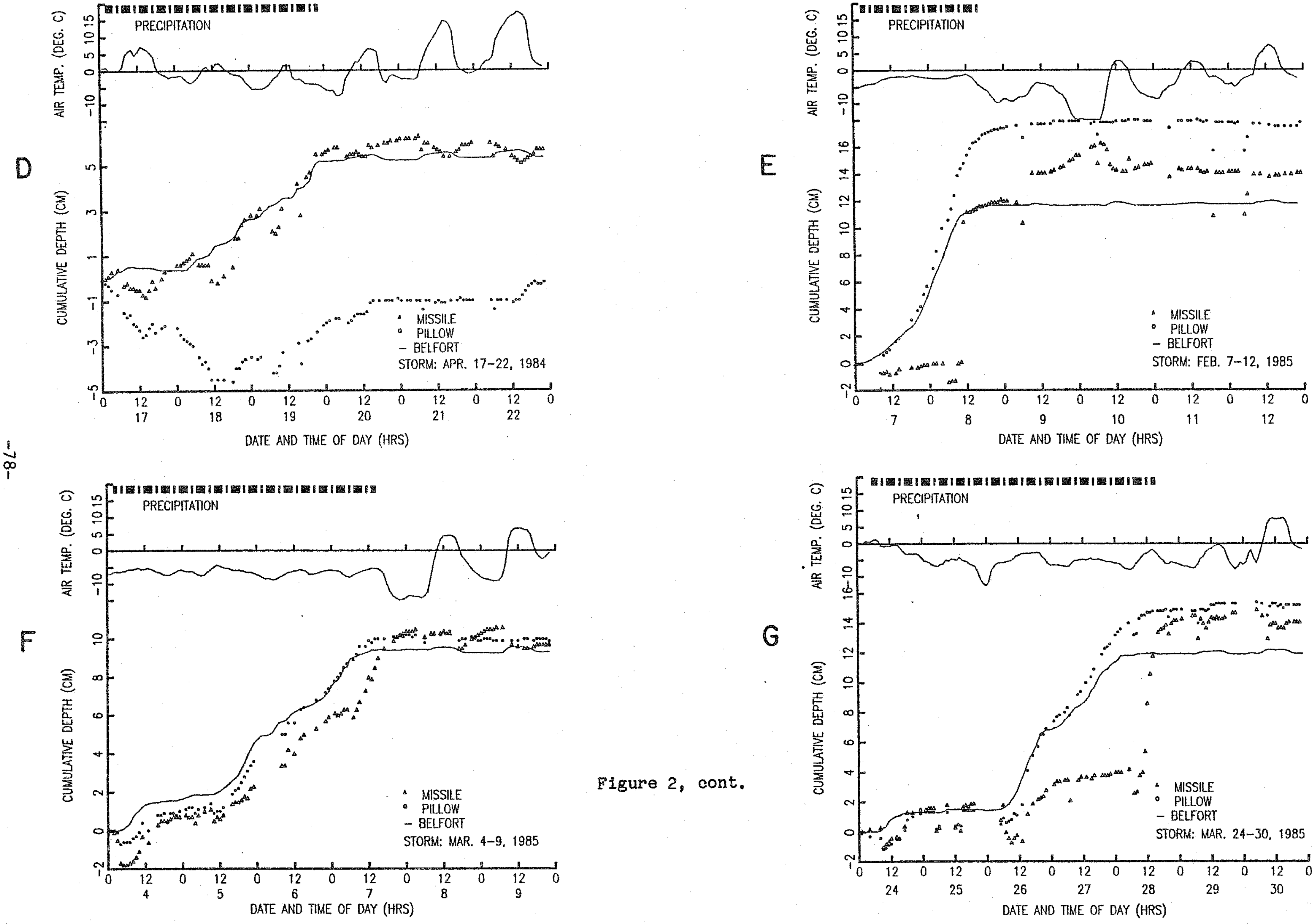


Figure 2, cont.

the catch by the missile gauge by 2 cm for the storm in late March 1985. Excluding the two April 1984 storms, the sums of the depths of the storms were 55.7 -- Belfort LVDT, 56.0 -- chart, 66.7 -- snow board, 66.8 -- missile, and 66.8 cm -- pillow. The close grouping of the board, missile, and pillow totals implies that the Belfort gauge tends to produce values about 15 percent below the other instruments.

Sensor Performance During Storms

Plots of the accumulated precipitation and hourly average temperature show many differences among the sensors during the seven storms (Figure 2). The February 1984 plot shows a 5-cm variation in the missile gauge's reading that is the inverse of the air temperature pattern (Figure 2A). Traces for early and late April 1984, and February 1985 (Figures 2C, 2D, and 2E) also show a diurnal cycle of increased depth associated with nighttime low temperatures. Both the SNOTEL transducers and the transmitter are rather well isolated from temperature extremes in the CSSL garage, but the diurnal pattern is still evident.

The delays in the response of the missile gauge are clear in all storms except in March and late April 1984 (Figures 2A, 2C, and 2E-G). The delay in March 1985 (Figure 2G) appears to be a bridge-over of the orifice, but the slow registration of the increase does not correspont to the sudden increase associated with the collapse of a cap, so an interior plug is most likely. Bridging is usually released when air temperatures rise above 0°C, but the temperature plot shows subzero temperatures until the end of the storm. However, the collapse of the apparent bridge-over or interior plug corresponds with insolation levels in excess of 42 KJ/m^2-min (1 Ly/min) for the first time since the start of the storm. In spite of the cold air temperature, the sun's warmth apparently melted the snowplug inside the gauge and let it gradually slide down and be registered.

The response of the sensors in March 1984 (Figure 2B) is close to ideal. All the sensors show similar rise points and patterns, and there are few severe variations. The missile gauge record exceeds the Belfort's by 2.5 cm (17 percent), and the pillow and the snow board records are midway between the two. The pillow's response to the storm was delayed about 5 hours, and loading continued for a day after the precipitation stopped.

The variation in the pillow and missile traces in early April 1984 (Figure 2C) illustrates deviations in both temperature and excitation voltages. The nearly 2-cm increase in the missile trace at the end of April 8 is associated with a sharp drop in temperature. During April 9, both sensors recorded a sharp drop as the excitation voltage dropped from 7.511 to 7.490 v and then returned to 7.511 v. Interpretation of this pattern without knowledge of the temperature interaction and the excitation voltage would be difficult and unwarranted.

Loss of water due to snowmelt is suggested by the warm noontime temperatures on April 7 (Figure 2C) and April 17 (Figure 2D), in 1984. The continued sharp decline through April 18 (Figure 2D) is not supported by either the near-0°C air temperature or the meltpan record (Table 3). In Figure 2C, the gradual decline on April 12 and 13 is nicely supported by the meltpan data.

The Belfort gauge appeared to seriously undermeasure as compared with both the pillow and the missile gauge in February 1985 (Figure 2E). The wind records for February 7 and 8 show average hourly values consistently between 2 and 3 m/s, which is unusually high for the CSSL clearing. The snow board storm total of 15.5 cm exceeded even the missile gauge total of 14.1 cm. The sharp drops in the SNOTEL traces on February 11 and 12 are due to low excitation voltages.

The pillow's response to the March 4, 1985 storm was delayed by 3 hours, but no poststorm loading is evident (Figure 2F). The strong decline in the SNOTEL traces at the beginning of the storm was due to the occurrence of a temperature- affected peak at the zero point (midnight) of the accumulation interval. Both the pillow and the missile gauge storm totals end up exceeding the Belfort in spite of the initial negative values. The missile gauge trace shows evidence of a partial plug during late March 7, but the plug apparently dissipates during the early hours of March 8.

Voltage effects are evident in the deviations of the pillow and missile gauge compared with the Belfort trace for the March 24, 1985 storm (Figure 2G). The traces from the three sensors are closely overlaid during the initial two days of the storm except for the dips caused by the voltage dropping repeatedly from 7.515 v to 7.496 v. The SNOTEL "constant voltage" power supply was apparently malfunctioning, but the reason for the temporary fluctuations is not known. The voltage stabilized by 1700 hours on March 26, but evidence of occasional dips can be seen during the rest of the storm.

CONCLUSIONS

Although meltwater outflow from two of the late-season 1984 storms made some comparisons difficult, a number of conclusions can be reached.

If the snow board measurements are accepted as "ground truth" (Goodison and McKay, 1978), and if the agreement between summed totals from the pillow, the missile gauge, and the board is accepted, then the CSSL Belfort weighing precipitation gauge undermeasures snowfall by at least 10 percent. Because all four devices are located near to each other, the undermeasurement is either due to location or is a function of the small orifice of the Belfort gauge. Little difference was discerned between storm totals derived from the LVDT and the weekly strip chart.

That the snow pillow measured the greatest amount in five of the seven events confirmed its sensitivity to SWE changes in the snowpack. It is unclear why the pillow measurements exceeded those of the snow board for six of the seven storms. The pillow is several meters closer to the center of the forest clearing than are the boards, so there may be variable patterns of deposition within the clearing. Also, wind scour on newly cleaned snow boards or incomplete sample cores may have reduced the reported board SWEs. The pillow exhibited response lags of 2 to 5 hours from the start of a storm, and a day or more of poststorm loading was evident in several cases. No delayed loading was observed in other cases, but the reasons for the presence or absence of poststorm loading are not known.

The missile gauge's storm total agreed well with the pillow and the snow boards, but its daily totals were unreliable. The missile gauge is not an accurate indicator of the start or stop of precipitation at CSSL.

Excitation voltage variations caused routine fluctuations of over 1 cm in both the pillow and the missile gauge readings, and occasional fluctuations in excess of 2 cm were observed. Inclusion of the excitation voltage in the transmission data and reduction equation would eliminate this problem.

Wind appeared to affect the precipitation gauge catch in one storm. The effect of wind on snow deposition in other cases was not noticeable.

REFERENCES

Barton, M. and M. Burke, 1977: SNOTEL: An Operational Data Acquisition System Using Meteor Burst Technology, Proceedings of the 45th Western Snow Conference, Albuquerque, NM, 82-84 pp.

Beaumont, R.T., 1965: Mt. Hood Pressure Pillow Gage, Proceedings of the 45th Western Snow Conference, Colorado Springs, CO, 29-35 pp.

California Department of Water Resources, 1976: Sensor Evaluation in the Sierra Nevada, California, State of California, Sacramento, CA, 55 pp.

Cox, L.M., L.D. Bartee, A.G. Crook, P.E. Farnes, and J.L. Smith, 1978: The Care and Feeding of Snow Pillows, Proceedings of the 46th Western Snow Conference, Otter Crest, OR, 40-47 pp.

Farnes, P.E., 1978: Future Snow Survey Operation with SNOTEL, Proceedings of the 46th Western Snow Conference, Otter Crest, OR, 15-20 pp.

Goodison, B.E., and D.J. McKay, 1978: Canadian Snowfall Measurements: Some Implications for the Collection and Analysis of Data from Remote Stations, Proceedings of the 46th Western Snow Conference, Otter Crest, OR, 48-57 pp.

Linsley, R.K., Jr, M.A. Kohler, and J.L. Paulhus, 1982: Hydrology for Engineers, 3rd Ed., McGraw-Hill, NY, 508 pp.

Shannon, W.C., 1968: Snow Surveying by Electronic Telemetry, Proceedings of the 36th Western Snow Conference, Lake Tahoe, NV, 95-98 pp.

Smith, F.W., and H.S. Boyne, 1981: Snow Pillow Behavior Under Controlled Laboratory Conditions, St. George, UT, 13-22 pp.

Suits, R.D., 1985: California Snow Sensor Performance, Unpublished Master's Thesis, University of California, Davis, CA, 142 pp.

U.S. Army Corps of Engineers, 1956: Summary Report of the Snow Investigations: Snow Hydrology, North Pacific Division, U.S. Army Corps of Engineers, Portland, OR, 437 pp.