THE CONTRIBUTION OF SNOTEL PRECIPITATION MEASUREMENTS TO CLIMATE ANALYSIS, MONITORING AND RESEARCH IN COLORADO

by

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INTRODUCTION

Insufficient precipitation data in the mountains of Colorado, particularly in the primary snow accumulation zones above 2800 m MSL (Crow, 1967) has repeatedly been blamed for limiting the accuracy of climate and water supply forecasting and monitoring capabilities (Shafer et al., 1984; Doesken et al., 1983). Many aspects of climate analysis and research have long been compromised by a lack of year-round high elevation precipitation data (Marlatt and Riehl, 1963). National Weather Service (NWS) station networks, the traditional source for climate data for analysis and research in the U.S., locate most of their stations at low elevations and in populated mountain valleys. Studies have shown that extrapolating this lower elevation data to higher areas is often not valid (Loren W. Crow Consultants, 1982). As of 1986, out of a total of 155 NWS weather stations in the mountainous portion of Colorado, only 12 were above an elevation of 2800 m and only 3 were above 3300 m.

Beginning in the late 1970s, the U.S. Department of Agriculture Soil Conservation Service (SCS) began implementing a network of year-round automated weather stations. This well documented SNOwpack TELemetry (SNOTEL) system was designed to provide cost-effective data from high snow accumulation regions to improve water supply monitoring and forecasting throughout the Rocky Mountain West (Crook et al., 1987). Snow pillow measurements of snowpack water content are the most utilized information from the SNOTEL system during the winter months, but independent measurements of daily precipitation are also available throughout the year. Since most of the 72 currently active SNOTEL sites in Colorado are located in snow accumulation areas between elevations of 2500 m and 3500 m, this network adds a whole new dimension to climate data resources.

This paper compares operational SNOTEL precipitation data to traditional NWS records. Possible differences and inconsistencies between the two data sources are identified through comparative analyses of annual, monthly and daily data. Applications of the SNOTEL data are then described in an effort to show how this new climatological data source may be used to improve our understanding of the climate of Colorado.

DATA

Daily and monthly precipitation data for National Weather Service cooperative weather stations in Colorado were obtained from the computerized climatological data base maintained by the Colorado Climate Center at Colorado State University. SNOTEL precipitation data were accessed through the SCS Centralized Forecast System (Shafer and Huddleston, 1986) at Portland, Oregon. The 52 SNOTEL sites having at least 4 years of complete records for the 1980-1986 period were examined. Approximately 100 NWS cooperative stations in and near the mountains were used. From this larger set, 15 pairs of SNOTEL-NWS stations were selected for special examination (Figure 1 and Table 1). Only two pairs of stations were approximately co-located, but the others were all judged to be close enough to justify direct comparison.

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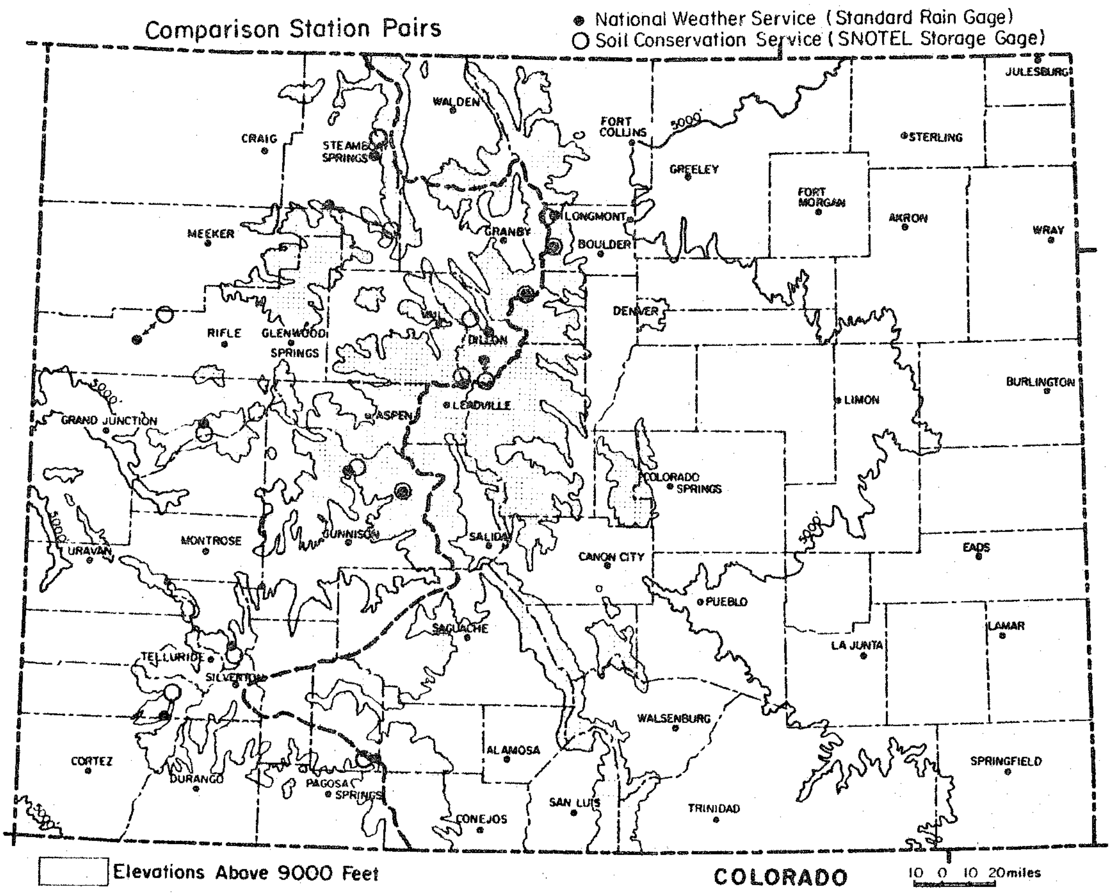

Figure 1. Locations of National Weather Service-Soil Conservation Service SNOTEL precipitation gage pairs for comparative analysis.

Table 1. Comparative locations of 15 SNOTEL-NWS station pairs in Colorado used in this study.

National Weather Service				Soil Conservation Service			
Name	Elev (m)	Lat	Long	Name	Elev (m)	Lat	Long
Steamboat Springs	2060	40°29'	106°50'	Dry Lake	2560	40°32'	106°47'
Pyramid	2441	40°14'	107°05'	Lynx Pass	2707	40°05'	106°40'
Allenspark	2536	40°13'	105°32'	Copeland Lake	2621	40°12'	105°34'
Silver Lake	3158	40°02'	105°35'	University Camp	3139	40°02'	105°34'*
Berthoud Pass	3449	39°48'	105°47'	Berthoud Summit	3444	39°48'	105°46'*
Dillon 1E	2763	39°38'	106°02'	Summit Ranch	2865	39°43'	106°09'
Breckenridge	2920	39°29'	106°02'	Hoosier Pass	3475	39°22'	106°03'
Climax	3459	39°22'	106°11'	Fremont Pass	3475	39°22'	106°12'
Altenbern Ranch	1734	39°30'	108°23'	West Fork Parachute	2377	39°38'	108°13'
Bonham Reservoir	3002	39°06'	107°53'	Park Reservoir	3036	39°02'	107°52'
Crested Butte	2700	38°52'	106°58'	Butte	3098	38°53'	106°57'
Taylor Park	2806	38°49'	106°37'	Park Cone	2926	38°49'	106°35'
Ouray	2390	38°01'	107°40'	Idarado	2987	37°56'	107°40'
Rico	2676	37°42'	108°02'	Lizard Head Pass	3109	37°48'	107°56'
Wolf Creek Pass 1E	3244	37°29'	106°47'	Upper San Juan	3109	37°29'	106°49'

* approximately co-located.

NWS precipitation data are derived from once a day manual readings of precipitation collected in unshielded, non-recording rain gages with a 20 cm orifice. Gage openings are normally 1 m above ground except in high snow accumulation areas. The time of the daily observation is established for the convenience of each observer and is not the same for all stations. Observation times vary from early morning to midnight but the majority of gages are read early morning (7-8 AM) or early evening (5-7 PM). Measurement resolution is 0.25 mm. Data are transmitted monthly by traditional mail to the National Climatic Data Center and the Colorado Climate Center for quality control and digitization. Editting changes are occasionally made to the manually recorded precipitation observations. Missing daily values are not filled in with estimates, but monthly estimates may be made by the National Climatic Data Center when there are short duration missing periods.

Advantages of the NWS cooperative precipitation records are: 1) relatively dense nationwide network with 1 or more stations per 1600 km area in most regions, 2) consistent procedures and equipment used for many decades, 3) daily manual surveillance of equipment, and 4) data all quality controlled, nationally archived and published for public availability. Disadvantages include 1) non-uniform observation times, 2) data quality inconsistencies due to site-specific observer practices, attitudes and errors, 3) unshielded gages result in reduced efficiency in catching winter precipitation, 4) stations are frequently relocated to accomodate changes in observers, and 5) stations tend to be concentrated where population is concentrated. Mountainous regions of the Western U.S. are poorly represented.

Unlike the NWS network, SNOTEL sites are unattended and fully automated. Precipitation measurements are taken with 30.5 cm orifice storage gages whose heights above bare ground vary from 3.6 m to 5.5 m depending on maximum expected snowdepths in the area. These storage gages, referred to as missile gages, are charged annually with an oil-antifreeze solution to preserve the incoming precipitation in the liquid state with minimal evaporation. All missile gages are equipped with standard Alter wind screens to improve catch efficiencies. Gages are typically mounted in forested areas where catch efficiencies are expected to be higher than in open terrain.

SNOTEL precipitation measurements are communicated daily to the SCS central computer in Portland, Oregon. Two master stations poll field sites using meteor burst communications at approximately 0600 MST each morning. The digital signal, which is transmitted, represents the hydraulic fluid pressure inside the gage as monitored by a pressure transducer. The measurement is proportional to the depth of the accumulated precipitation. The resolution of the precipitation measurements is 2.5 mm. Daily precipitation values are computed by simple examination of 1-day changes in total gage accumulation. Schaefer and Shafer (1982) showed that telemetered values corresponded nearly identically to on site manual readings during earlier years of SNOTEL operations. Upon capture, SNOTEL precipitation data are archived and manually checked by SCS snow survey personnel for obvious errors and inconsistencies. An editted data set of accumulated daily precipitation is maintained for operational and research applications.

Advantages of SNOTEL precipitation measurements are 1) daily accessibility to remote high elevation information, 2) system-wide measurements not affected by human error and inconsistency, 3) nearly uniform observation times across the entire network, 4) shielded gages to improve catch efficiencies, 5) adjacent snowpillow data available to double check winter precipitation, 6) minimal relocation of instrumentation, and 7) data for western U.S. archived on SCS Centralized Forecast System.

Disadvantages include 1) lack of frequent manual on-site maintenance, 2) sensitivity of measurements to temperature and pressure fluctuations, 3) relatively poor resolution, 4) subjective quality control, 5) up until 1987 data not published or readily available to all data users, and 6) short track record from which to evaluate long-term performance characteristics.

ANALYSIS

A number of basic climatological analyses were performed using both NWS and SCS SNOTEL precipitation data. Data from each source were used at face value, just as it would be operationally available to users. Annual (October-September water year) time series comparisons for the 1980-86 period were produced for the 15 NWS-SCS station pairs shown in Table 1. Examples of 3 of these time series are presented in Figure 2. In 13 of 15 cases, good correlations were observed. The Berthoud Pass-Berthoud Summit station pair, which are essentially co-located, showed the most similar results. In all other cases, SNOTEL sites showed consistently higher precipitation than NWS sites. Both data sources identified the past 5 years as unusually wet compared to long term averages.

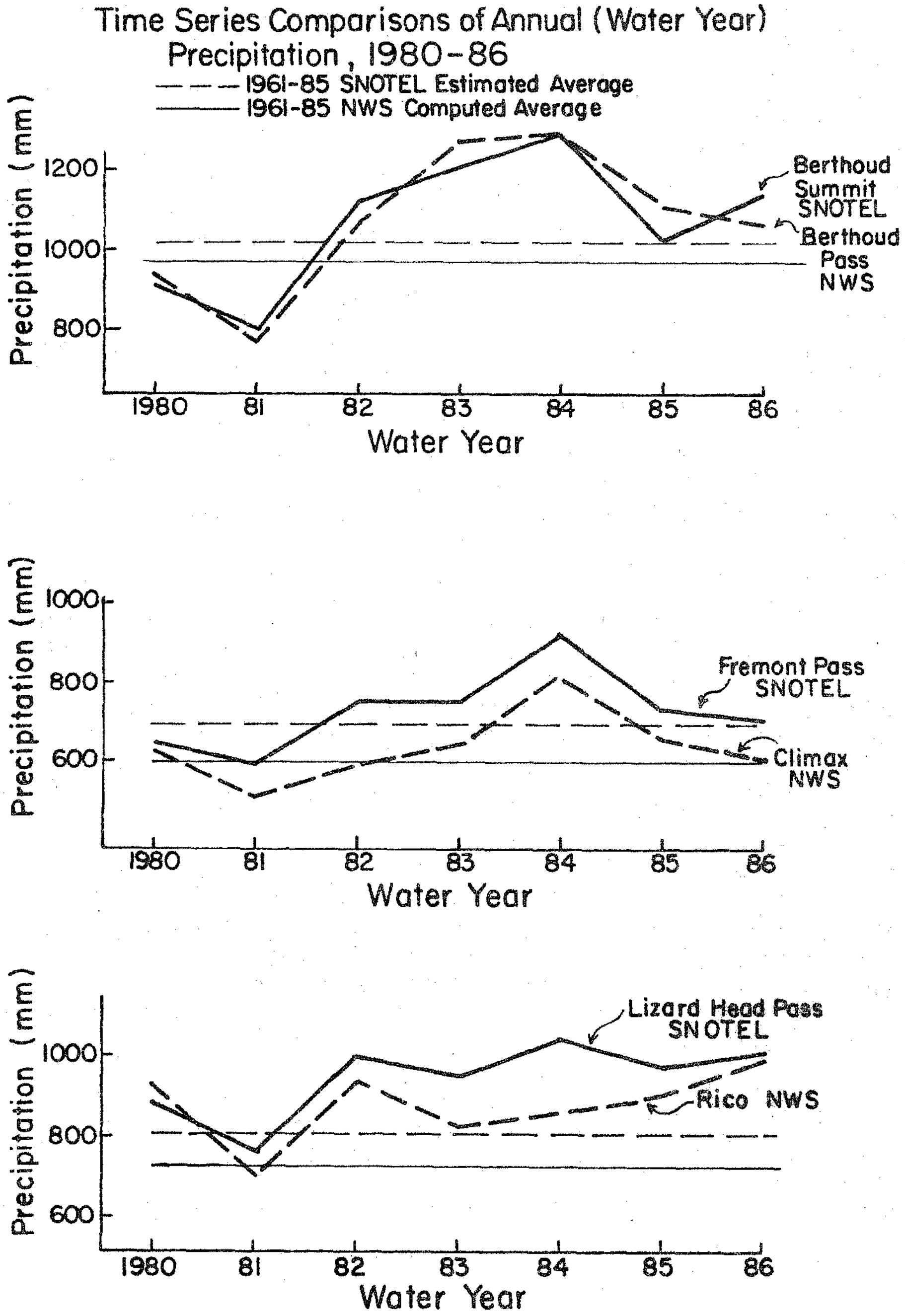

Figure 2. Time series of annual water year (October-September) precipitation, 1980-86, for selected National Weather Service and Soil Conservation Service SNOTEL station pairs in the Colorado mountains.

Monthly precipitation averages, 1980-86, were computed for each of the 15 station pairs. Results are shown in Figure 3 for 4 of the pairs. A three-peaked distribution was observed at nearly all stations. The wettest periods have been early winter (November-December), late winter-early spring (March-May) and mid summer (July), separated by distinct lulls. This seasonal distribution is consistent with longer-term precipitation records from NWS stations (Kleist et al., 1986) although the early and late winter peaks and mid winter lull have been somewhat exaggerated in recent years. The relative magnitudes of these peaks varied spatially across Colorado. The early winter peak has been most apparent at the higher elevation sites. The spring peak has been longer in the northcentral Colorado mountains than in the remainder of the mountain areas. This is also consistent with longer term records and is related to the northward shift of the jet stream and storm track as summer approaches. Summer peaks are more pronounced at lower elevation sites with broader peaks observed in the southern mountains where the Southwest Monsoon pattern is more consistent.

Both the SNOTEL and NWS sites showed the same approximate seasonal distribution of precipitation but with some obvious and reliable differences. Monthly precipitation totals for the winter months, and particularly November through April, were consistently higher at SNOTEL sites than at the nearby NWS gage. During the summer months this relationship reversed. Summer peaks were much more dramatic at NWS stations. In fact, for 13 of the 15 station pairs NWS precipitation exceeded SNOTEL precipitation in all or part of the summer (June-September) regardless of elevation difference and spatial

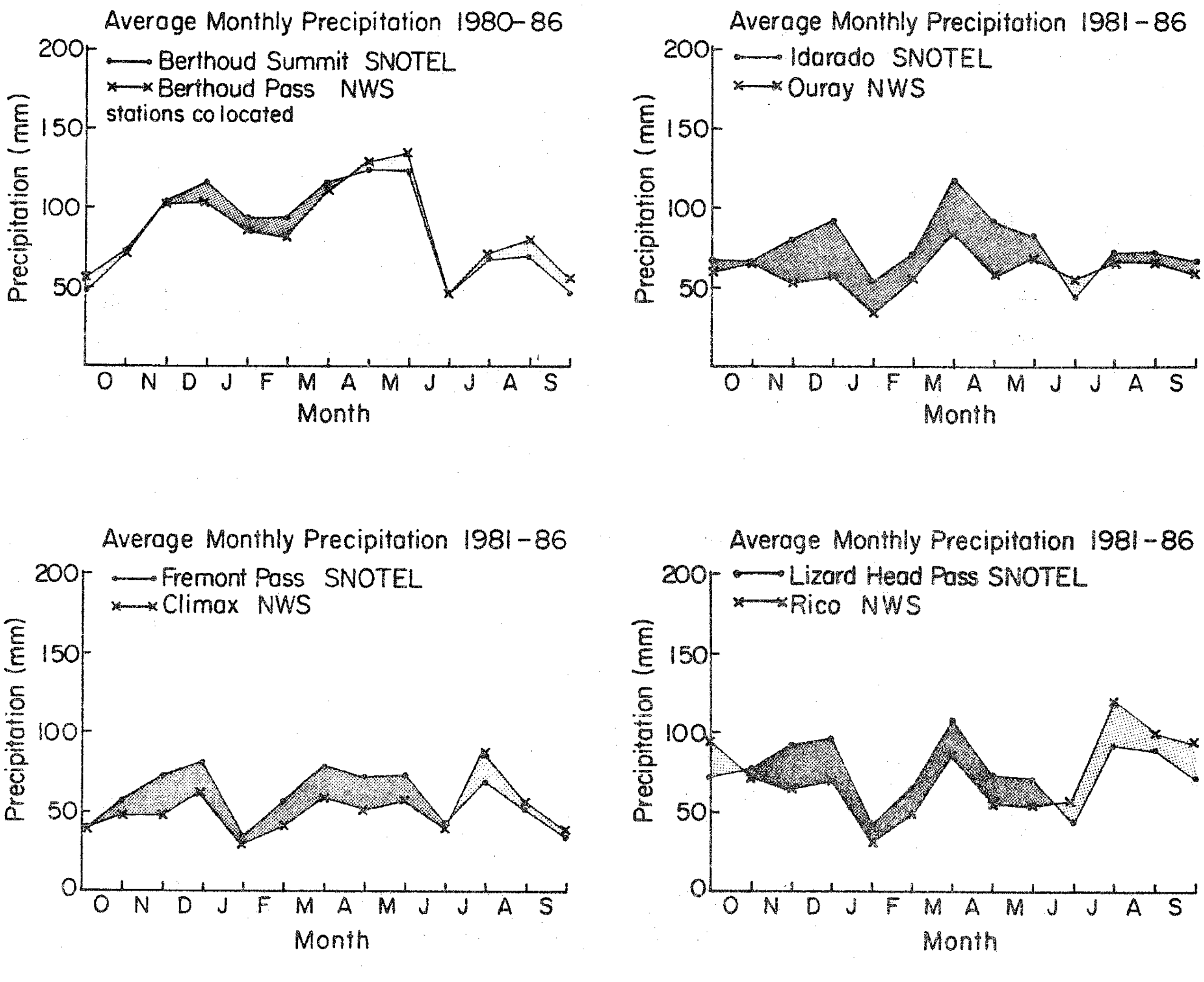

Figure 3. Comparison of average monthly precipitation at selected National Weather Service and Soil Conservation Service SNOTEL station pairs in the Colorado mountains.

separation. The Rico-Lizard Head Pass combination clearly shows this relationship. Despite being 430 m lower in elevation than the Lizard Head Pass SNOTEL gage, summer precipitation was 68 mm (23%) greater at the NWS gage.

To explore the seasonal differences in the relationships between SNOTEL and NWS precipitation data, scatter diagrams were produced (Figure 4). At Berthoud Pass an excellent correlation (correlation coefficient, $r^2 = 0.91$) was observed between NWS and SNOTEL monthly precipitation totals with a slope very close to 1. Separating by seasons, summer correlations were found to be poorer than winter but still very good. The Fremont Pass-Climax station pair were not as well correlated over all months of the year ($r^2 = 0.76$). However, upon separating winter and summer data, two distinctly different relationships were observed. The slope of the summer regression line was 1.2 compared to 0.76 for winter. Both winter and summer correlations were significantly better than for all months combined. For the Wolf Creek Pass 1E-Upper San Juan comparison, correlations degraded to only 0.48. But again, seasonal differences could readily be observed with better correlations achieved when winter and summer data were separated.

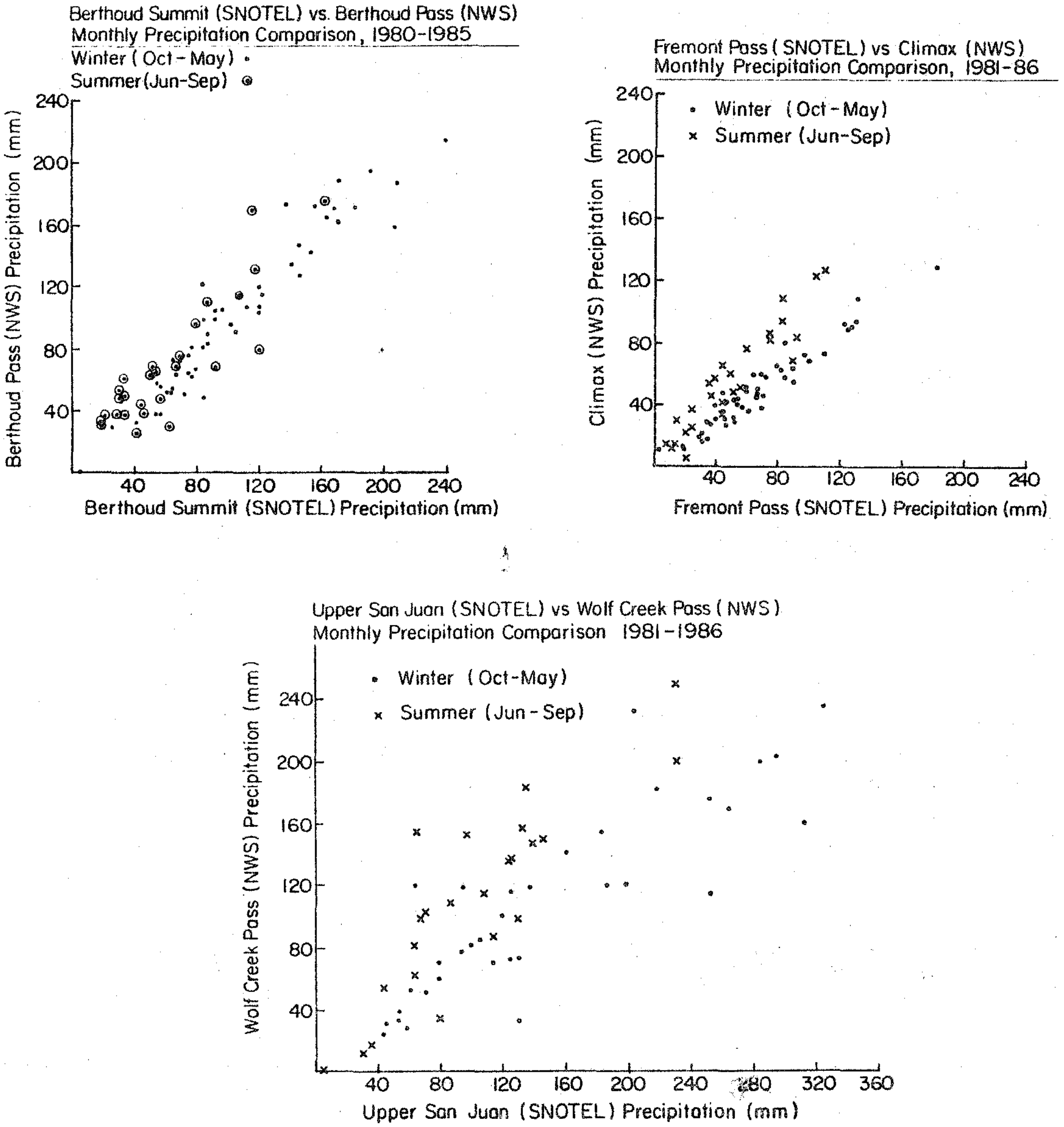

Figure 4. Scatter plots of monthly totals of SNOTEL precipitation versus National Weather Service precipitation for selected station pairs in the Colorado mountains.

Daily precipitation totals were also analyzed and compared for the Berthoud Pass-Berthoud Summit, Climax-Fremont Pass, and Wolf Creek Pass 1E-Upper San Juan station pairs. An example of comparative daily accumulations for Upper San Juan and Wolf Creek Pass 1E is shown in Figure 5. On inspection, it appears that daily events recorded at each station are fairly well correlated. A more specific analysis of daily events performed for water year 1984 (Table 2) was less encouraging. Since the resolution of the two gage types is different, exact comparison of daily events is impossible. Comparing only those days during the year when at least 2.5 mm of precipitation were measured at the NWS site, 82% of those days (120 out of 146) also reported precipitation in the SNOTEL gage at Berthoud Summit and 83% (85 out of 102) at Fremont Pass. At Upper San Juan, measurable precipitation was transmitted on only 61% of the days (81 out of 132 days) when NWS precipitation was reported. There were also a significant number of days when SNOTEL sites reported precipitation although no NWS precipitation was detected. The percentage of days with precipitation measured at both gages was significantly higher during the winter than during the summer for all 3 station pairs again indicating a seasonal change of gage collection characteristics.

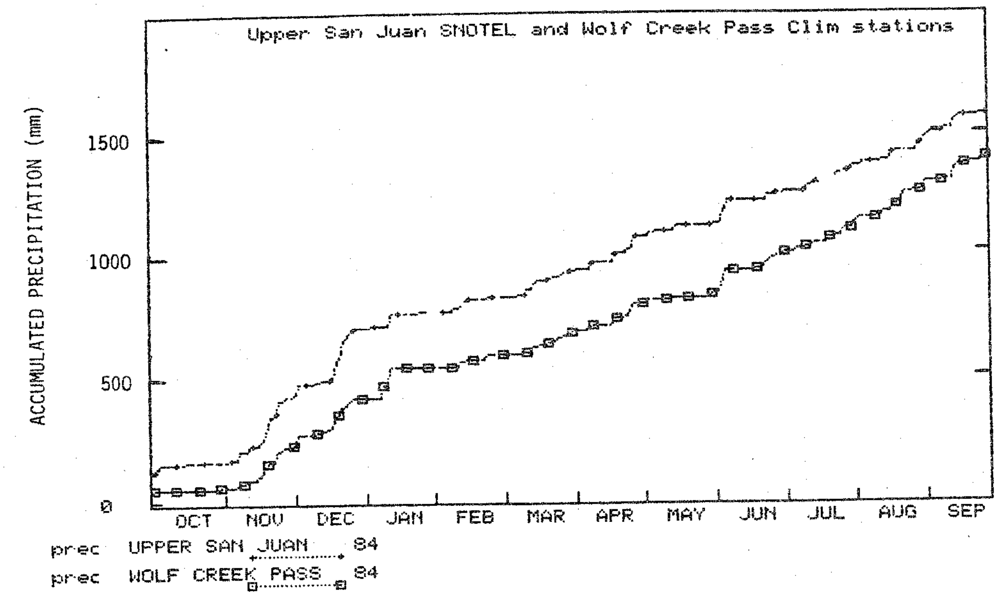

Figure 5. Comparison of daily accumulated precipitation at Upper San Juan SNOTEL precipitation gage and Wolf Creek Pass 1E National Weather Service gage for the 1984 water year.

Table 2. Comparison of daily precipitation occurrences for the 1984 water year.

	Berthoud Summit* vs Berthoud Pass			Fremont Pass* vs Climax			Upper San Juan* vs Wolf Creek Pass 1E		
	winter	summer	total	winter	summer	total	winter	summer	total
Total # of days	244	122	366	244	122	366	244	122	366
NWS precip ≥ 0.25 mm	142	57	199	123	66	189	76	65	141
NWS precip ≥ 2.5 mm	107	39	146	67	35	102	75	57	132
≥ 0.25 mm precip in both gages	101	33	134	74	33	107	51	31	82
≥ 2.5 mm precip in both gages	93	27	120	58	27	85	50	31	81
Days with measurable precip in SNOTEL gage but no NWS precip.	18	12	30	16	7	23	41	17	58

*Daily observation times not identical: Approx. 6 AM MST for SNOTEL stations and approx. 8 AM MST for NWS sites.

DISCUSSION OF SNOTEL-NWS PRECIPITATION COMPARISONS

There are a number of obvious and a few not so obvious causes for the observed differences between precipitation measurements from SNOTEL and NWS gages. The NWS gages at Berthoud Pass, Climax, and Wolf Creek Pass 1E all had 8 AM MST observation times compared to 6 AM reporting times for SNOTEL stations. This 2-hour difference could explain some differences in daily precipitation but should have almost no effect on monthly or annual comparisons or even comparisons of daily occurrences of summer precipitation (since the vast majority of summer precipitation in the mountains falls during the afternoon). Likewise, differences in gage resolution between SNOTEL and NWS networks will affect daily comparisons while having little or no impact on monthly and annual statistics.

Results of these analyses of both daily and monthly precipitation point to a relationship between SNOTEL and NWS precipitation which is a function of season. Two factors are likely responsible for the consistently higher winter precipitation measured by SNOTEL gages. It has previously been shown that precipitation in the Rockies increases most dramatically with elevation during the winter months (Peck and Brown, 1963). Since most of the SNOTEL sites are at a higher elevation than their companion NWS sites, higher precipitation is expected at the higher sites. This does not, however, explain the differences at co-located sites. As stated before, SCS uses 30.5 cm diameter shielded gages for all their precipitation measurements. As a result, gage catch efficiencies throughout the snow season should be significantly higher than for the 20 cm orifice unshielded NWS gages. Inspection of monthly SNOTEL-NWS relationships show that differences increase during the fall, reach maximum values during winter and then taper off as summer approaches (Figure 3). This relationship is consistent with the results of previous studies of gage catch efficiencies that show that catch efficiencies decrease with increasing wind speed and with decreasing snow density.

The close similarity in precipitation measured at the Berthoud Pass and Berthoud Summit gages seemed to indicate that differences in catch efficiencies between gages was not as great as might be expected. However, closer examination of the NWS station revealed that this site, a special avalanche research station of the U.S. Forest Service (until being closed in 1985), did not use standard NWS procedures for cooperative stations but took core samples of new snow in addition to measuring the water content of the standard raingage. Gage readings were often adjusted upwards to compensate for poor catch efficiencies. These readings, while more accurate than simple gage readings, were not consistent with other NWS cooperative weather stations. Therefore, it is reasonable to conclude that under normal circumstances, SNOTEL measurements of accumulated winter precipitation are more accurate and representative than NWS measurements in the high mountain areas. Highly variable precipitation and wind speed regimes, and the lack of co-located SNOTEL-NWS gages, makes it impossible to assign quantitative estimates to the effect of catch efficiency differences. The Fremont Pass-Climax station pair may be the best indicator of the magnitude of this problem in high elevation moderately windy locations. The Climax NWS gage measured 26% less precipitation October-May, for the 1981-86 period than Fremont Pass SNOTEL.

Climatic factors and gage catch efficiencies may adequately explain differences in monthly precipitation totals during the winter, but they do not explain some of the daily discrepancies that were noted. Daily discrepancies during winter occurred most frequently in the mountains of southern Colorado. Throughout the state, discrepancies were more common during fall and spring than during mid winter. Wet snows could be the culprit. Wet snows have been known to stick inside and occasionally totally clog unattended storage gages only to drop down into the gage some hours or days later. This has likely been the case on several occasions at the Upper San Juan SNOTEL site where very heavy, wet snows are common (Schaefer and Shafer, 1982). Previous research has also identified problems with the accuracy and timing of precipitation events measured by SNOTEL storage gages (McGurk, 1986). Unfortunately NWS daily data are not always perfect either. In reconstructing records for the Wolf Creek Pass 1E site, daily events do not always coincide with known storm occurrences. The weather observers there are snowplow operators and, quite possibly, don't always get around to taking the observation until after the storm is over. In recent years there has been rapid turnover of observers. By comparison, at Berthoud Pass the same person has been in charge of observations for the entire period of record--an ideal but unusual situation. This is an excellent example of the impact of the human factor on climatic records. There is no doubt that daily manual inspection of weather instruments should produce more accurate daily measurements than unattended SNOTEL sites. This advantage turns into a liability when the reliability of daily measurements changes with time and cannot be confirmed.

During the summer months, June-September, a distinct change in the SNOTEL-NWS precipitation relationships was observed. Total precipitation at NWS stations reliably surpassed SNOTEL precipitation during those months. At co-located sites the difference was about 10% with greater differences at several of the other station pairs. Event analyses also showed a sharp decline in the percentage of NWS precipitation events that were also detected by SNOTEL gages (Table 2). This pattern corresponds to the period of the year when precipitation falls primarily as rain and is consistent with the gage catch efficiency argument used to explain winter precipitation differences. Differences in catch efficiencies between gages are smaller for rain than for snow. But this does not explain how NWS gages report more precipitation than SNOTEL gages during the summer.

Climatic factors could explain some of the daily discrepancy and some of the monthly scatter since summer thunderstorm precipitation is so spatially variable. It is also known that the rate of change of precipitation with elevation is much less in summer than in winter (Peck and Brown, 1963). Still an increase with elevation has been assumed due to an increase in the frequency of precipitation events at higher elevations. (Up to this time there has been inadequate high elevation precipitation data to confirm this assumption.) Face value use of the SNOTEL and NWS precipitation records shown here indicate that precipitation may actually decrease with elevation in some mountain areas.

Could evaporation be occurring from the fluid reservoir in the SNOTEL storage gages? The brown painted gages are reasonable solar collectors. Internal fluid temperatures are monitored at a few sites in the western U.S., and elevated daytime temperatures have been observed. However, the concentrations of oil-antifreeze solution used to charge these gages, even after a wet winter, still seem to be adequate to suppress evaporation. If evaporation were a problem, a downward trend in gage readings would be expected during the long summer dry periods. This tendency has not been observed.

We would like to suggest the following theory. Even after a wet winter, the typical summer distance from the top of an SCS missile gage to the fluid level inside is more than 2 m and as much as 4 m. Rain rarely falls straight down, so before water is added to the fluid reservoir, the inside of the gage must first become fully wet. Dirt and debris accumulation on the inside of the gage also could absorb significant moisture. Evaporation from these surfaces could account for additional measurable losses. The nature of summer precipitation in the Rockies, with frequent light showers separated by interludes of sunshine, is such that wetting and evaporation from gage side walls could account for the observed discrepancies. It should be possible to theoretically estimate the amount of water that could be lost as a result of this problem. Such a study should be done if SNOTEL summer precipitation data is to be widely used in climatic analysis.

APPLICATIONS

Several applications of SNOTEL precipitation data have been tested. The 1980-85 monthly data were extrapolated to produce estimates of monthly and annual precipitation totals consistent with the 1961-85 period. These annual values were compared with 1951-80 precipitation averages published in a recent detailed isohyetal map for Colorado (Doesken et al., 1984). Estimates were very similar at about half of the 52 sites that were tested. At 8 sites SNOTEL averages were at least 130 mm less than published map values while at 16 locations SNOTEL averages exceeded map values by at least 130 mm. An evaluation of these differences indicate that some of the estimates of long-term averages from short term data are unreliable. However, in several instances it appears that mapped values could be improved based on just these few years of SNOTEL data. SNOTEL data will be very valuable in future efforts to document total surface water resources in Colorado.

The Colorado Climate Center routinely produces maps of precipitation as a percent of average for each month and water year using NWS data. SNOTEL monthly precipitation data as a percent of estimated 1961-85 averages were superimposed on maps for selected months during 1985 and 1986. There is insufficient room in this paper to show results, but SNOTEL data neatly fit NWS precipitation patterns during winter months and added beneficial detail. Results were less consistent during the summer, but summer patterns are often extremely variable simply due to the nature of convective precipitation.

The nature of frequency and size of daily events is an important factor in assessing climatic variability. A comparison of the frequencies of precipitation events at 3 SNOTEL sites is shown in Figure 6. The Berthoud Summit site in the northern mountains of Colorado experienced significantly more precipitation days than Fremont Pass or Upper San Juan from November to June. During the July-October period, Upper San Juan experienced the most events. A significantly different pattern emerged when only large daily precipitation events ≥ 13 mm were examined. Upper San Juan experienced many more large events than the other gages except in April and May when large events were most common at Berthoud Summit. Similar regional variations in the effect of large events on total precipitation have been shown (Cowie and McKee, 1986). Despite problems with accuracy of daily precipitation data from SNOTEL gages, data appear to be very useful for comparing relative differences in precipitation frequencies between SNOTEL sites.

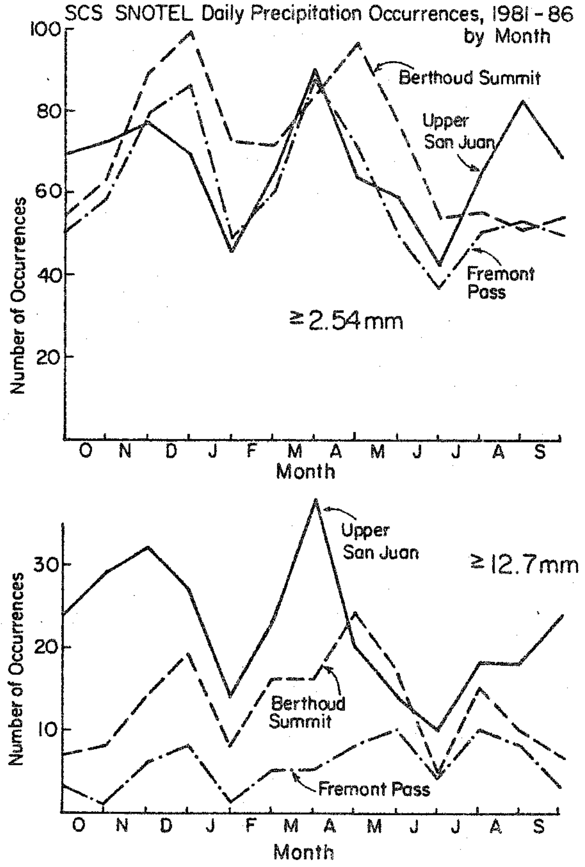

Figure 6. Comparison of monthly frequencies of daily precipitation occurrences ≥ 13 mm (right) for selected SNOTEL precipitation gages in the Colorado mountains, 1981-86.

CONCLUSIONS

SNOTEL precipitation data appear to be an excellent and valuable addition to high elevation climatic data sources in the Colorado Rockies. However, the data set has unique characteristics which make direct comparison to NWS gage measurements difficult and sometimes inappropriate. Improved gage catch efficiencies make the SNOTEL accumulated precipitation measurements superior to regular cooperative NWS data for the October-May winter period. Summer accumulations are well correlated with NWS data but under measure total precipitation by at least 10%. Problems exist with response characteristics of SNOTEL precipitation gage which results in many erroneous daily precipitation totals compared to NWS data. NWS data are superior to SNOTEL data for assessing timing and frequency of daily precipitation events, but SNOTEL data are adequate to show relative differences in the frequency of precipitation from one location to another. NWS data quality is degraded by observer changes and inconsistent observational practices -- problems which the automated SNOTEL sites do not have. Expanded use of SNOTEL precipitation data for climate monitoring, analysis and research appears to be justified. A comparative study placing NWS gages at selected accessible SNOTEL sites throughout the Rockies is recommended in order to better quantify differences between these two important data sets.

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