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Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data

Mark C. Serreze, Martyn P. Clark, and Richard L. Armstrong
Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder

David A. McGinnis
Department of Geography, University of Iowa, Iowa City

Roger S. Pulwarty
Program of Regional Integrated Assessments, Office of Global Programs, National Oceanic and Atmospheric Administration, Silver Spring, Maryland

Abstract. Daily station data from U.S. Department of Agriculture snowpack telemetry (SNOTEL) archives through the 1995/1996 season are used to examine the climatic characteristics of snow water equivalent (SWE) for the mountainous western United States and linkages with precipitation (PRE) and temperature. Quality control procedures were developed to screen outliers in each variable. SWE for April 1 at the SNOTEL sites compares favorably with colocated snow course values. Regional differences in the seasonal cycle of SWE are discussed in terms of winter-half precipitation, temperature, and the corresponding SWE/PRE ratio. The percentage of annual precipitation represented by snowfall is highest for the Sierra Nevada (67%), northwestern Wyoming (64%), Colorado (63%), and Idaho/western Montana (62%) sectors, manifesting high SWE/PRE ratios and winter-half precipitation maxima. Lower percentages for the Pacific Northwest (50%) and Arizona/New Mexico (39%) reflect lower ratios and, especially for the latter region, a larger fraction of PRE falling outside of the accumulation season. Interannual variability in SWE in the colder inland regions is primarily controlled by available precipitation. For the warmer Pacific coast regions and Arizona/New Mexico the more important factor is the SWE/PRE ratio, illustrating the sensitivity of these areas to climate change.

1. Introduction

The bulk of western United States surface water resources, represented by the flow of the Colorado and Columbia river systems, is derived from melt of the winter snowpack. In terms of flow volume the Columbia River system is the fourth largest in the United States (averaging 167.7×10^9 m^3), with half the annual flow stored for flood control, hydropower, and irrigation. By contrast, the Colorado River annual flow is about 17.2×10^9 m^3 with up to 4 times the annual flow in storage. Annual water consumption in the west averages 44% of renewable supplies compared with 4% in the rest of the country [*el-Ashry and Gibbons*, 1988]. The U.S. Bureau of Reclamation has indicated that during a dry period such as occurred from 1931 to 1940, the water needs of the lower Colorado River Basin would not be met [*el-Ashry and Gibbons*, 1988]. In the Colorado River Basin and southern California, groundwater is being mined and water supplies are being imported from adjoining states. Trade-offs among urban, agricultural, and environmental water needs have increased electricity transfers between the northwest and southwest regions during their respective peak and low periods [*Pulwarty and Redmond*, 1997]. Hence management of western water resources into the next century and beyond presents a formidable challenge. Water resources are finite with inherent natural variability and are potentially sensitive to climate change [*McGinnis*, 1997]. In turn, changes in population, water allocation, laws, institutional practices, and land use must be addressed to determine whether resources will be sustainable both within the limits of natural climate variability and potential future climate states [*Pulwarty*, 1995].

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Recognition of the close link between the western United States economy and water has led to a growing body of climate research focusing on this area. The Pacific North American (PNA) teleconnection pattern is a major mode of atmospheric variability that influences climate in the western United States [*Wallace and Gutzler*, 1981; *Barnston and Livezey*, 1987]. Positive PNA extremes describe an amplified midtropospheric wave train over North America, with a strong Aleutian Low, a strengthened ridge over the Pacific Northwest and western Canada, and a deeper than normal trough over the eastern United States. In the Pacific Northwest, temperatures are higher than normal and storm systems are deflected northward, resulting in decreased precipitation [e.g., *Yarnal and Diaz*, 1986; *Redmond and Koch*, 1991]. These changes lead to decreases in snow water equivalent (SWE) and streamflow [*Cayan and Peterson*, 1989; *Cayan and Webb*, 1992; *Cayan*, 1996]. Variations in sea surface temperatures in the tropical Pacific Ocean associated with the El Nino Southern Oscillation modulate climate variability over the North Pacific Ocean and North America and thus also snowpack conditions over the western United States. *Cayan* [1996] shows that El Nino years are associated with below-normal April 1 SWE over the Pacific Northwest and above-normal SWE over the southwest. Generally opposing signals are found during La Nina years.

Regarding potential future changes in snowpack conditions and runoff, *Nash and Gleick* [1991] argue that increases in temperature of 2°C can decrease streamflow in the upper Colorado Basin by 4–12%, with a temperature increase of 4°C resulting in larger reductions [see also *Gleick*, 1987; *Lettenmaier and Sheer*, 1991]. *McGinnis* [1997] provides climate change scenarios for the Colorado Plateau using techniques of circulation "downscaling," in which daily SWE records from United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) sites were reconstructed on the basis of circulation indices, with these indices then applied to the general circulation model output with a doubled carbon dioxide concentration. He found significant reductions of SWE as the snow season is reduced 58 days on average. By contrast, precipitation showed little change. Studies conducted using the Martinec-Rango snowmelt runoff model [*Rango and Martinec*, 1994; *Rango*, 1995] also show that changes in temperature will have a much larger impact on the seasonal snowpack and snowmelt runoff than changes in precipitation.

Despite all these studies we have little appreciation of regional differences in the mean seasonal evolution and melt of the snowpack, how interannual variations in seasonal snowpack conditions are related to the relative roles of changes in precipitation and temperature, and the contribution of the seasonal snowpack to surface water resources. To address these issues, we utilize data from 625 SNOTEL sites distributed over the montane western United States. Advantages of using SNOTEL data for this assessment are the daily resolution, the availability of precipitation, and more recently, temperature records.

2. SNOTEL Network

The *McGinnis* [1997] study represents one of the first efforts to use SNOTEL SWE records in a research mode. *Mock* [1996] has used these data along with other station records to examine seasonal aspects of western United States precipitation. Most studies have focused on snow course records [e.g., *Aguado*, 1990; *Changnon et al.*, 1991, 1993; *McCabe and Legates*, 1995; *Cayan*, 1996] which provide long-term monthly assessments of SWE for over a thousand sites throughout the western United States, peaking at near 2000 sites in the late 1970s, for water supply monitoring and forecasting. SNOTEL data are available for more than 600 sites (Figure 1). SNOTEL was designed to provide cost-effective data from high snow accumulation regions throughout the west to supplement, and to some extent, replace, snow course records [*Schaefer and Werner*, 1996]. SNOTEL sites were colocated with those snow course sites which correlated well with streamflow volumes over a long period [*Schaefer and Johnson*, 1992]. In addition, emphasis was given to automating those snow course sites that were particularly hazardous or costly to access. SWE data are generally available from the early 1980s onward, although records at some sites extend back to the 1963/1964 season (Figure 2). Since the early 1980s, precipitation began to be measured at the sites, and minimum and maximum daily air temperature began to be measured in the late 1980s (Table 1).

SNOTEL stations are fully automated and unattended. SWE measurements are made using snow pillows filled with an antifreeze solution. As the snow accumulates, the weight of the snowpack forces the solution into a manometer column inside the instrument shelter. The increase/decrease in manometer height is equal to the increase/decrease in SWE. A pressure transducer monitors the pressure of the fluid column and converts the pressure to SWE (in inches). The precipitation gauges have a 30.5-cm orifice and utilize an Alter wind shield to maximize catch efficiency. The gauges are charged annually with an oil-antifreeze solution to mitigate against freezing and evaporation. Each gauge stores precipitation for an entire year (also reported in inches) and works on the same manometer/pressure transducer principle as the snow pillow. Once daily, just after midnight, a system-wide poll is conducted, and each site transmits data for the previous day. Data capture is based on a meteor burst telemetry system which uses the reflection of radio signals by ionized meteor trails to enable communication. Precipitation gauges and the snow pillows are reset on October 1 of each year. Each site is powered by a battery pack charged from single or multiple solar panels.

Given the relatively dense spatial coverage of the daily SNOTEL records of SWE, precipitation, and temperature, it is perhaps surprising that few attempts have been made to use these data in climate studies. In part, this may reflect the relatively short period of time for which SNOTEL data are available. Furthermore, there have been concerns regarding data quality. These stem from lack of on-site maintenance, sensitivity of measurements to temperature and pressure fluctuations, relatively poor resolution of the instruments, and subjective quality control [*Doesken and Schaefer*, 1987]. Quality control procedures which we have developed are discussed in the section 3 and in the appendix. In addition, we provide comparisons between the snow course and SNOTEL records and present results from the SNOTEL climatology, evaluating the climatic characteristics and interannual variability of western United States SWE and relationships with precipitation and temperature. The SNOTEL climatology used here extends from the beginning of available records (1963/1964 season for some stations) through the 1995/1996 season. The SNOTEL data were obtained from the USDA NRCS anonymous ftp site wccdmp.wcc.nrcs.usda.gov. The state of California maintains an additional snow sensor and snow course network, but these data are not included in this study.

3. Data Preparation

3.1. Instrument Limitations

The cumulative daily values of SWE should in theory rise or fall only in response to gain or loss of snow mass. Similarly, cumulative precipitation (PRE) should never decrease. However, SNOTEL records of SWE and PRE contain errors related to limitations of the manometer/pressure transducer system and the possible formation of snow or ice bridges above the pillow surface. In any given annual record one may encounter situations in which a small rise in SWE from one day to the next is not reflected in a corresponding precipitation event. Similarly, small precipitation events during winter are sometimes not paired with a positive change in SWE. Small decreases in SWE may also occur with recorded temperatures well below freezing. Although, in part, this can reflect effects such as drifting, wind scour, sublimation, and blowing snow being recorded as precipitation, as well as foreign material being deposited on the snow pillow (e.g., sticks), in general,

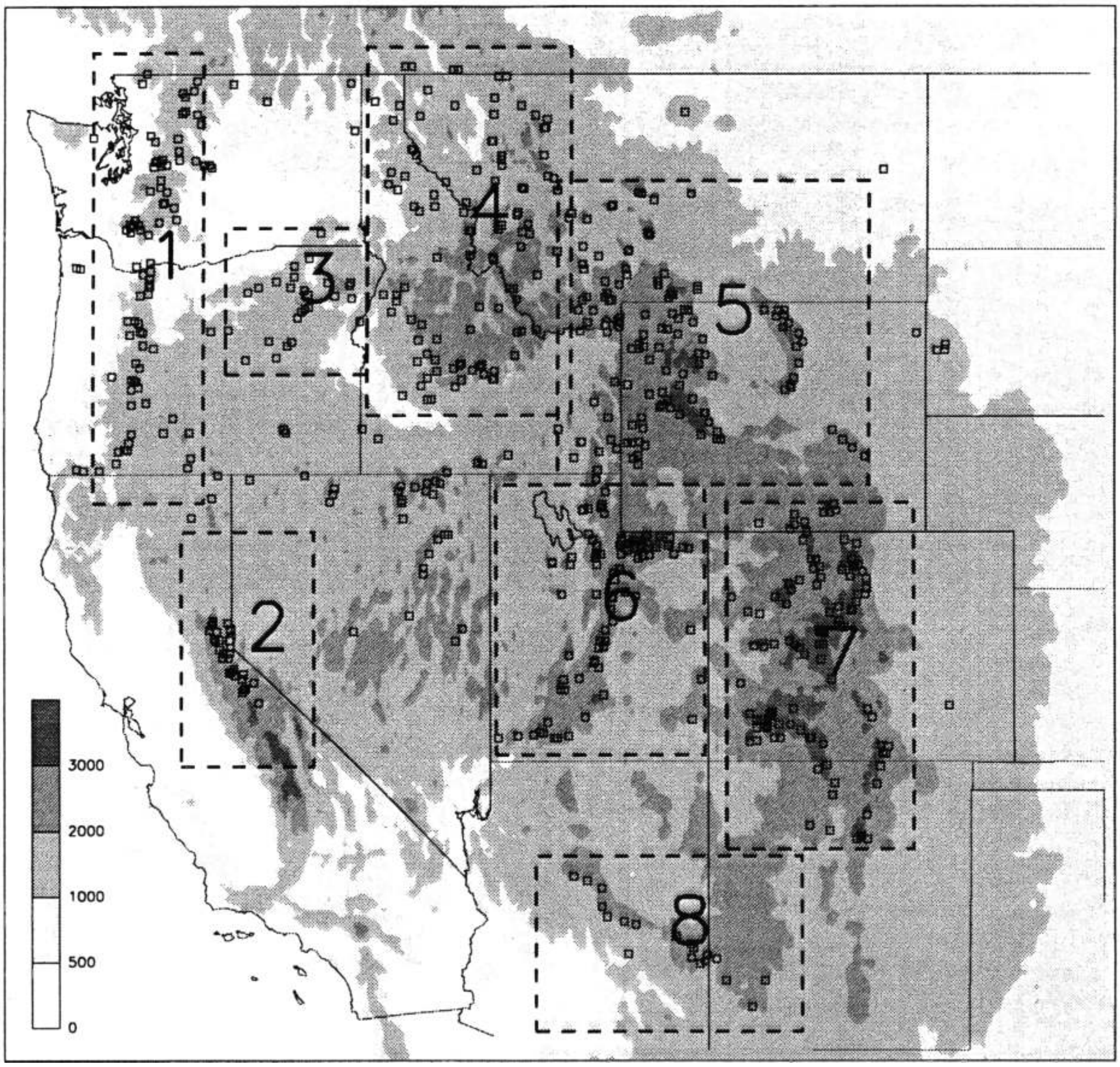


Figure 1. Distribution of snowpack telemetry (SNOTEL) stations and topography, showing regions for focused analyses (see text).

one cannot separate such effects from simple instrument errors. SWE errors are most obvious during summer when values of zero are interspersed by negative values of typically −0.24 to −1.2 cm or occasionally larger, apparently reflecting solar heating of the pillow. Negative PRE values of similar magnitude were also encountered but only rarely.

Doeskin and Schaefer [1987] compared precipitation at SNOTEL sites with precipitation at National Weather Service (NWS) stations and showed that the Alter wind shield on the SNOTEL precipitation gauges (NWS gauges are unshielded) and the larger orifice (30.5 cm at SNOTEL gauges compared with 20 cm at NWS gauges) improves catch efficiency. However, a problem was found with the response time when in autumn and spring wet snow sticks to the inside of the precipitation gauge only to be recorded hours or days later.

3.2. Quality Control

Quality control consisted of assuring that all station records used in the study represented the same time periods to avoid undue biases in the analysis of cumulative SWE and PRE records. Routines were developed to screen outliers in each variable and all negative SWE and PRE values, nearly all of which occurred during the summer. A description of the specific quality control steps taken is provided in the appendix.

3.3. Comparisons With Snow Course Measurements

As a test of the quality-controlled SNOTEL data set, April 1 SWE at the SNOTEL sites was compared with April 1 SWE at colocated snow courses available through 1987. We use April 1 data as it is typically close to the date of peak SWE and is also the time of year with the greatest frequency of snow course sampling [*McCabe and Legates*, 1995; *Cayan*, 1996]. With observations generally based on about 10 samples [*Cayan*, 1996], snow course data should provide a more representative measure of SWE than is measured at the SNOTEL sites. A total of 92 locations were identified where SNOTEL and snow courses sites are colocated. April 1 SNOTEL data for at least 5 years are available at 75 of these sites. The long-term

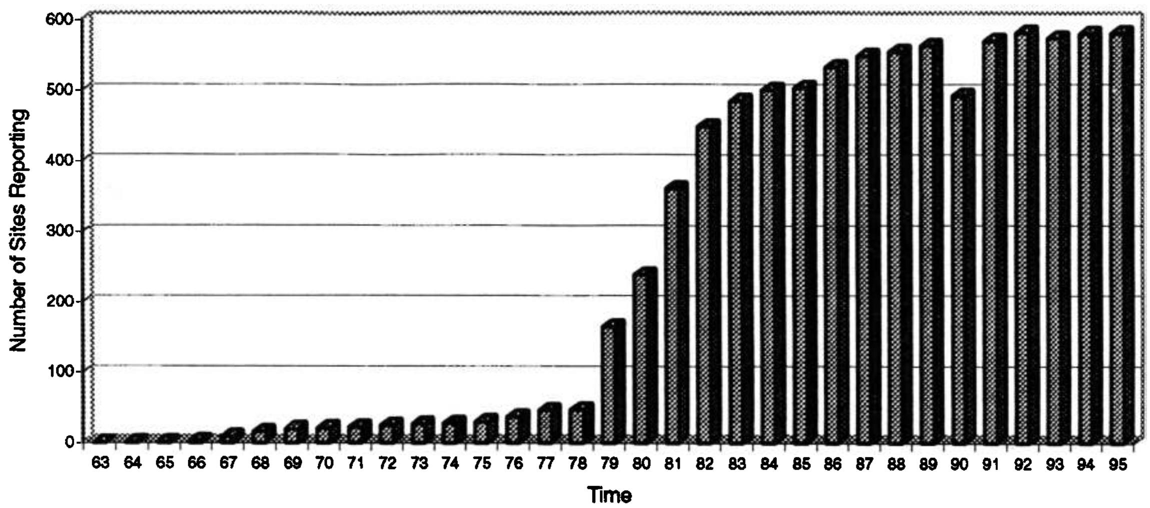


Figure 2. Number of SNOTEL stations by year.

mean April 1 SWE at the 75 SNOTEL sites compares favorably with the corresponding snow course values. At 51 (68%) of the SNOTEL sites, SWE is within 15% of the snow course value, while at 21 (28%) of the SNOTEL sites, SWE is within 5% of the snow course value. These differences are not biased toward overmeasurement or undermeasurement of SNOTEL SWE. As a further test, we computed the spatial correlation of April 1 SWE between all colocated SNOTEL and snow course sites for each year (Table 2). Results illustrate strong coherence between the two independent data sets, with correlations ranging from 0.87 in 1981 and 1984 to 0.93 in 1986.

Table 1. Number of Stations for Which <25% of Records Were Originally Missing or Discarded From Quality Control Checks

Year	SWE	PRE	TEMP
1963/1964	0	0	0
1964/1965	1	0	0
1965/1966	1	0	0
1966/1967	3	0	0
1967/1968	9	0	0
1968/1969	15	0	0
1969/1970	19	0	0
1970/1971	20	0	0
1971/1972	21	0	0
1972/1973	21	0	0
1973/1974	25	0	0
1974/1975	27	0	0
1975/1976	26	0	0
1976/1977	32	0	0
1977/1978	46	0	0
1978/1979	40	0	0
1979/1980	147	114	0
1980/1981	177	157	0
1981/1982	322	310	0
1982/1983	374	384	0
1983/1984	426	426	12
1984/1985	456	445	47
1985/1986	481	479	59
1986/1987	491	475	118
1987/1988	530	531	177
1988/1989	539	538	181
1989/1990	541	544	294
1990/1991	479	455	397
1991/1992	550	546	520
1992/1993	554	549	531
1993/1994	554	549	502
1994/1995	554	560	537
1995/1996	542	559	568

See section 3 in text. Abbreviations are as follows: SWE, snow water equivalent; PRE, precipitation; and TEMP, temperature.

4. Mean Snowpack Conditions

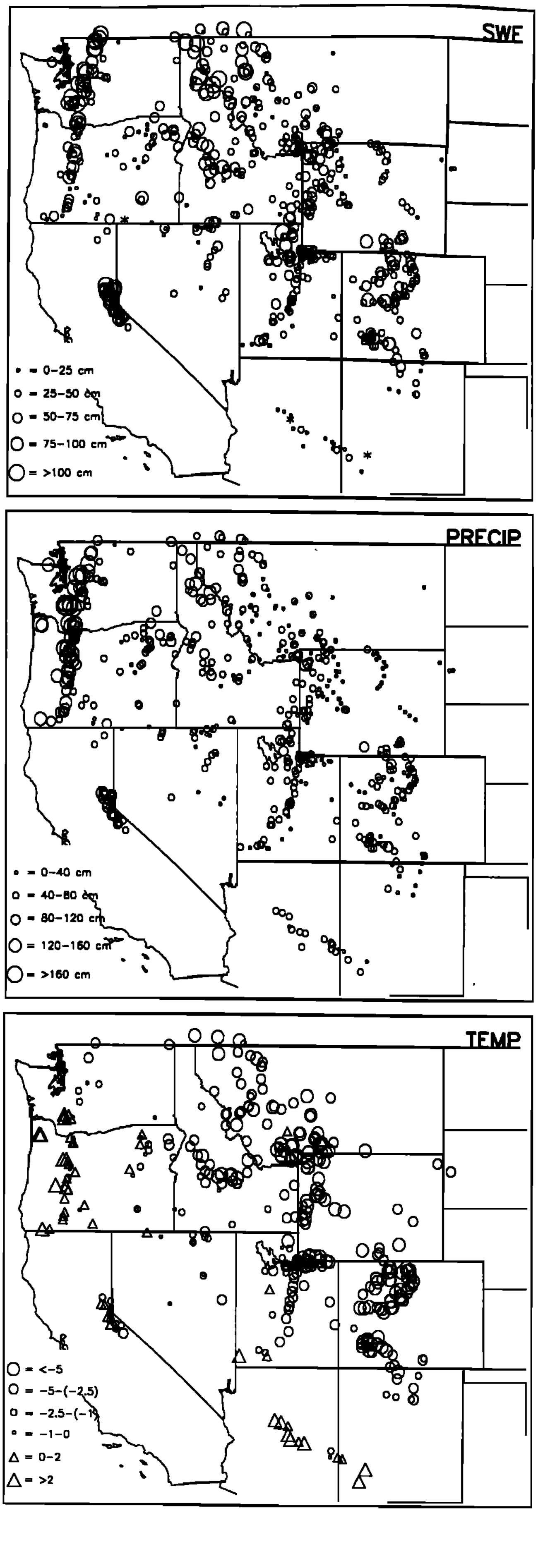
Water resource planners typically make use of April 1 SWE as an estimate of potential spring runoff. As such, it is useful to first examine the spatial patterns of April 1 SWE from the SNOTEL network, along with corresponding patterns of PRE and temperature. Spatial plots of mean cumulative April 1 SWE and PRE and mean temperature from October 1 through April 1 are shown in Figure 3.

Figure 3 shows April 1 SWE and PRE to be highest in the Pacific Northwest, the Sierra Nevada, and in northwestern Montana and Idaho. The high PRE totals for the Pacific Northwest and Sierra Nevada are expected as the mountains in these areas represent the first orographic barriers to intercept onshore pulses of moist Pacific air, typically associated with storms originating in the Gulf of Alaska which tend to stall off the coast and dissipate before penetrating far inland [*Zishka and Smith*, 1980; *Mock*, 1996]. Compared to SNOTEL sites in other areas, mean temperatures in the Pacific Northwest are high. As discussed shortly, this reflects the low median eleva-

Table 2. Spatial Correlations Between Colocated SNOTEL and Snowcourse Sites

Year	Correlation	*N*
1980	0.92	31
1981	0.87	63
1982	0.90	69
1983	0.92	67
1984	0.87	75
1985	0.89	79
1986	0.93	80
1987	0.92	88

All correlations are significant to the 99% confidence level.



tion of the stations, implying frequent rain events early in the season and a higher frequency of melt events during winter. The high SWE and PRE totals for northwestern Montana and Idaho are understood as this area is associated with frequent leeside cyclogensis and the occasional passage of Pacific systems [*Whittaker and Horn*, 1984; *Cayan*, 1996]. Lower mean temperatures also imply that compared to the Pacific Northwest, the winter-half precipitation is more likely to occur as snowfall. The comparatively low SWE values for stations in the Colorado Front Range and the Wasatch Mountains are associated with more limited precipitation. However, high SWE and PRE totals comparable to those in northwestern Montana and Wyoming are found for individual stations in favored locations. The low SWE totals over Arizona and New Mexico are associated with precipitation totals comparable to those along the Colorado Front Range. This indicates frequent winter melt events as well as a large fraction of precipitation early in the season falling as rain because of higher temperatures.

To examine these results more closely, we subjectively defined eight regions over the western United States (Figure 1) and plotted the annual cycles of SWE, PRE, and temperature averaged for each region (Figure 4). For clarity the annual cycle of air temperature is smoothed with a 30-day moving average. Table 3 lists the median elevation of SNOTEL sites within each region, as well as the elevations of the lowest and highest stations. For our purposes the subjective regionalization was more appropriate than objective techniques. This is illustrated in the results of *Cayan* [1996], where a principal component (PC) analysis of the interannual variability in SWE over the western United States reveals five broad regions, with all PCs covering fairly large spatial areas. The dominant PC (the Idaho pattern), for example, has high loadings from the Pacific Northwest through to Wyoming. Obviously, there are large differences in climatology over such a large area. Principal component analyses on the climatological means reveal differences between elevation and aspect but do not separate geographical regions.

While the eight regions defined describe the major mountain areas of the western United States, there are obviously within-region differences due to smaller-scale influences such as variable orographic precipitation patterns. For example, *Barry* [1973] shows that on the eastern flank of the Colorado Front Range, high-elevation sites near the Continental Divide have a winter precipitation maximum and an autumn minimum, while lower elevation sites have a spring maximum and a winter minimum. *Pitlick* [1994] divides the Colorado region into "alpine" and "foothills"; the alpine region is dominated by snowfall, and the foothills region is dominated by thunderstorms. Although we acknowledge variability within our regions, as will be made clear, they effectively capture the larger-scale climatic differences across the western United States.

To assist in interpreting Figure 3, Table 4 provides a regional breakdown of monthly PRE, SWE, and the SWE/PRE ratio for October through March. The monthly ratios are based on the change in cumulative SWE and PRE between the first day of successive months (e.g., ratios for January are based on the

Figure 3. (opposite) Spatial characteristics of April 1 snow water equivalent (in centimeters), April 1 cumulative precipitation (in centimeters), and October 1 to April 1 mean temperature (in degrees Celsius).

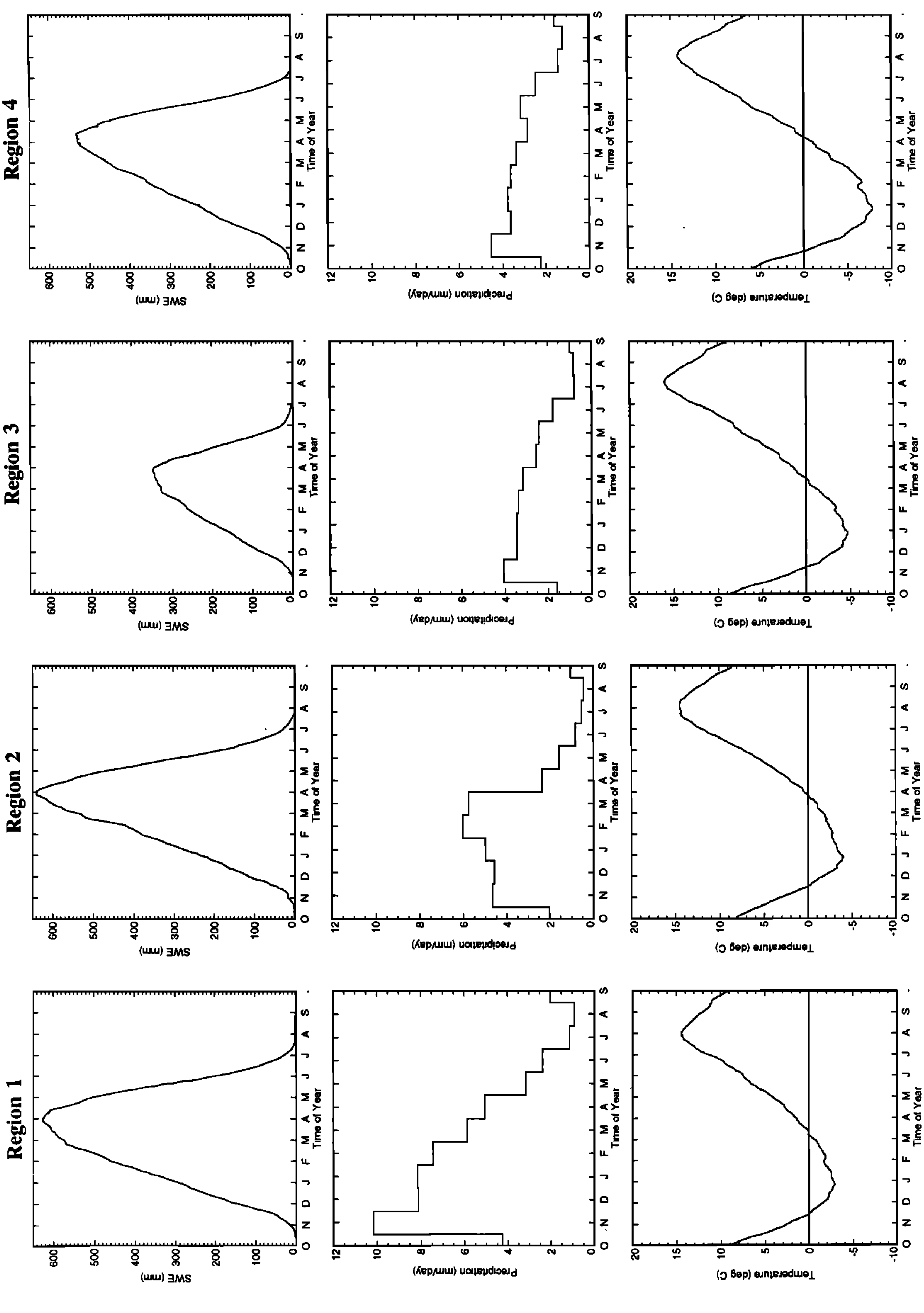


Figure 4. Seasonal cycles of snow water equivalent (mm), monthly precipitation (mm d^{-1}), and temperature (°C) for the eight regions defined in Figure 1. The seasonal cycles of temperature are smoothed with a 30-day moving average.

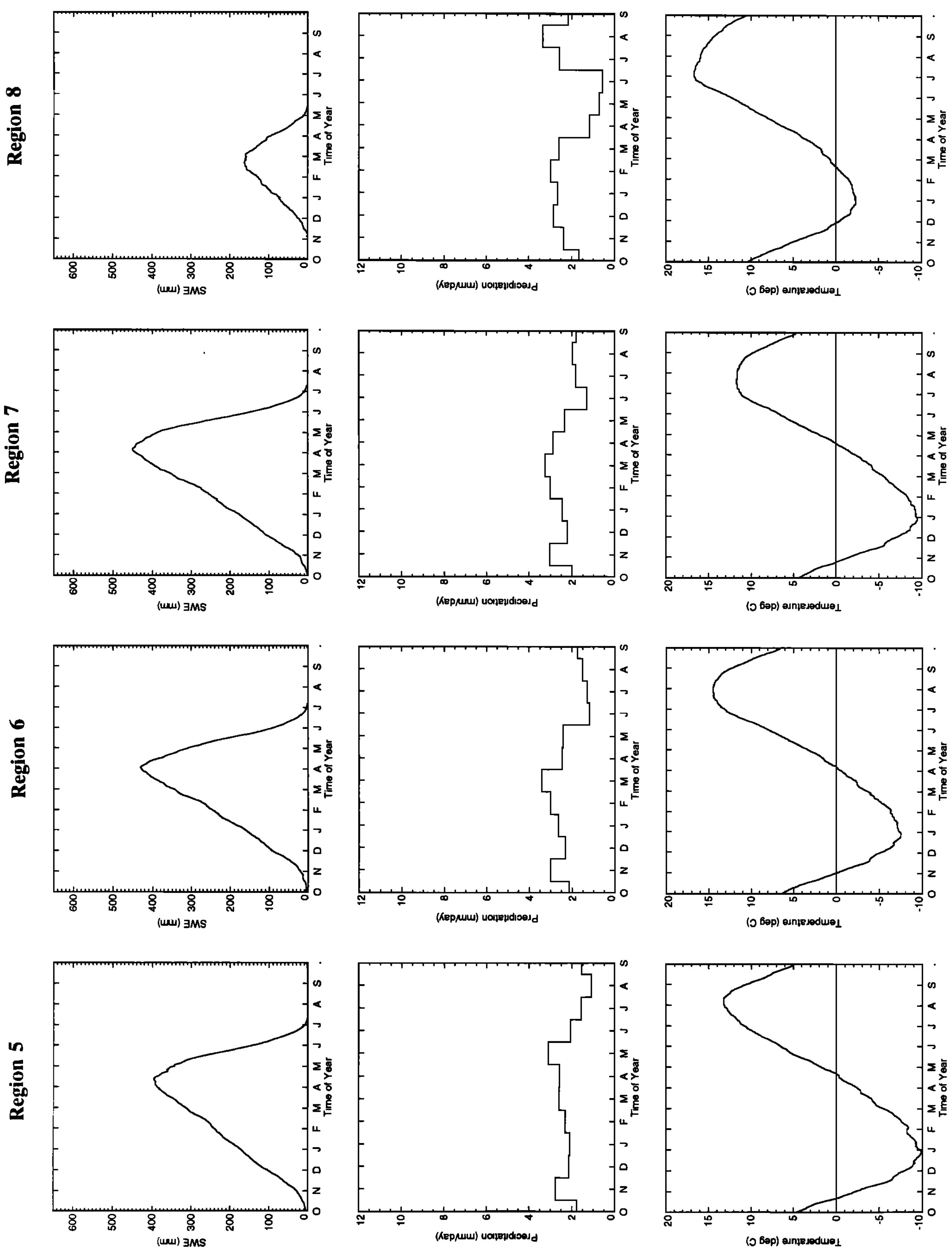


Figure 4. (continued)

Table 3. Characteristics of the Eight Regions

Region	Boundaries	Elevation, m Low	Median	High	*N*
1, Pacific Northwest	41.5°–49.2°N; 123.0°–120.5°W	793	1422	2165	81
2, Sierra Nevada	37.0°–41.0°N; 121.0°–118.0°W	1890	2439	2865	28
3, Blue Mountains, Oregon	43.7°–46.2°N; 120.0°–116.8°W	1197	1646	2412	26
4, Idaho/western Montana	43.0°–49.3°N; 116.8°–112.2°W	960	1905	2790	105
5, NW Wyoming	41.8°–47.0°N; 112.5°–105.5°W	1456	2470	3079	126
6, Utah	37.2°–41.8°N; 113.9°–109.2°W	1829	2774	3329	80
7, Colorado	35.6°–41.5°N; 108.7°–104.5°W	2268	3037	3537	104
8, Arizona/New Mexico	32.5°–35.5°N; 113.0°–107.0°W	1866	2418	2805	19

change in regionally averaged PRE and SWE between January 1 and February 1). Also shown is the accumulation season ratio based on the April 1 and October 1 PRE and SWE totals. Ratios are only computed for months in which the change in SWE is positive. The ratios of SWE to PRE are primarily a function of temperature. The ratio has a theoretical maximum value of 1.0. The simplest possible scenario in which the theoretical value could occur is when all precipitation falls as snow and there is no mass loss due to melt, evaporation, and sublimation. Another possible scenario is that some of the precipitation falls as rain, but the liquid water is incorporated into the snowpack with no resultant runoff.

In looking at the raw SWE and PRE totals in Table 4, it is evident that despite the improved catch efficiency provided by the Alter wind shield, precipitation is still underestimated. This is most obvious in regions 5 and 7, where from December through February the monthly accumulated SWE exceeds monthly PRE, which would result in ratios exceeding 1.0. To provide an estimate of the undercatchment, we computed the ratio between daily positive SWE increments exceeding 2.5 cm and the corresponding daily PRE increments based on all stations in each region using data for January and February only. The average regional ratio was then used to adjust upward the monthly PRE at each SNOTEL site for October

Table 4. Monthly Average Totals of PRE, SWE, and the SWE/PRE Ratio

Region	Variable	October	November	December	January	February	March	Total
1	PRE (raw)	13.17	30.36	25.09	25.29	20.80	18.31	133.02
	PRE (corrected)	13.17	31.74	26.82	27.10	21.95	18.71	139.48
	SWE	1.27	10.81	13.48	14.11	8.96	3.13	51.76
	Ratio	0.10	0.34	0.50	0.52	0.41	0.17	0.34
2	PRE (raw)	6.08	13.72	13.99	15.18	16.50	17.50	82.97
	PRE (corrected)	6.08	15.00	15.56	17.04	18.42	18.79	90.88
	SWE	1.40	9.06	11.09	13.17	13.58	9.10	57.40
	Ratio	0.23	0.60	0.71	0.77	0.74	0.48	0.59
3	PRE (raw)	5.09	12.31	10.70	10.79	9.53	9.84	58.26
	PRE (corrected)	5.09	13.32	11.95	12.11	10.44	10.08	62.98
	SWE	0.83	7.20	8.92	9.37	6.48	1.68	34.48
	Ratio	0.16	0.54	0.75	0.77	0.62	0.17	0.50
4	PRE (raw)	7.04	13.60	11.18	11.62	10.02	10.32	63.78
	PRE (corrected)	7.04	14.87	12.50	13.04	11.21	11.29	69.94
	SWE	2.03	9.34	9.72	10.40	8.71	7.12	47.32
	Ratio	0.29	0.63	0.78	0.80	0.78	0.63	0.65
5	PRE (raw)	5.50	8.28	6.64	6.53	6.47	8.04	41.46
	PRE (corrected)	5.50	9.47	7.74	7.63	7.53	9.22	47.09
	SWE	2.56	7.62	7.03	7.01	6.79	7.54	38.55
	Ratio	0.47	0.80	0.91	0.92	0.90	0.82	0.80
6	PRE (raw)	6.65	8.92	7.18	8.03	8.30	10.54	49.62
	PRE (corrected)	6.65	10.81	8.98	10.32	10.65	12.72	60.13
	SWE	1.69	7.31	6.99	8.87	9.12	8.44	42.42
	Ratio	0.25	0.68	0.78	0.86	0.86	0.66	0.68
7	PRE (raw)	6.26	9.10	6.94	7.56	8.45	10.07	48.38
	PRE (corrected)	6.26	10.84	8.47	9.24	10.39	11.99	57.18
	SWE	2.33	8.10	7.12	7.86	9.06	8.95	43.42
	Ratio	0.37	0.75	0.84	0.85	0.87	0.75	0.74
8	PRE (raw)	5.17	7.20	8.83	8.26	8.34	8.04	45.84
	PRE (corrected)	5.17	7.49	9.41	8.91	8.64	7.32	46.94
	SWE	0.08	2.52	4.96	5.56	2.59	−6.22	9.49
	Ratio	0.01	0.34	0.53	0.62	0.30	NC	0.36

PRE and SWE values are given in centimeters.

through March, and monthly SWE/PRE ratios were obtained from the corrected values. The 2.5-cm limit of SWE restricts the analysis to large snowfall events for which the effects of instrument noise will be minimized. The restriction to January and February also limits cases to those for which it is unlikely that snowfall will be mixed with rain and events in which the tendency for a temporal lag in the recording of precipitation events because of wet snow clogging the precipitation gauge will be minimized. Some obvious caveats regarding this correction are the following: (1) The daily SWE increments may reflect not only snowfall but the effects of wind scour and drifting. (2) The undercatchment of precipitation is unlikely to be consistent between months. (3) The undercatchment may differ between stations within a region. Nevertheless, we believe that this correction is an improvement upon using raw ratios.

As illustrated in Figure 4, the high peak SWE values for the Pacific Northwest (region 1) and the Sierra Nevada (region 2) are associated with strong winter-half (October–March) precipitation maxima and summer-half precipitation minima. However, within this general pattern the two regions differ substantially. Monthly precipitation for the Pacific Northwest peaks in November, decreasing thereafter. By contrast, the Sierra Nevada shows more even amounts from November–March, with a modest late winter peak. The summer precipitation minimum for both regions is understood as the strong Pacific High steers storms to the north. During autumn the high weakens, allowing moisture-bearing systems to track into the Pacific Northwest. As the jet stream migrates south during winter, precipitation tends to remain high over the Pacific Northwest but decreases from its autumn maximum. Attendant increases in storm activity to the south result in precipitation increases over the Sierra Nevada region, such that the precipitation maximum in this area occurs later in the season. This seasonality of precipitation for the west coast is clearly evident in the analysis of *Mock* [1996], which includes station data from many sources including measurements from SNOTEL sites.

On the basis of greater winter-half precipitation over the Pacific Northwest we would expect a higher seasonal peak in SWE, but this is not observed. For both regions, mean SWE peaks at over 600 mm. This can be understood from the effects of temperature and elevation on the SWE/PRE ratio. For both regions, autumn temperatures are well above freezing, implying that early-season snowfall events tend to be offset by melt events and that especially in October precipitation frequently falls as rain, delaying the seasonal rise in SWE. October and November precipitation is much higher for the Pacific Northwest, but SWE/PRE ratios are smaller by a factor of 2. The temperature contrast between these two regions as shown in Figure 4 is rather small, and we acknowledge a bias in the temperature statistics as they are based on shorter records than for either PRE or SWE (Table 1). Nevertheless, it appears that for these two comparatively warm regions, the small temperature differences are sufficient to yield large differences in SWE/PRE ratios. Because of the decreased SWE/PRE ratio (Table 4), the "head start" on SWE accumulation in the Pacific Northwest that would be expected on the basis of precipitation does not occur. Winter SWE/PRE ratios are also lower in the Pacific Northwest, implying more frequent midwinter melt events. Finally, note the sharper peak in SWE for the Sierra Nevada. This is understood as a response to the tendency for precipitation to peak during February and March, while it declines in the Pacific Northwest.

Turning to the northern tier of inland regions, the Blue Mountains, Oregon (region 3) and Idaho/western Montana (region 4) show some similarities with the Pacific Northwest, with a precipitation peak during November and amounts slowly falling off through winter, spring, and summer. However, the seasonal cycles are much weaker with lower winter-half precipitation totals. The winter-half precipitation maxima reflect the occasional passage of Pacific storms through these areas and for Idaho/western Montana, the development of leeside lows [*Whittaker and Horn*, 1984], some of which presumably represent the redevelopment of Pacific systems. The lower precipitation totals as compared to the Pacific Northwest manifest increasing distance from Pacific moisture sources and interception of moisture by mountain ranges to the west (collectively interpreted as increasing continentality). By comparison, northwest Wyoming (region 5) shows a more even precipitation distribution, with generally lower monthly totals than either regions 3 or 4. The median station elevation of these three regions increases eastward (Table 3) and is seen as an eastward decline in mean minimum winter air temperatures and an increase in the duration of below freezing temperatures. The observation that precipitation is comparatively low for the northwest Wyoming region despite the high median station elevations is clearly indicative of the effects of continentality.

The seasonal cycles of SWE in these northern continental regions (regions 3, 4, and 5) can again be explained in terms of the precipitation and temperature regimes and corresponding SWE/PRE ratios. Compared to the Pacific Northwest, these regions are characterized by lower peak SWE, consistent with the less abundant precipitation. However, as revealed in Table 4, the precipitation is utilized more effectively in increasing SWE such that peak seasonal SWE is higher than would be expected simply given the available precipitation. For example, for the cold NW Wyoming region the SWE/PRE ratio in October is 0.47 versus 0.10 for the Pacific Northwest and is 0.92 versus 0.52, respectively, for January. Consequently, while NW Wyoming receives only 35% of the October–March precipitation found for the Pacific Northwest, SWE is 75% of the Pacific Northwest value.

Utah (region 6) and Colorado (region 7) show seasonal cycles of precipitation most similar to NW Wyoming with fairly even autumn and winter values and a weak spring maximum. This spring precipitation peak corresponds to increased cyclogenesis in the lee of the central and southern Rocky Mountains as well as increased cyclogenesis in the eastern Great Basin [*Whittaker and Horn*, 1984; *Mock*, 1996]. End-of-March precipitation totals for the two regions are nearly identical, but peak SWE for Colorado is slightly higher. This is understood from the lower temperatures and the correspondingly higher SWE/PRE ratios.

The seasonal cycle of SWE for Arizona/New Mexico (region 8) is in sharp contrast to the continental regions just discussed. Although the end-of-March precipitation is little different from the Utah and Colorado sectors (Table 4), peak SWE (Figure 4) is less than half that for these regions. Winter-half precipitation in this region is associated with cyclogenesis in the eastern Great Basin [*Mock*, 1996]. This cyclogenesis tends to occur in association with the transport of Pacific moisture by the southern branch of the jet stream (the subtropical jet), which is generally stronger in El Nino conditions. The comparatively low SWE, given the reasonably ample precipitation, is explained by the high temperatures and low SWE/PRE ra-

Table 5. Mean Dates of Maximum SWE, Disappearance of the Snowpack, and Mean Length of the Snowmelt Season

Region	Date of Max SWE	Date of Disappearance of Snow	Days of Snowmelt
1	March 30	July 19	110
2	March 30	July 21	112
3	March 27	June 27	91
4	April 12	July 9	88
5	April 13	July 5	83
6	April 3	June 30	88
7	April 6	July 7	92
8	February 20	May 8	77

tios. Snowfall is uncommon in October (a SWE/PRE ratio of 0.01), indicating that most precipitation falls as rain and that occasional accumulation events are offset by melt. Even in January, the coldest month, the PRE/SWE ratio is only 0.62, which is still higher, however, than for the Pacific Northwest. Note also that the annual cycle of precipitation in this region is bimodal, characterized by both winter and summer peaks. While, as discussed, the winter peak reflects cyclone activity, the summer pattern relates to convective precipitation associated with the southwestern monsoon [*Carleton*, 1986, 1987; *Rowson and Colucci*, 1992].

Finally, Table 5 shows for each region the date of the climatological seasonal maximum in SWE, the date at which the snowpack disappears, taken as the date for which SWE drops from its seasonal maximum to 0.5 cm, and the duration of the melt season, taken as the difference in Julian days between the date of peak SWE and the date at which the snowpack disappears. As expected, peak SWE occurs earliest (February 20) for Arizona/New Mexico (region 8), which represents a response to the comparatively high late-winter and spring temperatures in this region (Figure 4). Peak SWE occurs latest, variously from April 3–13 in the remaining interior regions, which from Figure 4 relates to the later onset of above-freezing temperatures, although the dates for Utah and Colorado are little different from the Pacific Northwest and Sierra Nevada (March 30). The latest snowpack disappearance dates, in turn, also associated with the longest duration of snow melt, are found for the Pacific Northwest and Sierra Nevada. This is understood in that the massive snowpack in these regions (Figure 4) simply takes longer to melt. The remaining regions, which show lower peak SWE, tend to lose their snowpack around the end of June to the first week in July, the obvious exception being Arizona/New Mexico, which shows an early loss of the snowpack (May 8) and a short melt season of 77 days, indicative of both the low peak SWE and high temperatures.

5. Significance of Snowfall for Surface Water Resources

With the SNOTEL data it is also possible to provide for each region an estimate of the fraction of annual precipitation derived from snowfall, which, in turn, provides a sense of the relative significance of snowfall for surface water resources. In Table 4 we assessed the SWE/PRE ratio based on the differences in cumulative SWE and PRE between the first day of successive months and between the April 1 and October 1 values. Here a similar procedure is used. The simplest estimate would be to calculate for each region the ratio between peak seasonal SWE and annual precipitation, the adjustment by annual precipitation accounting for regional differences in the seasonality of precipitation. However, a better estimate is provided by computing at each SNOTEL site the ratio between the sum of all positive daily SWE increments (events) throughout the year and total annual precipitation and then finding the regional average. Using the sum of all positive SWE increments accounts for additional contributions to runoff from snow associated with melt events during the accumulation season as well as snowfall events during the spring ablation season that temporarily add mass. A correction for precipitation undercatchment was applied using the same techniques as for Table 4. Note also that the percentages are actually based on "effective snowfall" as occasional positive SWE increments, especially during the transition months, could be partly or entirely due to liquid precipitation events that add to the snowpack mass.

Interpreting our calculation in terms of the regional percentage of surface water resources derived from snowfall does not follow exactly because of the following: (1) We do not account for infiltration and evaporative losses. (2) While we assume that the SNOTEL sites provide a reasonable spatial representation of the mountain snowpack and precipitation, results are biased to the higher elevations in each region where more precipitation falls as snow. Nevertheless, the percentages do provide a useful basis to compare the relative importance of snowfall for water resources between different regions.

The percentages will tend to be high (low) when SWE/PRE ratios are high (low) (Table 4) and the bulk of precipitation falls during the accumulation (ablation and summer) season. With this in mind, Table 6 shows the region with the highest percentage of annual precipitation derived from effective snowfall is the Sierra Nevada (67%). In terms of the October–March SWE/PRE ratio (Table 4) this region ranks the third lowest, behind Arizona/New Mexico and the Pacific Northwest. Consequently, the high percentage in Table 6 largely reflects the sparse summer precipitation (Figure 4). Also high (above 60%) are the Rocky Mountain regions of Idaho/western Montana, NW Wyoming, Colorado, and Utah. Although a comparatively greater fraction of precipitation in

Table 6. Percentage of Annual Precipitation Derived From Snowfall

Region	Raw*	Undercatchment†	Corrected‡
1. Pacific Northwest	54.37	12.80	50.01
2. Sierra Nevada	75.28	14.13	66.85
3. Blue Mountains, Oregon	62.06	14.04	56.78
4. Idaho/western Montana	67.65	13.61	61.83
5. NW Wyoming	71.29	15.65	64.15
6. Utah	70.81	25.81	59.56
7. Colorado	72.77	21.42	62.62
8. Arizona/New Mexico	41.10	11.64	39.24

*Initial estimate of the percentage of annual precipitation is derived from snowfall computed from the mean ratio between the sum of positive SWE events measured at snow pillows and total annual precipitation measured at precipitation gauges.

†Estimate of the mean undercatchment of precipitation (in centimeters) is calculated from the mean ratio between daily SWE events at snow pillows and daily PRE events at precipitation gauges, using data for January and February and SWE increments exceeding +2.5 cm.

‡Corrected estimate of the percentage of annual precipitation derived from snowfall is calculated as above except that annual precipitation is adjusted by adding the estimated undercatchment to the raw annual totals.

these regions falls during summer, this is offset by the higher SWE/PRE ratios during the accumulation season.

SWE in the lower-elevation Pacific Northwest has a higher seasonal maximum than these inland regions, but because of lower SWE/PRE ratios during the accumulation season and relatively high precipitation totals through the ablation season, SWE is of lesser relative importance in terms of surface water resources. The lowest percentages from Table 6 are for Arizona/New Mexico (39%). Following earlier discussion, this is accounted for by lower SWE/PRE ratios during the accumulation season, especially in October when much of the precipitation falls as rain, as well as the large fraction of annual precipitation falling during summer in association with the southwestern monsoon (Figure 4).

6. Interannual Variability

Figure 5 provides time series of regionally averaged April 1 SWE and PRE and the October 1 to April 1 SWE/PRE ratio over the period 1981–1995 for which the SNOTEL network is reasonably robust. The range in SWE between the highest and lowest years is a factor of 2 for Idaho/western Montana, NW Wyoming, Utah, and Colorado and is much greater in the Pacific Northwest, Sierra Nevada, Blue Mountains of Oregon, and Arizona/New Mexico. Note in particular Arizona/New Mexico (region 8) where during 1989, essentially no snowpack developed (and was less than 2.5 cm also for several other years) as compared to 1983, when nearly 30 cm of SWE was recorded. For available years the variability shown in Figure 5 corresponds well with the years of high and low SWE in the regional analyses of *Cayan* [1996], based on April 1 snow course data from 1931 to 1988.

On the basis of time series data used to construct Figure 5, Table 7 presents linear correlation coefficients between SWE and PRE, between SWE and the SWE/PRE ratio, and between PRE and the SWE/PRE ratio. Because of the shortcomings in air temperature data (appendix) and the short length of the temperature records (Table 1), we use the SWE/PRE ratio as a proxy for temperature. Hence the correlation between SWE and this ratio effectively illustrates the extent to which variations in SWE relate to temperature. Also shown in Table 7 is the coefficient of deviation (the standard deviation divided by the mean) of SWE, PRE, and the SWE/PRE ratio. There is some redundancy in the correlation between SWE and PRE and that between SWE and SWE/PRE as the independent variables share a common term. Similarly, because of the common term there will be a natural tendency for PRE and SWE/PRE to be correlated. However, by examining the strength of these different correlations, it is possible to get a sense of the relative importance of different factors in controlling interannual variability in SWE.

All regions show significant correlations of at least 0.60 between SWE and PRE. This is, of course, expected as PRE places a fundamental limit on how much snowfall is possible. However, for the Pacific Northwest, the stronger role is played by the SWE/PRE ratio. Here precipitation is abundant but not particularly variable, as is evident from the coefficient of deviation of 0.16. By contrast, because of the low median elevation and high temperatures, temperature anomalies have a strong effect on midwinter melt and precipitation phase, especially during the transition months. This is seen in the higher coefficient of deviation in the SWE/PRE ratio (0.29) and the factor of 4 range between extreme years in the ratio from 0.16 to 0.67 (Figure 5). The importance of the SWE/PRE ratio in the Pacific Northwest and the influence on this ratio by temperature, rather than precipitation, is further evident in the low correlation between PRE and the SWE/PRE ratio (0.18).

By comparison, precipitation in the other Pacific region, the Sierra Nevada (region 2), is much more variable, but the PRE/SWE ratio is much less variable, with a factor of 2 range between the high and low years. The more stable ratio is interpreted in terms of the higher elevation and lower temperatures, so that temperature fluctuations have less of an impact on melt and precipitation phase. As such, April 1 SWE in this region is more strongly controlled by the high variability in precipitation. This is immediately apparent in Figure 5. Nevertheless, the correlation with the SWE/PRE ratio is still fairly high (0.70). The finding that SWE is correlated with both PRE and PRE/SWE is understood from the significant positive relationship between PRE and SWE/PRE. Put differently, while the strong relationship between SWE and PRE reflects higher elevation as compared to the Pacific Northwest, the relationship also manifests the reinforcing tendency for abundant (meager) PRE to be associated with lower (higher) temperatures, with the available precipitation more (less) efficiently converted into SWE. This relationship is not surprising as anomalous years when the storm track drops far enough south to result in high precipitation totals will be associated with colder air masses.

The interior regions, with the exception of Arizona/New Mexico and the Blue Mountains, Oregon, are similar to the Sierra Nevada in showing a more important role played by precipitation, which, again in contrast to the Pacific Northwest, stems from the low temperatures in these regions. Accordingly, these regions show the lowest coefficients of deviation in the SWE/PRE ratio, quite evident in Figure 5. However, for Colorado the correlation between SWE and the PRE/SWE ratio is again fairly high (0.67). Like the Sierra Nevada, this positive relationship reinforces the effect of the climatologically low temperatures. Results for the Blue Mountains, Oregon, are broadly similar except that the SWE correlations with PRE and the SWE/PRE ratio are both above 0.80.

Arizona/New Mexico represents a situation most similar to the Pacific Northwest in that the stronger role on SWE is played by the SWE/PRE ratio. The coefficient of deviation is high for SWE and PRE as well as the ratio (see also Figure 5). Clearly, with the high temperatures characteristic of this region, interannual variability in SWE will be sensitive to precipitation phase and midwinter melt. However, the highly variable winter-half precipitation (the most variable of all regions) also plays a strong role.

7. Summary and Conclusions

Daily records for the western United States of snow water equivalent (SWE), precipitation, and temperature from the automated United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) network are used to examine the climatic characteristics and interannual variability of western United States SWE. The SNOTEL network contains over 600 stations. Data examined here extend through the 1995/1996 season, and while the majority of records begin in the early 1980s, some extend back to 1963/1964. For earlier years, generally only SWE is available. Precipitation began to be re-

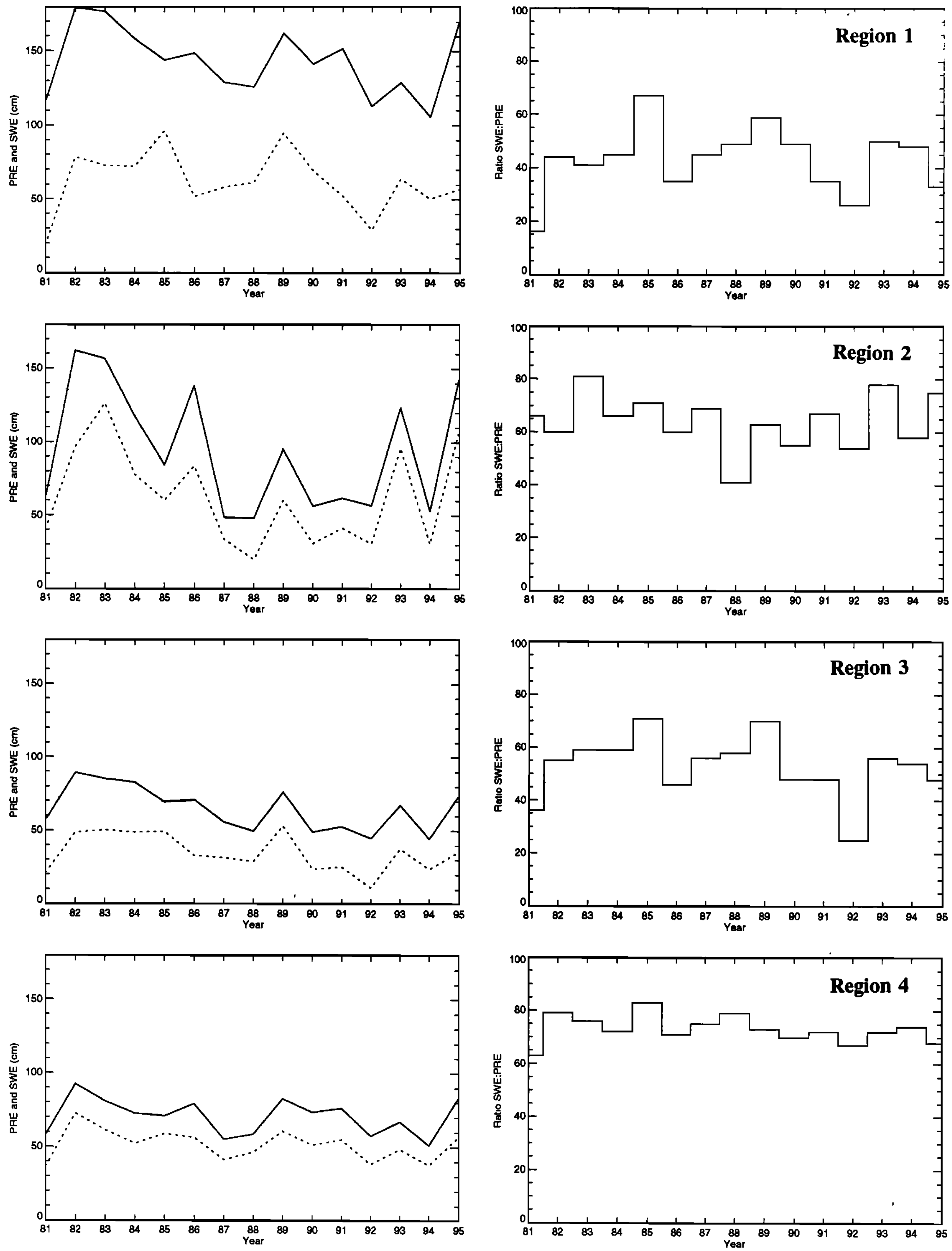


Figure 5. Monthly time series (1981–1995) of April 1 snow water equivalent (in centimeters, dotted lines), April 1 precipitation (in centimeters, solid lines), and the October 1 to April 1 ratio of snow water equivalent to precipitation (at right) for the eight regions shown in Figure 1.

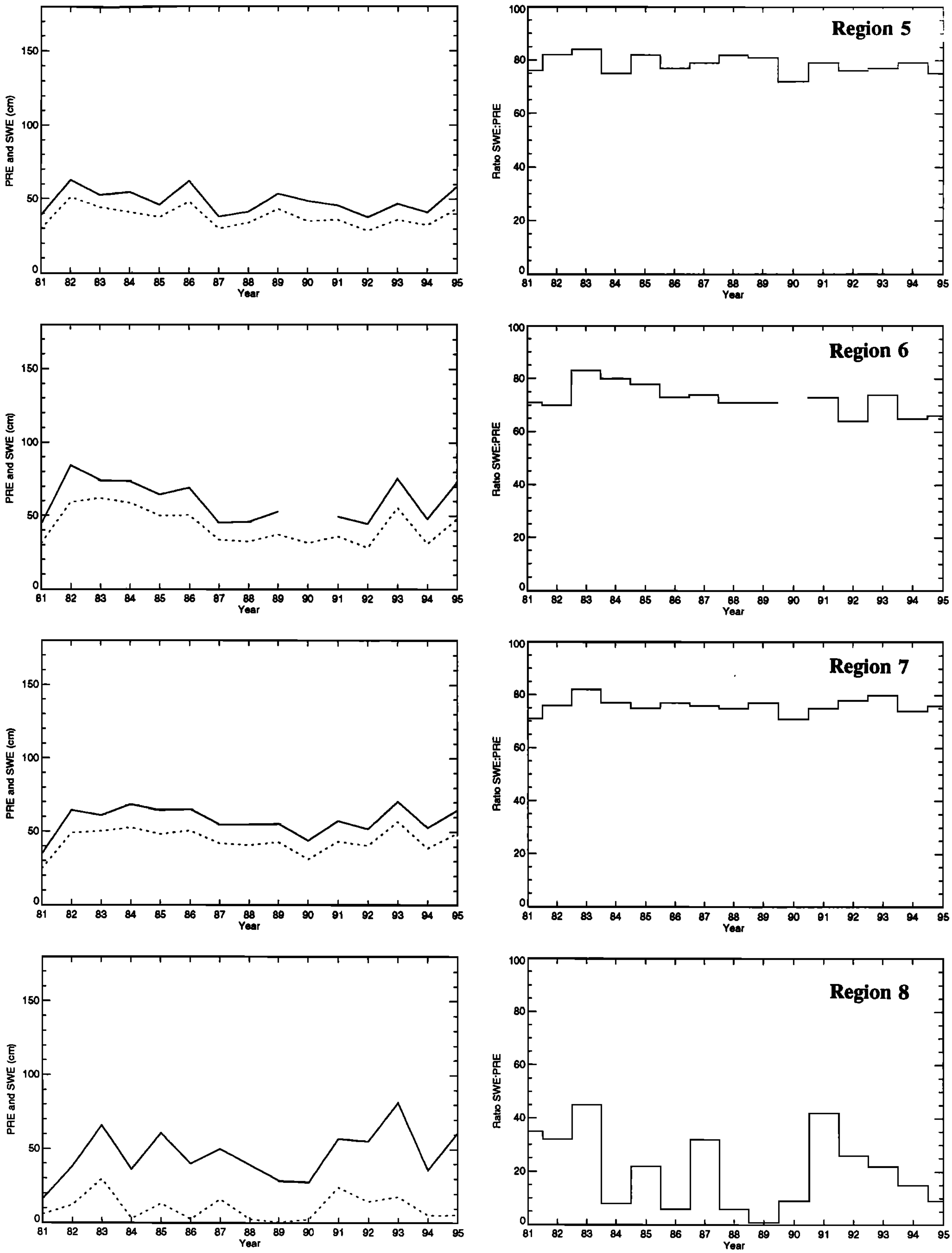


Figure 5. (continued)

Table 7. Summary Statistics of SWE, PRE, and the SWE/PRE Ratio

	Region							
	1	2	3	4	5	6	7	8
Correlation								
SWE versus PRE	0.60*	0.97*	0.88*	0.94*	0.97*	0.96*	0.99*	0.70*
SWE versus ratio	0.89*	0.70*	0.82*	0.49*	0.31	0.64*	0.77*	0.86*
PRE versus ratio	0.18	0.52*	0.47*	0.17	0.07	0.40	0.67*	0.32
Coefficient of Deviation								
SWE	0.34	0.54	0.37	0.20	0.18	0.28	0.19	0.85
PRE	0.16	0.45	0.23	0.17	0.17	0.24	0.17	0.38
Ratio	0.29	0.16	0.22	0.07	0.04	0.08	0.04	0.68

*These correlations are statistically significant to at least the 95% confidence level.

corded at SNOTEL sites starting in the early 1980s; temperature was also recorded since the late 1980s. Data were subjected to quality control procedures based on identification of obvious outliers and limits checks based on means and standard deviations for each station. The SWE and PRE records are quite clean, while about 7–8% of temperature data were flagged as erroneous. SWE for April 1 at the SNOTEL stations set compares favorably with SWE at colocated snow course sites.

As expected, maximum seasonal SWE is found for the Pacific Northwest, Sierra Nevada, and Idaho/western Montana regions, with the lowest values found for the Arizona/New Mexico region. This regional variability is explained in terms of the seasonal cycles in winter-half precipitation, temperature, and the SWE/PRE ratios. The estimated percentage of annual precipitation represented by snowfall is highest for the Sierra Nevada region (67%) followed closely by the northwestern Wyoming (64%), Colorado (63%), and Idaho/western Montana (62%) sectors, because of both high SWE/PRE ratios and the tendency for most precipitation to fall during October–March. The percentage is lower for the warm and low-elevation Pacific Northwest (50%) and is lowest for Arizona/New Mexico (39%), where peak seasonal SWE is small and a large fraction of precipitation falls during summer in association with the southwestern monsoon.

Interannual variability in SWE is examined in terms of PRE and the SWE/PRE ratio. In the Pacific Northwest and Arizona/New Mexico the stronger control is exerted by the SWE/PRE ratio (primarily a function of temperature), whereas in the remaining colder regions, available precipitation is the more important factor. For the Blue Mountains, Oregon, the Sierra Nevada, and Colorado sectors, there is a tendency for years of high (low) precipitation to be associated with low (high) temperatures, which reinforces the impact of precipitation in contributing to interannual variability in SWE.

Our results suggest regional differences in sensitivity to climate change. Recall from Figure 5 and Table 7 that SWE and the SWE/PRE ratio are much more variable in the Pacific Northwest, the Sierra Nevada, the Blue Mountains, and Arizona/New Mexico than in colder continental regions. Since temperature variability has such a large impact on SWE in these regions, they are likely to be most susceptible to climate warming. Increases in temperature are likely not only to decrease the length of the snow season and advance the timing of runoff but also may increase the rainfall flood hazard. For example, *Cline* [1997] points out that even rapid snow melting provides a water yield that is less than a moderate rainfall event, and *Pitlick* [1994] shows the variability in floods to be much higher for rainfall-dominated basins. Climate change research should focus on regions along the Pacific Coast and Arizona/New Mexico where the snowpack is sensitive to temperature fluctuations. Further research using SNOTEL and other data is underway by our group examining the climatic controls on the western United States snowpack and potential responses of the seasonal snowpack to climate change.

Appendix: Quality Control

It was occasionally found that missing values were inserted into the station records early in the measurement season, apparently because of delays in servicing the site. To avoid undue biases in the cumulative SWE and PRE records, we first inspected the first 15 days in October for the presence of inserted missing values. If values were inserted, the PRE and SWE records for that station were coded as missing for the entire year. Several cases arose where the precipitation gauge was not reset to zero on October 1. This problem was addressed by checking whether the October 1 PRE was >5 inches. If so, all PRE values for that station and year were coded as missing. Following the above checks, all negative SWE and PRE values (of which nearly all cases occurred during summer) were simply coded as missing.

Some erroneous precipitation values could be adjusted. PRE on day N was compared to that on the previous day ($N - 1$) and subsequent day ($N + 1$). Occasionally, it was found that while the totals on day $N - 1$ and $N + 1$ were the same, the day N total was higher or lower. If so, the total on day N was set to that for day $N - 1$. Situations also arose when the difference in PRE between day $N + 1$ and $N - 1$ was positive, but PRE on day N was either less than that on day $N - 1$ or greater than that on day $N + 1$. If the positive difference between day $N + 1$ and $N - 1$ was less than 0.5 inches, the day N precipitation value was set to the average of the $N + 1$ and $N - 1$ values.

The PRE and SWE values (including those adjusted as above) were then used to create daily increment (event) values (SWE1 and PRE1), based on the difference in cumulative values between day N and $N - 1$, provided that data for both days were available. Otherwise, PRE1 and SWE1 were coded as missing. To flag gross errors, SWE1 values with an absolute value greater than 10 inches were flagged. A second check flagged questionable situations in which a large snow accumulation event (SWE1 >2.5 inches) was followed on the next day by a large loss event (SWE1 <−2.5 inches), or, conversely (and based on the 2.5 inch limit), a large loss event was followed on the next day by a large accumulation event. Positive PRE1 values over 10 inches were also flagged. Realizing that negative PRE1 values may arise because of instrument limitations, negative increments up to −0.5 inches were allowed to pass. Larger negative increments were flagged. Data were then converted into metric units.

If either the maximum, minimum, or mean temperature was >40°C or <−40°C, then all temperature values for that day were flagged (maximum, mean, and minimum temperature are measured from the same sensor). The temperature sensors occasionally repeat the same value for multiple days. These situations were flagged by inspecting changes in the mean, maximum, and minimum temperatures between day N and $N + 1$. If any values (maximum, mean, or minimum) were identical, all temperature records for those days were flagged. Temperature data are provided to the nearest tenth of a degree. While it is possible for consecutive days to have the exact same temperature, it was felt that the loss of a few good points was outweighed by the desire to flag errors.

The above procedures flagged less than 0.1% of the SWE and PRE values. However, a much higher percentage (7–8%) of the temperature data was flagged. Data not flagged or set to missing were used to compile long-term monthly means and standard deviations for each station based on positive and negative SWE1 values separately and nonzero PRE1 values as well as maximum, minimum, and mean temperature. To provide a sufficient number of cases, the statistics were based on overlapping 60-day periods straddling the midpoint of each month. For example, statistics for April are based on data from March 15 through May 15, and those for May are based on data from April 15 through June 15. To achieve reasonably normal distributions, a square root transformation was first applied to the positive and negative SWE1 values as well as the nonzero PRE1 values.

These means and standard deviations were used in a second round of quality control procedures. SWE1, PRE1, and temperature data not flagged from the above checks were inspected. If a positive SWE1 value was more than five standard deviations above or below the respective monthly mean, it was flagged. The same check was performed for negative SWE1 values. Erroneous PRE1 values were also flagged based on a five-standard-deviation check. The flagged values were then reinspected. If a positive SWE1 value more than five standard deviations out was paired with a positive PRE1 value more than five standard deviations out, it was assumed that as the values are independent of each other, they are both recording a valid extreme event and the flags for both variables were removed. Similarly, flags were removed if a positive SWE1 value was flagged from the five-standard-deviation check but PRE1 was more than three standard deviations out or if PRE1 was more than five standard deviations out and SWE1 was more than three standard deviations out. Note that such checks are not possible for negative SWE1 values. Temperature data were flagged using a tighter three-standard-deviation check. For some months and stations, there were not enough cases of positive or negative SWE1 values to compute means and standard deviations (we required a minimum of 30 cases for each variable). For these cases the quality control is based only on the initial limits checks described above.

The second set of checks discarded an additional 0.03% and 0.05% of all daily SWE and PRE values, respectively, and an additional 0.7% of temperature values. Although our checks are based on large standard deviations, we conclude that the SWE and PRE records are reasonably clean. As a final step, we inspected the daily records for each station and year and truncated the SWE time series at the first occurrence of a flagged value. PRE time series were also truncated at the first occurrence of a flagged value. This approach is justified since both records are cumulative; a single bad value may contaminate the remainder of the record. Less than 5% of the station records were truncated. The quality control procedures do not include any spatial (i.e., station to station) comparisons. Such procedures are arguably not appropriate in the western United States, where large variations in elevation and topography occur over relatively short distances. All results described in this study, which variously examine April 1 conditions and annual cycles based on daily data as well as monthly and seasonal means, are based on stations for which valid data are available for at least 5 years.

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R. L. Armstrong, M. P. Clark, and M. C. Serreze, Cooperative Institute for Research in Environmental Sciences, Campus Box 449, University of Colorado, Boulder, CO 80309-0449. (rlax@kryos.colorado.edu; clark@hoth.colorado.edu; serreze@kryos.colorado.edu)

D. A. McGinnis, Department of Geography, 316 Jessup Hall, University of Iowa, Iowa City, IA 52242-1316. (dmcginni@blue.weeg.uiowa.edu)

R. S. Pulwarty, Program of Regional Integrated Assessments, Office of Global Programs, National Oceanic and Atmospheric Administration, 1100 Wayne Avenue, Suite 1225, Silver Spring, MD 20910. (pulwarty@ogp.noaa.gov)

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