Satellite Passive Microwave Observations of the Upper Colorado River Snowpack

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Seasonal snow cover in the mountains of the Upper Colorado River Basin is a major source of water for a large portion of the southwestern United States. The extent and amount of this snowpack not only reflects changes in weather patterns and climate but also influences the general circulation through modification of the energy exchange between land and atmosphere. Traditional surface-based snowpack observations consist of point measurements at a relatively limited number of sites when compared to the extent and variability of the snowpack. These point measurements may not be representative of the water storage of the snowpack at the meso- and regional scales. Airborne measurements (Carroll 1992) use the attenuation of terrestrial gamma radiation by the snowpack to determine average snowpack water equivalent over flight lines as long as 8 kilometers. However, neither observational technique is capable of providing the synoptic observations over the large scales necessary to determine the role of seasonal snow cover in the general atmospheric circulation.

Satellite observations and remote sensing techniques can enhance the standard snowpack observations to provide the temporal and spatial measurements required for understanding the role of snow in the surface energy balance and improving the management of water resources. The most extensively used satellite observations are those in the visible and near infrared bands, and they are used only to determine snow extent. The NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC) uses the Advanced Very High Resolution Radiometer (AVHRR) data to map the snow extent in 4,000 basins in the United States and Canada, at a resolution of 1 kilometer (Carroll 1992). However, satellite observations in the visible and near infrared bands are limited by cloud cover and solar illumination and do not provide any information on the snowpack water equivalent. Rango (1993) reviews the use of remote sensing in studying snow hydrology processes.

The Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) provided passive microwave observations of this snowpack from 1979 through 1987. Gloersen *et al* (1984) give a complete description of the SMMR; its capabilities, frequencies, wavelengths and footprint sizes. The SMMR instrument makes observations in 10 channels, and Chang *et al* (1976) show that the 18- and 37-GHz frequencies are best suited for snowpack remote sensing. The sensor footprints for these channels are 50 km and 25 km, respectively. The Special Sensor Microwave Imager

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(SSM/I), which is part of the Defense Meteorological Satellite Program, provides continuing global passive microwave coverage from 1987 to present. When these latter data become readily available, the resulting continuous 15-year record will provide new insights on snowpack properties for the Upper Colorado River Basin and the entire globe.

Microwave radiation from a snowpack, as observed by a satellite sensor, consists of the emission by the snow and the emission from the underlying ground, with a small atmospheric effect. Chang *et al* (1976) and Stiles and Ulaby (1980a,b) describe the scattering process and have determined the dependence of the brightness temperature of various frequencies on snowpack water equivalent and grain size. The microwave emission of a snowpack provides information on the water equivalent and other internal snowpack properties because the emitted radiation results from the combination of the substrate emission, as attenuated by the snow, and that emitted by the snowpack itself. The result is a microwave emitter with an emissivity of less than one, and the reduction of emitted radiation is a measure of the snowpack mass or water equivalent.

Chang *et al* (1976) show the dependence of the 37-GHz brightness temperature on both the snowpack water equivalent and the grain size, for grains up to 0.5 millimeter radius. Sensitivity to grain size is strong. For example, an increase in radius from 0.3 to 0.5 millimeter for a snowpack with a water equivalent of 0.5 meter, reduces the 37-GHz brightness temperature by about 50 Kelvin. These studies were carried out assuming snow grains were spherical and uniformly distributed within the snowpack, conditions seldom found in natural snowpacks. Hence, development of accurate algorithms to extract snowpack properties from satellite passive microwave observations requires knowledge of not only the water equivalent but also the internal snowpack structure, particularly the grain size distribution.

In addition to water equivalent, passive microwave observations can be used to determine other snowpack parameters of hydrologic importance. First, time series of differences between day and night observations indicate the presence of liquid water in the snowpack. Early in the season, the difference is small, indicating the absence of liquid water. As spring approaches the difference grows, indicating the daytime presence of liquid water that refreezes at night. When the liquid water does not refreeze at night, the difference becomes small and the "ripe" snowpack will start melting.

A second parameter is the snow extent. Passive microwave observations can augment observations in the visible and near infrared bands and are particularly useful during long periods of cloudiness. Josberger and Beauvillain (1989) developed a criteria for determining the snow extent of the Upper Colorado River Basin from passive microwave observations. Finally, Josberger *et al* (1993) found a strong relationship between the discharge of the Upper Colorado River and an index derived by spatially integrating the SMMR observations from the entire basin.

SMMR/SNOTEL Correlations

For this study, we mapped the 9 years of SMMR observations into ¼-degree latitude by ¼-degree longitude pixels for the region bounded by 36°N to 44°N and 105°W to 113°W, which contains the Upper Colorado River Basin. Figure 1 shows the study area and the mountains of the region as delineated by the 7,000-foot elevation contour. This mapping yielded a complete night map of the region every 6 days. The 6-day interval resulted from the SMMR swath width, orbital parameters and a 1-day-on/1-day-off duty cycle that was a consequence of power availability on the Nimbus-7 satellite. We also produced the corresponding day maps to investigate day/night differences.

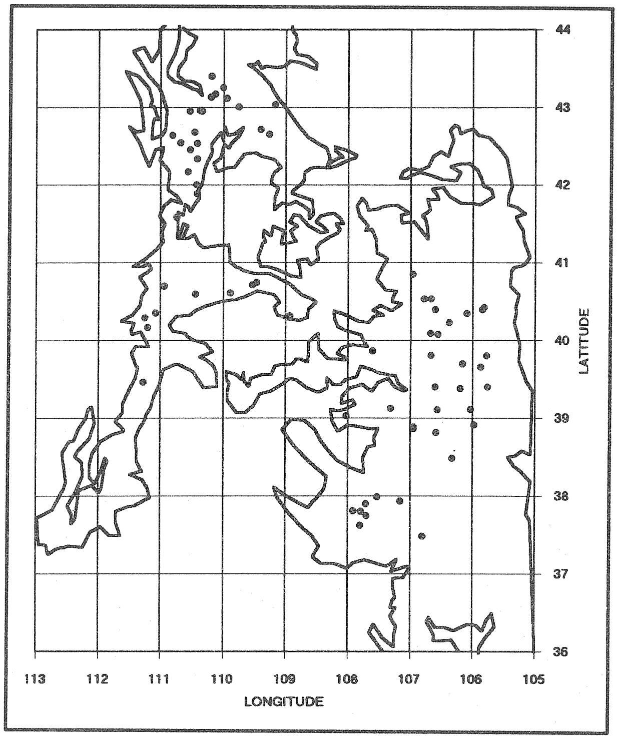

Figure 1. Location of Snow Pits within the SMMR Study Region and the 7,000-foot Contour Line

Despite the complex snowpack structure and snowpack variations within the mesoscale footprint, the satellite observations show strong correlation with point snow observations by the USDA Soil Conservation Service SNOTEL program (snow telemetry). The SNOTEL observations consist of daily observations of water equivalent made by a snow pillow as well as minimum and maximum temperatures. Figure 1 shows the location of all the SNOTELs used in this study, and Table 1 gives the number of SNOTELs in 1979 to 1987, for each of the three mountainous areas, called Colorado, Wyoming, and Utah. For the satellite observations, we defined a parameter called the negative gradient ratio (NGR), which is –1,000 times the difference between the 37- and 18-GHz vertically-polarized channels divided by the sum of the two channels. Taking the difference removes, to first order, surface temperature effects. This variable is a non-dimensional positive integer quantity.

Table 1
NUMBER OF SNOTEL SITES IN EACH REGION

Year	Colorado	Utah	Wyoming	Year	Colorado	Utah	Wyoming
1979	11	8	3	1984	34	20	8
1980	14	8	3	1985	35	22	8
1981	30	15	3	1986	42	26	15
1982	32	19	3	1987	39	26	16
1983	25	18	3				

We obtained the average correlation for each of the nine years from the individual correlations that result from comparing the NGR values from a pixel to the SNOTEL observations in the pixel. The time series is generated by calculating the correlation with the first 60 days of the water year (about 10 pairs of data points), and then adding a new observation every 6 days and recalculating the correlation. Figure 2 shows the time series of average correlation between the NGR and the SNOTEL water equivalent observations for the three regions. Because 1979, 1981, and 1986 exhibit special characteristics (described later), these three years are denoted by separate symbols. The other six years show similar behavior and are all plotted with the same symbol.

The general behavior of the time series is the same for all regions. Initially, the correlations range from 0.3 to 0.8 and then rise to a broad plateau that typically begins near water-year day (WYD) 100 (January 8). The increase in correlation results from the snowpack completely covering the pixel. Maximum correlations are as high as 0.95. The correlations decrease around WYD 175 (March 26), as the snowpack warms and begins to melt but the liquid water does not refreeze at night. For clarity, the standard deviations for each correlation point are not shown, but they are typically less than 0.1. These standard deviations decrease as the water year progresses and then increase when the correlations drop.

The Wyoming region initially has the highest correlations and also shows the greatest correlations with the least amount of spread. The Utah and Colorado regions each begin with lower correlations that increase as the water year increases, but these regions never attain the correlations found in the Wyoming region. This behavior may result from several reasons. The Wyoming SNOTELs may be more representative of snow conditions in their respective pixels. The snowpack may have more consistent grain size and structure from year to year. The temperatures in the Wyoming region may be colder which would result in drier snow over the entire elevation range, from valleys to mountain tops. Finally, as Table 1 shows, there are fewer SNOTELs in Wyoming which would tend to make correlation coefficients higher.

The interesting behavior in 1979, 1981, and 1986, is worth a few comments. For 1979, the satellite began acquiring data on WYD 82, hence the data set is much shorter than that from the other years. As a result, these correlations represent the lower bound of almost all the correlations for all years; however, they still attained values of 0.75. The very low-snow year, 1981, had the greatest effect on correlations from the Utah region. These are the lowest correlations found for any of the regions, ranging between 0.5 and 0.7. Correlations from the Colorado and Wyoming regions for this year show no abnormal behavior, and it is not obvious why the Utah region should exhibit such behavior. Finally, as shown by Josberger *et al* (1990), a strong basin-wide warming in 1986 produced a sudden drop in correlation at about WYD 150, much earlier than normal, which can be as late as WYD 200.

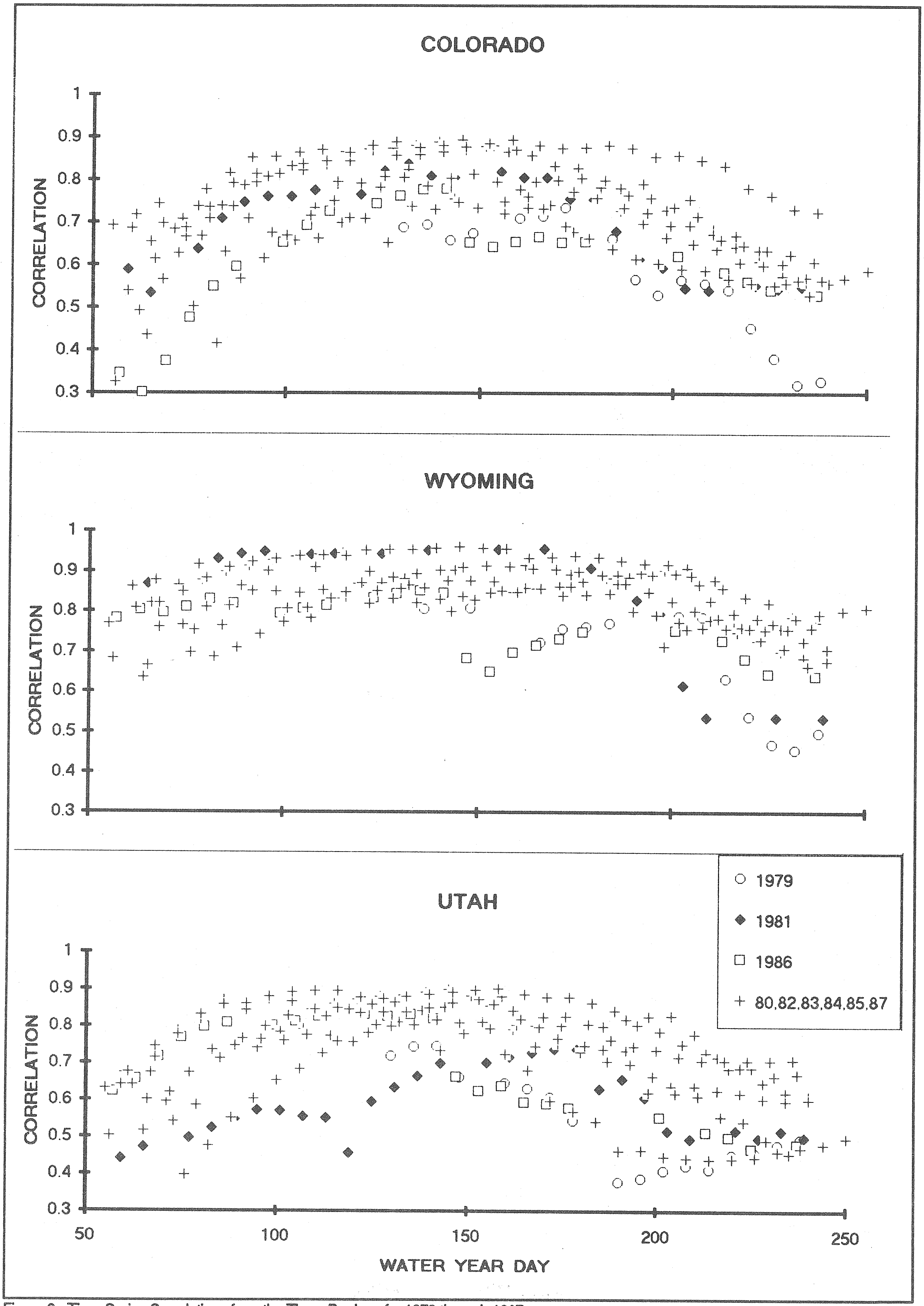

Figure 2. Time Series Correlations from the Three Regions for 1979 through 1987

Effects of Snowpack Grain Size

The interannual variations in these correlations result primarily from differences in water equivalent and in the grain size of the snowpacks. Because systematic observations of snowpack grain size, density, and structure were not available, we began a sampling program in 1984 to obtain these data from representative sites within the entire Upper Colorado River Basin. At about the time of maximum snowpack at the end of March, field teams visited as many as 30 SNOTEL sites, dug a snow pit, and measured vertical profiles of grain size, density, temperature, and stratigraphy. This field program has continued since 1984 and has collected a unique dataset of snowpack properties specifically for passive microwave studies.

Table 2 gives the vertically-averaged grain size of the snow pit observations from each region for 1984 through 1987, which are the years when the SMMR instrument operated and for which we have grain size measurements. The table also gives the average water equivalent from all of the SNOTELs in each region at the time of maximum water equivalent.

Table 2
AVERAGE SNOW WATER EQUIVALENT FROM SNOTEL SITES,
THE GRAIN SIZE FROM SNOW PITS, AND MAXIMUM NGR FROM SMMR
IN THE WYOMING REGION AND THE COLORADO AND UTAH REGION, 1984 THROUGH 1987

	Wyoming			Colorado and Utah		
Year	SWE (mm)	Grain Size (mm)	NGR	SWE (mm)	Grain Size (mm)	NGR
1984	428	2.10	82	413	1.00	48
1985	290	1.50	64	351	1.50	31
1986	347	1.40	85	330	1.20	22
1987	235	2.70	30	208	1.50	17

A multiple regression analysis of the average grain sizes, the water equivalent, and the satellite observations gives:

$$NGR = 0.153\ SWE + 3.31\ Grainsize - 6.87 \qquad R = 0.76,$$

where both water equivalent and grain size are measured in millimeters. The fact that the grain size coefficient is 20 times larger than the water equivalent coefficient clearly shows the strong dependence of NGR on the snowpack grain size.

The snowpack in the Upper Colorado River Basin is a continental type that consists of a bottom layer of large depth hoar crystals (up to 5 mm) and an upper layer of fine- to medium-grained new and old snow with grain sizes up to 2 millimeters. Variations in the depth hoar layer strongly affect the averages in Table 2 and, hence, the satellite signatures. Characteristics of the depth hoar layer are determined early in the accumulation season, which allows us to compare the average grain size measurements with the water equivalent values even though these data are usually from different times of the snow year.

Conclusions

The 9-year SMMR passive microwave record of the Upper Colorado River Basin shows strong correlations with the snowpack water equivalent as measured by the SNOTEL system. These correlations can reach values of 0.9 or greater and, hence, provide synoptic large-scale observations of this important snowpack. The utility of these observations for global change and water resource investigations will greatly increase when the datasets become longer and when more accurate algorithms are developed for mountainous snowpacks through improved spatial resolution and a greater understanding of snow deposition in mountainous terrain. The Special Sensor Microwave Imager (SSM/I) observations, when available, will yield a 15-year dataset that continues to grow.

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