Winter Climate Variability and Snowpack in the West

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Introduction

Snowpack is an important source of water supply in the western United States. This study examines the seasonal variability of an extensive history of snow observations over the western United States and Canada. It links variations in snowpack to variations in atmospheric circulation, surface temperature, and precipitation.

The purpose of this study is to determine how snow variations are related to atmospheric circulation, temperature and precipitation, and snowpack over the West. To accomplish this, we derive four categories of snow and precipitation anomalies at a particular snowcourse and examine whether these are accompanied by distinct anomaly patterns in the other variables. Specifically, this investigation seeks to establish:

- Whether the seasonal fluctuations of snowcourse variability are related to atmospheric circulation and, if so, what are the flow patterns associated with different seasonal snow characteristics.
- Whether temperature variability represented by the divisional temperature set is associated with differences in snow.
- Whether these fluctuations have regional-scale spatial coherence.

Data

For several decades, the USDA Soil Conservation Service (SCS) has archived snow observations at several hundred mountain snowcourses in the western United States. This study employs a set of about 400 snow water-content (WC) records for 1950-1989. Many snowcourses have observations taken at the beginning and sometimes the middle of each of the substantial snow-covered months, from January through May. For this study, we use only those taken on or about February 1 and April 1. The SCS snowcourse dataset does not include several snowcourse records on the west side of the Sierra Nevada in California, which are archived by the California Department of Water Resources. These records are on hand, but have not yet been merged with the SCS set and are not included in the analyses shown here. To limit the material presented in this article, we focus on variations associated with variations of snowpack

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In K.T. Redmond, Editor, 1992. Proceedings of the Eighth Annual Pacific Climate (PACLIM) Workshop, March 10-13, 1991: California Department of Water Resources, Interagency Ecological Studies Program Technical Report 31.

at Carson Pass at 2621 meters, near the crest of the central Sierra Nevada. Atmospheric circulation is represented by monthly average northern hemisphere 700-mb height.* Monthly "divisional" temperature and precipitation from the National Climatic Data Center are used to represent variability over the coterminous United States and Alaska, augmented by a collection of well-sampled stations from western Canada. The 700-mb height, temperature, and precipitation all cover the 1950-1989 period.

Water Content Variability

The climatology of WC at Carson Pass and precipitation at a nearby station, Twin Lakes, is indicated by means, standard deviations, and extremes of monthly WC and monthly total precipitation in Figure 1. WC statistics are limited to the five months from January through May. In comparison to the winter (about January 1) maximum in precipitation, the WC maximum appears at the beginning of April. This lag, of course, occurs because WC is a cumulative measure of the precipitation. WC variability is relatively uniform throughout the five months, although the maximum WC has occurred in March, followed closely by April and May. The history of seasonal WC at Carson Pass since 1930 is plotted in Figure 2. This record exhibits extremely low WC in the springs of 1931, 1939, 1951, 1976, 1977, 1988, and 1990, in contrast to very high WC in 1952, 1958, 1967, 1969, 1982, and 1983. For the April 1 subset, WC fluctuations vary from about 23% to 188% of the long-term average.

Snow/Precipitation Categories

The WC at Carson Pass and precipitation in the closest climate division (Sacramento drainage) are used to partition the 40-year record into four equal parts depending on whether the November-January precipitation was wet or dry and whether the ratio of February 1 snow to November, December, and January precipitation (denoted WC/PPT) was high or low. The order of this sorting operation was first to divide the years into wet and dry halves, and then to divide each of these into high and low WC/PPT classes of 10 members each. Thus a given year was classified as dry high (DH), dry low (DL), wet high (WH), or wet low (WL).

Snow Water Content *vs.* Large-Scale Climate Variables

To study climate variability associated with these categories at Carson Pass, we constructed composites of four variables by averaging the 10 years entering each. These variables, all expressed as anomalies, included the November-January mean 700-mb height, the November-January mean surface temperature and accumulated precipitation over

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* The height of the 700-mb pressure surface is typically about 3 kilometers aloft and provides a good representation of the mid-tropospheric circulation.

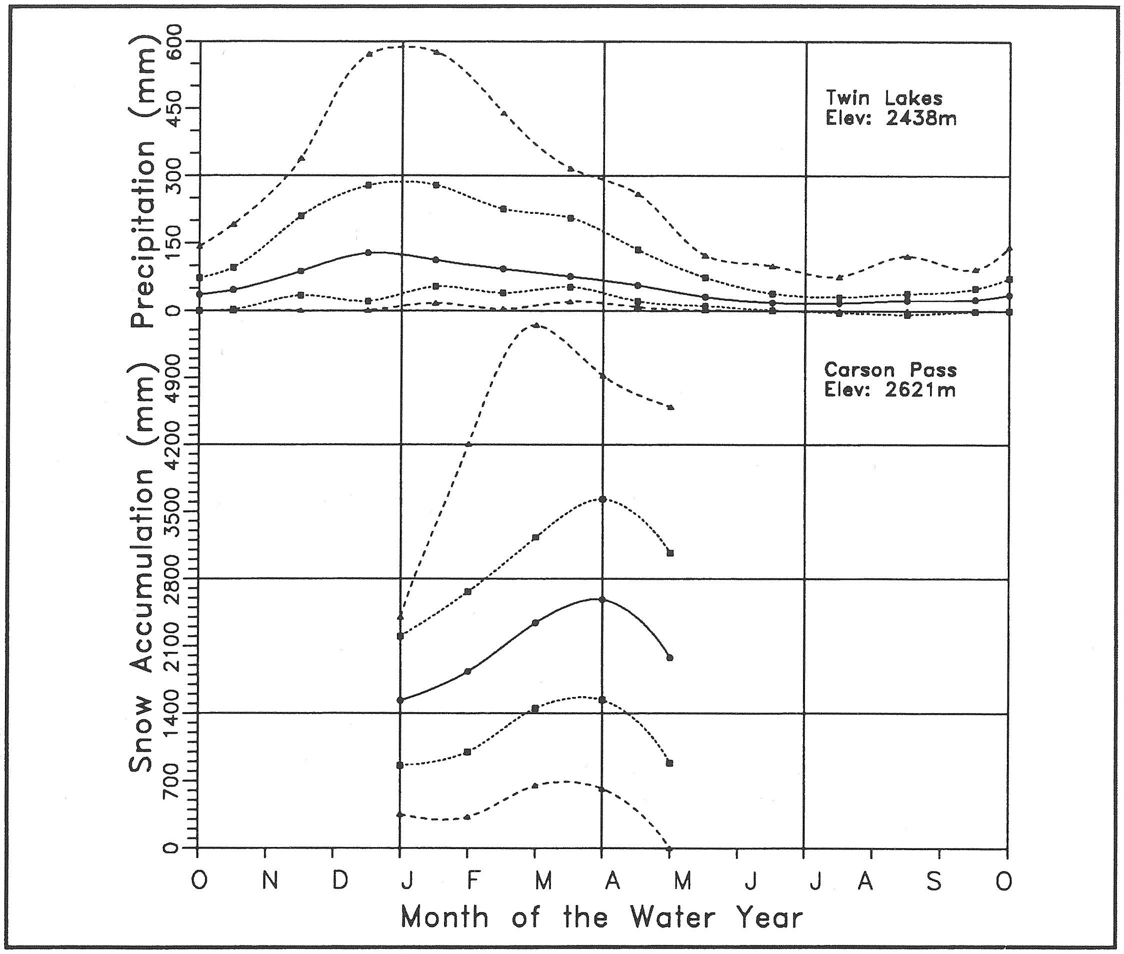

Figure 1. Climatological statistics of Carson Pass snowcourse water content and precipitation at nearby station, Twin Lakes, based on 1950-1988 data. Solid center curve is long-term mean. Upper/lower solid curves are long-term mean +/– one standard deviation. Upper/lower dashed curves are maximum and minimum values within record. Curves are smoothed fits to one value per month (January 1, February 1 ... May 1 for water content; monthly long-term mean for precipitation).

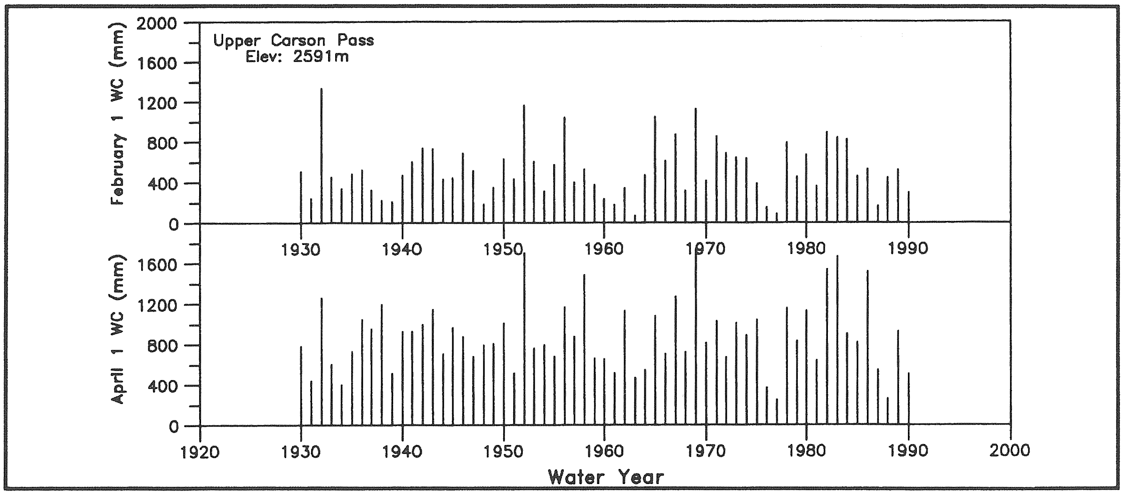

Figure 2. Time history of Carson Pass water content, February 1 (above) and April 1 (below).

the United States and Canada, and the snow water content at snowcourses over the West.

To determine whether the WC records contain a climate signal, we first examine the relationship between the four WC/PPT classes and atmospheric circulation. Composite maps of the 700-mb height anomalies for DH, DL, WH, and WL are shown in Figure 3. The 700-mb patterns have relatively large magnitudes and are distinctly different for the four classes. These patterns are organized with large regional scales over a major portion of the Pacific and North American sector. Furthermore, the physical interpretation of these patterns is consistent with the WC/PPT classes. As expected, positive anomalies over the West Coast dominate the two dry maps (DH and DL), while negative anomalies just offshore characterize the two wet maps. However, there are significant differences between the DH and DL maps. The positive anomaly center is offshore in DH, which permits a northerly flow of cold continental air in California. The positive anomaly in DL is centered directly over the West Coast, preventing the incursion of cold air into the region and keeping the weather dry. Also, the DL positive center extends northward across the North Pole, implying anomalous warmth far to the north. Considering the WH and WL maps, there are important differences in orientation of the negative anomaly features. Those in WH have a more northwesterly axis, implying a cool Gulf of Alaska origin of the winter storms. On the other hand, those in WL have a west-to-east configuration, with high pressure positive anomalies to the north, over the Bering Sea. This implies a lower latitude, warmer storm pattern in WL than in WH.

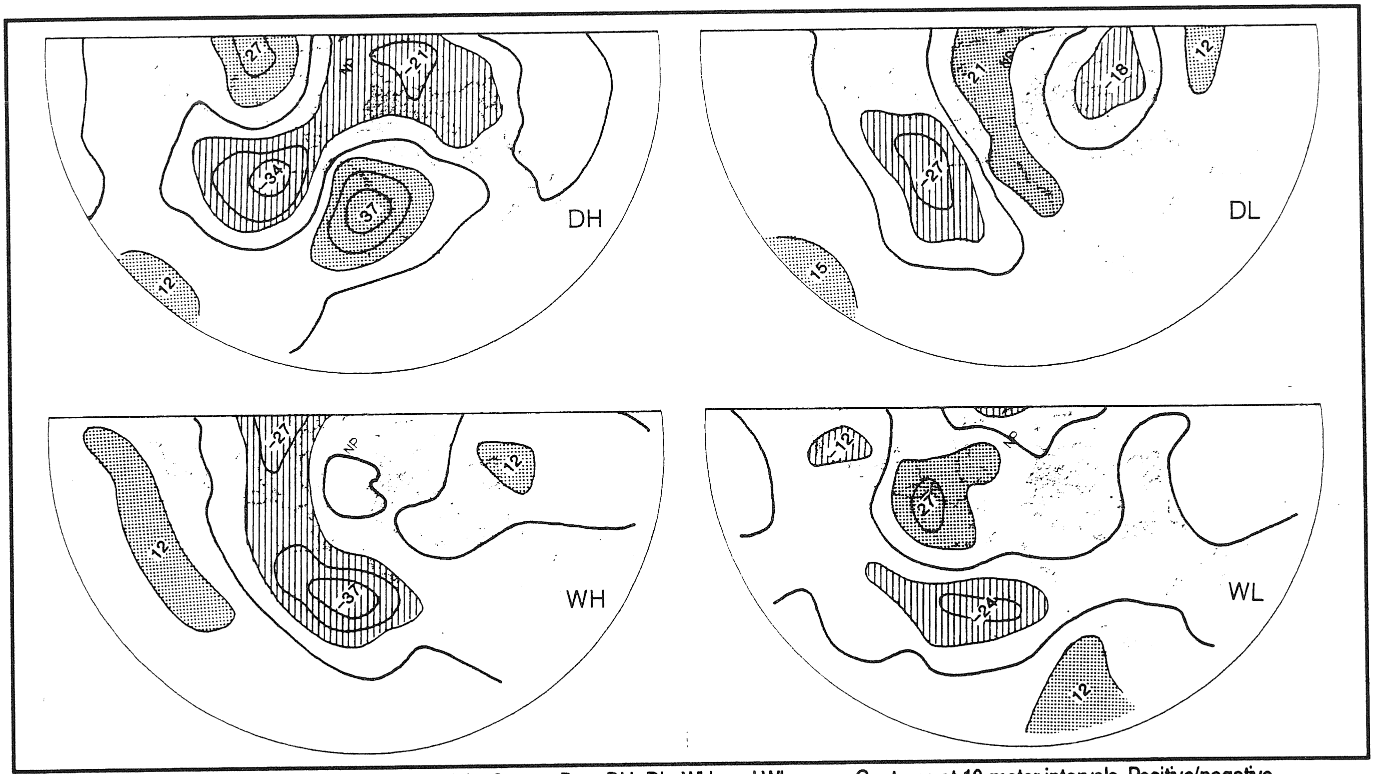

Figure 3. Composite 700-mb height anomalies (m) for Carson Pass DH, DL, WH, and WL cases. Contours at 10-meter intervals. Positive/negative anomalies denoted by stippling/hatching.

The air mass/temperature implications of the four circulation patterns are borne out by the surface temperature anomaly maps in Figure 4. Both of the high ratio classes have negative temperature anomalies in California, although the composite anomaly is not large in the WH case. Both DH and WH have larger negative anomalies elsewhere in the West, and both have positive anomalies downstream. Both of the low ratio classes have positive temperature anomalies in California, although the composite anomaly is not large in the DL case. However, consistent with the strong western high pressure ridge exhibited by the DH 700 mb height, it has an extensive positive anomaly covering virtually the entire West, with strongest magnitudes over western Canada and southern Alaska.

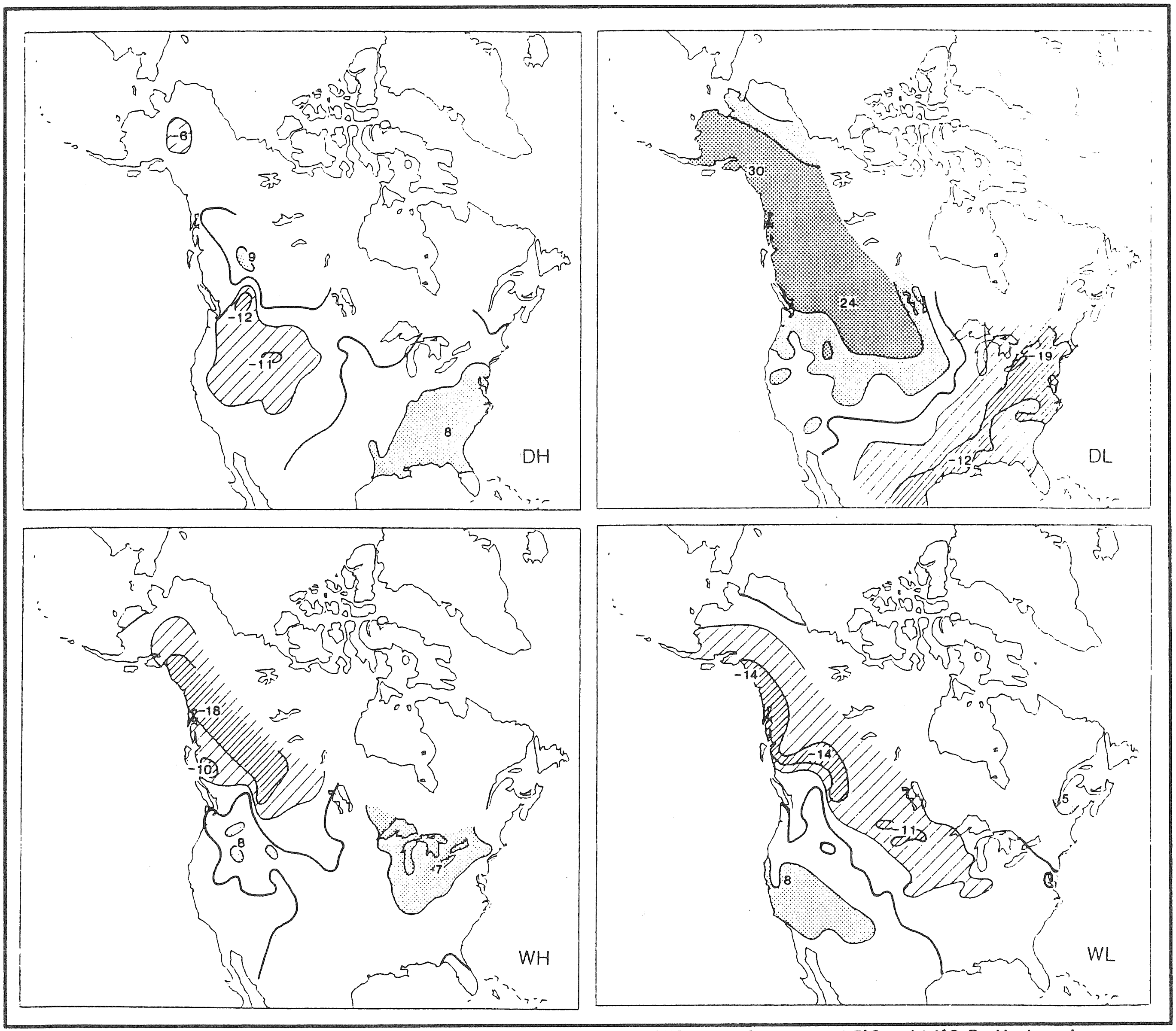

Figure 4. Composite temperature anomalies (0.1°C) for Carson Pass DH, DL, WH, and WL cases. Contours at 0.5°C and 1.0°C. Positive/negative anomalies denoted by stippling/hatching.

The composite precipitation maps, shown in Figure 5, illustrate the distribution of precipitation over the United States that characterizes the four classes. Of course, both DH and DL have negative precipitation anomalies in California, while WH and WL have positive anomalies. Consistent with the circulation and temperature composites, the differences among the two dry and the two wet cases are very marked, however. The driest case over the continent is DL, where both the West Coast and the eastern half of the United States have negative anomalies. Clearly, the North Pacific storm track has been diverted north in this case, as British Columbia and coastal Alaska have positive precipitation anomalies.

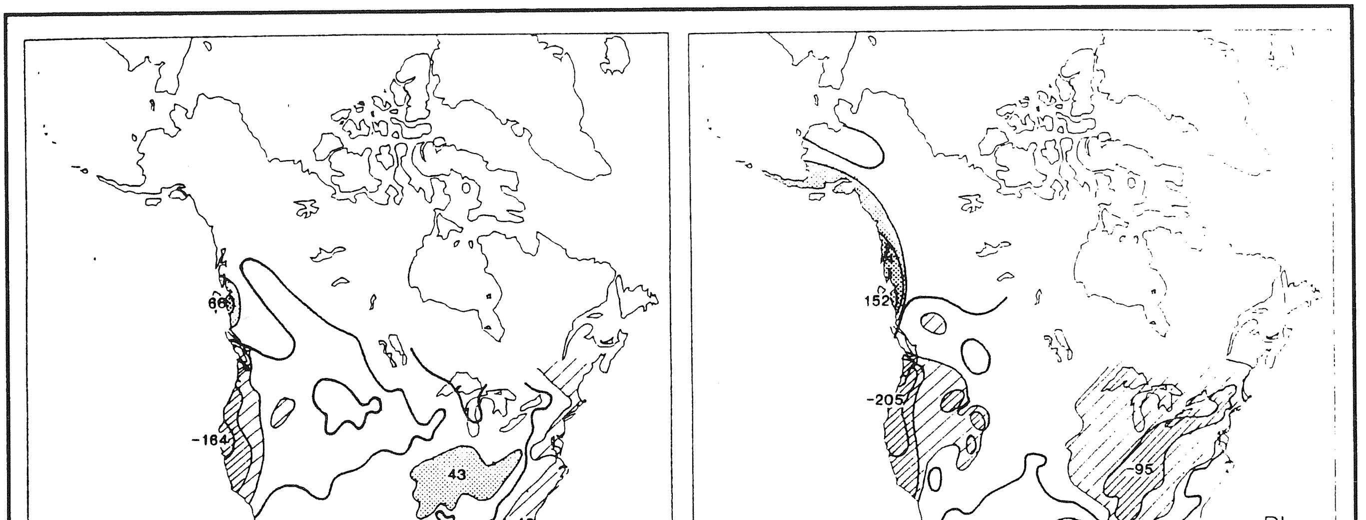

Figure 5. Composite precipitation anomalies (mm) for Carson Pass DH, DL, WH, and WL cases. Contours at 20, 50, and 100 mm. Positive/negative anomalies denoted by stippling/hatching.

Since the composites were based on the WC/PPT ratio and not the WC itself, it is important to note that the two wet classes exhibited positive WC regional anomalies while the two dry classes exhibited negative WC regional anomalies (Figure 6). Even though the classes were based on local WC/PPT behavior, large-scale patterns emerge. In fact, the four composites of snowcourse WC exhibit spatial coherence on a scale of several hundred kilometers that span major portions of the western states. (Part of the reason the WC maps look "spotty" is that the low-lying areas of the west do not generally have snowcourses and the amount of WC [mean and variance] is affected by the elevation of the snowcourse.) This spatial coherence is particularly evident in the WH, and especially

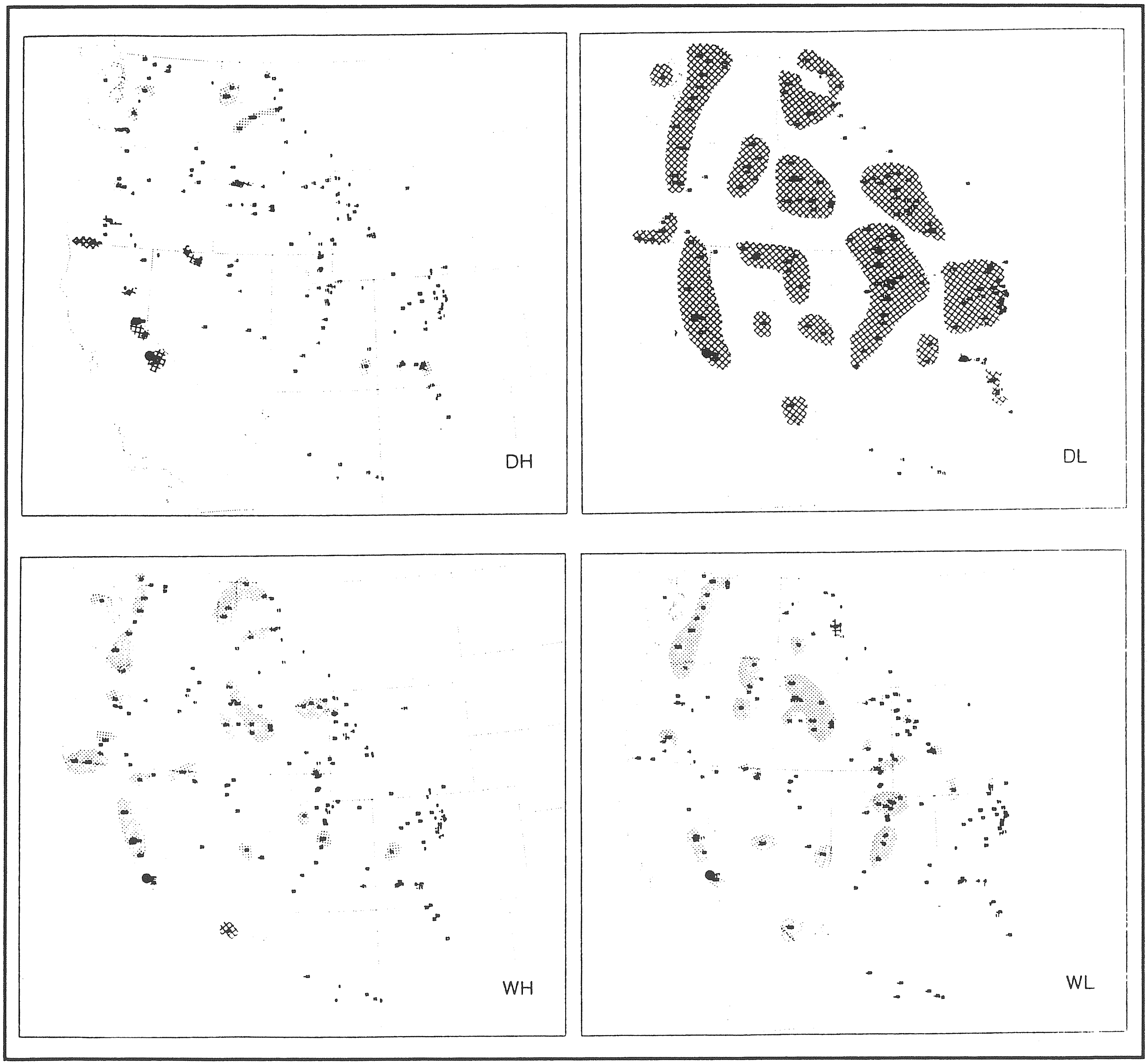

Figure 6. Composite February 1 snowcourse water content anomalies (mm) for Carson Pass DH, DL, WH, and WL cases. Shading for anomaly magnitudes equal or greater than 50 mm. Positive/negative anomalies denoted by stippling/hatching.

the DL patterns where the positive and negative WC anomalies cover virtually the entire western states. On the other hand, the DH pattern exhibited a tendency for a teleconnection — negative WC anomalies in the Sierra, parts of Nevada, and southern Oregon are accompanied by positive WC anomalies through the northwest. The scale of these features is consistent with the large-scale anomalies exhibited by atmospheric circulation (Figure 3) and by the associated regional-scale anomaly patterns in temperature and precipitation (Figures 4 and 5). The major WC anomalies in Figure 6 exceed 50 mm and often exceed 100 mm; tests of statistical significance using a two-tailed *t*-test (not shown) indicate many of these composite anomalies are significantly different from zero at the 95% confidence level.

Table 1

Autocorrelation of Snowcourse Water Content at Upper Carson Pass

	Jan	Feb	Mar	Apr	May
Jan	(19) 1.00	(19) 0.89	(19) 0.64	(19) 0.68	(19) 0.69
Feb		(59) 1.00	(59) 0.83	(59) 0.70	(59) 0.68
Mar			(59) 1.00	(59) 0.87	(59) 0.76
Apr				(59) 1.00	(59) 0.90

Numbers in parentheses are number of pairs of data entering correlation.

The overall persistence of WC at Carson Pass is indicated by the lagged correlations linking the January-May records in Table 1. One-month lag correlations are high, exceeding 0.8. Even at 4 months, the lag correlation from January to May is still 0.68.* The strongest persistence of regional scale WC anomalies is exhibited by the WH, and especially the DL cases, as indicated by the April 1 composites in Figure 7. Recall that the April 1 composites were based on winter PPT and February 1 WC; that is, they are a view of the WC behavior shown in Figure 6 as it progressed into spring two months later. The DL case, which is warm and dry over most of the West, has serious implications as it persists strongly into spring with a water supply deficit, as shown by the negative WC anomalies.

Conclusions

Several decades of seasonal snowcourse measurements in the western United States exhibit realistic climate variability. The snowcourse WC fluctuations are well related to interannual variations in atmospheric circulation, surface temperature, and precipitation. Variations of WC are not locally confined, but exhibit substantial coherence with snowcourses

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* Note that although there are relatively few data pairs (19) entering the January-May correlation, the February-May correlation is nearly the same and consists of many more data pairs (59).

elsewhere in the West, in accord with the regional-scale (or larger) variability of the atmospheric circulation, temperature, and precipitation. While this study focused on only one such snowcourse, Carson Pass in the California Sierra Nevada, these conclusions are anchored by similar behavior of WC at other selected snowcourses from other western states.

Concerning the water supply, there is significant persistence of WC from February 1 to April 1. This emphasizes the importance of winter climate variability in determining the water supply.

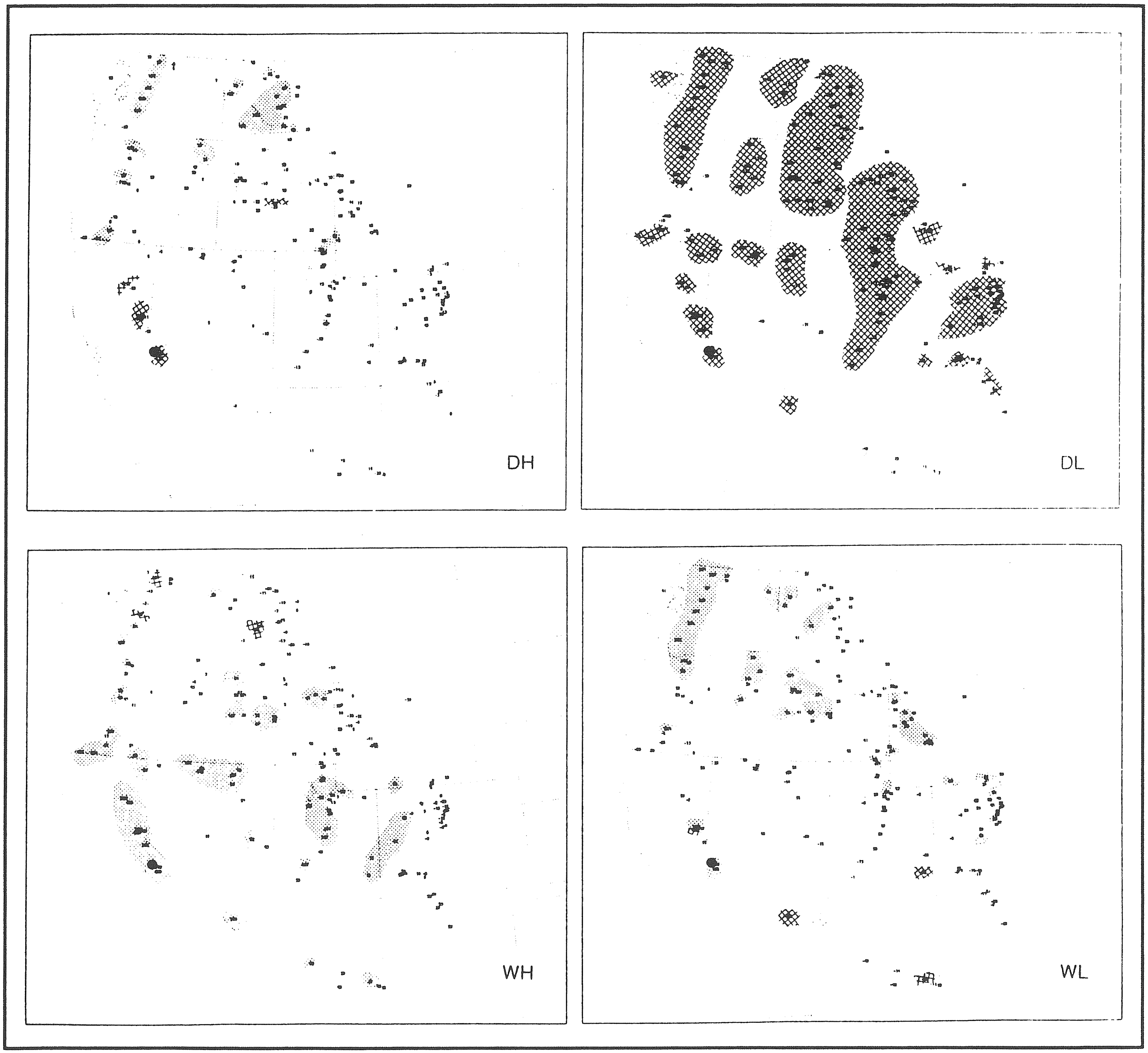

Figure 7. Composite April 1 snowcourse water content anomalies (mm) for Carson Pass DH, DL, WH, and WL cases. Shading for anomaly magnitudes equal or greater than 50 mm. Positive/negative anomalies denoted by stippling/hatching.

Acknowledgments

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