5.1 VARIABILITY AND TRENDS IN MOUNTAIN SNOWPACK IN WESTERN NORTH AMERICA

Philip W. Mote[1], Martyn Clark, and Alan F. Hamlet

1. INTRODUCTION

In western North America, most of the annual precipitation falls during the cool half of the year and is stored as snowpack in the mountains. Springtime warming melts this snow starting at low elevations, and the melt continues through the summer at some of the coldest locations. Such meltwater provides the majority of water resources during the region's dry summers, watering millions of acres of farmland and providing other economic, environmental, and recreational benefits. Snow is thus a key aspect of the region's economy.

Evidence is mounting that winter and spring temperature have increased in western North America. Such evidence includes direct meteorological observations (Folland et al., 2001), declines in snow cover (Groisman et al., 1994), earlier spring melt peak in most streams (Cayan et al. 2001) and earlier occurrence of key phonological indicators in several species (Cayan et al. 2001). Recently, a study of springtime mountain snowpack in the Pacific Northwest (Mote, 2003) showed widespread declines in snowpack since 1950 at most locations with largest declines at lower elevations indicating temperature effects.

This study expands the geographic scope of the earlier study to encompass all snow courses in the western U.S. and British Columbia.

2. DATA

Snow water equivalent (SWE) has been measured manually since the early 20th century, and at many sites sufficiently long records exist to examine variations and trends over 50 years. In some cases manual snow courses have been supplemented and then replaced by automated (SNOTEL) observations. The data used here were described by Clark et al. (2001) and Mote (2003). Data through 2002 were downloaded from the web site of the NRCS Water and Climate Center (www.wcc.nrcs.usda.gov/snow/snowhist.html) for the U.S., and from the web site of the Ministry of Sustainable Resource Management (srmwww.gov.bc.ca/aib/wat/rfc/archive/historic.html) for British Columbia. Each state or province had different priorities in measuring SWE, with different measurement frequencies (e.g., Arizona sites were almost always visited semi-monthly, while most others were visited monthly), spatial distribution (in many states the sites are well-distributed, whereas sites in California and Washington are clustered), and longevity. However, most snow course locations have data for March 1 and April 1, and the peak SWE occurs within 2 weeks of April 1 in most locations except in Arizona and New Mexico where it is substantially earlier (Serreze et al. 1999) and in BC where several sites reach a peak in May. A total of 597 snow records have April 1 records spanning the time period 1950-2000.

As in Mote (2003), the April 1 SWE measurements are compared statistically with climate observations at nearby stations for the months November through March, which roughly corresponds to the snow accumulation season for many sites. These climate observations are drawn from the US Historical Climate Network (USHCN; Karl et al. 1990) and from the Historical Canadian Climate Database (HCCD; Vincent and Gullett, 1999). These climate data are combined into reference time series as described by Mote (2003). There are a total of 394 stations with good precipitation data and 443 with good temperature data. The period of record used here is 1950-2000; the climate data for Canada mostly end in 2000, although the snow data extend to 2002.

3. RESULTS

Figure 1 shows relative trends in April 1 SWE with red circles indicating decreasing trends and blue circles showing increasing trends. At most snow course locations, trends have been negative. Exceptions occur primarily south of the 42nd parallel (northern border of California and Nevada). Climatic influences will be discussed shortly. Substantial declines (some in excess of 50%) were common in the Cascades, especially in Oregon, and are now seen to be unusual in the West. Only a few sites in other states (e.g., in eastern Nevada) experienced such large declines. Changes in the northern Rockies were mostly in the range of 15-30%. Largest increases occurred in New Mexico, where most sites recorded increases in excess of 30%. Fully 85% of snow course locations experienced decreases in April 1 SWE during this interval.

Absolute trends (Figure 2) were largest in the mountains of the Northwest (where mean SWE is quite

[1] *Corresponding author address:* Philip W. Mote, Climate Impacts Group, JISAO, Box 354235 University of Washington, Seattle WA 98195. philip@atmos.washington.edu

large) and smallest (typically < 5cm) in the four corners states (Utah, Colorado, Arizona, New Mexico) where snow quantities are smaller. Losses in excess of 20cm of SWE were observed at several locations in the Oregon Cascades and at a few locations in British Columbia and Washington. Statistical comparisons with climate, numerical simulations with a hydrology model, and local experience (Baccus, personal communication 2003) suggest that the large decreases in the Olympic Mountains of western Washington were probably spurious.

Trends in SWE on March 1 (Figure 3) are substantially similar to those on April 1 (Figure 1), but far more trends were positive in the southern part of the region, especially in Arizona and Nevada.

4. CLIMATE CONNECTION.

As in Mote (2003), we plot the trend results as a function of altitude in order to identify a possible temperature effect, which should be most pronounced at lower altitudes. The results are shown in Figure 4, confirming for the entire West what Mote (2003) showed for the Pacific Northwest: largest negative relative trends tended to occur at lowest elevations, suggestive of a temperature effect. (Relative trends less than –100% can occur when the best-fit line passes through zero sometime before 2000: this happened at some locations, where observations of nonzero SWE became increasingly rare.) Absolute negative trends are largest at a slightly higher altitude.

In order to more quantitatively relate the results to climate trends, we first plot the trends in November-March temperature (Figure 5) and precipitation (Figure 6). Trends in temperature during this season were positive (generally >1.0°C) at nearly every location, and statistically significant at about half the stations. (Unfortunately, climate-quality precipitation records in the USHCN record are rare, especially in Nevada, Wyoming, and Colorado.) Precipitation trends were rarely statistically significant, but were generally positive except in the Oregon Cascades and about half the stations in the Washington Cascades and the northern Rockies. Relative changes of +30-50% were common in the Southwest. Note that the Northwest and Southwest tend to have out-of-phase anomalies in temperature and precipitation, owing to the climate relationships with El Niño-Southern Oscillation and Pacific Decadal Oscillation, and the behavior of these two phenomena over the last 50 years is broadly consistent with the precipitation trends (but not temperature trends).

Correlating the year-to-year variations in these climate records with the April 1 SWE data shown in Figure 1 provides a way to compare the relative importance of long-term changes in precipitation and temperature. These correlations are presented in Figure 6 as vectors, with the x-direction corresponding to the correlation between April 1 SWE and November-March precipitation and the y-direction corresponding to the correlation with temperature. A latitude-dependent scaling factor is applied so that at each location, an orientation of 45° means the correlations are equal. Throughout the domain, the correlation with precipitation is positive, as expected (i.e., the vectors point eastward). In the warmer parts of the domain – Washington, Oregon, and the southwest – there is a substantially negative correlation with temperature (the vectors point southward). In some places the correlation with temperature is stronger than the correlation with precipitation. Almost nowhere is the correlation with temperature positive, and nowhere greater than 0.2: warming by itself essentially never leads to greater snow accumulation.

This map suggests that different regions, and different snow course locations within each region, have different sensitivities to warming. That is, given both an increase in temperature and an increase in precipitation of (say) 20%, some locations would experience a decrease in April 1 SWE and some would experience an increase. Regression analysis (to be presented elsewhere, but see Mote (2003)) is partially successful at explaining the observed trends in SWE.

5. CONCLUSIONS

We have demonstrated that the widespread decline in springtime SWE noted by Mote (2003) in the Northwest is broadly true in the West. In parts of the southwest, large increases in winter precipitation have successfully offset the decreases driven by warming. The Oregon Cascades experienced the largest losses in the region owing to a combination of high temperature sensitivity and declines in precipitation.

Owing to the uneven distribution of snow course locations, and their tendency to be sited in relatively flat locales in the mountains (valleys and benches), it is not possible to aggregate these data up to a regional scale. However, simulations with a hydrological model to be presented elsewhere (see Paper P2.8) corroborate the main snow course results and permit valid regional averaging.

REFERENCES.

Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson, 2001: Changes in the onset of spring in the western United States. *Bull. Amer. Meteorol. Soc.* **82** 399-415.

Clark, M.P., M.C. Serreze, and G.J. McCabe, 2001: The historical effect of El Niño and La Niña events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River basins, *Water Resour. Res.,* **37***,* 741-757.

Folland, C. K., T. Karl, J. Christy, R. Clarke, G. Gruza, J. Jouzel, M. Mann, J. Oerlemans, M. Salinger, and S.-W. Wang, 2001: Pages 99-182 *In* J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (editors), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K.

Groisman, P. Ya., T.R. Karl, R.W. Knight, and G.L. Stenchikov, 1994: Changes of snow cover, temperature, and radiative heat balance over the northern hemisphere, *J. Clim.,* **7,** 1633-1656.

Karl, T.R., C.N. Williams Jr., F.T. Quinlan, and T.A. Boden, 1990: United States Historical Climatology Network (HCN) serial temperature and precipitation data, Pub. 304, 389 pp., Environ. Sci. Div., Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN.

Mote, P.W., 2003: Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophys. Res. Letts.,* **30**, DOI 10.1029/2003GL017258.

Serreze, M.C., M.P. Clark, R.L. Armstrong, D.A. McGinnis, and R.S. Pulwarty, 1999: Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data*, Water Resour. Res.,* **35,** 2145-2160.

Vincent, L.A., and D.W. Gullett, 1999: Canadian historical and homogeneous temperature datasets for climate change analysis, *Int. J. Climatol.* **19,** 1375-1388.

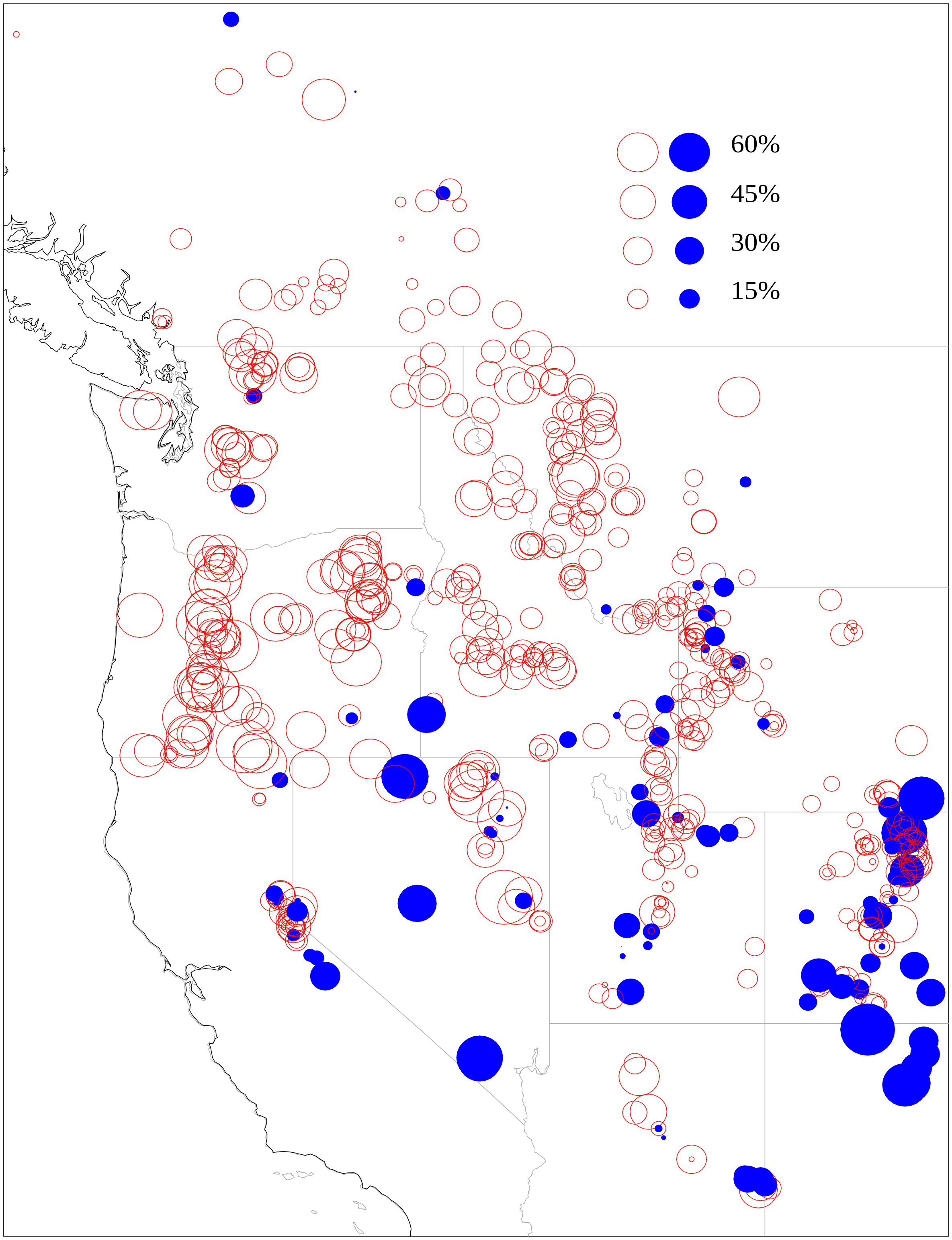

Figure 1. Linear relative trends in April 1 snow water equivalent (SWE) at 594 locations in the western U.S. and Canada, 1950-2000. Negative trends are shown by open red circles, positive by solid blue circles.

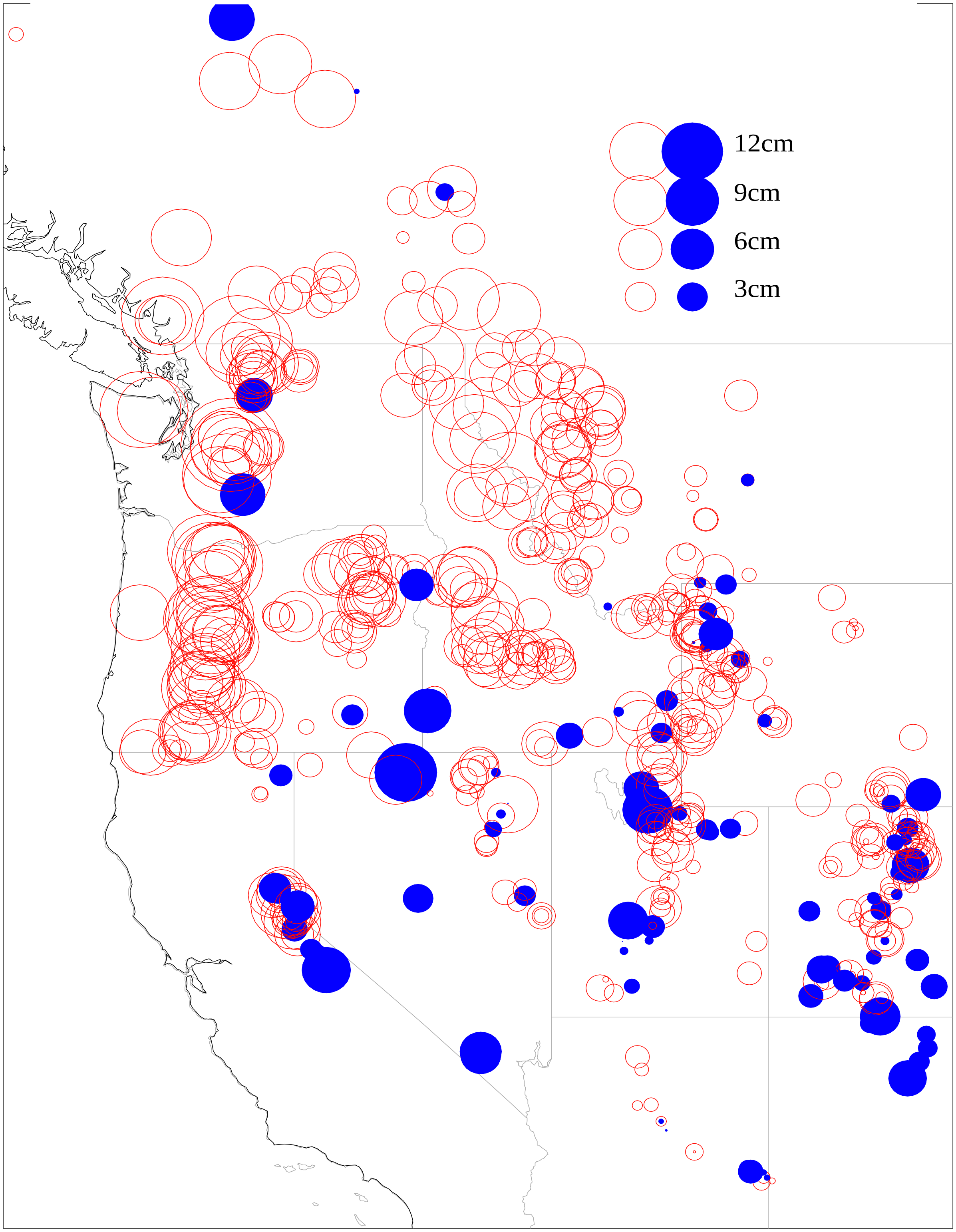

Figure 2. As in Figure 1 but for absolute trends.

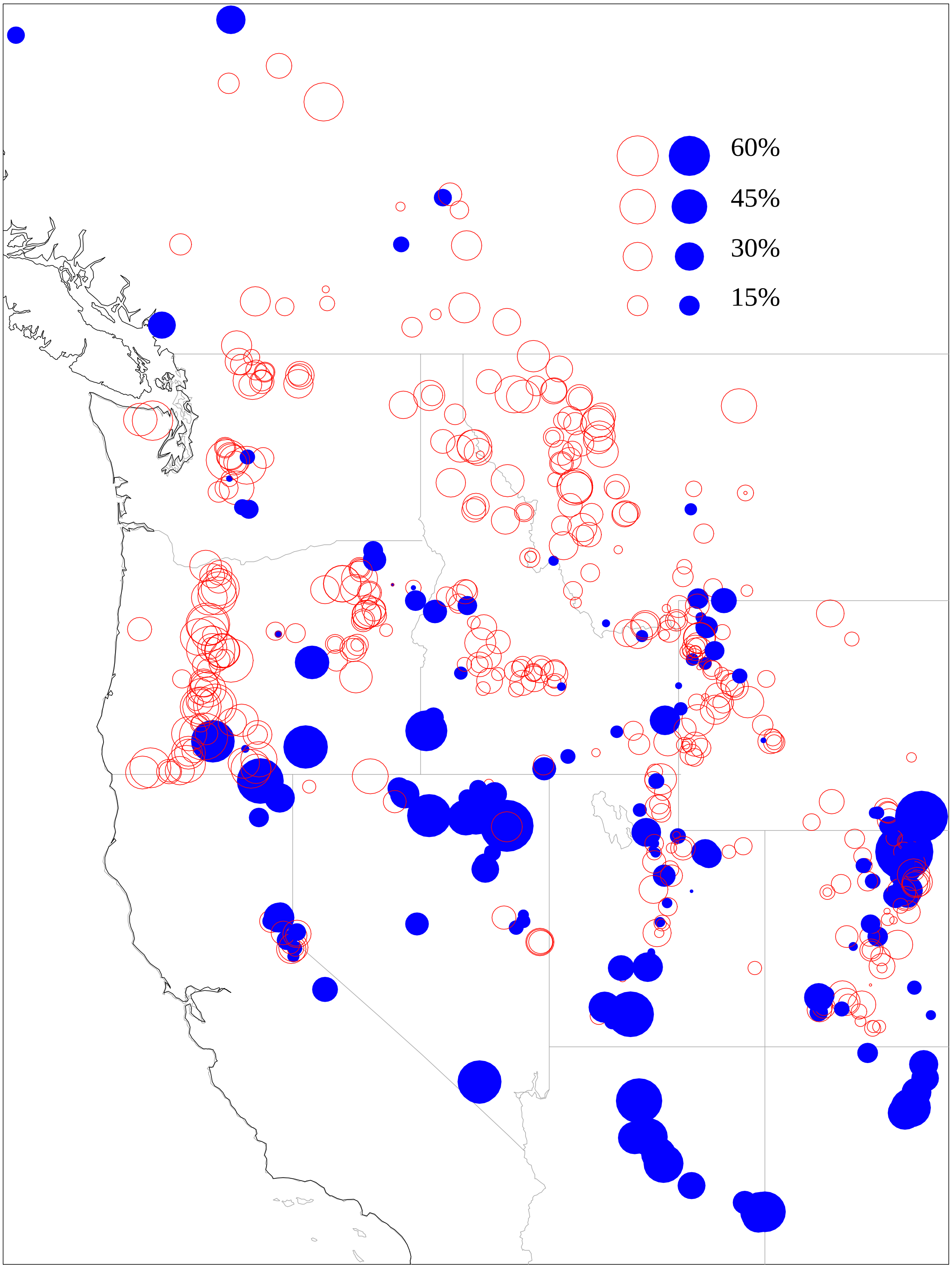

Figure 3. As in Figure 1 but for March 1.

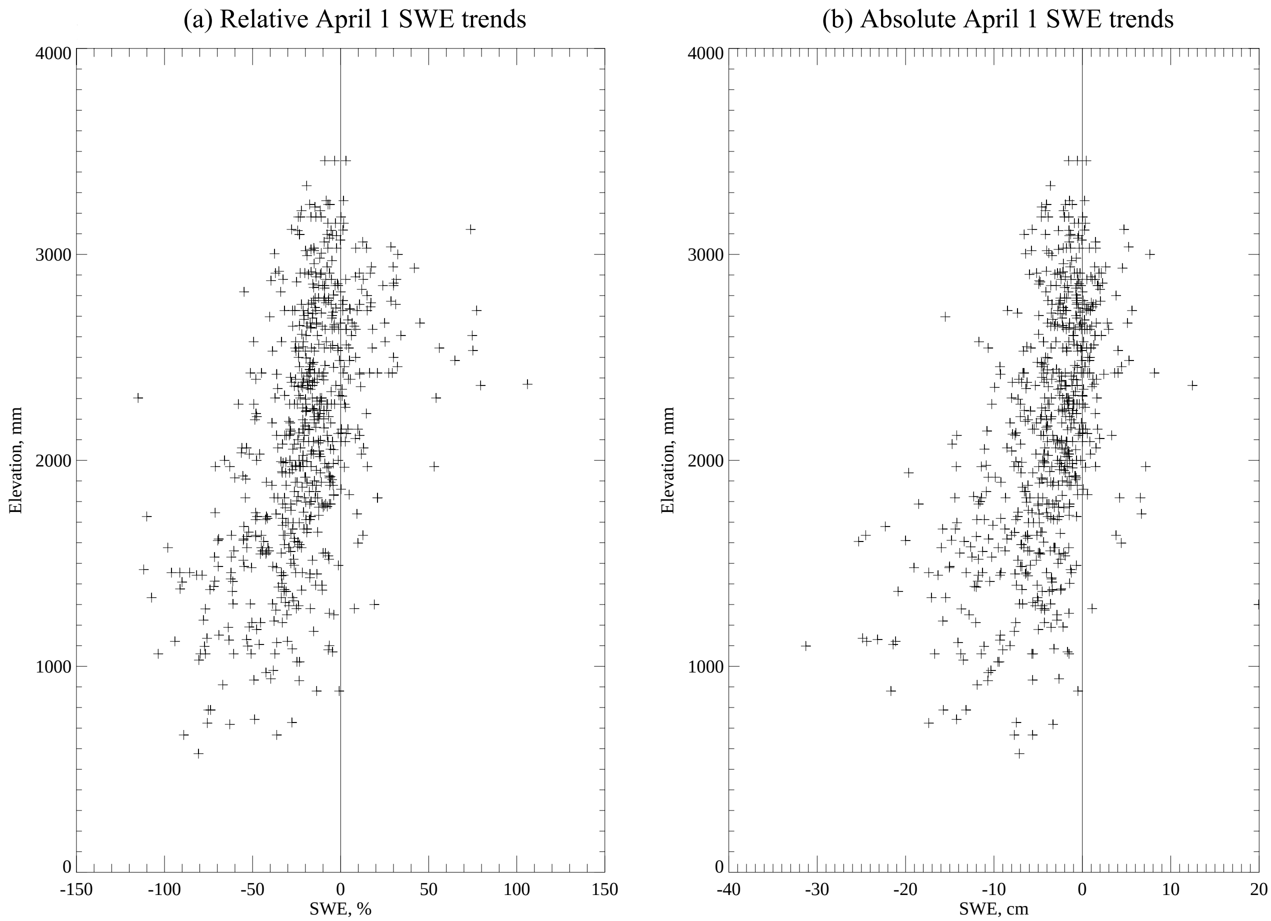

Figure 4. Relative (left) and absolute (right) April 1 SWE trends (1950-2000) plotted against altitude of snow course. Relative losses tend to be largest at low elevations, consistent with a strong influence from regional warming.

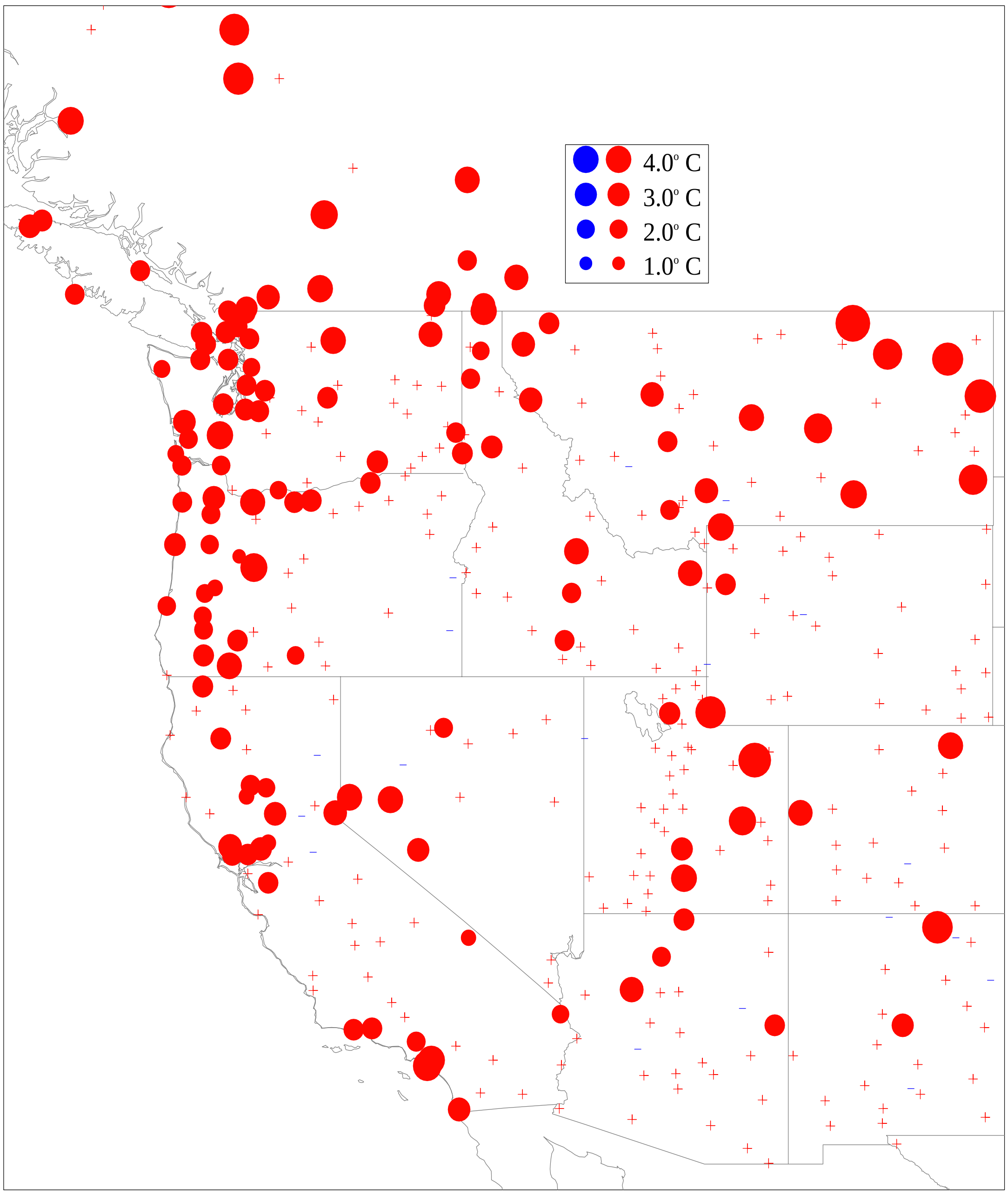

Figure 5. Trends in November-March temperature, 1950-2000. Red circles indicate positive trends that are statistically significant at $p<0.05$, red '+' symbols trends that are not significant, and blue '-' symbols negative trends.

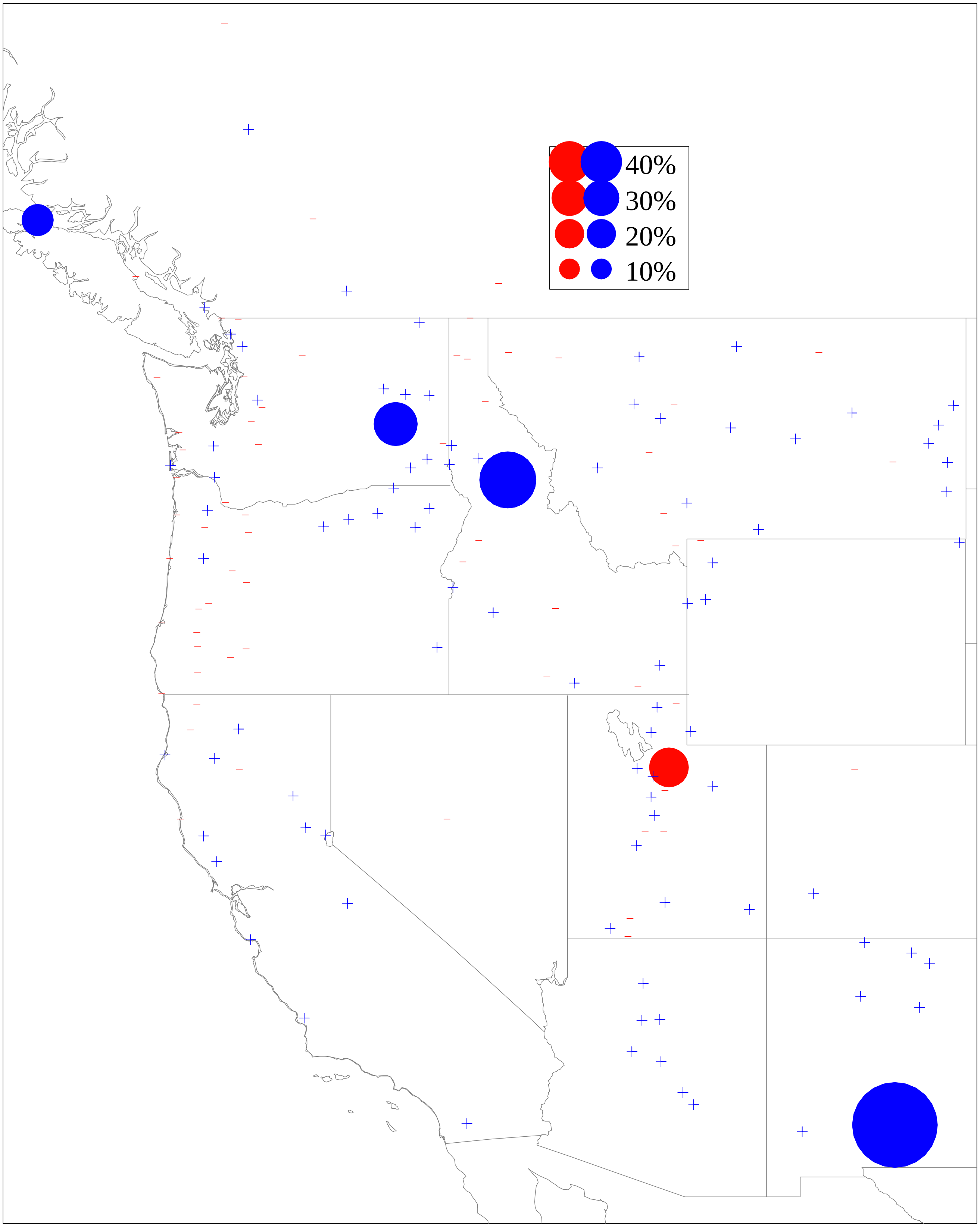

Figure 6. As in Figure 5 but for precipitation, with blue now indicating positive trends. Although few of the trends pass a significance test, many are in excess of 25% in 50 years.

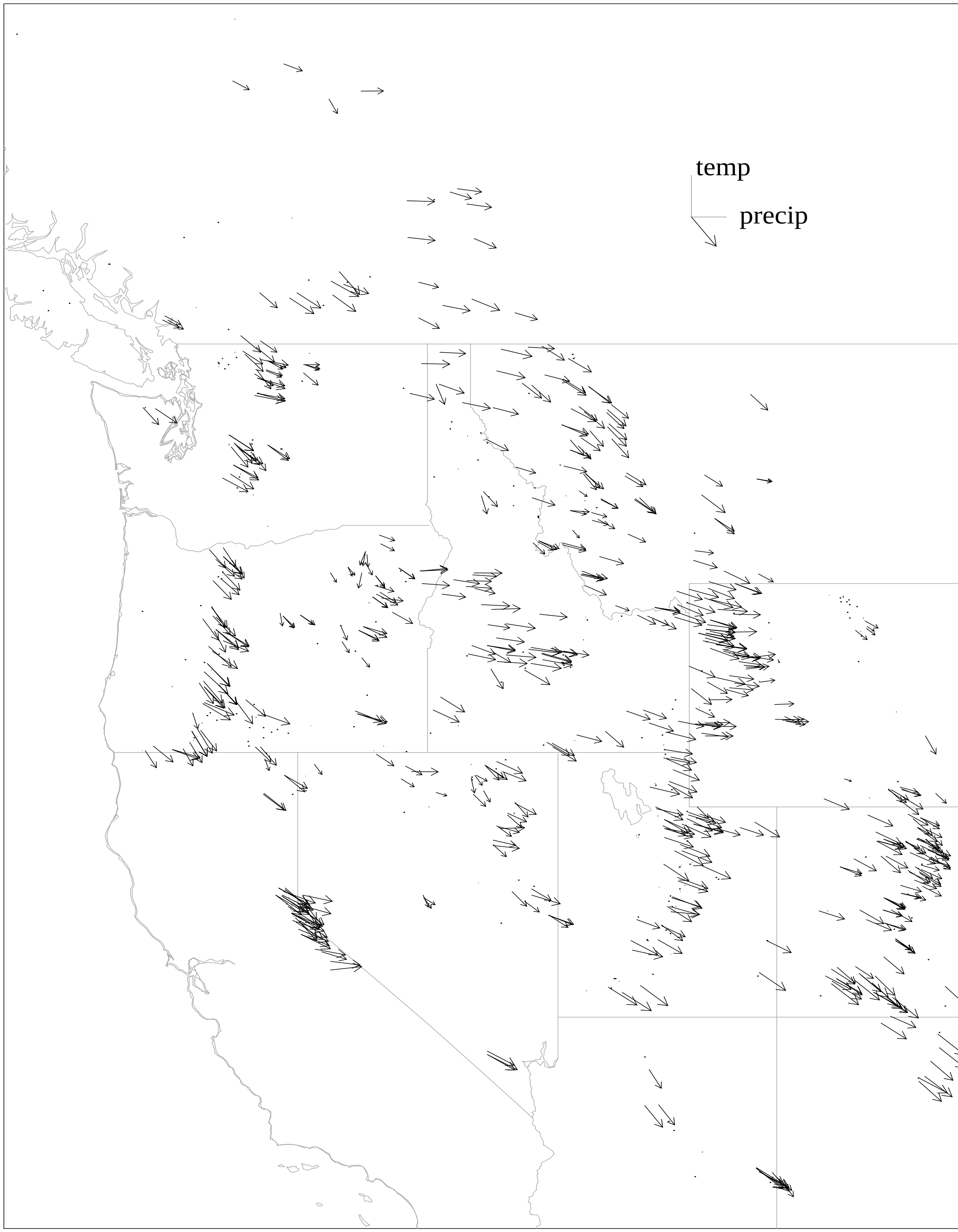

Figure 7. Arrows show correlations between April 1 SWE and November-March precipitation (x-direction) and temperature (y-direction), 1950-200. Virtually every snow course has significantly positive correlations with precipitation, as expected. Most snow courses, especially in the Cascades and in the southwest, also have significantly negative correlations with temperature, indicating sites where an effect of regional warming (Figure 5) should be evident. At many locations (see Figure 1) the trends in SWE are negative despite positive trends in precipitation (Figure 6).