# Climatic and Hydrologic Trends in the Western U.S.: A Review of Recent Peer-Reviewed Research

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## Introduction

A number of recent scientific papers address the nature of annual snowpack levels and subsequent streamflows in relation to changing temperature and precipitation trends. This article will review the major findings of five peer-reviewed studies on the topics of snow water equivalent (SWE), streamflow amounts and timing, temperature and precipitation trends, and the proportion of rain versus snowfall over the last three years (2004-2006). The authors of these studies represent the National Oceanic Atmospheric Administration (NOAA), the Natural Resources Conservation Service (NRCS), the United States Geological Survey (USGS), and several universities including the University of Colorado, the Scripps Institution of Oceanography at the University of California, San Diego (Scripps), and the University of Washington (UW). Many of the studies were produced in part by NOAA-funded Regional Sciences and Assessments (RISAs) like the Western Water Assessment including the Climate Impacts Group at UW, and the California Applications Program at Scripps.

It is important to note that many of our observing systems were not constructed and maintained with the goal of detecting long-term trends. Therefore, changes in instrumentation, station locations, time of measurement and other factors can affect temperature data. In addition, precipitation, especially winter precipitation, is challenging to measure accurately. For example, snow data is subject to nearby weather modification efforts, vegetation growth near the site, and changes in instrumentation. Finally, stream gages suffer from changes in stream channel geometry, and human impacts upstream. In all of these studies the scientists attempted to correct for data problems by using specifically identified 'clean' datasets, by culling records that seem incorrect, and by other measures. Despite these efforts, the data still suffer from a variety of shortcomings. Nonetheless, the authors are quite clear that the major findings of these studies are robust. Regonda et al., for example, say, "…we believe that the (data) limitations do not affect the interpretation of the results."

### Trends in Snow Water Equivalent

Three of the current studies investigated trends in snow water equivalent (SWE). Two of the studies, Mote el al. and Regonda et al., looked at historical trends, and one study, Hamlet et al., created a modeled snow water equivalent dataset back to the early 1900s in order to investigate snow trends before snow measurements were widely made.

Phil Mote, Alan Hamlet, Martyn Clark, and Dennis Lettenmaier wrote Declining Snowpack in Western North America, published in the *Bulletin of the American Meteorological Society* in 2005.[1] This research utilized 824 snow stations from the NRCS, the California Department of Water Resources, and the Ministry of Sustainable Resource Management for British Columbia. The found decreases in April 1 snow water equivalent between 1950-1997 at the majority of sites, with the largest decreases found in western Oregon and Washington, and northern California (Figure 1a). Decreases in the Northern Rockies of Montana and Wyoming were generally between 15% - 30%, while a number of stations in southern Utah, Colorado and elsewhere in the Southwest, indicated increasing trends in SWE. Some of this increasing trend can be attributed to changes in long-term climatic signals such as the Pacific Decadal Oscillation (PDO) and the El Nino Southern Oscillation (ENSO).

| Author | Title | Data Used (Source) | | | |
|---|---|---|---|---|---|
| | | Snow | Temp/ Precip | Streamflow | Other |
| Alan Hamlet, Philip Mote, Martyn Clark, Dennis Lettenmmaier | *Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States* | March 1, April 1, May 1 SWE via VIC Model (NRCS, CA, BC Snow Data) | Temps, Precip (Eischeid, PRISM) | | PDO, ENSO Influence |
| Noah Knowles, Michael Dettinger, Dan Cayan. | *Trends in Snowfall versus Rainfall in the Western United States* | Daily Snow Water Equivalent(NCDC COOP Data) | Temps (COOP), Precip (COOP) Fraction of Snow vs. Rain | | PDO, ENSO influence |
| Philip Mote, Alan Hamlet, Martyn Clark, Dennnis Lettenmaier | *Declining Snowpack in Western North America* | April 1 SWE (NRCS, CA Snow Survey, BC) | Temps, Precip (PRISM) | | PDO, ENSO influence |
| Satish Regonda, Balaji Rajagopalan, Martyn Clark, John Pitlick. | *Seasonal Shifts in Hydroclimatology over the Western United States* | March, April, May SWE (NRCS) | Temps, Precip (COOP) | Runoff Timing, Means (USGS HCDN) | PDO, ENSO Influence |
| Iris Stewart, Dan Cayan, Mike Dettinger | *Changes toward Earlier Streamflow Timing Across Western North America* | | Temps (PRISM, COOP) | Runoff Timing by 3 measures, Means (USGS HCDN) | PDO, ENSO influence |

**Table 1.** A list of the authors, study title, and variables considered. Data source for each variable is in parentheses.

[1] All except Clark participate in the Climate Impacts Group at the University of Washington, the sister program to the Western Water Assessment. Clark was the Director of the Western Water Assessment until 2005.

Trends in SWE were found to be closely related to mean winter temperature, with the warmest snow-dominated basins experiencing the greatest relative decreases in SWE.

Satish Regonda, Balajj Rajagopalan, Martyn Clark and John Pitlick wrote Seasonal Shifts in Hydroclimatology over the Western United States, published in the *Journal of Climate* in 2005.[2] This research looked at 469, 501, and 239 NRCS snow stations for March 1, April 1 and May1 SWE, respectively, containing data for at least 80% of the years between 1950 and 1999. For March, April and May, almost all of the surveyed stations in Washington, Oregon, Idaho, and Montana show statistically significant decreases in SWE of 15cm (6 in) or more (Figure 1b, March and May not shown). Note that these results are reported only in absolute numbers, not percentages, and the study did not include California snow survey data. Unlike the Pacific Northwest, the Intermountain states of Wyoming, Utah and Colorado do not exhibit any spatially coherent trend in SWE. Regonda et al. also present the same data for March, April and May by elevation (Figure 1c for April 1). While there is significant scatter in this data, stations below 2500m (8200 feet) clearly exhibit the most SWE loss. An accompanying elevation map also shows that almost all of the stations in Utah, Wyoming and Colorado are above 2500m. Therefore, the higher elevations in the Intermountain West seem to help the region continue to have average SWE, while lower elevations mountains elsewhere are seeing a decline in SWE.

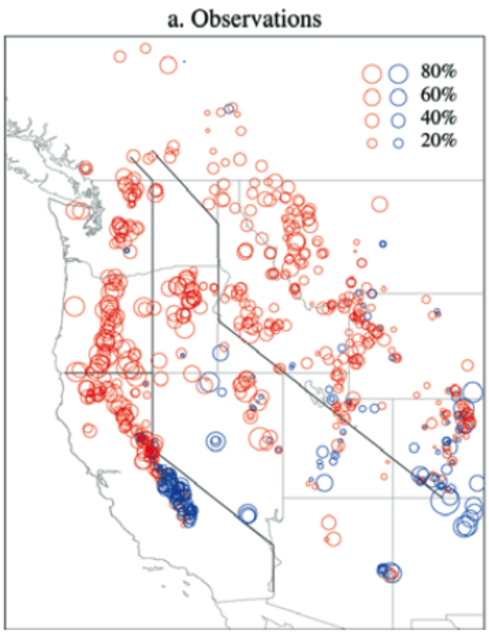


**Figure 1a.** Linear trends in April 1 Snow Water Equivalent for 824 snow data stations from 1950 to 1997. Negative trends in red, positive trends in blue with circle size proportional to trend size. (from Mote el al. Figure 1)

Alan Hamlet, Phil Mote, Martyn Clark, Dennis Lettenmaier wrote Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States, published in the *Journal of Climate* in 2005. This study used the Variable Infiltration Capacity (VIC) hydrologic simulation model[3] to examine trends in SWE across the western U.S. between 1915-2003. The authors pursued a modeling study for three reasons: extensive snow data only starts in the 1950s, the influences of ENSO and PDO confound analysis, and existing snow data is present only for a small geographical subset of the West. Hamlet et al. reconstructed SWE on March 1, April 1, and May 1.

The authors found that, "Widespread warming has occurred in the western U.S. from 1916-2003, resulting in downward trends in 1 April SWE over large areas of the domain… results show that almost all the upward trends in SWE are due to modest upward precipitation trends and that many of the downward trends in SWE are caused by widespread warming." In addition, they state, "These temperature related trends are not well explained by decadal climate variability associated with the PDO," and ENSO variability is on a shorter time scale than the observed changes in temperature trends. However, "decadal variability [i.e. PDO] probably does account for the trends in winter precipitation" that "have occurred over portions of the record." In many high elevation areas of the Interior West[4], SWE was found to be relatively

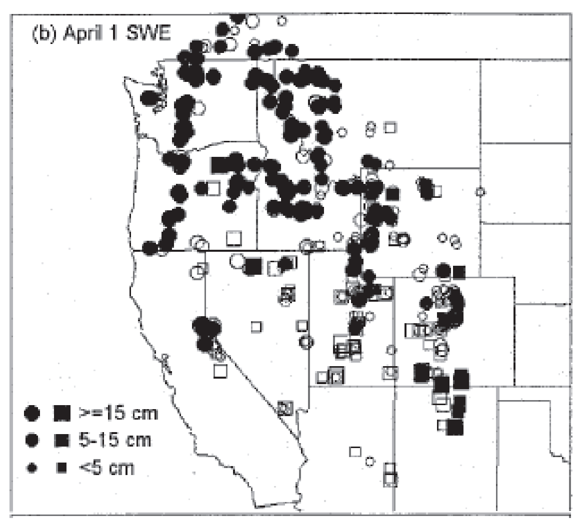


**Figure 1b.** Changes in snow water equivalent in cm from 1950 to 1999 for April 1 (501 stations) . Circles indicate decreasing trends, squares increasing trends. Solid shapes are statistically significant and the size of the shape is proportional to the change. Compared to Mote et al, measurements are in absolute numbers (15cm = 6in), not percentages and this data extends two more years. (from Regonda et al. Figure 4)

2 University of Colorado and associated with the Western Water Assessment.
3 VIC is a water & energy balance model with some subgrid scale approximations for vegetation, elevation and soil dynamics.
4 Note the distinction in this article between Interior West (AZ, CO, ID, MT, NM, NV, UT, WY) and Intermountain West (CO, UT, WY).

insensitive to recent temperature trends and changes in SWE at those sites are primarily due to trends in precipitation.

**Trends in Streamflow Timing and Amounts**

Two of the recent studies expressly dealt with streamflow timing and amounts. Stewart et al. looked at several different measures of streamflow timing including onset of the major pulse associated with spring, an annual center of mass measure, i.e. when the date when half the annual flow has occured, and the fractional totals of annual flow in March, April, May, and June. Regonda et al. performed a center of mass analysis. Both briefly considered changes in mean flow.

Iris Stewart[5], along with Dan Cayan and Mike Dettinger wrote Changes toward Earlier Streamflow Timing Across Western North America, published in the *Journal of Climate* in 2005. They used 241 U.S. (specifically, USGS Hydro Climate Data Network (HCDN) gages, stations relatively free from the impacts of humans) and 53 Canadian (Environment Canada) snowmelt-dominated streamflow gages with at least 30 years of data from 1948 to 2002 in the eleven western states and Canada. In general, all three of these measures show a consistent (66% of all gages) 1-4 week earlier shift throughout the West in recent decades compared with the 1950s to 1970s (Figures 1d). These trends were found to be strongest in the interior Pacific Northwest, western Canada and coastal Alaska for mid-elevation gages. In the Western U.S., the months with the greatest trends in earlier streamflow, as measured by changes in average monthly fractional amount, are March and April. Over the period studied (1948-2002), mean annual streamflows have remained constant or increased slightly at most locations. The primary cause for earlier snowmelt and streamflow was found to be a large-scale increase of winter and spring temperatures by about 1-3 $^{O}$C over the period studied. The authors also investigated how much of the trends in streamflow timing might be attributed to the known climatic drivers like PDO and ENSO. The authors concluded that, "A significant part of the long-term regional change in streamflow timing can be attributed to decadal climatic variation in the Pacific basin though the Pacific Decadal Oscillation (PDO)…yet, there remains a sizeable residual fraction --in addition to natural variation -- of the streamflow timing trend that is not explained by PDO and appear(s) to be related to temperature increases consistent with observed changes in global temperature."

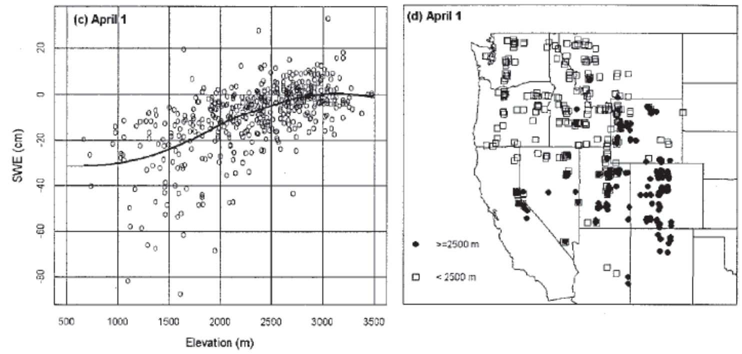


**Figure 1c.** Changes in snow water equivalent for April 1 SWE by elevation on left (501 stations), and elevation of stations right. Figures for March 1 and May 1 are substantially similar. Note how 2500m (8200 feet) is the approximate line between stations losing SWE and not losing SWE on average. Also note that most Intermountain stations are higher than 2500m. (from Regonda et al. Figures 5c and d)

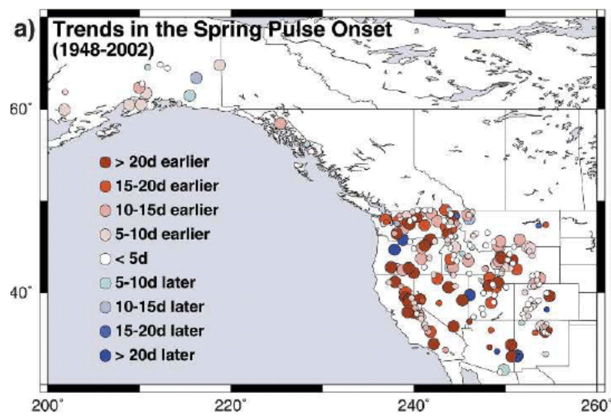


**Figure 1d.** Trends in spring pulse onset measured in days for the 1948 to 2002 period for 294 gages. Red circles represent earlier streamflows and blue circles represent later streamflows. Larger circles represent greater changes. Trends in date of center of annual streamflow mass look similar to this graphic. (from Stewart Figure 2a)

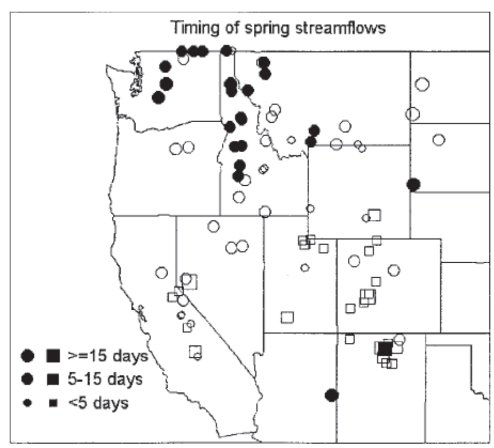


**Figure 1e.** Changes in the center of mass of annual streamflow timing in days for 89 USGS HCDN gages from 1950 to 1999. Circles indicate earlier runoff, squares later runoff, with filled shapes statistically significant, and shape size proportional to trend. Compared to Stewart et al, the data began two years later and ended three years sooner and had significantly fewer gages (89 vs. 294). (from Regonda et al. Figure 2)

5 Post-doctoral scientist at the California Applications Program at Scripps, a sister program to the Western Water Assessment.

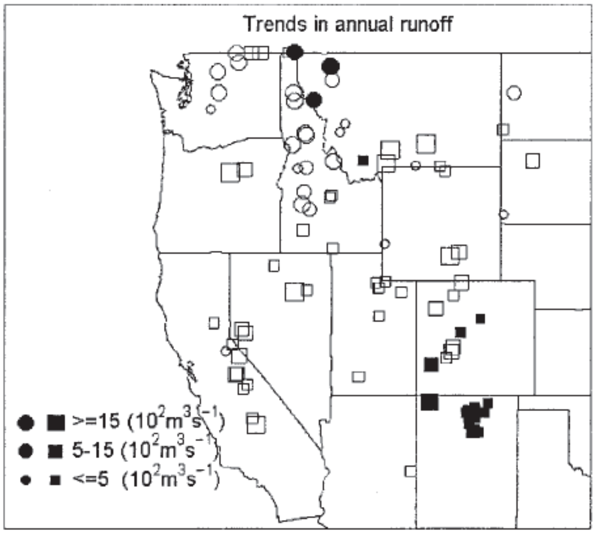


**Figure 1f.** Trends in annual streamflow in cubic meters from 89 stations during 1950 to 1997. Circles indicate less runoff, squares more runoff, with filled shapes statistically significant, and shape size proportional to trend. Note: data is given in absolute numbers and hence analysis of relative size of trend is not possible. (from Regonda et al. Figure 8)

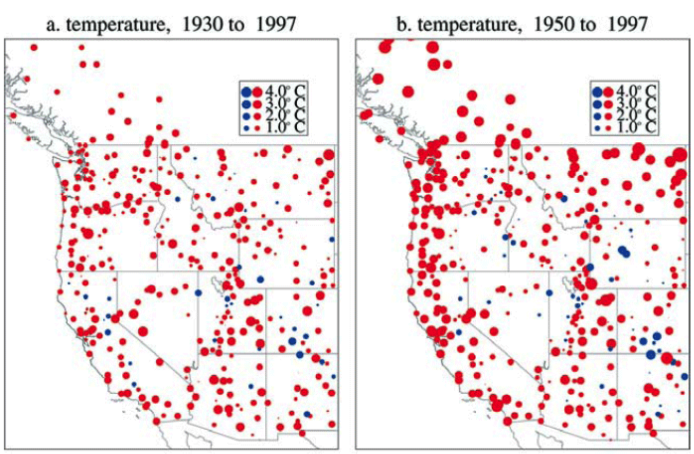


**Figure 1g.** Nov-Mar temperature trends from 1930 and 1950 to 1997 in oC per century. Red is warming, blue is cooling, with size of circle proportional to trend. (from Mote et al. Figure 6)

Intermountain water managers should note that the Stewart et al. findings for Utah, Colorado and Wyoming are, in general, outliers from the overall findings (Figure 1d). Spring pulse onset and center of mass have changed little in Colorado, and somewhat in Wyoming and Utah depending on the exact area. The fractional flow analysis shows that March flows have changed little in the three states while the June fractional flows appear to have significantly decreased (not shown). Stewart et al. did not show results for May, which might shed light on the June decreases.

Regonda et al. used 89 snowmelt-dominated streams with continuous records from 1950 to 1999, also from the USGS HCDN dataset. They found that for a majority of gages the date when half of the annual flow (i.e. center of mass) occurs happens earlier by 10 to 20 days, but these trends are only statistically significant in the Pacific Northwest (Figure 1e). More importantly to Intermountain water managers, this trend is highly linear with elevation. The lowest stations show the greatest advancement while stations above about 2500m (8200 feet), show little change (not shown). In Utah, Colorado and Wyoming the pattern reverses, with more gages showing later runoff (but none of these gages are statistically significant). This later runoff may result from increased precipitation in these states (Figure 1f and see 1k below) and is discussed below under Trends in Precipitation.

**Trends in Temperature**

Four of the recent studies investigated changes in both temperature and precipitation trends. A wide variety of temperature datasets were used.

Mote et al. used two separate temperature datasets: one was a combination the U.S. Historical Climatology Network (USHCN - a subset of National Weather Service Cooperative (COOP) data), and the Historical Canadian Climate Database (HCCD). Both are relatively free from data problems. The other was a 'gridded' data set developed by Jon Eischeid of the University of Colorado and a widely-used temperature and precipitation dataset known as Parameter-elevation Regressions on Independent Slopes Model (PRISM) from Oregon State University. Mote et al. report temperature trends from both the 1930 to 1997 and 1950 to 1997 periods for the entire West using the first dataset (Figure 1g). Significant west-wide warming occurred during both of these periods, with the 1930-97 period showing less warming (1-2 $^{O}$C (34-35 $^{O}$F) per century compared to 2-3 $^{O}$C (35-37 $^{O}$F) per century) due to the inclusion of the very warm 1930s at the start of the period. The few sites that show cooling in the Intermountain West are in the southern San Juan Mountains in Colorado, in the Wasatch Mountains in Utah, and widely scattered in Wyoming.

Regonda et al. found that an overwhelming majority of National Weather Service cooperative weather (COOP) stations with continuous records from 1950 to 1999 showed a trend towards earlier spring warm spells (defined as 7 days greater than 12 $^{O}$C /53 oF) during the period (Figure 1h). This warm spell analysis is unique and was not repeated by other studies. This trend was statistically significant at many stations in Colorado, Utah, Wyoming and the entire Pacific Northwest. In California, Arizona and New Mexico this warming trend was evident, but in general was not statistically significant. Regonda et al. note that at a few stations in the Sierras, Colorado and Utah, generally higher than

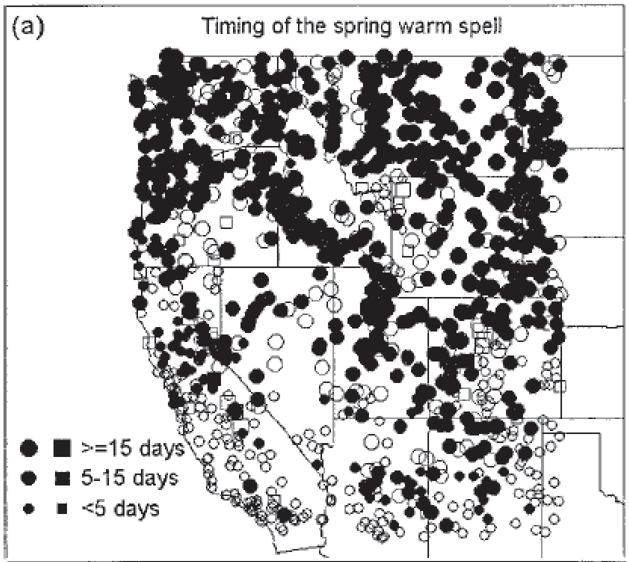


**Figure 1h.** Trend in days for first spring seven-day long warm spell above 12 °C/53 °F from NWS COOP stations from 1950 to 1999. Circles are earlier spells, squares are later spells, with solid shapes statistically significant. Size of shape is relative to size of trend. (from Regonda et al. Figure 6)

2500m (8200 feet), there is a trend towards later warm spells, but this is rarely statistically significant.

Stewart et al. found temperature trends increasing throughout the 11 western states with warming of between 0.5 - 2.0 °C (33-35.5 °F) during the 55-year period from 1948 to 2002. No map or seasonal information was provided. They used temperature data from Eischeid, discussed above, and from NOAA Climate Division averages.

Noah Knowles[6], Mike Dettinger and Dan Cayan[7] looked at how the character of precipitation is changing in Trends in Snowfall versus Rainfall in the Western United States, published in the Journal of Climate in 2006. Knowles et al. were primarily interested in changes in the proportion of rain to snow (see below) but they also looked at temperature trends from 634 NWS COOP stations across the 11 Western states from 1949 to 2004. Positive temperature trends were found at the vast majority of stations across the West, with wet-day daily minimum and maximum temperatures increasing by 1.4 °C (2.5 °F) and 1.0 °C (2 °F), respectively, over the period studied. The greatest warmings were generally in the Interior West, in January and March, and at higher elevations (Figure 1i). The March warming in the Intermountain West is particularly striking (Figure 1j).

### Trends in Precipitation

Three of the studies looked at trends in precipitation. All three studies attempted to investigate the influence of the PDO and the ENSO on these trends.

Mote et al. show precipitation for both 1930 to 1997 and 1950 to 1997 utilizing data from the USHCN and HCCD stations (Figure 1k). The period starting in 1930 shows very large increasing precipitation trends across the West. The 1950 to 1997 period shows increases, with the important exception of western Washington, western Oregon and a small portion of Northern California. Mote et al. describe the SWE results (Figure 1a) as a competition between long-term warming and precipitation increases and decreases. In the Southwest higher precipitation has overcome warming leading to higher SWE, while SWE in the Pacific Northwest has declined substantially because of the double blow of increased temperatures and decreased precipitation.

Regonda et al. using COOP stations with continuous daily records from 1950 to 1999 show a distinct north-south demarcation in winter precipitation trends with stations south of Wyoming showing more precipitation, and stations north showing less precipitation (Figure 1l). There is, however, significant scatter within this general pattern. The authors suggest that this pattern bears similarity to ENSO and PDO cycles, and these drivers might explain a large portion of the precipitation trend. They also say that the increases in winter precipitation in the Interior West may have offset the increases in temperature, the timing and volume of snowmelt has not significantly changed. In the Pacific Northwest, they agree with Mote et. al. that decreases in precipitation combined with warming has had a particularly strong effect on the timing of snowmelt.

Stewart et al. looked at precipitation trends as part of additional research not described. While hinting that the trends were

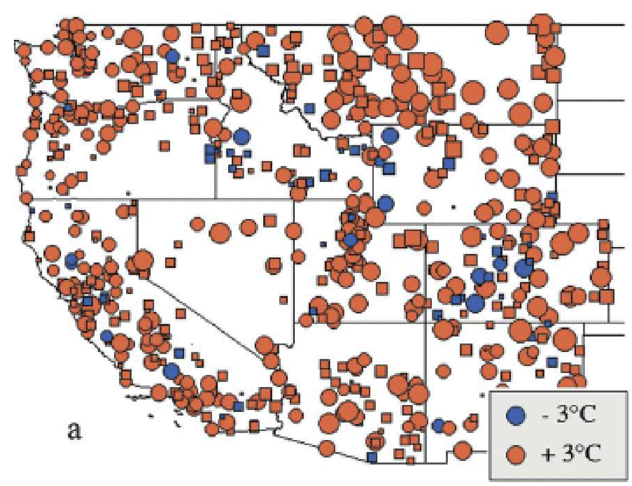


**Figure 1i.** November to March warming trend in wet-day miniumum termperatrues from 1949 to 2004 in °C using NWS COOP data. Red indicates an increase in temperature and blue indicates a decrease. The size of the circle is proportional to the degrees of temperature change. The circles represent significant findings and the squares are not significant. (from Knowles et. al. Figure 5)

[6] United States Geological Survey
[7] Both of the Scripps Institution of Oceanography.

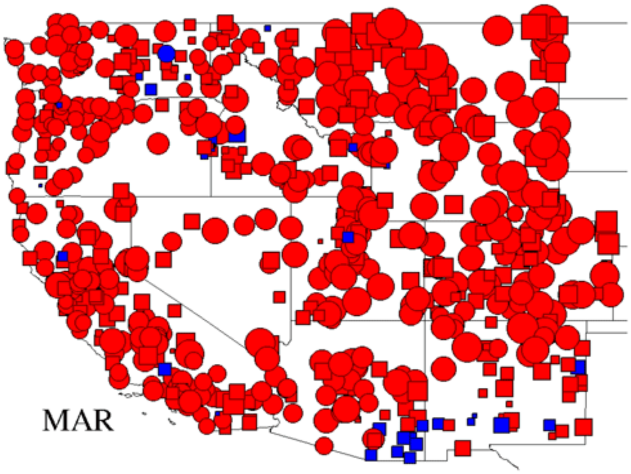


**Figure 1j.** Trend in average minimum temperature in March from 1948 to 2004 in °C . Scale is the same as in Figure 1i. Notice the large minimum temperature warming in March in the Intermountain West. (from Knowles et. al. Figure 9)

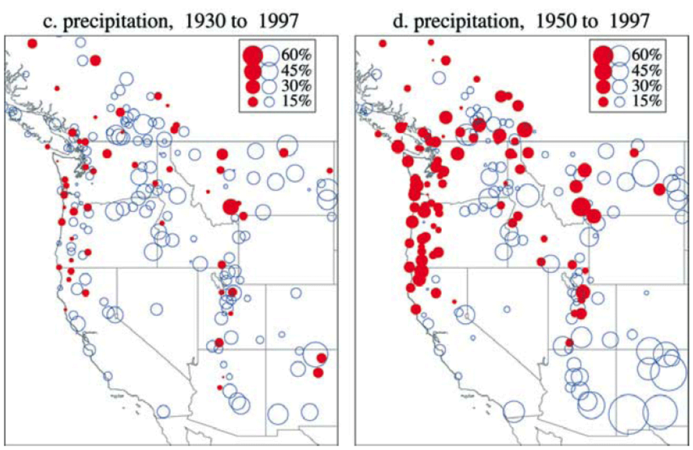


**Figure 1k.** Nov to Mar precipitation trends during periods shown using approximately 400 USHCN and HCCD stations. Red is a decrease, blue is an increase, with size of circle proportional to trend. (from Mote et al. Figure 6)

small, they describe the trends as statistically significant decreases in the Pacific Northwest and western Canada. They found no trends in California or the Rocky Mountains.

**Trends in Snowfall versus Rainfall**

Knowles et al. examined daily temperature, precipitation and snowfall records from observations dating from 1949 to 2004 at NWS COOP stations in the Western U.S to determine if the annual ratio of winter snowfall liquid water equivalent (SFE) to winter total precipitation (P) has changed (SFE/P). Snowfall liquid water equivalent is similar to Snow Water Equivalent except that it is a running total of the water amounts in each snowfall during the winter season rather than a total of the water equivalent from snow on the ground.

Over the period 1949-2004, they found that November-March SFE/P has decreased over the vast majority of stations across the West, although results are somewhat mixed over the interior West including Colorado, Utah and Wyoming (Figure 1m). They concluded that "most of the significant changes in SFE were found to be unrelated to changes in total precipitation," and hence that the proportion of winter precipitation falling as rain must have increased during this period.

As noted above, positive temperature trends were found by Knowles et al. at the vast majority of stations across the West. Of the cold season months, January and March have particularly widespread (and significant) warming trends. The impact of this warming on SFE/P in the Interior West is, however, less due to the colder mean winter temperatures. Knowles et al. found that "the largest reductions (in SFE) were shifts from snowfall to rainfall driven by warming and occurred at relatively warm, low to moderate elevations."

**Conclusions**

For the most part, these six studies are remarkably consistent in their findings. Multiple independent datasets confirm (1)widespread warming in the West, (2) statistically significant declining snowpacks in the Pacific Northwest and California, and (3) advances in spring runoff timing in the Pacific Northwest and California. The data also show some long-term precipitation trends with a slight increase in precipitation in the southern states of the West but little change in long-term streamflow means across the West.

Many of the studies attempted to remove the influences of known changes in precipitation and temperature from PDO and ENSO. In general, these authors agree that the loss of snow, and advanced spring runoff is partly, but not entirely, due to these effects. They suggest that significant west-wide warming over the last 50 years has also played a significant role in the major changes described above.

Findings for the Intermountain West are, however, quite different. These studies show few consistent, statistically significant trends in streamflow runoff timing, streamflow mean amounts, and snow water equivalent. There has been some increase in precipitation in the Intermountain West south of Wyoming, in part due to large scale climatic cycles (e.g. PDO and ENSO). The key statistically significant finding is that the Intermountain West has warmed considerably and this warming trend is apparently greater than other parts of the West. It appears that despite the warming, winter temperatures well below freezing along with some increases in precipitation have protected the snowpack from losses. It should be noted that the SWE studies of Mote et al. and Regonda et al. used data that stopped in 1997 and 1999, respectively, prior to the current drought. How the inclusion of the recent 2000-2004 drought would change these results is not known. But what is known is that snowpack losses in 2002, 2004, and 2006 in the Intermountain West were quite significant, and were caused in part by substantial spring time warm periods without precipitation.

The conclusions of many of these studies contain explicit warnings for water managers. Stewart el al. say, "Almost everywhere in western North America, a 10% - 50% decrease in the spring-summer streamflow fractions will accentuate the typical seasonal summer drought with important consequences for warm-season supplies, ecosystems, and wildfire risks." Regonda et al. conclude, "If the trends in temperature, snowfall, and streamflow demonstrated in this paper persist and even intensify, changes in water management practices will be necessary to adapt to the altered hydrologic regime." Mote et al. ask, "Are these trends in SWE an indication of future directions?...The increases in temperature over the West are consistent with rising greenhouse gases, and will almost certainly continue. ..It is therefore likely the losses in snowpack observed to date will continue and even accelerate with faster losses in milder climates like the Cascades and the slowest losses in the high peaks of the northern Rockies and southern Sierra."

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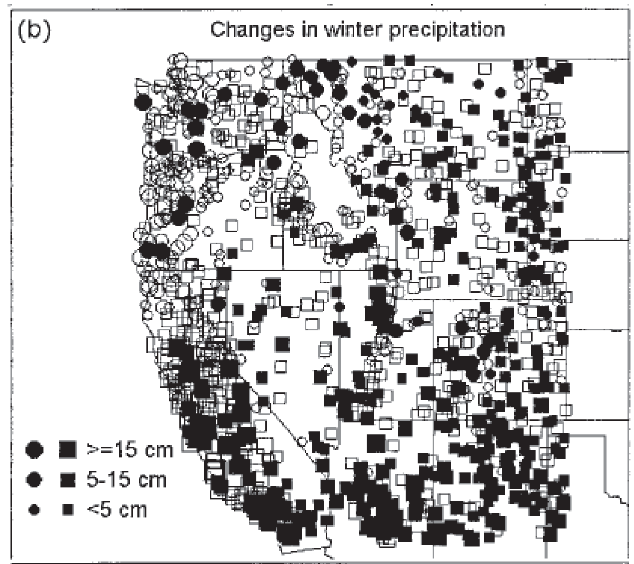


**Figure 1l.** Trend in winter precipitation in cm from 1950 to 1999. Circles are less precipitation, squares are more precipitation, with solid shapes statistically significant. Size of shape is relative to size of trend. Note the increase in the southern portion and decrease in northern portion. The authors suggest this is in part due to increases in certain phases of ENSO and PDO. (from Regonda et al. Figure 6)

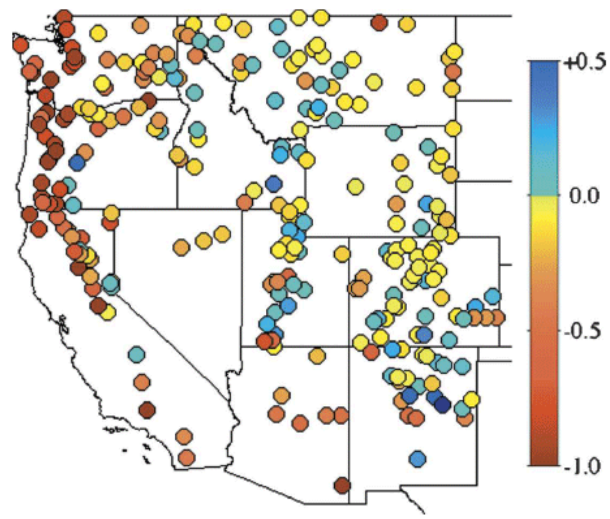


**Figure 1m.** Fractional change from 1949 to 2004 in winter snowfall equivalent after correcting for changes in winter precipitation amounts. Blues indicate increasing SFE/P (more snow) and yellows-reds decreasing SFE/P (less snow). Data is from NWS COOP stations. (from Knowles et. al. Figure 7)