System Indicators

Water & Air Quality, Temperature, Precipitation, and Snowpack

SIERRA NEVADA CONSERVANCY

Temperature, Precipitation & Snowpack (2009/2012)

September 2012

Temperature, Precipitation and Snow Pack

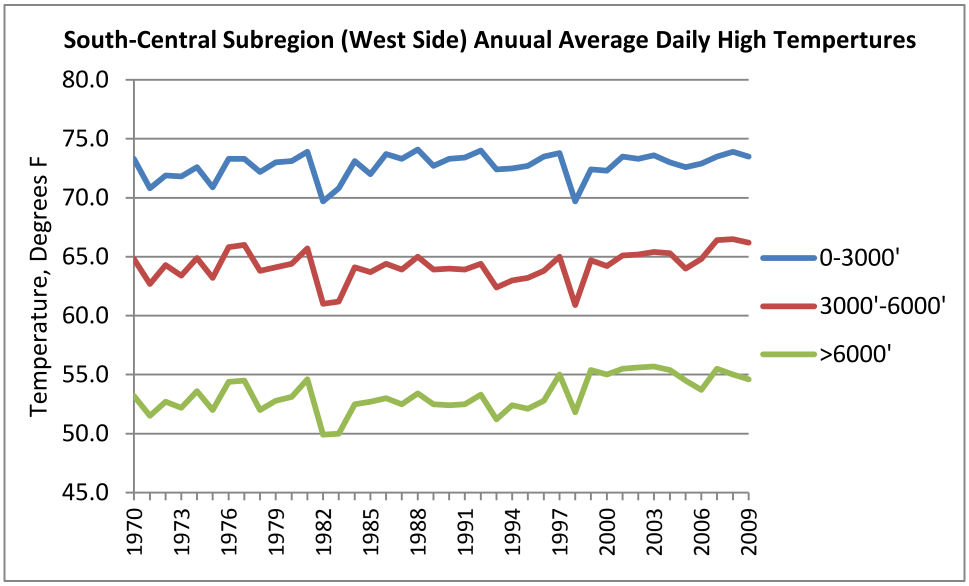
Data for the temperature and precipitation analyses were developed from the PRISM Climate Group data sets (PRISM data set methodology is described at the end of the Temperature section), which are the highest quality spatial climate data sets currently available. Because potential warming and weather pattern shifts could occur differently in different parts of the Region and at different elevations, these data were analyzed not only for the Region as a whole, but were also separated out for each Subregion, and further differentiated for three elevation bands and the western and eastern slopes of the Sierra Nevada.

Temperature

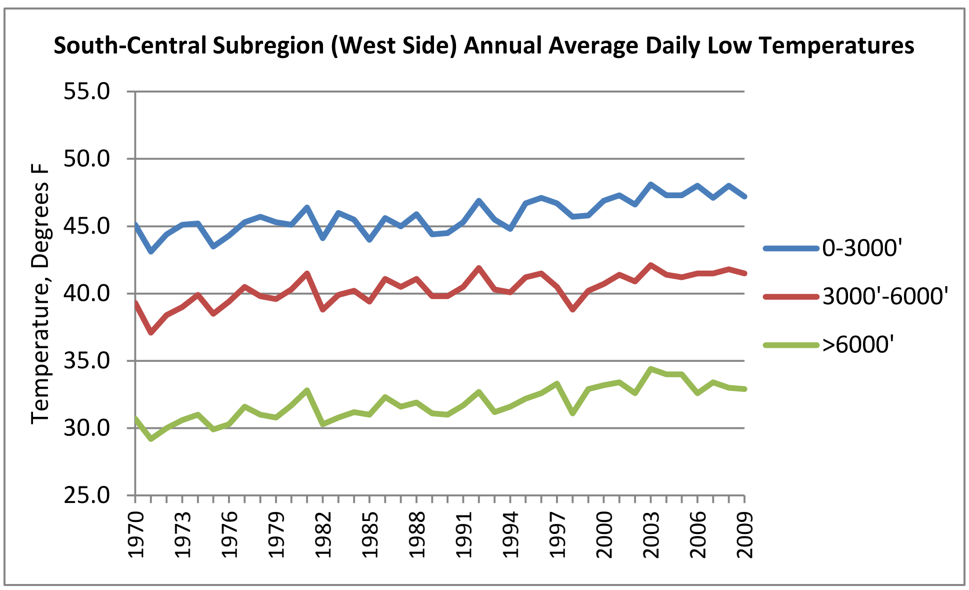
Data were developed for both annual average daily high temperatures (daytime highs) and average daily low temperature (nighttime lows from 1970-2009.

Two trends are evident from the data:

- while there is a overall noticeable increase in average annual temperatures over the past 40 years, temperatures have risen more at higher elevations
- nighttime lows have risen more than daytime high temperatures.



For example, the two charts to the right display the annual average daily highs and daily lows for the South-Central Subregion on the west side of the Sierra. This Subregion is fairly typical of the pattern for all of the Subregions.

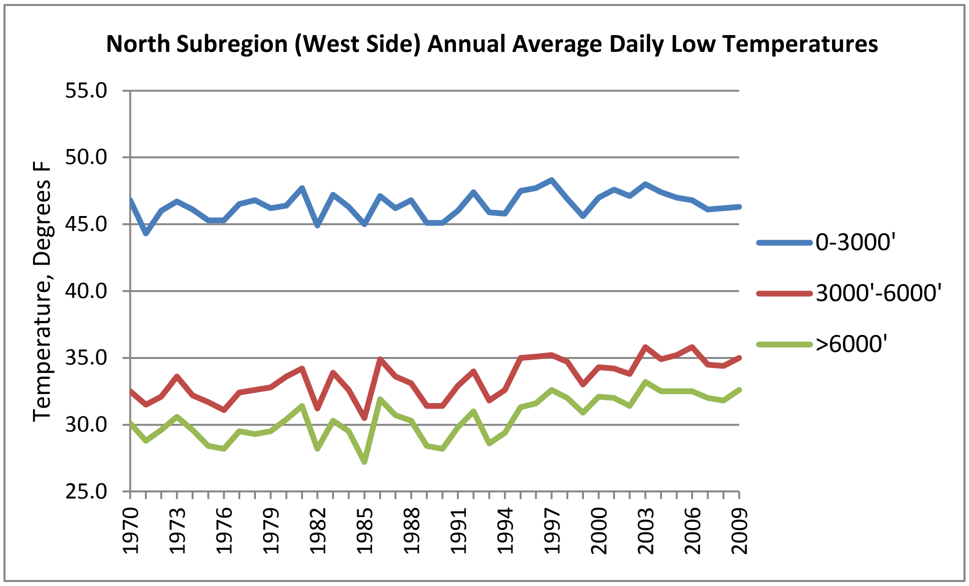


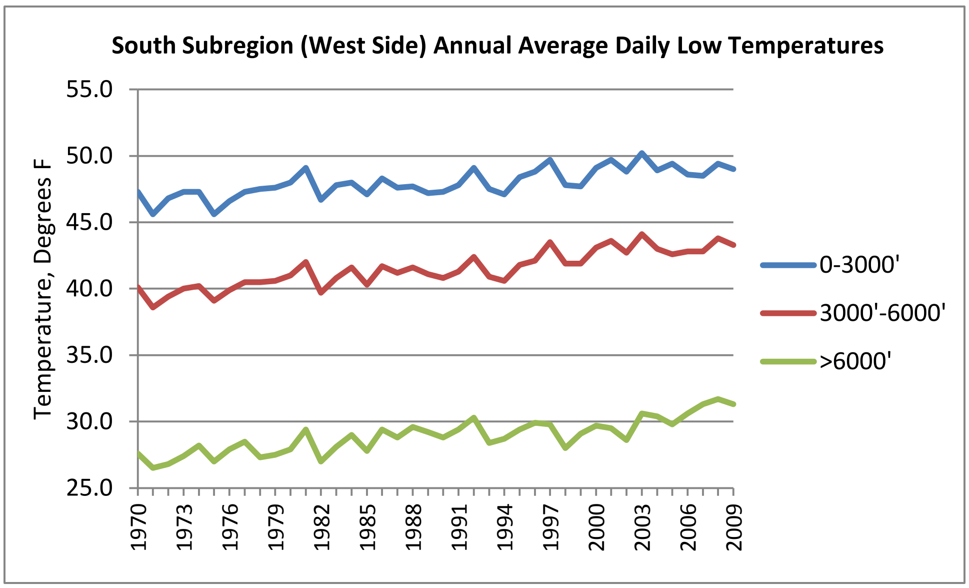
There has been only a slight increase in daytime high temperatures at lower elevations over the past 40 years, but there is a more noticeable increase above 6,000’.

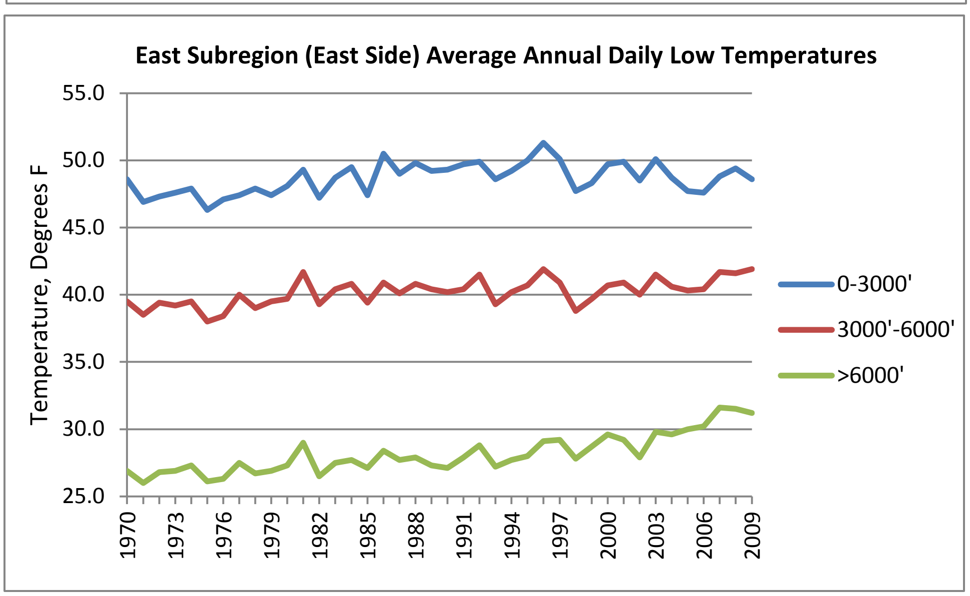
On the other hand, nighttime low temperatures have increased noticeably at all elevations, and are even more pronounced at the highest elevations.

The three charts to the right show the average annual low temperatures for three of the other Subregions. They demonstrate the consistency of the trend across the Sierra, from North to South, and West to East. (However, nighttime lows below 3,000’ appear to have increased more in the South-Central Subregion than for most of the other Subregions.)

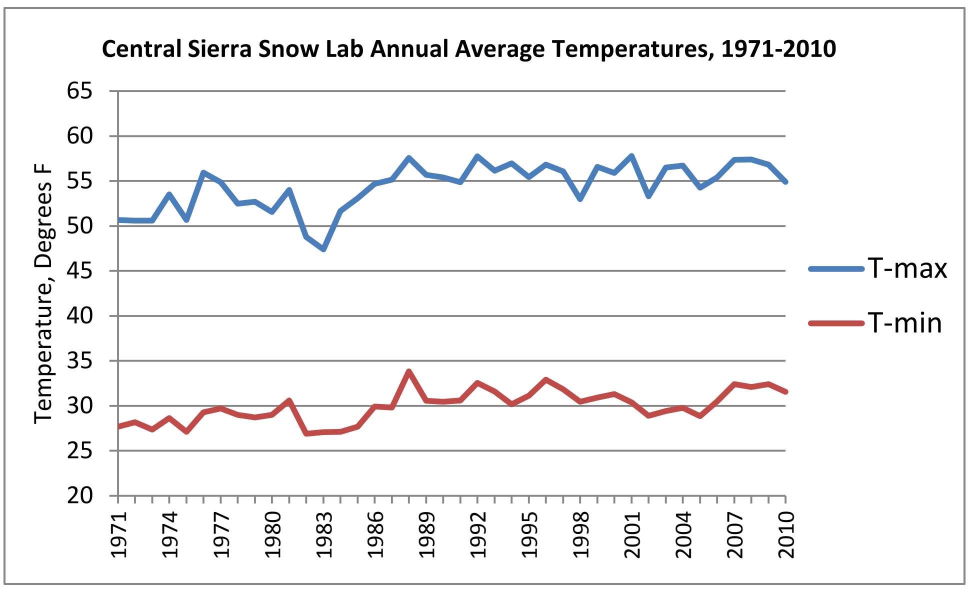
In all cases, average nighttime low temperatures at higher elevations have risen faster than at lower elevations.







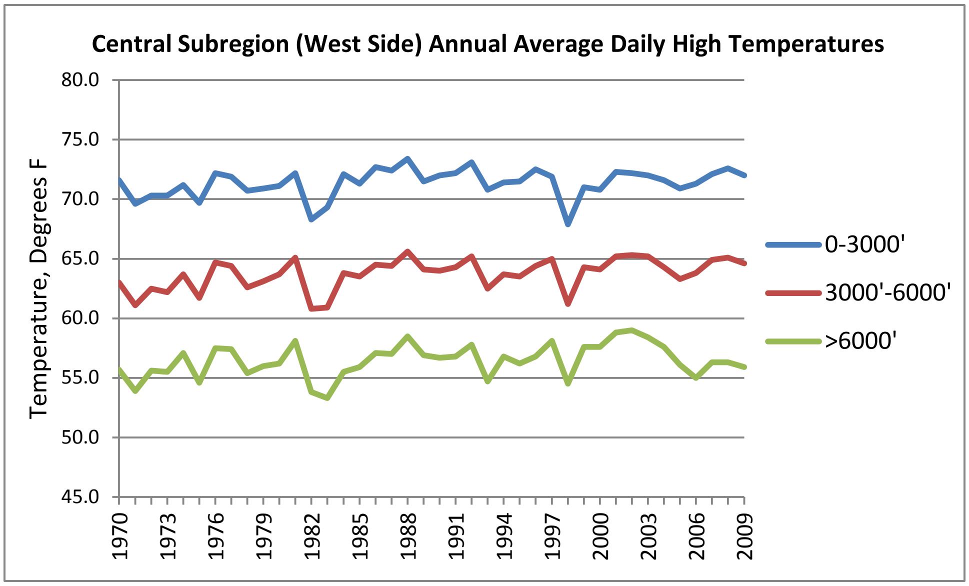
While the PRISM data is the best comprehensive measure of temperature in the Sierra Nevada available, it is a modeled data set, meaning that it takes actual temperature measurements and applies sophisticated techniques to estimate temperatures between the known points to create a temperature grid of the Region. In rural and high elevation areas, there are fewer physical readings from which to develop the database than in more populated areas, so there is less confidence in the accuracy of the modeled data. Therefore, a detailed temperature measurement history from the Central Sierra Snow Lab, operated by UC Berkeley, was used as a means of corroborating the trends identified using the PRISM data analysis. Annual averages of daily high and low temperatures were developed from daily data over the past four decades supplied by the Snow Lab. A graph of annual average daily high and low temperatures is shown below. The Snow Lab is located at approximately 7,000' elevation at Donner Summit, and so compares to the elevation band on the other graphs of >6,000' where increasing temperature trends are the strongest.

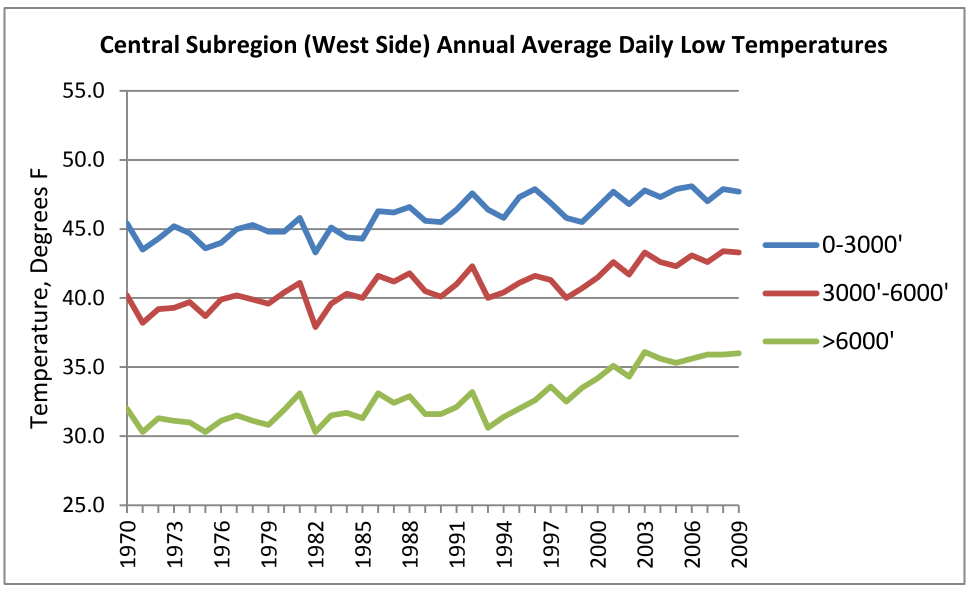


At the Snow Lab, annual average daytime ***high*** (T-max) temperatures are substantially higher now than 40 years ago, though the trend has been somewhat erratic, and daytime highs show no sign of increase since the mid-1980's. Average annual ***low*** (T-min) temperatures have also risen over the past 40 years, in a similar pattern. The vertical scaling on the graph make the trend appear flatter than the other charts, but the actual nighttime temperature increase has been similar to the Subregional PRISM data. A conservative analysis of the Snow Lab daily low temperature data indicates a temperature rise of approximately 3^{o} F from 1971 to 2010[3]. The South-Central Subregion nighttime lows indicate a 3 to 3.5 degrees F rise from 1970-2009.

[3] A centered 5-year moving average was applied to the T-min data, smoothing out annual variations. A linear trend line was then run on the moving average. The temperature increase over the shorter time span of the moving average (1973-2008) was 3.0 degrees F.

It should be noted the Central Sierra Snow Lab is located in the Central Subregion. The graphs of Central Subregion for both daily high and low temperatures are shown below. The trend for average annual daily high temperatures above 6,000' is fairly similar to the Snow Lab nighttime low temperature trend. However, the annual average daily low temperatures above 6,000' indicate a particularly rapid increase in temperatures over the past 15 years which is not indicated at the Snow Lab location. Further assessment is warranted to determine if this is because the Snow Lab location is not indicative of average high elevation temperatures in the Central Subregion, or if there is a problem with the PRISM modeling in this area.



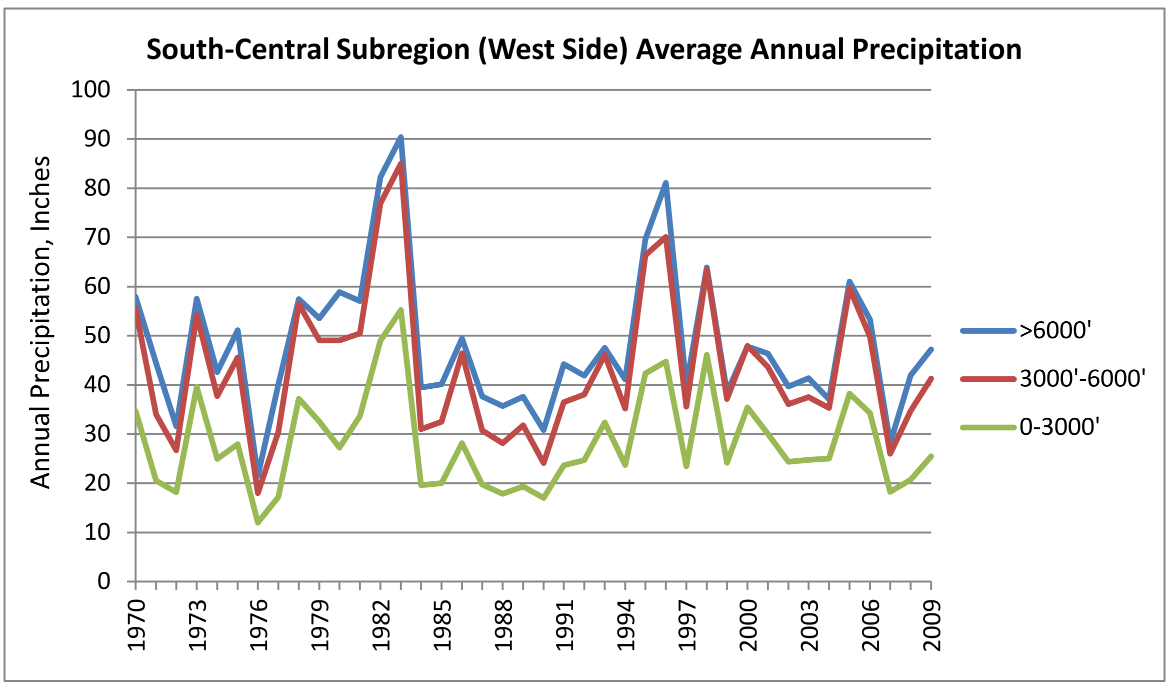


The PRISM (Parameter-elevation Regressions on Independent Slopes Model) data sets are developed by the PRISM Climate Group at Oregon State University. PRISM is a knowledge-based system which uses point measurements of temperature, precipitation, and other climate factors to create continuous, digital elevation-based mapping coverage through GIS (Geographic Information system). SNC utilized an 800 meters elevation-based raster set to provide continuous temperature and precipitation layers specific to the SNC Region. PRISM is utilized by USDA Forest Service, NCRS, and NOAA (National Oceanic and Atmospheric Administration).

Precipitation

Unlike temperature, there is no meaningful trend in the amount of rain or snowfall. Linear trend lines (not shown) applied to the Subregion graphs indicate a slight decrease in precipitation generally over the past 40 years. However, because the trend is slight and highly influenced by the first and last years in the data sets, this trend really cannot be viewed as significant. If there is a gradual change in the average precipitation in the Sierra Nevada occurring now or in the future, it will take a much longer timeframe to bring it to light. The data sets that have been created as a result of the Sierra Nevada System Indicators Project provide a framework for identifying potential future long-term changes in precipitation between Subregions, different elevations, or for the Region as a whole.

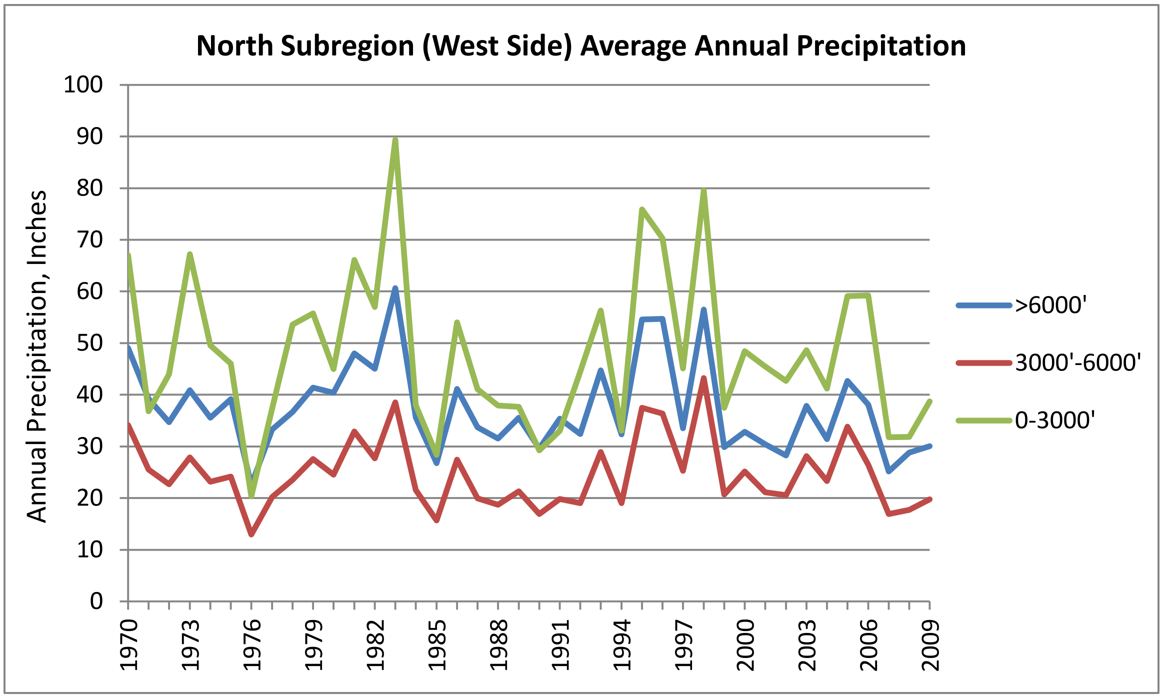
The data do allow us to compare the differences in precipitation levels at different elevations and among Subregions. These comparisons tell us that precipitation patterns in the South-Central (shown below), Central, and North-Central Subregions are fairly similar. They also tell us that precipitation is greater above 3,000’ than at foothill elevations for most of the Sierra Nevada. The exception is the North Subregion (see chart on next page). With lower mountains but extensive high plateau, it has a quite different elevation rainfall pattern. Here, the heaviest rain falls below 3,000’, while the plateau elevation within the 3,000’- 6,000’ elevation band

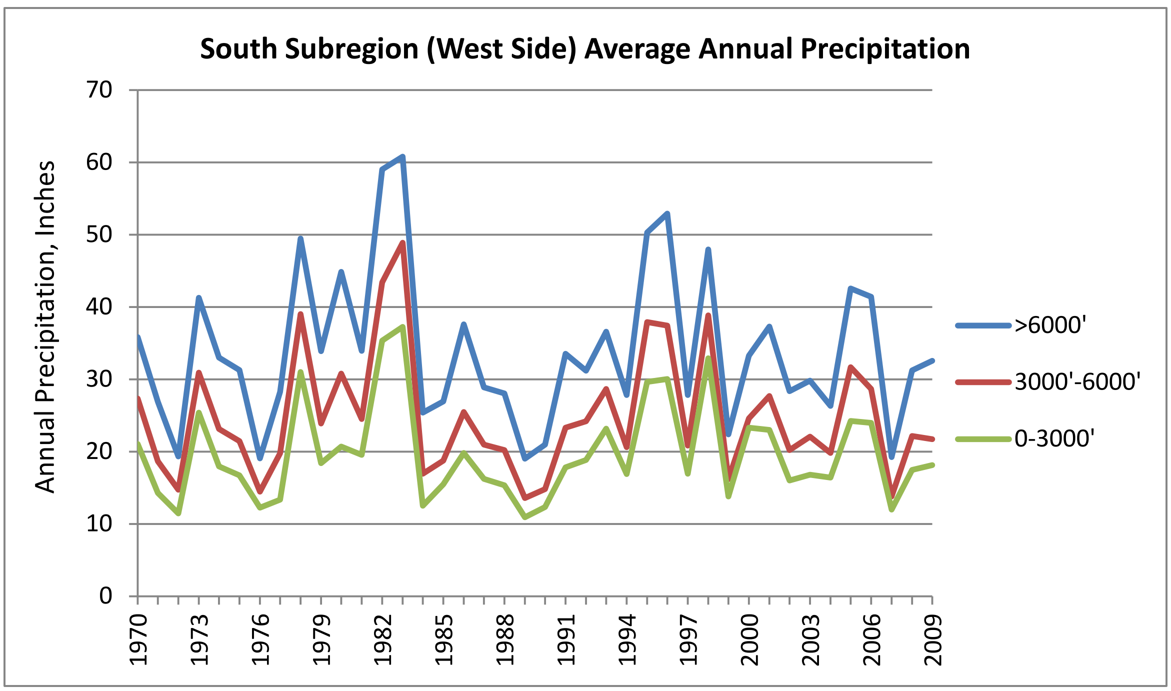


receives the least precipitation.

The South Subregion (see chart on next page), with its high peaks, receives proportionally heavier snow above 6,000’ than other west facing Subregions. The East Subregion (chart not shown), in the rain shadow of the mountains, receives the least amount of rain and snow. This Subregion receives only 5 to 10 inches of precipitation per year averaged over the elevations between 3,000’ and 6,000’. While elevations above 6,000’ receive considerably more precipitation, it is still significantly less than what is received at those elevations on the west slope of the Sierra.

Below are two Subregions with very different precipitation patterns.





Snow Pack

In California, most of the precipitation falls during the winter while much of the need for water, particularly for agriculture, is in the summer. The Sierra Nevada provides an invaluable service by capturing a tremendous amount of precipitation as snow and storing it as snowpack for gradual release through the spring into scores of supporting reservoirs for distribution to the rest of the state.

Because California is so dependent on the supply of water that flows from the snowpack each year, the Department of Water Resources (DWR) measures the snow and estimates the water that will be available for the coming year. DWR reports to the public the year's snowpack depth as a percent of average annual snowpack, rather than the number of inches of snow that has fallen. Also, the snowpack depth is converted to inches of 'snow water equivalent' (Snow WEQ). There are good reasons for this; it is vital to know how much water the winter's snow will provide. Measuring snowfall is problematic. Snow may fall relatively 'dry' and fluffy (full of trapped air on the ground) or wet and heavy. Simply, cores of snow are taken down to the ground surface with a metal tube, the depth is measured, the snow is weighed, and converted to the number of inches it would be in the tube if it were melted.

The DWR Cooperative Snow Surveys ('cooperative' because DWR relies on cooperating partners such as the Forest Service, irrigation districts, and PG&E to take measurements in their geographic domains) measures more than two hundred snow courses scattered throughout the mountains multiple times throughout the snow season (on or as close as possible to the first day of each month).[4]

Although there is large variability from year to year in the total amount of snowfall in the Sierra, where it falls across the Region, and how quickly the snowpack melts, it is possible to use different data sources to uncover a consistent picture of the trends in annual snowpack across the Region. The following analysis shows that the year-to-year ***pattern*** of snowpack creation and melt is quite consistent across the Sierra wherever it is rigorously measured. While there is no significant trend indicating that average annual snowfall/snowpack is increasing or decreasing in the Sierra overall, there is a clear trend that snowpack is melting earlier (or more late-season snow is falling as rain instead). As shown in the various following charts comparing March and April snowpacks, the equivalent of several inches of water has been lost between April 1st snowpack as compared to the March 1st snowpack over the past 20 years or so.

The importance of April 1st snowpack

April 1st is the most important snow measurement of the year, and is the primary benchmark for estimating water availability and comparing years. Generally, most of the year's snow has fallen by then and little snow has yet melted with the onset of spring. In most years, the snowpack is deepest then. Because of its importance, more snow courses are measured for April than in other months, as many as 250, in order to provide the most accurate estimate of total snow-water volume for the year.

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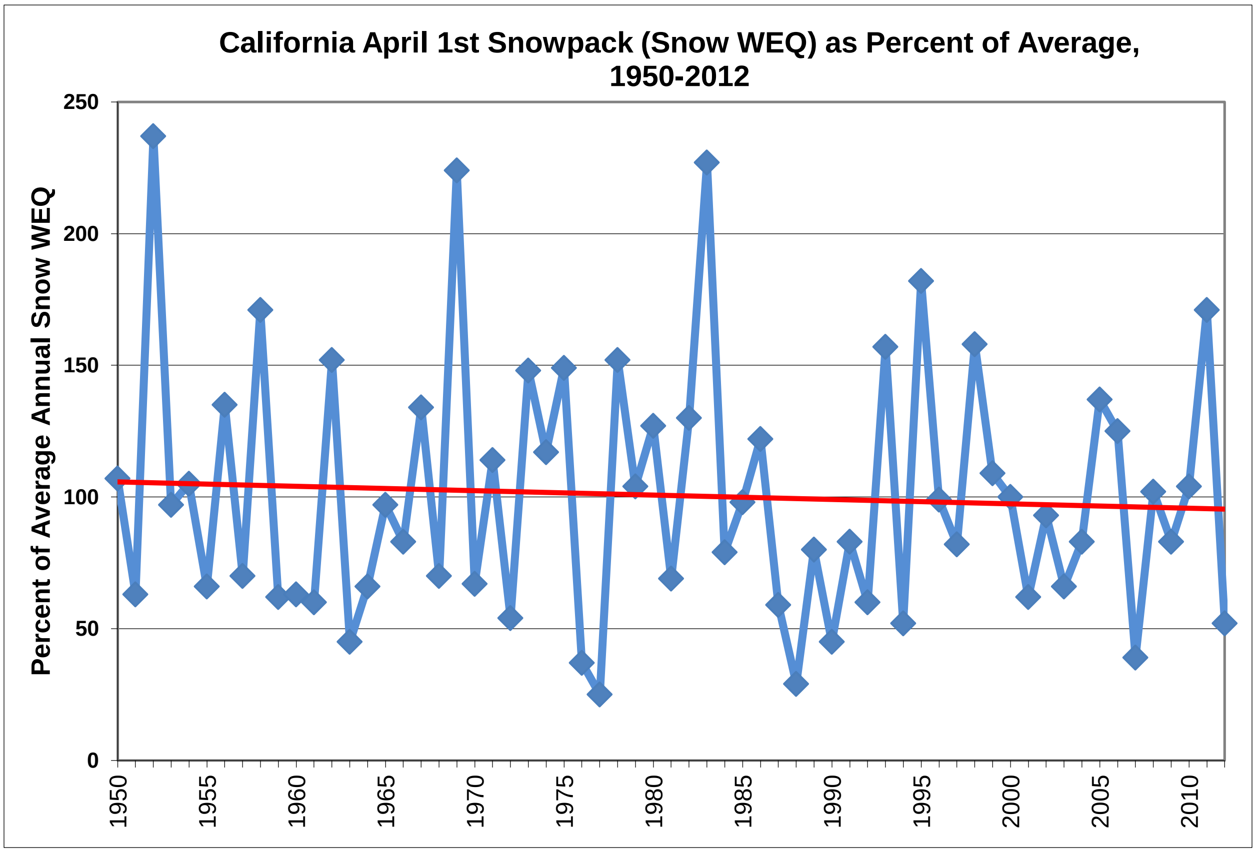
[4] Data for snowpack was acquired from the Department of Water Resources CDEC (California Data Exchange Center) site, as well as directly from the DWR cooperative Snow Surveys Chief.

The chart below graphs the April 1st Snow WEQ from 1950 through 2012 as a percentage of average April 1st Snow WEQ. Snow WEQ varies greatly from year to year, from nearly 240% of average in 1952 to only 25% of average in 1977, a ten-fold spread. This makes it challenging to discern any real trend. The red line on the chart is the linear trend line – but it is shown for illustrative purposes only. While it indicates an 8 - 10% decline in April 1st snowpack statewide over the past 63 years, the trend line cannot be taken to be meaningful. With such wide swings from year to year, the trend line is very sensitive to even one year of extreme data, even over six decades. For example, if the graph did not include the first three years, which include the huge 1952 snowfall, the resulting 60 year trend would not show any noticeable decline. If the graph ended with the heavy snow year of 2011 rather than including the low snow year of 2012, the trend line would also be much flatter. A more sophisticated approach is needed to



assess any real decline (or increase) in snowpack.

Another problem with analyzing snowpack in this way over a long period is that 'average' changes over time. For quite a long time, the 'average' that is being used for comparison has been the mean of the 50 year period from 1950 to 2000. That is expected to change soon, with the new average being 1960 to 2010. Of course, the raw data can be adjusted for the new average, but it would be cumbersome over the long haul. A better way is to analyze real Snow WEQ data measured in inches rather than looking at it as a percent of average.

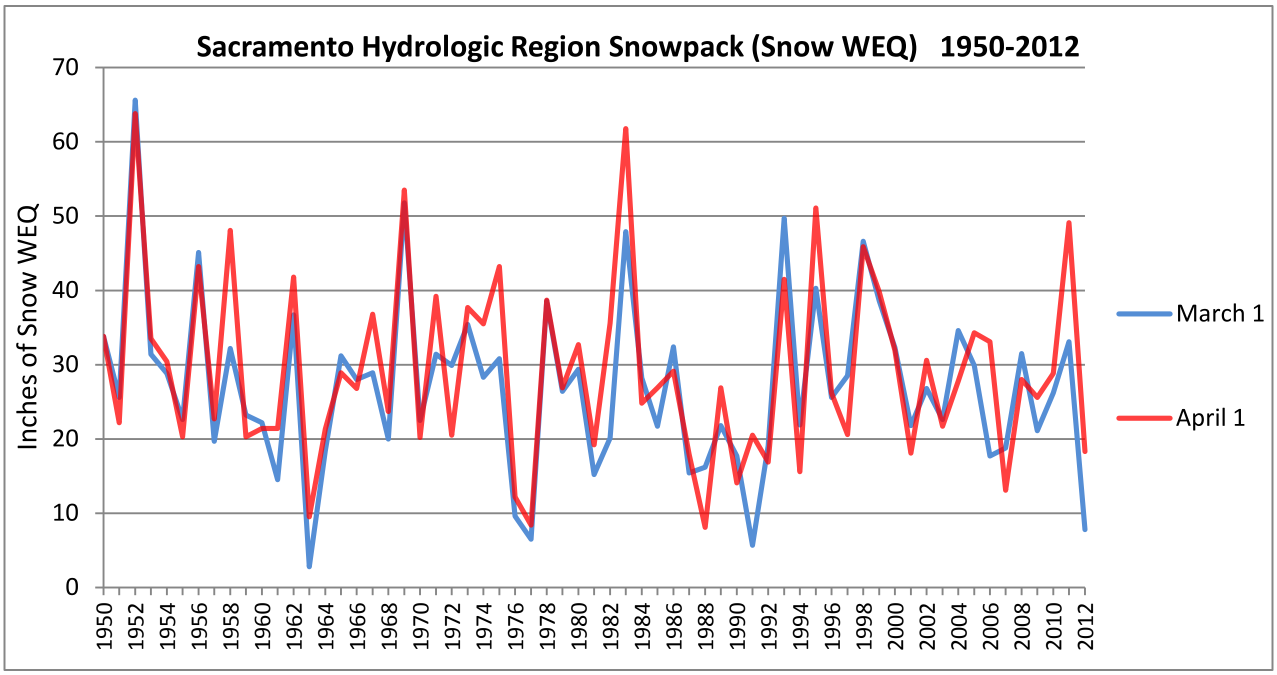
Using actual Snow WEQ measurements

Measuring snowpack in inches of Snow WEQ affords an unchanging, objective standard for comparing years. In addition, we would like to be able to analyze changes in snowpack regionally rather than just at the state level. Figures are available in inches of Snow WEQ, averaged for each of the state's hydrologic regions.

There are six hydrologic regions that contain all the mountain areas that are covered by the Cooperative Snow Survey. Only the North Coast is irrelevant to the SNC Region. The five hydrologic regions that encompass the Sierra Nevada are the Sacramento, San Joaquin, Tulare, North Lahontan, and South Lahontan.

Comparing April 1st and March 1st

The chart below is for the Sacramento Hydrologic Region (which includes the Pit, Feather, Yuba, and American River watersheds) and shows snowpack in inches of Snow WEQ rather than percent of average snowpack. The April 1st snow course measurement averages are the red line. As expected, the year to year pattern of snowpack for this large region is quite similar to that of the overall state, whether reported in actual depth of snow or as a percent of average snowpack. Close to 80 snow courses are measured on or about each April 1st in this hydrologic

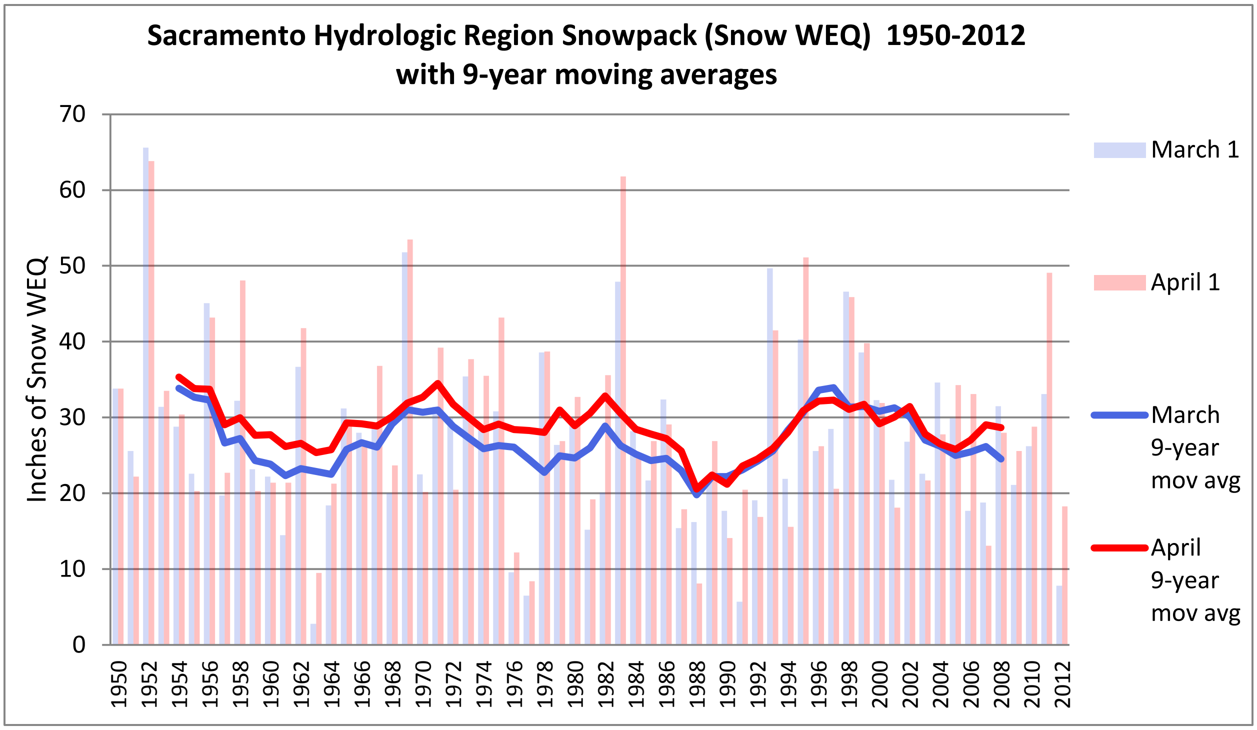


region to produce an average snowpack measurement for each year. As it was for the state in general, 1952 was the biggest snow year, with 63.8 inches WEQ in April. 1977 had only 8.4 inches, though 1988 had even less at 8.1 inches WEQ.

The chart also includes the March 1st snow course measurements for the Sacramento Region. A visual inspection of the chart reveals that in most years, but certainly not every year, the April 1st snowpack (in WEQ) is deeper than March 1st. In discussions with Frank Gehrke, the DWR Snow Surveys Chief, it was thought that comparing snowpack depth between March and April over time would highlight any changing relationship between the two measurement periods.

Because April 1st is taken to be the time of year that the snowpack is deepest, if the average April 1st depth decreases relative to the March 1st depth, it would indicate that either less snow was falling in late winter or snow was beginning to melt earlier.

The chart below is the same as the one above (converted to a bar chart), except that a 9-year moving average for each of the two months is added. The 9-year moving average is much more informative than a simple linear trend. It indicates changes throughout the time period rather



than taking the time period as a whole; and is not subject to the distortions of the beginning and end points of the time series. It aids analysis by evening out the large year-to-year variations into 9 year groupings.[5]

As indicated in the charts above, in some years the April 1st snowpack (in Snow WEQ) was a foot-or-more deeper than March 1st while in other, albeit fewer, years the March 1st snowpack was deeper than April. What's most interesting, however, are the more general patterns revealed by looking at the 9-year moving average. From the mid-50's through the mid-80's, the 9-year moving average for the Sacramento Region shows April 1st snowpack to *average* typically 3 to 5 inches deeper than March 1st during this time period. However, that gap closed up in the late 1980's and since that time, on average, April and March snowpack depths have been about the same. This more recent trend has been interrupted by the last two winters; for while 2011 had far above average snowfall and 2012 was far below average, both years had substantial March snows, which are reflected in a re-emerging gap in the 9-year moving averages. This serves to highlight that this analysis is not predictive. However, if over the coming years and

[5] The trend lines start as the average of the first 9 years as the data point for the middle year of that group, and then shifts the average each subsequent year (e.g. the average of 1950-1958 becomes the data point for 1954, the average of 1951-1959 becomes the data point for 1955, and so on).

decades, the moving average of the April 1st snowpack should continually fall at or below that of March 1st, it would document earlier snowmelt in the Sierra than the recent historical pattern.

The analysis above was just for one hydrologic region. Each of the five hydrologic regions encompassing the SNC Region has its own history, but the overall patterns for all five are similar. However, unlike the Sacramento hydrologic region, most of the regions still average a slightly deeper snowpack on April 1st than on March 1st. The charts of the other four hydrologic regions are included in the appendix.[6]

Beyond the March-April comparison, the data for the hydrologic regions do illustrate differences in regional amounts of late season snowpack. The Eastside regions – North and South Lahontan – receive less snow than the Westside (which is certainly not news), while the Sacramento hydrologic region averages a bit less March and April snowpack than the more southerly San Joaquin and Tulare regions. Tulare is the only hydrologic region where overall annual snowpack appears to have increased somewhat over the past half century.

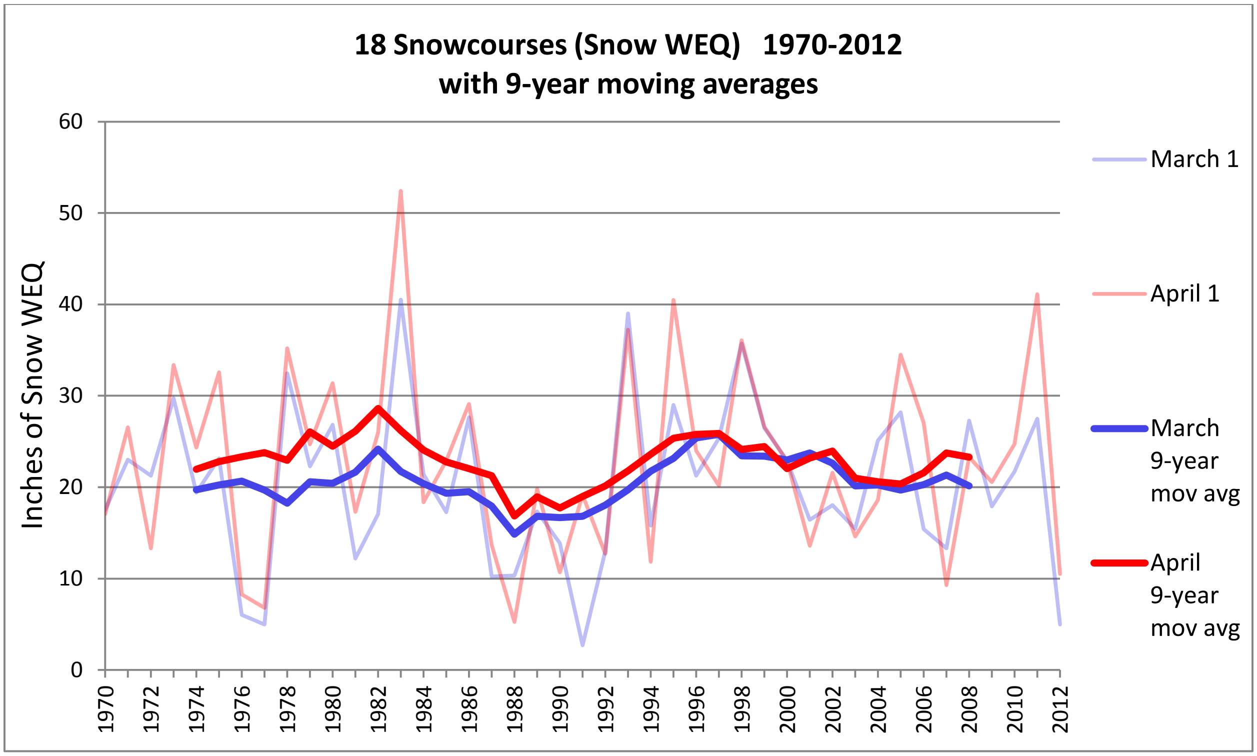
Verifying with single location measurements

To the extent possible, the DWR Snow Surveys collects data for the same snow courses year after year. Measuring the same courses provides year-to-year data consistency and measuring a large number of courses provides the best estimate possible of the average regional snowpack depth and resulting total volume of water.

In a typical year, the April 1st Snow Survey includes almost 80 snow course measurements in the Sacramento Hydrologic Region, about 70 in the San Joaquin Region, about 45 in the Tulare, 17-18 in the North Lahontan, and about 20 in the South Lahontan. The March 1st Survey generally includes five to ten fewer snow courses than April. However, through the measurement history, data gaps emerge in many of the snow courses for either April or March.

As a supplement to the hydrologic region averages, an analysis was made to identify individual snow course locations where there is a complete record for both March and April for a long time frame with no missing years. An SNC review of data provided by DWR, covering 1970 to 2012 (43 years), yielded 18 snow courses that had Snow WEQ measurements for both months for all 43 years. (Almost 100 more were missing only one year or just a few years for either March or April.) These 18 courses are spread across the Sierra, from the Pit River watershed in the north to the Kern watershed in the south. Taken together, these 18 snow courses provide an excellent cross section of Sierra snowpack from year to year. The snowpack Snow WEQ was averaged for the 18 courses, and are displayed along with 9-moving averages on the chart below.

[6] Note: DWR does not have March data for the South Lahontan region before 1958, and there were only 2 snow courses measured in 1958, and so was not included.

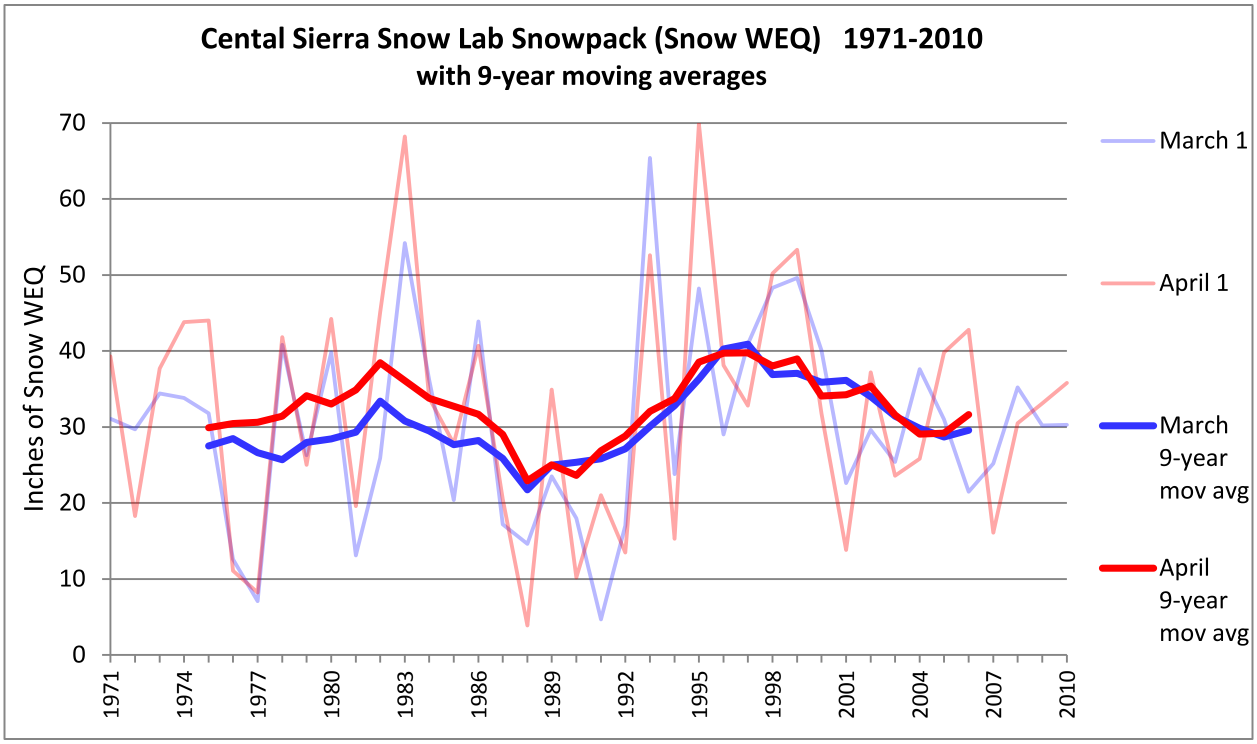


Over the same time period (1970-2012), this graph is barely distinguishable from the Sacramento Hydrologic Region graph, especially in the moving-average relationship between March and April snowpack. The amount of average snowpack for these combined 18 snow courses is less than for the Sacramento Region, but the year-to-year patterns are the same. In other words, using a targeted set of snow courses with complete data is entirely consistent with the hydrologic region-scale analysis.

Data from the Central Sierra Snow Lab

The UC Berkeley Snow Lab, located at 6,900' elevation at Donner Summit, provides the most detailed single location snow analysis in the Sierra Nevada. Although they take much more frequent snow measurements than just monthly, the March 1st and April 1st Snow WEQ was graphed to provide yet another single location comparison under the same parameters. The chart, including 9-year moving averages, is shown below. The time series is slightly different; it starts into 1971 and does not include 2011 and 2012.

Once again, the relationship between April and March is entirely consistent with all the other data sets. Because it does not include 2011 and 2012, both years of which had heavy March snows throughout the region, a growing gap between the March and April snowpacks after 2010 would be expected, as with all the other data sets from the influence of these years on the moving average.



Conclusion related to snowpack

This analysis clearly demonstrates a decline in April 1st snowpack relative to March 1st, and also indicates some degree of actual decline in average April snowpack depth, though it does not quantify the change. It does appear that the relative decrease in April snowpack compared to March is in the range of perhaps several inches of Snow Water Equivalent, which is quite substantial, given an average April 1st snowpack depth in the range of 20 to 35 inches of Snow WEQ. A Department of Water Resources report claims a 10 percent decline in April snowpack over the past century, with presumably much of this decline since 1950.[7] That report employed a very different analysis in its finding – assessing runoff water flow changes rather than snow depth changes to indicate reduced snowpack. This SNC report provides a different strategy to look at snowpack change that is potentially complimentary, and certainly points in the same direction.

[7] 2008 DWR report "Managing an Uncertain Future: Climate Change Adaptation Strategies for California's Water." This report states that early spring snowpack in the Sierra Nevada has decreased by 10% in the past century. The methodology used a "full natural flows" approach that looked at percent changes to April through July water flows.

Precipitation, Temperature, and Snowpack Relationships

There are three important questions to ask when considering potential future changes in snowpack (and hence the timing of California's water supply): 1) is there a long run change in precipitation? 2) Is more (or less) precipitation falling as rain rather than snow? And 3) is snowpack melting earlier (or later)?

As to the first question, at this point there is no clear evidence of significant change in total precipitation in the past four decades. The year to year variation is so great that it would take many years or decades to tease out any real change in the rainfall pattern.

For any particular elevation, the second and third questions are primarily dependent on any specific changes in temperature – the season and the actual temperatures. Depending on elevation and ambient temperature, warming weather may cause more rain (rather than snow) and faster snow melt. There is substantial evidence of generally warming temperatures, dependent on elevation and time of day. What has not been investigated yet is if indicated warming is occurring in any particular season. That is another level of analytical complexity yet to be tackled.

Question number 2 is the most difficult to address. There is not really a system in place (that we have been able to find) to measure whether precipitation is falling as rain or as snow on a geographic scale. The Central Sierra Snow Lab does consistently note observations proportioning precipitation as to rain or snow. With considerable effort, over time, a relationship could be determined on how much snowpack loss is due to melting and snow not falling in the first place. However, a single location provides a weak basis for a regional assessment.

Regarding question 3, if April 1st snowpack in any one year is less than March 1st snowpack, we know that more snowpack melted than new snow fell, and that April 1st is not the best date to characterize the annual snowfall. If April 1st snowpack is greater than March 1st, we know that some snow has fallen, but it challenging to determine if there was also increased rain and/or snow melt that reduced the potential snowpack for that month.

At this point, the data for rising temperatures does correlate with a relative decrease in the amount of April 1st snowpack compared to a month earlier.