UNIVERSITY OF CALIFORNIA

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CLIMATE CHANGE AND SIERRA NEVADA SNOWPACK

A Thesis submitted in partial satisfaction

of the requirements for the degree of

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in

Geography

by

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INTRODUCTION

In California, almost all precipitation occurs in the winter and spring months while the summer and fall are dry. Half of California's water resources accumulate as snow and are stored within the snowpack until it melts, usually beginning around the first week of April. With a system of reservoirs and aqueducts, snowmelt is routed primarily to agricultural areas throughout the state in the summer, when irrigation water is needed most. This fresh water reserve system of natural and engineered storage is potentially vulnerable to changes in climate. In order to understand how water resources may be affected by future changes, it is important to analyze how they have responded to variations and changes in the 20^{th} Century.

Climate research has revealed changes that occur quickly, as if the system jumps past a threshold and enters a different set of probable weather patterns. One of these "steps" was discovered to have occurred throughout the Pacific Ocean and the Americas in 1976 (Ebbesmeyer et al., 1991). Time-series analyses of 40 multidisciplinary variables, including oceanic, atmospheric and biological data collected from 1968 to 1984, indicated a consistent shift in 1976. These results of fish catch, winds, El Niño Southern Oscillation strength, chlorophyll, etc. were compared with a random simulation to emphasize the certainty of this step.

About ten years ago, a hydrologist at the Department of Water Resources (DWR), noticed that the spring and early summer fraction of total annual streamflow had been decreasing in the Sacramento area (Roos, 1991). Correspondingly, a decrease in the April-July fraction was reported across California (Wahl, 1991). However, the total flows have not significantly changed in these four main Northern California rivers. Since these calculations were run on unimpaired streamflows, the effects of dam building were removed. Mr. Roos suggested that the cause could be a general trend towards increased precipitation and warmer weather.

Historic weather records do show that central California mountainous regions have undergone significant warming during the last 50 years in January, February, March, and June. The winter surface-air temperatures have increased an estimated 2°C since a minimum near 1950

(Dettinger and Cayan, 1995). This warming has had a greater effect on streamflow from lower elevation river basins than the higher ones (Dettinger and Cayan, 1995). Further studies investigating river runoff suggest that winter and early spring streamflow have increased in the northern Sierra Nevada due to higher temperatures and rain on snow events in lower elevations, which cause earlier snowmelt (Pupacko, 1993).

While precipitation most strongly influences streamflow at lower elevations, changes in Sierra Nevada streamflow during May, June, and July, are influenced mostly by temperature at elevations above 1000 meters (Aguado et al., 1992). The highest streamflows are governed by the overall amount of snow water equivalence (SWE) (Cayan et al., 1993).

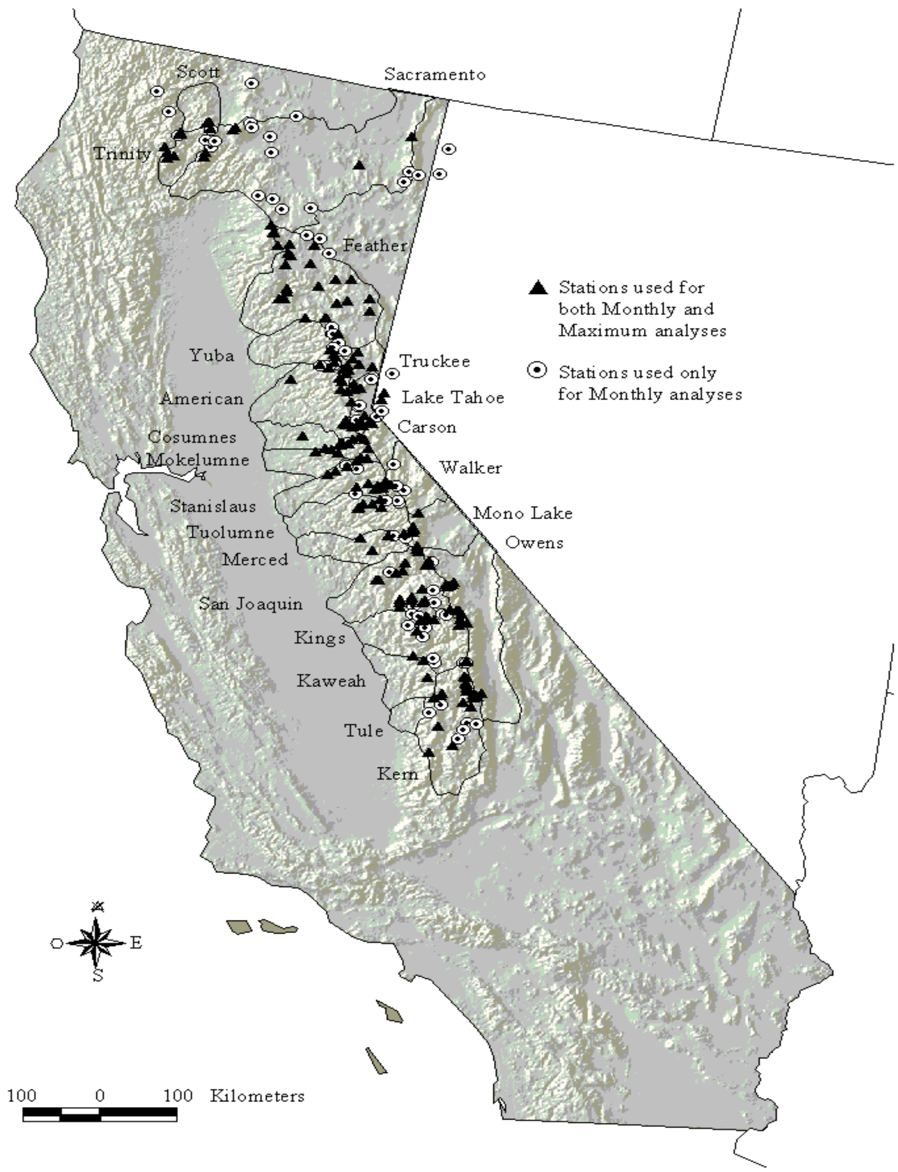
General circulation model (GCM) scenarios for an expected doubled-CO_2 climate in the next several decades show greater warming in western North America in winter, 4-6°C (Mitchell et al., 1990). Utilizing 3 GCMs, average California temperatures were predicted to increase 3.8°C while winter temperature increases averaged 3.5°C and ranged from 1.3°C to 5.0°C (Lettenmaier and Gan, 1990).

Along with elevated temperatures, many climate models predict more precipitation, too. The mountain climate response to these changes is that snowpack will first increase with the additional precipitation. However, this trend will reverse as higher temperatures raise the snowline (Barry, 1990).

A site in the Sequoia National Forest at 2813 meters above sea level was modeled using the doubled-CO_2 GCM outputs, coupled with an energy-based snowmelt runoff model. Predicted snowmelt runoff hydrograph changes ranged from 19 to 93 days earlier, depending on which temperature inputs were used. The SWE is also estimated to dramatically decrease by 14% to 60%, with the snow season ending a month or two earlier (Tsuang and Dracup, 1991) (Lettenmaier and Sheer, 1991). Calculations also suggest increased winter flood risk, when the reservoirs are already full (Lettenmaier and Gan, 1990). Elevations below 2300 meters were most affected (Tsuang and Dracup, 1991).

These findings suggest earlier snowmelt runoff and possibly increased annual precipitation. However, specific changes have been unclear since streamflow integrates snow accumulation and melt throughout the season and across all elevations of entire river basins. This research uses historical snow data collected at specific sites on a monthly schedule to analyze these trends at a higher spatial and temporal resolution.

Monthly Snow Course Data



The California cooperative snow courses are designated, flat open areas a thousand feet in length. Ten samples are collected along a transect and averaged to provide one monthly measurement, usually several times a year until the time of melt, which averages one week before April. Cooperative snowcourse surveys provide SWE data for 393 snow courses spanning 9° latitude, 7° longitude and 3450 meters in elevation (Figure 1) and are accessible via the world wide web (http://snow.water.ca.gov/). These stations are remotely located, away from developing areas that may introduce uncertainties such as an urban heat island effect. This is the tendency for urban areas to maintain a higher nighttime temperature minimum than the surrounding landscape (Klein and Goodridge, 1994).

The first courses were measured in 1910, and most contain over 50 years of monthly SWE and snow density measurements, which were collected from zero to six times per season. Most stations were sampled at least four times per year, within a few days from the first of February, March, April and May. Many of these courses were created and regularly sampled in the 1930's, with sampling increasing steadily until more stations were added in the 1950's.

The courses were sampled with the Mount Rose sampler by experienced samplers and field notes were later checked for arithmetic errors. The number of samples taken changed after 1940, when 10 samples were averaged instead of the former 25 per course. Moved courses were usually assigned a new station number, although some stations are suspect.

METHODS

Data Reduction

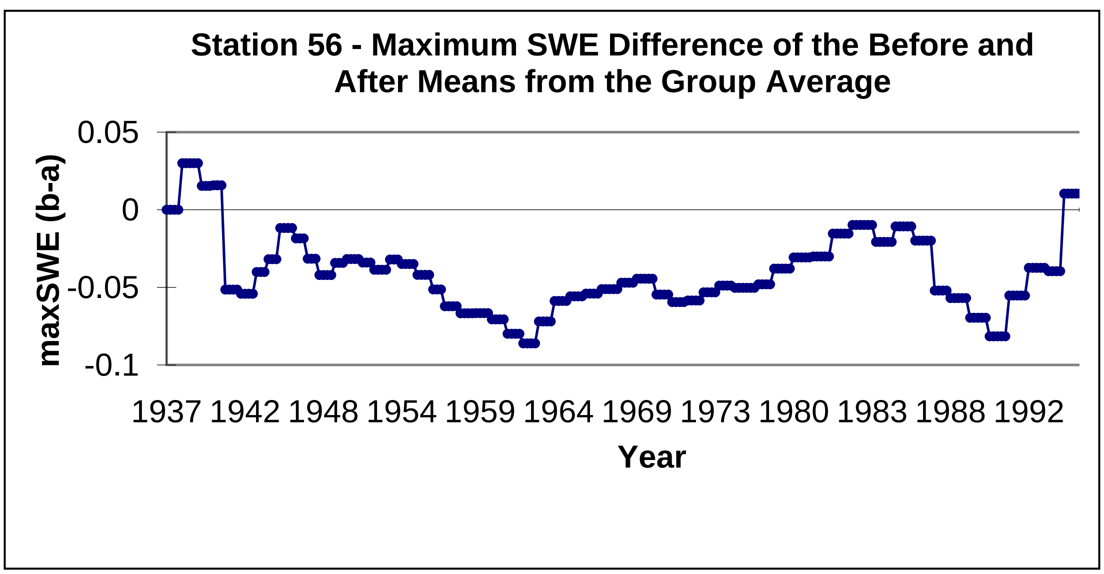
All available snow course data through the 1996/1997 water year were downloaded from the DWR web page. This file included 51,168 SWE and depth measurements for 394 stations, representing 18,298 station-years with data. Of these data, one measurement was discarded because its SWE value was 800 inches, an obvious error. Thirteen additional observations were eliminated because they had impossible densities, as calculated from the SWE and depth measurements. This left 51,154 observations with the same number of stations and station-years as before.

Although these measurements are of exceptionally high quality, these data present several challenges for climate analyses because they were collected for water resources management and were not consistent from year to year. The average day that monthly sampling was conducted changed by 3.2 days over the time series, occurring earlier in recent years. Furthermore, stations were added and removed throughout the years and these newer stations were not evenly distributed by elevation, which accounts for about 6% of the SWE variability (Aguado, 1990).

Discontinuous Stations

To identify possibly altered stations, I generally followed a procedure for detecting discontinuities in historic temperature data (Easterling and Peterson, 1995). First, each station's measurements were normalized to account for differing elevations, which is most responsible for snow variability after overall seasonal wetness. Stations were then grouped by river basins and elevation bins with at least 5 nearby, highly correlated reference stations. Group averages were subtracted from station data and the differences were plotted in a time series to find discontinuities.

These normalized differences from group means were then checked for sudden changes, which indicate possible alterations to a particular station. Calculating means before and after every station-year, and subtracting the difference did this. Every station had a number for every year with data, which represented any changes in the data before and after that year for that station. Large positive or negative differences pointed to possible station discontinuities. The first and



last 10 years with data were not considered in the difference of before and after means analyses because of edge effects.

Potential problem stations were defined to have trending differences that also exhibited extreme difference of the mean values. Station 56 is the most obvious example of the 33 stations removed that there could be a discontinuity, in this case near 1962 (see Figure 2). All stations with trending mean differences also contained years that were two standard deviations from the mean. These stations, although most likely unmodified, were discarded to err on the side of caution. These eliminated data are distributed throughout the range, at all elevation bins and trend positively from the mean about as often as negatively. The remaining 361 stations cover 45,237 station measurements, which is 88% of the original data.

Climate Criterion

The next criteria for inclusion in the analysis were a minimum 30-year range with at least 10 observation years. This dataset included 37,520 observations for 260 stations representing 14,151 station years.

Monthly Dataset

Like the previous requirement, the dataset for monthly analyses required a minimum 30-year record with at least 10 years with observations for a given month. In addition to this, at least 3 years per decade for each month were required. This resulted in 33,941 observations for 259 stations and 808 station-months.

January and June were omitted due to sparse data. This left 33,215 observations for 259 stations covering 782 station-months (see Figure 1). The resulting monthly data distribution, including January and June, is given in table 1.

Observation Characteristics by Month

	Jan	Feb	Mar	Apr	May	Jun
Obs	700	7733	7351	13,574	4383	26
Range	81	76	80	88	81	52
Stations	25	191	188	259	144	1
% Complete	67%	84%	80%	98%	78%	50%

Table 1

Station-Year Maximum Dataset

To determine station-year maximum SWE values and timing, I reduced the monthly dataset in the following ways: stations were selected for time series analyses that had at least 3 measurements per year and 10+ years of measurements covering 30+ years. These data also had to meet the following quality assurance: the day of maximum SWE was not simply the last day measured unless that month was the average month of melt and it was an average-to-wet year. This criterion discouraged false snowmelt timing calculations due to sampling bias, yet accounted for precipitation variability and associated snowmelt fluctuations.

Seasonal maximum SWE and the month of maximum SWE were computed for each station, then these values were normalized by dividing yearly amounts by station averages. This resulting wetness factor can be compared to other stations in various latitudes and elevations with different SWE levels. Where a station-year's maximum SWE occurred in more than one month, the later month was selected as the timing of melt.

Maximum Dataset Quality Assurance

Whereas the monthly dataset quality assurance was fairly straightforward, the time of maximum SWE dataset was much more difficult to substantiate. I felt that it was important to distinguish any possible snowmelt timing and maximum accumulation trends, since snowmelt timing is predicted to change so drastically in a doubled carbon dioxide atmosphere.

Usually four monthly sampling days were used to determine a time of maximum snow accumulation and an amount. The effect of monthly sampling on a regression analysis of trends in date of maximum accumulation had to be determined, and trends in sample dates further complicated the analysis. However, a trending sample time cast further doubt as to the validity of these results.

Fortunately, extensive snow sensor and precipitation measurements in the Sierra Nevada led to three different methods to verify that these trends were meaningful. About 100 daily snow sensor stations have measurements spanning a couple of decades. This was useful in two ways. First, 47 of these stations are located adjacent to snow course stations so comparisons can be made for yearly maximum SWE and monthly estimates. Second, the effect of trends in sample dates can be calculated by comparing the real maximums, as recorded by the daily instruments, with any other results generated by sub-sampling this daily dataset. With these data I compared various sample days' (in time from the first-of-the-month) effects on the month of maximum SWE determination.

The third test, which also determined the effect of a trending sample day, was to compare DWR first-of-the-month corrected SWE values with the original SWE measurements. These are data based on the measurements but corrected to what the SWE probably would have been on the first of the month. Adjusted SWE is calculated by multiplying precipitation between the sample day and the first by a correction factor.

Adjusted SWE = measured SWE * precipitation * correction factor

Precipitation is positive if the day sampled is before the first.

Correction factors are unique for each snow-rain station pairing.

Sampled Station Bias

Analyses were separated into 100 meter elevation bins to both diminish station sampling bias and to exploit the spatial snow course clarity that is missing from the river data.

Daily Snow Sensor Experiment

I used the daily snow sensor data to determine the effects of a trending sampling schedule on the time-series regressions. With daily data, I could create monthly datasets with various sampling schedules to check the effects of earlier sampling. However, first I quality checked the sensor data and found that it contained many obvious errors. I rejected the obviously erroneous data and ran a cubic spline interpolation to fill in the missing daily data. A cubic spline is a segmented function consisting of third-degree polynomial functions joined together so that the whole curve and its first and second derivatives are continuous. Missing dates were filled-in with the appropriate spline function.

Using validated daily sensor data, actual seasonal maximum SWE and the month of maximum SWE was calculated for each station. Then these real values were compared to sensor estimates using only monthly sampling to check the effects of monthly sampling. Finally, errors were calculated for both maximum SWE and the month of maximum SWE and fit to the number of days of earlier or later sampling. These errors associated with the 15 days before and after the real maximum first-of-the-month measurement were used to calculate the effect of the earlier sample timing.

I considered each day in the real maximum SWE month as the monthly sample day. This value was compared to the remaining monthly measurements, which were first-of-the-month values. This represented a perfect monthly dataset with the exception of one month off by a set number of days. The SWE value for any day was compared to the next highest, first-of-the-month, monthly SWE value to decide which of those two measurements would be classified as the maximum SWE value and month.

The error associated with a given number of days from the first could then be calculated by subtracting its results with the actual maximum SWE and month of maximum SWE values. The differences were fitted with the number of days from the first to determine the error due to an inconsistent sampling schedule. For example, daily snow sensor SWE data, dates and station information were run through a program to calculate these numbers listed in Table 2 for station

162 in May 1991. Station 162 is on the east side of the Sierra Nevada, in the Tuolumne river basin at 2562 meters above sea level. The second highest first-of-the-month SWE value is 26.6 inches and occurs in April. The actual highest measurement recorded is 27.0, which is recorded in the table with the 2nd day before the first (April 30th).

Example of Sampling Effects Calculations

SWE	*Days to the First (neg. = prev. month)*	*Different SWE (less than actual)*	*Different Month (pos. = false early)*
24.2	-14	0.4	1
23.9	-13	0.4	1
23.6	-12	0.4	1
23	-11	0.4	1
22.8	-10	0.4	1
23	-9	0.4	1
22.9	-8	0.4	1
23.8	-7	0.4	1
24.8	-6	0.4	1
25.6	-5	0.4	1
24.9	-4	0.4	1
25	-3	0.4	1
25.2	-2	0.4	1
25	-1	0.4	1
26.8	0	0.2	0
26.6	1	0.4	0
27	2	0.4	0
25	3	0.4	1
25.6	4	0.4	1
26.5	5	0.4	1
27	6	0	0
26.6	7	0.4	0
25.9	8	0.4	1
26.8	9	0.2	0
26.6	10	0.4	0
26.8	11	0.2	0
26.6	12	0.4	0
26.2	13	0.4	1
26.4	14	0.4	1
26.6	15	0.4	0
26.6	16	0.4	0

Table 2

The following explains the program that calculated the error, or difference values. It was not used to adjust any results, but only to indicate potential errors due to the sampling scheme.

The first step in the process was to filter the daily data and interpolate missing values. The day of the month and the month numbers were pulled out of the date, and these numbers were grouped so that all measurements after the 15th of the month are grouped with the following month. Years are also adjusted to water years in this way.
The days until the first-of-the-month are then calculated. I accounted for varying monthly length but I didn't calculate exact February leap year days, so February 29th readings will appear to be on the first of March.

Then I simulate perfect monthly sampling by pulling all SWE values on the first of each month. The highest monthly SWE value and month are then stored. To compare the errors associated with various sample days, the next highest first-of-the-month measurements and months are also recorded. Finally, the actual highest daily SWE measurements for each station-year are recorded.

The resulting error in maximum SWE is the difference between the actual highest SWE value and the monthly measurement. The monthly SWE used is either the maximum month daily SWE amount (the one being tested for timing effects) or the second highest first-of-the-month maximum SWE value (whichever is highest). All of these results are positive or zero, indicating how much lower the SWE result is from the real maximum SWE.

Sampling effects on snowmelt timing were calculated similarly. The month of snowmelt timing error was called zero if the given daily SWE measurement was higher than the second highest first-of-the-month SWE measurement. In this case a measurement was as accurate as the "perfect" one for determining the timing of maximum SWE, despite when it was collected. However, if the SWE value dropped below the next highest monthly sample value, it was inaccurate. The error was determined by how many months the result was off. I subtracted the second month from the real maximum SWE month, so positive numbers indicate false earlier melt.

The errors were fit to the number of days from the first-of-the-month to calculate the maximum SWE and month of maximum SWE change as the sample time changes. All station-years were used to calculate average sample timing effects.

Climate Changes

Climate cycles or steps were checked by a method similar to the discontinuous station procedure, but instead of taking differences from means of yearly group averages, each station's standardized wetness was analyzed. Calculating means before and after every station-year, and subtracting the difference did this.

The first and last 10 years with data are not considered in the difference of before and after means analyses because of severe edge effects. Very high or very low differences indicate climate change.

Time-Series Regressions

All station measurements were standardized to station means to account for changing station elevations with time. Estimated slopes were further standardized to changes per 50 years for comparison. Percent changes and absolute changes were computed for monthly, maximum and the timing of maximum for river basins above and below 2400m and 100-meter elevation bins. River basin changes are mapped throughout the Sierra Nevada and elevation bin changes are plotted.

RESULTS

Sample Timing Effects

Monthly sample timing has very little effect on measured maximum SWE. The average bias is a 0.3% reduction per day sampled after the first. The monthly sampled maximum will always be either less than or equal to the true maximum. However, there is a greater effect on the calculated timing of maximum SWE. Monthly sampling and earlier sample timing cause a false later maximum SWE timing change of 0.8 days over the 50-year period. When broken into elevation bins, the greatest schedule change of 7.2 days amounts to a false later melt of 2.1 days. Although 80% of the monthly sample days identify the correct maximum SWE month, monthly sampling creates melt-timing errors with 3.4 times more erroneous earlier melt months than false later ones.

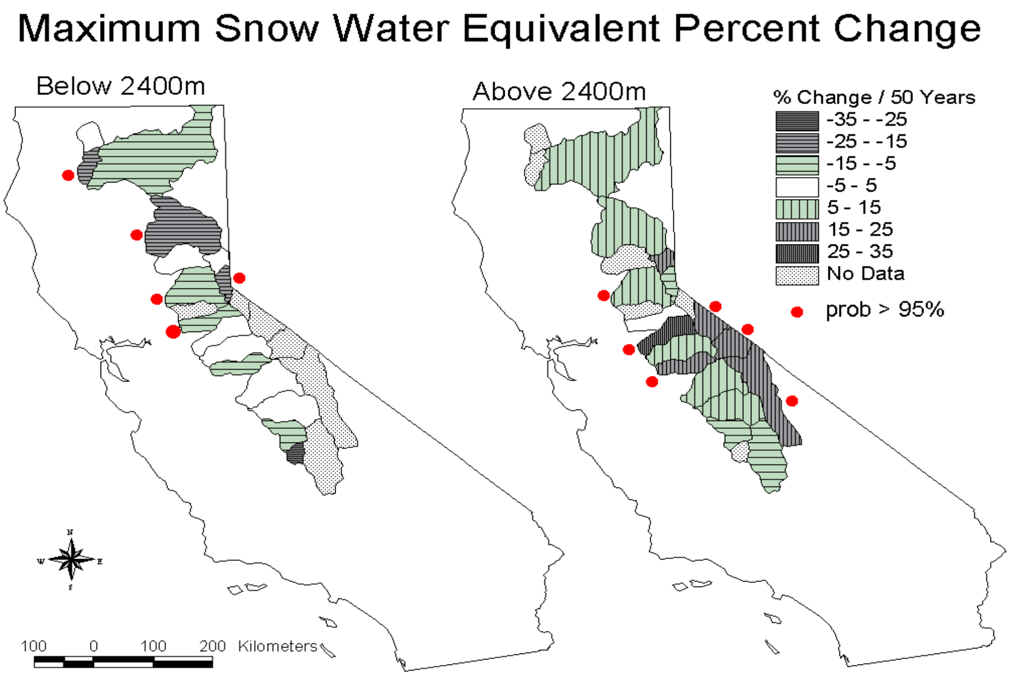
An examination of the sample data indicates that on the first-of-the-month with maximum SWE, the sampling error indicates false earlier melt. The snow is actually melting later. This is probably because the SWE levels tend to drop faster than they accumulate throughout the season. The result is that monthly measurements are more likely to catch the upside (earlier) rather than the steeper downside. Earlier sampling appears to be catching more times near this peak.

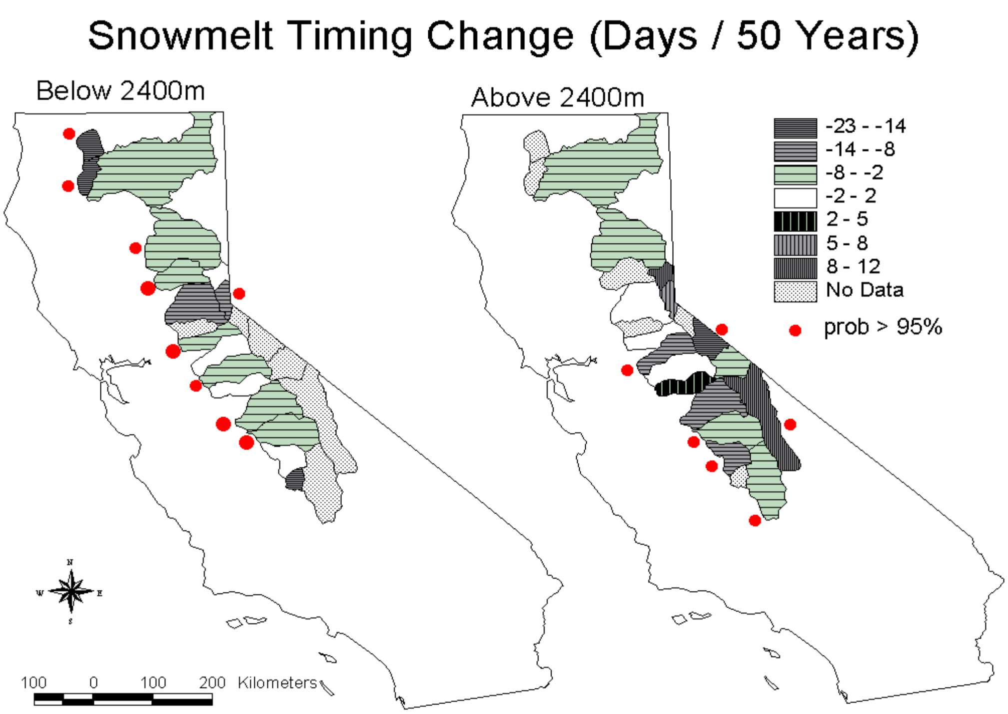
These slight changes were not corrected in the analyses. Instead, results staying within 5% of the maximum SWE and within 2 days per 50 years for snowmelt timing were considered to be unchanged.

River Basin Trends

Regressions on time of station data from individual river basins below 2400 meters consistently indicate less maximum SWE or no change (Figure 2). Downward maximum SWE trends of 5% to 25% per 50 years are supported by 95% confidence in the Trinity, Feather, Lake Tahoe, American and Mokelumne basins. The Tule's estimated change of 33% less SWE per 50 years lacks confidence because there is only one station that survived the data quality filters. It has 31 observations.

Above 2400 meters, most river basins show upward maximum SWE trends. The southern east-draining Walker, Mono Lake and Owens basins all show significant maximum SWE increases of 15% to 25%. The west-draining American, Stanislaus and Merced also indicate more snow accumulation


Maximum Snow Water Equivalent Percent Change
Below 2400m
Above 2400m
% Change / 50 Years
-35 - -25
-25 - -15
-15 - -5
-5 - 5
5 - 15
15 - 25
25 - 35
No Data
prob > 95%
100 0 100 200 Kilometers


Snowmelt Timing Change (Days / 50 Years)
Below 2400m
Above 2400m
-23 - -14
-14 - -8
-8 - -2
-2 - 2
2 - 5
5 - 8
8 - 12
No Data
prob > 95%
100 0 100 200 Kilometers

Snowmelt timing changes in the lower elevations consistently indicate earlier melt or no change. Nine of the 15 basins' trends are supported with 95% confidence. The Scott and Trinity River basins in the northwestern corner are melting two and three weeks earlier, respectively

At higher elevations, snowmelt has also tended to occur earlier, with six basins showing a clear change in the time of maximum snow accumulation. Only one of these indicated later melt, the east-draining Owens, which is estimated to be melting a week and a half later than it did 50 years ago.

Monthly estimated changes for the basins are summarized in Table 3 and all estimates supported by 95% confidence are in bold. The basins are arranged by latitude, with the west-draining basins listed first, followed by the east-draining results. All 15 lower elevation, monthly basin trends with strong statistical confidence indicate decreasing SWE levels. Of the six higher elevation estimates with good confidence, four suggest increasing SWE trends. Three of these basins are located on the east-draining side of the range.

Range-Wide Trends

When analyzed by 100-meter elevation bins, the reason for breaking river basin analyses up into component to the observed snow accumulation trends. Throughout the Sierra Nevada, snow courses below 2400 meters have lost 14% of their maximum SWE while higher ones have gained 8%.

Figure 3 clearly shows a strong elevational component affecting the trends in maximum SWE. The snowmelt timing graph does not exhibit a strong linear relationship through the higher elevation bins, but there is obviously earlier melt in the lower elevations. Half of the lowest elevation bins' trends are supported with 95% confidence.

Figure 2

	Monthly Snow Water Equivalent Estimated Percent Change Per 50 Years							
	Below 2400 meters				***Above 2400 meters***			
Basin	***Feb***	***Mar***	***Apr***	***May***	***Feb***	***Mar***	***Apr***	***May***
Scott	-2.3	-15.5	**-32.2**	-16.2				
Trinity	-24.3	**-38.1**	**-14.9**	-31.1				
Yuba	-1.6	-3.3	0.5	-10.3				
American	**-16.4**	**-15.7**	**-17.5**	-18.1	16.1	11.7	8.4	2
Mokelumne	-16.1	-13.7	**-17.9**	-7.5	0.6	-5.7	-1	-2.6
Stanislaus	6.3	-4	-8.2	7.1	41.7	38.6	3.7	27.4
Tuolumne	31.1	0.6	-19.5		21.3	3.9	6.7	20.1
Merced	-8.8	-11.2	-12.4	-7.3	28	-3	8	20.6
San Joaquin	7.1	2.9	6.1	-3	6.3	10.8	**11.5**	-2.4
Kings	-2.6	-12.7	-9.7	22.9	14	15.4	8.6	-34.4
Kaweah	-20.2	-19.9	-17.8	-26.5	-43.4	19.2	2.5	-47
Tule	-14.4	-8.2	**-36**					
Kern	-5		-20		**-19.3**	10.7	10.3	**-36.6**
Sacramento	-19.2	-17.3	-3.5	-16	13.9	7.6	12.7	13.9
Feather	-9	**-13.1**	-7.6	**-20.2**	5.8	-5.6	2.7	4.3
Truckee	**-35.4**	**-20.4**	0.6	-1.6	10.7	15.1	9.9	26.5
Lake Tahoe	**-19.4**	**-19.2**	-8	**-53.8**	-1.5	-3.2	6.2	7.7
Carson							-0.5	
Walker			32.4		26.3	22.8	13.3	34.3
Mono Lake					5.6	17.7	**25.2**	
Owens					-8.9	**16.5**	**14**	11

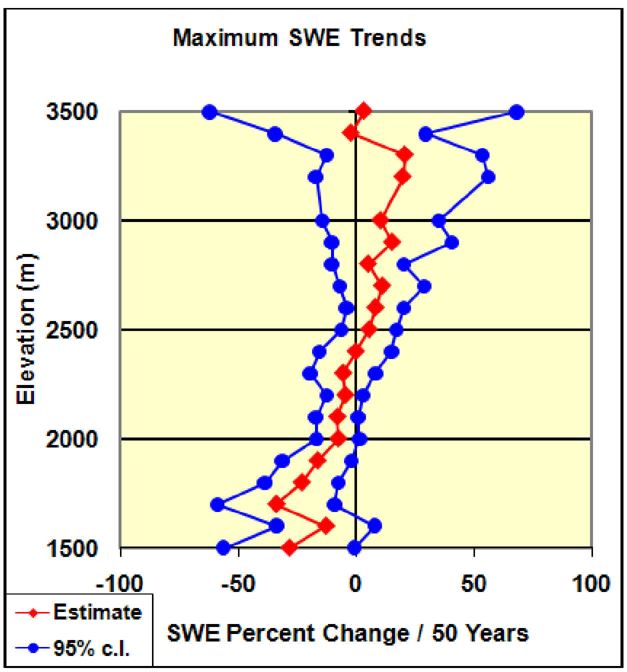
Table 3

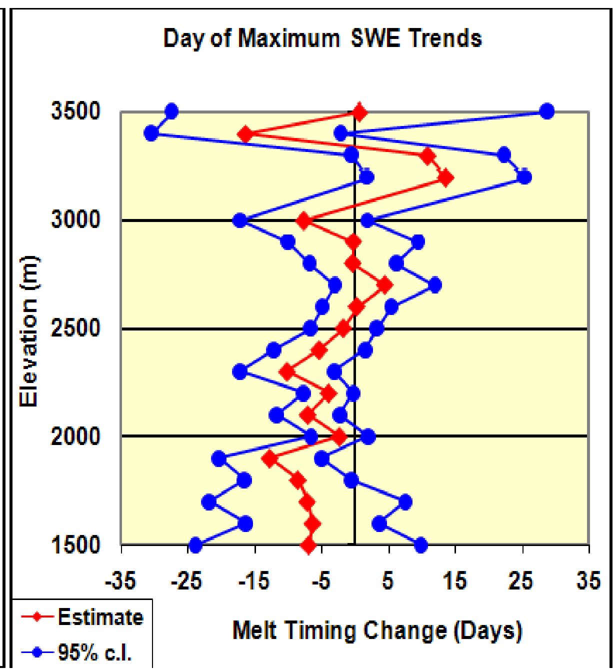
At lower elevations, February through May show increasingly less SWE (Table 4). At the higher elevations, February looks unchanged. By March 1st, The higher elevations have gained 18% more snow. This extra snow per 50 years remains through April then decreases in May. (The May graph is broken because an elevation bin lacked sufficient data to run the time-series regression.)

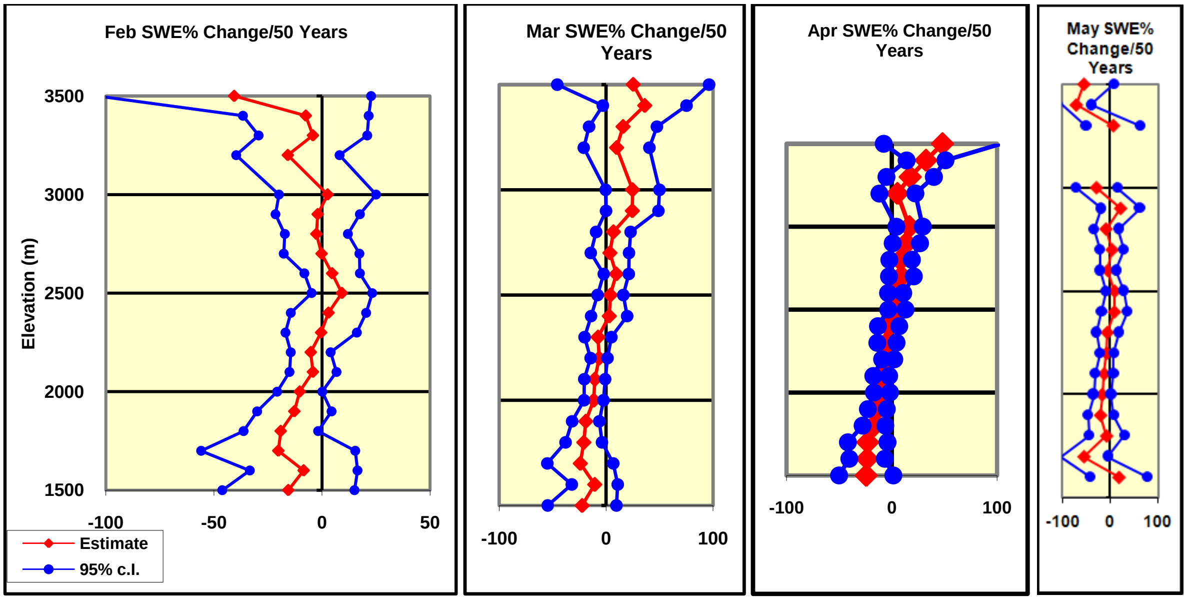
Monthly SWE Percent Change Per 50 Years

Month	Below 2400m	Above 2400m
February	- 6.9 %	- 0.8 %
March	-11.0 %	17.8 %
April	- 19.0 %	18.3 %
May	- 33.7 %	- 12.5 %

Table 4







Climate Step

Differences in normalized station averages for each year are plotted in Figure 4. This is not a depiction of changes in a given year, but changes in the mean for all years before minus all years after that year. The 1976 step reported in the literature is seen in the SWE data as a sharp peak in the 1975 water year. Seasonal SWE decreased in the following years.

Although the 1976 peak is the sharpest shift, there are a few smoother curves in 1946, 1965 and 1982 that indicate changes over several years.

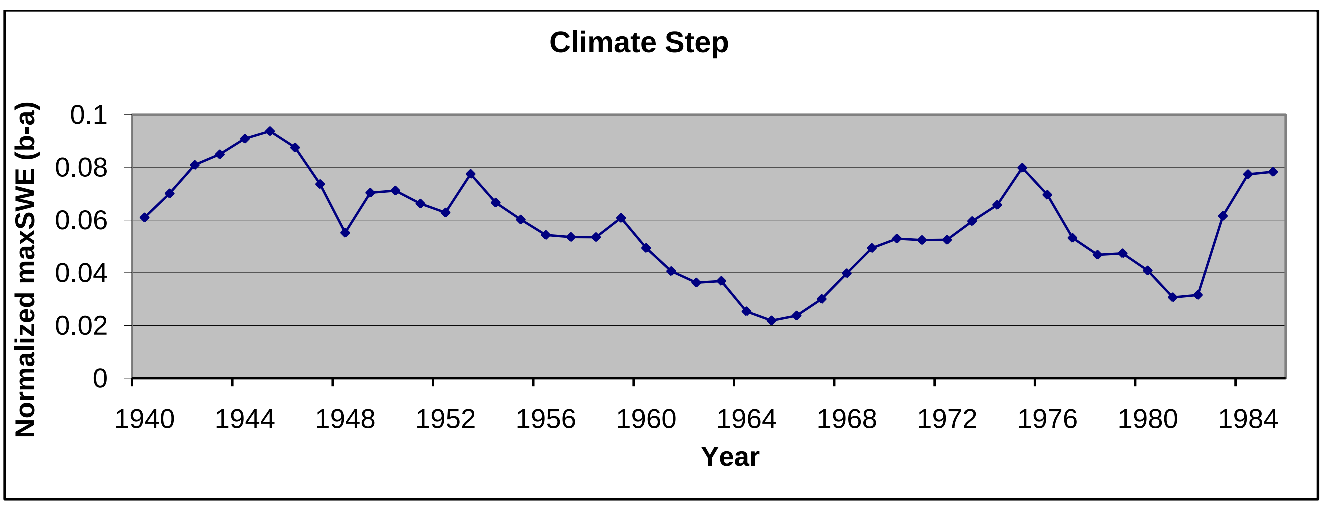


Figure 4

DISCUSSION

All analyses of elevation bins below 2400 meters indicate a strong elevational component to SWE accumulation, indicating that lower elevation snow losses are probably a result of warmer winter temperatures and rain-on-snow events. Increased April 1 and maximum SWE values at higher elevations suggest increased precipitation in these areas. This could be the result of warmer air masses having higher moisture contents.

Although these results fit in with climate model predictions, these analyses only look at relatively short trends and do not account for climate cycles. Research that endeavors to understand the mechanisms and cycles may yield more predictive value for managing water resources.

ACKNOWLEDGEMENTS

I must begin with thanking Jeff Dozier, who so casually mentioned that this dataset would make a good thesis project. It was fun to unravel and should continue to provide many travel opportunities. But seriously, Jeff offered critical comments that helped make this work possible. Joel Michaelsen is the California climate guru. I'm lucky he enjoys teaching and working on these sorts of projects. David Hinkley exhibited impressive open-mindedness, assisting with research that includes pretty simple statistics.

Of course I must thank the Department of Water Resources for making this data so readily available. Dave Hart, Maurice Roos and J. Pierre Stephens were especially helpful. NASA's Earth Observing System funded this research, thereby reducing the frequency of my stress attacks. I'd also like to thank Pete Fohl for teaching me how NOT to end up on a security surveillance/widely circulated internet mpeg, batting my computer monitor with the keyboard. He's a good friend, very patient and an unsurpassed programmer. I'd also like to thank Tom Painter for finding (hopefully) every error in the analyses. The work is much more solid because of his insight.

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