RIVER BASIN VARIATIONS IN SIERRA NEVADA SNOWPACK ACCUMULATION TRENDS

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ABSTRACT

Mountainous areas, particularly in the western United States, provide a large fraction of the fresh water supply. This reserve, which supplies most of California's growing water needs, is vulnerable to changes in climate. Regional precipitation patterns, especially snow, which is a sensitive indicator of change, are predicted to vary according to future climate models. This study uses a statistical model which links snow water equivalent (SWE) measurements over a 60-year time series to analyze the snow accumulation trends in the Sierra Nevada.

We utilized snow course measurements with data difficulties including inconsistent monthly sampling, added and removed stations and possibly a few moved or otherwise altered snow courses. To determine the effects of a monthly and irregular sampling schedule we analyzed daily snow sensor data spanning 25 years. Furthermore, we employed a statistical test to check for possibly discontinuous snow course stations.

We found that the overall maximum amount of seasonal SWE is not changing. However, below 2700 meters, snowmelt timing has recently been occurring earlier, whereas elevations above 2900 meters are melting later. The eastern draining river basins consist of steeper, drier slopes that have mostly increasing SWE trends. The Owens River basin, in the southeastern tip of the range, has gained the most SWE while the neighboring, westside Kern has received less snow.

INTRODUCTION

Historic weather records show that central California mountainous regions have undergone statistically 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].

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, 1990]. Utilizing 3 GCMs, monthly California temperatures were predicted to increase an average 3.8°C, with 1 model forecasting greater winter increases. Winter temperature increases averaged 3.5°C and ranged from 1.3°C to 5.0°C [Lettenmaier and Gan, 1990].

A site at 2813 m in the Sequoia National Forest was modeled using these GCM outputs, coupled with an energy-based snowmelt runoff model. Predicted snowmelt runoff hydrograph changes ranged from 19 to 93 days earlier [Tsuang and Dracup, 1991].

Studies investigating river runoff suggest that winter and early spring streamflow has increased in the northern Sierra Nevada due to higher temperatures and rain on snow events in lower elevations, which cause earlier snowmelt [Pupacko, 1993]. Correspondingly, a decrease in the April-July fraction was reported across California [Wahl, 1991] and in the local Sacramento area [Roos, 1991]. While precipitation most strongly influences streamflow at lower elevations, changes in Sierra Nevada streamflow during May, June, and July, is influenced mostly by temperature in mid-(1000-2000 m) and high-elevations [Aguado et al., 1992].

A problem with river runoff is that it integrates snow collected throughout the season and across elevations, thereby blurring changes which are probably clear in the snow record. We investigated Sierra Nevada snow course measurements, a largely untapped historic data set, to search for possible snow accumulation and melt trends.

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SNOW COURSE DATA

Cooperative snowcourse surveys provide SWE data for 305 snow courses spanning 9° latitude, 7° longitude and 3450 meters in elevation and is accessible via the world wide web [http://snow.water.ca.gov/]. 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. Many of these courses were created and regularly sampled in the 1930's, with sampling increasing steadily up until more stations were added in the 1950's. Most stations were sampled at least four times per year from the 1960's until the present.

The California cooperative snow courses are designated, flat open areas around a thousand feet in length. About 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 a week before April. Automated, daily snow measurements began 20 years ago; however, only monthly, manually collected sample measurements were analyzed for trends in this study to maintain data consistency.

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, but some stations are suspect. Although these measurements are of exceptionally high quality, these data present several challenges for climate analyses because they were collected for water resources management.

Sampling was conducted on a semi-monthly basis, usually within a week of the first day of the month. 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].

METHODS

Stations were selected for time series analyses that consisted of at least 3 measurements per year and 10 years of measurements covering 30 years. These data meet the following quality assurance: the day of maximum SWE is not simply the last day measured unless that month is the average month of melt and it is an average-to-wet year. This discourages false snowmelt timing calculations due to sampling bias, yet accounts for precipitation variability and associated snowmelt fluctuations.

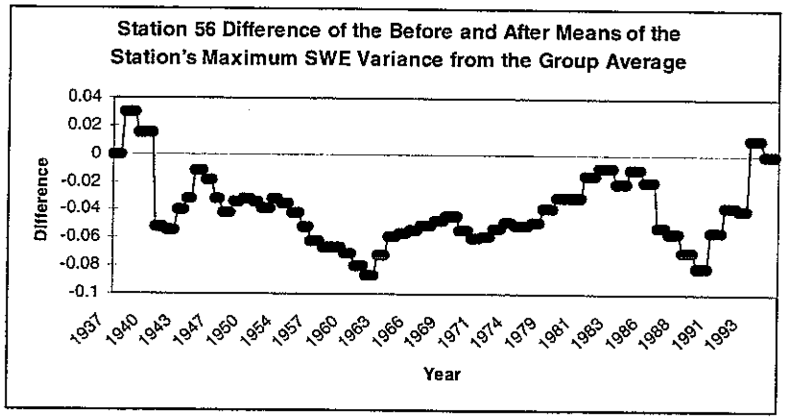
Seasonal maximum SWE and the month of maximum SWE were computed for each station, then these values were standardized by dividing yearly amounts by station averages. The resulting wetness factor can be compared to other stations in various latitudes and elevations with differing SWE levels.

Discontinuous stations

In order to find possibly moved or otherwise inconsistent stations, we generally followed a procedure for detecting discontinuities in historic temperature data [Easterling and Peterson, 1995]. Stations were 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 standardized variances from group means were then checked for jumps, which indicate alterations to a particular station. This was done by calculating means before and after every station-year, and subtracting the difference. Very high or very low differences flag possible station discontinuities. 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. Figure 1 is an example of a possibly discontinuous station since there is a large change in the idfference of the means midway through the series. The end points are more variable since additional yearly variances have a larger impact on the mean.

Figure 1



Potential problem stations were defined to have trending variances that also exhibited extreme difference of the mean values. All 33 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 error 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 166 stations cover 26,668 station measurements, which is 60% of the original data.

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

Daily snow sensor data were analyzed to estimate irregular and semi-monthly sampling errors on SWE and timing of maximum SWE. The sensor data contained many obvious errors, requiring a spline interpolation to fill in the missing daily data.

Semi-monthly sampling

Using daily sensor data, maximum SWE and the month of maximum SWE was calculated, then these actual values were compared to sensor estimates using only monthly sampling to check the effects of monthly sampling.

Monthly sample timing

To check the effects of sampling timing in days from the first of the month, we considered each day as the monthly sample day. The SWE value for any day was compared to the next highest, first-of-the-month, monthly SWE value to determine which of those two measurements would be classified as the maximum SWE value and month. The maximum SWE value and month for each day, which was calculated as the number of days from the first, was compared to the data obtained from the first of the month measurements. The differences were fitted with the number of days from the first to get an idea of how big the error became with various different sample times.

RESULTS

Effect of monthly sampling on false trends

Monthly sampling causes a false earlier maximum SWE timing trend of 0.22 days over 60 years. Although 80% of the monthly sample days identify the correct maximum SWE month, monthly sampling creates melt timing errors with 3.4 times more false earlier melt months than false later ones. Additional SWE melts before the next monthly measurement is taken.

Effect of sample timing on false trends

Monthly sample timing has very little effect on measured maximum SWE. The average erroneously reduced amount is 0.3% per day sampled from the first. However, there is a greater effect on the calculated timing of maximum SWE. An erroneous 0.84 day earlier melt trend over the 60 year, 3.2 day earlier sampling, is due to the changing sampling schedule. These monthly sampling effects total to an average false trend of 1.1 days. However, when broken into elevation bins, the most extreme schedule change of 8.6 days earlier amounts to a false earlier melt of 2.5 (2.3 + 0.22) days.

Course results

We found that the overall maximum amount of seasonal SWE is not changing (figure 2). However, below 2700 meters, snowmelt timing has recently been occurring earlier, whereas elevations above 2900 meters are melting later (figure 3).

Figure 2

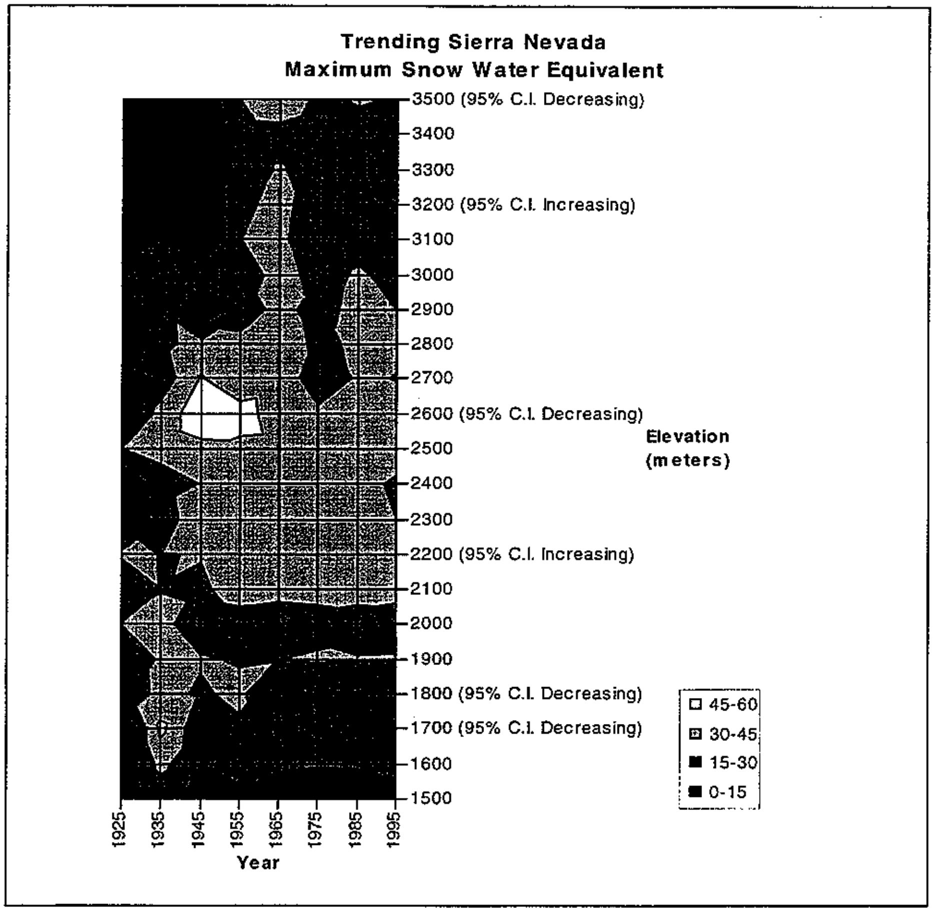


Figure 3

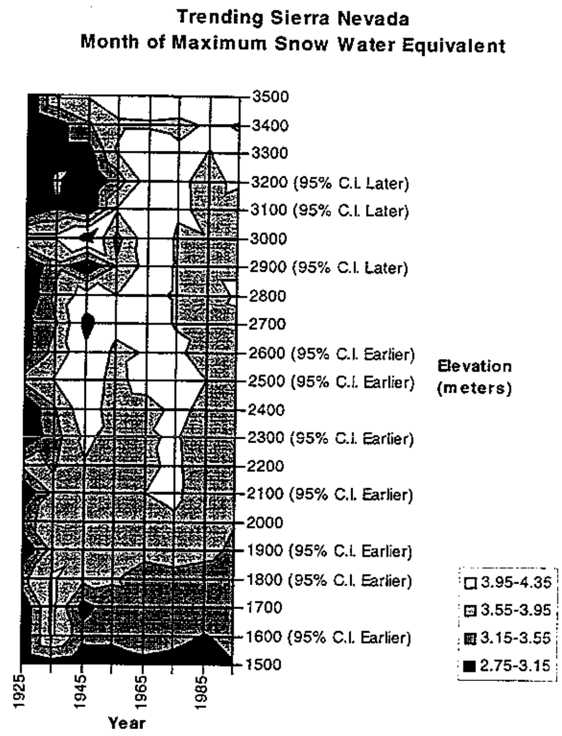


Table 1 Trends with a 95% confidence interval are in bold.

Maximum SWE Percent Change of West Draining and Northern River Basins over 60 Years

River Basin	Latitude	Elevation Bin (meters)						
		1400	1700	2000	2300	2600	2900	3200
Shasta	41.4		-10	4				
McCloud	41.3			**-8**	-4			
Scott	41.3		-3	-6				
Sacramento	41.3			-2	7			
Trinity	41.1	**-16**	**-31**	-8				
Pit	40.9		-6	-6				
Feather	40.1	-8	**-10**		-4			
Stony Creek	39.8		-5	**-22**				
Yuba	39.5	-12	2	-2				
American	38.9		**-13**	**-18**	-4			
Mokelumne	38.6	14	-14	4	-5	-21		
Stanislaus	38.3	**-28**			7	-14		
Tuolumne	38.1			-9	**-8**	-1	1	
Merced	37.7			**-9**	-10	3		
San Joaquin	37.4				5	-4	8	-7
Kings	36.9			-5	6	**40**	4	**-31**
Kaweah	36.5		-11		-1	-23		
Kern	36.4			-9	-16	-8	-7	**-17**
Tule	36.2		-3	-8				
Santa Ana	34.2			-4	**41**			

Table 2 Trends with a 95% confidence interval are in bold.

Maximum SWE Percent Change of East Draining River Basins over 60 Years

River Basin	Latitude	Elevation Bin (meters)						
		1400	1700	2000	2300	2600	2900	3200
Truckee	39.4				2			
Lake Tahoe	39.0		-7	**-19**	-8			
Walker	38.2					0		
Mono Lake	37.9					10	4	2
Owens	37.2					5	**10**	18

Table 3 Trends with a 95% confidence interval are in bold.

Maximum SWE Timing Change (Days Later) of West Draining and Northern River Basins over 60 Years

River Basin	Latitude	Elevation Bin (meters)						
		1400	1700	2000	2300	2600	2900	3200
Shasta	41.4		**-15**	-9				
McCloud	41.3		-2					
Scott	41.3		**-13**	**-24**				
Sacramento	41.3			0	-3			
Trinity	41.1	**-15**	**-21**	**-20**				
Pit	40.9		-9	**27**				
Feather	40.1	**-8**	**-11**	**-24**	3			
Stony Creek	39.8		-6					
Yuba	39.5	-9	**-6**	0				
American	38.9		1	-2	-3			
Mokelumne	38.6	6	-11	4	-2	-13		
Stanislaus	38.3	4		-3	-3	-12		
Tuolumne	38.1			-8	0	**11**	**-22**	
Merced	37.7			1	2	5		
San Joaquin	37.4			0	-4	**-17**	-6	-6
Kings	36.9			-6	2	1	1	**-29**
Kaweah	36.5		-3		5	-16		
Kern	36.4				1	-6	1	-5
Tule	36.2			-23				
Santa Ana	34.2				-15			

Table 4 Trends with a 95% confidence interval are in bold.

Maximum SWE Timing Change (Days Later) of East Draining River Basins over 60 Years

River Basin	Latitude	Elevation Bin (meters)						
		1400	1700	2000	2300	2600	2900	3200
Truckee	39.4		**-14**	6	**16**			
Lake Tahoe	39.0			**-10**	6			
Walker	38.2					-13		
Mono Lake	37.9					6	-5	**-27**
Owens	37.2				7	15	**24**	16

DISCUSSION

Many of the river basin elevation bins contain one station that represents a large area. Some adjacent trends don't make spatial sense, partly the trends are susceptible to time series beginning and end points. A station series terminating in the 1980s will look differently than others encompassing a large drought cycle. For example, the Pit River shows contradictory trends at neighboring elevations. Between 2000 and 2300 meters, station 30, which is the only station in that group, does indicate maximum SWE about a month later. However, the data were collected from 1945 to 1984, whereas most other stations continue until the present.

ACKNOWLEDGEMENTS

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REFERENCES

Aguado, E., 1990: *Elevational and latitudinal patterns of snow accumulation departures from normal in the Sierra Nevada*, Theoretical Applied Climatology, **42**, 177-185.

Aguado, E., D. Cayan, L. Riddle, and M. Roos, 1992: *Climatic fluctuations and the timing of West Coast Streamflow*, Journal of Climate, **5** (12), 1468-1483.

Barry, R.G., J.-M. Fallot, and R.L. Armstrong, 1995: *Twentieth-century Variability in Snow-cover Conditions and Approaches to Detecting and Monitoring Changes: Status and Prospects*, Progress in Physical Geography, **19** (4), 520-532.

Dettinger, M.D., and D.R. Cayan, 1995: *Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California*, Journal of Climate, **8**, 606-623.

Easterling, D.R., and T.C. Peterson, 1995: *A New Method of Detecting Undocumented Discontinuities in Climatological Time Series*, International Journal of Climatology, **15**, 369-377.

Lettenmaier D.P. and T.Y. Gan, 1990: *Hydrologic Sensitivities of the Sacramento-San Joaquin River Basin, California, to Global Warming*, Water Resources Research, **26** (1), 69-86.

Mitchell, J.F.B., S. Manabe, V. Meleshko and T. Tokioka (Eds), 1990: Equilibrium Climate Change and its implication for the future. In *Climate Change: The IPCC Scientific Assessment*, Houghton, J.T., G.J. Jenkins, and J.J. Ephraums (Eds), Cambridge, Cambridge University Press, 131-172.

Pupacko, A., 1993: *Variations in Northern Sierra Nevada Streamflow: Implications of Climate Change*, Water Resources Bulletin, **29** (2), 283-290.

Roos, M., 1991: *A Trend of Decreasing Snowmelt Runoff in Northern California*, Proceedings of the 59th Western Snow Conference, Juneau, Alaska, 29-36.

Tsuang, B.J. and J.A. Dracup, 1991: *Effect of Global Warming on Sierra Nevada Mountain Snow Storage*, Proceedings of the Western Snow Conference, Juneau, Alaska, April 12-15, 1991, Fifty-Ninth Annual Meeting, 17-27.

Wahl, K.L., 1991: *Is April to July Runoff Really Decreasing in the Western United States?*, Proceedings, 59th Annual Western Snow Conference, April 12-15, 1991, Juneau, Alaska, 67-78.