Climate Change and Sierra Nevada Snowpack

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ABSTRACT

Mountainous areas, particularly in the western U.S., provide a large fraction of the fresh water supply. This reserve is possibly vulnerable to changes in climate. Regional precipitation patterns, especially snow, which is a sensitive indicator of change, are predicted to vary with global warming. This study uses a statistical model to link snow water equivalent (SWE) measurements over a 65 year time series to analyze the snow accumulation trends in the Sierra Nevada.

We found that snowmelt timing has recently been occurring earlier in the mid-elevations while the maximum amount of seasonal SWE is not changing. However, the monthly snow fraction of the season maximum (snow fraction) are shifting both by month and elevation. Overall, the snow fractions are decreasing, which indicates that snow is accumulating later and melting earlier in the Sierra Nevada. The exceptions are January 1, which is unchanged; low elevations in the early part of the season; and high elevations in mid-season, where the SWE fraction has been increasing. Since values are given for the first of the month, this suggests less snow in January and February, yet more in March, as reflected in the April 1 values. The decrease of SWE fractions on May 1 average to a 23% loss over the last 65 years, while June 1 fractions are down 32%, with greater losses in the higher elevations.

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 [Dettinger and Cayan, 1995]. Furthermore, general circulation models predict that temperatures will continue to increase and snowmelt runoff timing will occur earlier in California [Mitchell, 1990; Lettenmaier and Gan, 1990; 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 are 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 accumulations throughout the season and across elevations, thereby possibly blurring changes which are clear in the snow record. We investigated Sierra Nevada snow course measurements, a largely untapped historic data set, to search for possible trends.

The California cooperative snow courses are designated, flat open areas about 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 10 to 15 years ago; however, only monthly, manually collected sample measurements were analyzed in this study to maintain data consistency.

Cooperative snowcourse surveys provide SWE data for 305 snow courses spanning 9° latitude, 7° longitude and 3450 meters in elevation which are accessible via the world wide

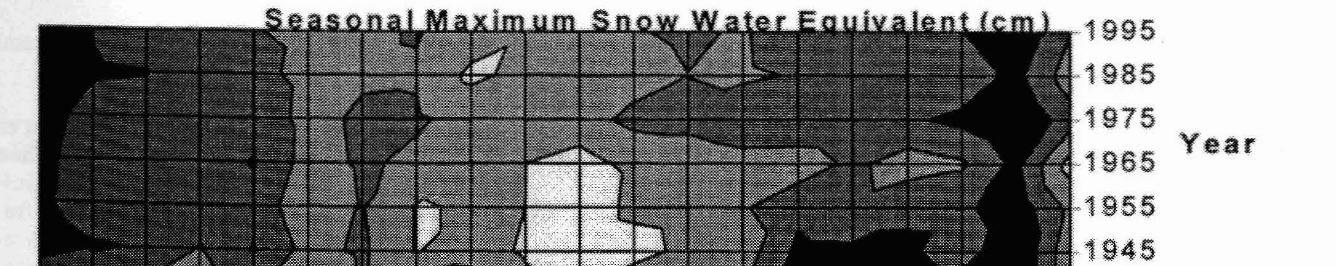

Fig 1. In the following charts, light shades represent more snow and darker areas indicate less snow. Overall, monthly maximum snow amounts appear stable. Snow water equivalent is the depth of the resulting water column if the snow were melted.

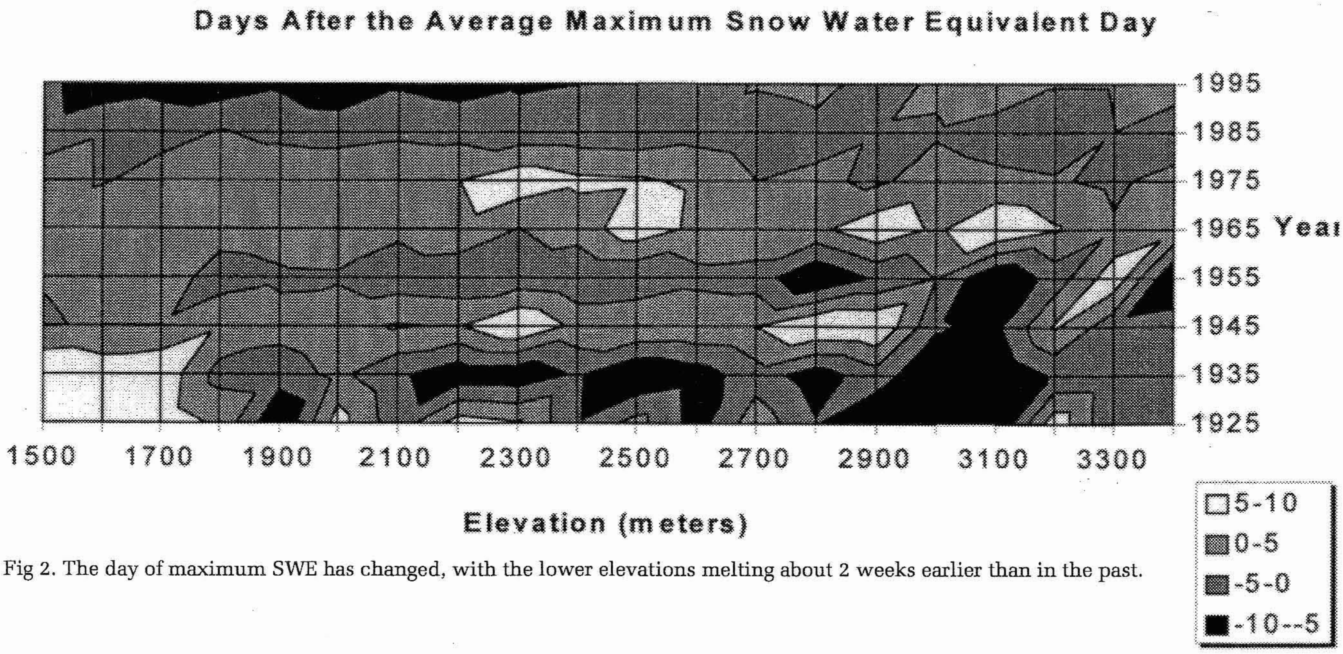

Fig 2. The day of maximum SWE has changed, with the lower elevations melting about 2 weeks earlier than in the past.

web [http://snow.water.ca.gov/]. The first courses were measured in 1910, and most contain 50 years of monthly SWE and snow density measurements, which were collected from one to six times per season. Many of these courses were created and heavily sampled in the 1930's, though measurements in the 1940's are sparse, sampling density increases again in the 1950's. Most stations were sampled at least four times per year from the 1960's until the present.

METHODOLOGY

These data present several challenges for climate analyses because they were collected with the intended use for water resources management. Ideally, stations would be measured daily throughout the season and continuously over many decades, or even millennia. However, about 20% of the 44,000 SWE measurements were unusable for time series analysis due to infrequent sampling, having less than three measurements per station-year.

Sampling was conducted on a monthly basis, usually clustered within a few days of the first day of the month. Therefore, maximum monthly SWE values were interpolated to the first of the month. Furthermore, missing data points were calculated with linear regressions. Additional problems include that the maximum SWE day is estimated and hence possibly an artifact if the actual maximum day is after the last sample, and finally, stations were added and removed throughout the years.

Newer stations were not evenly distributed by elevation, which accounts for about 6% of the SWE variability [Aguado, 1990], so regressions were grouped by elevation zones to minimize error stemming from station fluctuations. Also, individual station SWE values and snowmelt timing was standardized by converting estimates into monthly fractions of the station's season maximum and differences from this station's average snowmelt month.

The three samples per year screen leaves 281 qualifying stations (figure 12) ranging between 1500 and 3500 meters in elevation, constituting 34,500 station-years of data. These data also 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.

The yearly data points and snow course information was imported into the statistics software package SAS for analysis and data screening. Measurements were interpolated to the first of the month by adding a station's SWE to the product of the slope to the adjacent month's value and the number of days from the first for that station-year.

(1) $SWE_{interpolated} = SWE_x + days_x(SWE_{x+1} - SWE_x)/(DOY_{x+1} - DOY_x)$

SWE_x = given monthly SWE measurement

SWE_{x+1} = following month's SWE measurement

DOY_x = day of year on which a given month was sampled

DOY_{x+1} = day of year on which following month was sampled

$days_x$ = number of days after the first of the month sample was measured

Equation (1) applies if the sample day is after the first of the month. When the sample day is before the first, then a similar equation applies to the previous month to minimize the interpolation error. Equation (1) requires frequent sampling which does not exist for many station-years. Therefore, station-decade averages and overall station averages were used as the slope when required. In some cases, especially January or June adjustments, a station average did not exist, so an average accumulation slope from that elevation zone was substituted. Measurements taken before January 1 used a January-February slope. Likewise, samples taken after June 1 used a May-June slope since only seven measurements were carried out in December and none in July.

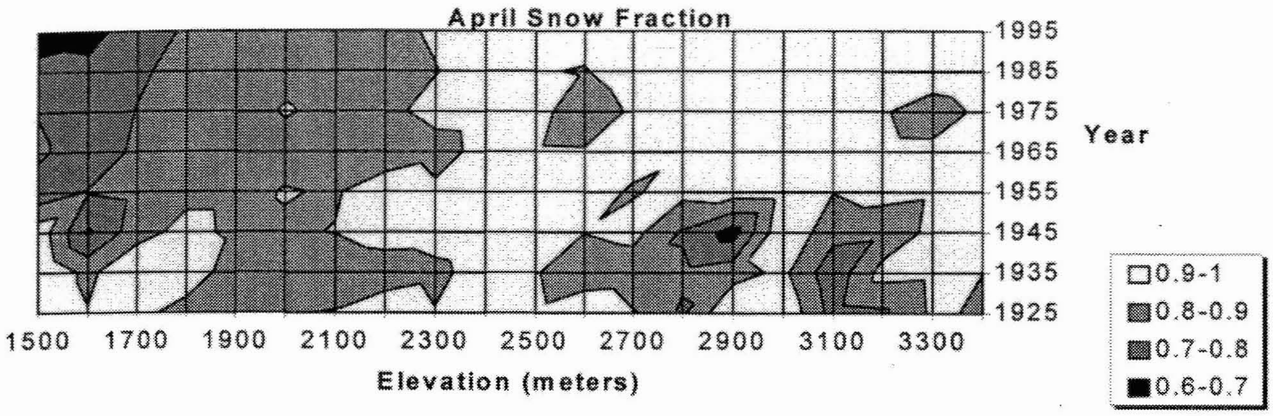

Fig 3. The April fraction in the April SWE divided by the maximum for that season. Mid-elevation April snow amounts have decreased this century, while high-elevation levels have increased.

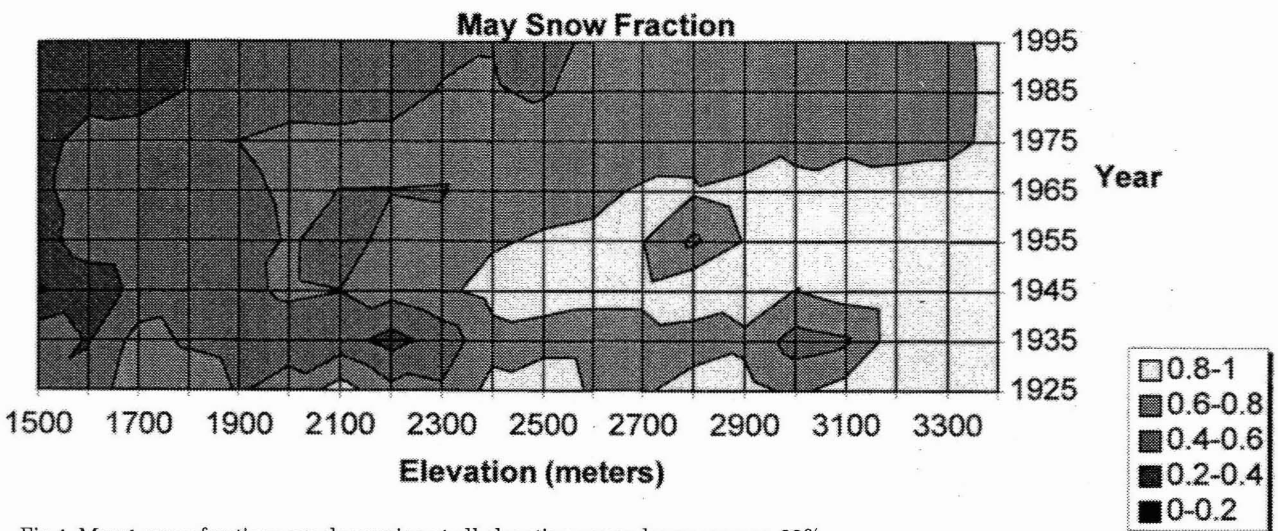

Fig 4. May 1 snow fractions are decreasing at all elevation zones, by an average 23%.

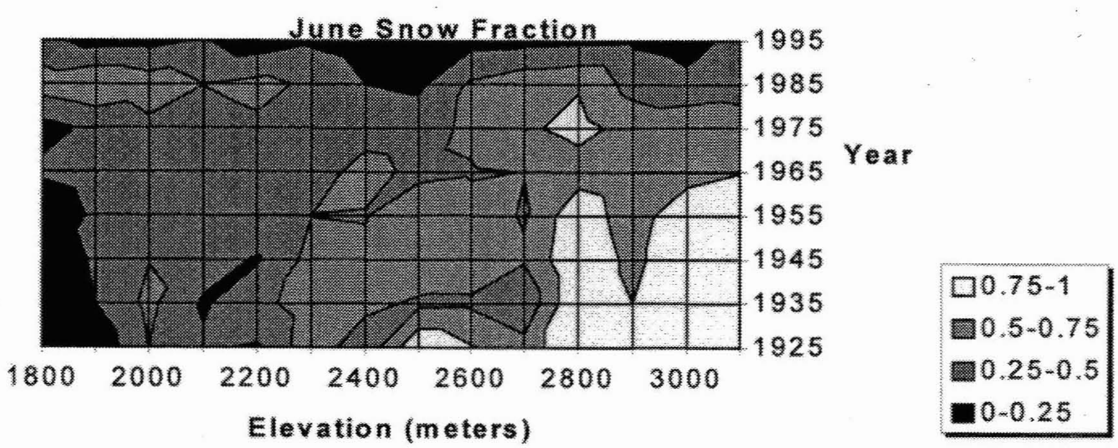

Fig 5. June 1 snow fractions have decreased significantly, especially in the higher elevations. Overall, there is 32% less snow on June 1.

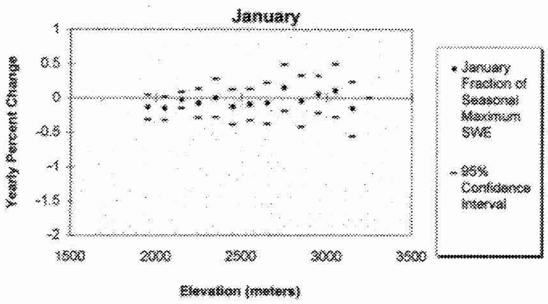

Fig 6. January snow fractions look stable.

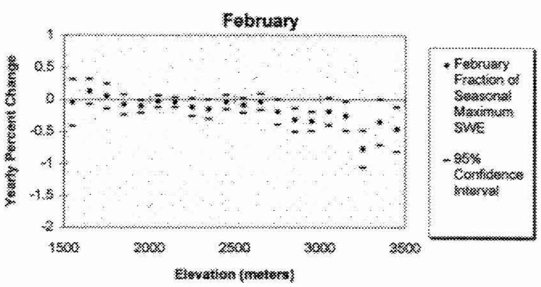

Fig 7. February 1 levels show a slight decrease, reflecting less snowfall in January.

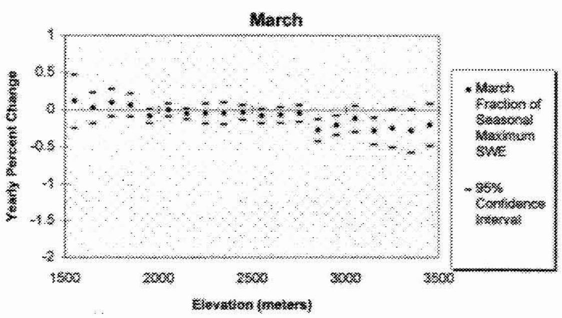

Fig 8. Declining winter snow is indicated by reduced March 1 values.

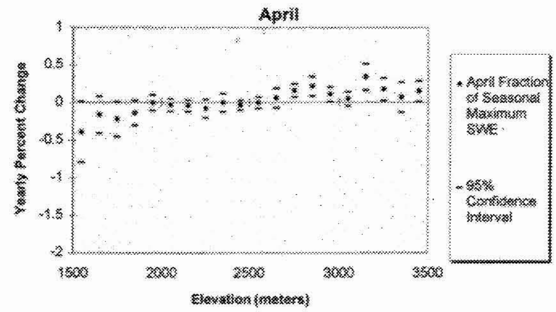

Fig 9. This trend abruptly changes in April, when more March snowfall occurs in the higher elevations.

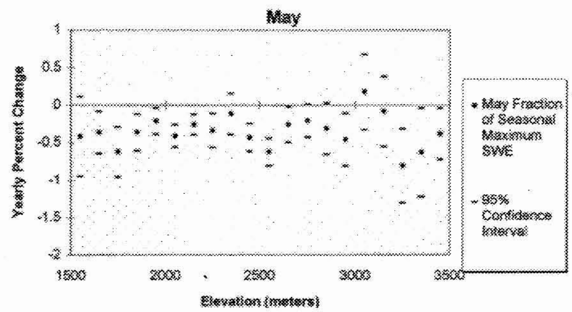

Fig 10. The May 1 records shows significant declines.

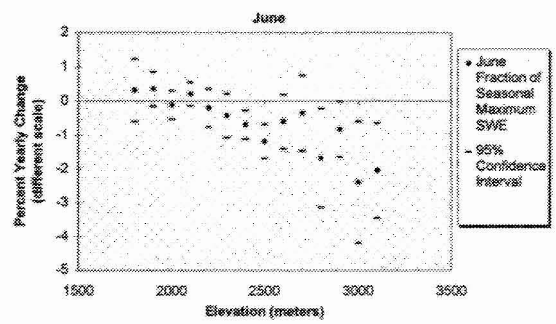

Fig 11. June 1 snow records also show significant declines.

Average melt months and maximum yearly SWE values were computed for each station. The month of maximum SWE was calculated for each station-year, as well as the difference from the average melt month. Monthly fractions of the station-year's maximum SWE were calculated, yielding 9000 station-years with at least three months of data each and spanning up to 78 years.

We computed linear regressions of monthly fractions, maximum SWE values, and different melt month data over an average of 65 years and grouped them into 20 elevation zones, each extending 100 meters. These regressions were checked with a robust kernel estimator, which is useful for nonparametric regressions with one explanatory variable. This technique uses generalized cross-validation, where points are left out one at a time while the regression is estimated on the remaining observations, thereby minimizing the mean square error and selecting that fit.

RESULTS

Our findings indicate that the overall amount of SWE has not significantly changed over the past 65 years throughout the Sierra Nevada (figure 1). However, the snow accumulation patterns have narrowed, with less snow both early and late in the season. January 1 snow fractions seem stable (figure 6), which suggests that average December snow levels remain unchanged. February and March (figures 7, 8) also show stable SWE fractions below about 2000 m, but at higher elevations the slopes are consistently estimating less snow, with significant declining trends at 30% of the elevation zones.

Due to increasing precipitation in March, the April 1 levels indicate that the snow has "caught up," and looks like past April amounts, but with an elevational distinction (figures 3, 9). The lower elevations retain less snow, while higher areas receive more. This is most likely due to rain on snow events, which melt snow in the lower elevations.

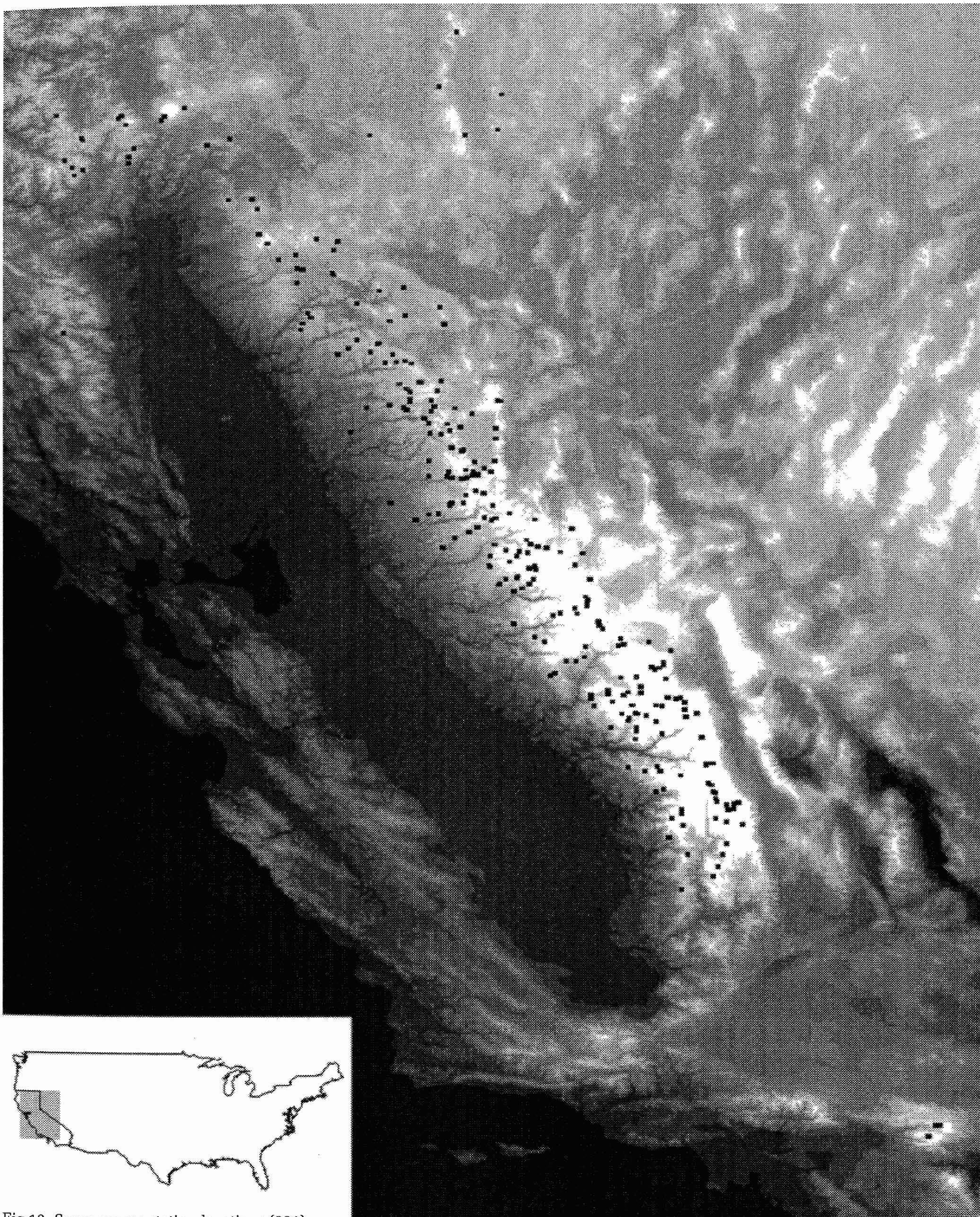

Fig 12. Snow course station locations (281).

The May 1 and June 1 SWE fractions have markedly decreased (figures 4, 10, 5, 11), 23% and 32%, respectively. May snow estimates are down in almost all elevation zones. In the May elevation zones, 70% of the yearly percent changes are supported with 95% confidence.

The day of maximum SWE has also changed, occurring about a week earlier overall, with a stronger influence in the lower elevations. In areas between 1500 and 2500 m, the snow accumulation peaks about 2 weeks earlier than before, with 40% of these estimates supported by 95% confidence (figure 2).

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