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John R. Christy
Justin J. Hnilo

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CHANGES IN SNOWFALL IN THE SOUTHERN SIERRA NEVADA OF CALIFORNIA SINCE 1916

John R. Christy
Justin J. Hnilo
Earth System Science Center
University of Alabama in Huntsville

ABSTRACT
A time series (1916–2009) of annual snowfall totals for Huntington Lake (HL, elev. 2141 m) in the southern Sierra Nevada of California is reconstructed. A reconstruction is (a) necessary because HL data after 1972 are mostly missing and (b) possible because nearby stations reveal high correlations with HL, two above 0.90. The results show mean annual snowfall in HL is 624 cm with an insignificant trend of +0.5 cm (+0.08%) ±13.1 cm decade^{-1}. Similar positive but insignificant trends for spring snowfall were also calculated. Annual stream flow and precipitation trends for the region again were insignificantly positive for the same period. Snow-water-equivalent comparisons, measured on 1 Apr since 1930 at 26 sites and since 1950 at 45, show similar small, mostly positive, and insignificant trends. These results combined with published temperature time series, which also reveal no significant trends, form a consistent picture of no remarkable long-term changes in the snowfall of this area and elevation of the southern Sierra Nevada of California since the early 20th century.

INTRODUCTION

Paleo-reconstructions of western U.S. precipitation indicate significant periods of drought and surplus with relatively high multi-decadal variability (e.g. Meko et al. 2007). Could the region be entering a period of reduced precipitation, with a reduction in snowfall in the mountains, perhaps as dry as that estimated from 12th century tree-rings (Meko et al 2007)? In terms of recent trends, Mote et al. 2005 found mostly upward trends in snow water equivalent in the southern Sierra for the period limited to 1950–1997 (48 years, or about half of the current study). They found positive trends as well in the southern Rocky Mountain region, while poleward of approximately 38°N there were widespread declines.

Barnett et al. 2008 indicate that for 1950–1999 most of the Western U.S. snowy regions show warming temperatures and earlier peak runoff, suggesting a trend toward less snow and more rain. This could be an ominous development for water resource planners as the mountain snowmelt, both its quantity and timing, provides a major resource on which municipal, industrial and agricultural systems rely. We shall examine snowfall itself because it is a vital metric to understand since it is critical for businesses and operations related to snow (winter sports, road clearing, etc.) as well as snow-dependent ecological systems.

The question we will examine is whether a tendency in snowfall in the Southern Sierra Nevada (So. Sierra) is detectable. The So. Sierra are important for many reasons including their location as one of the most southern mountain ranges in the U.S. with significant water resource impacts and thus potentially an early indicator of climate change since modeled changes show significant warming here due to enhanced greenhouse gas concentrations (e.g. Snyder et al. 2002). Mote et al. 2005 examined only 48 years of data and Barnett et al. 2008 only 50 years, but both found a slight upward trend in water-resource availability in the So. Sierra. In an earlier study of snow water equivalent (SWE) measured on 1 Apr of each year, Howat and Tulaczyk 2005 found no trend in SWE for 177 snow courses. However, by subtracting 1 Apr from 1 Mar SWE there appeared to be a small gain (loss) in Δ SWE for 1950–2002 at the higher (lower) elevations along with insignificant increases in water volume for Nov–Mar. The implication here is that over a shorter period of time, the SWE contours on 1 Apr have risen in elevation. However, while extremely valuable as a water resource index for late-spring and summer runoff, SWE on 1 Apr often misrepresents the actual total snowfall during the cold season as early snows may have melted by this time and later snows are not included (see examples later). We shall look at annual snowfall as a different, though obviously related, climate metric relative to SWE.

Has snowfall changed over a longer period in the mid-elevation (~2000 m) of the So. Sierra? This question has links to our previous study of the So. Sierra in which seasonal maximum (TMax) and minimum (TMin) temperatures were produced (Christy et al. 2006). The wet-season (Dec-May) temperature trends for 1910–2003 were not significantly different from zero (TMax +0.08, TMin –0.01 °C decade^{-1}), suggesting that if precipitation trends were near zero, then snowfall might also show little change. Indeed, an examination of annual "water year" (Jul – Jun) precipitation totals for this region's climate division indicates a trend of +0.2% decade^{-1} (1916–2009) while that of the nearest long term station (Fresno) shows +2.7% decade^{-1}. Thus a look at a longer snowfall record, and attendant variables such as runoff, is one way to examine consistency, at least obliquely, to the temperature record.

DATA

We have examined the snowfall records for stations in the So. Sierra from Mariposa County in the north to Kern County in the south. The metadata for these stations had been manually keyed for Christy et al. 2006 and thus was available for understanding the conditions of the stations and other useful information.

We looked at over 30 stations and found six that meet a minimal set of standards (consistent observations for at least 35 years) to be used to generate the desired product. These stations measured daily snowfall using a "snow stake" to determine the accumulation from the day before. A "year" in this paper refers to the 12 months beginning in July and ending in June of the year so named. Thus "1960" is the period for July 1959 through June 1960. We accessed the monthly and daily snowfall measurements through the archive at the National Climatic Data Center.

Of great concern is the desire and necessity for the observations to have been made systematically. The Southern California Edison Company reported daily snowfall for Huntington Lake (HL) and nearby Big Creek (BC, Fig. 1). Information taken from the various NWS metadata forms (530, 5310, 4005, 4029, etc.) indicates a diligent and consistent methodology as the power company's need for systematic data was economically and operationally significant. HL's weather observations became sporadic after 1972. We note that early in the record the observer had problems estimating the rainfall-equivalent, determined by heating the gauge with interior 100W light bulbs to melt the snow. Problems were documented (bulbs often burned out), raising serious questions about the liquid-equivalent's accuracy. This made it even more important to monitor the snowfall as such information was often more reliably measured.

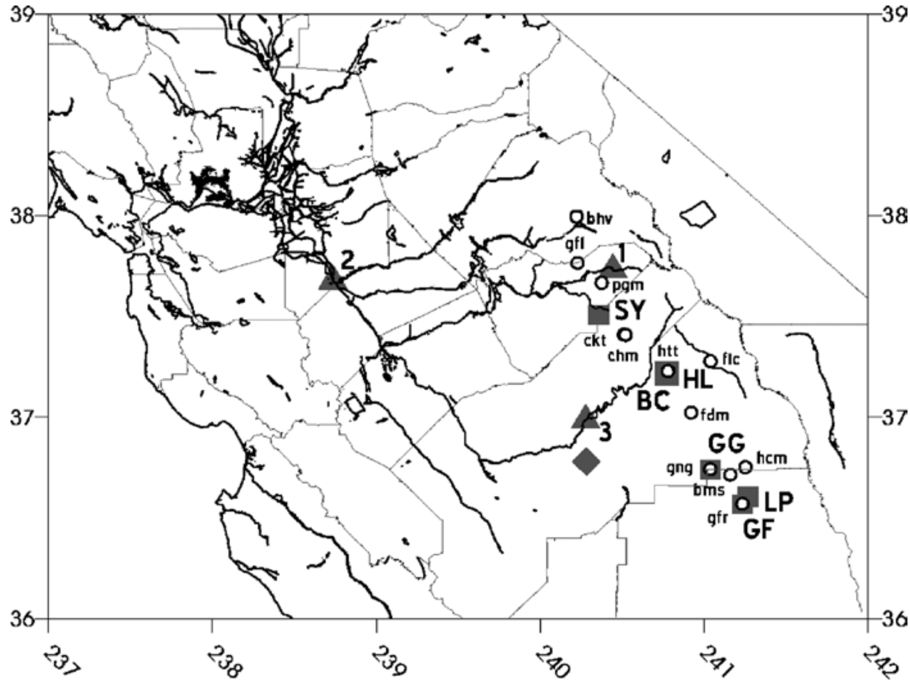

Figure 1. Central California with (a) snowfall sites (boxes), (b) river gauges (triangles, 1: Happy Isles on the Merced River, 2: San Joaquin River, 3: San Joaquin River below Friant Dam,), (c) rainfall station (Fresno, diamond) and (d) 12 snow water equivalent measuring sites within 100 km and 200 m elevation of HL (open circles, see Table 3). Longitude is degrees east. The internal political boundaries are county lines, the western boundary is the Pacific coast and the eastern boundary, the California state line. Major rivers are indicated with heavy lines

The other four sites were monitored by the National Park Service (Fig. 1, Grant Grove-GG, Giant Forest-GF, Lodgepole – LP and South Entrance Yosemite Park – SY) and their records also indicate the same due diligence except in the case of SY where the records were spotty for a long period (1970–2007.) In cases where a month was listed as missing, we first examined the daily record to determine if a monthly value could be calculated as the sum of the daily totals. This was possible in a few of the missing months. If this was not possible, the missing monthly total was estimated from nearby stations. No more than 2 months of any annual total were estimated (if 3 or more months were estimated, the year was set to missing for that station.) Lower altitude stations in general did not provide long records of systematic, quality measurements (discussed later).

Comparisons using snow water equivalent (SWE) were then carried out in two groupings of data from survey sites documented by the California Department of Water Resources Cooperative Snow Surveys (http://cdec.water.ca.gov/cgi-progs/snowQuery_ss. These values were taken near 1 Apr of each year beginning in 1930 at the sites with longest records. SWE represents the equivalent depth of liquid in the snow cover. The first studied group consists of the 12 SWE survey sites within 100 km distance and 200 m elevation of HL. The second group represents all (45) SWE survey sites within the Merced, San Joaquin, Kings and Kaweah basins which (a) encompass all of the snowfall stations used in this study and (b) have observations beginning at least by 1950 and through 2009. In this group there were 26 sites with 80 years of record (beginning in 1930) and 45 sites with 60 years of record (beginning in 1950.)

SNOWFALL RECONSTRUCTION

After examining the available snowfall data (Fig. 2) and cross-correlations among the annual totals, we chose to use Huntington Lake (HL, COOP ID 044176) as our reference target (Table 1). Because multiple stations do not together have common overlap periods with HL (thus multiple regression was not useful), our rather simple

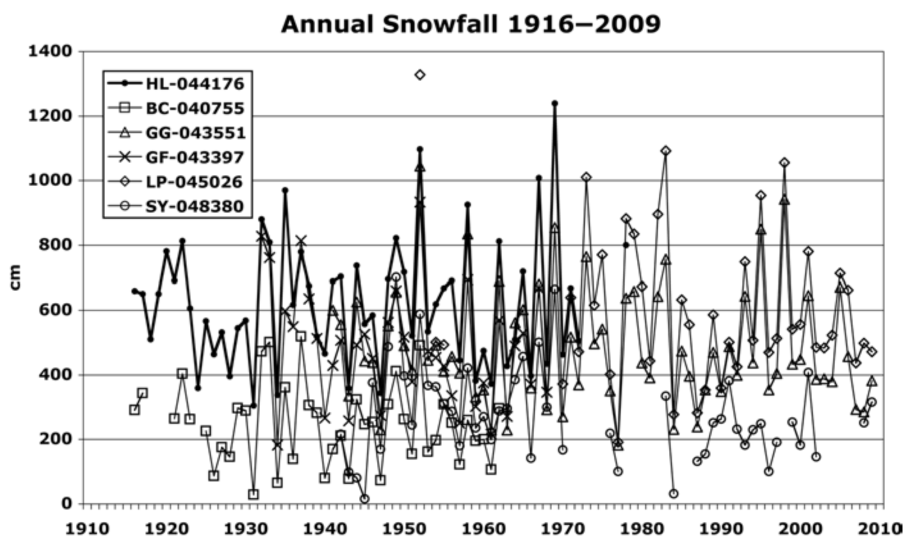

Figure 2. Annual snowfall totals for the six stations used in this study

strategy is to create from the individual overlaps with HL, regression equations which estimate HL totals individually (Table 1). We then combine these individual estimates for HL in a number of ways to complete the 94-year time series.

Table 1. Listing of the six stations used in the reconstruction of Huntington Lake (HL) snowfall with regression information (r = correlation). In the equation Y = bX + a, Regr = regression coefficient, or "b", intercept is "a" (cm), "Y" is HL snowfall estimate and "X" is the snowfall at the station indicated in the row (cm). The COOP ID is the station identifier number used by NCDC (each begins with "04" representing California) with our initials as follows: BC = Big Creek, GF = Giant Forest, GG = Grant Grove, LP = Lodgepole and SY + South Entrance Yosemite National Park

COOP ID		ELEV (m)	No. Years	First Yr.	Last. Yr.	Mean (cm)	r vs. 044176	Regr. "b"	Intercept ("a")
040755	BC	1488	43	1916	1962	247	0.83	1.22	317
043397	GF	2008	37	1932	1968	484	0.87	0.96	167
043551	GG	1947	69	1941	2009	489	0.92	1.06	107
044176	HL	2141	58	1916	1978	622	1.00	1.00	0
045026	LP	1944	45	1952	2009	619	0.94	0.75	210
048380	SY	1562	52	1942	2009	275	0.72	0.99	315

The high correlations with HL indicate the spatial scale of the snowfall variability of annual totals is large enough to fairly represent all of the stations (Table 1). This also indicates that a single, accurate station record will provide good information for a relatively wide spatial extent for annual snowfall.

Table 1 indicates that annual totals at GF and LP are very highly correlated with HL (r > 0.90). Additionally, they provide observations in all of HL's missing years and so are the best candidates for completing the time series. BC, only 5 km from HL but down a steep valley from HL (over 650 m in elevation lower), is useful (r = 0.83) but is only present in the early years and thus helpful in reproducing HL when HL is not used directly in the reconstruction. GG, r = 0.87, completely overlaps with HL, so is useful only, as with BC, when HL itself is not used. Finally SY is the poorest correlated with HL and used the least.

HL reports snowfall in 58 of the 94 years, thus to complete the time series, we require 36 additional estimates. HL also supplies four years not observed by any other station, so these four (1918, 1919, 1920 and 1924) will always be HL observations.

A similar reconstruction was performed for two spring time series, Mar plus Apr (MrAp) and Apr plus May (ApMy). Our interest here is to determine whether the late season snow has changed because this is the part of the year that is warmer already and has seen slightly rising temperatures (Christy et al. 2006).

RESULTS

We generate six individual time series as described in Table 2 in a step-wise manner, calculating from the regression equations those years not calculated from the previous step until complete. The versions are ordered according to the correlations in Table 1, i.e. the highest correlated stations will dominate the reconstruction in the first version, with lesser correlations in the remaining versions. There are numerous permutations of this process, but we show ones basically distinct from one another. The estimated standard error in step 1 is ±36 cm or about 6% for the 36 calculated years. In versions 4 to 6, the estimated standard errors rise to ± 60 cm.

Table 2. Results of reconstructing the 1916-2009 time series of Huntington Lake in the step-wise process. The notation, "[]", means the value of HL calculated as the result of the regression equations of the stations within the brackets. "[Avg w/o HL]" means the average of all stations reporting for the given year but without HL. The number of years in each step is given. The 95% statistical error range calculated to account for interannual variability produces a range of about ™13 cm decade^{-1} for these time series, indicating no trends approach significance

Version	Step 1	Step 2	Step 3	Step 4	Trend cm/Decade
1	HL 58	[GG+LP] 36			+4.0
2	HL 58	[GG+LP+SY] 24	[GG+LP] 12		+1.2
3	[GG] 69	HL 25			−1.3
4	[Avg All] 94				–0.3
5	[Avg w/o HL] 90	HL 4			−1.7
6	[GG+LP] 45	[SY] 23	[BC] 22	HL 4	+1.3
Avg	Average				+0.5

As mentioned, the versions are ordered by their amount of dependence on and reproducibility of the non-HL stations data, and thus by an indication of the confidence in the results. In the 1st and 2nd versions, all HL data were used with infilling for the remaining 36 years using stations which have the highest correlations. Further versions reduce the amount of direct HL observations inserted in each time series while infilling the missing years with progressively less confident results.

The trend-error due to temporal-sampling of these time series is relatively high given the high magnitude of variance relative to the mean value, with the 95% C.I. values of the trend about ±13 cm decade^{-1}. The 7th version is the average of the first six time series and by statistical properties possesses a smaller standard error so is our "best estimate" (Fig. 3.) The version seven (HL AVG) trend is +0.5 cm decade^{-1} (+0.08% decade^{-1}) ±13.1 cm decade^{-1} while the other six trends range from −0.3% to +0.6% decade^{-1} with none, obviously, even approaching significance.

Another way to understand trend variability in this time series is to calculate all 25-year trend values from the 94-year time series. These values show a wide range of +82.8 (+13.3%) to –83.0 (–13.3%) cm dec^{-1}, with a median value of +10.0 (1.6%) cm dec^{-1}. Similarly, 50-year trends range from +24.1 (+3.9%) to –17.1 (–2.7%) cm dec^{-1} with a median of +3.1 (+0.5%) cm dec^{-1}. The most recent 25-year and 50-year trends ending in 2009 are +15.9 (+2.6%) and −3.9 (–0.6%) cm dec^{-1} respectively.

The average time series of MrAp (mean 185 cm) and ApMy (mean 84 cm) reveal insignificant trends of –0.3 (–0.2%) ± 10.1 cm decade^{-1} and +1.4 (+1.7%) ±9.5 cm decade^{-1} respectively. Though a trend of +1.7% decade^{-1} is relatively large over a

94-year period, the high variability against a relatively low mean value renders the trend insignificant.

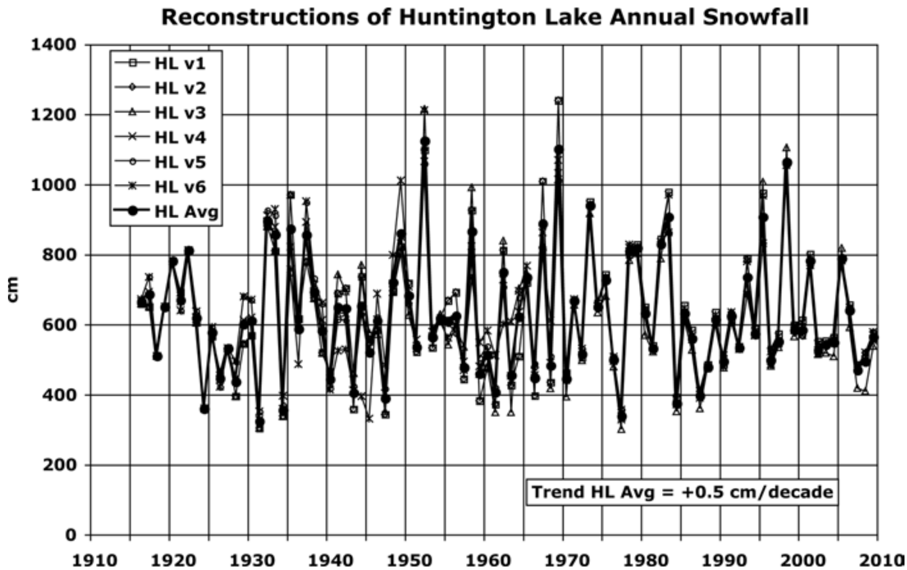

Figure 3. Reconstructed values of Huntington Lake snowfall for 1916–2009 as described in the text

An independent assessment of these relatively minimal snowfall trends is provided by three stream gauge measurements starting in 1916 (unimpeded flow). The three basins examined are the San Joaquin River at Friant (drainage 4,453 km^2 which includes HL and BC), the Merced River at Happy Isles (465 km^2 drainage, 60 km NNW of HL) and the full San Joaquin River basin (drainage 35,087 km^2, Fig. 1). The annual correlations between runoff and HL snowfall (v.1) for the three gauges are 0.66, 0.65 and 0.64 respectively. The trends are positive, but insignificant at +2.4, +2.0 and +2.3% $decade^{-1}$ respectively. These results do not explicitly confirm our non-significant snowfall trends since the stream flow could be masking a shift of snow to rain or vice versa. However, in combination with the temperature and snowfall trends, the picture is one of consistency with a result that no significant change in snowfall of the mid-elevation So. Sierra since 1916 has occurred.

We now turn to the comparisons of snowfall with SWE from 1930. The two metrics, annual snowfall and SWE, are highly related, but different. SWE represents a snapshot of conditions near 1 Apr of each year. While snowfall does accumulate to reach a maximum near 1 Apr in many years in terms of liquid equivalent, natural factors conspire to reduce the correspondence of the two metrics. For example, periods of warm rain can melt much snow prior to 1 Apr while heavy snows after 1 Apr would not be captured in the SWE surveys.

In Table 3 we display the trends and correlations between our reconstructed snowfall time series (HL AVG) and the 1 Apr SWE for the 12 closest sites (in terms of horizontal and vertical distance) and their 12-site average. None of the trends

Table 3. Row 1: Three-letter identifiers of 12 SWE measurement sites in the region (see http://cdec.water.ca.gov/cgi-progs/snowQuery_ss/ for information on the sites). "Mean": Mean of SWE (1930–2009 only) in cm of liquid water on 1 Apr. "HL AVG" is also cm but is annual snowfall amount. "Trend": units of Percent per Decade. "95%CI": the magnitude of the statistical significance range in percent per decade. "Correl": Correlation of SWE on 1 Apr with annual HL reconstructed snowfall. See notes for station names and elevations

	BVH	BMS	CHM	CKT	FDM	FLC	GFL	GFR	GNG	HCM	HTT	PGM	SWE AVG	HL AVG
Mean	62.6	66.5	94.5	93.9	53.6	19.0	8.8	40.1	34.9	43.8	48.7	77.0	60.1	635.4
Trend	–3.9	–1.0	+1.3	+0.2	–2.0	–3.2	–1.5	–4.1	–4.6	–1.9	+2.4	–3.3	–1.3	+0.2
95%CI	7.3	8.9	5.7	7.2	12.7	13.1	6.8	10.3	12.4	10.4	11.8	8.9	8.3	5.6
Correl	0.81	0.77	0.77	0.75	0.83	0.81	0.79	0.82	0.81	0.80	0.85	0.78	0.84	1.00

Notes to Table 3, names and elevations of stations.

BVH: Beehive Meadow, 1981m

BMS: Mig Meadows, 2316m

CHM: Chilkoot Meadow, 2179m

CKT: Chilkoot Lake, 2271m

FDM: Fred Meadow, 2118m

FLC: Florence Lake, 2195m

GFL: Gin Flat, 2134m

GFR: Giant Forest, 1951m

GNG: Grant Grove, 2012m

HCM: Horse Corral Meadow, 2316m

PGM: Peregoy Meadows, 2134m

HTT: Huntington Lake, 2134m

approaches statistical significance. The significance bands are larger for SWE in percentage terms than annual snowfall, sometimes twice as large, because the variance is higher as annual values range from near zero when snow melted by 1 Apr, to near the annual snowfall total. Annual snowfall total appears to be a more robust variable due to its accumulation of daily sampling points as the snow falls, eliminating the confounding factor of melt periods or post-1Apr snowfall.

We display the standardized values in Fig. 4 of the nearest SWE site to HL (HTT), the 12-site average (SWE AVG) and annual snowfall total of HL AVG. The plot demonstrates the strong correlations in Table 3 between SWE and annual snowfall. The trend difference between HL snowfall and average SWE since 1930 (+0.2% vs. −1.3% decade^{-1}) is insignificant. As mentioned earlier, SWE does not capture snowfall after 1 Apr. Two examples of post-1 Apr heavy snow events in Fig. 4 are 1967 and 2001 which being in the second half of the time series, would tend to influence snowfall to posses a more positive trend than SWE.

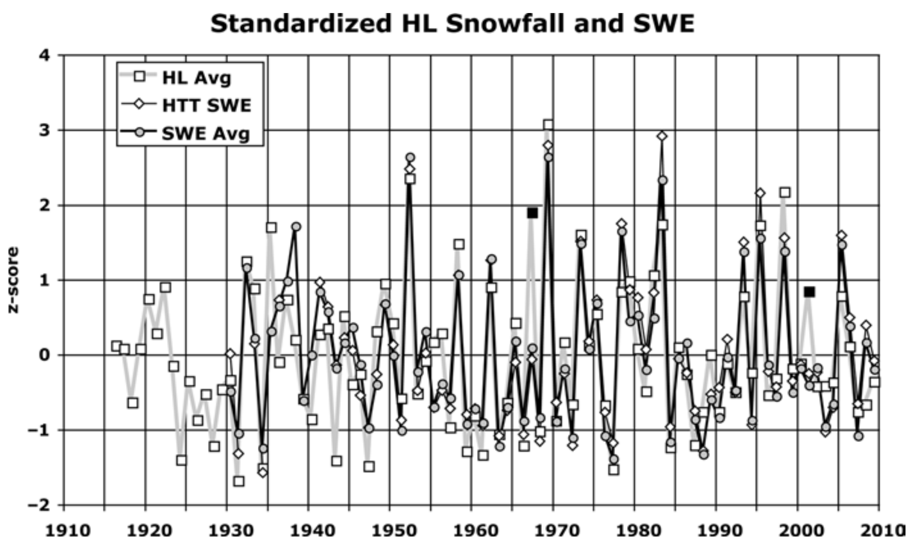

Figure 4. Comparison of the Huntington Lake snowfall reconstruction (gray line open squares, HL Avg) with the SWE measurements on 1 April at HTT (gray line, open diamonds, nearest Huntington Lake) and an average of 12 SWE sites within 100 km distance and 200m elevation of HL (black line, filled circles). All values are anomalies in terms of standard deviation magnitudes. For the three times series, the mean (represented as zero on the diagram) and standard deviations are HL: 635 and 197, HTT: 48.7 and 30.9 and SWE AVG: 60.1 and 33.5 all in cm. 1967 and 2001 are filled squares indicating examples of significant snowfall after the SWE surveys

Our second SWE comparison (Fig 5) reveals the relationship between trends in SWE (and HL snowfall) versus elevation in the four river basins of the study area for all SWE survey sites. The metric used for trends is the normalized decadal trend as a z-score, which expresses the anomalies in standardized form for intercomparison. The average station has a mean of 75.1 cm of SWE and a standard deviation (1.0 z-score) of 40.9 cm. Thus a trend of +0.04 in Fig. 5 is about a trend of +1.6 cm dec^{-1} per average station.

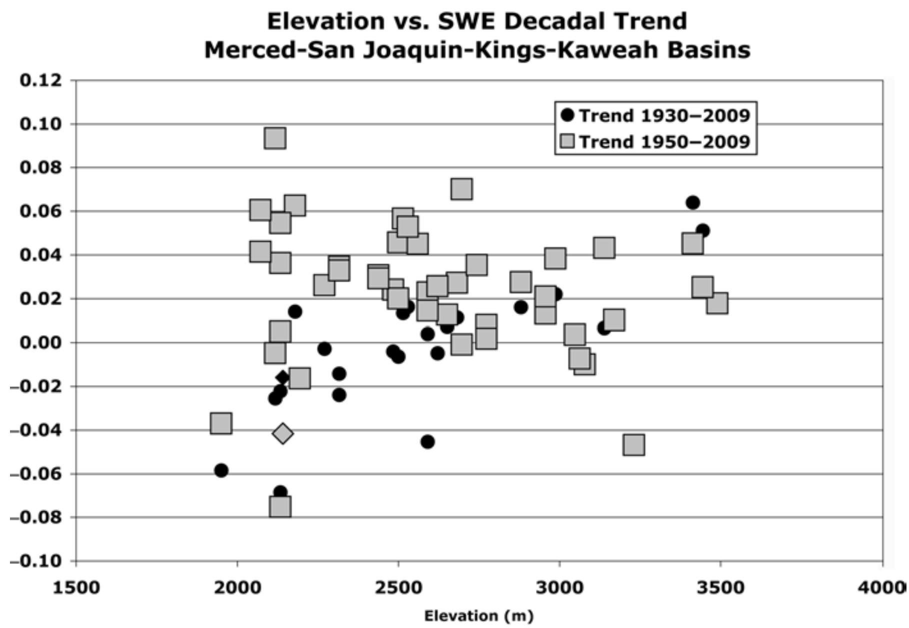

Figure 5. Scatter plot of individual survey site values of SWE-trend since 1930 (solid circles) and 1950 (gray squares) and ending in 2009. All sites having observations from at least 1950 in the Merced, San Joaquin, Kings and Kaweah basins were used. Trends are in z-score per decade values. The mean SWE value is 75.1 cm with a mean standard deviation of 40.9 cm. Thus a trend value of +0.04 per decade is roughly +1.6 cm SWE per decade. No trend value on this plot is significantly different from zero as 95% error bars range from ±0.09 to ±0.17. The diamond shaped symbols represent the 1930 and 1950 z-score trends for snowfall at HL

Twenty-six stations reported observations from 1930 onward (solid circles) and 45 from 1950 onward (gray squares). There appears to be a strong relationship between elevation and trend value (solid circles) for 1930–2009 trends (80 years) with the lower elevations (near that of HL – diamonds) showing near or below zero trends with higher elevations showing positive trends. The correlation between elevation and SWE is quite high at +0.70. However, none of the individual 80-year trends is close to being significant with 95% confidence intervals ranging from ±0.09 to ±0.17 z-score km^{-1}. It was apparently a fortuitous distribution of values which created this seemingly significant result (only 4 of the 26 data points account for 70% of the variance explained.) The regression result is +0.052 z-score km^{-1} ±0.035 assuming all sites are independent. When three end-point sites are removed, the relationship becomes insignificant. We also calculated the same statistics for all stations with 60-years of record (1950–2009) where now we have no discernable relationship between SWE trend and elevation (r = –0.11, slope of regression line –0.017 z-score km^{-1}). Thirty-seven of the 45 sites report positive trends.

The key point of Fig. 5 for this study is that the shorter period snowfall trends at HL of 80-years and 60-years are consistent with those of the SWE measurements. The composite SWE trend (trend of the mean of the anomalies over time) for 80 (60) years was –0.001 (+0.013) z-score dec^{-1} ±0.11. Converting to percentages, the SWE trends for 80 (60) year periods become –0.1 (+0.7) % dec^{-1} ±5.9%. Similar trend percentages for HL snowfall for 80 (60) year periods are –0.4 (–1.1) % dec^{-1} ±4.9%. For the shorter 35-year period beginning in 1975, the HL snowfall trend is –1.0 % dec^{-1} ±10.0%.

An attempt was made to reconstruct lower elevation snowfall (<1000 m) by using reports from COOP stations. The thinking here was that since snowfall was a relatively rare event (few times per year) it should have been diligently reported by the observer. Additionally, because the lower elevations are more marginal in snowfall, trends might be more detectable. However, the consistency of the records was much poorer in comparison to those used above, with many moves, openings, closures and errors in data keying. In North Fork (046252 802 m), for example, the record seemed consistent until the mid-1950's where a sudden decline to near zero annual snowfall totals occurs. An investigation by the Weather Bureau in 1957 noted the observer's lack of interest in recording observations and the station was downgraded.

We also examined images of the original COOP observational forms. In the case of Auberry (040379, 637 m) we found 33 snow events from 1962 through 1990 not keyed into NCDC records. A common error occurred when the observer wrote the snow total in the "comments" column rather than the "snowfall" column, which then was keyed as zero snowfall. This was disappointing because of the potential long-term changes these low-elevation stations would have the ability to inform.

CONCLUSION

With the available data from six mid-elevation stations in the Southern Sierra region of California we reconstructed annual snowfall totals for 36 missing years of the Huntington Lake record to complete the time series (1916–2009). The standard error of the missing years is calculated to be ±36 cm, or 6% of the 94-year annual mean of 624 cm in the most robust estimation method (though we utilized the average of six methods which reduces the standard error further.)

The results of both the annual and spring snowfall time series indicate no remarkable changes for the 1916–2009 period in the basins drained by the Merced, San Joaquin, Kings and Kaweah Rivers. In the six reconstructions the range of trend results varied only slightly from –0.3% to +0.6 % $decade^{-1}$. With a consensus trend of only +0.5 cm (+0.08%) $decade^{-1}$ ±13.1 cm $decade^{-1}$ there is high confidence in the "no-significant-trend" result. The corroborating information on temperature trends (Christy et al. 2006), stream flow, precipitation and shorter period snow water equivalent trends presented here are consistent with "no-significant-trend" in So. Sierra snowfall near 2000m elevation since 1916.

The statistical properties of annual snowfall, and associated annual variables mentioned above, demonstrate the high level of variability in western precipitation. For example, calculating trends over short periods, such as in 25-year segments, produces a wide range of trends as low as −83.0 to +82.8 cm dec^{-1} with a median of +10.2 cm dec^{-1} and a most recent (1985–2009) value of +15.9 (+2.6%) cm dec^{-1}. This suggests that the impacts of interannual and interdecadal variations are to be considered of serious import in comparison with impacts of long-term trends which have been shown to be negligible in this region to this point.

ACKNOWLEDGEMENTS

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