DIMINISHING SNOWFALL IN CENTRAL AND NORTHERN CALIFORNIA'S MIXED RAIN AND SNOW ELEVATIONAL ZONE

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ABSTRACT

Snowfall over large areas of the low elevation snow zone in central and northern California below the 1,524 m (5,000 ft) elevation has significantly diminished since the mid-twentieth century and for some areas where it has historically snowed, precipitation now occurs only as rainfall. An analysis of snowfall measurements from several NOAA National Weather Service cooperative weather stations throughout central and northern California revealed a significant decrease in measured snowfall in recent years. Earlier studies have mostly focused on snow courses and automated snow sensors at elevations above 1,524 m (5,000 ft). This study analyzed snowfall measurements only between the 457 m (1,500 ft) and 1,524 m (5,000 ft) elevations. Snowfall is typically measured manually utilizing a snowboard that is measured daily, swept clean, and then reset for the following day's collection. Hundreds of NOAA cooperative weather stations exist at all elevations throughout California. Some of the snowfall records are incomplete and not usable for producing a meaningful time series, but many climate stations do offer usable data and are an excellent source for evaluating low elevation precipitation type utilizing measured snowfall. Several mountain communities in California exist in the rain-snow zone between the 457 m (1,500 ft) and 1,524 m (5,000 ft) elevations. In addition to US Forest Service Ranger Stations and Highway Maintenance Stations, the NOAA cooperative weather stations that exist in these relatively small mountain towns and communities are often maintained by highly dedicated families and individuals. It's been my experience that people living in the low elevation mountain communities often take great pride in their dedication to collect accurate information. People frequently move to small towns and communities located relatively low mountain elevation zone to get a balance between cooler summer temperatures with occasional winter snowfall, without having to deal with the strenuous tasks of constantly removing snow. Continuing reductions in snowfall for these mountain communities reduces the need for snow removal equipment, designing building structures for heavy snow loads, and is creating a changed winter lifestyle, one with less snowfall.

INTRODUCTION

Earlier studies (Mote et al, 2005, Julander and Bricco, 2008) have focused their findings on the impacts of climate change in the western states to data from snow courses and automated remote mountain snow sensors, mostly located at or above the 1,524 m (5,000 ft) elevation. Impacts ranging up to approximately 25-30% have been found by Freeman (2003) at low elevation snow courses in California's Sierra and southern Cascade Mountains. The scarcity of snow courses and sensors located at elevations lower than 1,524 m (5,000 ft) feet doesn't provide sufficient information to understand impacts happening in the transitional mixed rain- and snow-fall elevational zone. In recent years, this low mountain region that surrounds California's Central Valley is one in which a significant proportion of the population has moved into, establishing either second homes or for simply getting away from the congested and more populated urban valley and coastal areas of California. Cooler mountain temperatures and rural settings are often an attraction for people choosing to move into these small community mountain locations. Many seek the cooler temperatures above the Central Valley floor, but choose to not move higher on the hill in order to avoid the arduous task of snow removal and hazardous winter driving conditions. Other studies have utilized climate station snowfall data to study newly fallen snow over a larger area of the Western United States (Knowles et al, 2006). This study however focuses specifically on central and northern California for the elevation range below 1,524 m (5,000 ft where snowfall has historically occurred, with reviews of the record to better understand the impacts of climate change on snowfall reduction. Abundant record of snowfall data from the NOAA cooperative network is available to compile and identify trends in snowfall. While the quality of record varies from station-to-station, overall the author believes there is sufficient record of reasonable quality to establish useful trends. While data from any given station may be suspect in terms of its quality over time, when a sufficient number of stations is reviewed; the results appear consistent and meaningful in terms of providing useful and reasonable information. In recent years a number of climate stations have been discontinued and some of the remaining stations may no longer be maintained to NOAA National Weather Service standards. Increased

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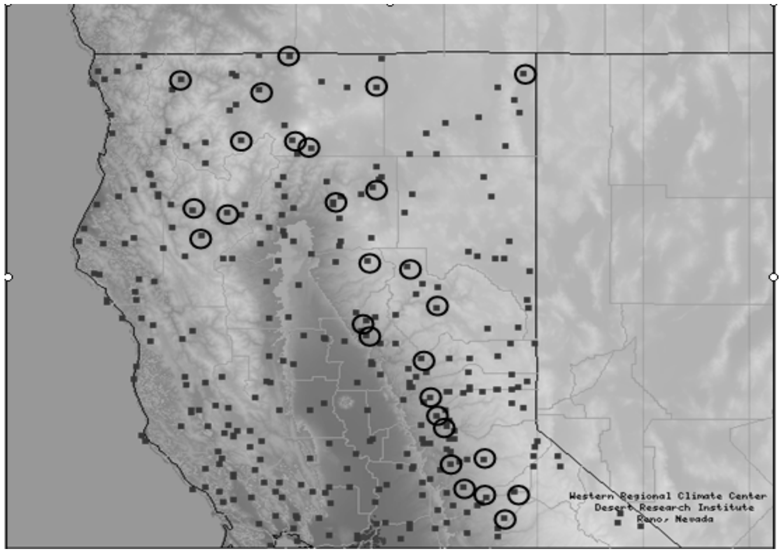

Figure 1. Circled dots represent approximate location for stations (2 not shown) selected for this low elevation snowfall study. Stations were selected primarily based on data quality, length of record, and elevation.

automation and financial cutbacks are partly to blame for some of the stations, which no longer collect snowfall snowfall transitional elevation zone (Freeman, 2003). The author believes that snowfall information may have value for future planning of community services, structures, and other decision making for those who choose to visit or live in this relatively low elevational mountain ran and snowfall zone. The central and northern regions of California were chosen primarily for their relatively large extent of low elevation area, which occurs in this transitional mixed rain-snowfall elevational zone as compared with the steeper southern Sierra topography that rises to significantly higher elevations. Figure 1 shows a general map of the climate station locations in central and northern California that were selected for this study.

MEASURING SNOWFALL

Figure 2 illustrates the NOAA approved standard method for measuring snowfall with a snowboard. This technique requires that an observer physically be present during the snowfall season to measure snowfall depth

Figure 2. Measuring daily snowfall on a snow board with a ruler.

using a ruler, clean the board following the daily measurement, and record the reading. Since the quality of record is totally dependent on the observer's due diligence to accurately collect this information, the quality of recorded information and data for any given station has some uncertainty and may also vary over the period of record depending on the integrity and due diligence of the climate station observer. The observers are frequently highly dedicated, but often unpaid volunteers who participate in the cooperative program. For purposes of this study, specific years that contained one or more months during the year with 12 or more missing days of observation were excluded from a climate station's time series. For some stations, there were insufficient available years with good data to produce meaningful results. These stations were not used in the study. Figure 3 is an example of monthly the snowfall record for Burney, California for the years 1947-48 through 1965-66. These data are available from the Western Regional Climate Center.

BURNEY, CALIFORNIA

-41214

Monthly Total Snowfall (Inches)

File last updated on Dec 4, 2008
*** Note *** Provisional Data *** After Year/Month 200808
a = 1 day missing, b = 2 days missing, c = 3 days, ..etc..,
z = 26 or more days missing, A = Accumulations present
Long-term means based on columns; thus, the monthly row may not
sum (or average) to the long-term annual value.
MAXIMUM ALLOWABLE NUMBER OF MISSING DAYS : 5
Individual Months not used for annual or monthly statistics if more than 5 days are missing.
Individual Years not used for annual statistics if any month in that year has more than 5 days missing.

YEAR(S	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	ANN
1947-48	0 z	0 z	0 z	0 z	0 z	0 z	0 z	0 z	0 z	0 z	0 z	0 z	0
1948-49	0	0	0	5	1	25	11.5	8 x	5	0	0	0	47.5
1949-50	0	0	0	0 c	1.5 b	0.5	23.8	18	4	0	2.5 a	0	50.3
1950-51	0	0	0	0	0	4	20	28.5	4 e	0	0	0	56.5
1951-52	0	0	0	0	0.5	10.5	45	15	45.5	0	0	0	116.5
1952-53	0	0	0	0	2 b	22.5	2	0	3.5	5.5	0	0	35.5
1953-54	0	0 e	0 c	0	2	0 f	6	1.5	5.5	0	0	0	15
1954-55	0	0	0	0	0	21.3	11.5	9	0.5	5 a	0	0	47.3
1955-56	0	0	0	0	10.5 a	21	18	7.1	3	0	0	0	59.6
1956-57	0	0	0 i	0	0	3.5 b	11 c	1	1	0	0	0	16.5
1957-58	0	0	0 j	0 a	1	1	7	0 z	16	2.5	0	0	27.5
1958-59	0	0	0	0	0.1	1	12.5	9	0	0	2	0	24.6
1959-60	0	0	0	0	0	1	18	7	0	10	0	0	36
1960-61	0	0	0	0	20	0	0	1	4	13	0	0	38
1961-62	0	0	0	0	9	5.5	5	14.5	9	0	0	0	43
1962-63	0	0	0	0	0.5	0	9	0	16	1.5	0	0	27
1963-64	0	0	0	0	5	3	13	2.5	5	0	7	0	35.5
1964-65	0	0	0	0	2	17	15.5	0	0.5	6	0	0	41
1965-66	0	0	0	0	0	21	8.5	16	2	0	0	0	47.5

Figure 3. An example of monthly snowfall record for Burney, California for the years 1947-48 through 1965-66. The number of missing days for the month can be determined from the alphabetic character and it numerical position in the alphabet, such as c=3 days, d=4 days.

DECLINING ANNUAL TREND AND VARIANCE

In recent years low elevation mountain climate stations below 1,219 m (4,000 ft) and which have historically received snowfall are revealing a significant decline in snowfall. Figure 4 compares trends in annual snowfall for four low elevation stations. All trends in Figure 4 reveal a significant decline in annual snowfall. The charts of selected locations in Figure 4 also show large annual variation from year to year especially during the earlier periods of record. This declining trend in variance magnitude seems somewhat explainable because the low snowfall years are bounded by zero. The range between zero and low snowfall years such as occurs in the more recent period is less than that which occurred during earlier years. The consequence of large years during the earlier pre-1970 period is that sufficient frequency of large snowfall years can cause the terrestrial environment to evolve in balance with this variance. Snowfall in the earlier years for some stations was sufficiently large to occasionally last on the ground all winter. In the recent period, for many areas this over-winter snowpack is often no longer the case. Soils that may have once been insulated from freezing by an over winter snowpack may now be exposed directly to subfreezing air every winter (Hardy et al, 2001). The increased frequency of precipitation in the form of rainfall and loss of snowpack could lead to an increase in soil freezing. Frozen soils could potentially

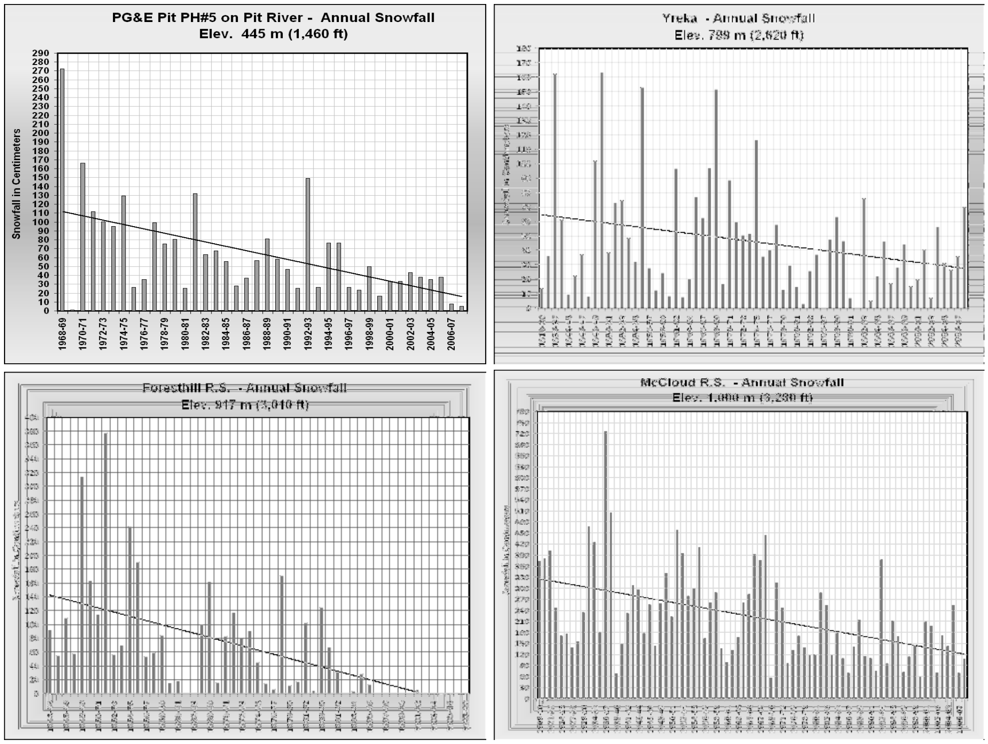

Figure 4. Four low elevation plots below 1,219 m (4,000 ft) reveal a significant decline in snowfall.

affect both the infiltration rate and rate of surface runoff. The variance drops to zero when snowfall no longer occurs. At the town of McCloud near Mt. Shasta, the frequency of additional days per year with precipitation in the form of rainfall rather than snowfall has increased significantly in recent years. A trend of declining snowfall, starting with 1921 is revealed in Figure 5. The decrease indicates an approximate 60% decrease in precipitation in the form of snowfall for the town of McCloud. Because of the year-to- year variance, the local residents may not be fully aware of the rapid rate of snowfall decline since 1921. Analysis of the available snowfall record indicates that if the downward trend continues, snowfall in 10-15 years will likely be absent in most winters.

PERCENT ANNUAL SNOWFALL DECLINE BY ELEVATION

For the stations utilized in this study at elevations below 1,524 m (5,000 ft), Figure 6 provides an indication of snowfall loss by elevation. While the annual snowfall decline by specific elevational station site has an R^2 of 0.64, the specific decline for any given station is likely dependent on a number of factors such as topography, microclimate including local air dynamics, vegetation, aspect, and other parameters that provide each of the stations observed with their unique characteristics and response to snowfall decline over time. Local air dynamics can likely impact cooling sufficiently to slow the annual decline rate from continued climate change, however over time it seems likely that all stations below about 1,524 m (5,000 ft) elevation will experience significant decline with an increasing frequency of years eventually having no annual snowfall. Eight of the 25 climate stations with annual snowfall decline greater or equal to 89% took place at or below the 917 m (3,010 ft) elevation. Three of those stations had 98% or greater snowfall loss. While snowfall for a given elevation at some point no longer occurs, it is not always an abrupt cutoff. Instead there may be a decreasing frequency of snowfall such that it occurs first every other year, followed by maybe one in three years, then one in 5 years, one in ten years, and maybe very rarely beyond that point.

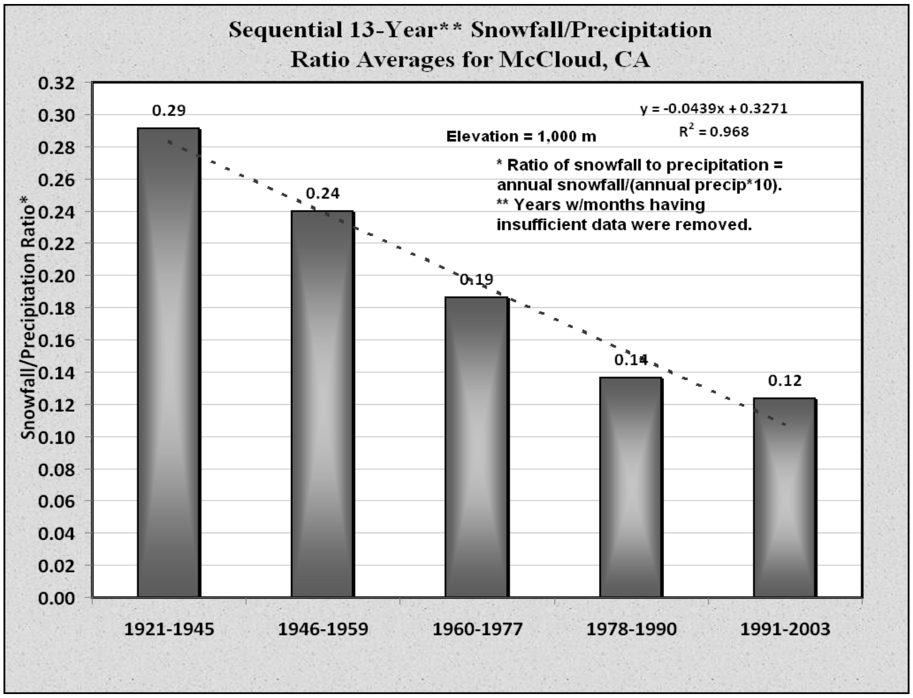

Figure 5. Five sequential 13-year periods of annual ratios of annual snowfall (annual precipitation was multiplied by a factor of 10 to produce a meaningful ratio index).

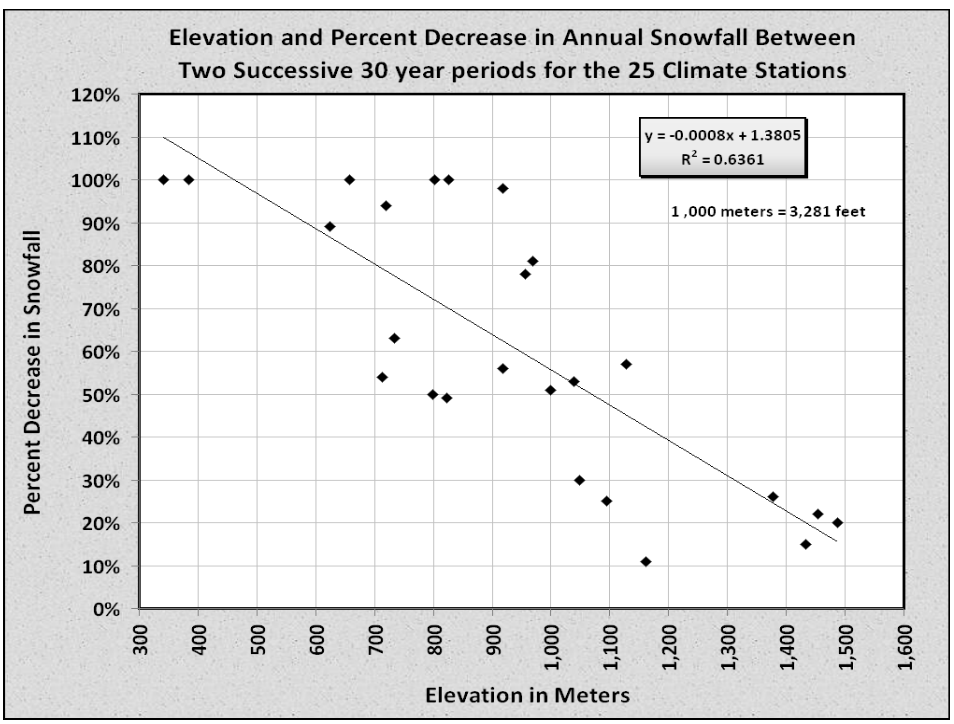

Figure 6. The elevation relationship for percent decrease in annual snowfall between two successive 30-year periods for the 25 climate stations studied.

DECLINING SNOWFALL BY MONTH

An analysis was done for 25 climate stations in central and northern California to determine if any given month had significantly greater snowfall loss over time. For each station the number of years with quality data was divided evenly by two and the two sequential periods compared for percent change. In comparing the losses for December, January, and February in Table 1, January clearly stood out for the majority of stations analyzed as having the greatest snowfall loss between the two sequential equal periods. Over three times more snowfall disappeared for the climate stations located between 999.7 m (3,280 ft) and 1,487 m (4,880 ft) than below 999.7 m (3,280 ft). This is likely due to the larger historical snowfall amounts in the higher elevation range that could be impacted from climate change. For the low elevation stations, January has historically had much more snowfall than either December or February and the percent decrease in snowfall for the two successive periods is greatest in January. The average decrease for the January precipitation for the same 25 climate stations and successive periods was only 2.0%, so precipitation changes were minor in terms of explaining loss of snowfall. The calendar year precipitation change for the two successive periods for the 25 climate stations analyzed was 4.0% increase in the more recent period with a standard deviation of 14.3%. However, when one compares the annual precipitation change for the two sequential periods with elevation, there may have been a decrease in annual precipitation for the lower elevation climate stations. It is possible that if the frontal air mass is warmer, the air is increasingly not reaching the dew point at the lower elevation stations and therefore less precipitation may be occurring at the lower elevation stations. In recent years if this were the case then one may possibly expect to see slightly more precipitation at higher elevations where the dew point is reached and the untapped moisture becomes available for precipitation. Figure 7 shows this relation of precipitation change for the two successive periods with elevation.

Table 1. The average and median monthly distribution of snowfall loss for 25 climate stations in central and northern California for elevations between 341 m (1,120 ft) to 1,487 m (4,880 ft)

Lowest Elevation	Highest Elevation	Stations		Dec	Jan	Feb
341 m (1,120 ft)	1,487 m (4,880 ft)	25	**AVERAGE**	33.5%	57.8%	36.5%
341 m (1,120 ft)	1,487 m (4,880 ft)	25	**MEDIAN**	27.6%	59.4%	42.4%
341 m (1,120 ft)	1,487 m (4,880 ft)	25	**STD DEV**	37.3%	28.8%	41.9%

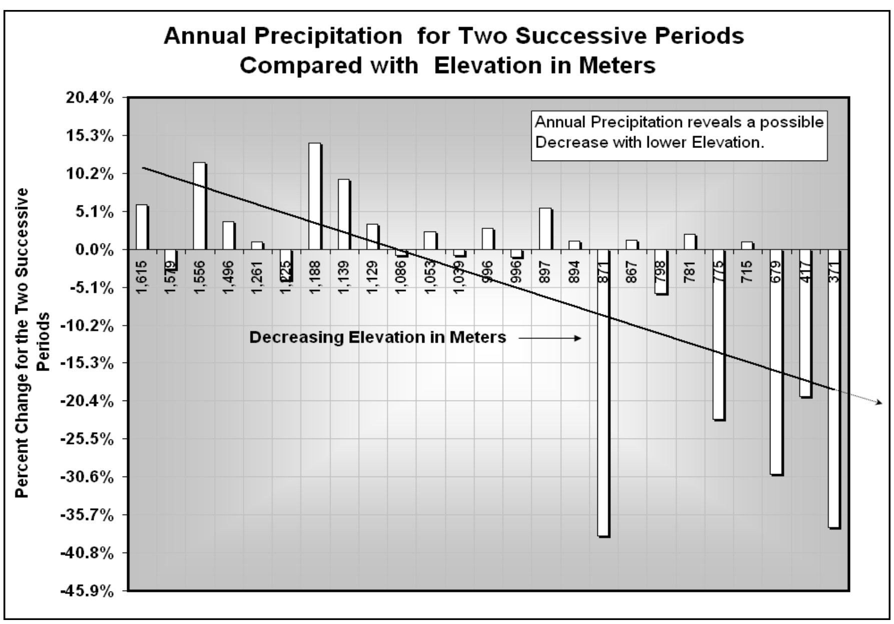

Figure 7. Precipitation for the two sequential periods for the 25 climate stations analyzed may have dropped significantly in the more recent period for climate stations below about 914 m (3,000 ft) elevation.

RISING JANUARY MEAN MONTHLY TEMPERATURES IN RECENT YEARS

Precipitation in the form of snowfall has decreased in recent years along with rising winter temperatures in the elevations below 1,524 m (5,000 ft). While the precipitation type is mostly dependent on freezing levels at time of the frontal system passing through, the average monthly temperatures for winter months such as January have increased in recent years. This can have multiple implications as to its affecting dew point, amount of precipitation, and form of precipitation. Twelve climate stations in the rainfall-snowfall transitional elevation zone were through 2008. Table 2 shows the specific climate station with a comparison of the three successive periods. For the twelve stations, an average increase of 1.8 degrees C (3.2 degrees F) was observed. The observed increase in mean January temperature may have a possible relationship to monthly precipitation amount for stations below 914 m (3,000 ft), which reveals an annual precipitation decrease in recent years. While a decrease in annual precipitation for recent years was observed it was not an objective for the study.

Table 2. Mean monthly January temperatures for twelve rain-snowfall transitional zone stations

	Elevation	Elevation	January Mean Monthly Temperature ^{0}C			**Full Period Change in ^{0}C**
	Meters	Feet	1949-1968	1969-1988	1989-2008	**1949-2008**
Happy Camp R.S.	341.4	1,120	2.6	4.5	4.7	**2.2**
Weaverville R.S.	624.8	2,050	2.1	3.1	4.0	**1.9**
Yreka	798.6	2,620	0.7	1.4	1.7	**1.0**
DeSabla	826.0	2,710	4.7	5.4	5.7	**1.1**
Placerville	838.2	2,750	4.4	5.9	7.7	**3.3**
Nevada City	847.3	2,780	3.0	4.8	5.5	**2.5**
Burney	954.0	3,130	-0.8	-0.6	0.8	**1.6**
McCloud	999.7	3,280	0.4	1.9	2.1	**1.7**
Quincy	1,039.4	3,410	0.7	0.7	2.7	**2.1**
Mt Shasta	1,094.2	3,590	0.6	1.5	1.8	**1.2**
Fort Bidwell	1,371.6	4,500	-1.6	-1.3	0.6	**2.2**
Mineral	1,487.4	4,880	-0.9	-0.4	-0.1	**0.8**

WHERE HAVE ALL THE BIG SNOWFALL YEARS GONE?

Historically large snowfall years were relatively common in northern and central California at or below the 1,524 m (5,000 ft) elevation. People who lived in or around the relatively small mountain communities were used to dealing with large amounts of snowfall and likely prepared their community and themselves accordingly. For some communities, where snowfall typically remained on the ground all winter, these areas may no longer be covered by snow or if so only for a brief few days in some winters. Figure 8, Groveland R.S. at the 957 m (3,140 ft) elevation illustrates a typical example representative of several low elevation stations. For the record starting in 1957, ten of the years with greater than 50.8 cm (20 in) of snowfall occur in the period 1957-1982 with none occurring after 1982. Four of those ten years prior to 1982 were greater than 101.6 cm (40 in) with two of those years at or above 114.3 cm (45 in). The relatively common occurrence of these large snowfall years likely occurred from an increased frequency of wet, relatively cold weather fronts characteristic of those bringing snowfall into the low mountain elevations. Unless records of historical snowfall are analyzed, after 40 to 65 years, people's memories along with generational change may eventually lead to "losing track of" or "simply forgetting" how large some of the past snowfall years were. It may have been no joke when our elders remind us how they commonly trekked through 0.6- 0.9 m (2-3 ft) of snow to get to the school house in most winters. For the entire 1957 through 2007 period analyzed, the Groveland Ranger Station had 13 years with snowfall greater than 38.1 cm (15 in) during the first 22 years of record, while only 5 yrs greater than 38.1 cm (15 in) during the following, most recent 21 years of record. This is a significant drop-off in annual snowfall during two nearly equal length periods having almost equal annual precipitation. Ten stations below the 762 m (2,500 ft) elevation were examined for average rate of snowfall decline since 1968. The mean decline in annual snowfall for the ten stations was approximately 2.54 cm (1.0 in) per year. This average rate of decrease included rates as low as 0.51 cm (0.2 in)/year and one at PG&E's Pit PH#5 with a 6.35 cm (2.5 in)/year decline. The standard deviation for the ten stations was 1.96 cm (0.77 in)/year, which indicates a lot of variance in the low elevation sample. The annual trend for the decline in snowfall

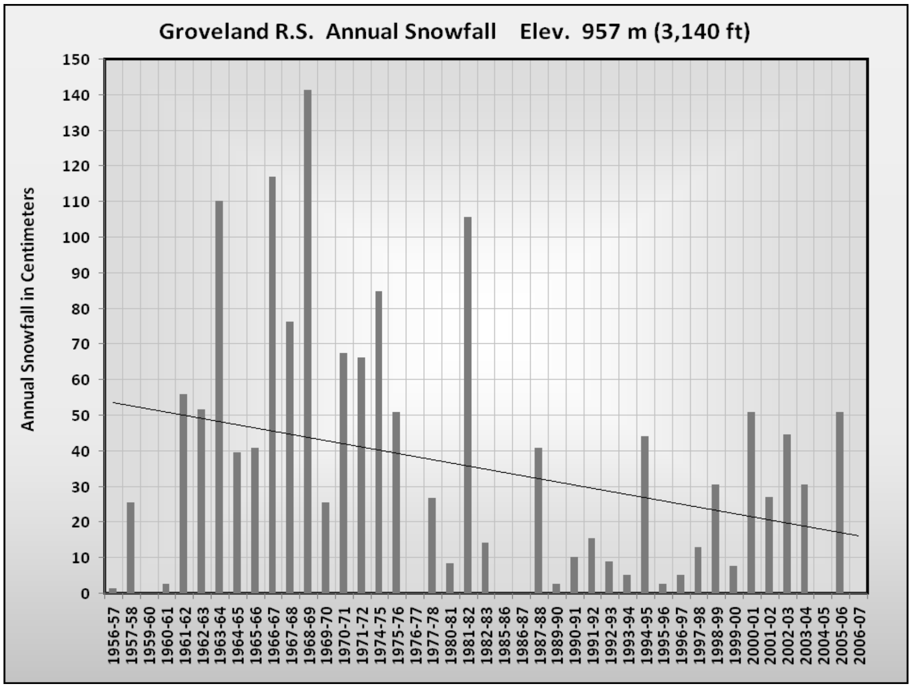

Figure 8. Annual snowfall at the Groveland Ranger Station. Large snowfall years in excess of 50.8 cm (20 in) did not occur again after the winter of 1981-1982.

is highly specific to individual station location. Figure 9 compares two equal length successive periods for 30 climate stations to illustrate the affect of elevation with reduced snowfall in the recent period. All climate stations below the 999.7 m (3,280 ft) elevation for the recent period have an increase in "the less than or equal to 15.2 cm (6.0 in) of annual snowfall" years compared with the prior, earlier period. 12 out of 21 climate stations below the 1,048.5 m (3,440 ft) elevation more than doubled the number of years that had annual snowfall equal to or less than 15.2 cm (6 in). Specific conditions for the various climate stations create variance in the sequential period comparison, however a sufficient reduction in snowfall for a large number of the very low elevation stations provided a convincing case that no single climate station was alone in making the large snowfall lose conclusion. It is likely that snowfall for some of these locations will only rarely occur in the future and snow on the ground or snow board may not last for 24 hours, possibly resulting in zero measurement recorded for the day.

CLIMATE STATIONS WHERE IT NO LONGER SNOWS

Snowfall no longer or only rarely occurs at several of the very low elevation climate stations. If snowfall occasionally occurs, it can melt quickly and may miss getting measured. Figure 10 which charts annual snowfall for Fiddletown Dexter Ranch is a good example of a climate station where snowfall may likely no longer occur. It fits the expected pattern where annual snowfall declines, then occasionally doesn't occur, and finally totally stops or occurs in amounts that melt quickly and the daily opportunity to be recorded may be missed. Except for some small amount of snowfall in the winters of 1979 and 1991, snowfall stopped at the Fiddletown Dexter Ranch climate station after 1976. Prior to 1977, the first year of record without snowfall, snowfall occurred each year for the period of record beginning in 1945. The record of snowfall data collection for this station indicates very little missing record for the period used. One of the concerns that the author has is that some of the climate stations in recent years may have become automated. While acoustic sensors can effectively be utilized to measure snow depth, if a snow board is still utilized, and the observer no longer manually reads it on daily basis, the published record may indicate no snowfall. This could potentially occur if the observer has not officially stopped the record with N.O.A.A. Depending on the diligence of the cooperative observer, there is often some uncertainty as to whether or not snowfall may have continued to occur in recent years.

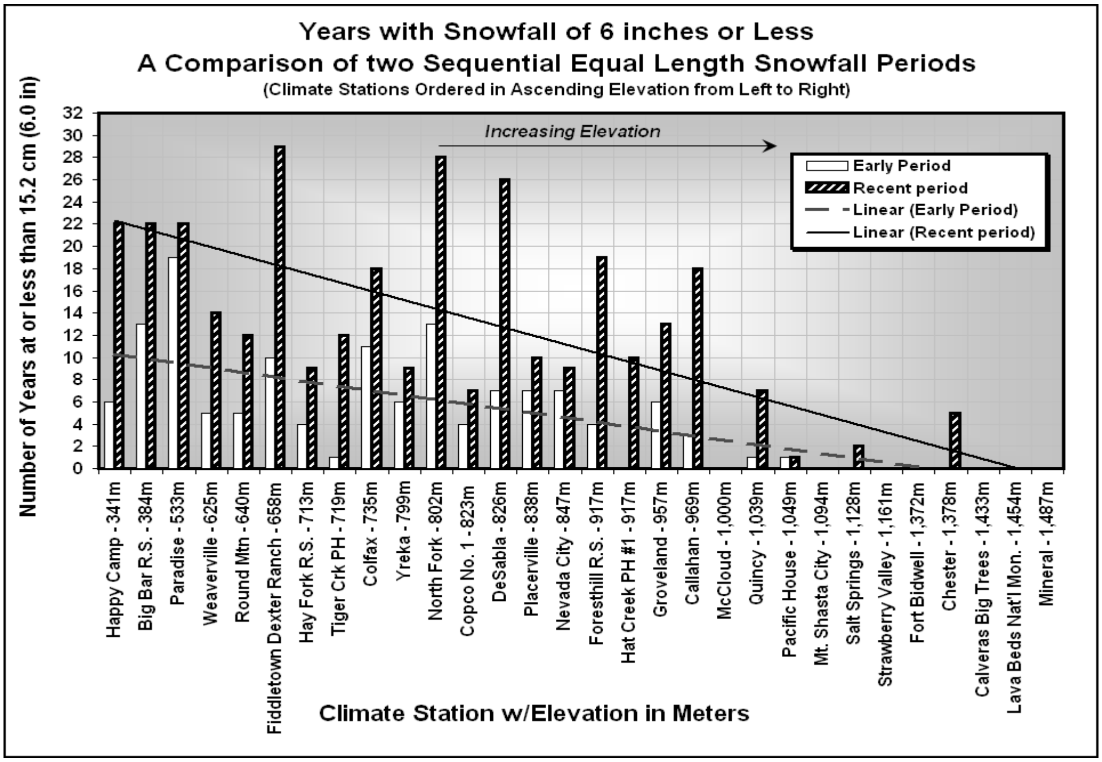

Figure 9. Comparison of two successive equal length periods (early period followed by recent period) for 30 climate stations in central and northern California

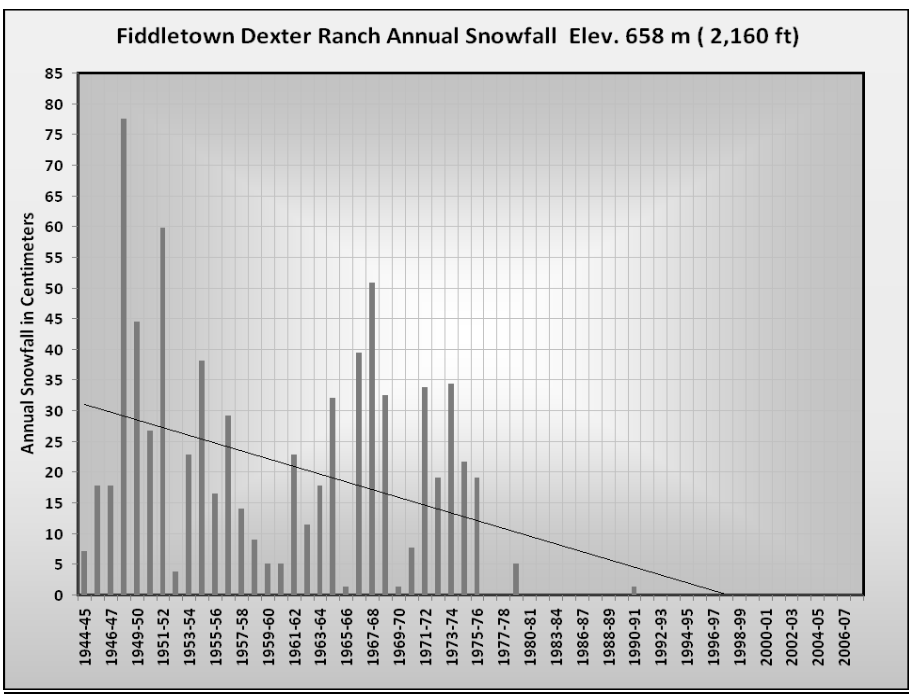

Figure 10. The record for Fiddletown Dexter Ranch climate station. Except for some small amount of snowfall in the winters of 1979 and 1991, snowfall stopped after 1976.

SOME POTENTIAL CONSEQUENCES FROM REDUCED SNOWFALL

As winter snowfall decreases, other changes may occur as a consequence of snow cover loss. Several of the low elevation climate stations between elevations that range from 762 m (2,500 ft) elevation to the 1,524 m (5,000 ft) elevation now report an increased frequency of years with no winter snowfall. For some of these elevations, that will likely translate to bare soils being exposed for all or most of the winter period. Exposed soils without the benefit of snowcover would likely be more prone to freezing and an increased rate of runoff. Typically the drainages above 762 m (2,500 ft) are sloped and may have over recent history developed landforms in geomorphic balance with historical precipitation form, return period intensity, and variance. Changes from the normal pattern would likely lead to increased erosion and mass movement until the landform over time can again re-stabilize in terms of shear strength with the changed erosion energy of the increased rainfall available to it. This would likely lead to increased sedimentation rate accompanied by increased peak winter and spring runoff events.

For the many foothill and low elevation mountain communities located above the Sacramento Valley that have become thriving communities desired for their cooler summers, but located below the elevation of the historical medium and deep snowpack, these areas will likely no longer have to deal with hardship of frequent snow removal. Winter travel for these locations should become easier. Higher rates of runoff from rainfall may initiate the need for changes in drainage design. This could also lead to increased erosion potential. In essence one would expect that adaptation to a reduced frequency and loss of snowfall will likely lead to increased movement of people into higher foothill and mountain elevations. The loss of low elevation snowpack also has potential to affect soil moisture and groundwater recharge efficiency (Jefferson et al, 2008), especially for headwater recharge areas that overlay volcanic soils. This loss of recharge efficiency may vary in magnitude for northern California depending on levels of volcanic porosity. Specific areas with relatively shallow volcanic layers that reveal a decline in aquifer outflow may have historically benefited from the snowpack's ability to store water and its relatively slow rate of melt. For some of these important relatively low elevation snowmelt recharge areas, it is anticipated that both soil moisture and aquifer recharge opportunity may significantly decline with a continued trend of low elevation snowfall loss.

CONCLUSIONS

This study reviewed the snowfall record for climate stations below the 1,524 m (5,000 ft) elevation in central and northern California. Several of the stations revealed a large decrease in snowfall over the period of record with some stations that historically had snowfall in nearly all years, now no longer experiencing snowfall or only infrequently. For the town of McCloud, CA, a snowfall precipitation ratio was set up as an index, which revealed an approximately 60 percent trended loss over the period of record. January was observed to have significantly more snowfall than either December or February. There may have been some loss of precipitation in recent years for climate stations below about the 828.8 m (2,719 ft) elevation compared with higher elevations, which showed some increase in recent precipitation. However the number of stations utilized for this study was insufficient to make any conclusions regarding significant precipitation changes between the historical and more recent period. For several of the climate stations, monthly snowfall has significantly decreased in recent years. For some of the relatively low elevation climate stations that used to experience frequent winter snowfall, there is no record of snowfall in recent years. It is anticipated that many of the foothill and low elevation towns and cities in central and northern California that experienced snowfall historically may in the not-to-distant future have an increasing frequency of snow-free winters.

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