Sierra Nevada Snowpack Decline: Warming Ambient Air Temperature or Shifting Seasonal Temperatures?

by

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Abstract

This research analyzes possible correlations between snowpack depth and other weather variables in the Sierra Nevada mountain range located in California. The dataset, published by Dryad, measured snowpack depths, air temperature (maximum and minimum), snowfall, rainfall, and snow water equivalent from 1971 to 2019 (Osterhuber and Schwartz). An OLS Regression Model was employed to analyze the effect of the weather variables on snowpack depth. We found the independent variable, Max Air Temp, to have a possible correlation to the decline of snowpack depths. Based on this finding, a Panel Linear Regression Model was incorporated to factor in time since our dataset covered four decades. T-Tests backed our findings that overall rising air temperature (both Max Air and Min Air Temperatures) has in fact increased from the 1970s to the 2010s. The paper concludes that the increase in air temperature has influence over the decline of snowpack depth, and there is statistically significant evidence to suggest that the Sierra Nevada snowpack is declining due to this increase in air temperature.

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3. Introduction

The Sierra Nevada mountain range, located in California, USA, has played a significant role in both the history and ecosystems of the Western United States. The range hosts a number of different biotic zones, which each in turn host many interdependent species. In recent years, an increase in droughts and wildfires in California have led researchers and public interest groups to study how climate change will affect the livelihoods of both human and non-human inhabitants of the region. In this paper, we will explore this phenomenon through an analysis of changes in snowpack depth in the Sierra Nevada mountains, since the Sierra Nevada snowpack provides drinking water to California residents and supports the non-human inhabitants that depend on it.

Published literature in the topic suggests that snowpack depth is decreasing, and that this decrease is correlated with rising air temperatures. The literature also suggests that droughts, which may be related to man-made climate change, also have an impact on snowpack levels in the region. In our paper, we explore the relationship between air temperature and snowpack depth using Andrew Schwartz and Randall Osterhuber's 2021 dataset "Snowpack, precipitation, and temperature measurements at the Central Sierra Snow Laboratory for water years 1971 to 2019." Using the data collected by the Central Sierra Snow Laboratory between 1971 and 2019, we explore the following research questions: Is air temperature rising over time in the Sierra Nevada Mountains? Are snowpack levels depreciating in the Sierra Nevada Mountains? 2.a) If so, which variables contribute to the depreciation of snow pack levels? Can we predict snowpack depth using air temperature?

3.1 Research Questions

1. Is air temperature rising over time in the Sierra Nevada Mountains?
2. Are snowpack levels depreciating in the Sierra Nevada Mountains?
    a. Which variables contribute to the depreciation of snow pack levels?
3. Can we predict snowpack depth using temperature?

3.2 Hypothesis

We hypothesize that air temperatures will rise over time.

We hypothesize that rising air temperatures will negatively correlate with snowpack depth.

4. Literature Review

Sarah Elizabeth Godsey et.al.'s 2013 study "Effects of changes in winter snowpacks on summer low flows: case studies in the Sierra Nevada, California, USA," measure the snowpack's decrease over time, analyze the decrease in snow pack and snow water equivalents against streamflow records over a multi-decade period. The study argues that the correlation between snowpack and snow water equivalents remains strong, but that seasonal timings of the amount of water and snow may vary in the future (for instance, waterflows may happen earlier in the season). The study argues that there is a critical gap in knowledge as to how groundwater recharge and melt as well as the vegetation ecosystem will be affected by these shifts in future.

In Michon Scott's "Warming winters and dwindling Sierra Nevada snowpack will squeeze water resources in parts of California," we found evidence to support our hypothesis that warming ambient air temperatures influence the decline of overall snowpack depths in the Sierra Nevada; "Based on the new study, this figure shows how the snowpack could fare in the Sierra Nevada with a 1°C (1.8°F) increase in average winter air temperature" (2018). The 1°C (1.8°F) increase in average winter air temperature is a possible benchmark to hit with our T Tests comparisons of minimum and maximum air temperatures between the 1970s and 2010s. "Given a 1°C (1.8°F) increase in average winter temperature, the snowpack is likely to decline, and snowlines are likely to rise to higher elevations," (Scott 2018). Per Scott's report, there is a correlation between this increase in air temperature and reduced snowpack depth due to more rainfall and melting of snowpack earlier in the season. Furthermore, if snowlines are to rise to higher elevations there will also be less overall snow coverage due to the limited surface area at the peaks of the Sierra Nevada which would contribute to less snow water equivalent.

Additionally, "Characterizing the extreme 2015 snowpack deficit in the Sierra Nevada (USA) and the implications for drought recovery," by Margulis et al. (2016) concludes that 2015 saw a drought on the Sierra Nevada mountain range, which resulted in a multi-year snowpack deficit. The authors of the paper predict that because of the drought, it will take around four years for the snowpack to recover to pre-drought levels. This paper also notes that climates with increased frequencies of drought and concurrently higher temperatures will likely lead to additional multi-year recoveries for snowpack levels.

5. Methods

5.1 Dataset

This dataset contains information on the measurements of snowpack, precipitation, and temperature in the Sierra Nevada Mountains. Snowpack is the snow that falls on the ground and does not melt. The data has been collected by Central Sierra Snow Laboratory since 1971 to 2019, which proves useful for looking at the effects of climate change in western US. In particular the first 10 years and last 10 years of the study were chosen for closer analysis due to comparisons between those decades likely showing the overall trends in the variables measured by the study. The analysis on those decades would allow for answering the research questions within the time constraints of the study and with less computational resources expended.

5.2 Data cleaning

The dataset was cleaned after being downloaded as the data was originally formatted in single years of measurement beginning on the first of October, which was the end of the dry season which spans from April to October (Sun et al. 2018), and continuing to the end of September of the following year. So all of the various datasets for each year were collated into a single dataset and then the “Date” column was further split into “Year”, “Month”, and “Day” columns in accordance with the tidy data principles (Wickham, n.d.). This allowed for easier data analysis and manipulation of those variables in the original “Date” column; following that various columns from the original dataset were renamed for machine readability. This included removing various parenthesis, punctuation, and spacing that could cause issues with readability in the R program. The columns “% of precipitation as Snow,” and “% of precipitation as Rain” were also removed as the large portions of NA values in them made analysis difficult and unproductive. The “Remarks” column was also removed as it contained qualitative data about the weather conditions on a particular day of measurement which was unnecessary in the analysis of this project. In the rows the values “T” and “--” were coded as “0” and “NA” respectively, as according to the original project notes “T” referred to a measure of less than 0.5cm and “--” referred to missing or unmeasured data (Osterhuber et al. 2021). All of these changes in turn produced the final clean dataset that was used in analysis. We were skeptical of the data from 1994 to 1996 as there were too many errors and NAs to make analysis fruitful in that period.

5.3 Measurement

Table 1. Variables and Measurement Units	
Year	Full dataset: 1970-2019 Our analysis: 1970-1980 2009-2019
Month	1-12 months of a calendar year
Day	1-31 days in a month
Air Temp Max	Degrees Celsius
Air Temp Min	Degrees Celsius
Snowpack Depth	Centimeters T = less than 0.5 cm
Season Total snow	Centimeters T = less than 0.5 cm
Snow Water Equivalent	Centimeters
New Snow	Centimeters T = less than 0.5 cm
24 Hour Total Precip	Millimeters

5.3.1 Independent Variables.

The independent variable we are testing is snowpack depth. Each dependent variable is represented as a quantitative measurement for each day.

5.3.2 Dependent Variables.

The dependent variables we are testing are maximum air temperature, minimum air temperature, new snow, season total snow, snow-water-equivalent, and 24 hour total precipitation. Each independent variable is represented as a quantitative measurement for each day.

5.4 Data analysis

Descriptive and inferential analyses will be used to describe and summarize our dataset and interpret the results effectively. We were working with panel data, this type of data consists of repeated measurement of the same subject over time. As such our standard linear model package will not work. That is why we will use the panel linear model package to analyze the data.

To analyze the variables of snowpack depth and air temperature, we will perform a panel linear regression of our panel data to assess the correlation between the snowpack depth and air temperature over time. We performed this analysis on data collected from 1970 to 2019.

We also conducted t-tests to determine the strength of the relationship between maximum air temperature from 1970 to 1980 and minimum air temperature from 2009 to 2019. This test was used to determine whether our hypothesis that maximum air temperature has risen from the 1980s to the 2010s is true.

6. Results and Discussion

6.1 Descriptive results

Table 2. Summary Statistics		
Variable	**Range**	**Mean**
Year	1970 - 2019	–
Month	1 - 12	–
Day	1 - 31	–
Air Temp Max	-12.21 - 37.00	12.63
Air Temp Min	-25.53 - 87.00	-0.9053

Snowpack Depth	0 - 920	69.11
Season Total snow	0.0 - 1704.30	652.30
Snow Water Equivalent	0 - 1401	17.41
New Snow	0.00 - 132.08	2.732
24 Hour Total Precip	-1.01 - 164.84	4.41

Although most values computed within our statistical summary (mean, median, etc.) (see Appendix A) aligned with our expectations, we observed a few anomalies or outliers that need to be taken into consideration within the dataset such as the max value assigned to the air temperature minimum value (max = 87) which evidently skewed the range value computed above.

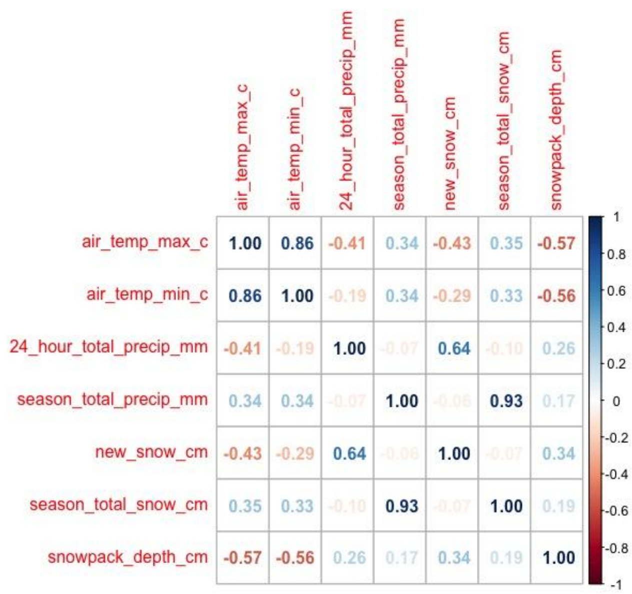

Figure 1: Correlation Plot of Features

By observing the correlation heat map above, we can conclude that air temperature (min/max) has a relatively strong correlation with snow pack depth which renders it a suitable predictor variable for a regression model meant to predict snow pack depth.

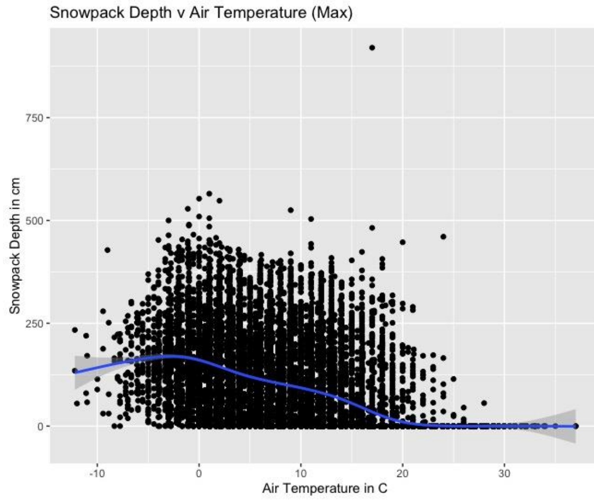

Figure 2: Scatter Plot of Snowpack Depth & Air Temp Max

Using the scatter plot above, we can observe that snow pack depth and maximum air temperature have an approximately linear relationship which allows us to further quantify their relationship using linear regression models.

Table 3: T-test Results - 1970 to 1980 vs. 2009 to 2019

	Mean of x	Mean of y	P-value
Air Temp Min	-2.02	0.31	< 2.2e-16
Air Temp Max	11.16	13.41	< 2.2e-16
Snowpack Depth	57.47	72.19	1.76e-09
New Snow	2.81	2.57	0.25
Season Total Snow	657.29	628.34	0.0057

Air Temp Min: 1970 to 1980 vs. 2009 to 2019

Since p-value < 2.2e-16 < 0.05, we can reject the null hypothesis which states that there is no difference in minimum air temperature (C) between the ranges of 1970-1980 and 2009-2019.

Air Temp Max: 1970 to 1980 vs. 2009 to 2019

Since p-value < 2.2e-16 < 0.05, we can reject the null hypothesis which states that there is no difference in maximum air temperature (C) between the ranges of 1970-1980 and 2009-2019.

Snowpack Depth: 1970 to 1980 vs. 2009 to 2019

Since p-value = 1.757e-09 < 0.05, we can reject the null hypothesis which states that there is no difference in snowpack depth (cm) between the ranges of 1970-1980 and 2009-2019.

New Snow: 1970 to 1980 vs. 2009 to 2019

Since p-value = 0.2551 > 0.05, we cannot reject the null hypothesis which states that there is no difference in new snow (cm) between the ranges of 1970-1980 and 2009-2019.

Season Total Snow: 1970-1980 vs. 2009-2019

Since p-value = 0.005658 < 0.05, we can reject the null hypothesis which states that there is no difference in season total snow (cm) between the ranges of 1970-1980 and 2009-2019.

Overall, the t-test results for all variables above, excluding new snow, were found to be statistically significant. This finding further corroborates our research hypothesis which assumes a relationship between snow pack depth and air temperatures. These results support Michon Scott's findings that a 1C increase in air temperature will contribute to the decline of the Sierra Nevada snowpack (2018).

6.2 Regression Results

Table 4: Panel Linear Regression Results for Snow Pack Depth Prediction

	Predictor Variable	Estimated Coefficient	P-value	R^2 value
1970 - 1980	Max Air	-5.32	< 2e-16	0.35

	Temperature			
	24 Hour Total Precipitation	0.32	0.01	
2009 - 2019	Max Air Temperature	-5.93	< 2e-16	0.29
	24 Hour Total Precipitation	0.08	0.43	

Regression Model 1 (1970-80):

Snowpack depth ~ Air Temperature (Max) + 24 Hour Precipitation

The regression coefficient estimated for the maximum air temperature variable has a value of -5.32 which is statistically significant since p-value < 2e-16 < 0.05, and therefore indicates a negative relationship where every unit increase of maximum air temperature, snowpack depth decreases by 5.32.

The regression coefficient estimated for the 24 hour total precipitation variable has a value of 0.32 which is statistically significant since p-value = 0.01 < 0.05, and therefore indicates a positive relationship where every unit increase of 24 hour total precipitation, snowpack depth increases by 0.32.

Regression Model 2 (2009-19):

Snowpack depth ~ Air Temperature (Max) + 24 Hour Precipitation

The regression coefficient estimated for the maximum air temperature variable has a value of -5.93 which is statistically significant since p-value < 2e-16 < 0.05, and therefore indicates a negative relationship where every unit increase of maximum air temperature, snowpack depth decreases by 5.93.

The regression coefficient estimated for the 24 hour total precipitation variable has a value of 0.08 which is not statistically significant since p-value = 0.43 > 0.05, and therefore should not be considered to indicate a positive relationship where every unit increase of 24 hour total precipitation, snowpack depth increases by 0.08.

Overall, addressing our research question stated above, we can conclude that snowpack depth can be predicted using temperature as for both time ranges the estimated regression coefficients were found to be statistically significant.

7. Conclusion

After performing T-tests and panel linear regression on our chosen variables we concluded that that air temperature is rising overtime, that temperature can be used to predict snowpack depth, and that it is likely that snowpack levels are depreciating overall due to rising air temperatures. These conclusions fall in line with the conclusions of our secondary literature as to decreasing levels of snowpack depth in the Sierra Nevada mountains. As was said there, this could have severe ecological and climatological ramifications on all of California and forecasts placing an increased attention on combating the effects of climate change. Future research could include a more granular focus on specific ecological sectors or the water table in the area and continued data collection as to the weather and climatological conditions in the area.

8. References

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9. List of Appendices

Appendix A:

```
     year          month            day       
 Min.   :1970   Min.   : 1.000   Min.   : 1.00  
 1st Qu.:1982   1st Qu.: 4.000   1st Qu.: 8.00  
 Median :1995   Median : 7.000   Median :16.00  
 Mean   :1995   Mean   : 6.523   Mean   :15.73  
 3rd Qu.:2007   3rd Qu.:10.000   3rd Qu.:23.00  
 Max.   :2019   Max.   :12.000   Max.   :31.00  

 air_temp_max_c   air_temp_min_c     24_hour_total_precip_mm
 Min.   :-12.21   Min.   :-25.5300   Min.   : -1.016
 1st Qu.:  4.44   1st Qu.: -5.0000   1st Qu.:  0.000
 Median : 12.00   Median : -1.0000   Median :  0.000
 Mean   : 12.63   Mean   : -0.9053   Mean   :  4.419
 3rd Qu.: 21.00   3rd Qu.:  4.0000   3rd Qu.:  1.000
 Max.   : 37.00   Max.   : 87.0000   Max.   :164.846
 NA's   :76       NA's   :65         NA's   :10
```

```
season_total_precip_mm  new_snow_cm      season_total_snow_cm
Min.   :   0           Min.   :  0.000   Min.   :   0.0
1st Qu.: 456           1st Qu.:  0.000   1st Qu.: 233.0
Median :1002           Median :  0.000   Median : 655.5
Mean   :1054           Mean   :  2.732   Mean   : 652.3
3rd Qu.:1545           3rd Qu.:  0.000   3rd Qu.: 983.6
Max.   :3064           Max.   :132.080   Max.   :1704.3
NA's   :1              NA's   :258       NA's   :38
snowpack_depth_cm snow_water_equivalent_cm
Min.   :  0.00    Min.   :   0.00
1st Qu.:  0.00    1st Qu.:   0.00
Median :  0.00    Median :   0.00
Mean   : 69.11    Mean   :  17.47
3rd Qu.:124.50    3rd Qu.:  15.51
Max.   :920.00    Max.   :1401.00
NA's   :1736      NA's   :5030
```

Appendix B:

```
        Two Sample t-test

data:  airtempmin1clean and airtempmin2
t = -15.842, df = 7649, p-value < 2.2e-16
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -2.616734 -2.040443
sample estimates:
 mean of x  mean of y 
-2.0210729  0.3075159 
```

Appendix C:

```
        Two Sample t-test

data:  airtempmax1clean and airtempmax2
t = -10.796, df = 7651, p-value < 2.2e-16
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -2.663085 -1.844587
sample estimates:
mean of x mean of y 
 11.15585  13.40968 
```

Appendix D:

```
        Two Sample t-test

data:  snowpack1clean and snowpack2
t = -6.0269, df = 6962, p-value = 1.757e-09
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -19.506421  -9.931455
sample estimates:
mean of x mean of y 
 57.46883  72.18777 
```

Appendix E:

```
        Two Sample t-test

data:  newsnow1clean and newsnow2
t = 1.1381, df = 7553, p-value = 0.2551
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.1700705  0.6409584
sample estimates:
mean of x mean of y
 2.810094  2.574650
```

Appendix F:

```
        Two Sample t-test

data:  seasontotal1clean and seasontotal2
t = 2.7678, df = 7668, p-value = 0.005658
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
  8.445572 49.451360
sample estimates:
mean of x mean of y
 657.2906  628.3422
```

Appendix G: Regression for 1970 - 1980

```
Oneway (individual) effect Within Model

Call:
plm(formula = df_1970_80$snowpack_depth_cm ~ df_1970_80$air_temp_max_c +
    df_1970_80$"24_hour_total_precip_mm", data = df_1970_80)

Unbalanced Panel: n = 11, T = 76-347, N = 3023

Residuals:
     Min.   1st Qu.    Median   3rd Qu.      Max.
-173.9981  -44.0810   -9.3704   32.2210  321.1115

Coefficients:
                                     Estimate Std. Error  t-value Pr(>|t|)
df_1970_80$air_temp_max_c            -5.32416    0.14834 -35.8913  < 2e-16 ***
df_1970_80$"24_hour_total_precip_mm"  0.31748    0.12429   2.5542  0.01069 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Total Sum of Squares:    22999000
Residual Sum of Squares: 14834000
R-Squared:      0.35501
Adj. R-Squared: 0.35244
F-statistic: 828.373 on 2 and 3010 DF, p-value: < 2.22e-16
```

Appendix H: Regression for 2009-2019

```
Oneway (individual) effect Within Model

Call:
plm(formula = df_2009_19$snowpack_depth_cm ~ df_2009_19$air_temp_max_c +
    df_2009_19$"24_hour_total_precip_mm", data = df_2009_19)

Unbalanced Panel: n = 11, T = 273-366, N = 3925

Residuals:
     Min.   1st Qu.    Median   3rd Qu.      Max.
-221.6662  -51.5220   -4.8129   40.8488  387.3425

Coefficients:
                                     Estimate Std. Error  t-value Pr(>|t|)
df_2009_19$air_temp_max_c            -5.92993    0.16369 -36.2273   <2e-16 ***
df_2009_19$"24_hour_total_precip_mm"  0.08878    0.11215   0.7916   0.4286
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Total Sum of Squares:    37077000
Residual Sum of Squares: 26235000
R-Squared:      0.2924
Adj. R-Squared: 0.29023
F-statistic: 808.282 on 2 and 3912 DF, p-value: < 2.22e-16
```