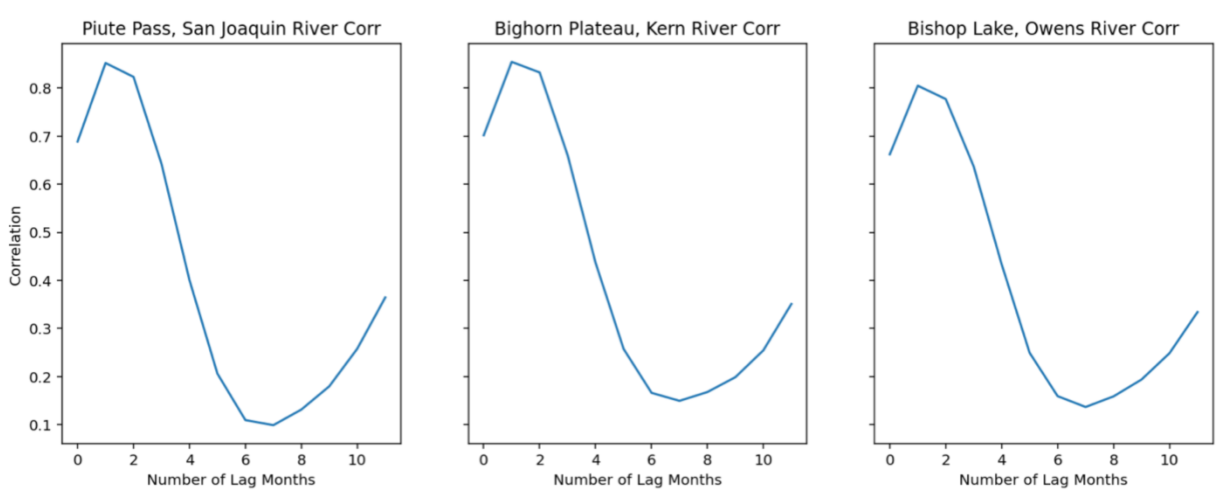
ENSO, Snowfall, and Runoff in the Sierra Nevada
APMA E4990 Final Project – Cy Gilman

1. Background

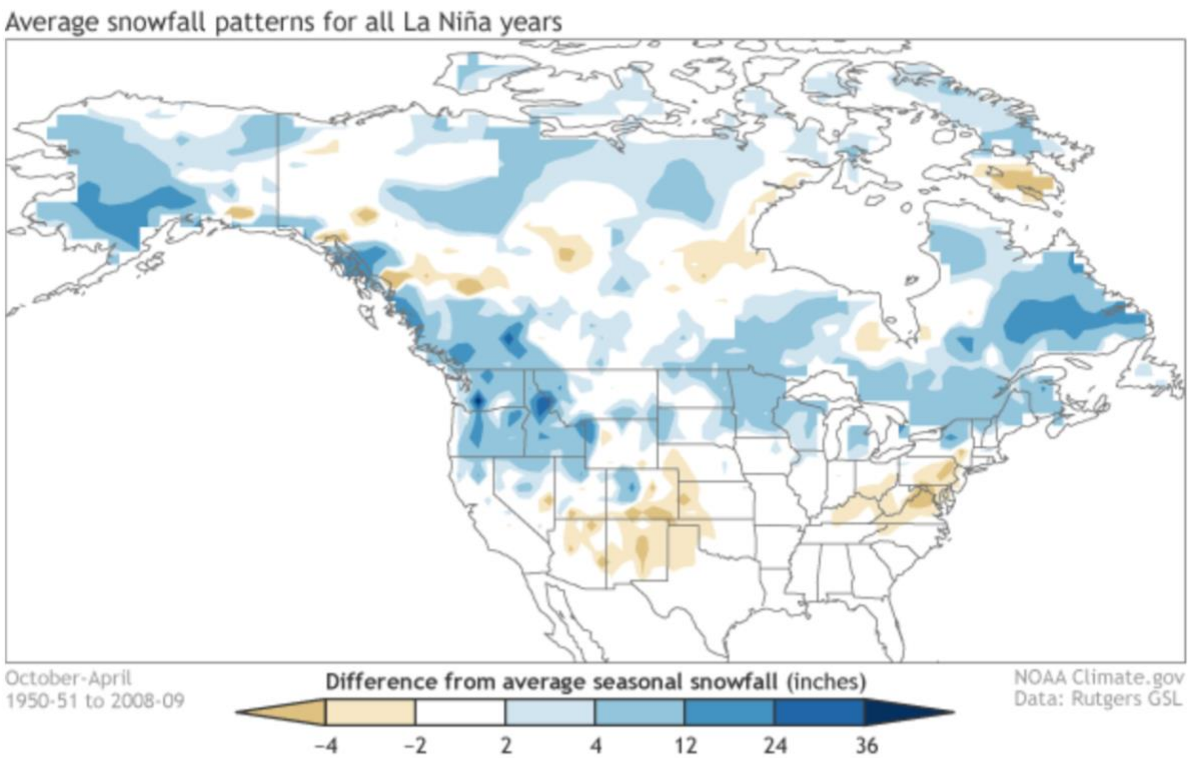
The study of California's water system is arguably among the applications of climate modelling in general – and within the study of ENSO's effects, more specifically – most scrutinized by the public at large, due in large part to the state's tendency for extreme drought in recent years, coupled with a massive agricultural industry and extremely large population, many of whom are concentrated in naturally dry areas (3, 8). Much study has been dedicated to the relationship between El Niño levels and overall levels of California precipitation, with mixed success: although, as Wang summarizes, "roughly speaking, El Niño tends to bring rain, and La Niña tends to withhold it" (6), Wang himself, along with Di Liberto and others, have noted that this relationship is not exact: it varies according to the different climatological behaviors in different parts of the state, and it is often possible for real weather patterns to violate expected ENSO-based patterns (8). In recent years, winter in 2015-16 was a relatively dry season compared to what might have been expected from the simultaneous ENSO levels, which skewed very heavily towards El Niño (6); California's drought, meanwhile, was greatly alleviated by an extremely wet season in 2016-2017, which did not correspond to the year's mid-to-low Niño levels (10, 11).

Focusing exclusively on rainfall, however, misses the particular impact California's snowpack has on the state's water system. California's extensive system of aqueducts, reservoirs, and dams divert water from the state's river for use by farms and cities, as well as storage for use during dry seasons – these rivers, in turn, are fed by the runoff from the state's snowpack, mainly in the Sierra Nevada mountains. The San Joaquin River, for example, according to Jackson, has "two major runoff sessions," with the river fed in November through March by rain, and April through July by snowmelt – and snowmelt accounts for approximately 70% of the river's water supply (4). This is crucial not only because it shows how significant of a water source snow runoff is to California, but because there is a crucial temporal difference between the two physical states of precipitation; snowmelt comes in what would otherwise be drier months, and the late arrival of such a substantial water source might be crucial to its usage for irrigation and hydraulic power, among others.



Commentators have credited snowmelt with dragging California out of its long-running drought (11, 13), while concerns about such droughts themselves – and their increasing frequency with the advent of climate change – have been expressed in terms of snowpack levels, which have declined in recent years to an alarming degree (9, 10).

Previous work has been done on ENSO's impact on snow levels in general, but most study has been applied to a much larger spatial field – many databases of snow data, for instance, apply to the entire Northern Hemisphere, or a similarly large area. Baxter's piece on La Niña's impact on snowfall, for example, covers all of North America, and focuses most of its textual attention on the more Northern regions of the continent – regions with more snow data to work with (1).



NOAA CPC maps of snowfall anomalies during La Niña year do not give much information about snow in California or the Sierra Nevada specifically. In this paper, I am attempting to link the study of ENSO's link to snowfall levels with the study of its impact on California water levels as a whole. I wish to look at ENSO's relationship to snowfall and snowpack levels in the Sierra Nevada specifically, and to see if we can use ENSO to predict snow levels in the region.

In addition to studying snow measurements that apply to the state/region as a whole, I also have selected for closer examination three specific locations, whose snowfall is particularly important to the state. These are sites whose runoff feeds (12) 1. The San Joaquin River, mentioned above as highly dependent on snowmelt, feeds into a namesake river valley, and supports a large portion of the state's agriculture industry (4) – when river levels decline as in recent years, the water supplies become embattled territory between fish hatcheries, attempts by environmental groups to restore the natural ecosystem destroyed by draining for purposes of agricultural irrigation, and farmers in the river valley (3). 2. The Kern river, which feeds into the extensive California Aqueduct (12). 3. The Owens river, the source for the original Los Angeles Aqueduct – a structure which controversially drained the entire region's water supply, leading locals to demand to retake control of it (8).

2. Datasets

For this study I use September, JJA, and JFM Nino 3.4 values from the IRI/LDEO data library, taken from 1979 through 2020. For studying snowfall across the entire state, I use IRI/LDEO data of modelled snowfall flux, in units of k* m^-2*s^-1, taken monthly from 1979 through 2019 – limited to a grid from 114W to 124W, and from 32N to 40N, with grid points every 0.25 degrees. This grid encompasses all of California and Nevada, though the latter is outside the field of my consideration. In my analysis I resample the data so that it encompasses either the total snowfall for Winter seasons from 1980 through 2020, or "water years," beginning in October and ending in September, from 1980 through 2020.

In addition to using statewide data, I also use data from three snow stations – each of which feeds a river mentioned in the above section – collected through direct measurement, provided by the CA Department of Water Services (12). These stations are Piute Pass, which feeds the San Joaquin River, Bighorn Plateau, which feeds the Kern River, and Bishop Lake, which feeds the Owens River. The data is expressed as the snow's water content, in inches, and is recorded monthly from 1980 into 2020. Like the IRI/LDEO data, I have resampled this data to be in the form of water years from 1980 to 2020.

Finally, I also use CA DWS data measuring Full Natural Flow, measured in AF, at river sites downstream from each of the above snow sites, kept in the form of monthly data, in order to demonstrate the connection between snowpack levels and connected river data.

3. Methods

To begin, I took the IRI data, averaged over all spatial data points, and plotted the anomalies over time for both each winter and each water year. I then found the correlations between September Nino 3.4 values/JFM Nino 3.4 values and winter anomalies, as well as between September/JJA/JFM Nino 3.4 values and water year anomalies. I then proceeded to create three graphs of Nino/Snowfall Flux correlations mapped spatially onto a map of the geographic region concerned – calculating the correlation between September and JJA Nino 3.4 with water year flux anomalies, as well as the correlation between September Nino 3.4 and winter anomalies, (each combination of Nino value and Flux measurement of course corresponding to a single graph) for each grid point.

I then created a K-nearest-neighbors-based prediction for snowfall flux in the water year 2020 – as the IRI dataset's final values are in 2019 – for the map constraints previously defined. I used a K value of 10 out 40 total time points, and JJA Nino 3.4 as the predictor value, and expressed the results both in terms of total value and anomaly.

I proceeded then to check the statistical significance of this prediction using the variance test, difference in means test, and permutation test, each at the five percent significance level. I created a map for each significance test, determining the test statistic at each grid point, then plotting a map showing the KNN predicted values at only the grid points where the graph's respective significance test deemed the predicted value to be statistically significant. All other grid points were left as NANs, or white space, on the graph.

Then, I turned to the CA DWS data at particular locations. First, in order to verify that the statistical information gained from the state-wide flux data matched the data collected on the ground by the CA DWS, I calculated the correlations between the snowfall data at each station and the IRI flux data closest to that station's coordinates. Then, in order to more firmly establish the stakes of this analysis, i.e., the change from snowfall to snowmelt, I proceeded to calculate the correlation between snowfall data at each station and at the river stations each one fed, both calculating a single correlation between sets of water year data, and graphs of correlations with respect to a lag period, with monthly data. (I used this latter graph in the introduction to this paper to demonstrate the delay between snowfall and its impact on river flow.) I afterwards calculated the correlation between water year snowfall data at each location and September Nino 3.4 values from the previous year – as water years start in October, this would be the Nino value immediately before the year's start.

Finally, for each location, I calculated a linear regression with snowfall data and September Nino 3.4 values, and used the regression to come up with a prediction for snowfall data in 2021, with an 80% confidence interval attached.

4. Analysis

Available in the file cmg2233-final-project-analysis.ipynb, also uploaded to the GitHub page.

5. Results

The initial correlations between IRI data and various Nino 3.4 values were 0.041131219309373336, -0.008582343, 0.029964720190378345, -0.004818869, and 0.0039696973, respectively, all of which have absolute values far below the test statistic of 0.31234752377721214, and so are not statistically significant.

For each correlation map: no value in the map correlating Winter snowfall flux with September Nino values had an absolute value exceeding 0.02; no absolute value in the water-year/JJA Nino map exceeded 0.004; no absolute value in the water-year/Sep Nino map exceeded 0.04. All of these values are far below the test statistic, so we can say that at no grid point in California was any correlation between El Nino values and snowfall flux statistically significant.

The KNN prediction produced a map with positive anomalies in the Sierra Nevada region, and negative anomalies in the far North of the state. All anomalies were an order of magnitude lower than the predicted values themselves.

After filtering out statistically insignificant values using the variance test for the KNN prediction, the remaining values were mostly North, West, and South of the high Sierra region, and generally came from points with far less snow predicted than the highest predicted values. The difference in means test proved even harsher, with the only statistically significant values, at least an order of magnitude lower than the highest predicted values, along the West coast – where there is little or no snow – and in Northern Nevada, outside the scope of our inquiry. The permutation test proved the harshest, with no more than five grid points in the state left as statistically significant, all several orders of magnitude lower in snow flux than the highest predicted values.

The CA DWS data – in water years – correlated very strongly with both IRI flux data at corresponding grid points, and corresponding river flow measurements with each correlation value exceeding 0.9. However, each also correlated poorly with September Nino 3.4 values, with 0.05371568112077138 as the greatest value of the three stations' correlation – significantly lower than the test statistic of 0.31234752377721214.

The linear regression was similarly ineffective, as the regression proved almost flat in comparison with the variation itself. The regression produced predicted values for 2021 snowfall at each of the three locations, but the width of the 80% error intervals were almost double the predicted values themselves – at Bishop Lake, the interval width was *more* than twice the predicted value! As such, these predictions are likely not very useful in making predictions at all.

6. Conclusions

The most obvious conclusion that can be drawn from analyzing the data, is that evidence suggests that El Niño values and snowfall in the Sierra Nevada regions in California are not directly related – every correlation between snow data and El Nino data proved insignificant, and any snowfall predictions made using El Nino values were either statistically insignificant or included too large a confidence interval to be useful in the least bit.

However, the different sources of snowfall/runoff data proved consistent with one another – shown with high correlations between flux data and collected data, and between collected snow data and river data. Such data reaffirmed the importance of snowfall to the state's water levels – something which is particularly significant if we have indicated that snowfall is difficult to predict using El Nino values.

It should be noted that we here are only looking at direct connection between El Nino and snowfall in this region; future work might be done in looking at the integration of ENSO into a more extensive set of factors – such as temperature, time (to account for climate change), and overall precipitation. Many of these factors are themselves connected, tentatively, to ENSO (8, 9) and so one might determine a more indirect connection to snowfall than investigated in this paper. Future work might also look beyond the "water year" data used here, and investigate more closely the seasonality of the snow data.

Finally, every method used in this paper uses precise Nino 3.4 values, rather than levels of Nino classification. Baxter makes particular mention of Nina winters in relation to snowfall, and therefore, perhaps future work might focus on the particular connection of ENSO to California snowfall during strong La Niña seasons.

Within the scope of this project, however, snowfall in California appears to be a vital component of the state's water system that ENSO does not – or does extremely little to – help us predict.

Citations:

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