

Auxiliary material for

Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models

Charles H. Luce¹, Viviana Lopez-Burgos¹, and Zachary Holden²

1. U.S. Forest Service Research and Development, Rocky Mountain Research Station, Boise, Idaho, USA
2. U.S. Forest Service Region 1, Missoula, Montana, USA

Water Resources Research

Introduction

The State of California Department of Water Resources (CADWR) maintains a separate automated snowpack monitoring network similar to the SNOTEL network analyzed in the accompanying paper. While the SNOTEL network provides coverage for primarily eastward draining basins, the CADWR system has greater North-South coverage and includes basins draining to the west slope of the Sierra Nevada. Despite basic similarities in purpose between the two networks there are slight differences in equipment and protocols that make direct inclusion of the CADWR data into our analysis questionable. Here we provide some analysis of the two data sets to help other researchers see the differences, and potentially provoke further discussion on whether the differences are equipment/protocol related or demonstrate some unique behaviors not accounted for in the SNOTEL data. Data for the CADWR network are available at <http://cdec.water.ca.gov/cgi-progs/queryCSV>. Some of the stations in the network are operated by CADWR and others by the U.S. Bureau of Reclamation (USBR) so may have different instruments or instrument placement.

Results

We screened the initial list of 75 stations by looking at the number of missing days of temperature and precipitation data in each year. With a limit of no more than 10 missing temperature or precipitation values in a given year (temperature data seemed generally to be limiting), we reduced the available data to water years 2006-2013 at 7 stations (Table S1). We calculated the Nov-Mar temperature and precipitation as was done for the SNOTEL stations and found the April 1 SWE value. The CADWR data plotted somewhat colder and wetter than most of the other stations, including the SNOTEL stations from California (Figure S1).

Table S1: CADWR Stations with less than 10 days of missing P and T data and at least 8 years of data.

<u>Code</u>	<u>Name</u>	<u>Operator</u>
BLC	Blue Canyon	USBR
CWD	Cottonwood Lakes	CA DWR
GRV	Graveyard Meadow	USBR
HNT	Huntington Lake	USBR
SIL	Silver Lake	USBR
TMR	Tamarack Summit	USBR
TUM	Tuolumne Meadows	CA DWR

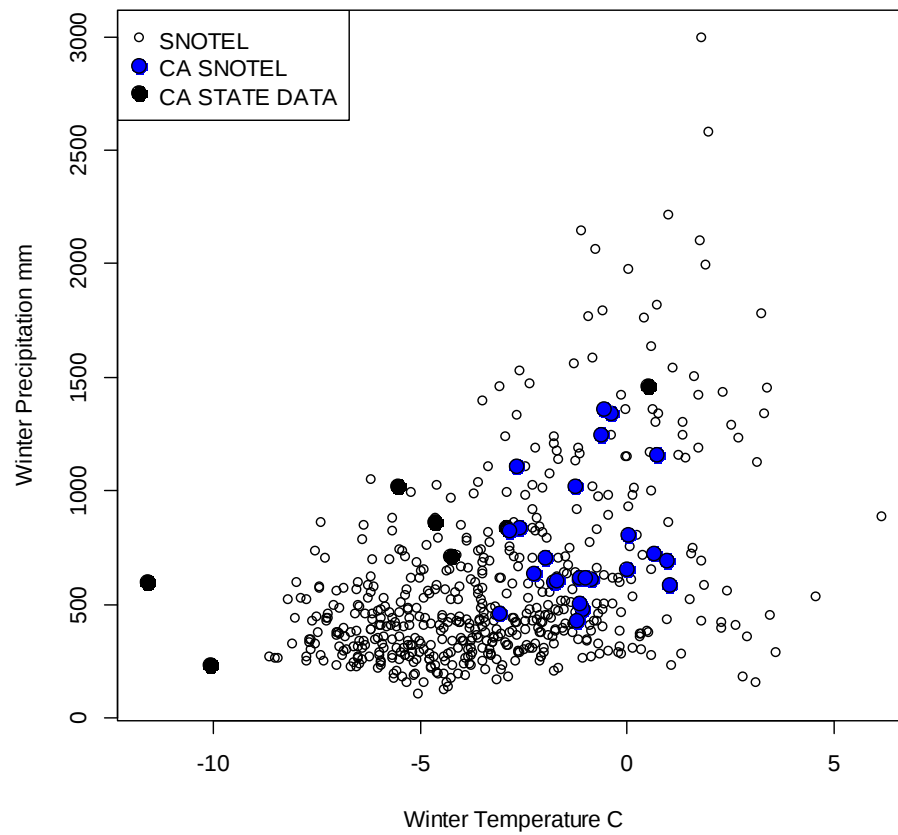


Figure S1: Precipitation versus temperature for the CADWR data (black), California SNOTEL stations (blue) and the full set of SNOTEL stations analyzed in the paper (open).

The CADWR stations record generally colder temperatures than SNOTEL stations at an equivalent elevation in California. To an extent, they are relatively cold for their elevation even within the greater SNOTEL data (Figure S2), which has a substantial range of latitude and influence from arctic air. The coldest of the CADWR stations is the Tuolumne Meadows (TUM) station, which is known to be in a

location with cold air pooling [Lundquist and Cayan, 2007], and the other very cold station (Cottonwood Lakes) is at 3096 m. At TUM about 0.14% of the days in November-March have a daily average temperature greater than 0°C. At CWD it is about 1.4%. In contrast at Leavitt Lake (SNOTEL station in CA at 2931 m), the average temperature is -1.8 C, with 40% of the days in Nov-Mar having a positive average temperature (in °C). Note that TUM and CWD are both operated by the State of California while the other 5 stations in the CADWR network are operated by USBR.

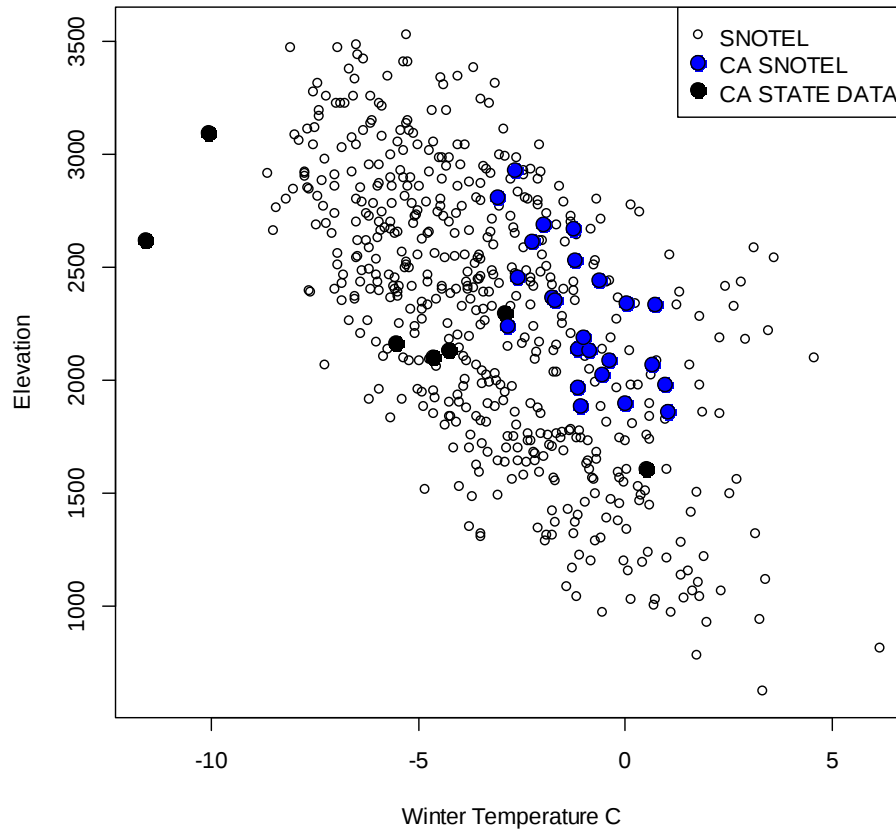


Figure S2: Temperature and elevation for the new data (black), California SNOTEL stations (blue) and the full set of SNOTEL stations analyzed in the paper (open).

Using the CADWR data as a validation data set for the spatial model built on the SNOTEL data yields an RMSE of 345 mm, mostly overpredicting April 1 SWE. Application of a local fit polynomial to predict values well outside of the range of observed temperatures would be expected to yield poor predictions. Since many of these stations are relatively cold, we examined the ratio of Apr 1 SWE on the pillow to the Nov-Mar precipitation as a function of temperature. Most of the CADWR stations fell below both the bulk of the SNOTEL stations (Figure S3) at an equal temperature, but particularly so relative to the California SNOTEL data. This could indicate any of a number of differences in the CADWR data relative to the SNOTEL data, whether it be differences in measurements or siting of the stations. The cold

temperatures could be an indication of persistent cold air drainage or pooling, for example. This aspect would be of particular interest to us if it is a broad disconnect from the SNOTEL results, as cold air drainage effects may be captured based on topographic information [Holden *et al.*, 2011], providing some potential basis for modeling differences.

Unfortunately, it may be more likely that the discrepancy results from differences in the measurement systems used by SNOTEL and CADWR stations. Differences in temperature could simply result from the heights of the temperature sensors above the ground, for instance. Alternatively, the lower SWE/P ratios could result from a different degree of undercatch in the precipitation gauge, a greater proportion of precipitation as rain, more melt, or a different amount of drift or scour on the snow pillow. Just for reference, the Leavitt Lake site mentioned earlier with the warmer temperature at high elevation had a SWE/P ratio of 1.4. A value greater than one represents a combination of gage undercatch, drifting on the pillow, snow accumulation starting before November, little melt before Apr 1, and a large fraction of the precipitation as snow instead of rain.

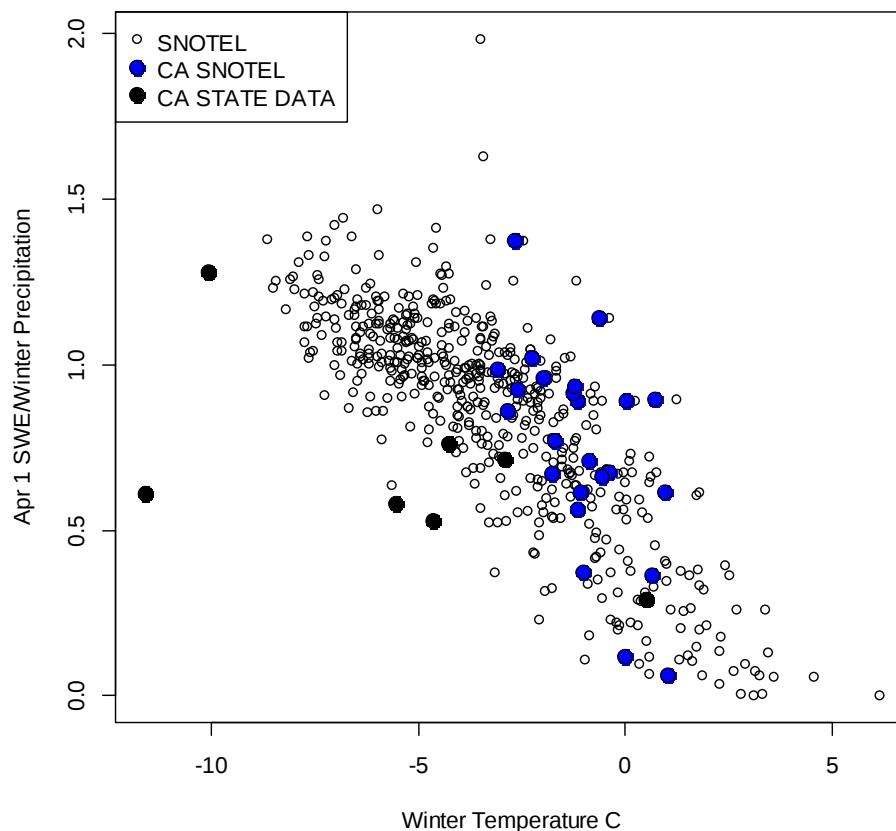


Figure S3: Ratio of April 1 SWE to Nov-Mar Precip against temperature. Most of the CADWR has SWE/P ratios less than those observed at SNOTEL stations for an equivalent temperature. This can result from differences in site selection or differences in meteorological equipment.

While some variability in gage catch, drifting, and cold air drainage would also be expected within the SNOTEL station data, they do not seem as apparent as they are in the CADWR data set. The cold temperatures could argue for the CADWR stations as being situated in particularly cold air pooling or drainage sites, which could be taken to suggest that a model fit to the SNOTEL network does not work well for sites with strong cold air drainage, a viable hypothesis. However, the departures of the spatial analog model at CADWR stations seem to be strongly related to the SWE/P ratios. At these cold stations, there is an expectation of a relatively high SWE/P, but most of these stations report a relatively low SWE/P (compared to SNOTEL stations), even for temperatures a few degrees warmer. The magnitude of error seems to be a fairly strong function of SWE/P (Figure S4), which could argue that different precipitation measurements, or local scouring of snow from the pillow could be a source of disagreement, as could a cold bias in temperature measurement. It could also result from different data curation that makes corrections for precipitation gage undercatch (although one of the CADWR stations still has a SWE/P greater than 1).

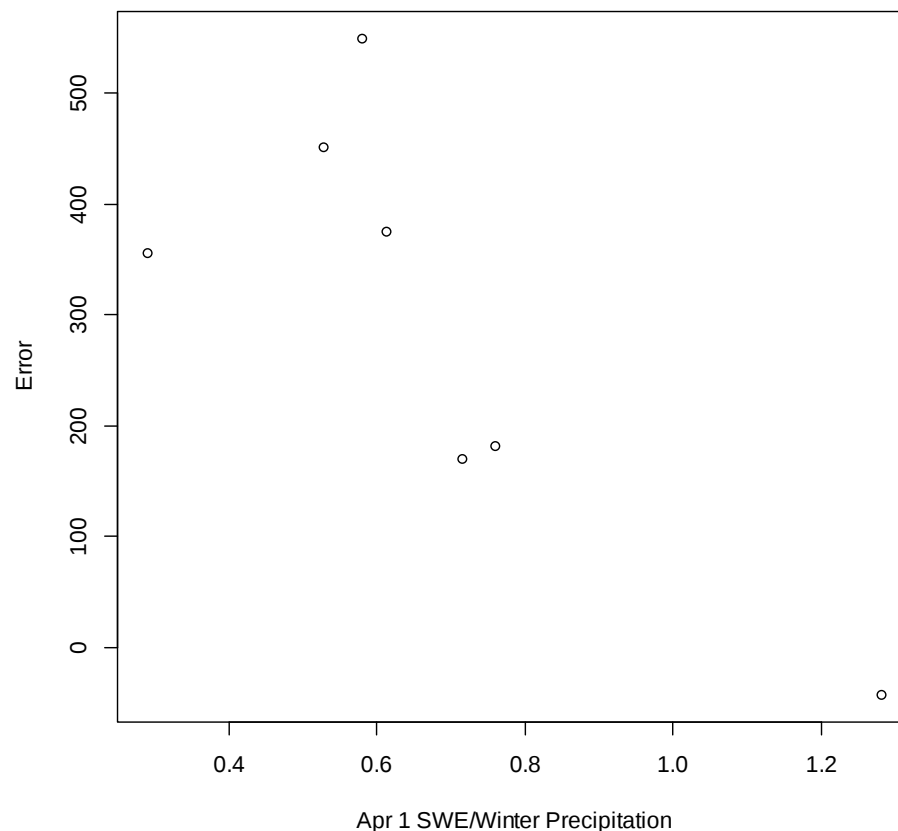


Figure S4: Error (model tends toward overprediction of these data so most values are positive) as a function of the ratio of Apr 1 SWE to Nov-Mar Precipitation.

Without clearly knowing whether these represent unique snow environments not sampled by SNOTEL or there is some difference in equipment or protocols, we can only speculate about causes of

differences. Without substantial additional information it is not fruitful to compare these data from apparently different networks with potentially different equipment and data curation. In particular the fact that several of the sites could be somewhat biased in their SWE/P ratio relative to sites with similar temperatures is a concern, as is the possibility that two of the sites have cold biases in temperature measurements. The measured values could well be correct, but comparisons with other sites would need assurances of equivalent equipment and lack of scouring.

The exercise of comparing to the CADWR data, however, raises some good questions about additional factors that should be considered. In particular, the cold air pooling might be expected to generate a different relationship between P, T, and SWE (assuming it is not present in the SNOTEL data).

Presumably, then, topographic metrics that indicate cold air pooling might be useful in tightening the relationship found at the SNOTEL stations.

References:

Holden, Z. A., J. T. Abatzoglou, C. H. Luce, and L. S. Baggett (2011), Empirical downscaling of daily minimum air temperature at very fine resolutions in complex terrain, *Agr. Forest Meteorol.*, 151, 1066-1073.

Lundquist, J., and D. Cayan (2007), Surface temperature patterns in complex terrain: daily variations and long-term change in the central Sierra Nevada, California, *J. Geophys. Res.*, 112, D11124, DOI: 10.1029/2006JD007561.