Snow-to-Liquid Ratios over the Northern Sierra Nevada: Climatology and a Predictive Methodology

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ABSTRACT

While snow-to-liquid ratios (SLRs) are a crucial component of snowfall forecasting, historical SLRs for the Sierra Nevada of California are difficult to find. Thus, forecasters are often left to use rules-of-thumb and previous experience in snow forecasting. To develop a better scientific basis for SLR forecasting, this study uses several years of data from two locations along a major Sierra interstate highway pass to a) Document climatological SLRs and b) Develop a forecasting tool to predict SLR based on in-cloud and surface conditions.

SLRs in the west slopes of the northern Sierra Nevada are found to average around 9, roughly agreeing with existing local knowledge at the National Weather Service (NWS) office in Sacramento. A modest correlation was found between 700mb temperature and SLR as well as forecasted surface temperature and SLR. A software tool was created to predict SLR based on these two relationships. This tool increased accuracy of SLR forecasts 15-30% on average versus the official NWS forecast for data from 2011-2012.

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1. Introduction

Snow forecasting in areas of complex terrain and varying climatic zones generally consists of three components; quantitative precipitation forecast (QPF), snow-to-liquid ratio (SLR), and snow level. When National Weather Service (NWS) forecasters created gridded snowfall forecasts, they are usually also making forecasts of these three elements. Historically, the NWS office in Sacramento placed much attention on QPF and snow level forecasts, while the SLR was either created via rule-of-thumb, forecaster best guess, or local tools relating SLR to elevation. In fact, the SLR was sometimes increased to physically unrealistic values in order to compensate for QPF guidance being too low. Unfortunately, these methodologies are not scientifically sound and in practice produced mixed results. In the rule-of-thumb method, the forecaster would apply a specified constant SLR to the entire forecast area (perhaps from local knowledge or past research such as Baxter et al. [2005]); this is not meteorologically sound as in-cloud physics producing the snow will vary across the forecast area, sometimes substantially. For the elevation method, the forecaster would use a tool which used interpolated forecaster-specified SLRs to topography. This method is also not scientifically robust as SLR does not linearly change with elevation; rather, microphysics with the clouds aloft determine the initial ice crystal properties and hence the SLR, while melting and other process may alter effective SLR by the time the ice crystal reached the ground. A more scientifically sound method to create SLR would ideally involve some type of cloud physics responsible for ice crystal growth, as well as recognition of crystal modification if melting is involved. This research will attempt to create a tool using such a method.

To see the impact of improving SLR forecasts, consider Fig. 1 which depicts snow forecasts and QPF/SLR errors at Kingvale, CA, from NWS Sacramento over two winters. A methodology was used to determine the contribution to forecast errors from SLR and QPF respectively (see Appendix). Though SLR errors varied in their contribution to overall snow forecast errors, it is clear that a reduction in SLR forecast error (blue bars) would improve snow forecasts, substantially so in certain cases.

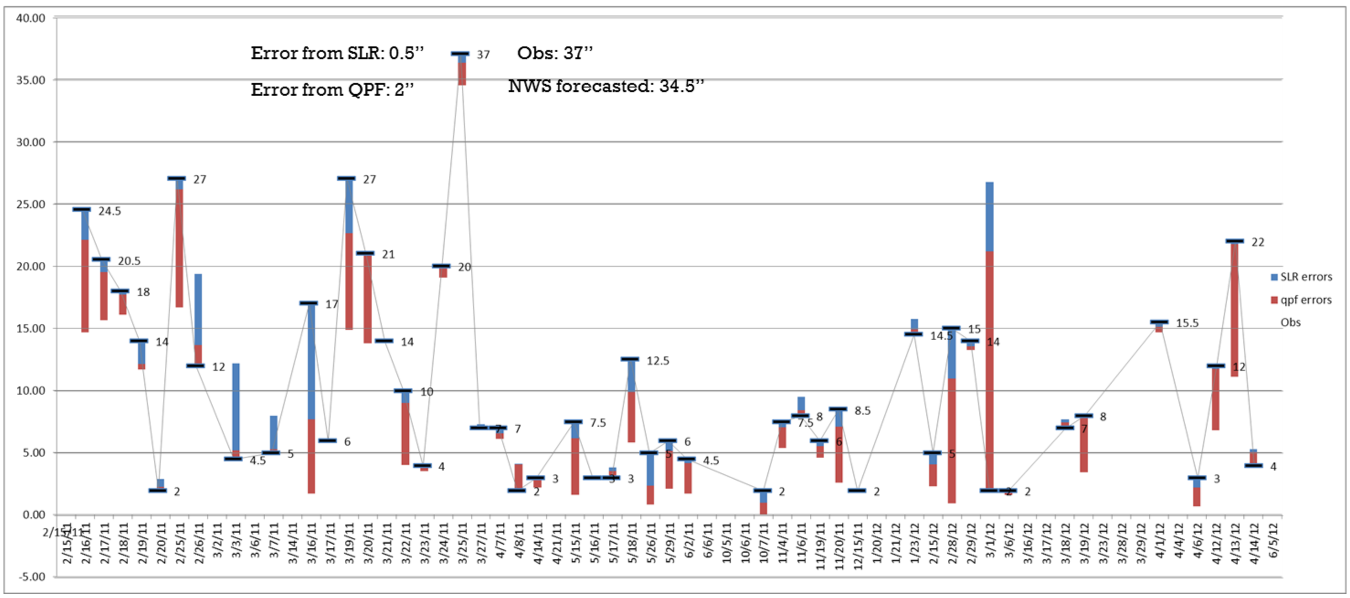

Fig. 1 – Snow forecast errors for each snowfall > 2" at Kingvale. Black lines indicate observed snowfall. The tip of the bar represents the official forecast. Bars under the line are under-forecasted events, and visa-versa. Blue bars represent error contribution from SLR forecast errors, while red represents contributions from QPF errors. The goal of this research is to reduce the contribution from SLR errors.

Previous studies have tried to link SLR to atmospheric variables, either from radiosonde data or forecast models (Diamond and Lowry, 1956; Alcott and Steenburgh, 2010). Diamond and Lowry researched SLR at the Sierra Snow Lab near Donner Pass, CA (a location near the two sites used in this study), and found a modest correlation (R =0.64) between 700mb temperature from upper-air soundings in Oakland, CA and snow-density (a relative of SLR). Many years later, Alcott and Steenburgh were able to correlate 650mb temperature (R=-0.62) and winds (R=-0.39) from model data over the Wasatch mountains of Utah to SLR at a ski area near Salt Lake City.

The underlying idea behind connecting temperatures aloft to SLR lies in the microphysical properties of ice crystal formation within clouds. Consider Fig. 2 from Libbrecht (1999), which demonstrates the various types of ice crystal development as a function of temperature. Most notably, dendrite growth (which supports higher SLR's due to lower density) is preferred at temperatures of -12 to -18c, with a gradual shift from lower-SLR columns and needles to higher-SLR dendrites as temperature decreases (assuming adequate supersaturation). SLR then tends to decrease at colder temperatures as crystal tendency trends back towards columns. However, temperatures found in snow-producing clouds over the Sierra do not frequently reach these colder column-favoring temperatures due to the influence of warmer maritime airmasses. Not shown in this plot is the manner in which wind magnitude can also impact SLR; stronger winds can fracture dendrite structures and thus decrease their densities (Alcott and Steenburgh, 2010), and stronger winds from orographically-favorable directions can enhance lift and hence increase supersaturations.

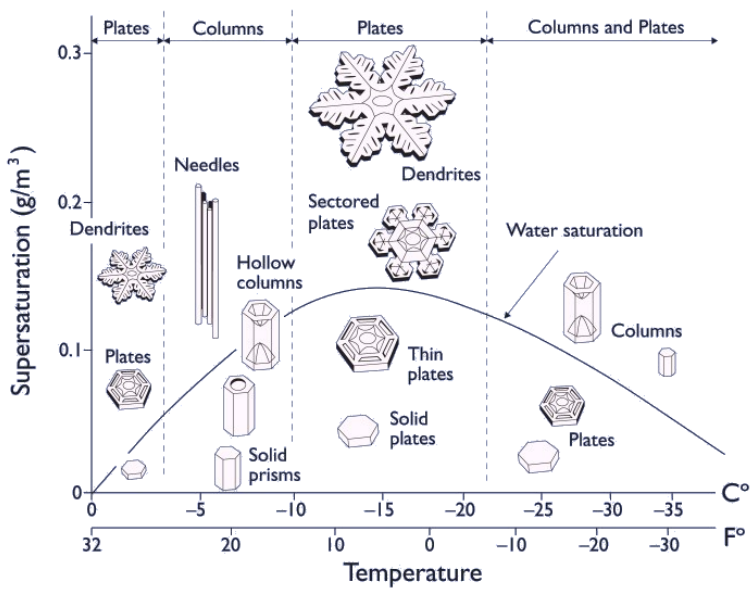

Fig. 2 – Ice crystal growth habits as a function of temperature and supersaturation. From Libbrecht (1999).

2. Data

Measurements of snow and melted liquid precipitation were retrieved from the CoCoRaHS network (Cifelli et al, 2005) at two locations near Donner Summit, CA, as marked in Fig. 3. The two sites used in this study varied in elevation but were located only a few miles apart, providing an internal quality control for suspicious data. One of the data sources, Kingvale, happened to also be a well-trusted weather spotter for NWS Sacramento, which provided extra confidence in the data. The Sierra Snow Laboratory, located nearby, was also briefly considered as a data source due to its long history of snow observing as well as its use in a related study

(Diamond & Lowry, 1956). It was ultimately excluded, however, due to differences in measurement and recording methods. It is included in the figure for reference. Lastly, Blue Canyon, which is mentioned later on in this study, is also included.

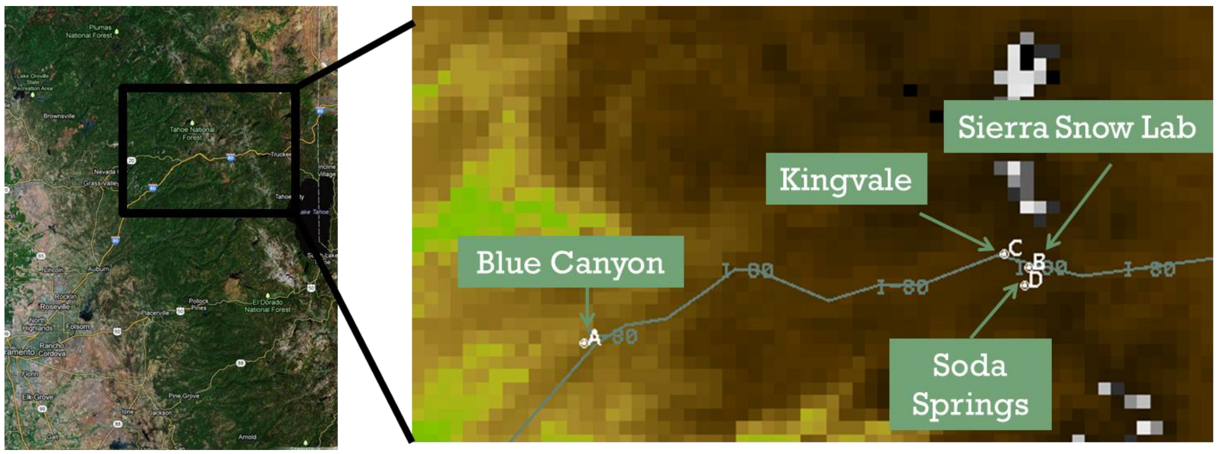

Fig. 3 – Location of observations sites mentioned in this study; Google satellite image on left, AWIPS screenshot on the right. For orientation, the grey line running left to right in the right-hand image is Interstate 80.

Cases of snowfall greater than 2 inches were retrieved for four winter seasons dating back to 2008 for the two sites, Kingvale and Soda Springs. Cases with mixed rain and snow were removed to eliminate contamination of the dataset. The existence of mixed precipitation was inferred from temperature and weather observations at the nearby Blue Canyon ASOS and weather observations from the Sierra Snow Lab. Blue Canyon ASOS lies around a thousand feet lower than the CoCoRaHS sites at 5,280 feet elevation, while the Sierra Snow Lab is slightly higher than Soda Springs and around 800 feet higher than Kingvale. For each case, if the Sierra Snow Lab reported any liquid, the case was thrown out. If Blue Canyon reported all snow, the case was included. If Blue Canyon reported mixed rain and snow while the Sierra Snow Lab reported all snow, the surface temperature at Blue Canyon was interpolated along a moist adiabat to Kingvale's elevation. If this process yielded below-freezing temperatures, the case was included.

Official NWS Sacramento gridded forecasts of snow and QPF were retrieved from local office records through the BOIVerify program commonly used at NWS offices. Unfortunately, this dataset was temporally limited due to disk space constraints, only going as far back as winter 2011. Thus, for climatological information the full CoCoRaHS dataset was used; for SLR forecasting methodology and verification, on the other hand, only the combined period of record dating back to February 2011 could be used.

3. Snow Ratio Climatology

Histograms of the overall snow ratios for both sites were created. These revealed a median SLR value of 9 with relatively few cases reaching above 20 as shown in Fig. 4. This is remarkably similar to Baxter et. al (2005) who found an average of 9 over the Sacramento forecast area despite using a much different dataset over a different period of time (30 years of data from NWS cooperative observer data). Histograms by month for one of the stations, Soda Springs, are provided in Fig. 5. As would be expected, SLR trends upward towards the colder months in the middle of winter and visa-versa in the spring. Interestingly, January is actually a local minimum in SLR. One could argue that this is simply an artifact of the particular data set; however, Alcott and Steenburgh (2010) show a similar feature in their Fig. 3. While February shows the highest average SLR, December is the month with the most extreme cases of SLR greater than 20. These observations are all also true of the data from Kingvale (not shown).

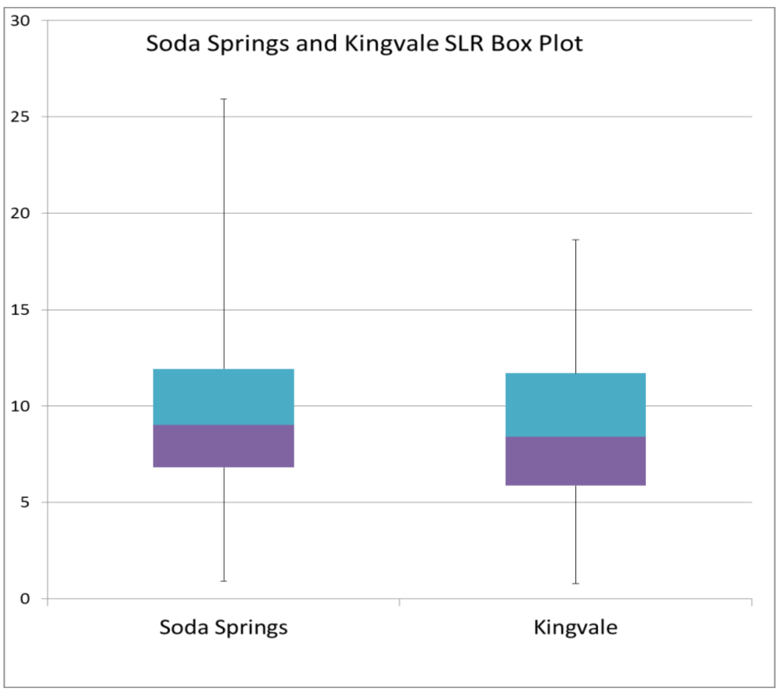

Fig. 4 – Histogram of SLR as measured at Soda Springs and Kingvale, 11/2008 – 6/2012. The indigo region indicates values within one standard deviation above the mean, while the violet section is one standard deviation below the mean. The endpoints of the lines are the maximum and minimum values.

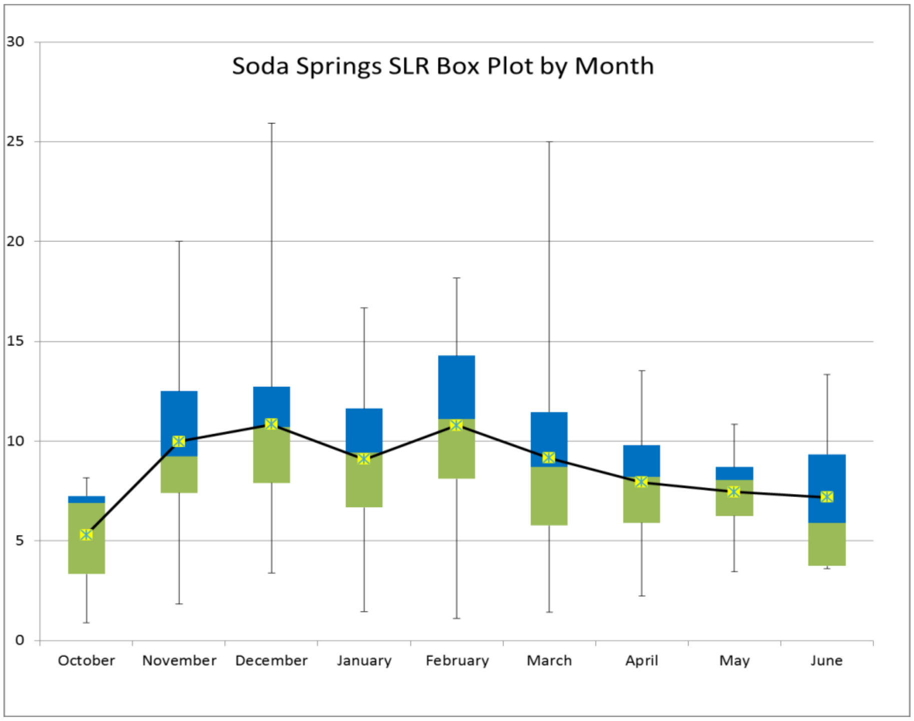

Fig. 5 – Monthly Histogram of SLR at Soda Springs, 11/2008-6/2012 .

4. Tool Methodology

Following Alcott and Steenburgh (2010) and Diamond and Lowry (1954) it was attempted to correlate the four winter seasons of CoCoRaHS SLR data to modeled winds and temperatures aloft. The North American Regional Reanalysis (NARR; Mesinger et al. 2006) model was selected due to its temporal coverage and ease of use. A grid point between Kingvale and Soda Springs was selected to be the representative model point. Winds and temperatures from 800-600mb were tested for correlation with SLR at both Kingvale and Soda Springs. Before correlations were computed, the CoCoRaHS data was filtered by removing SLRs more than four standard deviations from the mean (this removed the few strongest outliers which may have been bad data points). The best correlations for both wind magnitude and temperature were found at 700mb, which happens to be the same height used by Diamond and Lowry (1954). As shown in Fig. 6, temperature correlations were much more robust than wind correlations. Given its correlation, 700mb temperature was selected to be the predictive field. It is not entirely known why temperature correlations vastly exceeded wind correlations as opposed to Alcott and Steenburgh who found the two correlations to be much closer. Fig. 7 shows the 700mb correlation to SLR at Soda Springs, which exhibits a nearly uniform spread across all 700mb temperatures.

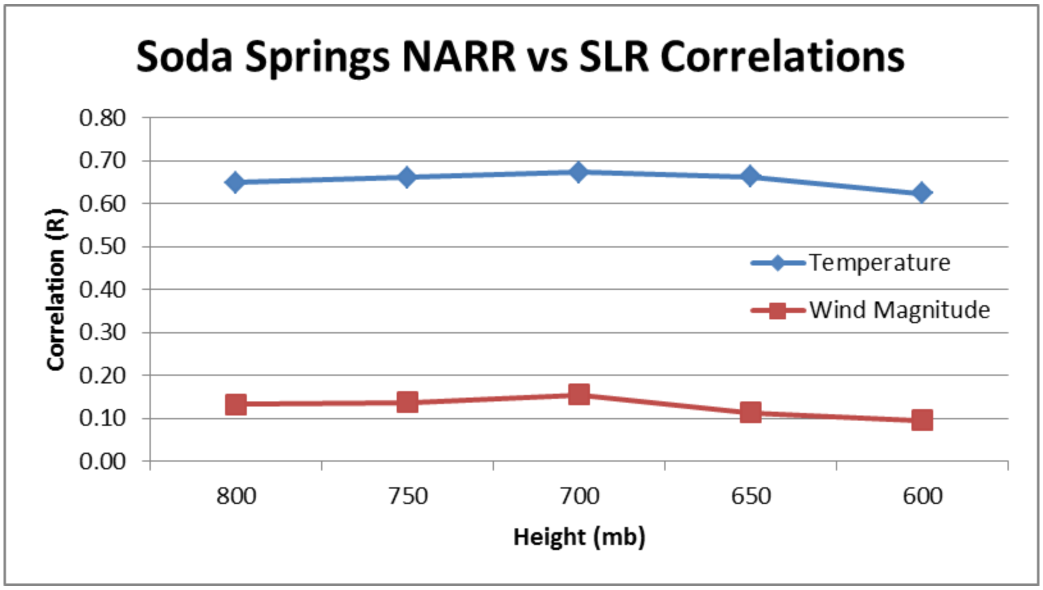

Fig. 6 – Correlations of various NARR parameters to SLR at Soda Springs.

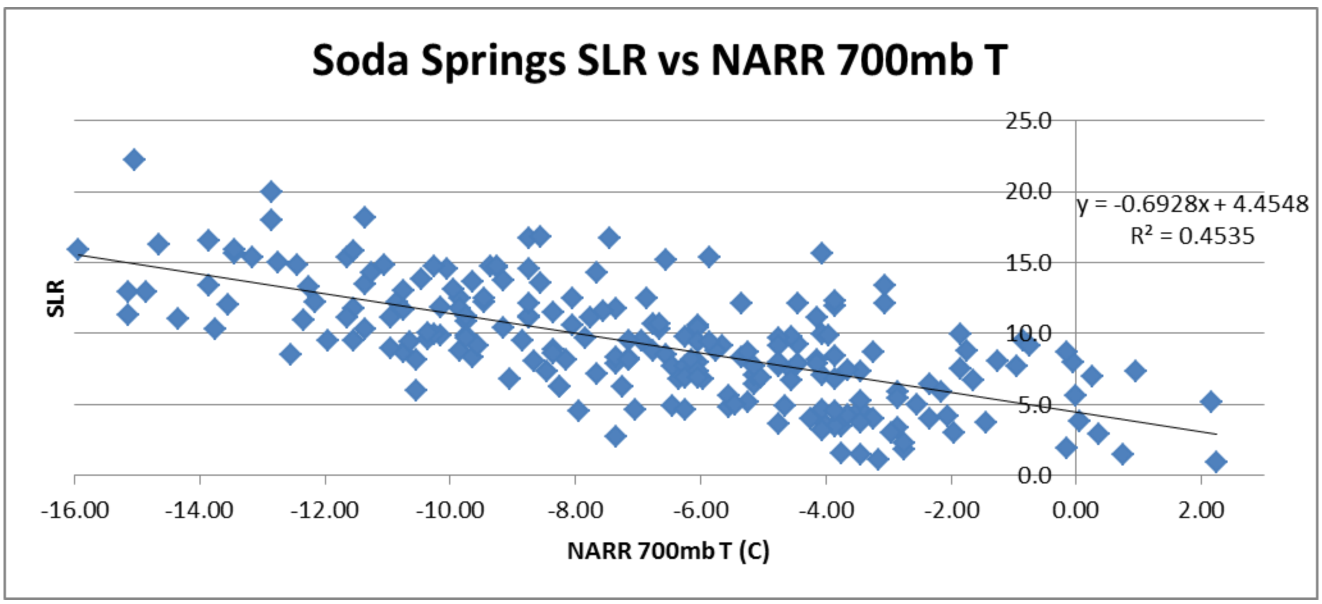

Fig. 7 – Scatter plot and fit line of SLR at Soda Springs compared to 700mb temperature from the NARR model.

While this 700mb relationship works well for ice crystals unaltered during their decent to the surface, modification by elevated warm layers, refreezing in surface cold pools, and many other interactions can introduce additional challenges. The latter two situations are not as impactful for the western slope of the Sierra Nevada due to local climate. However, melting of snow at lower elevations and eventual transition to rain is a common feature of virtually all winter storms in the area. Compounding this is the fact that population density generally increases at lower elevations, and thus the areas with the biggest swings in snow level and precipitation type are also areas of increased human sensitivity to winter storms. Frequently, forecasts from

NWS Sacramento will garner more media and public attention as snow levels drop into the foothills of the Sierra, and at the same time forecast "busts" and inter-element forecast inconsistencies become more obvious. These inter-element inconsistencies include hourly temperature forecasts which are obviously too warm for snow or too cold for rain, snow in the weather wording when the snow level is actually higher, and others. Generally the three elements which are difficult at times to sustain consistency with are temperature, weather, and snow level. In light of these concerns, the 700mb relationship had to be modified to better incorporate melting near the surface.

Local NWS Sacramento forecasting knowledge as well as previous research shows that SLR has some relationship with surface temperature (Judson and Doesken, 2000). The difficulty in applying this relationship to a forecasting situation is incorporating forecast temperature, in this case hourly temperature forecast grids, which are not as robust as other forecast elements and are not as thoroughly quality controlled (for most NWS offices, maximum and minimum temperatures are the only truly forecasted temperature fields; hourly forecasts are generally created via a tool with limited human manipulation). Despite this difficulty, records of gridded hourly temperature forecasts were compared to SLR data, with the hourly temperatures averaged over 12 hour periods (an admittedly crude method but the only available way to compare hourly grids to SLR). Surprisingly, a notable correlation (R^2=0.41 at Kingvale and 0.27 at Soda Springs) resulted. The results for Kingvale are shown in Fig. 8. Interestingly, this result is within range of the findings of Judson and Doesken (R^2=0.27, 2000) who researched snow density over the Rocky Mountains, a mountain range influenced by more continental-type airmasses (as opposed to the Sierra which are more oceanic in origin). While the correlation is not as strong as the 700mb relationship, it was considered robust enough to be used as a second component to an eventual SLR forecasting tool.

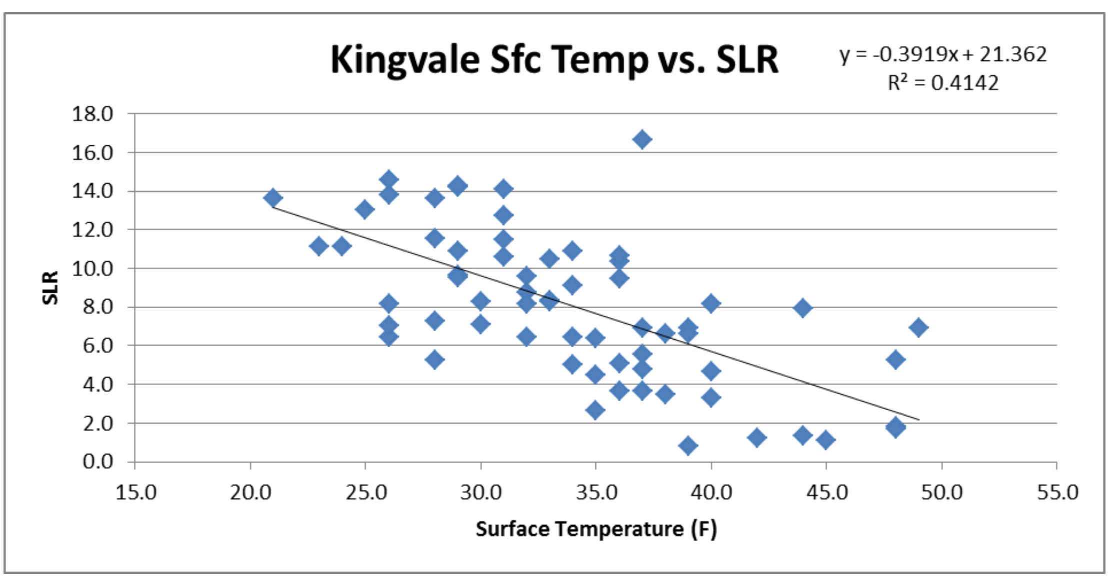

Fig. 8 – Scatterplot of surface temperature from the official forecast grids (the 0-hr forecast) compared to observed SLR.

A conceptual model for a SLR forecasting tool is described conceptually in Fig. 9. The 700mb relationship is used at elevations above the snow level (and for above freezing temperatures in the hourly weather grids) where cloud physics are the driving factor in SLR; below this level, the surface temperature relationship is used. By connecting SLR to surface temperature near the freezing level, inter-element consistency between the weather, hourly temperature, snow amount, and snow level grids is increased (assuming the snow level grid is used to create the rain/snow transition zone in the weather grid). Internal consistency can still be lost between the snow level and hourly temperature grids, especially if the forecaster uses significantly different model guidance for the two fields (this SLR forecasting methodology does not address this particular problem).

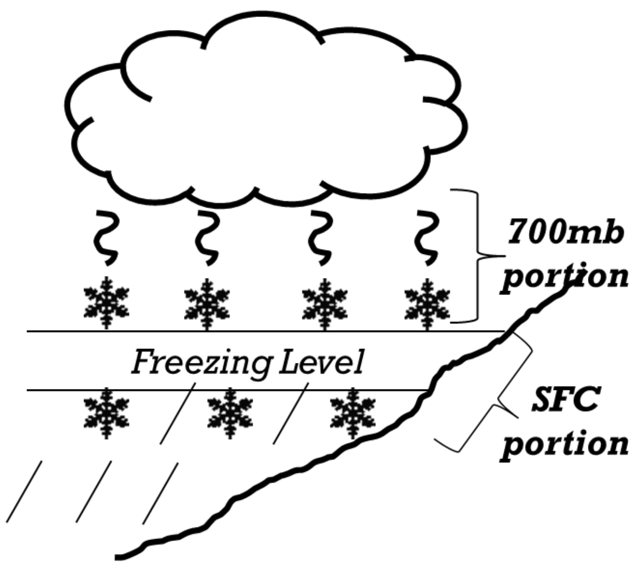

Fig. 9 – Conceptual schematic of GFE SLR tool algorithm.

A tool was created at NWS Sacramento within the Graphical Forecast Editor (GFE) to perform the previously mentioned methodology. The GUI is shown in Fig. 10. With default settings, this tool calculates SLR at all locations using the 700mb relationship, calculates SLR using the surface temperature relationship where the average hourly temperature is forecasted to be below 35, divides SLR in half where the weather grid contains mixed rain and snow, and removes SLR where the weather grid contains no snow. Several options are provided to the forecaster, including the selection of models for the 700mb portion and the ability to select the 700mb or surface relationships only. This helps to encompass the wide range of real-world situations encountered on the forecast desk which often do not fall within the bounds assumed in the aforementioned conceptual model.

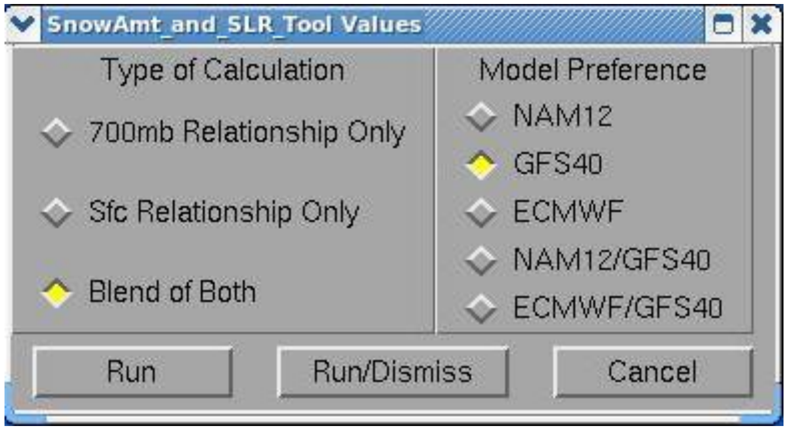

Fig. 10 – Screenshot of GFE tool.

5. Results

Using the methodology described above, output from the SLR tool was compared to official NWS forecasts. The forecast errors (observed-forecasted) for both the NWS forecast and the SLR tool forecast at Kingvale are plotted in Fig. 11. While the SLR tool does not always perform better than the official forecast (actually performing worse on occasion), it does, on average, reduce the magnitude of errors, particularly the 'big busts' (errors > 15 inches). Considering both Kingvale and Soda Springs together for winter 2011, the SLR tool offered a 15-30% reduction in forecast error. More notably, for cases over 10 inches, the tool yielded improvements of 25-40%.

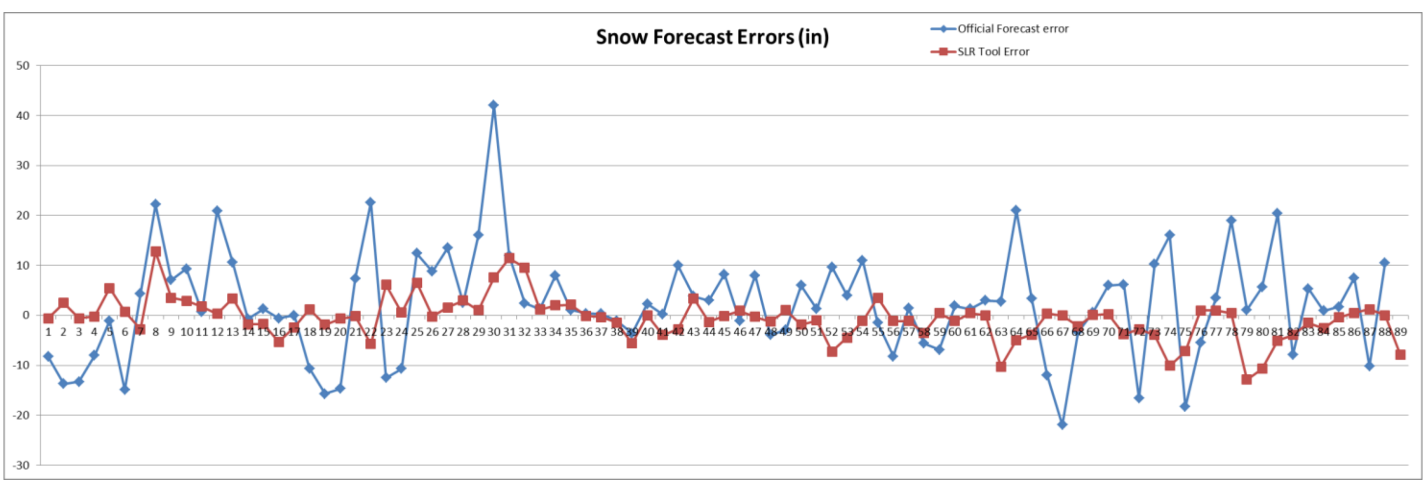

Fig. 11 – Snow forecast error for the official NWS forecast from 2/2011-6/2012 in blue, error from SLR tool in red.

Results of the GFE tool are shown in Fig. 12 for a snow event in December 2012. The official forecast using the old methodology (SLR determined by forecaster best-guess combined with elevation dependency) was greatly improved and resulted in a snow forecast which was better coordinated with neighboring offices when the GFE tool was run.

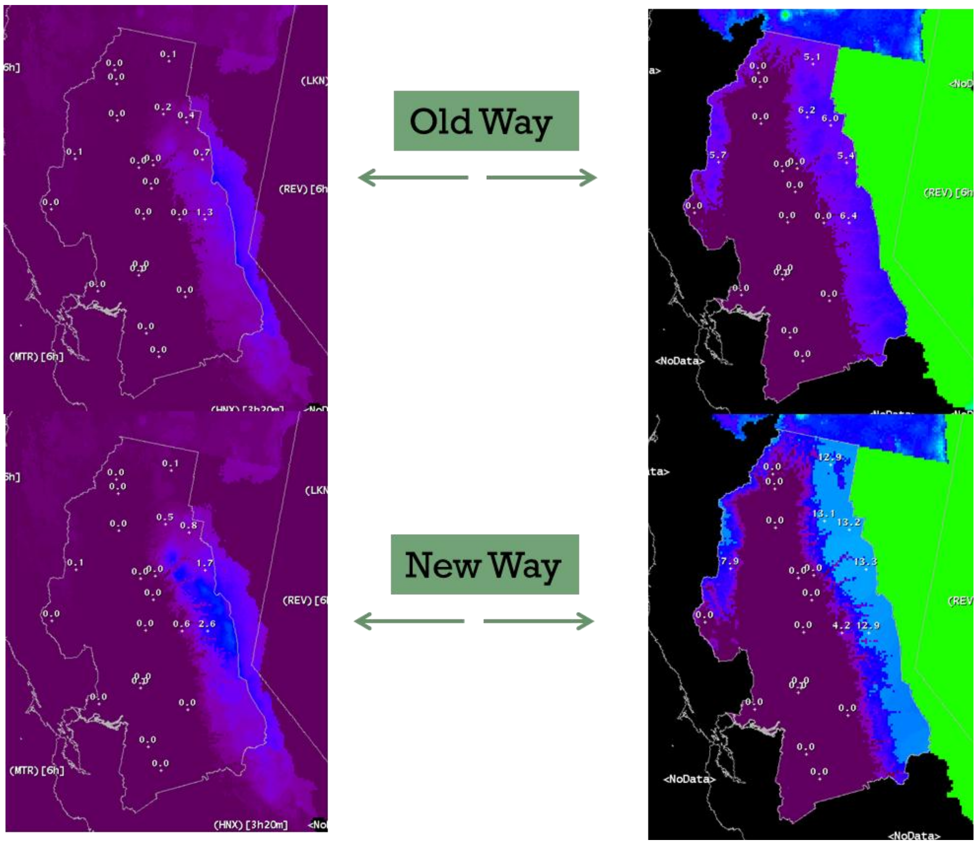

Fig. 12 – Screenshots from GFE forecasts of Snow (left) and SLR grids (right). Top images are using the standard Sacramento NWS method of elevation and forecaster specified-values to generate SLR (note relatively low values of SLR produced); this was the official forecast at the time of the screen capture. Bottom images are using the SLR tool described in this research. Note the higher SLR values which are more appropriate for the colder storm type, and that the resulting snow forecast was in better alignment with the neighboring Reno forecast office.

6. Weaknesses and Areas for Improvement

While this GFE tool represents an improvement in the scientific integrity of SLR forecasts and resulting snow forecasts, it has multiple areas for improvement. Practical limitations in this research project prevented the direct use of NAM, GFS, and ECMWF forecasts; namely, those models were not easily available for quick download via scripts as was the NARR. The GFE tool created through this research thus makes the inherent assumption that correlations of NARR data to SLR are applicable for other models; this may not necessarily be the case. Ideally, each model would need its own set of correlations. Fortunately, the NAM model is fairly similar to the NARR as the NARR's physics consist of the NAM as used in the early 2000's (Messinger, 2006).

Another weakness in forming this tool is using one climatic zone to forecast SLR for an entire forecast area. Unfortunately, there are not many sites in the Sierra which have reliable snowfall and melted snow data on a routine basis, particularly at the higher elevations such as Donner Pass. Ideally, data would be retrieved for several points representing the various climatic zones of the forecast area, and correlations could then be included in the tool which would vary spatially and allow for appropriate climatological variability within the forecast domain. With plentiful data, correlations could even be performed for different seasons to add another layer of precision.

One particular difficulty encountered in forming the tool was handling the transition from the 700mb relationship to the surface relationship. Ideally, the tool would transition from one method to the other via a small transition zone where the rate of change of the values is tied to the topography. This was beyond the skills of those working on this project, so instead the tool creates masks for each portions, then simply overlays them. This can create a rapid transition in SLR from higher to lower values as elevation decreases, which may not be reflective of nature.

After testing the 700mb relationship, surface relationship, and various models and blends within the tool over early winter 2012/2013, it became apparent that no one approach offers a one-size-fits-all result. Occasionally, in a warmer weather system, the tool would select the surface method with the exception of the highest peaks which would be using the 700mb method (due to warmer surface temperatures). In these cases, the 700mb method correctly analyzed the situation as being a low-SLR event while the surface method created unrealistically-high SLR's (due to its design, the surface method assigns the same SLR to a given temperature regardless of meteorological situation). This created a situation where SLR's gradually increased with elevation then suddenly dropped off at the highest elevations, which is obviously climatologically incorrect. An attempt to correct this weakness was made by finding a low-end SLR from the 700mb method (mean-3σ) and then weighing the surface method to peak at this low-end SLR. Unfortunately, this correction created additional problems when colder air was present in one portion of the forecast area; the low-end SLR value would not be representative of the whole forecast area in this situation, and therefore the surface method would be incorrectly weighted. **An important takeaway is that the surface method performs well when SLRs are near climatology (seasonal temperatures), while the 700mb method is desirable when airmasses are changing across the forecast area (e.g. a cold front moving in) or SLRs are deviating from normal (cold or warm systems).** A future tool may be able to better handle all these more complicated scenarios.

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APPENDIX

Methodology to Determine SLR and QPF Contributions to Snow Forecast Errors

Recall that forecasted snow is the product of forecasted SLR and forecasted QPF. To determine the error contribution in inches of each when given SLR and QPF forecasts, first assume that one parameter is a perfect forecast and the other is in error. To do this, use the observed value for one parameter and multiply by the forecast of the other; this will yield an error amount in inches. Perform this same calculation for the other parameter. Add the two errors and determine the individual percentages of the whole they represent. Lastly, apply these percentages to the observed error; this will yield the simulated error in inches from each parameter. An example is provided below.

Suppose the snow forecast=10 inches and QPF forecast=2 inches. Hence, the forecasted SLR is 10/2=5. After the storm passes, observed snow=18 inches and the observed QPF=3 inches. Thus, the observed SLR is 18/3=6 and the snow error is 18-10=8 inches. The SLR error contribution begins as the product of the forecasted SLR and observed QPF, 5x3=15 inches. Similarly, the QPF error contribution begins as 2x6=12 inches. The total of these is 12+15=27 inches, so the percentages of each parameter are 12/27=44% for the SLR and 56% for QPF. Finally, the error magnitude for each is the previous percentage multiplied by the actual observed error; 0.44x8=3.5 inches from SLR error and 0.56x8= 4.5 inches from QPF error. Therefore, in this example, the error in the QPF forecast contributed more to the errant snow forecast than the error from the SLR forecast.

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