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Meteorology 455
Seasonal Forecasting

"Prediction of Snow Water Equivalent in the Snake River Basin"

Abstract

Mountainous regions of the United States are largely dependent on yearly snowfall amounts in order to maintain water resources. With extensive, high frequency droughts observed over much of the western United States in the last decade, prediction of these water resources is of primary importance to community managers and the agricultural community.

By utilizing a 10-member climate ensemble over four grid boxes surrounding the Snake River basin in Idaho, Montana and Oregon, we attempt to predict the snow water equivalent for the odd numbered years beginning in 1985 and ending in 1999 with October through March comprising one snow year. An extensive network of SNOTEL sites supplied observed data of monthly mean temperature, precipitation, and snow water equivalent from 1981-2004 in order to arrive at a climatological relationship of snow water equivalent to temperature indicative of our forecast period. The statistical relationship is then applied to hindcasts from output of NCEP's seasonal forecast model to yield predicted snow water equivalent for each of the four grids with bounds of prediction used to determine accuracy. The data compiled from our retrospective forecast can then be used to determine the utility of the model in predicting future snow accumulations over the region in question. From our data, we found that the snow water equivalent predicted performed well against observations for each grid box in our domain. The northeast grid box predicted snow water equivalent with decent accuracy especially in extreme events such as dry or wet seasons. The northwest grid box had a substantial wet bias in forecasting the snow water equivalent, yet still remained significant within our bounds of prediction. The southeast grid box also had a bit of a wet bias but trended quite well with seasonal oscillations in snow water equivalent, picking up on anomalously dry and wet years. Finally, the southwest grid box displayed relatively similar results with a rather significant wet bias thus yielding good skill in predicting wet snowfall seasons. As a whole, the predicted snow water equivalent for the four grid boxes displayed a noticeable wet bias for the odd numbered years forecasted but maintained superior accuracy for atypical snowfall seasons especially during wet years. The data presented in this paper can provide water resource agencies in the Snake River Basin with reliable trends in snow water equivalent forecasts to aid in the maintenance of city water reservoirs.

I. Introduction

Mountain snowpack is an import source of water for many communities in the western United States. Insufficient snow accumulation during the winter can lead to serious droughts and water shortages caused by a lack of spring snow melt and runoff.

Accurate prediction of snowpack accumulation through the use of long-range climate models could allow water users in affected areas to take action in advance to conserve water if shortages are likely.

The depth and water content of the snowpack is measured using SNOTEL stations. These stations measure the weight of snow accumulated through the use of a weight-sensitive snow pillow, as well as collecting daily high, low, and average temperatures. From these data it is possible to determine an estimate of the amount of snowfall each month given model estimates of precipitation and monthly average temperature. Summing these estimates over an entire winter will give an estimate of the total depth of the winter snowpack, which can in turn be employed by water users to determine if water conservation measures will likely be necessary in the coming year.

II. Data

For this study, we used data from 61 individual SNOTEL sites in the Snake River Basin, in the states of Idaho, Montana, and Oregon. These data were gathered from the website of the Natural Resources Conservation Service. The particular sites that were included were chosen based on their geographical location in relation to the grid spacing of the global climate model and their observation density. These sites were located within four grid boxes of the NCEP seasonal forecast model, with latitude extending from 43.12°N to 46.88°N and longitude extending from 113.43°W to 117.19°W. A graphical depiction of the location of our sites can be seen in map 1. For each site, data were collected for daily mean temperature, daily precipitation and daily accumulation of snow water equivalent (SWE) during the snow years 1981 – 2004. A snow year is considered to begin in October and end in September. For example, snow year 1981 began on October 1, 1980 and ended on September 30, 1981.

The hindcast data were obtained from the NCEP seasonal forecast model. This model is an ensemble of global spectral models with a resolution of approximately 1.9° by 1.9° degrees within our selected domain. The hindcast data included monthly predictions for precipitation and average temperature at each grid point. Because the hindcasts only provided a monthly value, we had to obtain a monthly average from the observed daily data. Monthly mean temperatures were computed from average daily temperatures and monthly totals for the accumulation of precipitation and SWE were also calculated.

Unfortunately, the NCEP seasonal forecast model did not provide output for monthly accumulation of SWE. In order to obtain a model estimate of SWE, we derived a relationship between monthly mean temperature and the average percentage of precipitation that fell as snow using the SNOTEL data for monthly mean temperature, precipitation, and SWE.

Several limitations exist in the SNOTEL data. First of all, because SNOTEL sites are designed to measure mountain snowpack, they are generally placed at high elevation—higher than the average elevation of the grid box they are representing. Because of this elevation bias, the temperature and precipitation measurements taken by these SNOTEL sites may not be completely representative of the model grid box as a whole; the elevation difference may cause precipitation and/or temperature biases.

Secondly, it was necessary for us to neglect melting when calculating a value for daily SWE accumulation. On days where snow fell and then melted, this snow would not be counted toward the accumulated total. This problem is not likely to be too severe, however, because any day on which it was cold enough for snow to fall probably did not, on average, have warm enough temperatures for significant melting to occur.

Third, the SNOTEL sites are not evenly distributed throughout the domain. Some areas are densely packed with multiple SNOTEL sites, while SNOTEL coverage in other areas is very sparse. This unevenness in the spatial distribution of the SNOTEL sites could lead to some errors in representing the grid boxes as a whole.

Limitations also exist in the hindcast output. Observations are only available at model grid points, which do not correspond exactly with the locations of the SNOTEL sites. Thus averaging was applied over the SNOTEL data for each grid box. Additionally, the seasonal forecast model doesn't have sufficient resolution to accurately represent the small topographic features that affect snowfall at the individual SNOTEL sites.

III. Methods

In order to compare hindcast output with observations from the same geographical region, the 61 SNOTEL sites were divided according to which model grid box they were located in. Separate analysis was conducted for each model grid box. In each grid box, we conducted a logistic regression analysis to determine a relationship between monthly mean temperature and percentage of precipitation falling as snow. This was done by dividing the monthly accumulation of SWE by the monthly accumulation of precipitation in order to obtain the percentage of precipitation that fell as snow. This was then plotted against monthly mean temperature in order to conduct the regression analysis.

In order to conduct a comparison between SWE predicted by the hindcasts and SWE observed by the SNOTEL sites, it was necessary to convert both sources of data into the same units. Therefore we converted the monthly precipitation rates given by the hindcast output into monthly totals in inches of precipitation. For each month, this total accumulation was converted into an estimate of accumulated SWE using the relationship previously derived between monthly mean temperature and percentage of precipitation falling as snow.

There was a significant bias between the model hindcasts and the observed SNOTEL data. For this reason, it was necessary to estimate the bias in order to try and eliminate it. To eliminate the bias, we compared the observed values for temperature and precipitation averaged over each grid box to the model hindcast output to determine an average bias in order to calibrate our predictions. Odd numbered snow years were used for calibration, and even numbered snow years were used for prediction. This was done so that no year would be used both for calibration and prediction, and to avoid any possible biases caused by decadal oscillations.

Finally, the SWE estimated by the hindcast was compared with the observed SWE totals in each grid box. To determine an observed accumulation of SWE for each grid box for each month, the mean was computed using all SNOTEL sites within that grid box. Monthly totals were summed up over the course of the entire winter so that hindcast predictions of total SWE accumulation for the season could be compared to the SNOTEL observations of total SWE accumulation for the snow year in question.

The NCEP seasonal forecast model contains an ensemble of ten separate realizations. In order to gauge the spread between different model realizations, we computed a maximum and minimum SWE prediction for each year in addition to the best estimate. The maximum SWE accumulation was calculated using temperatures one standard deviation below the ensemble mean and precipitation values one standard deviation above the ensemble mean. The minimum SWE accumulation was calculated using temperatures one standard deviation above the ensemble mean and precipitation values one standard deviation below the ensemble mean.

Because of the large volume of data involved in this study, it was necessary to write several computer programs to automate the process of assimilating and processing the raw SNOTEL and hindcast data. We used both S-Plus (a statistical modeling program) and a program written in C++ to determine the relationship between monthly mean temperature and percentage of precipitation falling as snow in each grid box, we wrote one program in FORTRAN to extract monthly precipitation accumulation for each grid box from the monthly precipitation rate provided by the seasonal forecast model, and used S-Plus to determine bias in the model and compare the hindcast output of the model with the SNOTEL observations.

IV. Results

The logistic regression curve we employed to fit our observational data took on a backward "S" shape, where, as temperatures decreased, the snow water equivalent to precipitation ratio increased and vice-versa. However, at the extreme ends of the temperature variable, the snow water equivalent ratio approaches the limit of 1.0 for cold conditions and 0.0 for warm conditions forming plateaus in these regions. The two southern grid boxes in our domain (see Figure 1c and 1d) appeared to maintain a slightly better fit than the two northern grid boxes (see Figure 1a and 1b). This observation is verified through an analysis of deviance (analogous to analysis of variance). The equations for predicting the ratio of snow water equivalent to total precipitation for each grid box are as follows:

Northeast Grid Box: $\hat{p} = \exp(0.440\text{-}0.179 * \overline{T})/(1+\exp(0.440\text{-}0.179 * \overline{T})$

Deviance: 506.2031 P-value = 0

Northwest Grid Box: $\hat{p} = \exp(0.648 - 0.231 * \overline{T})/(1+\exp(0.648 - 0.231 * \overline{T})$

Deviance: 515.5357 P-value = 0

Southeast Grid Box: $\hat{p} = \exp(0.671 - 0.234 * \overline{T})/(1+\exp(0.671 - 0.234 * \overline{T})$

Deviance: 604.032 P-value = 0

Southwest Grid Box: $\hat{p} = \exp(0.488 - 0.244 * \overline{T})/(1+\exp(0.488 - 0.234 * \overline{T})$

Deviance: 711.4952 P-value = 0

The slope parameters in all models are highly significant.

The bias of NCEP's model with our SNOTEL data allows us to apply scaling coefficients to the model output in order to attain the best results. A summary of the bias (observation - model) for average temperatures and precipitation over eight odd numbered snow years beginning in 1985 and ending in 1999 is shown in table 1 below.

Grid Box	Precip Bias [in]	Temp Bias [C]
NW	2.77	-2.9
NE	1.02	-4.22
SW	2.53	-4.68
SE	0.59	-3.87

Table 1. Model biases (observation – model) for precipitation [in] and temperature [C] averaged over eight odd numbered years. NW = Northwest grid box, NE = Northeast grid box, SW = Southwest grid box, SE = Southeast grid box.

A warm bias of between 2° and 5° C was observed in the model within our domain. No correlation was observed (correlation coefficient of less than 0.01) between predicted temperature and model bias, indicating that the warm bias was of the same magnitude regardless of the predicted average temperature for the month. Additionally, a dry bias of 0.5 to 3 in. per month was observed in the model when compared to SNOTEL observations. There was some variation from grid box to grid box, but all grid boxes showed the same quantitative behavior—a warm model bias and a dry model bias. No month to month pattern in bias were observed; there was no particular time of year when biases appeared to be worse than any other. No correlation was observed between the temperature and precipitation biases either; wetter years had comparable biases to drier ones. These biases were taken into account for our hindcast predictions of accumulated SWE.

One problem that we noted in the hindcast data was that both of our northern grid boxes produced identical hindcast output. After ruling out the possibility that we had entered erroneous data, we suspect that this is due to a problem in the model, one beyond the ability of the authors to correct.

Our method for generating a maximum and minimum prediction for accumulated SWE did not appear to be too liberal, and did not generate unrealistic results (such as zero or a negative yearly SWE accumulation).

In the northeast grid box, the observed value for total accumulated SWE fell within our predicted range for seven out of the eight snow years we forecasted for. Our best guess prediction tended to be slightly higher than observation—our prediction was higher than the observation in seven out of the eight snow years.

In the northwest grid box, the observed value for total accumulated SWE fell within our predicted range for four out of the eight years. Our forecast method produced a wet bias in all eight years. Prediction for the northwest grid box was generally not as good as for the northeast grid box. It should be noted that only eight SNOTEL sites were present within this model grid box, a number perhaps too small to accurately represent the entire grid box. This under-representation is a possible cause of the poor forecast in this grid box.

In the southeast grid box, the observed value for total SWE accumulation fell within our predicted range for four out of the eight snow years. Once again there was a noticeable wet bias in our predictions—in seven out of the eight forecasted snow years our forecast method overpredicted the total SWE accumulation.

In the southwest grid box, the observed value for total seasonal SWE accumulation fell within our predicted range four snow years out of eight, and once again a significant wet bias was observed, with six out of the eight years yielding a lower observed value of SWE accumulation than our forecast method predicted.

In general, we noted that our model performed well for some years and poorly in others. In the years that the model performed well, it did so in all four grid boxes, and in the years it performed poorly, it again did so in all four grid boxes. Our results tended to be most accurate in the northeast grid box, and slightly less so in the other three. A graphical interpretation of our forecast method accuracy can be seen in figures 2a-d.

V. Conclusions and Recommendations

While the monthly mean temperature showed some skill in predicting the percentage of precipitation falling as snow each month, there is still a great deal of spread in the plots of monthly mean temperature versus percentage of precipitation falling as snow (figures 1a-d). This suggests that other variables are at work besides monthly mean temperature in determining the percentage of precipitation that will fall as snow. Possible factors include short-lived cold spells, local elevation, and effects of terrain. If more factors were taken into account, it might have been possible to derive a more accurate method of predicting the percentage of precipitation that would fall as snow each month. In addition, more stringent restrictions may need to be placed on the processing of the data to ensure that observations are accurate.

Significant temperature and precipitation biases were observed when comparing the SNOTEL observations to model predictions. We can therefore conclude that it is important to conduct an evaluation of model bias before attempting a comparison between model output and actual observations.

We noticed that our forecast method produced a significant wet bias in almost all cases. Initially the model had a dry bias, and it is possible that we over-corrected for this bias when attempting to calibrate our forecast method.

Our method of predicting seasonal SWE accumulation seemed to be generally successful, if limited in its accuracy. For most seasons, the observed value of accumulated SWE fell within the range of values predicted by the model, though this range was often quite large, often around 15 inches. Our method did, however, tend to correctly capture qualitative variations in yearly SWE accumulation; for wet years it predicted a high SWE accumulation, and for dry years it predicted a lower SWE accumulation. It would probably be unwise to put too much confidence in the exact predicted value of SWE accumulation predicted, but our forecasts could still provide some very useful data to water managers in drought-prone areas. Since our forecast method is generally accurate in predicting drier than normal and wetter than normal years, local water managers could use a dry prediction to prepare for possible water conservation measures. Alternatively, if a wetter than normal year was predicted, local water managers would know that conservation measures would probably not be needed the following spring, as spring snow melt would be adequate to fulfill water needs.

Acknowledgments

We would like to acknowledge Dr. William J. Gutowski for his assistance with using the NCEP seasonal forecasting model and for advice with computational matters. We would also like to acknowledge NCEP for the use of their seasonal forecasting model.

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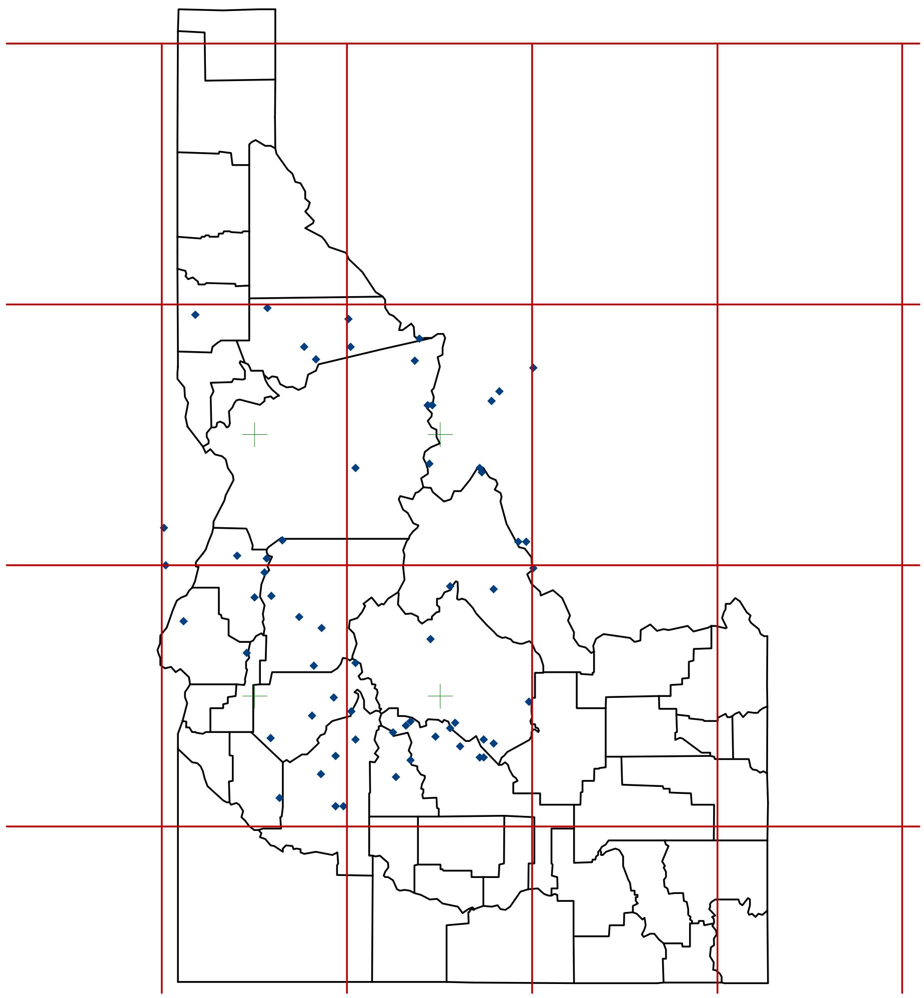

Map 1. Locations of SNOTEL sites and model grid boxes.

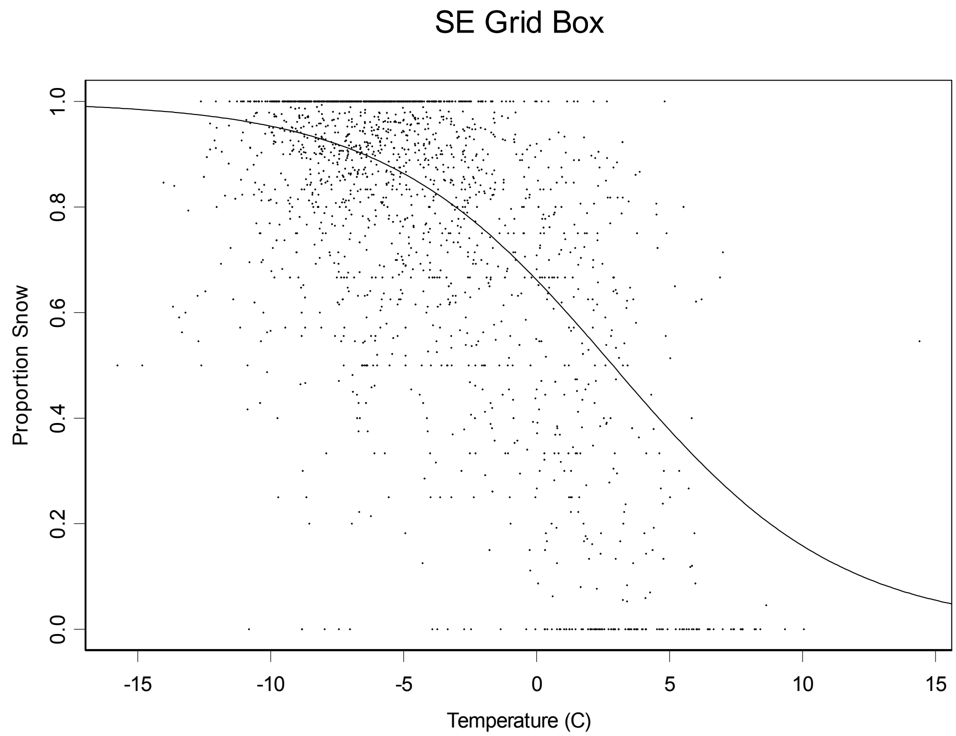

Figure 1a. Logistic regression curve for southeast grid box.

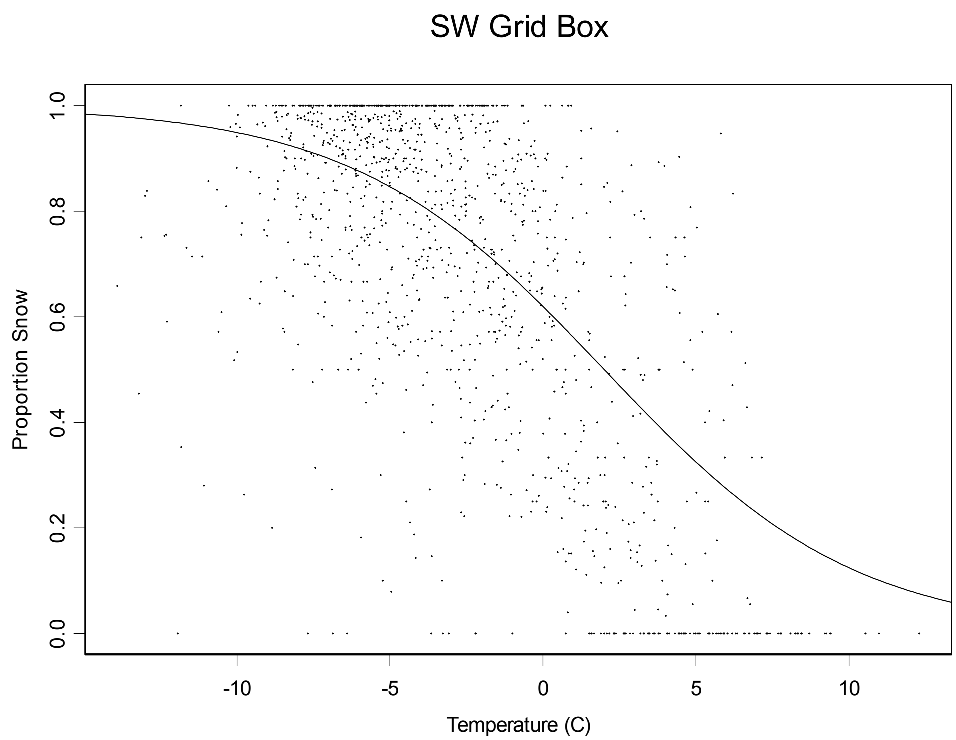

Figure 1b. Logistic regression curve for southwest grid box.

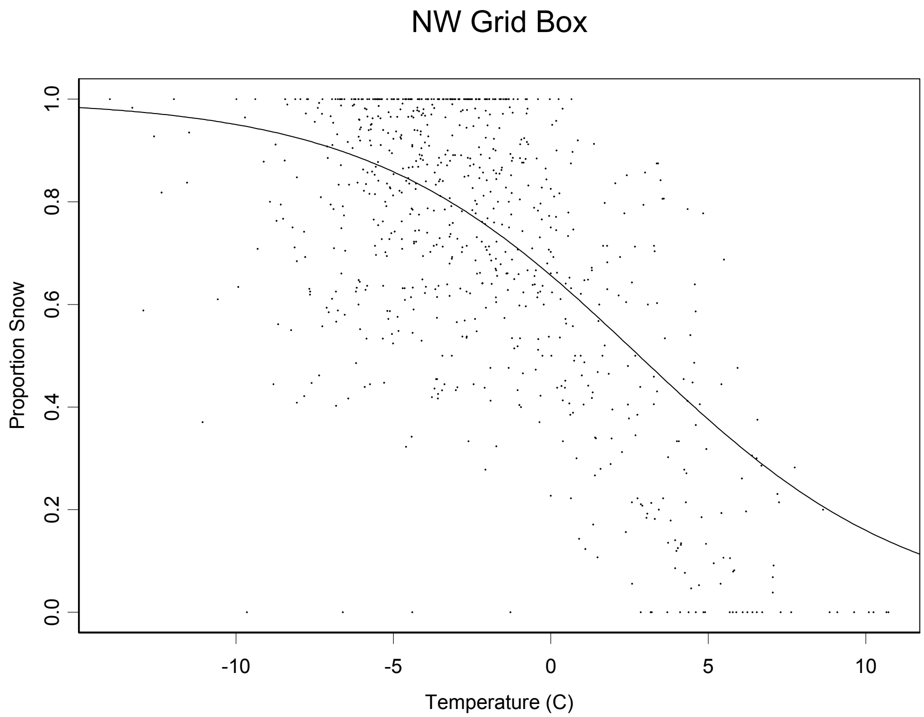

Figure 1c. Logistic regression curve for northwest grid box.

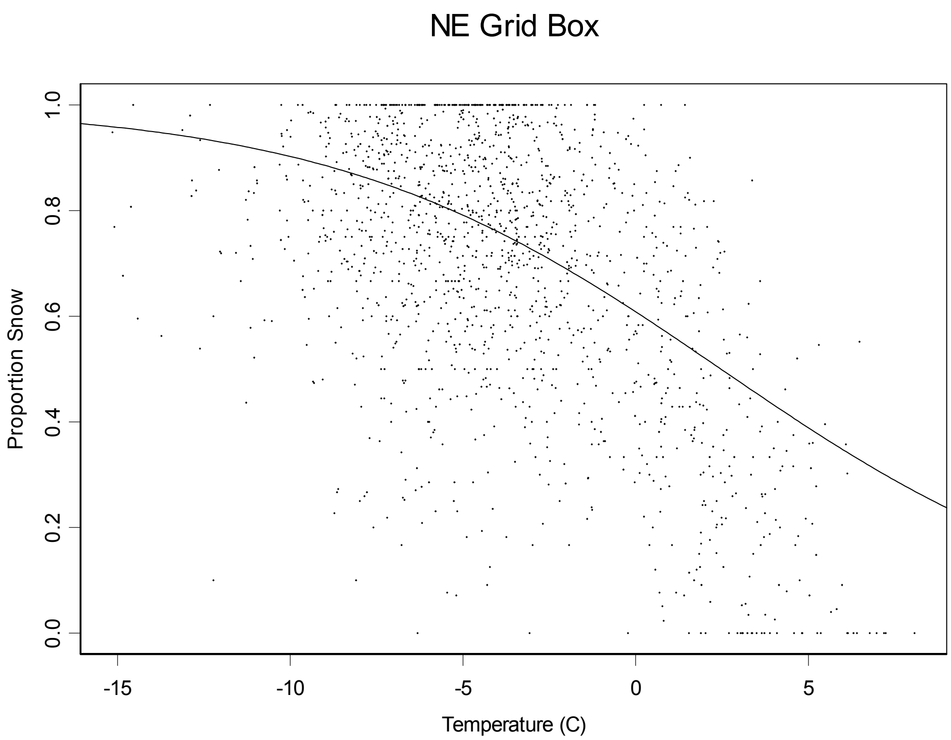

Figure 1d. Logistic regression curve for northeast grid box.

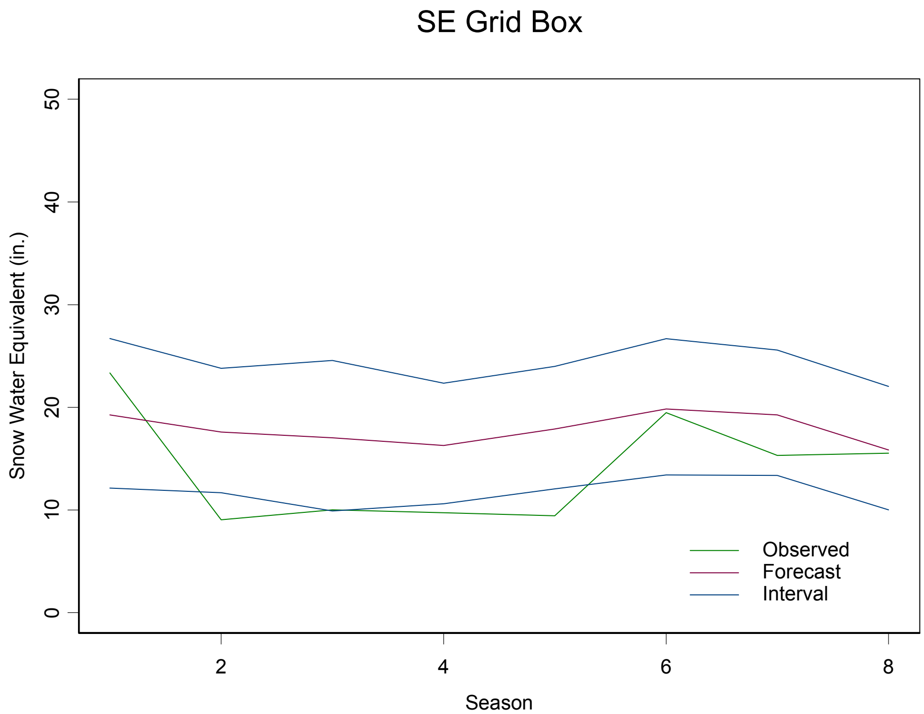

Figure 2a. Season-by-season forecast and observed snow water equivalent for southeast grid box.

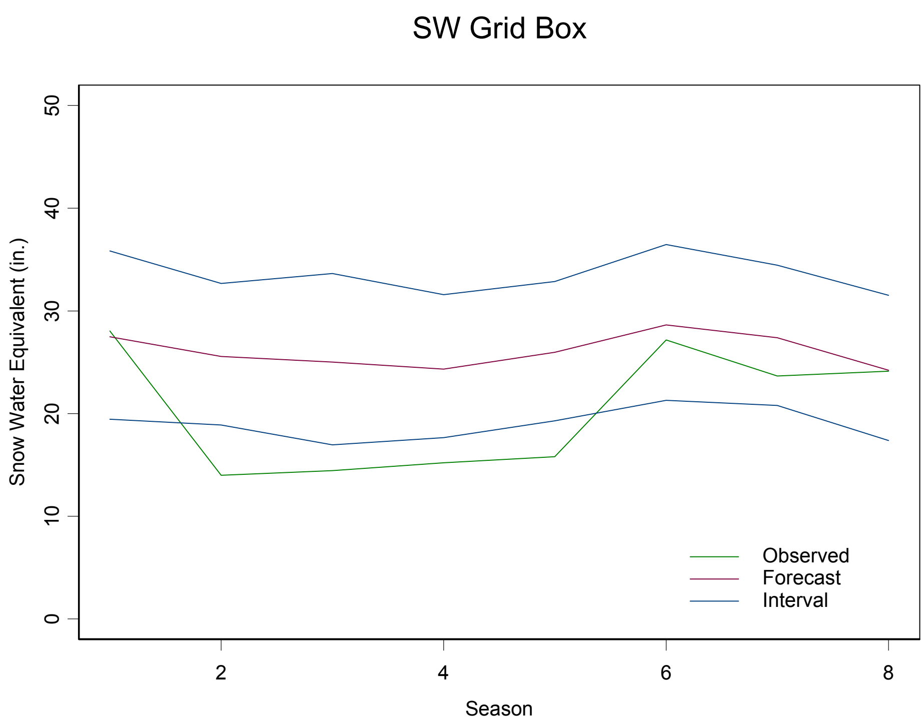

Figure 2b. Season-by-season forecast and observed snow water equivalent for southwest grid box.

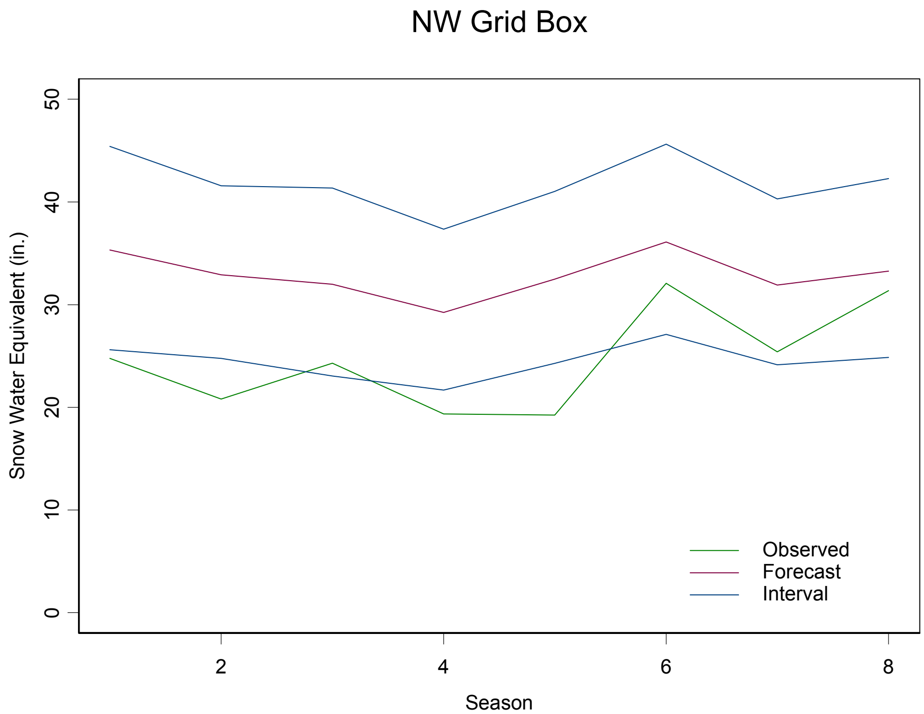

Figure 2c. Season-by-season forecast and observed snow water equivalent for northwest grid box.

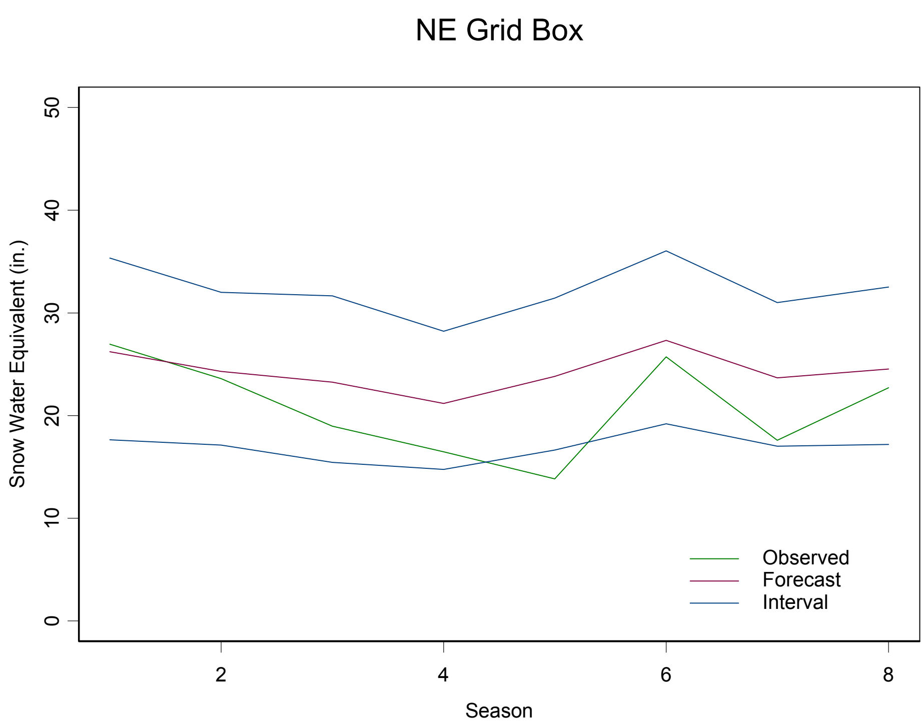

Figure 2d. Season-by-season forecast and observed snow water equivalent for northeast grid box.