Snowfall Projections for the Top of Ten Mile Weather Station

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Executive Summary

Two distinct statistical downscaling techniques are used to assess the projected change in snowfall at the location of the Top of Ten Mile weather station over the course of the 21st century. Output from five different climate models driven by a mid-range estimate of future greenhouse gas emissions was used in our analysis.

A Gumbel Extreme Value Type 1 distribution was fit to both observed and downscaled snowfall records. After correcting for biases in the downscaled present-day distribution, we calculated best estimates of projected snowfall changes over the period 2081-2100 relative to 1979-2004 at this site. A summary of our findings is given in Table below.

	Winter	**1-Day Snowfall**	**3-Day Snowfall**
Mean	15.0%	10.5%	12.5%
Standard Deviation	13.5%	7.1%	11.4%
95th Percentile	14.3%	9.2%	9.0%
99th Percentile	14.1%	9.1%	14.0%

Table 1. Projected increase in mean snowfall, standard deviation and 95th and 99th percentile events for the period 2081-2100 relative to the period 1979-2004. Results are provided for the average over winter (December through February) as well as one and three day snowfall events.

1 Introduction

In concert with increasing temperatures, overall precipitation for western Canada is projected to increase by up to 20% over the course of the 21st century with the majority of the increase occurring in the winter months [Christensen et al., 2007]. This large-scale effect is mediated by synoptic or regional weather systems and local scale topographic features, which are especially important in regions with complex terrain. Such terrain typifies the area surrounding the Top of Ten Mile weather station (51.27167°N, 116.76°W, Elevation 1100m residing off Highway 1 in a valley 17km east of Golden, British Columbia. Since global climate models typically do not adequately capture the effects of small-scale topographic features, further methodologies are required to reliably simulate climate statistics at the scale of a weather station. A method known as statistical downscaling offers a solution for reconciling the different spatial scales and enables more plausible projections to be made for the future.

Statistical downscaling establishes statistical relationships between the large-scale climate model output and the observations at individual weather stations. The resulting connection can be used to relate future projections from climate models to the smaller scales, producing a projection that incorporates both the large-scale weather patterns and local effects such as topography. To generate future projections of precipitation for the Top of Ten Mile weather station we employ two distinct downscaling techniques: 1) a synoptic typing method; 2) a stochastic weather generator known as LARS-WG. These methods receive large-scale information from global climate models and produce daily time series of precipitation that reflect the local climatology. In this report our analysis of projected changes in precipitation is based on climate model simulations driven by the mid-range A2-emissions scenario from the Special Report on Emissions Scenarios (SRES) [IPCC, 2000]. As noted in IPCC (2007), projected changes in climate are relatively insensitive to the emissions trajectory over the next several decades. The individual differences between the assumed greenhouse gas emission trajectories start to play a more important role as the century progresses.

2 Methodology

2.1 Data

Climate data used for downscaling in this report consist of precipitation observations and global climate model output from a range of models. Observations of precipitation were obtained from the Adjusted and Homogenized Canadian Climate Data (AHCCD)[1] service provided by Environment Canada, and from the British Columbia Ministry of Transportation and Infrastructure's Avalanche and Weather Program historical dataset[2]. The time series of daily precipitation totals from 1979-2004 were taken from weather stations with continuous records missing fewer than five percent of the total number of days in the record. Eighteen weather stations satisfied these criteria, and the observations from these weather stations

[1] http://www.cccma.ec.gc.ca/hccd/
[2] http://www.th.gov.bc.ca/mot_org/const_maint/avalanche_weather/

were used to derive downscaling relationships to the large-scale climate model output. In what follows, we focus our analysis on winter snowfall, where winter is defined December-February.

Large-scale climate variables during the 20th century were obtained using the National Centers for Environmental Prediction (NCEP) Reanalysis 2 Products [Kanamitsu et al., 2002]. NCEP Reanalysis 2 data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA. Atmospheric circulation variables from 1979-2004 over the Northeast Pacific and Western North America (spanning the coordinates 65°N to 30°N and 175°W to 95°W) were acquired from the reanalysis dataset. While NCEP Reanalysis 2 variables are based on both climate model and observational data, they are hereafter referred to as historical climate data and will be used as a standard to identify circulation patterns.

Global Climate Model data were retrieved from the Earth System Grid CMIP3 Multi-Model Data Portal [Meehl et al., 2007a]. All of the model simulations examined were produced for the IPCC Fourth Assessment Report [Meehl et al., 2007b]. Output was obtained from climate models developed at the Canadian Centre for the Climate Modelling and Analysis (CCCMA), le Centre National de Recherche Meteorologique (CNRM), the European Centre Hamburg Model (ECHAM), the Geophysical Fluid Dynamics Laboratory (GFDL) and the Meteorological Research Institute (MRI) organizations.

2.2 Downscaling Model Validation

Validation of the different statistical downscaling methods against the observed precipitation record from the Top of Ten Mile station was performed using two separate approaches to partition the observational record. LARS-WG was validated by calibrating the method using data from 1979-1995 and comparing a nine-year simulation for 1996-2004 against the observations for that same period. In the synoptic typing approach, the dataset was split differently with twenty years of data used to construct the downscaling functions while five years of observations were set aside for validation. This division of data was repeated (five times in this case) until all years in the dataset had served as part of the validation set.

The synoptic typing method of downscaling precipitation employed a statistical modelling technique derived from Vrac et al. (2007) to predict daily precipitation based on synoptic typing with a nonhomogeneous Markov model [Charles et al. 2004]. In this method, synoptic types were obtained using cluster analysis of precipitation distribution at the weather stations within the BC Rocky Mountains. Each synoptic state was associated with a particular probability, pattern and intensity of precipitation over all weather stations. The method fit unique Gamma Probability Distribution Functions (PDFs) to precipitation observations in each synoptic type at each station creating a record of the typical precipitation associated with particular atmospheric conditions. Coupled with the information regarding precipitation, each synoptic type was associated with a characteristic pattern of circulation in the atmosphere. The information obtained from these constructed states was then used to simulate precipitation for validation or future periods.

The selection of the atmospheric circulation variables that strongly influenced local precipitation was achieved by constructing heterogeneous correlation maps between the model data and the weather station data from the Top of Ten Mile weather station. Several available circulation variables (e.g. mean sea level pressure, winds, temperature) at several geopotential heights were correlated with the observed precipitation over the historical period to identify relationships between the different variables. The predictors were selected from model grid cells spanning the coordinates 65°N to 30°N and 175°W to 95°W. This region encompasses southern British Columbia and the Northeast Pacific containing the areas of influence of the semi-permanent pressure cells. Predictor domains were identified within this region from the correlation maps. These were used to constrain the areas where the potential predictors showed the strongest relationships to the observed precipitation.

The specific predictor variables to be used by the synoptic typing model were extracted from the large-scale climate model output by taking the spatial average of each selected variable over an area defined by the correlation maps as being influential in determining precipitation. This was an attempt to employ predictor variables that represented the connection between variability at the large-scale and observations at the small-scale while reducing the size of the datasets. All predictors were normalized to have zero mean and unit standard deviation before application with the downscaling model.

The choice of which predictors to include in the downscaling model was determined using a stepwise selection technique similar to that used in multivariate regression [Wilks, 1995]. Each of the potential predictors was tested individually with the downscaling model applying a cross-validated approach during the historical baseline (described below). The predictor that resulted in the best agreement between the simulated values and the observations was then retained. Successive predictors were found in the same way, with each candidate tested with the set already chosen and the most successful addition was again kept as a predictor for the statistical model.

To simulate daily precipitation values, the frequency of occurrence of the synoptic types during the training period was recorded in the form of a matrix of transition probabilities from one state to the next, and used to help determine predicted precipitation. Predictor variables were represented by a normally distributed term which, combined with the homogeneous Markov model, determined the transition probabilities from the observed state transitions, from one state to the next. The statistical model was validated by the cross-validation approach using the predictors from the averaged set of grid cells selected from the variables identified the correlation maps. Because of the stochastic nature of the simulation process in all of the projection versions, from the simulation of synoptic type to the sampled amount of precipitation, the statistical model was repeatedly evaluated for the validation and projection periods.

2.3 LARS-WG

The second downscaling technique, LARS-WG, consisted of a stochastic weather generator designed to simulate daily maximum and minimum temperatures, precipitation, wet and dry spells, and solar radiation at the scale of weather stations [Regniere and St-Amant, 2007; Semenov, 2008]. The downscaling method required times series of daily data to establish the necessary statistics in order to replicate the observed variability.

Precipitation was modelled by considering the data in the form of three components: wet spell lengths, dry spell lengths and precipitation intensity. Each of the wet and dry spells and precipitation amounts were simulated with semi-empirical distributions containing a fixed number of intervals, with separate distributions for each month. Simulated spell lengths and precipitation intensity were determined by a random selection from the fitted semi-empirical distributions. In each case, one of the intervals in the distribution was chosen at random with the probability of selecting a particular interval determined by how many events it contained. The value for a particular day was then chosen at random from within the selected interval. To generate a complete precipitation time series, LARS-WG determined precipitation occurrence by sampling wet and dry spells in an alternating fashion and then populated the wet days with precipitation amounts.

LARS-WG represented daily maximum and minimum temperature values separately for dry and wet days, approximating the values in each case with fitted normal distributions. Unlike the precipitation distributions, the mean and standard deviations of the temperature distributions were allowed to vary within each month. The parameters of the normal distributions for each day were modelled using a Fourier series to represent the changes induced by the seasonal cycle. Sampling from the daily normal distributions produced daily temperature values with some constraints applied to maintain the relationship between maximum and minimum temperature. These conditions were the imposition of the cross-correlation between maximum and minimum temperature residuals (set to be 0.6), and the autocorrelations for both maximum and minimum temperatures, which were constant for the entire year.

LARS-WG incorporated climatological changes from other sources such as global climate models or other large-scale datasets by adjusting the mean and standard deviations of the parameters of the distributions fitted to the observed time series. Monthly change factors (absolute values for temperature; relative changes for precipitation) were calculated between a time interval in which daily observations exist (to calibrate LARS-WG) and another time interval to be simulated. This was done for the site in question and inserted into the weather generator. The resulting time series of daily weather variables included the cumulative effect of these various statistical changes and provided the downscaled simulations or projections for the site in question.

3 Results

3.1 Correlation Maps

The correlation maps relating large-scale NCEP 2 Reanalysis variables to precipitation at the Top of Ten Mile weather station illustrate the regional influence of atmospheric variables in determining the local precipitation regime (Figure 1). In each of the four selected cases, the importance of the different atmospheric components is not merely confined to the grid cell within which the station resides, but covers many grid cells spanning a large area. This reflects the large size of the synoptic weather systems that transport precipitation to the region. As expected, large-scale precipitation is the most highly correlated with observed precipitation and the region of influence is centred on the weather station. The other surface variables, mean sea level pressure (MSLP) and minimum temperature occupy different areas, to the west and south of the weather station, respectively.

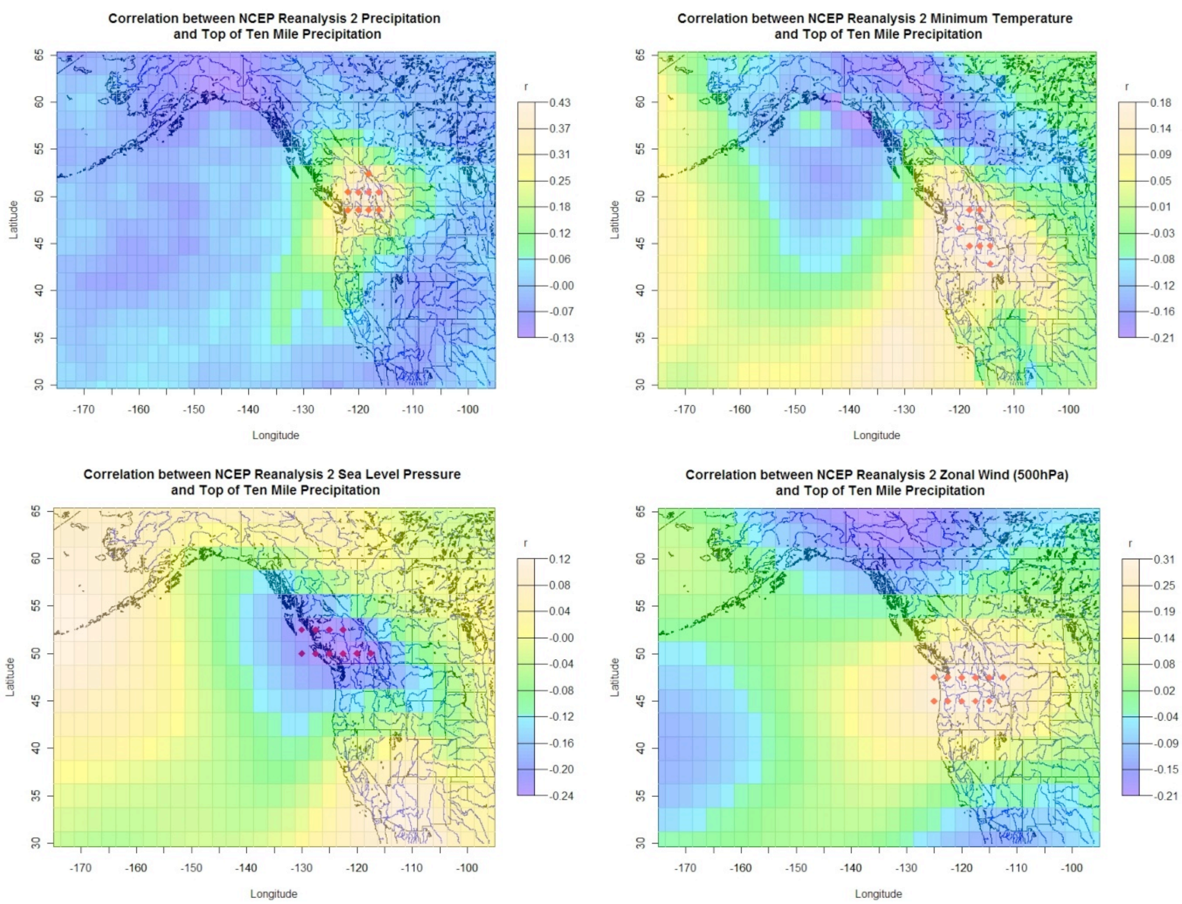

Figure 1. Correlation maps between atmospheric variables from the NCEP Reanalysis 2 dataset and precipitation observations from the Top of Ten Mile weather station. The red markers in each plot denote the grid cells selected for use as predictor variables in the synoptic typing downscaling method.

The region of influence of minimum temperature extends into the interior of BC and to the south of the US-Canada border, following the similar terrain of the Rocky Mountain Range. The higher correlations of the upper-level zonal winds are located to the south and west of the station and likely represent the dominance of the prevailing westerly winds during the winter months. The grid cells selected for MSLP extend to the west of the station and are anti-correlated with the observed precipitation, likely due to the effects of the passage of frontal systems through the interior of the province. While these correlation maps help to identify the influence of atmospheric contributions to winter precipitation, the relatively low correlation coefficients between the large-scale atmospheric variables and the observed precipitation suggest that other effects are also important. The influence of local topographic features, especially in the passes of the Rocky Mountains, contributes significantly to the precipitation received at the Top of Ten Mile station and is not readily represented by these large-scale variables.

3.2 Clustering Algorithm

The clustering component of the synoptic typing downscaling method returned three different types for the area around Top of Ten Mile representing the characteristic winter precipitation observed at eighteen weather stations (Figure 2). The types were determined using a cross-validation process in which a subset of the data was withheld during the clustering process. This was tested to see if there was a significant change in the assignment of days to a particular type should the dataset be altered in a small way. The resulting robust types were largely differentiated based on the magnitudes of precipitation in each type. Between the three cases there is little variation in the spatial distribution of the precipitation intensity. This suggests winter precipitation in this region of the Rocky Mountains may have fallen in a coherent fashion on average, or it may be a result of the small number of types used to describe all of the winter daily precipitation. In either case, the limited number of types reduced the ability of the synoptic typing method to replicate the variability of the precipitation at the various weather stations, and may explain why the validation of this method (described below) was less effective than that of the LARS-WG technique.

3.3 Downscaling Results

Both of the downscaling models are first evaluated by conducting simulations during the historical period (1979-2004) to compare each method's output against the observational record. Once the bias of the method is determined, future projections (correcting for the identified bias) are made using future climate projections from an ensemble of climate models. Given the altitude and location of the Top of Ten Mile weather station in the interior of a continental region, all precipitation in winter (December-February) is assumed to fall in the form of snow, and as such, the following plots all describe snowfall distributions. In each of the distributions the mean, standard deviation, 95^{th} and 99^{th} percentile values are displayed to illustrate the differences between the downscaled values and observations. One-day and three-day total snowfall distributions are represented by histograms, while the total winter snowfall amounts are described by a Type-1 extreme value distribution (Gumbel distribution).

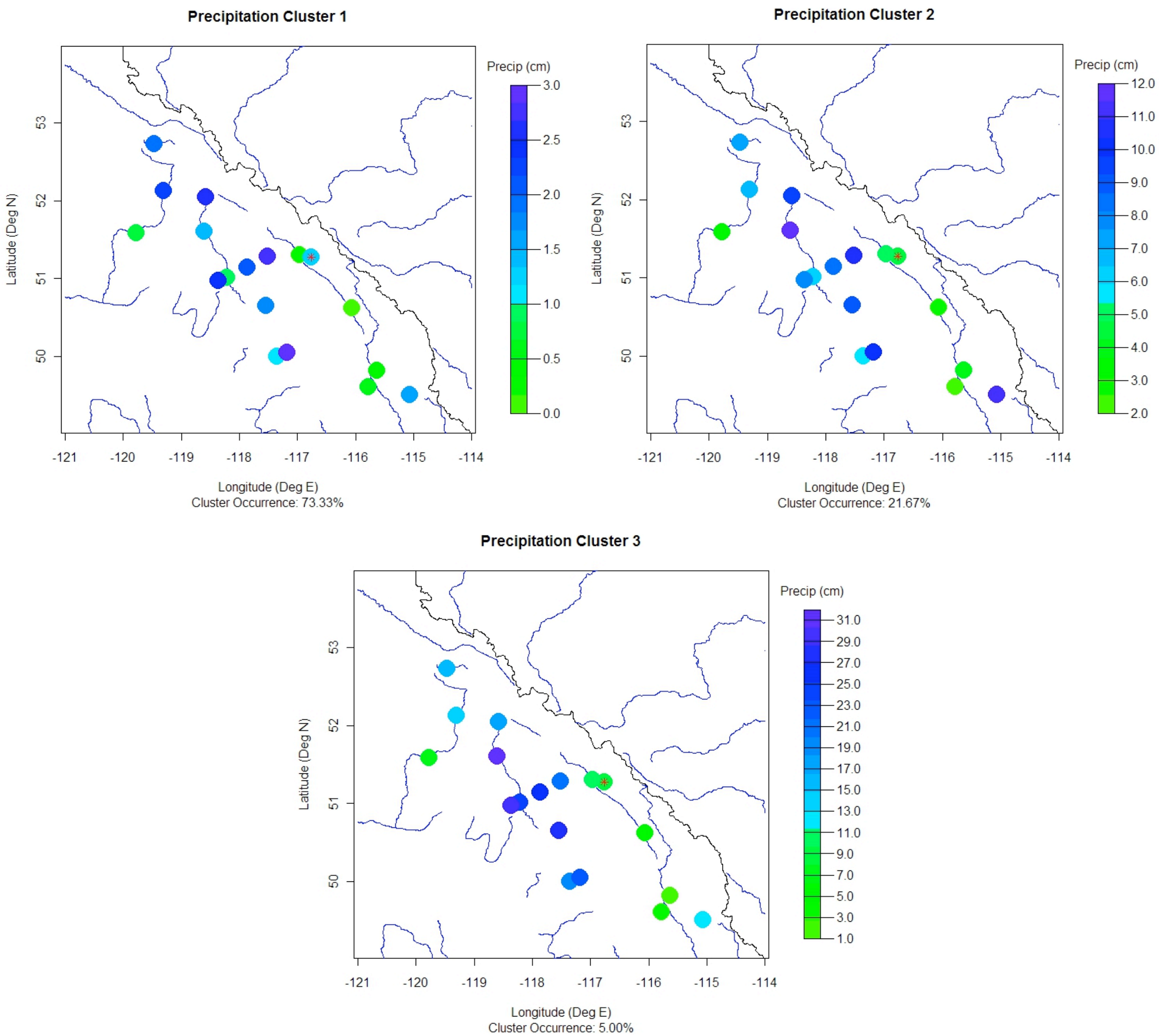

Figure 2. The results of the clustering process for the synoptic typing method as applied to eighteen weather stations over the years of 1979-1999. The shaded circles each represent weather stations and the colour of the circles describes the magnitude of the average precipitation at that station in each synoptic type. The frequency of occurrence of type is noted at the bottom of each plot. In each case, the location of the Top of Ten Mile weather station is noted by a red star.

3.3.1 Synoptic Typing: Validation

In each of the simulated snowfall distributions, the synoptic typing downscaling method underestimates the magnitude and variability of the winter snowfall received by the weather station (Figure 3). One-day and three-day snowfall statistics are between 11% and 30% lower than they should be, with the extremes (99^{th} percentiles) and standard deviations the least well replicated. In the case of winter totals, the synoptic typing method overestimates the average snowfall received by 6% but underestimates the other statistics, most notably a 27% underestimation of the variability. The results imply that the synoptic typing method is not adequately describing the full range of variability seen in the observations, due to the limited number of synoptic types as noted previously.

3.3.2 Synoptic Typing: Projections

Applying the synoptic typing model to future projections yields projected snowfall values that differ little from those of the baseline period (Figure 4). One-day totals remain constant; three-day totals decrease slightly (-1.5% change in mean); winter totals increase moderately (8% higher mean). In all cases however, the uncertainty of the future projections is larger than the difference between the projections and the observations from the baseline. In the case of the synoptic typing method, the statistical uncertainty is determined from the 95% confidence intervals and established from multiple simulations of the downscaling model using the same predictors. These results mean that the projected changes predicted by the synoptic typing model are not statistically significant.

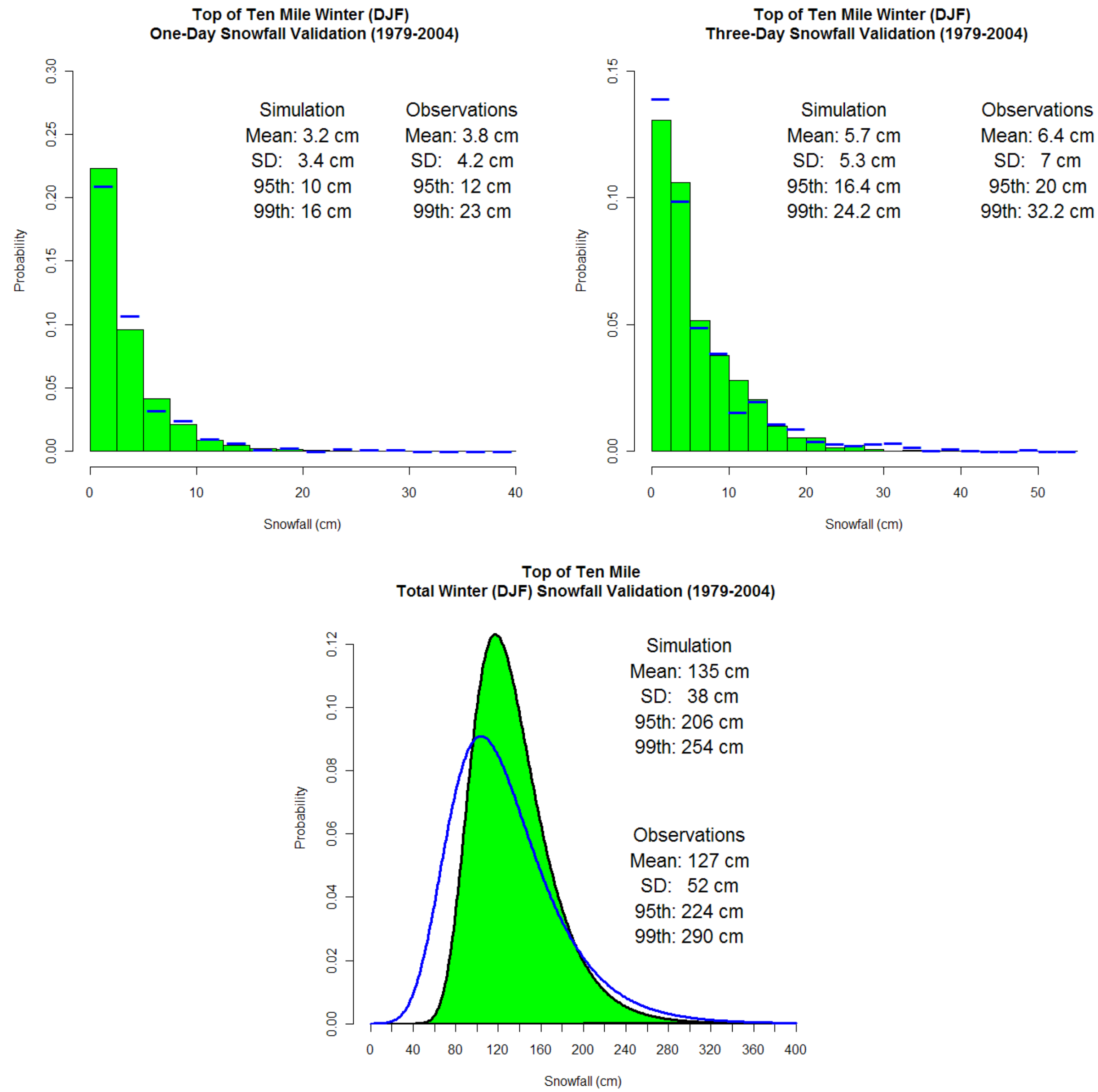

Figure 3. Validation results for one-day, three-day and total winter snowfall from the synoptic typing downscaling method. The shaded green area represents the output from the downscaling method, while the blue lines denote the observations for the same period (1979-2004). The total winter snowfall values are represented by a Type-1 Extreme Value Distribution (Gumbel distribution).

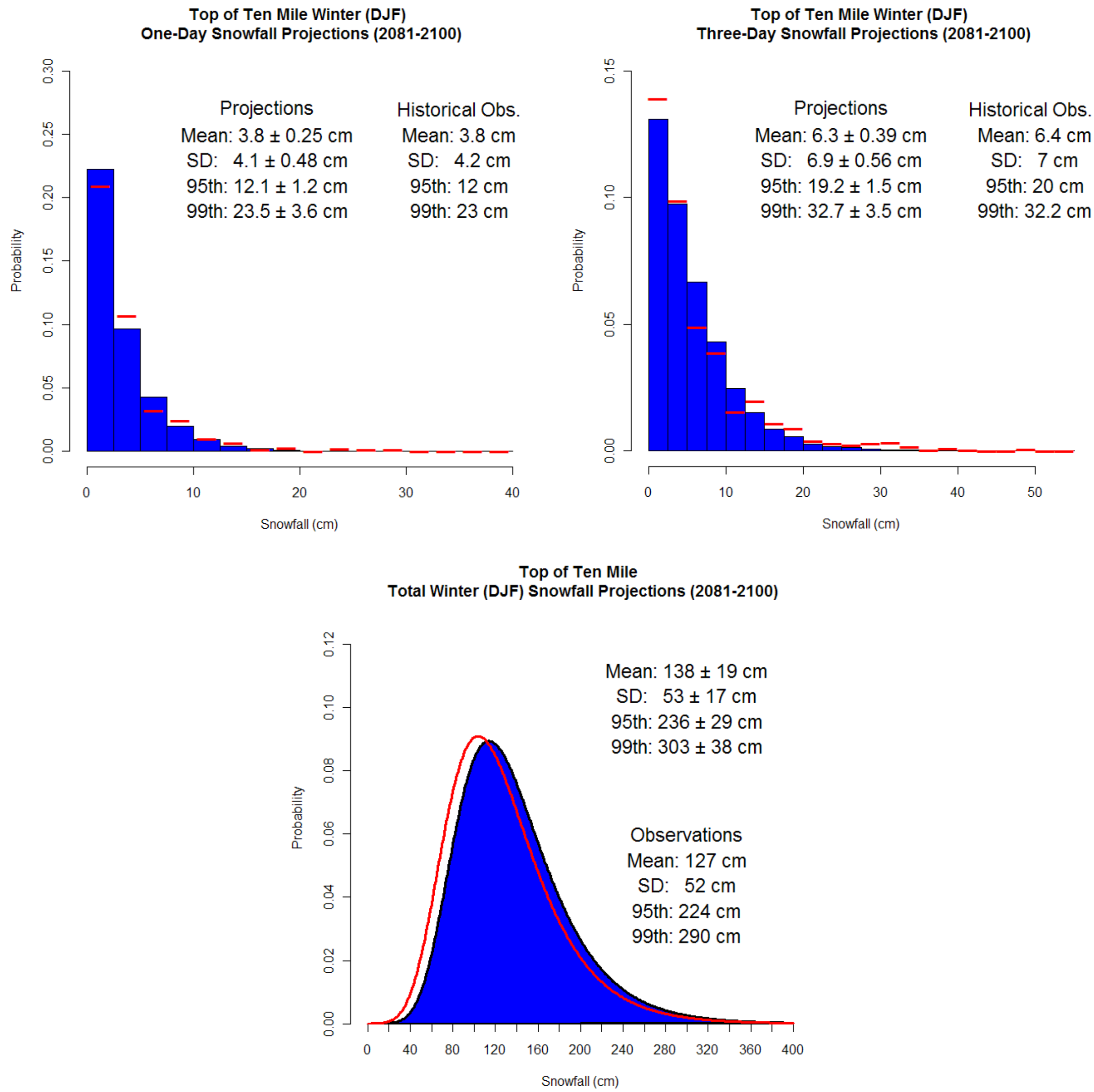

Figure 4. Projections of one-day, three-day and total winter snowfall amounts from the synoptic typing method for 2081-2100 made using an ensemble of climate models. The blue shaded area represents the downscaling method's projections, while the red lines denote the observations from the baseline period of 1979-2004.

3.3.3 LARS-WG: Validation

The simulation of historical snowfall observations by the LARS-WG downscaling method produces distributions of one-day, three-day and total winter snowfall that agree better with the observations than those of the synoptic typing method. Overall, LARS-WG tends to overestimate one-day total snowfall both in terms of the extremes (12% overestimation of the 95^{th} percentile) and the variability (15% overestimation of the standard deviation). In the case of three-day totals the results are mixed, with a small underestimation of the mean (-9%) and standard deviation (-6%), while the 95^{th} percentile is effectively replicated. A similar pattern is seen in the winter totals, with the mean value of the simulated data only 4% larger than the observations, and the standard deviation (-16%) and 95^{th} percentile (-5%) somewhat lower than expected. LARS-WG appears better able to replicate the more extreme value of snowfall in the tails of the different distributions, leading to the closer agreement between the simulated values and the observations compared to the results of the synoptic typing method.

3.3.4 LARS-WG: Projections

Unlike the results of the synoptic typing method, uncertainty bounds are not available for the LARS-WG output. Although both methods employ stochastic weather generators, LARS-WG imposes constraints on the values of the averages and variability of each experiment such that they are fixed even if the daily time series are different. Thus repeated simulations return exactly the same statistics, unlike the synoptic typing method where the stochastic variability of both the type selections and precipitation amounts leads to small variations in the statistics of the time series.

The future projections produced by LARS-WG yield uniformly positive changes in all of the snowfall distributions. In each case, both the magnitude and variability of the snowfall amounts increase by 7% to 15%. One-day average snowfall grows by 10.5%, while both extreme levels (95^{th} and 99^{th} percentiles) grow by 9%. A similar result is found for the three-day snowfall totals, with projected increases in the average amounts at 12.5% and the 99^{th} percentile rising by 14%. Total winter snowfall is projected to grow the most, with increases in the mean projected at 15%, a 14% increase in the variability, and 14% increases in both extreme values. The results of this downscaling method predict that the Top of Ten Mile weather station will experience significant growth in the magnitude of typical snowfalls, and that extreme snowfalls will become more frequent by the end of the 21^{st} century.

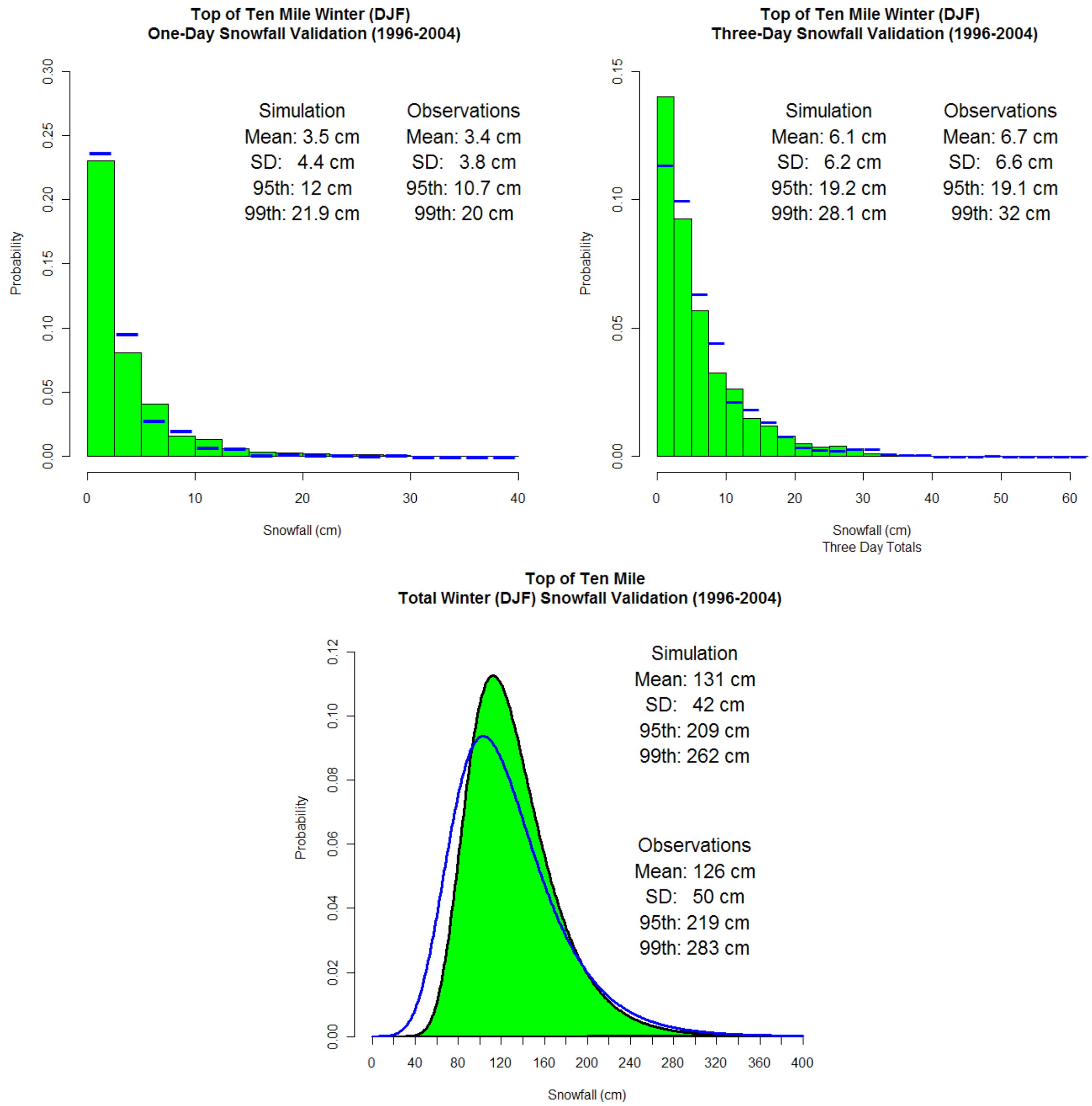

Figure 5. Validation results for one-day, three-day and total winter snowfall from the LARS-WG method at the Top of Ten Mile weather station. The green shaded areas denote the downscaling method output and the blue lines indicate observations for the same period (1996-2004).

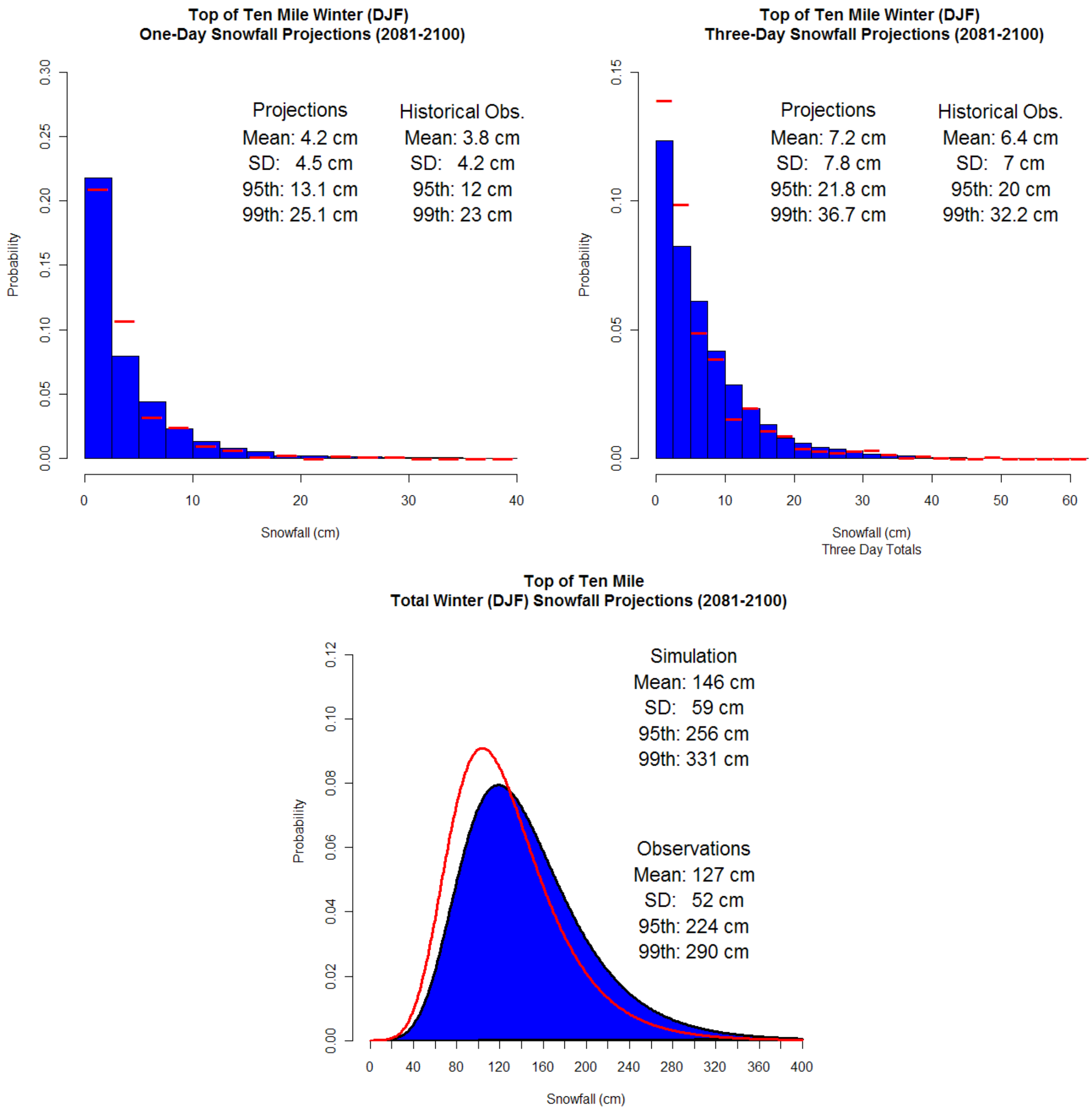

Figure 6. Future projections of one-day, three-day and total winter snowfall from the LARS-WG Method for 2081-2100 under the SRES A2 emissions scenario. The blue shaded areas describe the downscaling model projections while the red lines denote the observations from the baseline period (1979-2004).

4. Conclusions

The combination of low correlation coefficients between the large-scale predictor variables and the Top of Ten Mile precipitation, the similarity of the synoptic types and the high uncertainty of the downscaled projections suggests that the synoptic typing method is ill suited for the purpose of simulating precipitation in this region. The validation results indicate that the LARS-WG method offers a more effective representation of winter precipitation at Top of Ten Mile. As a result, the downscaling projections offered by the LARS-WG should be taken with greater confidence than those of the synoptic typing method at this weather station.

	Winter			1 Day			3 Day		
	Present	**Future**	**% Diff**	**Present**	**Future**	**% Diff**	**Present**	**Future**	**% Diff**
Mean	127 cm	146 cm	15.0%	3.8 cm	4.2 cm	10.5%	6.4 cm	7.2 cm	12.5%
SD	52 cm	59 cm	13.5%	4.2 cm	4.5 cm	7.1%	7 cm	7.8 cm	11.4%
95th %	224 cm	256 cm	14.3%	12 cm	13.1 cm	9.2%	20 cm	21.8 cm	9.0%
99th %	290 cm	331 cm	14.1%	23 cm	25.1 cm	9.1%	32.2 cm	36.7 cm	14.0%

Table 2. Observed 1979-2004 (**Present**) and projected 2081-2100 (**Future**) mean snowfall, standard deviation and 95th and 99th percentile events at the Top of Ten Mile site. The percentage increase is also given (**% Diff**). Results are provided for the average over winter (December through February) as well as one and three day snowfall events.

Incorporating the large-scale projections of the global climate models, LARS-WG predicts that significant increases in one-day, three-day and total winter (December-February) snowfall will occur by the end of the 21st century under the SRES A2 emissions scenario (see Table 2 above). Average one and three snowfall totals are projected to increase by 10.5% and 12.5%, respectively, while the average total winter snowfall increases by 15%. The variability and extreme values of each of these metrics are also forecast to increase by 7% to 15% by 2100. The projected increases in snowfall at this location reflect the increases in temperature and precipitation predicted to occur due to future climate change and will likely alter the existing avalanche regime around the Top of Ten Mile weather station.

5 References

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