CHANGING CLIMATE OF IDAHO: FUTURE PREDICTION MAPS

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ABSTRACT

Scientific evidence of decreasing snow packs (Mote et. al., 2005; Mote, 2006) and changing streamflows (Gahn et. al., 2006; Gahn and Shippert, 2006) in the Pacific Northwest (PNW) have prompted water managers around the West to begin planning for the potential effects of climate change on water resources. Idaho is particularly sensitive to potential changes in both water supply and demand, because the state's economy depends heavily upon agriculture, forestry, and tourism, as well as hydroelectric power generation; all of which are at risk due to rapid shifts in climate. Because of this, numerous scenarios of possible meteorological and hydrological conditions are needed to allow for planning of the state's future. We outline a method to improve the downscaling of climate scenarios from the Intergovernmental Panel on Climate Change, as well as how to combine the downscaled climate scenarios with historic snow cover images to produce future snow related products.

INTRODUCTION

In the semi-arid western United States, water from a melting snow pack is the major source of reservoir recharge, which is heavily depended upon by many. In the late 1970's, the annual economic value of melt water as a resources in the western United States was estimated at over 6 billion dollars (Hall and Martinec, 1985). This value will continue to increase as competition over water rights rises in accordance with a changing climate. Global warming, caused by rising atmospheric concentrations of carbon dioxide and other greenhouse gases, is expected to alter the radiation balance of the atmosphere. This will in turn cause increases in the temperature and changes in precipitation patterns, both of which will have a profound effect on snow accumulation, timing, and magnitude of melt in mountainous regions. Because of this, long-range planning is necessary to understand the magnitude and timing of potential climate change effects on water resources.

Over the past century, the global surface temperature has risen approximately 0.6°C (Folland et al., 2001) and is projected to further increase 1°C to 5°C (Cubasch et al., 2001). As concern about global warming increases, so does the knowledge basis of the research community and the number of climate scenarios depicting possible realizations of the future. Accurate projections of future local climate scenarios are needed for impact analysis in a variety of scientific disciplines. Numerous studies have been conducted as to the impact of climate change on hydrological (Hamlet and Lettenmaier, 1999; Salathe, 2005; Wood et al., 2004), ecological (Vitousek, 1994; Walther et al., 2002), and agricultural impacts (Mearns et al., 1997), as well as many others. While the coarse resolution of the Global Circulation Models (GCM's), typically 1 to 5 degrees horizontal resolution, may be sufficient for some impact studies, the lack of surface topography in complex terrain in the GCM's is a massive shortcoming. This paper focuses on downscaling climate scenarios from the Intergovernmental Panel on Climate Change (IPCC) to a finer spatial resolution and how to produce maps of snow related products in the complex terrain of Idaho using the downscaled climate scenarios.

DATA

Observed Data

In this study, we use the climatological data obtained from Parameter-elevation Regressions on Independent Slopes Model (PRISM). These high spatial resolution datasets provide maximum and minimum temperature, as well as precipitation at a 4km grid. The PRISM datasets (Daly, 1994) are high quality datasets that begin in 1895 and extend through to the present. Such an extended dataset is ideal for developing the statistical relationships required to downscale the climate scenarios.

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Climate Data

The climate scenario data used in this study are obtained from the International Panel on Climate Change Fourth Assessment Report (AR4). The data available through the IPCC Data Archive (www.ipcc-data.org/) contain a large number of models and climate scenarios. In this study we use the 20th century, A2, and B1 scenarios for three model runs: the GISS-ER, the IPSL, and the ECHAM5 models. The models were chosen based on their significance to the Pacific Northwest as shown by Mote et al, (2005) and Salathe et al. (2007).

Satellite Data

The satellite data used in this project are MODIS 8-day composite snow images. These data are used in combination with temperature data to develop a statistical distribution of average temperatures for each 4km grid cell to estimate critical temperatures for snow accumulation as well as for validation of snow cover extent. We are currently in the process of determining what other historic snow related satellite data are available.

METHODS

Downscaling Climate Scenarios

The lack of surface topography in complex terrain in the GCM's is a massive shortcoming and thus necessitates a need for finer spatial resolution data created by downscaling. Three methods can be readily identified in the literature and are examined in Murphy (1999). One such technique uses output from the GCM to force a Regional Climate Model that typically has topography built in at a much finer spatial resolution (Leung and Gahn, 1999; Duffy et al., 2006). A second technique is to create statistical relationships linking the localized variable in question to one or more atmospheric predictor variables (Wilby and Wigley, 1997). This technique assumes that the climate of the future can be predicted based on the same set of variables that best predict the climate of the past. A third technique is based on the local variable to be predicted can be characterized by the corresponding variable simulated at nearby GCM grid points with adjustments for simulation biases and topographic effects. The third technique is the method incorporated into this research. Figure 1 is a graphical depiction of the downscaling process.

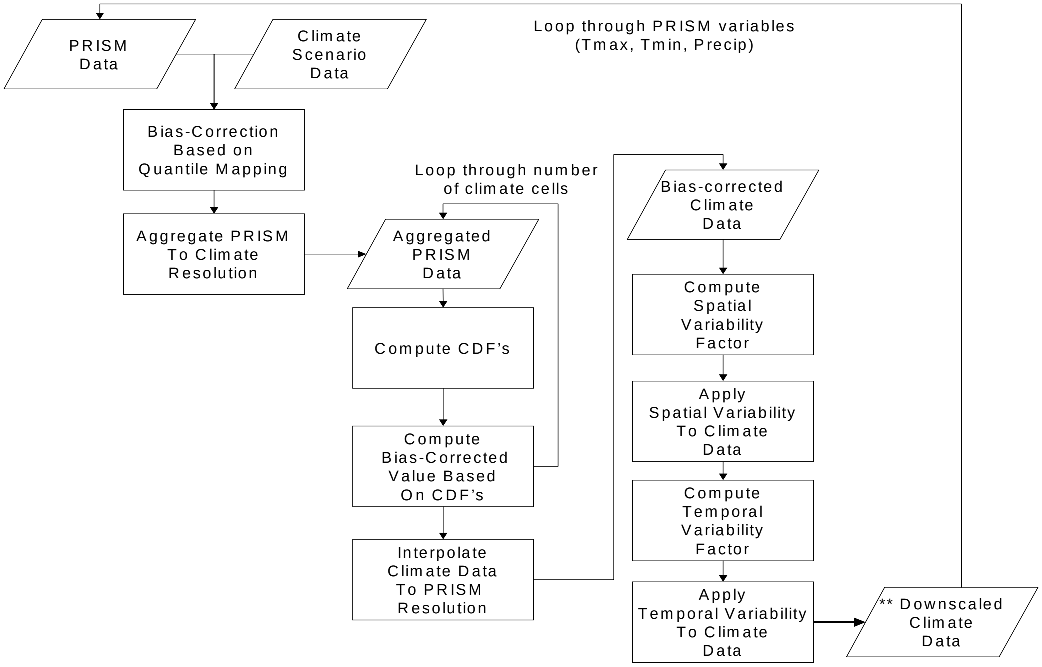


Figure 1. Graphical depiction of the process to downscale climate scenario data

Bias-Correction. The monthly mean climate scenario data are detrended, bias-corrected, and mapped to include spatial variability. For each climate model, the 20th century, A1 and B2 runs are included. While the 20th century run typically is comprised of data from 1860 through the 1900s, we use a much shorter time span (1950-1999) as a baseline to develop the statistical relationships used for the downscaling. Salathe et al (2007) provides an in-depth discussion on the bias-correction methodology used in this research, and will therefore only be discussed briefly here.

To perform this type of spatial downscaling of climate scenarios, PRISM data is first aggregated to the spatial resolution of the climate scenarios and cumulative distribution functions are generated based on the baseline data for both the climate scenarios and the observed data. The climate scenario data is then mapped to the distribution of the observed data using a quantile-quantile approach (bias correction). The bias-corrected climate scenario as well as the aggregated PRISM data is then interpolated between the climate scenario cells to match the PRISM resolution. The method in which a finer spatial resolution of the bias corrected climate scenario is created is a decision point. This is typically done either by assigning the bias-corrected climate value to each 4km cell that is centered in the GCM cell or by interpolating the bias-corrected GCM to a finer spatial resolution (IPCC-TGCIA, 1999). Interpolating the GCM cell data to a finer spatial resolution introduces a false sense of geographic precision, however, it smoothes out the effects of discontinuities that may exist between GCM grid cells. On the other hand, assigning each 4km cell that is centered in the GCM cell creates a discontinuity between the GCM cell boundaries. In this project, we chose to develop a finer 4km spatial scale by interpolating the bias-corrected climate values between the GCM grid cells using a triangular-based linear interpolation method.

Spatial Variability Component. To account for the lack of spatial variation due to topographic effects in the mountainous terrain of Idaho, a post-processing step is included. The baseline aggregated PRISM dataset (1950-1999) is interpolated back to the original 4km spatial resolution. Each year of the interpolated observed data is then subtracted from the corresponding year of the original observed (PRISM) dataset to generate a series of fifty spatial variability grids which are then added to the interpolated bias-corrected climate scenarios. To determine which spatial variability grid should be added to a particular year of the downscaled climate scenario, a time series of mean detrended regional values is computed for the downscaled climate data and a time series of mean regional observed values. A transfer function is then used to determine which year in the observed time series most closely matches the probability of the year of the mean detrended regional downscaled climate data. The corresponding spatial variability grid is then added to the downscaled climate scenario so that the spatial variability found in the mountainous terrain of Idaho is represented. A series of spatial variability grids are chosen instead of applying one mean spatial variability grid to negate the cancellation of the spatial variability when the data is differenced as is common when analyzing a regional change temperature or precipitation.

Temporal Variability Component. An effect of the transfer function used during the bias-correction process is the downscaled climate scenario no longer contains the temporal variability that the raw climate scenarios exhibited. In essence we are superimposing the temporal variability of the past climate from the observed (PRISM) data onto the climate scenarios. To accommodate the possibility of a change in the temporal variability in a changing climate, a temporal variance component was included. The following equations and explanation describe the process in detail.

The variance component is determined for every year and every month for each climate scenario. The first step is to determine how the variance of the aggregated PRISM data (σ_{obs}^2 in Eq. 1) is related to the variance of the detrended climate scenario (σ_{mod}^2 in Eq. 1).

$$r_{\sigma^2} = \frac{\sigma_{obs}^2}{\sigma_{\mathrm{mod}}^2} \tag{1}$$

This relationship is used for the duration of computing the changing variance for a given month and scenario. The next step is to determine how many standard deviations the detrended climate value for each time (t) from 1900-2100 ($X_{\mathrm{mod}}(t)$) is from the mean of the baseline shifted climate (μ_{mod}) by dividing the difference of the two by the standard deviation of the baseline shifted clime (σ_{mod}) as is shown in Equation 3.

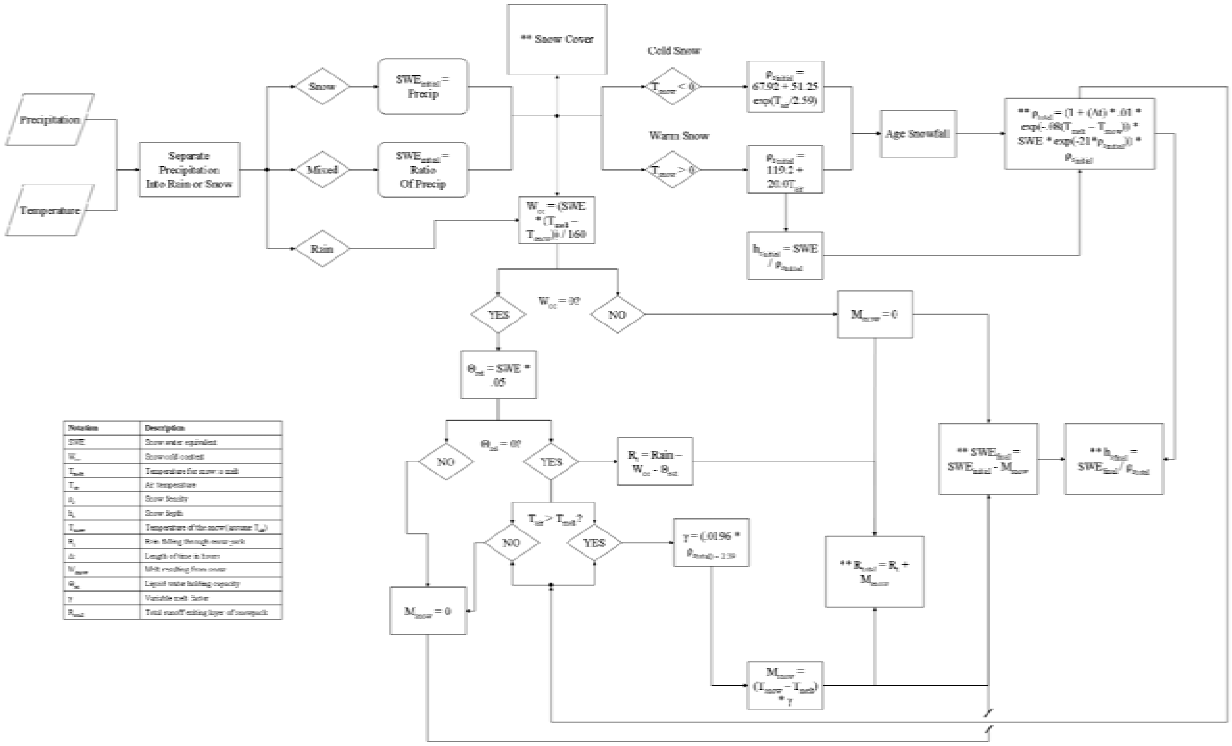
$$q(t) = \frac{\left(X_{\mathrm{mod}}(t) - \mu_{\mathrm{mod}}\right)}{\sigma_{\mathrm{mod}}} \tag{2}$$

The time series of variance values, *v(t)*, is then added to the downscaled climate scenarios to produce a dataset that is not only bias-corrected in regards to the mean, but also incorporates some information about the variability of the raw climate scenario.

$$v(t) = r_{\sigma^2} * q(t) \tag{3}$$

Creating Snow Related Maps

The process of creating snow related climate scenario products, shown graphically in Figure 2, is based on research by Anderson (1976) and Brown et al (2003). This is a distributed model that is run for every month throughout each year for each 4km grid cell located in Idaho. This essentially allows the model to accumulate and melt the snow. To generate the snow related products (shown by the asterisks in Figure 2); the downscaled temperature and precipitation data are used to predict the type of precipitation and thereafter the SWE for every month. If there is SWE, the pixel is snowcovered, and a snow aging process is then incorporated. A total snow density, based on compaction during the aging process is calculated and used to determine a monthly snow depth, as well as a variable melt factor. The cold content and the liquid water holding capacity of the monthly snowpack is also tracked, and when satisfied, runoff results.



Notation	Description
SWE	Snow water equivalent
W_{cc}	Snow cold content
T_{melt}	Temperature for snow to melt
T_{air}	Air temperature
ρ_s	Snow density
h_s	Snow depth
T_{snow}	Temperature of the snow (assume T_{air})
R_t	Rain falling through snow pack
Δt	Length of time in hours
M_{snow}	Melt resulting from snow
Θ_{wl}	Liquid water holding capacity
γ	Variable melt factor
R_{total}	Total runoff exiting layer of snowpack

Figure 2. Flow diagram of the process to produce snow related maps and table signifying the variable notation used

For a given month, the average temperature and precipitation for a given 4km grid cell is used to determine how much, if any, of the precipitation fell as snow. To determine if the precipitation fell as snow, a statistical relationship using the historical set of snowcover images is developed. By analyzing the time-series of when a pixel is and isn't snow covered, maximum and minimum critical temperatures associated with the snow cover can then be determined. These critical temperatures are used to determine what percentage of the precipitation fell as rain and snow. The amount of precipitation that fell as snow is then set as the initial snow water equivalent, and considered snow covered for that location. The liquid water holding capacity, which is set at 5% of the total SWE, and then cold content of the snow (W_{cc}):

$$W_{cc} = (SWE * (T_{melt} - T_{air}))/160, \tag{4}$$

where T_{melt} is the melting temperature of the snow and T_{air} is the air temperature, are then calculated. If there is enough precipitation that fell as rain for the month to satisfy both the cold content of the snowpack and the liquid water holding capacity, then the remainder of water moving through that layer of snow is the leftover rain (R_t) and is used to satisfy the W_{cc} and liquid water holding capacity of the snow layer below.

The density of the new snow (kg m^{-3}) for the month is determined as a function of the air temperature (Hedstrom and Pomeroy, 1998):

$$\rho_{snow} = 67.92 + 51.25 \exp(T_{air} / 2.59) \quad \text{when } T_{air} \leq 0°C \qquad (5)$$

$$\rho_{snow} = 119.2 + 20.0 * T_{air} \quad \text{when } T_{air} > 0°C \qquad (6)$$

The density of the snow is then aged as follows using a formula from Anderson (1976):

$$\begin{aligned}\rho_{agedsnow} &= (1 + (\Delta t) * .01 * \exp(-.08(T_{melt} - T_{snow})) \\ &* SWE * \exp(-21 * \rho_{snow})) * \rho_{snow}\end{aligned}, \qquad (7)$$

where Δt is the amount of time in hours. Once the SWE and the density of the snow are calculated, the model then determines if the air temperature is greater than then melt temperature. If $T_{air} < T_{melt}$, no snowmelt will occur and the runoff is equal to the amount of water that was able to flow all the way through the snow pack (R_t). If $T_{air} > T_{melt}$, a variable melt factor is computed based on the density of the snow is computed (Brown et al, 2003):

$$\gamma = (0.196 * \rho_{agedsnow}) - 2.39 \qquad (8)$$

And the amount of melt is computed as:

$$M_{snow} = (T_{snow} - T_{melt}) * \gamma \qquad (9)$$

The amount of runoff for that particular layer is then the sum of the melt (M_{snow}) and the amount of rain moving through the snow pack (R_t). A final SWE estimate is determined by subtracting the amount of melt from the initial SWE value and depth of the snow layer is calculated as:

$$h_s = SWE / \rho_{agedsnow} \qquad (10)$$

The runoff for that particular layer is then used as the water flowing into the previously deposited snow layer. This process is repeated for each month (snow layer) until there are no further snow layers for the runoff to go through. The amount of total runoff for the given month is then the amount of runoff that exited the bottom of the snow pack. Figure 2 shows the process of snow accumulation and melt for a single month as well as the notation of the flow chart.

SUMMARY

Extensive datasets exist for analyzing climate change throughout the United States. In this study, 4km PRISM data and climate scenario data were used to develop a method to downscale climate scenarios from the IPCC and to generate snow related products. The datasets derived from this methodology for the state of Idaho will be available online (www.idahoclimatechange.mines.uidaho.edu), once the procedure has been thoroughly validated. Currently available on the Idaho climate change website are grids of maximum and minimum temperature and precipitation, which have been produced by the Climate Impacts Group, and have the state of Idaho extracted from them.

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