

# The Development of GCM Based Climate Scenarios for use in Water Resource System Impact Evaluations

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**Abstract:** The traditional method for assessment of water resource systems includes the use of statistical analysis of climatologic and hydrologic variables based on historic observed climate and streamflow records. These assessment approaches rely on the presence of a long historic record to derive probabilistic statistics. As the evidence of global climate change continues to accumulate, the use of historic records as a proxy for possible future events becomes less appropriate. A method for combining historic observed climate variability with climate model based simulations of future climate is presented. The proposed method creates a steady-state approximation of future climate for a chosen future period of investigation, and then expands the steady-state climate to include the full range of observed natural variability. A case study application of the proposed method at four periods of investigation, 2000, 2025, 2050, and 2075 is presented using output from the ECHAM5 climate model and as applied to the South Fork of the Sultan River, near Sultan, Washington.

CE Database subject headings: Climate Change, Downscaling, Water Resource Management

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## **Introduction**

This research describes a proposed method for creating scenarios of future climate for use in the analysis of the impacts of climate change on water resource systems based on output from global climate models (GCM). The analysis of water resource systems, and their performance, is generally based on the assumption that the hydrologic features of climate do not change. If we accept the growing evidence that our global climate is changing, the changes in climate make the assessment of water resource systems more difficult. For system assessments during a changing climate, one must identify how a system responds to both the effects of the underlying climate trends as well as the effects of significant interannual variability. Most measures of system performance are based upon a statistical examination of historic stream flows. System impacts are best defined with an extended time series (fifty to seventy-five years) as they incorporate a range of potential variability, but the time series are assumed to represent a steady state condition (Arnell 1996). A simply stated question, thought difficult to answer, is how will characteristic flow events, used for system planning and design, change in the future? A method for answering such questions through the creation of climate model based scenarios has been developed. The proposed method contains both the full range of historic observed variability and a steady state representation of future climate at the specifically chosen period of analysis. The method blends traditional water resource evaluation methods with new techniques for evaluating the impacts of climate change.

The proposed method is based on the relationships between the cumulative distribution functions of climate variables at both the regional and local scales. By exploiting this relationship, global and regional scale climate data derived from GCM simulations are downscaled to local station points and this downscaled climate data can then be used in

simulations to evaluate water resource climate change impacts. A goal of the proposed downscaling method is to accurately reproduce the local phenomenon and statistics that are associated with the larger scale state. Meteorological downscaling describes a method for generating local scale climate data using regional scale information, such as that generated by a GCM or other climate projection models. The product is a time series of weather data for a local scale station that corresponds to the regional or global time series produced by a climate model, yet also contains features unique to the station location not present in the regional signal. These local features are defined by the observed record at each station.

Many different methods have been documented for performing downscaling operations (Wilby and Wigley 1997; Widdmann et al. 2001; Leung and Ghan 1999). A common feature of these approaches is that they yield a transient view of the climate state, a single realization of the many possible variations that could have occurred. When using climate data for water resource planning, it is necessary to incorporate methods that allow for the estimation of the entire range of potential variability that might occur within a time period. The proposed method captures the regional signal described by the climate models, contains local scale phenomena and patterns as defined by the observed history at a station, and expands the time series to include the entire possible range of variability.

The climate scenarios are developed in three stages (Figure 1) with each stage incorporating a new source of climate data; GCM output, gridded regional climate data, and local observed station data, respectively. The three stages are:

- 1) Downscale the climate variables from the GCM scale grid to a regional scale grid,
- 2) Bias-correct a single regional grid cell to an individual station location, and

3) Expand the station scale transient scenario into multiple, quasi-steady-state time series with the full historic variability.

### **Downscale from the GCM scale to regional scale**

Researchers often need climate data at scales more refined than that which is generated by GCMs. The transformation process is called regional downscaling. In essence data at a resolution of approximately  $10^7$  km<sup>2</sup> is rescaled at a resolution of approximately  $10^4$  km<sup>2</sup>. For example the global model grid shown in Figure 2 uses a  $2.5^\circ \times 3.75^\circ$  grid for the atmospheric component. The regional scale, for purposes of this downscaling approach is defined with a  $1/8^\circ$  latitude/longitude grid.

The process for converting GCM scale data to the regional scale is based on the statistical relationships between climate datasets at the two scales calculated over the same historic period. For each month of the year, Cumulative Distribution Functions (CDFs) are calculated for average temperature and total precipitation for each grid cell in the GCM simulated climate over a specified historic period. Monthly temperature and precipitation CDFs are also calculated for the same historic period for each grid cell at the regional scale. This process requires both a historic climate simulation from the GCM, as well as an observation based climate data set at the regional scale. The regional scale data set used is described in Hamlet and Lettenmaier (2005).

A set of transformation functions are then derived using the GCM and regional scale CDFs. This process of relating the CDFs is generically referred to as Quantile Mapping. The Quantile Mapping method is based on a bias correction scheme for downscaling climate model output described by Wood et al. (2002). Unlike the traditional delta method which applies a constant correction factor (the delta value) to all events within a season and which has been used in many climate impact studies (Smith and Tirpak 1989; Lettenmaier and Gan 1990; Kirshen and

Fennessey 1995; Lettenmaier et al. 1999; Loáiciga et al. 2000), the Quantile Mapping method assumes that shifts in climate variables occur with different magnitudes at different points along the variable's distribution. The quantile relationship between the historic simulation at the nearest GCM cell and the historic data set at the regional scale is shown in Figure 3.

The statistical downscaling method combines the methods described by Wood et al. (2002), Widmann et al. (2003), and Salathé (2004). As in Wood et al. the monthly-mean global climate model data are bias-corrected. The bias-corrected climate model is then downscaled to  $1/8^\circ$  resolution. For precipitation, the "dynamical scaling" method presented in Widmann et al. is used; for temperature the method described in Salathé (2004) is used.

The statistical downscaling is based on  $1/8^\circ$  gridded observed, temperature and precipitation (Maurer 2002). For the bias correction, the data are aggregated to the grid of the climate model under consideration. Observed and simulated data for the period 1950-2000 are used to form a transfer function based on the CDFs for each parameter for each calendar month. Temperature and precipitation simulated by the climate model are then bias corrected using the transfer function, assuring that the bias-corrected simulation returns the observed CDF during the training period (1950-2000).

The bias-corrected climate model is then downscaled and disaggregated using the same techniques employed in Salathé (2004). For temperature, the bias-corrected climate model data are sampled onto the  $1/8^\circ$  grid. The mean difference between the bias-corrected model and the  $1/8^\circ$  data for each calendar month during the training period (1950-2000) is computed to form a perturbation factor. The downscaled temperature is then formed by adding the factor for the appropriate calendar month to the monthly simulated temperature for each month of the simulated scenario. For precipitation, a similar method is employed using a multiplicative

scaling factor. In the simple case, the scaling factor is the mean ratio of simulated and observed precipitation on the  $1/8^\circ$  grid over the training period. In the “dynamical scaling,” the scaling factor is then modified to account for the effect of the interaction of large-scale winds and regional topography on the precipitation pattern.

The output from stage one is a transient, monthly time-series at the  $1/8^\circ$  scale of GCM simulated climate. This time series can be temporally disaggregated to daily values by re-sampling of the historic data set and applying small daily correction factors to maintain the appropriate monthly statistics. The daily, transient, regional climate grid can then be used as forcings in regional scale hydrologic models. This approach is useful for projecting future trends in hydrologic phenomenon, such as regional snow cover, soil moisture, and streamflow volumes over large, continental scale areas such as the Columbia or Colorado River Basins.

### **Transformation from regional grid to station locations**

To analyze future climate projections at the local scale, or to create forcings for higher resolution hydrologic modeling, data from the regional grid can be further downscaled to individual weather station locations by an additional application of the Quantile Mapping method. In this instance, CDFs used in the mapping come from a single cell for the regional grid, and from a historic observation record at the station location.

The process requires extracting the single grid cell in which the desired station is located from the regional data sets. The monthly transformation relationships are defined by mapping the historic climate CDFs from the regional cell and the CDFs from the observed station data. Future regional scale climate data can then be downscaled to the station location using these relationships. The difference, or bias, between the regional grid cell value and the station record

tends to be considerably smaller than the bias seen when comparing GCM scale cells to regional cells (Figure 4). The difference is considerably smaller in this second bias correction step (Figure 5).

As with the monthly, transient, regional data set, the station scale data can be temporally disaggregated using a process of selective re-sampling. Small corrections are applied to the daily data to maintain the monthly statistics. To minimize the correction factors, the re-sampling process is keyed to select the daily time series by selecting the month that most closely matches the total precipitation. The output from this process is useful for examining climate trends at the station scale and for examining transient hydrologic phenomena generated using a high resolution hydrologic model.

### **Expanding transient scenarios into quasi-steady-state time series.**

Using climate models to forecast impacts to water resources presents an unusual challenge with regards to the manner in which the climate of a region is represented. Climate is defined as the average condition of the weather over a period of time. This assumes that the climate state being defined is stationary, that is, the long-term average does not change over time. Analysis of observed records, however, shows that long-term averages do change, and can be influenced by the selection of the averaging period. The principal assumption behind climate change research is that anthropogenic forces have caused shifts in climate. Climate change impact studies must consider climate at a given point in time; for example, how will climate change affect our water supply by the year 2050? The range of natural variability, however, is often greater than the magnitude of change expected over several decades. Figures 6 and 7

demonstrate this phenomenon using 100 years of simulated climate data from the ECHAM5 climate model.

Figure 6 presents the average temperature for March from 1925 to 2075 at the Snoqualmie Falls weather observation station, as simulated by the ECHAM5 climate model. This dataset contains information from both the 20<sup>th</sup> century control simulation and the SRES A2 scenario simulations. An estimate of the steady state climate for March temperatures is computed as the average of 15 years on either side of the year in question (e.g. the 1960 March temperature value is the average of March temperatures from 1945 to 1975). The slope of the 31 year rolling average very closely approximates that of a third order trendline fitted to the yearly data.

This series of values represents the estimated magnitude of temperature change within the time frame chosen to approximate a steady state. The magnitude of the warming within each period is shown as the lower line in Figure 7. The upper line in Figure 7 shows the natural variability seen within the same period as measured by the standard deviation of the 31 values. The standard deviation is typically greater than the magnitude of change, and approaches being equal or greater after 2050. This implies that at any point in time, the magnitude of variability attributable to climate change will be less than or equal to that which can be expected from year to year due to natural variability. This is not to imply that climate change impacts are insignificant, but to make clear the importance of including the full range of potential variability in any estimate of future climate for a specified period.

Using a steady state approach to estimate climate conditions, such as the 31-year average, it is likely that a significant amount of potential variability will be excluded. Similarly, if a transient simulation is used (examining the entire time series), it becomes difficult to assess the

potential impacts of climate change at a specific point in time, because each simulation is only a single realization of the infinite number of possible combinations of events. There are potential pitfalls in using either a steady state or a transient approach. The rate of change seen in most climate models is significantly less than the magnitude of the natural variability that can be expected to occur from year to year. When looking at transient or steady state representations of climate, it is important to assess whether or not the data set's variability is sufficient to represent the full range of potential variability that may actually occur. If we use a range of years to identify a given year of interest and use that range to describe the average climate of a period (e.g. 1965-1995 to represent 1980 climate), the variability present within the range is often less than the full range that has been observed in the past. Extreme events are the defining events when describing the sustainability of a water resource; therefore, it is very important to include these events in any representation of potential future climate.

One option for addressing the truncated range of variability when using subsets of climate data is to incorporate into the downscaling process a step that expands the climate time series so that it includes the full range of observed, historic variability. This process uses a quantile relationship similar to the quantile mapping process to combine the climate variable distributions derived from one data subset with time series of events from a different subset. This approach allows use of a shorter period to define the climate state, yet maintain the variability of the full historic record. The process for creating an "expanded time series" is as follows:

- 1) The bias-corrected, transient, monthly GCM time series is divided by climate variable and by month into 24 (12 months  $\times$  2 variables) climate progressions.

- 2) A 31-year slice, centered on the Year of Investigation, is extracted from the transient GCM data. These 31 years are considered indicative of the average climate for that period.
- 3) The cumulative distribution functions of temperature and precipitation are calculated for each of the 12 months for both the GCM slice and station level historic climate data that has been aggregated to monthly values.
- 4) The CDFs from the two data sets for each month and climate data (e.g. January precipitation or March temperature) are used to create a Quantile Map.
- 5) Each value in the historic time series is then related to a corresponding value from the GCM based distribution, resulting in a time series of events identical to the original observed data set, but scaled or shifted using the CDFs of the GCM based distribution.
- 6) The output of the quantile mapping, a historic time series with GCM based climate distributions, is then compared to the original monthly historic time series with historic climate distributions. The differences in temperature and precipitation are computed as the difference in temperatures ( $dT$ ) and the quotient of the precipitations ( $dP$ ). The result is a full time series of monthly  $dT$  and  $dP$  values.
- 7) The monthly  $dT$ ,  $dP$  time series is then applied to the daily station level time series by adding the  $dT$  values to temperatures and multiplying daily precipitation by  $dP$ . The output of this step is a daily time series of temperature and precipitation that has the range of variability seen in the historic record, but also has the long-term climate properties of the GCM.

This procedure captures the climate change signal from the GCM with the shifts in the climate variable CDFs, while also creating an extended series that contains all of the extreme events in the observed record. The magnitude of these events is shifted to correspond with the altered climate signal from the GCM. The long-term climate trends from the GCM data are removed so that the station scale data set contains a long climatic sequence that is not complicated by the presence of an underlying trend. Instead, it is a steady-state approximation of the climate during a window of time that contains the full range of potential variability.

Many water resources planning and allocation decisions are based upon statistical metrics that are calculated using observed historic values. Calculating the shifts in these metrics requires examination the full range of potential variability. The process can be greatly complicated when using transient climate scenarios in which the rate of change is as great as or greater than the natural variability seen within the standard planning horizon. In these instances, the quasi-steady-state approach described above can provide a mechanism for examining the rate of change in a statistical metric that is defined by a return period greater than the interval at which it is being examined. For example, the change in magnitude of a 50-year flood event might be expected to occur over the next 25 years. As with the transient station scale approach, the quasi-steady-state station scale data set is useful when used with a high resolution hydrologic model.

### **Case Study: Impacts of Climate Change in the Sultan River Basin of Washington State**

The Sultan River is located in southern Snohomish County and is a part of the greater Snohomish River Basin. The Sultan River system is multi-purpose, providing both drinking water to the city of Everett, Washington, aquatic habitat for fish including the threatened Puget Sound Chinook Salmon, and hydroelectric power production for the Snohomish County Public

Utility District. Water destined for both power production and water supply is diverted from Spada Reservoir and piped to the Snohomish County PUD power station near the Sultan's confluence with the Skykomish River. A portion of that water is returned to Lake Chaplain for storage. Drinking water for the City of Everett is diverted from Lake Chaplain, and the remainder of the original diversion is returned to the Sultan River where it provides habitat for runs of Puget Sound Chinook Salmon and other anadromous fish species. Water from Lake Chaplain serves as a drinking water supply to nearly two-thirds of Snohomish County's population.

The watershed above Culmback Dam (which forms Spada reservoir) ranges from 440 to 1800 meters above sea level and receives, on average, over four meters of precipitation a year. The elevation range and proximity to the temperature moderating influence of the Pacific Ocean results in a transient rain and snow dominated hydrograph on the upper Sultan River. The upper portions of the basin receive the majority of their winter precipitation as snow, while rain falls nearly year round in the lower portions. This physical setting results in a characteristic, two peak hydrograph (Figure 9), where the winter peak is caused by the onset of the wet season that brings heavy fall rains to the lower basin and rain on snow at the upper elevations. The spring peak is caused by the melting of that snow. The impacts of climate change over the next 100 years are likely to significantly alter the hydrologic regime of the Sultan River. These hydrologic changes will effect hydropower operations and the ability to provide water for municipal and industrial supply. Given the likely impacts of climate change, and the history and complexity of the established systems, an assessment approach that incorporates future climate projections but presents that information in the same format and manner as used in the traditional planning process is needed

## Hydrologic modeling

The principal goal of the hydrologic modeling associated with this research is to provide a tool for investigating how climate model based changes in the meteorological data will affect long-term statistics of hydrologic variables. A hydrologic model that contains explicit spatial representations of watershed conditions, and simulates the flow of water using realistic physical relationships while minimizing lumped parametric rainfall-runoff relationships is appropriate for this purpose. The hydrologic model selected for this purpose is the Distributed Hydrology Soil Vegetation Model (DHSVM), originally developed in the early 1990s at the University of Washington. The physical representations of this model are described by Wigmosta et al. (1994, 1999). DHSVM is a regional-scale hydrologic model that can recognize spatial heterogeneity in a watershed and is intended for small to moderate drainage areas (typically less than about 10,000 km<sup>2</sup>), over which digital topographic data allows explicit representation of surface and subsurface flows. DHSVM has been used for stream flow forecasting and for addressing hydrologic effects of land management or of climate change. The model has been applied on several basins in the Pacific Northwest (Bowling et al., 2000; VanShaar et al. 2002; Schnorbus and Alila 2004).

## Data Sources

The physical basis of the DHSVM model relies on the daily fluctuations of incoming and outgoing radiation to perform the energy balances critical to proper simulation of snow melt driven systems. Therefore, it is necessary to operate the model at a sub-daily time step. The time-step used for this research is three hours. Meteorological data are available at a daily time step and are disaggregated to produce the appropriate input files for DHSVM. The application of DHSVM requires seven meteorological inputs at each time step: air temperature (°C), wind

speed (m/s), relative humidity (%), incoming shortwave radiation ( $W/m^2$ ), outgoing longwave radiation ( $W/m^2$ ), and precipitation (m/time step). These values are derived based on available data, including: minimum daily temperature, maximum daily temperature, total daily precipitation, station elevation, the geographic locations of the station, and at least one nearby wind record using the approach described by Waichler and Wigmosta (2003). The DHSVM representation of the Sultan River uses as forcing data daily temperature and precipitation records from five National Weather Service Cooperative Observation stations given in Table 1.

The climate change scenario chosen for this analysis is taken from the ECHAM5 General Circulation Model, run using the SRES A2 future atmospheric emissions scenario. The ECHAM5 model is based on a weather prediction model developed by the European Center for Medium Range Weather Forecasts, the details of this Climate model are given in Roeckner et al. (2003). The SRES A2 scenario describes the development of a heterogeneous, insular and fragmented global population with greater regional disparities in fertility, economic development, and technological advancement. Overall there is a greater increase in global population. Energy sources are not globally uniform, resulting in some regions with high carbon emissions and other with low carbon emissions (SRES, 2000)

This case study is an example application of the Quasi-Steady-State Downscaled Station Data. This approach allows for the creation of projected, future, climate altered stream flow sequences that contain the full range of observed historic variability. The initial data acquisition and processing of the ECHAM5-A2 climate scenario from the global scale to the PNW regional scale and the summary statistics from that analysis are described by Mote et al. (2005). The ECHAM5-A2 is then downscaled according to the process described above, and used to force the DHSVM hydrology model. Four periods of investigation are considered, each based on a

31-year period from the transient, ECHAM5 simulation of the 21<sup>st</sup> century. The four periods of investigation are centered on the years 2000, 2025, 2050, and 2075.

## Results

The downscaled station data shows consistent patterns of shifting temperatures and monthly precipitation totals as is expected from the broad scale climate patterns simulated by the ECHAM5 model. The magnitude of the shifts at each location and in each month varies based on the historic station characteristics. The five stations show an average rate of change for annual temperature between 0.4 and 0.5 °C per decade. This rate is at the upper end of the range projected for global average temperature increases over the 21<sup>st</sup> century (IPCC 2001).

Precipitation at all stations has modest decreases in November, December, and May, increase in January, April, August, September and October, and remain approximately the same in February, March, and July.

Using the downscaled scenarios as input to the hydrology model yields a set of 75-year stream flow sequences, each representative of the potential range of flows in each climate period. The average annual hydrograph from each period of analysis is shown in (Figure 8). Each 75-year streamflow sequence is then analyzed using the same statistical tests and metrics that are traditionally used to examine the historic record. For example, a series of flow duration curves can be generated and overlaid in order to present the impacts of climate change on streamflow variability. For low flows, a concern for water quality or aquatic habitat reasons, the commonly used metric of 7Q10 flow can be applied to the data set. The 7Q10 flow is the average streamflow that occurs over 7 consecutive days and has a 10-year recurrence interval period. Daily streamflows in the 7Q10 range are used as general indicators of drought conditions and are often for regulating water withdrawals and discharges into streams. For this case study, we

have generated a family of flow duration curves as well as computed the trends in both high and low 7Q10 flows, for the South Fork of the Sultan River, at the location of USGS gaging station #12137290.

The family of flow duration curves (Figure 9) indicates the projected impacts of climate change on the South Fork of the Sultan River have the greatest impact at the low flow end of the curve. The total amount of flow at this gaging point is shown to decline consistently with each successive future period. There are relatively small changes seen in the frequency of either the extreme low or high flows, however, low flow conditions are projected to occur for an increasing fraction of time. Using the flow time series based on the historic climate, the 7Q10 flow at this location is calculated to be  $0.07 \text{ m}^3/\text{s}$  ( $2.6 \text{ ft}^3/\text{s}$ ). Under the ECHAM5-year 2000 scenario, the  $0.07 \text{ m}^3/\text{s}$  flow is projected to be exceeded 98.2% of the time. The percent of time exceeded at this flow level declines to 97.9%, 96.6%, and 94.1% under the year 2025, 2050, and 2075 scenarios respectively. This implies a low flow condition that occurs only 1.8% of the time with year 2000 climate can be expected to be occur as much as 5.9% of the time within the next 75 years.

The 75-year streamflow scenario of each period of analysis can be used to derive a probability distribution for a selected metric or flow. Trends or rates of change in the selected metric can then be projected. The annual minimum and maximum 7-day average flow for each period of analysis were extracted and the minimum, 25<sup>th</sup> percentile, median, 75<sup>th</sup> percentile, and maximum values were then computed(Figure 10). The range of variability, as measured qualitatively by the size of the boxes and the extent of the whiskers in Figure 10, appears to decline for low flows and remain consistent for high flows. Looking at the median values for each period of analysis, we calculate a rate of change of the median annual 7-day low flow of

approximately -1.4% per decade, and a rate of change for the median annual 7-day high flow of approximately +2.6% per decade.

## **Conclusions**

Changes in climate are unlikely to occur as a uniform shift in values. Mearns et al. (1984) found by examining historic climate records at several sites in the midwestern U.S. that the relationship between shifts in mean temperature and shifts in the probabilities of extreme events is highly non-linear. Because of this fact, it is unreasonable to expect impact assessments that rely only on changes in the means of climate variables to fully describe the range of potential impacts (Gleick 1989). Examining shifts in average values via the delta method remains an often used technique for impact assessment, and does provide a reasonable approximation of the general trend of climate change impacts. However, an expansion upon the delta method that allows for differential shifts in climate variables at different probabilities has been proposed as a downscaling approach that maintains the computational efficiency of the delta method while allowing for different rates of change at the extremes of the climate distribution. The proposed method is shown to be effective for spatial downscaling of climate data from the global to the point scale. This method captures both the shifts in the monthly climate means simulated by GCMs as well as the shifts in probability of extreme events.

If we accept that our climate is changing, the examination of climate change impacts to water resources must be targeted to specific future periods. The transient nature of climate, as simulated by global climate models, makes system impact assessment difficult due to the combined effects of a constantly shifting underlying climate trend and large year-to-year variability. System impacts are best described using a long time series that incorporates the full range of potential variability, but that also represents a steady state approximation of climate as

defined for a chosen future period. A method for developing an expanded time series that contains the range of historic observed variability and a steady state representation of future climate at the targeted assessment period has been developed. The quantile mapping process used with an expanded historic time series reproduces the desired statistics of the target time period while providing the length and variability of record needed for most system reliability assessments. The proposed method is most appropriate for application to a water resources evaluation, where natural variability can strongly affect system performance and when small changes in extreme events can have a much larger impact than changes in the long-term means.

The case study reveals how the proposed method for developing climate scenarios can be used to quantify the shifts in climatologic and hydrologic statistics at a chosen future point. Multiple applications of the process at successive future intervals can be used to approximate the rate of change in these variables caused by future climate change. For example, the median annual 7-day low flow on the Sultan River is projected to decrease at a rate of approximately 1.4% per decade, based on the ECHAM5-A2 climate model. The uncertainty present in the downscaling process is not insignificant and cannot be ignored; however, it is not so great that it completely obscures the valuable information that can be obtained from climate simulations. Downscaling currently represents the best available method for assessing the potential impacts of climate change on local scale water resource systems. All water resource management must incorporate uncertainties; the uncertainty caused by the downscaling process is less than that which must be considered every year due to natural variability regardless of climate change considerations. The results presented in this research represent a single future climate scenario. A greater understanding of the uncertainty associated with this type of impact assessment could be gained by repeating the process presented here with multiple future climate simulations.

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Table 1 - Selection of Puget Sound Region weather stations and 1930-2004 climate statistics

COOP NO	Station Name	Location	Elevation	Period of record	Avg. Ann. Temp	Avg Total Precp
451992	DARRINGTON	48°15'36"N -121°36'13"E	168m	December 1911 to present	9.5°C	217cm
452675	EVERETT	47°58'34"N -122°11'42"E	18m	August 1894 to present	10.4°C	92 cm
455525	MONROE	47°50'43"N -121°59'04"E	37m	February 1929 to present	10.7°C	120cm
457773	SNOQUALMIE FALLS	47°32'33"N -121°50'11"E	134m	October 1898 to present	10.2°C	154cm
458034	STARTUP	47°51'59"N -121°43'03"E	52m	January 1924 to present	10.7°C	165cm

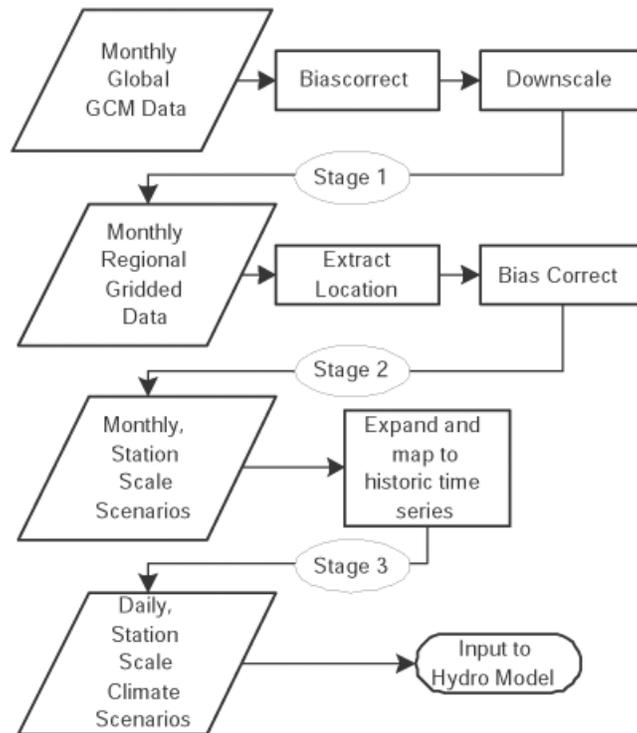


Figure 1. Process flow for downscaling and climate scenario development.

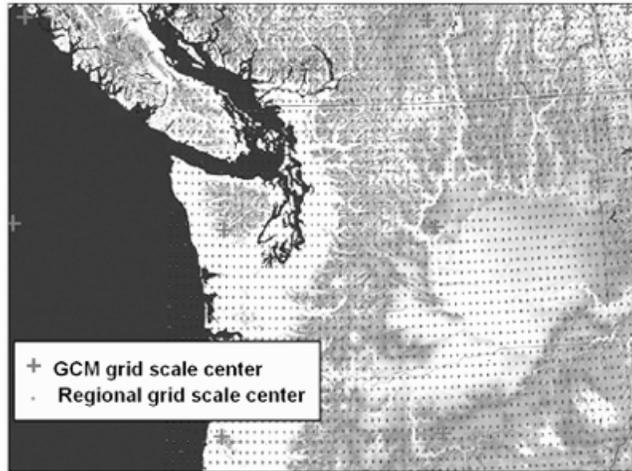


Figure 2: Global and Regional scale grid points over Washington State.

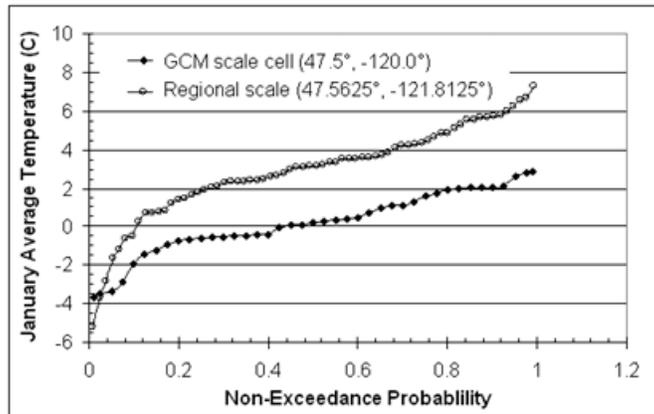


Figure 3: Quantile Map relating January temperatures for one GCM and Regional cell pair.

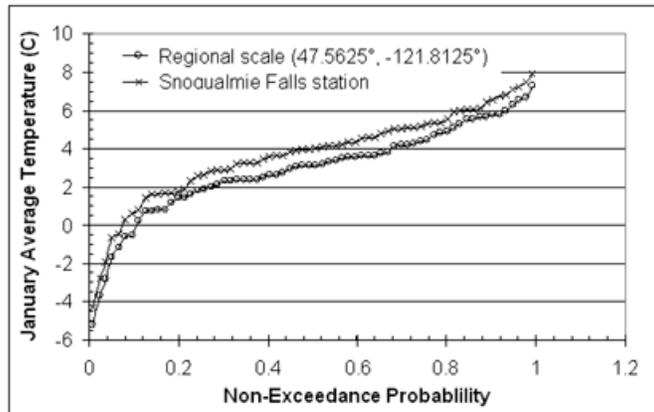


Figure 4: Quantile Map relationship between Regional scale grid cell and Station Scale data.

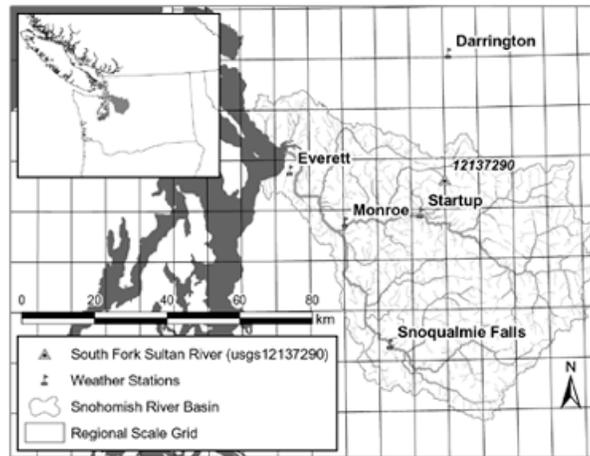


Figure 5: Regional Scale grid and individual station locations.

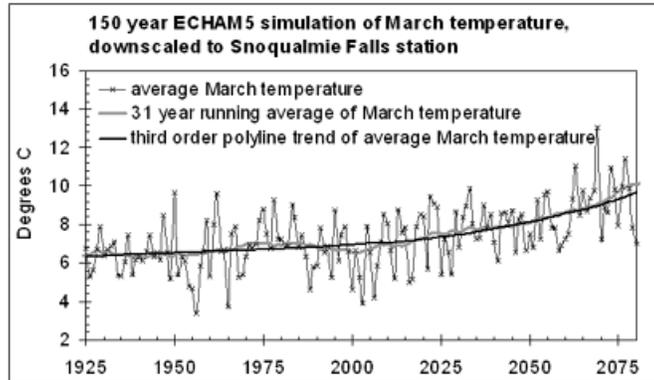


Figure 6: 150 years of average March temperatures as simulated by the ECHAM5 model and downscaled to the Snoqualmie Falls weather station. The rolling 31 year average demonstrates how a series of steady state averages can be used to closely approximate the long-term trend of the transient time series.

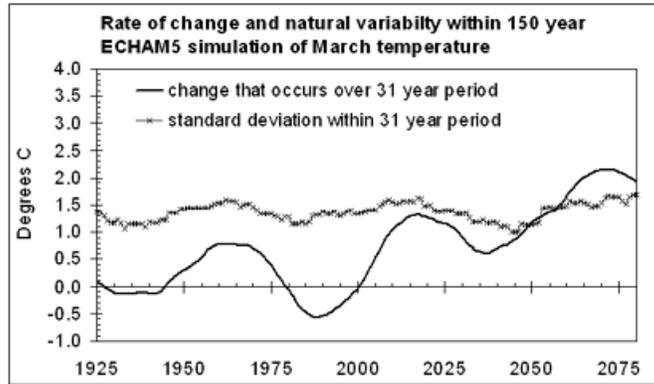


Figure 7: Rate of climate change versus magnitude of natural variability within a 150 year, ECHAM5 simulation of March temperature, downscaled to the Snoqualmie Falls station.

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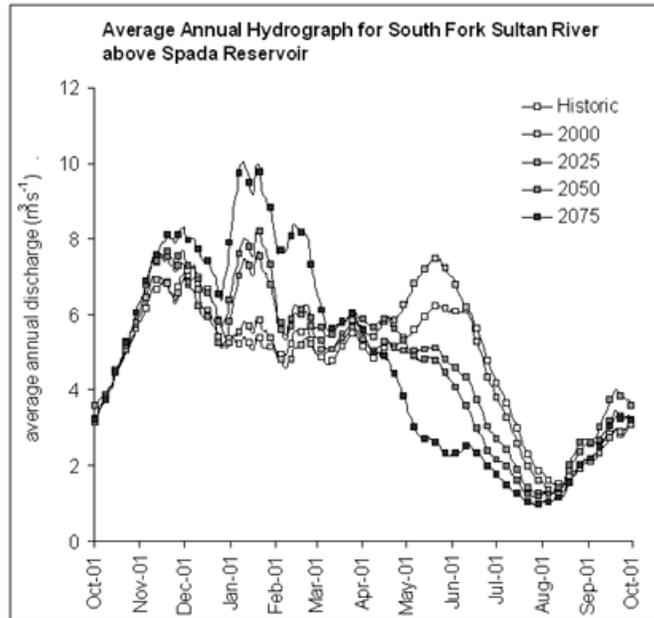


Figure 8: Simulated average annual hydrographs from historic climate and future climate scenarios.

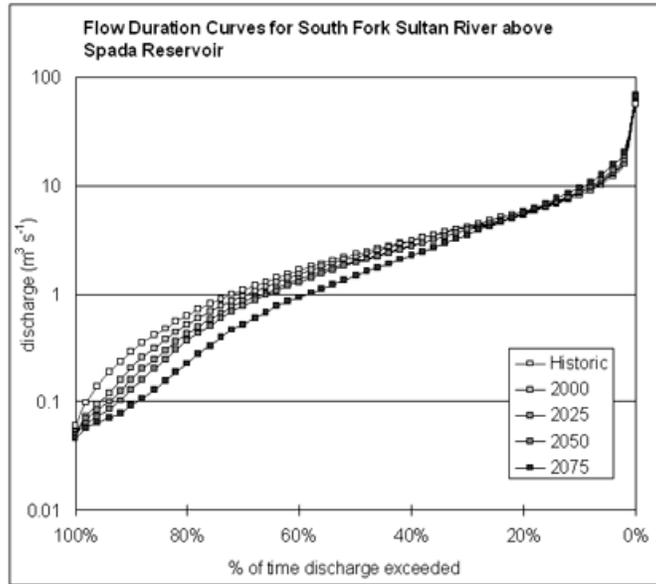


Figure 9: Flow duration curves from historic climate and future climate scenarios.

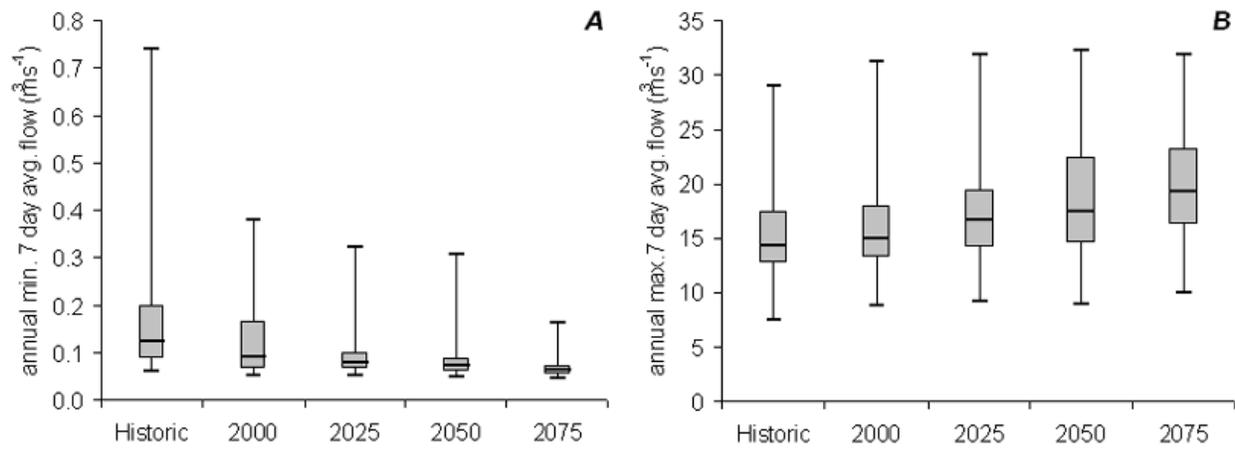


Figure 10: Annual minimum (panel A) and maximum (panel B) seven day average flow from historic climate and future climate scenarios.