

# Climate Downscaling for Adaptation Planning in the Souris River Watershed

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## 1. Introduction and Background

During a special session of the Canada Water Resources Association meeting in 2022, Commissioner Beland of the IJC emphasized the importance for the United States and Canada to jointly develop bias corrected and downscaled climate scenarios that transcend the geographical boundaries of the two countries. Global Climate Model (GCM) outputs are often in need of bias correction. Several bias correcting techniques exist. The basic assumption in most techniques is that the underlying process (or time series) is stationary. Therefore, techniques like Quantile Delta Mapping (QDM), which account for the non-stationary biases and preserve the climate change signal in the bias-corrected simulations, might offer a more appropriate choice. Nevertheless, many issues remain unresolved. For instance, most techniques tend to overlook non-stationarity in the observation time series, resulting in an inconsistent representation of the corrected process at coarser scales. This project addressed the methodological weaknesses in the bias-correction of the GCM outputs.

In collaboration with the University of Calgary and the University of Saskatchewan through the Cooperative Institute for Research to Operations in Hydrology (CIROH), investigators at the University of Hawai‘i at Mānoa and The University of Alabama produced downscaled projections of precipitation, maximum and minimum temperature, and other meteorological variables using the Semi-Parametric Quantile Mapping (SPQM), a downscaling method that preserves the statistical attributes of observations and projected climate change signals in terms of trends and variability. Other important forcing variables (e.g., humidity, radiation, and pressure) are disaggregated using the MetSim system, a meteorological simulator and forcing disaggregator for hydrologic modeling and climate adaptations. The project produced reliable and robust downscaled climate scenarios for the Souris River Basin (both US and Canadian parts) at a 10 km resolution that complement the limited suite of available downscaling products.

## 2. Methodology

### 2.1. Bias Correction and Downscaling

The Canadian researchers incorporated observational uncertainty and trends in the analysis of the Coupled Model Intercomparison Project phase 6 (CMIP6) data. A semi-parametric quantile mapping (SPQM) method was used to bias-correct the downscaled dataset, which includes four major steps: (a) fit a parametric distribution to the observations (b) calculate the empirical probabilities of the simulations, and (c) transform the empirical probabilities to precipitation values following the fitted parametric distribution, (d) apply the previous three steps for each month. A flow chart describing the implementation of SPQM is provided in Figure 1. Bias corrected and downscaled data are available on the Narval server ([narval.computeCanada.ca](http://narval.computeCanada.ca)) and will be made available upon request.

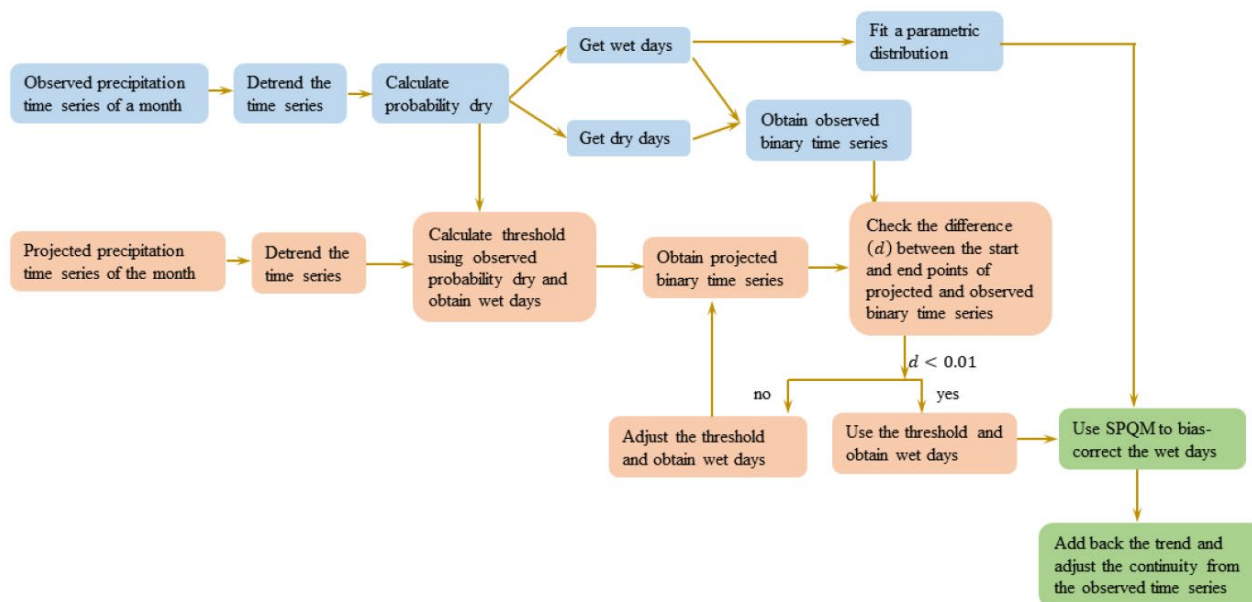


Figure 1: Flow chart describing the implementation of Semi Parametric Quantile Mapping (SPQM) for precipitation bias correction (Rajulapati and Papalexiou, 2023)

### 2.2. MetSim Disaggregation

MetSim was employed to generate spatially distributed sub-daily time series datasets that encompass key variables that are necessary for hydrologic modeling, including incoming

shortwave radiation, outgoing longwave radiation, relative humidity, vapor pressure, precipitation, and air temperature.

The MetSim software requires three essential input files: the domain file, state file, and forcing files (Bennett et al. 2019). The domain file contains crucial information regarding the spatial scope of the simulation, including elevation data for each grid and a mask variable that defines cells to be run. The state file captures daily records of minimum and maximum temperatures, along with precipitation, for the 90-day period leading up to the simulation start date (January 1, 2015, to March 31, 2015). This historical dataset is instrumental in calculating seasonal averages for both the daily precipitation and the daily temperature range. The forcing files encompass daily minimum and maximum temperature values, as well as precipitation data, for each designated grid cell in the model domain. This forcing data spans from April 1, 2015, to December 31, 2100.

### 2.3. Model Subsets

A list of 12 Global Circulation Models (GCMs) was selected to produce the bias corrected and downscaled data. Each model listed here includes a complete set of three climate change scenarios (ssp245, ssp370, ssp585) to be considered, all utilizing consistent realization/forcing. The selected 12 models are listed in the following table:

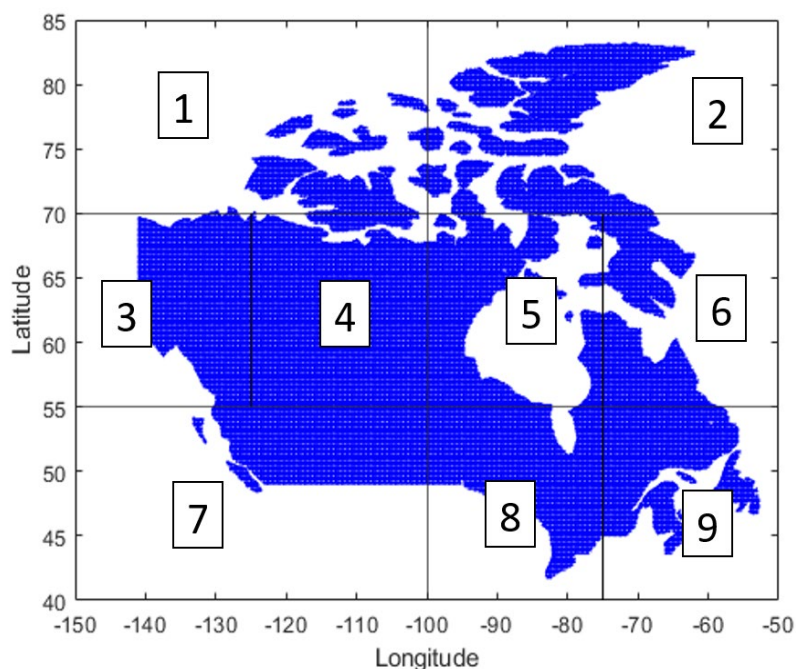
Table 1: The selected CMIP6 climate models and their variant labels

Model	Variant label	Model	Variant label
CanESM5	r1i1p2f1	MIROC6	r1i1p1f1
GFDL-ESM4	r1i1p1f1	IPSL-CM6A-LR	r3i1p1f1
FGOALS-g3	r2i1p1f1	CNRM-ESM2-1	r1i1p1f2
INM-CM5-0	r1i1p1f1	MPI-ESM1-2-HR	r1i1p1f1
CMCC-ESM2	r1i1p1f1	EC-Earth3-Veg	r1i1p1f1
CESM2	r4i1p1f1	ACCESS-CM2	r2i1p1f1

The selection of these CMIP6 GCMs was based on the recommendations provided in the Tables for Canada and its sub-regions, which are outlined in the accompanying map (see Figure 2). For more comprehensive insight into the GCM selection methodology, please

refer to the project report titled "Downscaled CMIP6 Climate Model Subset Selection (PCIC, 2023)." It is important to note that certain GCMs were excluded due to factors such as data availability, completeness, and quality.

The three SSP scenarios (Shared Socioeconomic Pathways) are as follows: SSP245 updates the CMIP5 scenario RCP4.5 with an additional radiative forcing of  $4.5 \text{ W/m}^2$  by the year 2100, which represents the middle of the road for future greenhouse gas emissions. This scenario assumes that there will be medium challenges to mitigation and adaptation. SSP370 refers to forcing with  $7 \text{ W/m}^2$  by the year 2100, which is in the medium to high range of the future forcing pathways. SSP585 corresponds to an additional radiative forcing of  $8.5 \text{ W/m}^2$  by the year 2100 and represents the high boundary of the range of future pathways as described in the literature (Riahi et al., 2017; O'Neill et al., 2016).



*Figure 2: Map showing sub-regions in Canada used in the bias-correction and downscaling of CMIP6 climate change projections.*

#### **2.4. Data Storage, Dissemination, Public Repository**

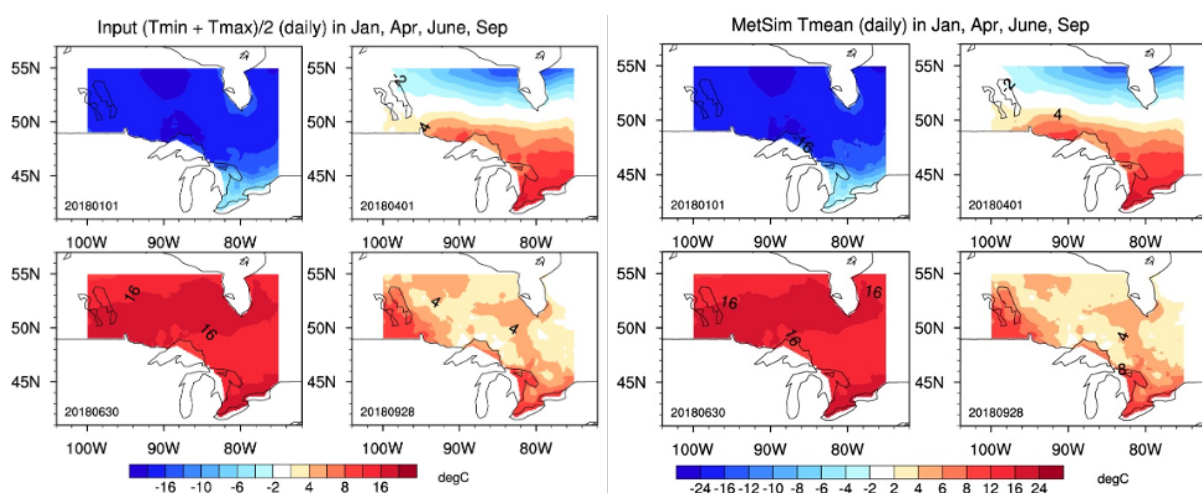
The deliverables are stored on the Graham server of Compute Canada ([graham.computecanada.ca](http://graham.computecanada.ca)). The data will be made available upon request.

### 3. Results

#### 3.1. Reasonableness check

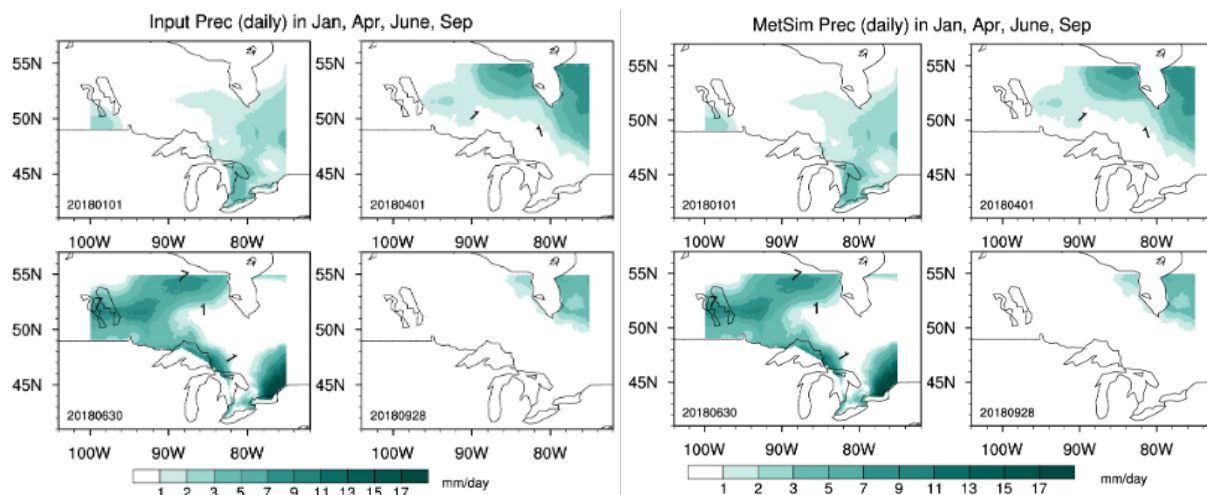
We conducted a data reasonableness (QA/QC) check to ensure the consistency between the input data and the disaggregated outcomes. This reasonableness (QA/QC) check encompassed both assessing consistency and verifying adherence to common physical laws.

Figure 3 displays the daily mean temperature derived from bias-corrected downscaling data in the left panel, while the reconstructed daily temperatures for the same four days are presented in the corresponding right panel. The daily mean temperature output matches the daily mean temperature from the input data (with the spatial correlation coefficients over 0.99), where the mean temperature is estimated as the average of the minimum (Tmin) and maximum (Tmax) temperatures (Figure 2).



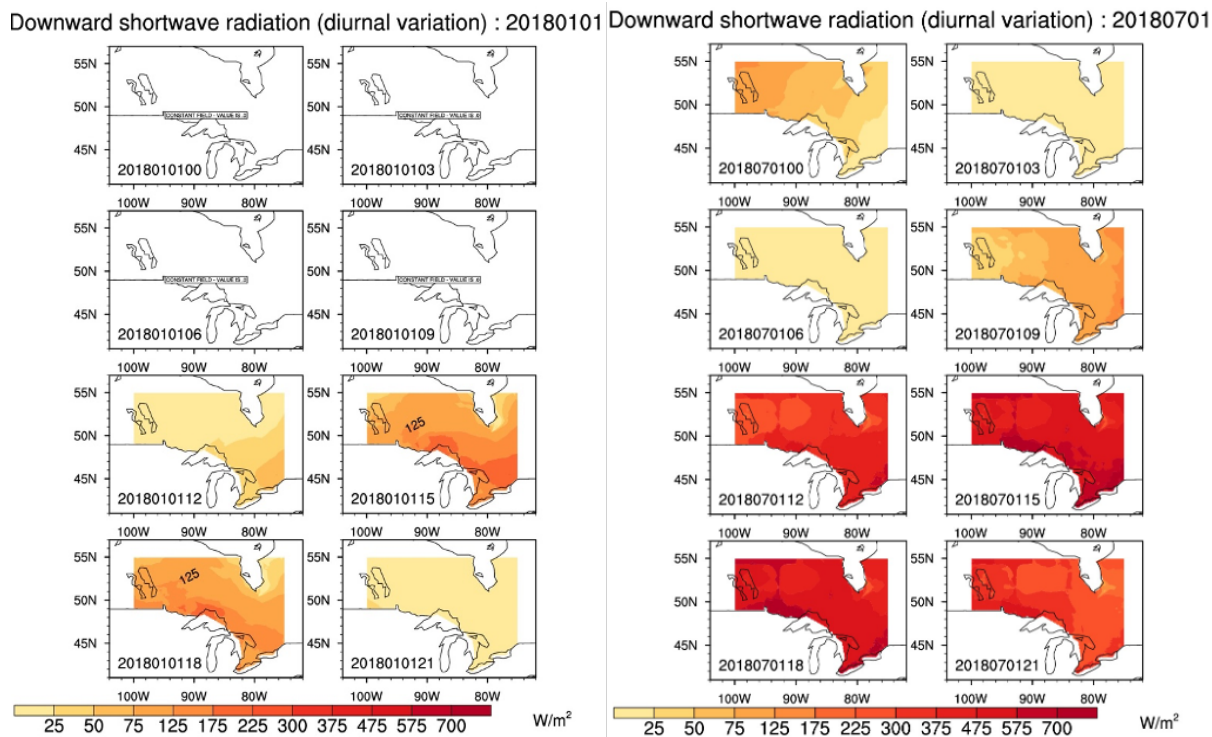
**Figure 3.** Comparison of daily mean temperature estimated by averaging Tmin and Tmax from the input data (left panel) and the daily mean temperature resulting from disaggregation (right panel) on January 1, April 30, June 30, and September 28, 2018. The data is from the CanESM5 (r11i1p2f1) model.

Similar scrutiny was extended to precipitation data (Figure 4), revealing a congruent spatial distribution between the input and output datasets.



**Figure 4.** Comparison of daily precipitation from the input data (left panel) and the daily precipitation resulting from disaggregation (right panel) on January 1, April 30, June 30, and September 28, 2018. The data is from the CanESM5 (r11i1p2f1) model.

Additionally, we examined the diurnal cycle of downward shortwave radiation during both summer and winter (Figure 5). The experiment successfully replicates the diurnal cycle, with minimal radiation in the evening and peak values around the midday period. Concurrently, the model captures the seasonal fluctuations, reflecting longer daylight hours in summer compared to the shorter daylight duration in winter.



**Figure 5.** Comparison of downward shortwave radiation during the summer and winter seasons. Diurnal cycle of shortwave radiation on January 1, 2018 (left panel) and July 1, 2018 (right panel). Shortwave radiation at 3-hour interval from the disaggregation output (00, 03, 06, 09, 12, 15, 18, 21 UTC ) are presented in each panel.

### 3.2. Challenges encountered and solutions developed

#### a. The Issue of One-Day Shift:

We found that there is a one-day (24-hour) shift between the input data and the MetSim output. The output data consistently shows a one-day delay compared to the input data. Upon investigation, we have verified that the one-day shift issue is attributed to an oversight in the MetSim code's handling of longitude offsets. Specifically, it did not adequately process cases where the input data's longitude range spans [0-360]. MetSim mandates longitudes to be confined within the range of [-180, 180]. To address the one-day shift issue, we have made necessary modifications to the MetSim code and validated their accuracy.

## b. Local Time-based Input Data:

MetSim requires input data to be structured around local time, given that all disaggregation activities are performed locally. However, the bias-corrected CMIP6 downscaled data are all UTC-time based.

In our specific case, the Souris River Basin is within the UTC-5/6 time zone. Typically, T<sub>min</sub> occurs locally at 2-3 am, while T<sub>max</sub> occurs at 2-3 pm. These local times correspond to T<sub>min</sub> at 8-9 UTC and T<sub>max</sub> at 20-21 UTC. This was verified by checking the temperature diurnal cycle within the designated domain. Consequently, a 5–6-hour time zone shift would still yield consistent T<sub>min</sub>/T<sub>max</sub> values whether evaluated within a local day or a UTC-day. The UTC-time based daily T<sub>min</sub>/T<sub>max</sub> values can be seamlessly integrated into MetSim for the SRB.

In terms of precipitation, MetSim employs a straightforward distribution approach, allocating daily total rainfall uniformly across 8 sub-daily time steps. This allocation process does not exert any influence on other variables. Therefore, we determined that no modifications were necessary for precipitation. We decided to turn off the UTC-time shift for precipitation.

### 3.3. Summary of results

Sub-daily meteorological data were estimated through a temporal disaggregation procedure, resulting in output data consisting of precipitation, minimum and maximum temperature, specific humidity, incoming solar radiation, incoming shortwave radiation, and barometric pressure with a time step interval of three hours. This disaggregation process was implemented for two specific regions within the broader coverage of 9 subregions across North America (see the map in Appendix 1). The chosen regions, denoted as region #7 and #8, encompass the Souris River Basin. The disaggregation was executed for three distinct climate change scenarios (SSP245, SSP370, SSP585) across data obtained from 12 GCMs, which have undergone bias correction and downscaling using the SPQM downscaling method.

## 4. Conclusions

We generated sub-daily output data from 12 GCMs across three scenarios, spanning the timeframe from 2015 to 2100. This comprehensive dataset covers the Souris River Basin region both in Canada and the US. Correctness and reasonableness (QA/QC) checks were applied with a focus on both assessing consistency and verifying adherence to the common physical laws. The data is available upon request.

## 5. Limitations

### - Temporal variability

The approach used for precipitation disaggregation is referred to as "uniform." This means that the precipitation pattern remains consistent at each disaggregated time step throughout a given calendar day. As a result, there is no variation in rainfall within a single day.

### - Selected GCMs

The disaggregated data was generated using MetSim for the selected 12 GCMs. The selection of GCMs was based on the report from Pacific Climate Impacts Consortium (PCIC) and can be extended to provide region-specific selections. However, the workflow we used in this project to disaggregate bias-corrected and downscaled data can be applied to any GCMs.

## 6. Next Steps

The next steps are to produce a bias-corrected, downscaled, and disaggregated set of atmospheric inputs to hydrologic models for a historical time period. This next step is needed to provide a complete historical and future bias-corrected, downscaled, and disaggregated suite of atmospheric inputs for use in climate adaptation and resilience planning. Additionally, there is need to investigate the reliability of several bias corrected and downscaled data products and evaluate their suitability for use in climate adaptation and resilience planning.

## 7. References

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