Response of hydrological systems to statistically downscaled GCM output in the northern Manitoba (Canada) boreal forest region

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Abstract

This study investigated how river basins would respond to climate scenarios generated from different GCM's (HadCM3 and CGCM3) in the northern Manitoba boreal forest region. The SLURP hydrological model was applied to the Taylor and the Burntwood River basins using climate scenarios generated with the output from the GCM's under the A1B, A2 and B1 SRES scenarios. The GCM output was downscaled using the delta method and the Statistical DownScaling Model (SDSM). The GCMs consistently forecast wetter and warmer climate with the emission scenarios. Warming is most prominent during winter, especially with CGCM3 under the A2 scenario. Precipitation projections reveal more variability between models and scenarios than temperature projections, but a general trend is that large increases are expected during winter and spring and only small fluctuations during summer and autumn. Such changes in climate are projected to lead to an overall increase in runoff in late 21st century. The increase is most remarkable in April and May and the least so in the winter months. For the same emission scenario and GCM, the delta method results in a larger runoff increase than SDSM. For the same GCM and downscaling, the A1B scenario results in a larger runoff increase than other SRES scenarios. In spite of different magnitudes, the direction of change is consistent between models and scenarios. The results indicate that the communities in the region need to be better prepared for spring floods while the increased runoff may contribute to more hydroelectric power generation. [Keywords: climate change; GCM; statistical downscaling; water resources; hydrological modelling]

1. Introduction

Global warming is projected to influence almost every aspect of physical and ecological systems and thus human life. Most global climate models (GCM's) project more severe warming into the future in high latitude regions than in low latitude regions. As a high-latitude country, Canada is likely to face formidable challenges from the impacts of global warming on water resources, ecosystem, economy, etc. We pay attention particularly to the impacts on water resources in the Province of Manitoba. Large rivers such as the Nelson River and the Churchill River flow through Manitoba and provide vast amount of hydropower. Impending climate change will affect the river flow and thus the energy generated from it.

This study aims to quantitatively assess the impact of climate change on the hydrological system in the northern Manitoba boreal forest region. Specific goals are (1) to investigate the response of the hydrological system to GCM-based climate scenarios through hydrological modelling and (2) to intercompare the results from different statistical downscaling techniques and greenhouse gas emission scenarios. In spite of the abundance in the literature on hydrological modelling with GCM-based climate scenarios, there is no published research conducted for Manitoba. The utility of statistical downscaling and the sensitivity of hydrological systems to climate scenarios will not be the same across the globe and this study aimed to provide some insight for a boreal forest region.

2. Study area

Two river basins in the Nelson River basins were selected for the case study: the Taylor and the Burntwood River basins. The Nelson River basin is home to not only a number of First Nations communities but also several hydropower generating stations of Manitoba Hydro. The two river basins were selected primarily to build this study on existing ones (e.g. St. Laurent and Valeo, 2007; Kim et al., 2007). The location of the basins is shown in Figure 1.

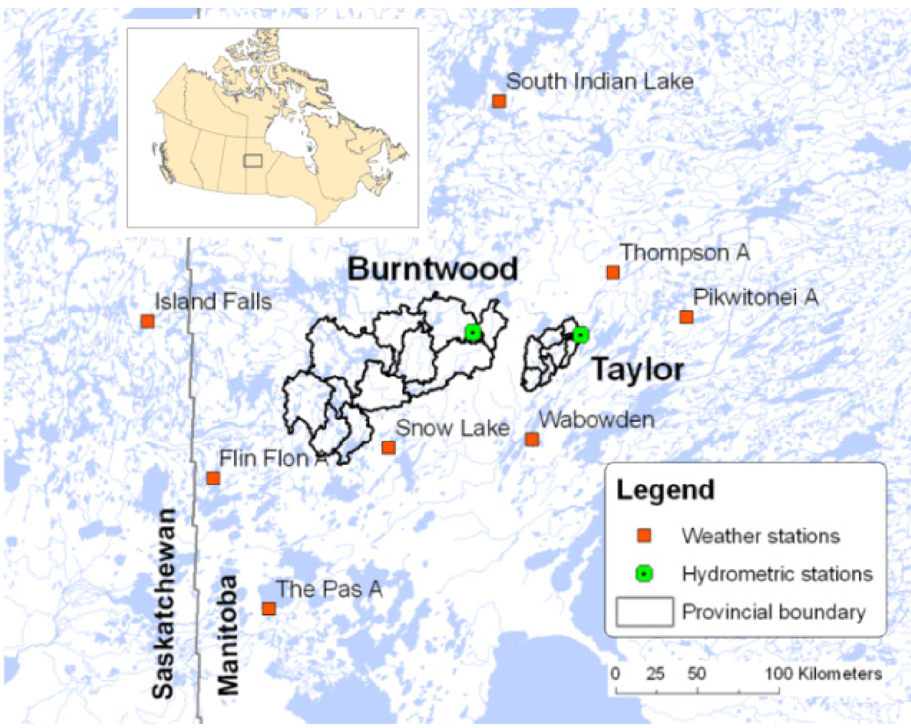

Figure 1. Study area: river basins, water bodies, weather and hydrometric stations, and provincial boundary along with a reference map of Canada.

The climate of the study region is characterized by long and cold winters and short summers. In The Pas, average daily temperature measured at the Environment Canada weather station is 17.7°C in July and below zero from November through March during the period 1971-2000. Mean annual precipitation during the same period is 443mm of which 44% occurs in June, July and August and 119mmfalls as snow (155cm).

3. Hydrological model

We chose the hydrological model SLURP (Kite, 2000) to simulate the hydrology of the selected river basins. SLURP requires four daily meteorological data sets: mean temperature, total precipitation, relative humidity, and bright sunshine hours or solar radiation. Using the data sets as input, SLURP simulates the vertical water balance (Figure 2) on each land cover type in each aggregated simulation area (ASA), which is delineated based on topography by a geographic information system. Water from each ASA is routed to downstream ASA's and eventually exits the system. The SLURP model was slightly modified by St. Laurent and Valeo (2007) to improve the snowmelt simulation. We used the SLURP model modified and calibrated by St. Laurent and Valeo (2007). The Burntwood River basin was divided into 11 ASA's and the Taylor River basin into seven ASA's, as can be seen in Figure 1.

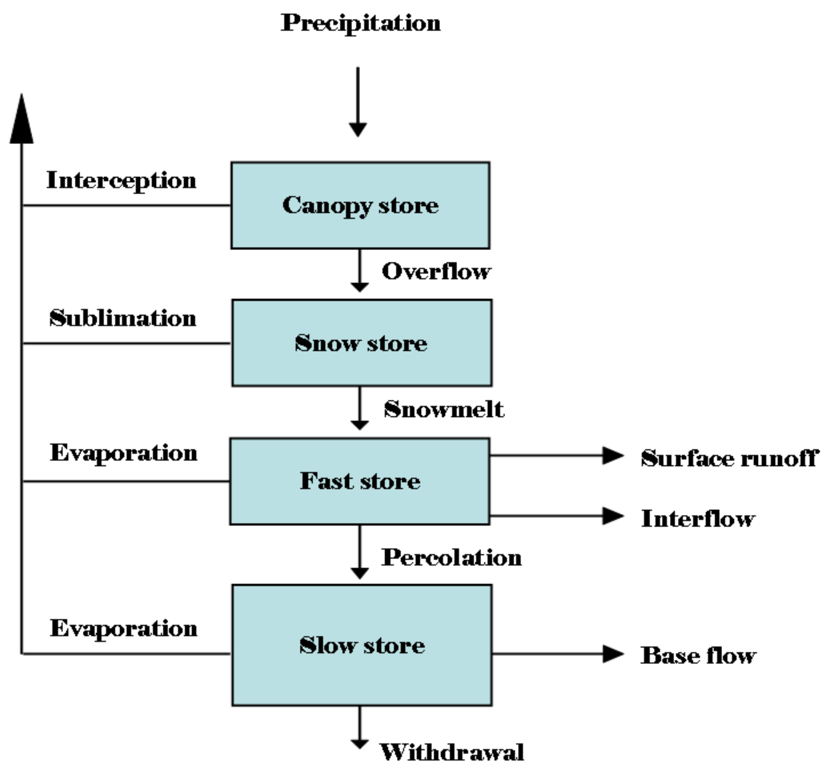

Figure 2. SLURP vertical water balance (Kite, 2000).

St. Laurent and Valeo (2007) validated the SLURP model for the period 1985-2000. As a result, the mean relative error was under 2% for both river basins, and the Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970) for daily streamflow was 0.63 (Taylor) and 0.47 (Burntwood), respectively. Figure 3 shows quantile-quantile (Q-Q) plots of the observed and simulated daily streamflow during the validation period. The red line connects first and third quartiles of the data. For Taylor, the slope of the line is almost 45°, meaning the first and the third qurtiles are well simulated. However, flows at high percentiles are generally underestimated. For Burntwood, the slope is well below 45°, meaning the third quartile is underestimated. The SLURP model is rather better for flows with high percentiles even though they are well off the line. Overall, the distribution of the observed and simulated flows are fairly idential for low and medium quantiles.

4. Experimental design

The overall procedure for the study can be summarized as follows: (1) running SLURP for the reference period ('control run'), (2) developing climate scenarios, (3) running SLURP for future periods ('scenario run'), and (4) comparing the results between the control run and the scenario run.

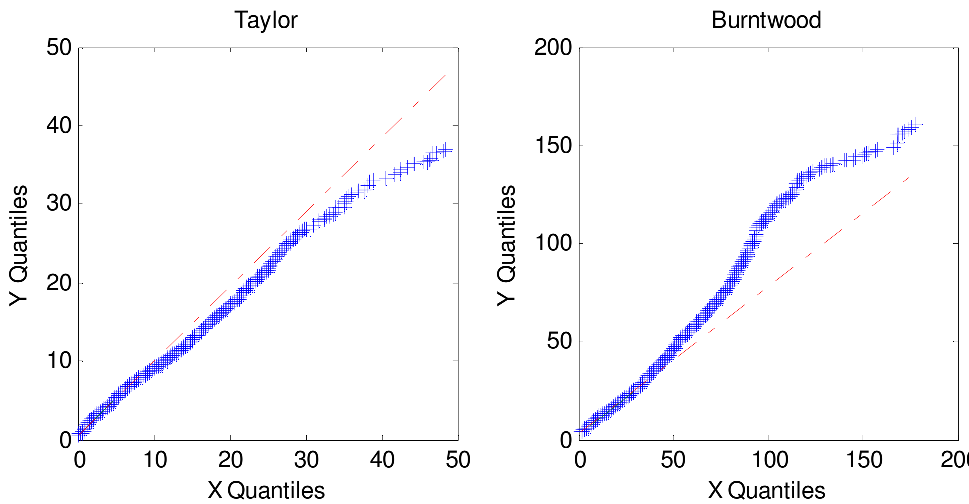

Figure 3. Quantile-quantile plot of the observed (X) and simulated (Y) daily streamflow (in m^3s^{-1}) during the SLURP validation period. The line joins the first and third quartiles of each distribution.

The control run was conducted with the validated SLURP model for the period 1971-2000. Two types of control runs were conducted. The first type was to run SLURP with the meteorological input data obtained from several Environment Canada weather stations around the basins (Figure 1). Available weather data from the stations were interpolated to the centroid of each basin with inverse distance weighting. The second type was to run SLURP with the meteorological input data obtained from a GCM. The Canadian GCM (CGCM3) daily output was obtained from the Canadian Centre for Climate Modelling and Analysis (CCCma) website (http://www.cccma.ec.gc.ca/data/cgcm3/cgcm3.shtml) and downscaled by the Statistical DownScaling Model (SDSM) (Wilby et al., 2002), which is primarily based on regression models between large-scale circulation variables (predictors) and local-scale surface variables (predictands). SDSM was implemented for The Pas and Thompson. The results from SDSM represented as mean annual temperature and precipitation during 1971-2000 are presented in Table 1 for comparison with the corresponding weather station data. SDSM slightly underestimates precipitation, but the difference in the mean is not statistically significant at the 95% confidence level.

Table 1. Mean annual temperature and precipitation from weather stations and SDSM-downscaled GCM, 1971-2000.

	Mean annual temperature (°C)		Mean annual precipitation (mm)	
	Station	GCM	Station	GCM
The Pas	0.19	0.18	443	422
Thompson	–3.18	–2.91	517	500

The results from the control runs are presented in Table 2. Mean annual runoff from the control run with the downscaled GCM data is significantly different from that with the station data at the 5% significance level, even though SDSM-derived mean annual precipitation is not significantly different from the station data. The primary reason is believed to be the fact that SDSM resulted in a number of wet days with minute precipitation amount. On such days precipitating water is immediately evaporated and so does not contribute to runoff on an annual basis. The 80th percentile of daily flows with the SDSM-downscaled GCM is also much lower than that with the station data. The Burntwood River basin includes some large lakes where evaporation is very active, which results in much less runoff than from the Taylor River basin.

Table 2. Results from control runs with station data and SDSM-downscaled GCM data.

	Taylor-station	Taylor-GCM	Burntwood-station	Burntwood-GCM
Mean annual runoff (mm/year)	168.7	142.0	124.1	94.6
80th percentile of daily flows (m^3s^{-1})	7.0	5.7	33.2	22.8
20th percentile of daily flows (m^3s^{-1})	1.3	1.1	7.2	6.4
Median daily flow (m^3s^{-1})	2.6	2.3	13.4	11.1

The mean daily flows of the two basins from the control runs are plotted in Figure 4. Snowmelt in late spring (spring: March, April, and May) results in a rapid surge of discharge followed by a recession over a month. The streamflow remains relatively low during summer (June, July and August) and early autumn (autumn: September, October, and November) mostly due to active evapotranspiration. The simulations with the downscaled GCM data result in much lower runoff in late summer and autumn than those with the station data.

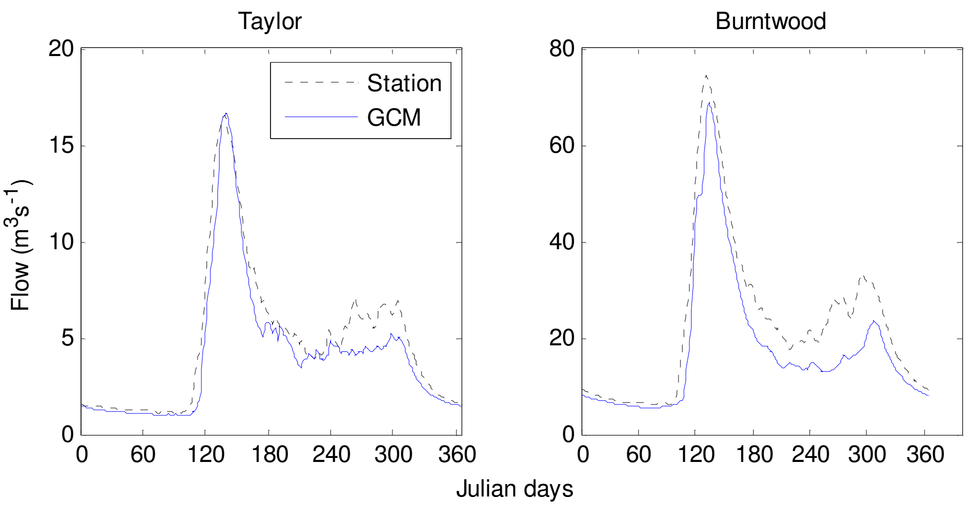

Figure 4. Mean daily flow from control runs with station data and SDSM-downscaled GCM data.

Future climate scenarios were created for the period 2081-2100 from different GCM's, greenhouse gas emission scenarios from the Special Report on Emission Scenarios (Nakicenovic and Swart, 2000), and downscaling techniques. The U.K. Hadley Centre GCM (HadCM3) output for the SRES A2 scenario was obtained from the IPCC Data Distribution Centre (http://www.mad.zmaw.de/IPCC_DDC/html/ddc_gcmdata.html) as monthly means. The CGCM3 monthly output for the SRES A1B, A2, and B1 scenarios was obtained from the CCCma website. The GCM output was downscaled in two different ways. The HadCM3 and CGCM3 output for the A2 scenario was downscaled by the so-called 'delta method' or 'perturbation method' (Diaz-Nieto and Wilby, 2005; Prudhomme et al., 2002). It applies mean monthly temperature and precipitation differences between a reference and a future period simulated by a GCM to existing data sets to create new data sets representing future conditions. The CGCM3 output for the A1B, A2, and B2 scenarios were downscaled by SDSM.

The scenario runs were conducted with the meteorological data from the future climate scenarios. The results from the scenario runs with the delta method were compared to those from the control run with the weather station data, and the results with SDSM were compared to those from the control run with SDSM-downscaled GCM.

5. Climate scenarios

Table 3 lists the climate scenarios and associated GCM, emission scenario, and downscaling method. The scenarios are grouped into two. Group 1 (CGCM3-S, CGCM3-D, and HadCM3-D) is based on the same emission scenario (A2). Simulations within Group 1 are intended to show the effect of different downscaling methods and GCM's. Group 2 (A1B-S, A2-S, and B1-S) is based on CGCM3 and SDSM. Simulations within Group 2 are for investigating the effect of different emission scenarios. Scenario CGCM3-S and Scenario A2-S are identical, but listed twice for comparisons between the simulations in each group.

Table 3. Climate scenarios and corresponding GCM, emissioin scenario, and statistical downscaling.

Scenario group	Scenario name	GCM	Emission scenario	Statistical downscaling
1	CGCM3-S	CGCM3	A2	SDSM
	CGCM3-D	CGCM3	A2	Delta
	HadCM3-D	HadCM3	A2	Delta
2	A1B-S	CGCM3	A1B	SDSM
	A2-S	CGCM3	A2	SDSM
	B1-S	CGCM3	B1	SDSM

The mean monthly temperature and precipitation changes from Group 1 are plotted in Figure 5 for each river basin. Temperature is projected to increase throughout the year with peaks in different months. Scenario CGCM3-S projects the greatest warming in November, CGCM3-D in January, and HadCM3-D in late summer in both basins. Precipitation is projected to decrease in some summer and autumn months in some scenarios while increase under all scenarios in other months, resulting in overall increases for both basins. The summer and late winter (winter: December, January and February) precipitation increase is fairly large under CGCM3-S compared to other scenarios. The results for both river basins are generally similar, but the difference is more noticeable in precipitation. When lumped annually, the largest increase in temperature is projected by CGCM3-S (6.8°C) and the least increase by HadCM3-D (4.8°C) for Taylor. The results for Burntwood are very similar to Taylor. For precipitation, the changes are 37%, 25%, and 16% for Scenarios CGCM3-S, CGCM3-D, and HadCM3-D, respectively for Taylor. For Burntwood, the corresponding numbers are 58%, 24%, and 15%.

The mean monthly temperature and precipitation changes from Group 2 are presented in Figure 6. Regardless of the emission scenarios, warming is consistent throughout the year with the greatest magnitude in November. The greatest warming is projected by A2-S and the least warming by B1-S. Precipitation is also projected to increase when lumped annually, but generally decrease in late autumn. The precipitation increase during the summer season is more remarkable in the Burntwood River basin. The changes in mean annual temperature for Taylor are 5.1°C, 6.8°C, and 3.5°C with Scenarios A1B-S, A2-S, and B1-S, respectively. When annually aggregated, the precipitation increase is 39%, 37%, and 32% from each scenario for Taylor, and 50%, 58%, and 40% for Burntwood.

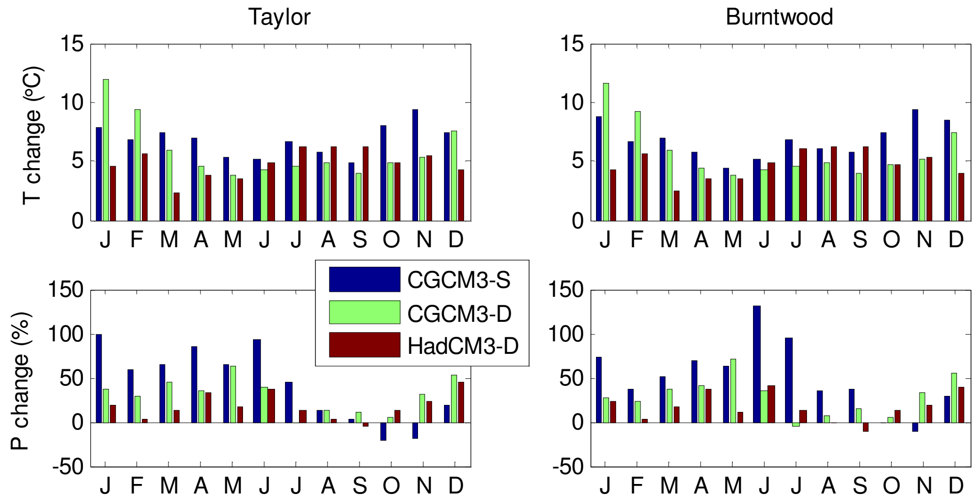

Figure 5. Mean monthly temperature and precipitation changes from Scenarios CGCM3-S, CGCM3-D, and HadCM3-D.

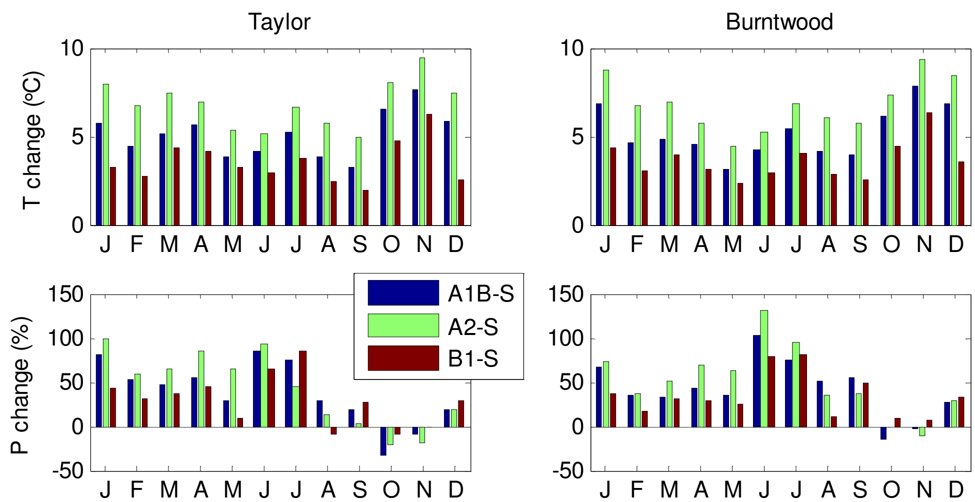

Figure 6. Same as Figure 5 but for Scenarios A1B-S, A2-S, and B1-S.

6. Results from scenario runs

SLURP simulations were conducted with each scenario listed in Table 3. The results from simulations with the Group 1 scenarios are presented in Table 4 as relative changes from the control run.

The greatest increase is predicted with Scenario CGCM3-D in every variable for both basins. Overall, Burntwood shows larger increases than Taylor, primarily due to greater precipitation increases. Median daily flow and the 80th percentile of daily flows generally show greater increases than mean annual runoff.

What is interesting is that the largest increase in mean annual precipitation is with CGCM3-S but the largest increase in mean annual runoff is with CGCM3-D. This discrepancy can be explained by the different runoff ratio (total runoff / total precipitation) values between two different input data sets. From the control run with the station data, the runoff ratio is 0.33 for Taylor. On the other hand, the runoff ratio drops to 0.29 in the control run with the SDSM-downscaled GCM data. The input data from SDSM results in underestimation of runoff primarily because SDSM resulted in numerous wet days with minute precipitation amounts. In scenario runs, while the runoff ratio with CGCM3-S stays at 0.28, the runoff ratio with CGCM3-D increases to 0.39. It means that the precipitation increment in CGCM3-D contributes to more runoff than the precipitation increment in CGCM3-S. The changes with Scenario HadCM3-D are fairly moderate compared to those with CGCM3-D due to the moderate precipitation change simulated by HadCM3.

Table 4. Relative changes in selected hydrological variables simulated with Scenarios CGCM3-S, CGCM3-D, and HadCM3-D.

Scenario and basin	Mean annual runoff	80^{th} percentile of daily flows	20^{th} percentile of daily flows	Median daily flow
Taylor				
CGCM3-S	33.1%	31.2%	44.6%	49.3%
CGCM3-D	48.1%	49.5%	78.4%	69.3%
HadCM3-D	28.7%	30.3%	37.2%	40.0%
Burntwood				
CGCM3-S	57.7%	62.6%	75.4%	64.9%
CGCM3-D	80.1%	86.5%	84.4%	93.4%
HadCM3-D	52.1%	59.4%	44.7%	52.5%

Table 5 shows the results from simulations with the Group 2 scenarios. For Taylor, the greatest increases in mean runoff and median daily runoff are projected by A1B-S, which is associated with the greatest precipitation increase. However, the difference in precipitation changes between scenarios is not substantial (32-39%). The percent change in mean annual runoff is significantly lower with A2-S than with other scenarios, primarily because the temperature increase is the greatest with A2-S. The results for Burntwood are somewhat different, in part due to different precipitation changes. The projected precipitation changes are much greater for Burntwood than for Taylor, and the largest precipitation increase is projected under A2-S. In combination with the largest temperature increase, A2-S results in changes in mean annual runoff and median runoff comparable to those from other scenarios.

Table 5. Same as Table 4 but for Scenarios A1B-S, A2-S, and B1-S.

Scenario and basin	Mean annual runoff	80^{th} percentile of daily flows	20^{th} percentile of daily flows	Median daily flow
Taylor				
A1B-S	54.5%	75.2%	36.5%	60.7%
A2-S	33.1%	31.2%	44.6%	49.3%
B1-S	50.5%	74.6%	26.2%	48.0%
Burntwood				
A1B-S	67.0%	93.5%	48.7%	76.7%
A2-S	57.7%	62.6%	75.4%	64.9%
B1-S	59.1%	90.4%	38.7%	61.9%

The distribution of daily runoff values are presented in Figure 7 and Figure 8 as Q-Q plots for the Group 1 and Group 2 scenarios, respectively. Figure 7 shows that the relationship is linear at the lower end (lower half of the data) but deviates from linear at the higher end. The plots imply that the distribution pattern of daily runoff values from future simulations is fairly similar to the control simulation in spited of overall increases, except for very high flow events. With Scenario CGCM3-S, very high flows are predicted to increase not as much as the majority of the flows for both Taylor and Burntwood (markers are below the line at the very high end). With the delta method scenarios, the results for Burntwood are similar to those with Scenario CGCM3-S, but some markers at the extremely high end are above the line for Taylor.

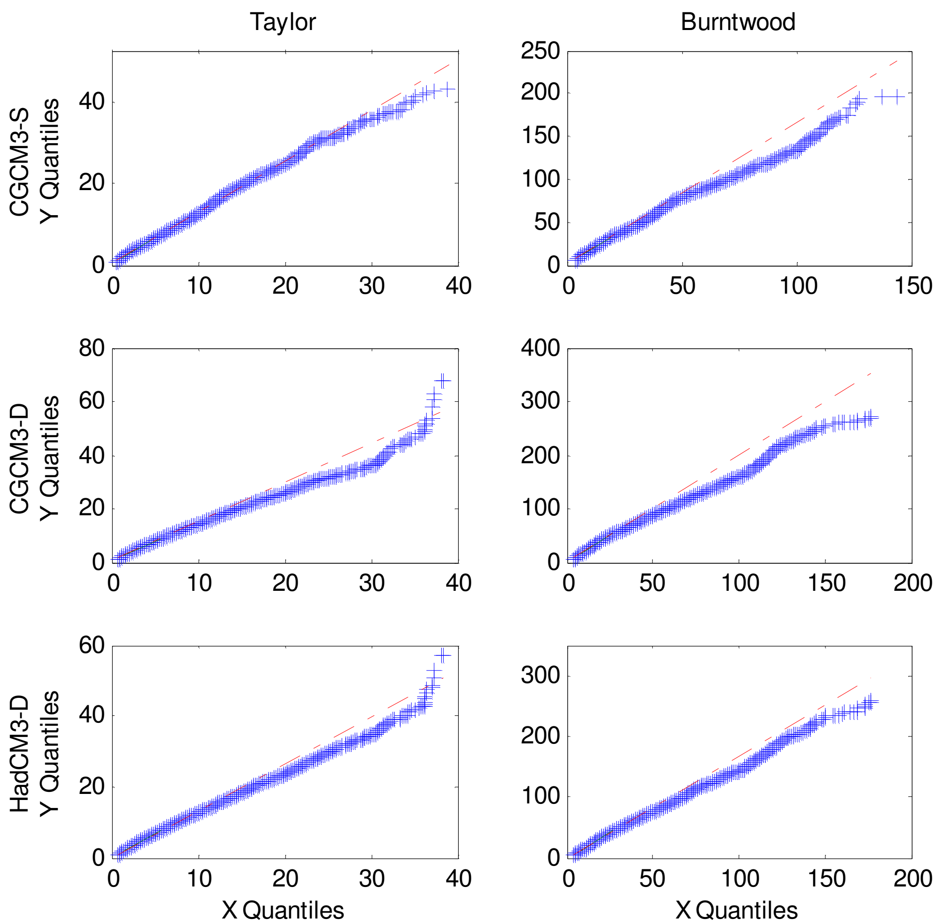

Figure 7. Quantile-quantile plots of daily streamflow (in m^3s^{-1}). X is the daily streamflow from control runs and Y is that from scenario runs with CGCM3-S, CGCM3-D, and HadCM3-D. The line joins the first and third quartiles of each distribution.

Q-Q plots for the SDSM simulations with the A1B and B1 scenarios reveal greater divergence from the line at the higher end than that with the A2 scenario (Figure 8). The markers below the line at the high end imply that at high quantiles the future streamflow does not increase as much as it does between the 25th and the 75th quantiles. Even though the 80th percentile of daily flows is predicted to increase by greater percentage than the median daily flow with Scenarios A1B-S and B1-S, higher percentile flows are predicted to increases with much smaller percentage than the 80th.

The simulation results were also analyzed at the daily scale. Figure 9 shows mean daily flows from the control run with the station data and the scenario runs with CGCM3-S, CGCM3-D, and HadCM3-D. Compared to the control run, peak runoff occurs earlier with greater magnitude in every scenario. It is strongly associated with an earlier start of spring snowmelt. As a result, the spring time (i.e. between day 60 and 150) runoff is predicted to substantially increase. But the magnitude of peak runoff from CGCM3-S is remarkably smaller than that from the delta method. The second peak in late autumn is also predicted to substantially increase with the delta method scenarios, which can be explained by increased precipitation and temperature in October, November, and December from the delta method scenarios. Summertime runoff shows moderate increases.

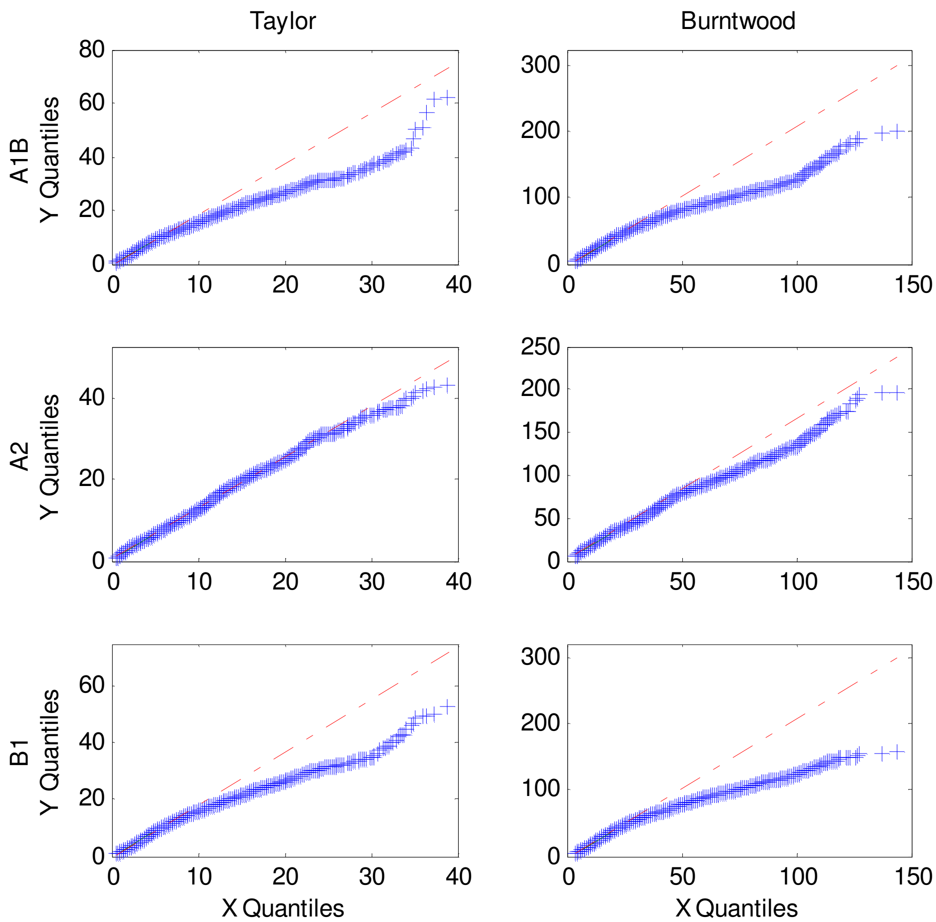

Figure 8. Same as Figure 7 but for Scenarios A1B-S, A2-S, and B1-S.

The results from Scenarios A1B-S, A2-S, and B1-S are presented in Figure 10 along with that from the control run with SDSM-downscaled GCM data. The difference between the control and future periods is especially remarkable during the summer time. With the delta method, the summer runoff change is moderate while the spring and winter runoff change is excessive. On the other hand, A1B-S and B1-S with SDSM result in larger runoff increases both in spring and summer. Runoff in late autumn also shows a large increase especially in Burntwood.

7. Discussion and conclusions

This study investigated the response of the hydrological system in northern Manitoba to climate scenarios derived from GCM output. Different GCMs and emission scenarios resulted in wetter and warmer climates in late 21st century with different magnitudes in the changes. As a result, runoff is consistently predicted to increase in all scenarios.

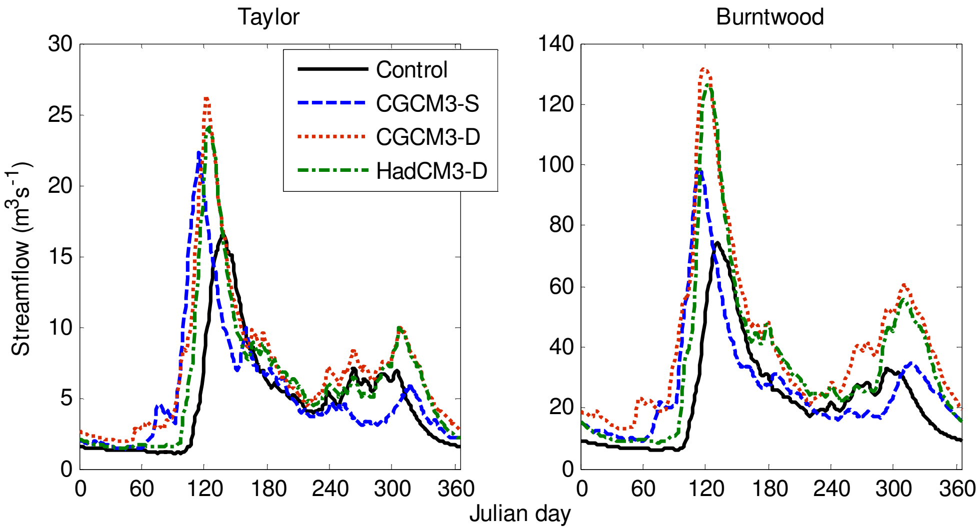

Figure 9. Mean daily streamflow from control run with station data and scenario runs with CGCM3-S (dashed), CGCM3-D (dotted), and HadCM3-D (dash-dot).

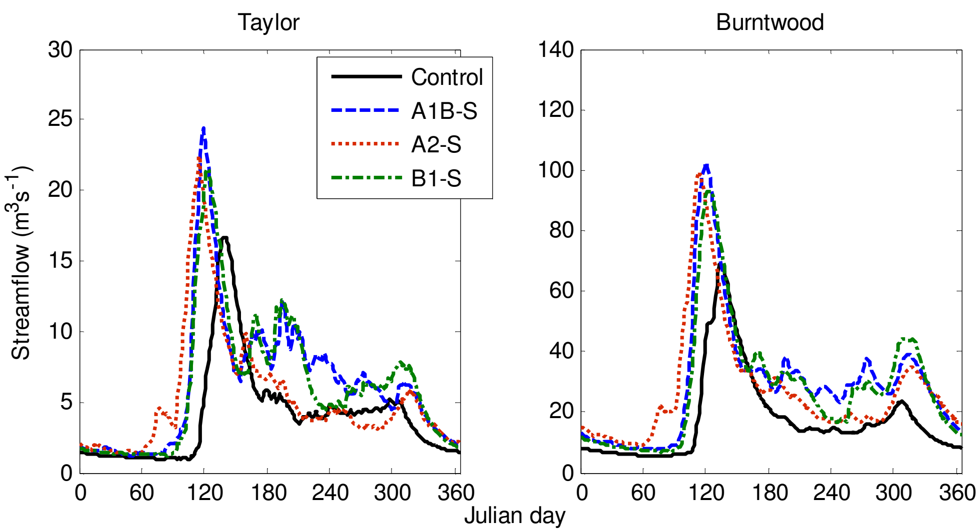

Figure 10. Mean daily streamflow from control run with SDSM-downscaled GCM and scenario runs with A1B-S (dashed), A2-S (dotted), and B1-S (dash-dot).

The strengths and weaknesses of the delta method have been well documented by other authors (e.g. Prudhomme et al., 2002; Diaz-Nieto and Wilby, 2005). It is easy to implement and transparent, while not able to accommodate the changes in data distribution and precipitation pattern, which are anticipated in future climates. Precipitation increases simulated by CGCM3 and downscaled by the delta method are far less than those from CGCM3 with SDSM and have somewhat different seasonal distribution. However, the delta method resulted in greater runoff increases than SDSM. Without any changes in precipitation sequence and frequency in the delta method, the increased precipitation mostly contributed to runoff.

SDSM involves both regression methods and stochastic components. It successfully reproduced the historical means of temperature and precipitation, but resulted in noticeable changes in precipitation pattern. Diaz-Nieto and Wilby (2005) reported good performance of SDSM for the number of wet days but mean dry spell length was underestimated by 13.5% in their study for a U.K. basin. In this study, wet days in The Pas simulated by SDSM are 59%

of the total days during 1971-2000 while those from the observation are only 34%. Certainly this is an area of concern and requires further investigation.

It looks obvious that the boreal forest region in northern Manitoba will have a wetter and warmer climate in late 21st century. In the changed climate, runoff is likely to generally increase with earlier and higher snowmelt peaks. The results imply that the communities in the region need to be better prepared for spring floods while the increased runoff may contribute to more hydroelectric power generation. The results also reveal that the daily flows in a range of high percentiles are less sensitive compared to those in medium quantiles in the region. Examining the changes in specific percentile values had better be complemented by Q-Q plots. One major point missing in the study is that the boreal forest may undergo transformation to some extent. It pinpoints the need to connect this type of study to modelling ecological impacts of climate change.

Acknowledgment

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