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Rajesh Shrestha

Yonas Dibike

Terry Prowse

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Modelling Climate Impacts on Hydrologic Processes in the Lake Winnipeg Watershed

Rajesh Shrestha[1], Yonas Dibike[1] and Terry Prowse[1]
[1]*Water and Climate Impacts Research Centre, Environment Canada, University of Victoria, Victoria, V8W 3R4, Canada, rajesh.shrestha@ec.gc.ca, yonas.dibike@ec.gc.ca, terry.prowse@ec.gc.ca*

Abstract: This paper presents results of spatial and temporal analyses of hydro-climatic regimes and simulation of climate-induced hydrologic changes in the Lake Winnipeg watershed. The hydrologic and agricultural chemical yield model, Soil & Water Assessment Tool (SWAT), was employed for the simulation of hydrologic scenarios in the Upper Assiniboine catchment of the Lake Winnipeg watershed, Canada. Analyses of future climate projections from three regional climate models (RCMs) corresponding to the SRES's A2 emission scenario, indicate that the total annual precipitation will increase by 5.5-7.5 % in 2041-2070 compared to 1971-2000, while temperature will increase by 2.0-2.9° C during the same period. Hydrologic scenarios simulated with the SWAT model project consistent changes in future snowmelt driven runoff, with an earlier onset of spring snowmelt and discharge peaks. Some of the results also show increases in discharge peaks. These changes can be expected to have implications on water availability and nutrient transport regime in the Lake Winnipeg watershed.

***Keywords**:* climate change, hydrologic model, Lake Winnipeg Watershed, regional climate model, SWAT.

1. INTRODUCTION

There is strong evidence that the quality of water in Lake Winnipeg, Canada has deteriorated in recent years due to excess nutrient loading from the surrounding watershed. Total nitrogen (N) and total phosphorus (P) loads to the Lake Winnipeg have increased by 13% and 10%, respectively, over the last three decades [Jones and Armstrong, 2001]. While non-point agricultural sources are the main contributors to the nutrient loading, rainfall and snowmelt-driven hydrologic processes play a key role in nutrient delivery to the lake. Previous studies of catchment-scale nutrient transport processes indicate that runoff from rainfall and snowmelt drive nitrate and phosphorus transport processes from catchments [Creed et al., 1996; Salvano et al., 2009]. Therefore, modelling of the hydrologic response is the first step in modelling nutrient transport processes.

Studies based on hydrometric observations indicate a general trend of decreasing mean annual streamflow in the Saskatchewan river [Zhang et al., 2001], and increasing flows in the Winnipeg and Red River catchments due to increasing precipitation [Stainton et al., 2007]. Climate change is generally expected to lead to an intensification of the hydrologic cycle, which will influence the hydrologic regime in the Canadian Prairies region. An evaluation of these trends into the future will help in the assessment of potential impacts of climate change on water availability, which is critical in the dry Prairies region.

The main objective of this study is to assess the potential impacts of climate variability and change on the hydrologic regimes of the Lake Winnipeg watershed. The first part of this paper presents the results of spatial and temporal analyses of precipitation and temperature projections from three regional climate models (RCM) within the watershed. The second part employs climate scenarios derived from the same three RCMs for the simulation of future climate-induced hydrologic changes in a representative sub-catchment.

2 DATA AND METHODS

2.1 Climate Scenario Data and Analyses

The data used for analyses of present and future climates in the Lake Winnipeg watershed are derived from the North American Regional Climate Change Assessment Program (NARCCAP) data base [Mearns, 2004]. NARCCAP produces climate data based on a set of regional climate models (RCMs) driven by a set of atmosphere-ocean general circulation models (GCMs) over a domain covering the conterminous United States and most of Canada. The RCMs are nested within the GCMs for baseline (1971-2000) and future (2041-2070) periods with forcings from observed emission and SRES A2 emission scenario for the 21st century, respectively. The RCMs runs are available at a spatial resolution of 50 km. Daily precipitation, and minimum and maximum air temperature data from three GCM/RCMs, namely: the Canadian CGCM3/CRCM [Music and Caya, 2007]; the UK HadCM3/HRM3 [Hudson and Jones, 2002]; and the NOAA GFDL/RCM3 [Pal et al., 2007], were used to analyze the future climate scenarios for the Lake Winnipeg watershed. Projected changes in the hydro-climatic regime were analysed by considering mean monthly and seasonal values of precipitation and maximum and minimum air temperature (T_{max} and T_{min}) over the region for the baseline (1971-2000) and future (2041-2070) time periods, and then calculating the differences between these two periods.

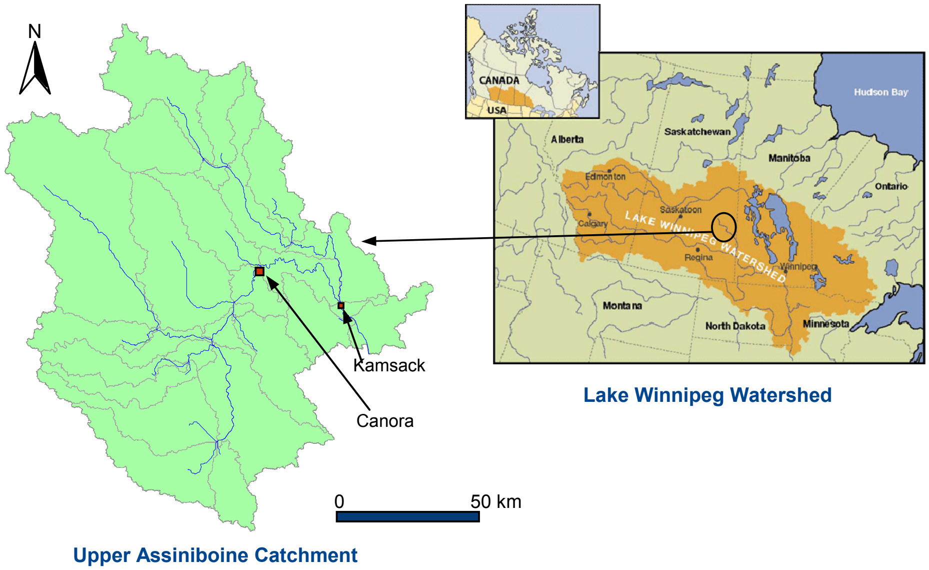
2.2 Hydrologic Model Setup and Simulation of climate-induced changes

The hydrologic model SWAT [Arnold et al., 1998; Neitsch et al., 2005] was set up in the Upper Assiniboine catchment (Figure 1) for a representative simulation of climate-induced hydrologic changes. The catchment covers an area of about 13,500 km^2, upstream of the Lake of Prairies (Shellmouth reservoir) in the province of Saskatchewan [Shrestha et al., 2009]. The topography is gently to moderately undulating with elevation ranging from 427 m to 723 m. Calculated average annual precipitation between 1979 and 2003 is about 390 mm [sourced from Gridded Climate Dataset for Canada; Hutchinson et al., 2009]. Major tributaries of the Assiniboine River include the Whitesand River, Shell River, Lilian River and Yorkton Creek.

The SWAT model was set up with: a) a 90-m resolution digital elevation model from Consultative Group for International Agriculture Research-Consortium for Spatial Information, CGIAR-CSI [Jarvis et al., 2008]; b) 1-km resolution land use data from Land Cover of Canada [Cihlar and Beaubien, 1998]; and c) 1:1x10^6 resolution soil data from Soil Landscapes of Canada [SLC Working Group, 2007]. The model was forced with the precipitation, maximum and minimum air temperature from Gridded Climate Dataset for Canada [GCDC; Hutchinson et al., 2009] and solar radiation, wind speed and relative humidity from North America Regional Reanalysis (NARR) datasets [Mesinger et al., 2006].

A set of 13 parameters related to snowpack accumulation and melt, and runoff generation were chosen for calibration of the SWAT model. Calibration was performed using Parameter Solutions [ParaSol; van Griensven and Meixner, 2003], which is a global optimization algorithm based on Shuffled Complex Evolution [SCE-UA; Duan et al. 1992]. Discharge data from Canora and Kamsack hydrometric stations (Figure 1) were used in a ten-year calibration (1986-1995) and an eight year (1996-2003) validation period. A warm-up period of one year was employed, so that initial conditions did not affect the model calibration. The sum of the squares of the residuals between the observed and simulated discharge was used as an objective function for model optimization. Discharge simulations from the two gauging stations were combined to a single objective for optimization.

Climate induced hydrologic changes were analyzed by comparing the simulations between the baseline and future periods. The GCDC precipitation, maximum and minimum air temperature, NARR solar radiation, wind speed and relative humidity were employed to simulate the baseline period (1979-2000) (NARR dataset begins in 1979). RCM outputs consist of these variables, which were employed as inputs to the SWAT model for the simulation of the future (2040-2061) period. The three RCMs used in the climate scenario analyses: CGCM3/CRCM; HadCM3/HRM3; and GFDL/RCM3 were used. Systematic biases in the RCM datasets were removed using the bias correction method [Graham et al., 2007]. Changes in the discharge and snowmelt signals in the catchment were compared between the baseline (1980-2000) and the future (2041-2061) periods, excluding the first year for the model warm-up period.



Lake Winnipeg Watershed

Upper Assiniboine Catchment

Figure 1. Location Map of Lake Winnipeg Watershed and Upper Assiniboine Catchment.

3. RESULTS AND DISCUSSION

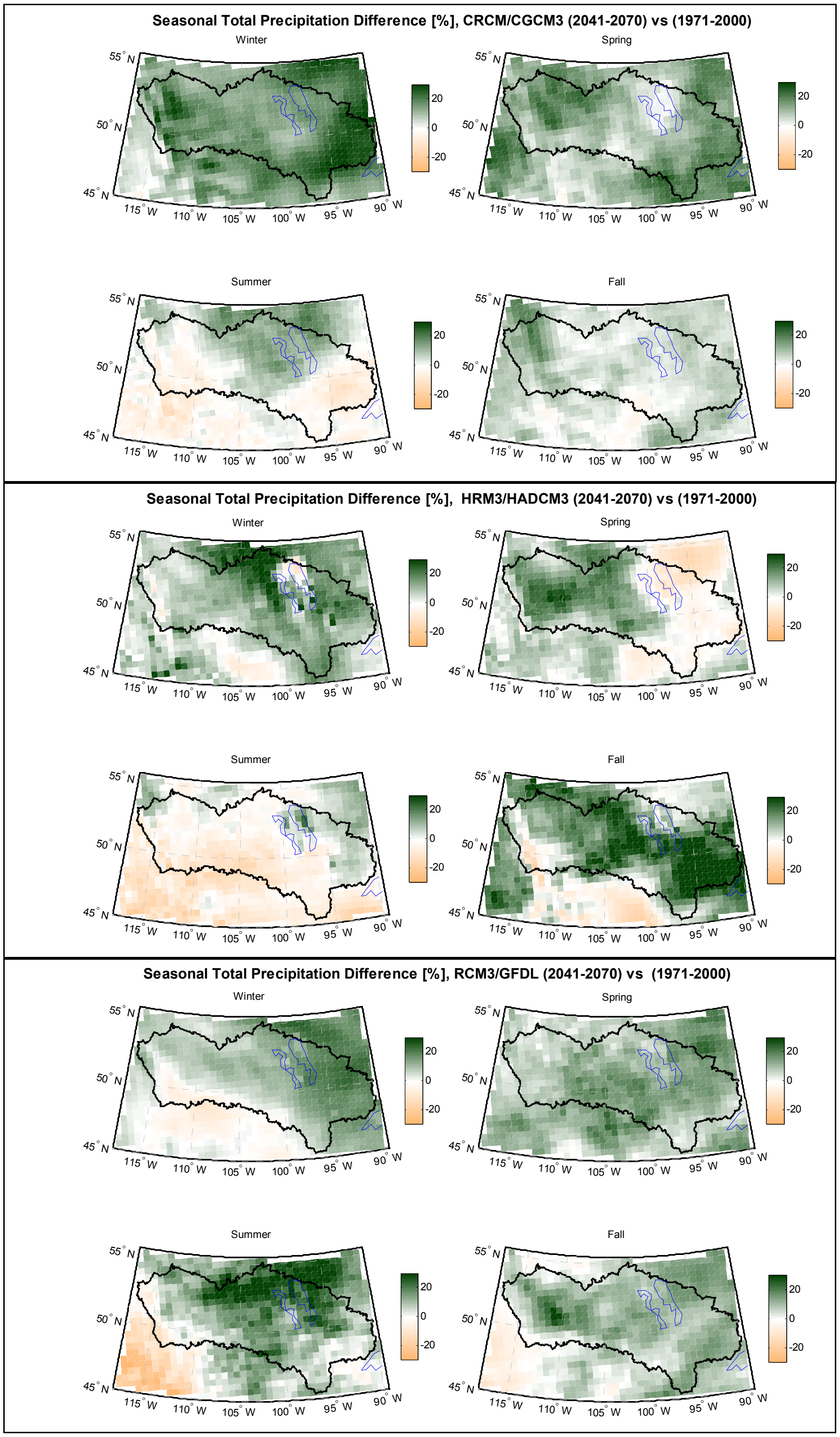
3.1. Projected Changes in the Precipitation and Temperature Regime

Figure 2 shows the changes in seasonal precipitation between the baseline (1971-2000) and future (2041-2070) periods. In general, all three GCM/RCM project increases in the mean annual precipitation for the future period. The CRCM/CGCM3 projected an increase of 6.4% over the entire basin, with seasonal changes between -0.7% and 15.2%. Similarly, the HRM3/HadCM3 also projected a wetter future, with an increase of 5.5% overall and changes ranging from -1.7 to 14.5%. The central areas of the basin show the highest change. The RCM3/GFDL projects the wettest future between the three RCMs, with an overall annual increase of 7.7% and seasonal changes between 5.6% and 11.3%.

The seasonal trends illustrate the differences between the RCMs in terms of magnitude of changes. For instance, the CRCM and RCM3 project greater precipitation increases (15.1% and 11.3%, respectively) in spring, while the HRM3 projects the largest precipitation increase (14.5%) in the autumn. The CRCM and HRM3 project a slight decrease in summer precipitation over the region, while the RCM3 projects a 7.6% increase for the same season. The spatial distribution of the changes over the watershed, with a few exceptions, depicts increases in precipitation in the northern and eastern part of the basin for all three RCMs, and no change or a decrease in precipitation in the southern and western part of the basin.

Precipitation patterns in the Upper Assiniboine catchment show increases of 11.0%, 16.0%, and 17.5% for the CRCM3, HRM3 and RCM3, respectively, which are greater in comparison to the corresponding changes in the entire Lake Winnipeg watershed. The

RCM precipitation datasets also depict differences with the baseline period characterized by sharp peaks (Figure 3). In comparison to the baseline period, June precipitation exhibits a 33% increase for the RCM3, while September precipitation exhibit 75% increase for the HRM3.


Seasonal Total Precipitation Difference [%], CRCM/CGCM3 (2041-2070) vs (1971-2000)

Seasonal Total Precipitation Difference [%], HRM3/HADCM3 (2041-2070) vs (1971-2000)

Seasonal Total Precipitation Difference [%], RCM3/GFDL (2041-2070) vs (1971-2000)

Figure 2. Spatial views of changes in mean seasonal precipitation in the Lake Winnipeg Watershed between the future (2041-2070) and baseline (1971-2000) periods based on the three GCM/RCM projections.

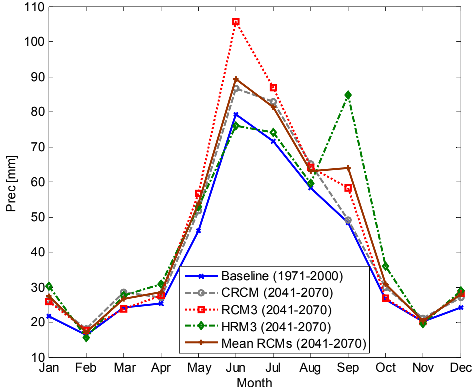


Figure 3. Comparison of monthly changes in mean precipitation from different RCMs between baseline (1971-2000) and future (2041-2061) for the Upper Assiniboine catchment.

In the case of daily maximum and minimum temperatures, the spatial variability in the projected changes over the Lake Winnipeg watershed is not significant with the exception of the relatively milder increase in average air temperatures over the Rocky Mountains (south-western part of the basin) compared to the rest of the basin. The annual mean T_{max} (T_{min}) increases for the CRCM3, HRM3 and RCM3 are 2.5, 2.8 and 2.0°C (2.9, 2.8 and 2.2°C), respectively. For the critical spring snowmelt season, the respective increases are 1.6°, 2.2° and 1.0°C (2.5°, 2.0° and 1.4°C).

3.2 Model Calibration and Climate-Induced Hydrologic Changes

Figure 4 shows the SWAT calibration results for the Kamsack station in the Upper Assiniboine catchment. Overall results of the calibration using the ParaSol procedure show a good performance, with R^2 and Nash-Sutcliffe coefficients of 0.87 and 0.81 for the calibration datasets and 0.72 and 0.65 for the validation datasets, respectively. Overall, the SWAT is able to reproduce the runoff dynamics for the calibration and validation datasets. Specifically, the peaks in discharge during the April-may snowmelt season are replicated reasonably well for most years.

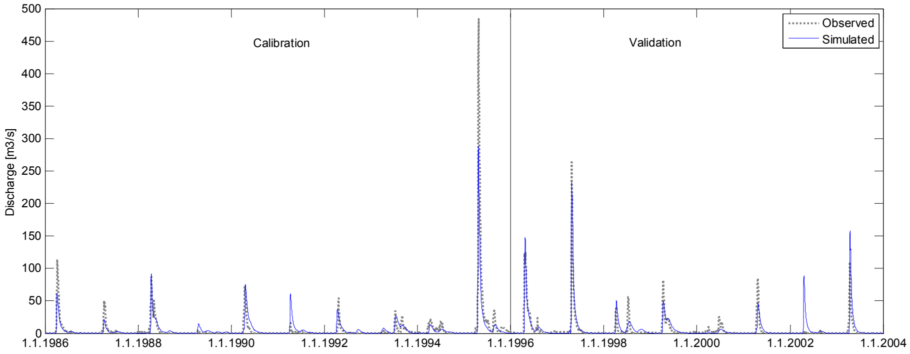


Figure 4. Comparison of observed and simulated discharge Kamsack gauge in Assiniboine River.

The comparison of simulated baseline (1980-2000) and future (2041-2061) hydrologic scenarios are shown in Figure 5. The scenarios depict significant changes in the runoff and snowmelt regimes. The spatial and temporal variability of different RCMs led to large differences in the runoff simulation. The results exhibit a large spread of the total runoff volume simulation, with the HRM3 (CRCM) future scenario depicting the largest (smallest) deviation from the baseline period (Figure 5a). Based on the scenario simulations with the three RCMs, increases in catchment runoff range significantly between 8.9 and 89.9% for precipitation increase between 11.0 and 17.5%. The seasonal differences in the precipitation in the three RCMs led to such discrepancy in hydrologic responses. Runoff in the Prairies region is dominated by snowmelt, despite snowfall contributing to only a third of total precipitation [Gray and Landine, 1988]. Hence, changes in snowfall-precipitation have the greatest influence on total runoff volume. Specifically, in the Upper Assiniboine catchment, greater autumn and winter precipitation in the HRM3 datasets (Figure 3) led to higher autumn and spring runoff, and higher overall runoff volume. In the case of RCM3 simulations, although there is a large increase in summer precipitation, the lower September-March precipitation resulted in a smaller increase in runoff.

Significant differences between the baseline and future simulations are observed, with respect to the timing of snowmelt. The effect of the temperature driven shift on the snowmelt regime can be seen in the future discharge simulations from all three RCMs. In comparison to the baseline period, higher monthly snowmelt in February and March, together with lower monthly snowmelt in April are observed for all future RCM simulations (Figure 5b). The earlier snowmelt is accompanied by higher March and April discharge (Figure 5c), and earlier peak yearly discharges (Figure 5d). A shift of 2-19 days towards earlier occurrence of the yearly peak discharge is observed for all RCM simulations. In addition, the results of the RCM3 and HRM3 simulations show 15% and 59% increases in average yearly average peaks of snowmelt discharge, respectively.

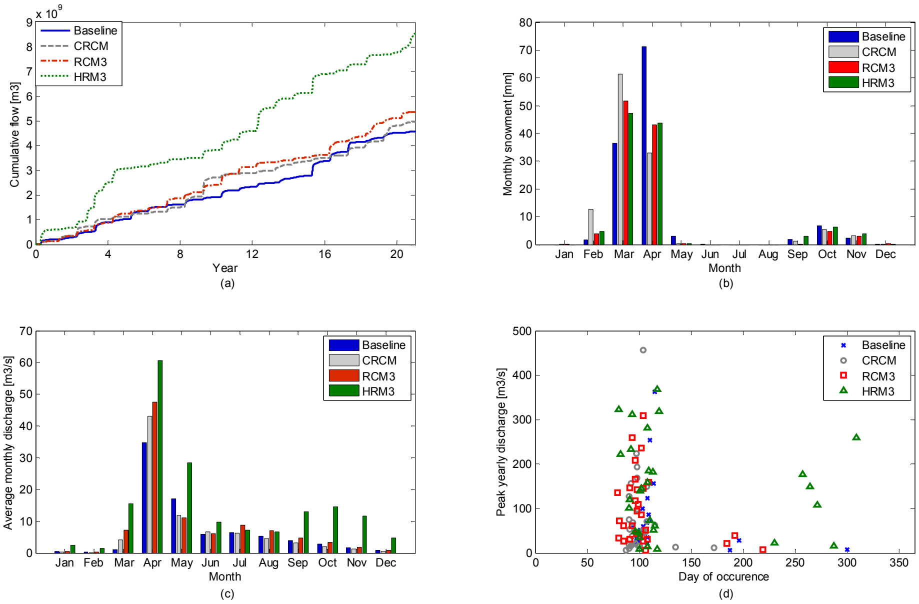


Figure 5. Comparison of RCM projections for future (2041-2070) with baseline (1979-2000) period (a) cumulative flow, (b) monthly total snowmelt, (c) monthly average discharge, (d) magnitude and day of occurrence of peak yearly discharge.

In summary, the effects of projected future changes in climatic variables, specifically precipitation and temperature, are clearly evident in the resultant snowmelt and runoff regimes. The most significant changes include: higher total runoff, earlier snowmelt and discharge peaks, and the possibility of larger average snowmelt-driven discharge. The results also show considerable differences between the RCM results, which emphasize the importance of using multiple RCMs for climate-change impact projections. Such a strategy provides a range of possible future changes, instead of a single output based on a single

RCM forcing. Such a range facilitates the consideration of employing different driving scenarios and developing different adaptation strategies to manage the possible future impacts. In addition, the seasonality of the precipitation datasets in the three RCMs led to a large discrepancy in hydrologic response, especially in the critical snowmelt response. Hence, it is important to make an assessment of how different RCMs represent the seasonality of the precipitation. The analysis will help in the selection of the best RCM for similar climate-induced hydrologic changes studies.

The climate-induced hydrologic changes can be expected to lead to changes in regional water availability. Increases in peak snowmelt discharge may also increase flood hazards. This may be especially important given the flood history of the Red and Assiniboine rivers. Moreover, hydrologic changes can influence the nutrient transport processes. Nutrient responses in the snowmelt dominated catchments exhibit strong relationships with the hydrologic responses for both nitrate [Creed et al., 1996] and phosphorus [Prepas et al., 2003]. Therefore, changes in the hydrologic responses, such as earlier occurrence of discharge peaks can be expected to lead to earlier nutrient responses. Further changes may occur in the N:P ratios and risk of eutrophication [Marshall and Randhir, 2008]. A detailed research is needed for investigating the potential impacts of climate change on hydrologic-nutrient cycle interactions.

3. CONCLUSIONS

The climate-induced hydro-meteorological change in the Lake Winnipeg watershed was investigated with spatial and temporal analyses of multiple RCMs and hydrologic modelling of a representative catchment. Based on a successful calibration of the hydrologic model SWAT, baseline (1980-2000) and future (2041-2061) climate scenarios were simulated based on forcings derived from selected RCMs. Analysis of future climate projection from three RCMs show that future annual precipitation will increase by 5.5-7.5%, while minimum and maximum temperature will increase by 2.0-2.9°C. The potential impacts of these changes are evident in the future runoff and snowmelt regimes of the Upper Assiniboine catchment. The results consistently show changes in future snowmelt-driven runoff, with an earlier onset of spring snowmelt and peak discharges as well as an overall increase in runoff volume. Such volume increases may be accompanied by increases in discharge peaks as shown by the results RCM3 and HRM3 simulations. These changes can be expected to influence water availability, flood magnitudes and frequencies, as well as nutrient-transport processes and loadings.

Results also show the variability in future climate projections resulting from the use of different RCMs. The three RCM datasets employed in these scenarios simulation consist of quite different spatial and temporal variability, which translated into significantly different simulations of runoff. For example, a precipitation increase of between 11.0 and 17.5%, produced a much magnified difference in runoff of between 8.9 and 89.9%. The seasonal differences in the precipitation in the RCMs, especially in the critical snowmelt season, led to such discrepancy in hydrologic responses. Specifically, in the Upper Assiniboine catchment, greater autumn and winter precipitation in the HRM3 datasets led to higher autumn and spring runoff, and higher overall runoff volume. Hence, until specific RCMs are proven to be superior in application, it is considered appropriate to employ multiple RCMs for providing a potential range of climate-change effects. Moreover, this approach facilitates the consideration of different forcing scenarios and development of different climate-change adaptation strategies.

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