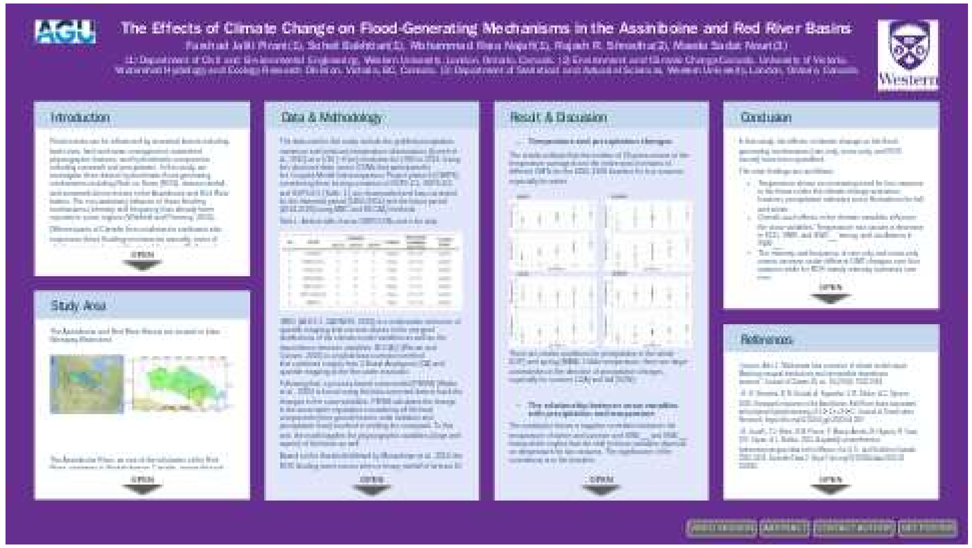
The Effects of Climate Change on Flood-Generating Mechanisms in the Assiniboine and Red River Basins



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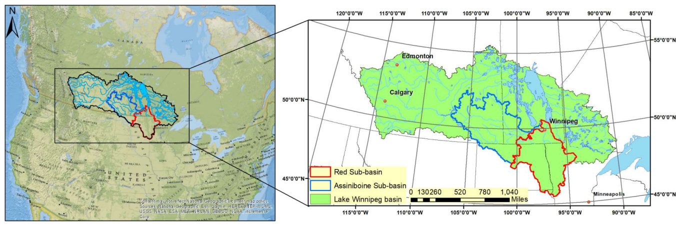
INTRODUCTION

Flood events can be influenced by terrestrial factors including land cover, land and water management, watershed physiographic features, and hydroclimatic components including snowmelt and precipitation. In this study, we investigate three distinct hydroclimatic flood-generating mechanisms including Rain on Snow (ROS), intense rainfall, and snowmelt-driven events in the Assiniboine and Red River basins. The non-stationary behavior of these flooding mechanisms (intensity and frequency) has already been reported in some regions (Whitfield and Pomeroy, 2016).

Different parts of Canada from southeast to southwest also experience these flooding mechanisms annually, some of which are counted as costly natural disasters (Buttle et al., 2016, Blais et al., 2016). In this study, we track the changes in the snow variables and these flood generating mechanisms' frequency and intensity on the Assiniboine and Red River Basins under different global temperature increases for the first time.

STUDY AREA

The Assiniboine and Red River Basins are located in Lake Winnipeg Watershed.



The Assiniboine River, as one of the tributaries of the Red River, originates in Saskatchewan, Canada, moves through Manitoba, and finally reaches the Red River at Winnipeg. The Red River begins between Minnesota and North Dakota and flows to the north into Manitoba (Shrestha et al., 2020).

The flood event in May 1997 which is known as the "Flood of the Century", was caused by record snow and rainfall over the upstream of Winnipeg. A flooded area of about 1840 km^2 forced 27,400 residents to be evacuated in Manitoba and caused direct damage of about CAD 750 million in 1997 dollars, and up to CAD 1 billion if indirect damages were included (Rannie, 2016).

Overall, the climate regime of the study area is cold from December to February; however, the Red River subbasin is wetter and warmer than Assiniboine subbasin. The annual temperature and precipitation are 4.2 C and 542 mm, and 2.9 and 437 mm for Assiniboine and Red basins, respectively. Over 60% of the flood events between April and July are due to the snowmelt process (Shrestha et al., 2020).

DATA & METHODOLOGY

The data used in this study include the gridded precipitation, maximum and minimum temperature observations (Livneh et al., 2015) at a 1/16 (~6 km) resolution for 1950 to 2013. Using this observed data, seven GCMs that participated in the Coupled Model Intercomparison Project phase 6 (CMIP6), considering three forcing scenarios of SSP2-4.5, SSP4-6.0, and SSP5-8.5 (Table. 1), are downscaled and bias-corrected for the historical period (1850-2014) and the future period (2014-2100) using MBC and BCCAQ methods.

Table.1 - Attribute table of seven CMIP6 GCMs used in this study

No.	GCM	Scenario			Country	Horizontal resolution (Lon x Lat)	Variant Label
		ssp2-4.5	ssp4-6.0	ssp5-8.5			
1.	CanESM5	✓	✓	✓	Canada	2.8° x 2.8°	r1i1p1f1
2.	CNRM-CM6-1	✓	×	✓	France	1.4° x 1.4°	r1i1p1f2
3.	FGOALS-g3	✓	✓	✓	China	2° x 2.3°	r1i1p1f1
4.	GFDL-ESM4	✓	×	✓	USA	1.3° x 1°	r1i1p1f1
5.	INM-CM5-0	✓	×	✓	Russia	2° x 1.5°	r1i1p1f1
6.	IPSL-CM6A-LR	✓	✓	✓	France	2.5° x 1.3°	r1i1p1f1
7.	MIROC6	✓	✓	✓	Japan	1.4° x 1.4°	r1i1p1f1

MBC (ALEX J. CANNON, 2019) is a multivariate extension of quantile mapping that corrects biases in the marginal distributions of the climate model variables as well as the dependence between variables; BCCAQ (Werner and Cannon, 2016) is a hybrid bias correction method that combines outputs from Climate Analogues (CA) and quantile mapping at the fine-scale resolution.

Following that, a process-based snow model (PBSM) (Walter et al., 2005) is forced using the bias-corrected data to track the changes in the snow variables. PBSM calculates the change in the snow water equivalent considering all the heat components (from ground heat to solar radiation and precipitation heat) involved in melting the snowpack. To this end, the model applies the physiographic variables (slope and aspect) of the basin as well.

Based on the threshold defined by Musselman et al., 2018, the ROS flooding event occurs when a heavy rainfall of at least 10 mm/day falls on a snowpack of at least 10 mm snow water equivalent (SWE), where the sum of rainfall and snowmelt contains at least 20% snowmelt.

$$Threshold: \begin{cases} Rainfall \geq 10mm, and \\ SWE \geq 10mm, and \\ Snowmelt \geq 20\%(Rainfall + Snowmelt) \end{cases}$$

If a flood event is generated based on the ROS definition, then two mechanisms of rain-only and snowmelt-only might also cause the same flood. Thus, three flood-generating mechanisms are taken into account in our analysis.

Having that, the changes in the precipitation, maximum and minimum temperature, snow variables, and flood generating mechanisms including rain-only, snow melt-only, and rain-on-snow events and the corresponding uncertainties under 1.0 C, 1.5 C, 2.0 C, 2.5 C, and 3.0 C GMT changes above the pre-industrial (PI) period of 1850–1900 are assessed.

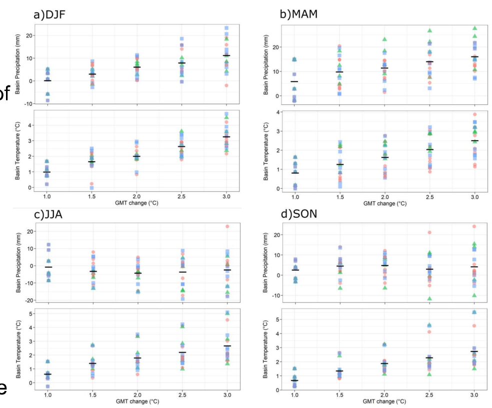
The analysis is performed over different seasons and presented just for the MBC model for the sake of brevity.

RESULT & DISCUSSION

- **Temperature and precipitation changes**

The results indicate that the median of 30-years means of the temperature averaged over the entire area increases at different GMTs for the 1850–1900 baseline for four seasons, especially for winter.

There are similar conditions for precipitation in the winter (DJF) and spring (MAM). Unlike temperature, there are larger uncertainties in the direction of precipitation changes, especially for summer (JJA) and fall (SON).



- **The relationship between snow variables with precipitation and temperature**

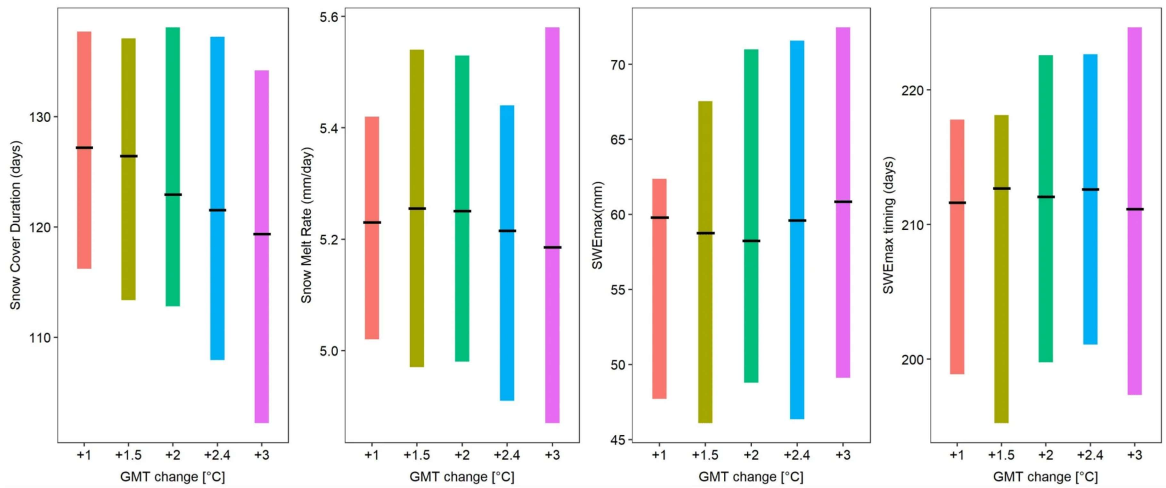
The scatterplot shows a negative correlation between the temperature of winter and summer and SWE_{max} and SWE_{max} timing which implies that the shift in these variables depends on temperature for two seasons. The significance of the correlations is in the brackets.

The negative correlation obtained for snow cover duration (SCD) and snowmelt rate (SMR), remarks a decrease in SCD and SMR in the future.

There is similar inference for precipitation.

- **Snow Change**

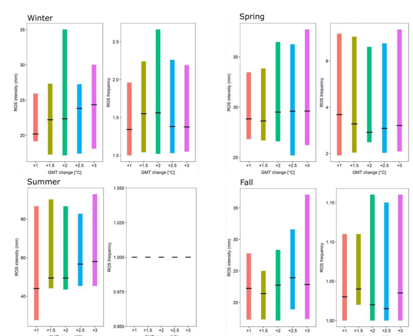
There is a decrease in SCD (Snow Cover Duration), SMR (Snow Melt Rate), and SWE_{max} timing; however, SWE_{max} has fluctuations under different GMT scenarios among the whole basin over the years. Overall, the temperature increase is the primary driver of SWE change that leads to lower SCD, slower SMR, almost lower $SWE_{max,}$ and earlier SWE_{max} timings with higher GMT increases.

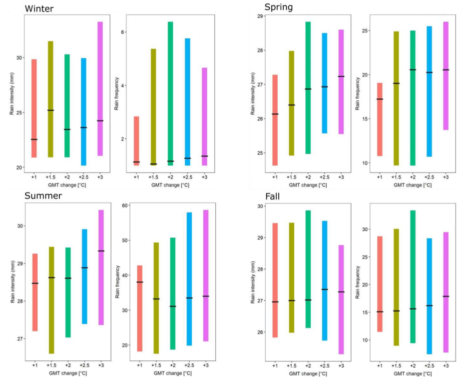


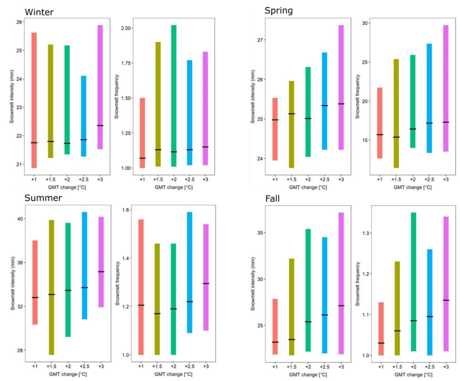
- **Flood generating mechanisms changes**

The results show variations in the intensity and frequency of ROS events at different GMT changes in the different seasons. Overall, the intensity of these events increases in different seasons with the GMT change raising for the whole basin, while the frequency of ROS events fluctuates.

Furthermore, the frequency and intensity of rain-only and snow-dominant events show an overall increasing trend at four seasons.




Winter
Spring
Summer
Fall
+1
+1.5
+2
+2.5
+3
GMT change [°C]


Winter
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+1
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+2.5
+3
GMT change [°C]

CONCLUSION

In this study, the effects of climate change on the flood generating mechanisms (rain-only, snow-only, and ROS events) have been quantified.

The main findings are as follows.

- Temperature shows an increasing trend for four seasons in the future under the climate change scenarios; however, precipitation indicates some fluctuations for fall and winter.
- Overall, such effects in the climatic variables influence the snow variables. Temperature rise causes a decrease in SCD, SMR, and SWE_{max} timing, and oscillations in SWE_{max}.
- The intensity and frequency of rain-only and snow-only events increase under different GMT changes over four seasons while for ROS mainly intensity increases over time.
- The rain-only mechanism is dominant currently and its frequency is increasing over time.
- The results BCCQ with a little bit difference approve the MBC results

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ABSTRACT

Flood events are influenced by terrestrial factors including land cover, land and water management, watershed physiographic features, and hydro-climatic components including snowmelt and precipitation. In Canada, flooding is a frequent and prominent natural disaster, which is modulated by different flood-generating mechanisms. In this study, we assess the intensity and frequency of three flood-generating mechanisms including Rain on Snow (ROS), intense rainfall, and snowmelt-driven flood events over the Assiniboine-Red River basin, which is one of the most flood-prone regions in Canada and located in the Lake Winnipeg watershed. We downscale and bias correct seven Global Climate Models (GCMs) that participated in CMIP6 using two methods of Bias Correction/Constructed Analogues with Quantile mapping (BCCAQ) (BCCAQ) and Multivariate Bias Correction (MBC). The observed and downscaled climate variables (precipitation and temperature) are used to drive a process-based distributed snow model to evaluate the changes in flood-generation mechanisms in the historical and future periods. The projected future changes are analyzed under policy-relevant global mean temperature (GMT) increases from 1.0 °C to 3.0 °C above the pre-industrial period. Overall, all models project higher regional temperature increases compared to the global mean with warmer and wetter winters. The snow model results indicate future decreases in the snow cover duration, snowmelt rate, and snow water equivalent (SWE), and earlier shifts in the maximum SWE timing. Moreover, both the intensity and frequency of ROS events increase in all seasons except summers. However, the increases in the rain and snowmelt events are mostly projected to occur in the spring.