Modelling the Athabasca watershed snow response to a changing climate

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Modelling the Athabasca watershed snow response to a changing climate

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Athabasca watershed
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ABSTRACT

Study region: The Athabasca River basin (ARB) with its head-waters located within the Canadian Rockies.

Study focus: Investigating the snow response of the Athabasca watershed to projected climate using the Variable Infiltration Capacity (VIC) hydrologic model and statistically downscaled future climate data from a selected set of CMIP5 GCMs forced with RCP4.5 and RCP8.5 emissions scenarios.

New hydrological insights for the region: High resolution end-of-century projections of SWE over the Athabasca watershed show an overall decreasing trend in the mean monthly SWE over the watershed, with the largest decreases occurring in March and April, especially in the high-elevation sub-basin. There are also widespread decreases in annual maximum SWE (SWEmax), with the middle-basin showing slight increases under the RCP4.5 scenario. The dates of SWEmax are generally getting earlier, with RCP4.5 showing a less linear response than RCP8.5. Increases in early spring snowmelt are followed by decreases during the late spring and summer months mainly as a result of earlier start of snowmelt. An overall decrease in snow-cover duration of up to fifty days is projected with the largest decrease occurring in the high elevation sub-basin. Such projected declines in snow water storage and a shift to earlier peak SWE and snowmelt over the ARB have significant implications for the magnitude and timing of the watershed soil-moisture content and hydrologic regime of the Athabasca River.

1. Introduction

Snowfall and seasonal snow cover are important components of the hydrologic cycle in cold regions because of their strong linkages with the regional climate and hydrology through their significant effects on energy and moisture budgets. Specifically, snow cover depth plays a significant role because of its water storage effect and role in generating spring snowmelt. Streamflow originating from mountainous-headwater catchments are primarily dependent on snow accumulation and melt from the higher elevations, which provide the major contributions to total basin flow. After the snowmelt, various processes, such as refreezing of water within the cold snow cover (Marsh and Woo 1985) and frozen soil infiltration (Gray et al., 1985) will affect the movement of water into the soil column below and to the stream channels. The relatively high albedo and low thermal conductivity of snow cover also have major influences on surface energy exchanges and the ground thermal regime with important consequences for snowmelt and soil hydraulic properties. After reviewing the potential impacts of a warming climate in snow-dominated regions, Barnett et al. (2005) indicated...
that less winter precipitation will occur as snow and the melting of winter snow will occur earlier in the spring. Berghuijs et al. (2014) have also indicated that one of the most widely anticipated changes in the hydrological cycle is the temperature-induced shift of precipitation from snow to rain that will affect snowpacks mostly in the mid to later part of the snow season. This shift has the potential to alter the frequency of rain-on-snow events that have a number of implications for hydrological processes over the land surface, including snow melt and streamflow (Cohen et al., 2015).

Snow response to projected changes in temperature and precipitation in northern and alpine dominated watersheds is complex, with the rate and sign of changes varying with local climate regime and elevation. Locally, snow water equivalent (SWE) responds to changes in both precipitation and air temperature, and the magnitude and seasonal characteristic of the change depends on the various interplay between a shortened snow-accumulation period, the fraction of precipitation that falls as snow, and the frequency and intensity of winter thaw events (Räisänen, 2008; Brown and Mote, 2009). Beniston and Stoffel (2016) identified that rain on snow events are major drivers of alpine flood events and future trends show that these events may increase as a first response to sustained warming but may decline thereafter. A global scale assessment of mountainous systems by Huss et al. (2017) shows the major shifts in seasonal runoff regimes around the world that will result from the effect of reduced snow cover and ice. Based on recent evidence over the European Alps, Marty et al. (2017) also reported a widespread reduction in snow mass, which is more pronounced for spring than for winter with even the highest elevation sites showing a decline in spring SWE. Using recently updated data to provide a comprehensive view of climate variability and long-term changes for the period of instrumental record over Canada, Vincent et al. (2015) reported a decrease in the amount of precipitation falling as snow in the south, fewer days with snow cover, an earlier start of the spring high-flow season, and an increase in April streamflow, all consistent with the observed warming and precipitation trends. They have also demonstrated that the different modes of low-frequency variability resulting from atmospheric teleconnections modulate the spatial distribution and strength of the trends; however, they alone cannot explain the observed long-term trends in these climate variables.

Most of the major rivers crossing the Canadian prairies originate in the Rocky Mountains, where deep snowpacks and melting glaciers maintain river and groundwater supplies (Schindler and Donahue, 2006). However, quantifying the volume of snow on the ground is challenging owing to its high spatial variability and sparse surface observations, as well as difficulties in retrieving relevant snow information from raw satellite data. Long-term observational data sets for snow cover extent have only recently been reconciled, and considerable observational uncertainty remains (Brown et al., 2010). Lapp et al. (2005) have demonstrated that the projected increase in winter precipitation over the upper Oldman River basin in southwestern Alberta, will not compensate for regional changes in the rain-to-snow ratios, and the net result will be a decline in winter accumulations of precipitation as snow, and hence, an expected decline in spring runoff. Pomeroy et al. (2015) have reported that a 2 °C warming in the Canadian Rockies will lead to a shift from snowfall to rainfall dominance, a substantial decline in snowpack magnitude, and a shortening of the duration of snow-season at all elevations. However, in many regions including the Athabasca River basin, the spatial and seasonal response of SWE to a warming climate has not been addressed in detail, with most previous studies focusing only on season average or annual maximum SWE (SWEmax).

The main objective of this paper is to present the findings of a detailed investigation conducted as part of the governments of Alberta and Canada Joint Oil-Sands Monitoring Program (JOSMP, 2012) on the Athabasca watershed snow response to a changing climate. With its head-waters located within the Canadian Rockies, snow accumulation and melt constitute a larger proportion of the Athabasca River discharge which plays an important role in sustaining aquatic habitats and in supporting various industrial activities in the region. The scenario based study is conducted using the Variable Infiltration Capacity (VIC) process-based and distributed hydrologic model (Liang et al., 1994) and the CMIP5 climate projection (Maloney et al., 2014). The VIC model has been used in numerous climate studies including evaluation of declines in western snowpack (Mote et al., 2005; Mao et al., 2015) and it has also been successfully applied for evaluating the effects of climate change on hydrologic regimes for watersheds with different basin size, climatology and hydrologic processes (Cuo et al., 2011; Christensen and Lettenmaier, 2007; Elsner et al., 2010; Werner et al., 2013). The VIC performance in modelling snow over the Athabasca watershed is first evaluated by comparing the SWE values simulated using gridded observed climate data with measured SWE data from snow course observations as well as an observation-based gridded snow product over the baseline period. This is followed by an assessment of the projected changes in the driving hydro-climatic variables (temperature and precipitation) over the watershed using the bias-corrected and spatially-downscaled climate projections from the latest CMIP5 data set. The CMIP5 daily precipitation and temperature data were also used to drive the VIC model to simulate the hydrologic response of the Athabasca River Basin (ARB) for the baseline and future periods, and compute the projected changes in the SWE over the entire watershed. This analysis focuses primarily on the spatial and seasonal changes in the magnitude and timing of the mean monthly and annual maximum SWE, snowmelt and Snow cover duration (SCD) in the 21 st century corresponding to the RCP4.5 and RCP8.5 emissions scenarios. The study area considered for this analysis, the ARB, is described in Section 2 followed by a description of the hydrologic modelling approach and the input data sets in Section 3. The results of the investigation are presented and discussed in Section 4 and a summary of key findings and final conclusions are presented in Section 5.

2. Studied basin description

The Athabasca River basin (ARB) originates in the Canadian Rockies from the Athabasca Glacier at over 3700 m above mean sea level (amsl) and flows approximately 1500 km north-eastward to Lake Athabasca at 187 m amsl. Its total drainage area attains approximately 156,000 km² near Old Fort before it flows into Lake Athabasca. Mean annual precipitation in the watershed ranges from around 300 mm at the downstream end near Lake Athabasca to over 1000 mm at the high elevation head-waters. The ARB has been divided into three hydro-physiographic regions based on differing climatic, hydrologic and topographic characteristics.
The three corresponding sub-basins along with their topographic characteristics are depicted in Fig. 1. The upper basin is characterized by mountainous topography and an alpine hydrologic regime dominated by significant snow and glacier-ice melt. The middle basin consists of rolling foothills dominated by boreal forest and is the origin of three major tributaries: McLeod, Pembina and Lesser Slave rivers. The lower basin begins at Fort McMurray where the river is joined by the Clearwater River and includes several smaller tributaries such as the Steepbank, Muskeg and Firebag rivers flowing from the east, and the MacKay and Ells rivers from the west. All three sub-basins display a typical nival hydrologic regime with low flows during the snow accumulation period of late autumn to early spring (November to March) and higher spring flows typically starting in April when air temperatures rise above 0 °C. Table 1 summarizes the physiographic and hydro-climatic characteristics for the upper, middle and lower sub-basins, including the percentage of each reach with respect to the total drainage area and the corresponding runoff coefficient depicting the generated runoff as a percentage of the total precipitation in each region.

The Athabasca River plays an important role in sustaining aquatic habitats and in supporting various industrial activities, such as utilities, mining and bitumen extraction in northern Alberta (CEMA, 2006). The viability of all these industrial activities in the region depends on water availability that could be affected by alterations to the basin snow regime resulting from a changing regional climate.

3. Data and methods

This study is conducted by running a calibrated VIC model (Eum et al., 2017) with observation-based daily gridded temperature and precipitation data and comparing the modelled SWE against observed snow surveys and observation-based gridded snow products over the 1981–2010 baseline period to determine the ability of the model to simulate observed SWE. This is followed by running a set of VIC model simulations with bias-corrected and statistically downscaled CMIP5 daily temperature and precipitation

Table 1

<table>
<thead>
<tr>
<th>Sub-basins</th>
<th>Elevation range (Average) [m]</th>
<th>Mean annual precipitation [mm]</th>
<th>Mean annual temperature [°C]</th>
<th>Percentage of total area (%)</th>
<th>Runoff coefficient (ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>3592 – 780 (1422)</td>
<td>724</td>
<td>1.8</td>
<td>15%</td>
<td>Hinton 0.76</td>
</tr>
<tr>
<td>Middle</td>
<td>1860 – 259 (802)</td>
<td>580</td>
<td>5.1</td>
<td>42%</td>
<td>Pembina 0.14</td>
</tr>
<tr>
<td>Lower</td>
<td>730 – 186 (525)</td>
<td>510</td>
<td>3.5</td>
<td>43%</td>
<td>Clearwater 0.25</td>
</tr>
</tbody>
</table>

Fig. 1. Topographic characteristics, river networks and the three sub-basins of the Athabasca watershed.
data for the 1981–2010 (1990s) baseline and two 30-year future periods (2041–2070 (1950s), 2071–2100 (2080s)) and computing projected change in monthly mean SWE, magnitudes and dates of SWEmax, snowmelt and SCD. A detailed description of the climatic drivers and the hydrologic model used in this study are presented below.

3.1. Climatic drivers

3.1.1. Observation-based gridded data

This study employed high spatial resolution, gridded daily precipitation and air temperature data for driving (forcing) a hydrologic model of the Athabasca watershed during a calibration and validation baseline period (Eum et al., 2017). The gridded data set, which includes daily precipitation and minimum/maximum air temperature, was developed by applying a thin-plate smoothing splines (ANUSPLIN) technique to station observations (Hutchinson, 2004; Hopkinson et al., 2011). The ANUSPLIN data generated by Natural Resource Canada provides a daily gridded data set covering the period from 1951 to 2010 at 10 km resolution over Canada taking into account complex spatial patterns in elevation and weather-station density (Hutchinson et al., 2009). A previous study has found that this data set provides one of the most reliable long-term, high-resolution gridded hydro-climatic data for the Athabasca watershed (Eum et al., 2014a). Therefore the ANUSPLIN daily precipitation and temperature data has been used as climatic drivers of the VIC hydrologic model during the calibration/validation period as well as for statistical downscaling of the CMIP5 Global Climate Models (GCMs) over both the historical and future periods.

3.1.2. Climate model projections

Hydrologic projections of future conditions are typically generated by forcing well-calibrated hydrologic models with global and regional climate projections that are based on a range of emissions scenarios, such as from the latest Representative Concentration Pathways (RCPs; van Vuuren et al., 2011). The latest generation of GCM projections originate from the CMIP5 long-term experimental runs corresponding to the four different levels of concentrations (RCP2.5, RCP4.5, RCP6.0, and RCP8.5) in which the labels of RCP represent an approximation of the radiative forcing in the year 2100 (Taylor et al., 2012). Murdock et al. (2013) suggested twelve representative CMIP5 GCMs to fully capture future climate variability for the Western North America (WNA) region. The ranking of the models, which differs by region, is carried out to provide the widest spread (range) in projected future climate for smaller subsets of the full ensemble (Cannon, 2015). The present study uses statistically downscaled data from the top six of the twelve GCMs, corresponding to mid-range mitigation (RCP4.5) and high emissions (RCP8.5) scenarios that represent a wider range of climate extremes and seasonal means of precipitation and temperature. Table 2 presents the six GCMs from the CMIP5 experiment used in this study.

3.1.3. Statistical downscaling of climate model projections

Murdock et al. (2013) compared the skills of different statistical downscaling (SD) techniques based on sequencing, distribution and spatial pattern related indicators, and recommended two of the more reliable SD techniques, the Bias-Correction Spatial Downscaling (BCSD; Maurer and Hidalgo, 2008) and the bias correction/climate imprint (BCCI; Hunter and Meentemeyer, 2005), for regional applications over Canada. These two SD techniques were adopted by the Pacific Climate Impacts Consortium (PCIC), at the University of Victoria, to downscale the climate scenario data for precipitation as well as daily minimum and maximum air temperature covering the period 1951–2100 to a 10 km spatial resolution using the ANUSPLIN data for the 1951–2010 reference period (Werner and Cannon, 2016). The BCSD method is an empirical statistical technique in which the monthly precipitation and temperature output from a GCM are downscaled using a quantile-based mapping of the probability density functions for the monthly GCM precipitation and temperature onto those of gridded observed data, spatially aggregated to the GCM scale. Daily results at high spatial resolution are obtained by spatial and temporal disaggregation using rescaled randomly sampled historical observations. The same low to high resolution mapping is applied to future GCM projections to generate statistically downscaled climate data corresponding to the various emissions scenarios. The BCCI method, on the other hand, uses long-term averages (i.e. 30 years) from the high resolution observational data as a ‘spatial imprint’ to represent spatial gradients. The ratio of daily GCM precipitation values to the long term average monthly climatology of the baseline period is multiplied by the corresponding fine-scale monthly values for a location to get the daily precipitation. The procedure is similar for minimum and maximum temperature, except values are calculated as the difference (instead of the ratio) between the monthly mean and the daily value (Hunter and Meentemeyer, 2005). Finally, the method applies quantile mapping as a post-processing step to the interpolated fine-scale outputs.

Based on the six CMIP5 GCMs identified earlier, this modelling study employs a total of 24 climate projections (6 GCMs × 2 RCPs

### Table 2

<table>
<thead>
<tr>
<th>Model Abbreviation</th>
<th>Institution</th>
<th>Resolution (Lon. × Lat.)</th>
<th>Primary reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNRM-CM5.1</td>
<td>Centre National de Recherches Meteorologiques and Cerfacs</td>
<td>1.4 × 1.4</td>
<td>Voldoire et al. (2013)</td>
</tr>
<tr>
<td>CanESM2</td>
<td>Canadian Centre for Climate Modelling and Analysis</td>
<td>2.8 × 2.8</td>
<td>Arora et al. (2011)</td>
</tr>
<tr>
<td>ACCESS1</td>
<td>Centre for Australian Weather and Climate Research</td>
<td>1.875 × 1.25</td>
<td>Marsland et al. (2013)</td>
</tr>
<tr>
<td>INM-CM4</td>
<td>Institute of Numerical Mathematics</td>
<td>2.00 × 1.50</td>
<td>Voldin et al. (2010)</td>
</tr>
<tr>
<td>CSIRO-Mk3.6.0</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
<td>1.875 × 1.86</td>
<td>Jeffrey et al. (2013)</td>
</tr>
<tr>
<td>CCSM4</td>
<td>National Center for Atmospheric Research (NCAR)</td>
<td>1.25 × 0.94</td>
<td>Gent et al. (2011)</td>
</tr>
</tbody>
</table>
[RCP4.5; RCP8.5] × 2 downscaling methods [BCCI; BCSD]) to investigate the snow response of the Athabasca watershed to projected climate change. Evaluation of the accuracy of these statistically downscaled climate data over western Canada and including the Athabasca watershed by Dibike et al. (2017) showed that the downscaled temperature and precipitation data were able to replicate the corresponding gridded historic data set over the baseline period, giving confidence in applying the data set for this study.

3.2. The VIC hydrologic model

The Variable Infiltration Capacity (VIC) land surface model is a process-based and spatially distributed macro-scale hydrologic model that simulates the water and energy balances necessary to accurately account for cold-climate hydrologic processes, such as snow accumulation, snowmelt, and infiltration into frozen ground, and to simulate the soil-atmosphere transfer processes based on prescribed land cover and three-soil layers (Liang et al., 1994, 1996). Specifically, it employs an energy-balance approach to represent snow accumulation and ablation on the ground (Andreadis et al., 2009). The model contains an explicit canopy snow interception scheme that accounts for sublimation, drip and release of intercepted snow based on the leaf area index (LAI). Ground snow accumulation and melt are simulated using a two-layer energy-balance model, in which the snowpack is divided into two layers (a thin surface layer and the underlying "pack" layer) and all the important heat and energy fluxes are considered (Anderson, 1968). Additionally, each grid cell is subdivided into elevation bands that represent the effect of sub-grid topography on snow accumulation and melt through orographic controls on precipitation and temperature. At each time step, the model calculates the rain or snow fraction that is added to the snowpack. There are several energy fluxes involved in the melting of snow that can act in opposing directions, that is either delivering heat to or removing heat from the snowpack. All those energy fluxes are then calculated and, if the energy balance is positive, melt occurs. Snowmelt is water produced by the melting of snowpack and if the liquid water holding capacity of both the surface and pack layers are exceeded then the excess liquid water is immediately released as snowpack outflow.

The features of such process-based modelling allow the extrapolation of plausible hydrologic processes corresponding to future climate projections (Ludwig et al., 2009). Mote et al. (2016) compared statewide average April 1st SWE from snow-course measurements over each of the three U.S. Pacific states of California, Oregon, and Washington with the corresponding VIC simulations and found them to be highly correlated with correlation coefficients of 0.92–0.94. Eum et al. (2014a, b) have also applied the VIC model (version 4.1.2) to the Athabasca River basin at 1/16’ grid resolution using 3 – hourly disaggregated ANUSPLIN precipitation and air temperature data, as well as surface pressure, wind speed, specific humidity, shortwave and longwave radiation data from the North American Regional Reanalysis (NARR). Because the CMIP5 climate projections used in this study have been downscaled based on the ANUSPLIN data at 10-km resolution, only three variables (daily precipitation, maximum and minimum air temperature: \( T_{\text{max}} \) and \( T_{\text{min}} \)) are available for long term hydrologic simulations. In recognition of this, Eum et al. (2017, 2016) previously applied the VIC model over the entire Athabasca watershed and to one of its sub-basins (the Muskeg River basin), using those variables from the ANUSPLIN and statistically downscaled CMIP5 climate model projections. Receiving the daily \( T_{\text{max}} \), \( T_{\text{min}} \) and precipitation values, VIC is able to empirically estimate the other energy flux terms over the basin based on geographic coordinates and topographic information. This study also used the Eum et al. (2017) setup of the VIC hydrologic model over the Athabasca watershed with more emphasis on the analysis of the snow response to the projected climate.

4. Results and discussion

4.1. Hydrologic model calibration/validation

The VIC hydrologic model calibration and validation for the Athabasca watershed was performed using daily discharge data from seven hydrometric stations for the periods 1985–1997 and 1998–2010, respectively (Eum et al., 2017). Five soil and baseflow parameters, which are most sensitive to runoff generation (Demaria et al., 2007) and that would considerably affect hydrologic responses for snow-dominated environments (Shi et al., 2008; Bennett et al., 2012), as well as two routing model parameters, were calibrated to minimize a multi objective function consisting of the Nash–Sutcliffe (NS) coefficient and a normalized form of root mean square error (RMSEnormal) computed from the daily observed and simulated streamflow. The performance of the VIC model to replicate the mean daily discharge of the Athabasca River mainstem during both the calibration and validation periods is summarized in Table 3 (for more information see: Eum et al., 2014b, 2017). With the best NS value being one, the VIC model NS values for the calibration period range between 0.78 and 0.90, while it varies between 0.74 and 0.80 for the validation period. Similarly, with the best RMSEnormal value being zero, the corresponding values for the calibration and validation period range between 0.27–0.33 and

<table>
<thead>
<tr>
<th>Station</th>
<th>Hinton</th>
<th>Windfall</th>
<th>Athabasca</th>
<th>Pt.McMurray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nash-Sutcliffe value</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>0.9</td>
<td>0.81</td>
<td>0.78</td>
<td>0.79</td>
</tr>
<tr>
<td>Validation</td>
<td>0.78</td>
<td>0.8</td>
<td>0.75</td>
<td>0.74</td>
</tr>
<tr>
<td>Normalized RMSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>0.28</td>
<td>0.27</td>
<td>0.33</td>
<td>0.3</td>
</tr>
<tr>
<td>Validation</td>
<td>0.34</td>
<td>0.27</td>
<td>0.35</td>
<td>0.33</td>
</tr>
</tbody>
</table>
The calibrated VIC model was then run with the high-resolution ANUSPLIN gridded climate data for the period 1981–2010. Fig. 2 presents the comparison of observed SWE values obtained from Alberta Environment and Parks’ snow-course measurement sites at three locations (from the upper, middle, and lower sub-basins of the Athabasca watershed) with the VIC-simulated SWE values at grid points nearest to each of the three sites. The comparisons are plotted for the 1981–2000 period during which there is a good record of SWE observations that covers a range of conditions with both high and low SWE and especially those years with lower SWE values that most probably correspond with the warm winters of the future scenarios. The maximum observed SWE is close to 300 mm for the Marmot-Jasper station in the upper sub-basin, while it is in the range of 100 mm and 150 mm for the Barrhead West and Embarras Port stations located in the middle and lower sub-basins, respectively. The VIC-simulated SWE values clearly show these same regional differences, although the model slightly overestimates SWE values in the upper reaches and sometimes underestimates them in the lower reaches. Mean absolute errors (MAE) between the observed and the VIC simulated SWE values are calculated to be 20.9, 19.5 and 75.5 mm corresponding to the station located in the lower, middle, and upper sub-basins respectively. These differences could be explained partly by the fact that the simulated results are average values over each model grid, but not point values exactly at the same location as the observing stations, while uncertainty in the observed SWE values could also have played a role. The other factor could be the fact that all the parameters needed for the snow energy balance calculation have to be derived from the three primary forcings (precipitation, minimum temperature, and maximum temperature) used in this study. Comparison is also made between the VIC simulated monthly mean SWE values and observation-based gridded snow product to see the broader special and seasonal validations as shown in Fig. 3. The observation-based gridded snow climatology for the 1981–2010 baseline period was deriving by combining the Atmospheric Model Intercomparison Project (AMIP2) monthly SWE product that covers the 1979–1997 period (Brown et al., 2003) with the Canadian Meteorological Centre (CMC) monthly SWE estimates for the 1998–2010 period.
While the VIC simulation resulted in slightly lower monthly mean SWE, especially at the high elevation region of the watershed, it was able to reproduce the overall spatial and seasonal pattern of the observation based AMIP2/CMC SWE analysis product. These validation results are considered to provide sufficient confidence for using the CMIP5-driven VIC hydrologic model projections to evaluate the long-term (to end of 21st century) spatial and seasonal variations in projected change in SWE over the Athabasca watershed.

4.2. Climate-change scenarios

The projected changes in seasonal (winter: December–February; spring: March–May; summer: June–August; autumn: September–November) mean precipitation and air temperature over the Athabasca River basin are shown as a scatter plot in Fig. 4. The figure shows projected changes (as percentage differences for precipitation, and absolute differences for air temperature calculated as the average of Tmin and Tmax) between the 1990s baseline (1981–2010) and the two future periods of 2050s (2041–2070) and 2080s (2071–2100) based on the statistically downscaled data from the six CMIP5 GCMs projections corresponding to the two climate projections (6 GCMs × 2 statistical downscalings) and two RCPs (RCP4.5 and RCP8.5). [winter: December–February; spring: March–May; summer: June–August; autumn: September–November.]
emission scenarios (i.e., RCP4.5 and RCP8.5) spatially averaged over the Athabasca River basin. The plots show projected increases in both precipitation and air temperature over the region except in the summer season when some models project decreases in precipitation (and one model even decreases in air temperature). The ensemble mean values for projected change in mean annual precipitation/temperature in the basin for the RCP4.5 scenario in 2050s and 2080s are 6.8%/2.7 °C and 12.5%/3.2 °C, while the corresponding values for RCP8.5 scenarios are 9.7%/3.3 °C and 14.4%/5.6 °C, respectively. Fig. 4 also shows that the inter-model variability in the climate projections becomes larger with increasing emission concentrations and projection horizons. However, there is a strong agreement among all the models that the highest increase in temperature is projected to occur in winter while the highest projected increase in precipitation is in spring. This is also evident in Figure A-1 of the supplementary material, which shows the highest projected increase in the ensemble mean-monthly precipitation occurring in May and June, and decreases in July and August. Considering the spatial variations in projected precipitation changes over the watershed also reveals that the highest increases in most seasons occur primarily in the upper alpine portions of the basin.

4.3. Snow response to projected climate

The potential response of the Athabasca watershed snow regime to a changing climate is investigated by forcing the calibrated/validated VIC model with the statistically downscaled CMIP5 climate projections for the baseline and the two future periods. Then the ensemble mean changes in the monthly mean SWE, magnitude and date of SWE max, snowmelt and SCD values between the baseline and future periods corresponding to each of the two emissions scenarios are computed over the basin. The inter-model variabilities in the projected changes in SWE values are also presented in the supplementary material provided with this paper.

4.3.1. Changes in monthly mean SWE

The ensemble mean projected changes in mean monthly SWE at each grid point over the Athabasca watershed are calculated by averaging the changes in mean monthly SWE values between the baseline (1990s) and each of the two future periods (2050s and 2080s) corresponding to each of the 12 sets of climatic drivers. Fig. 5 presents the snow response over the watershed corresponding to both the RCP4.5 and RCP 8.5 emissions scenarios. The results corresponding to the RCP 4.5 scenario indicate that while there are projected increases in SWE in some parts of the Athabasca watershed during the winter months from December to February, projections for all the spring months over the whole watershed, as well as some parts of the watershed in the winter months, show substantial decline in monthly mean SWE. The slight increases in SWE during the winter months are attributable to the projected increase in winter precipitation and the generally below freezing winter temperature in the region. In case of the RCP8.5 scenario, the model projects an overall decrease in SWE in both winter and spring seasons over all parts of the watershed. The decreases in SWE corresponding to RCP8.5 are also generally higher than those for RCP4.5. The SWE decrease over high-elevation portions of the upper basin even extends to the summer and fall seasons for both emission-scenarios. In general, while winter and spring precipitation in the region is projected to increase, it would not be able to compensate the effect of rising temperature in terms of reduced solid precipitation and enhanced melting of the snowpack.

The regional differences in SWE response to the projected climate are also depicted in Fig. 6, where the areal mean values of the ensemble monthly projected changes in SWE are plotted for each of the upper, middle and lower sub-basins of the watershed. The results show that while the decrease in SWE for the upper sub-basin occurs over the whole year, owing to the fact that the high elevation alpine areas in this region are covered by snow for most of the year, the largest decreases will be for the months of April, May and June with the monthly mean decreases by the end of this century ranging between 18 mm to 64 mm SWE, varying with the selected emissions scenario. The projected decreases for the middle and lower sub-basins are relatively lower than that of the upper

Fig. 5. Projected changes in ensemble mean monthly SWE between the baseline (1990s) and each of the two future periods (2050s and 2080s) over the Athabasca watershed under the RCP4.5 and RCP8.5 emissions scenarios.
sub-basin and are mainly in April and May ranging between 6 mm to 26 mm in monthly mean SWE. In all regions, the RCP8.5 scenario generally results in a higher decrease in monthly mean SWE especially during the 2080s period. However, there are also inter-model variations in the projected change in SWE especially for the winter and spring months and the variability is highest over the high elevation region of the upper sub-basin as shown in Fig. A-2 of the supplementary materials. One can also see in Fig. A-2 the differences between the results corresponding to each of the two SD methods used to downscale the climatic drivers. In general, the hydrologic model projections with the BCSD data shows higher decrease in SWE values during the winter and spring months compared to those with the BCCI data; and over the upper sub-basin, the differences in projected changes between the two SD methods are as big as, and some times more than those between the different GCMs. Box-and-Whisker plots of the ensemble mean monthly SWE values for the baseline and future periods for each of the three sub-basins are also presented in Fig. A-3 of the supplementary materials. The figure shows that the relative magnitudes of the projected changes in the monthly mean SWE values are quite significant as compared to their inter-annual variability. The inter-annual variability in the monthly mean SEW for the future periods remain more or less the same as the baseline period except for the months of February and March over the middle and upper sub-basins where the variability increases slightly for the future periods.

4.3.2. Changes in SWEmax

In most part of the Athabasca watershed, the SWEmax usually occurs in the winter months of February and March, although there may be some inter-annual and regional variations from those months. Fig. 7a presents the ensemble mean projected changes in the SWEmax value over the Athabasca watershed and the results under the RCP4.5 emissions scenario show a small projected increase (in the order of 1–10 mm) in the SWEmax values in most parts of the middle sub-basins, most probably due to the precipitation increase during winter, while other parts of the upper and lower sub-basins show a slight decrease or no change. At the same time, some very high-elevation areas in the upper sub-basin could experience relatively higher decreases (in the order of 30–50 mm) in their SWEmax. This result is consistent with those in Fig. 5 that show slight increases in mean monthly SWE values in some regions of the Athabasca watershed during the winter months and the generally below freezing winter temperatures. In the case of the RCP8.5 emissions scenario, the model projected some decreases in SWEmax over most part of the upper sub-basin with slight or no change in most part of the middle and lower sub-basins by the 2050s. However, by the 2080s under the RCP8.5 emissions scenario, all parts of the Athabasca watershed are projected to experience substantial decreases in the SWEmax ranging from 5 mm to over 50 mm depending on the region, with the largest decrease occurring in the upper sub-basin. These results are consistent with some earlier suggestions.
that increases in cold-season precipitation could mask the effects of climate warming until the warming is large enough to outweigh the effect of increased precipitation at which time snowpack may experience a sudden change. The corresponding ensemble mean changes in the dates of SWEmax are also examined and presented in Fig. 7b. The results show that the average date of SWEmax under the future climate will generally be earlier than that in the baseline climate while the magnitudes of the change varying between 3 to over 30 days depending on the location and climate scenario considered. The projected changes for the 2050s and the 2080s under RCP4.5 scenario are relatively small, ranging mostly between 3–15 days while the changes for the 2080s under the RCP8.5 scenario are relatively bigger ranging mostly between 15 to over 30 days. In all the cases, the high elevation region of the upper sub-basin will experience the largest change in the date of SWEmax. The Box-and-Whisker plots of the dates of SWEmax from all of the 12 GCMs for the baseline and future periods presented in Figure A-4 of the supplementary materials also indicate that the relative magnitude of the changes in the dates of SWEmax with respect to its inter-annual variability are quite significant at each of the three sub-basins and for both climate scenarios. Additional analyses on projected changes in the March 1st and April 1st SWE values are also presented in Figures A-5 of the supplementary materials. Those results also indicate that, while most regions corresponding to the RCP8.5 scenario and some regions corresponding to RCP4.5 emissions scenario show decreases in March 1st SWE values, almost all regions show decreases in the April 1st SWE values for both RCP4.5 and RCP8.5 emissions scenarios.

4.3.3. Changes in snowmelt

While part of the overall decrease in SWE is due to the decrease in the proportion of the total precipitation that falls in the form of snow (solid precipitation), the other important factor is the corresponding change in the snowmelt regime (melt magnitude and timing) over the basin, both resulting from projected increases in air temperature. Fig. 8 shows these projected changes in monthly snowmelt values over the Athabasca watershed corresponding to the RCP4.5 and RCP8.5 emission scenarios and the two future periods compared to the 1990s baseline period. The results indicate the general increase in snowmelt over the predominantly cold and snow-covered months between November and March, which are also expected to experience larger increases in air temperature. The snow cover gets depleted more quickly by earlier spring melt; hence there will be even less snow available on the ground to be melted, resulting in decreases in snowmelt during the late spring months of April and May, including the summer months for the upper sub-basin. There will also be a projected decrease in snowmelt for the early fall months of September and October most probably because of the decrease in snow fall as a result of the projected increase in temperature.
The regional difference in the snowmelt response to the changing climate is better visualised in Fig. 9. This figure shows a substantial change in the snowmelt regime over the high elevation alpine region of the upper basin with substantial increase in snowmelt, and hence depletion of the available snow on the ground, between November and April followed by a corresponding decrease in snowmelt between May and September. While the projected change in the snowmelt regime for the middle and lower reaches of the basin shows similar pattern, the magnitude of the changes are relatively smaller. All these changes in the snowmelt regime will have significant effect on the soil moisture regime over the watershed that would in turn affect the flow regimes in all tributaries and the main stem of the Athabasca River.

4.3.4. Changes in SCD

One other effect of climate change and the associated increase in temperature is the potential reduction in SCD; or the reduction in the average number of days with some snow on the ground. In this analysis, the average SCD is calculated using a threshold of 1 mm SWE to count the number of days with SWE > 1 mm within each model grid over the Athabasca watershed. Notably, while it is recognized that such a low SWE value corresponds to minimal depths of either newly fallen, light-density snow (e.g., 10 mm at $\rho = 100$ kg/m$^3$) or well-ripened melt-phase snow (e.g., 2 mm at $\rho = 500$ kg/m$^3$), the objective here is to simply show the basic changes in the presence/absence of snow in each model grid. SCD is computed from the VIC SWE output corresponding to each statistically downscaled GCM driver and each of the two emission scenarios for the baseline and the two future periods. Fig. 10a presents the spatial maps of ensemble mean SCD changes that show an overall reduction in the projected SCD over the Athabasca watershed. While the median SCD for the baseline period is in the order of 200 days [see Fig. A-6 in the supplementary materials], Fig. 10b shows that the reduction in SCD is generally in the order of 15 days to over 50 days by the 2080s with the largest decreases in the high elevation regions of the upper sub-basin. The reduction in SCD corresponding to the RCP8.5 emissions scenario is also much higher than that of the RCP4.5 especially for the 2080s period.

5. Summary and conclusions

The spatially distributed and process-based land-surface hydrologic model (VIC) of the Athabasca watershed driven by high-resolution gridded climate data was generally able to reproduce the spatial and seasonal patterns of the observed as well as the observation-based SWE analysis data over the watershed for the 1981–2010 baseline period. Application of VIC with a set of CMIP5 GCM climate projections, statistically downscaled to the same resolution of the observational gridded climate data, project future trends in the magnitude and seasonality of the watershed snow cover. While precipitation is projected to increase in all seasons except in summer, the hydrologic model simulations resulted in an overall decreasing trend in SWE over the entire watershed. The largest decreases of up to 50% are expected in March and April, with more decreases corresponding to the RCP8.5 than the RCP4.5 emissions scenarios. The decreases in SWE are generally higher in the upper (high elevation) regions than other parts of the watershed, mainly because of the generally higher than average snow accumulation at higher elevations and their relatively strong response to the warming trend. Most of these changes are largely attributable to the overall increase in temperature projected over the region that would result in lower than normal proportion of precipitation falling as snow. However, SWEmax (which usually occurs in February and March) is projected to increase in some parts of the watershed (mostly in the middle sub-basin) in the case of RCP4.5 scenario, while it decreases throughout the watershed for the case of RCP8.5 scenario. The projected increase in temperature also results in increasing snowmelt during winter and early spring months followed by decreases during the late spring months of April and May including the summer months for the upper sub-basin. All these changes will result in an overall decrease in the average SCD, in the order of 20–50 days, for end of century scenarios with the biggest decrease being again in the upper, high-elevation portions of the watershed.

In general, the overall projected reduction in snow cover over all regions of the Athabasca watershed is introduced by the warm
future climate that will reduce the average number of days with below freezing temperatures and lead to a portion of the precipitation shifting from snowfall to rainfall dominance. The projected increases in winter and spring temperatures will also increase the rate of snow ablation and melt, thereby reducing both the SWE and SCD over the entire watershed, with the reductions being more pronounced in the high-elevation alpine region of the upper sub-basin. The largest reductions in monthly mean SWE, however, are projected to occur in March and April except in the upper sub-basin where it extends from March to June. Moreover, while the differences in the projected changes in SWE and SCD corresponding to the RCP4.5 and RCP8.5 emissions scenarios are relatively small by the 2050s, they are significantly larger by the 2080s. The relatively small increases in the SWEmax over the middle sub-basin of the watershed corresponding to the RCP4.5 scenario could be attributed to the projected increase in winter precipitation with a more moderate increase in temperature for that particular scenario. The widespread decrease in SWEmax corresponding to the RCP8.5 scenario and especially during the 2080s indicate an enhanced response to higher emissions further into the future. The average date of the SWEmax is also shifted to earlier period by about 3 to over 30 days depending on geographic location and end of century climate scenarios considered, with the biggest shift being projected for the higher elevation region of the upper sub-basin and RCP8.5 scenario. However, there are also significant inter-model variabilities in the snow response to projected climate including

Fig. 9. Projected changes in ensemble mean monthly snowmelt between the baseline (1990s) and the two future periods (2050s and 2080s) averaged over each of the three reaches of the Athabasca watershed under the RCP4.5 and RCP8.5 emissions scenarios.
those between the different SD approaches. While the results presented in this study accounts some of the uncertainties resulting from different emission scenarios, climate model projections and downscaling techniques, a number of other uncertainties resulting from hydrologic model representation, model parameter estimation, etc. may still remain. All these changes in the snow accumulation and snowmelt regime over the Athabasca watershed is expected to have huge implications on the magnitude and timing of the watershed soil-moisture content and subsequently on the hydrologic regime of the Athabasca River resulting in warming-induced shifts in water availability over the region.

**Declaration of interest**

We wish to confirm that there are no conflicts of interest associated with this publication and there has been no financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.ejrh.2018.01.003.

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