Dear handling editor,

Thank you for giving us the opportunity to revise our manuscript following the second round of reviews. Your three final remarks are addressed below. Our response is shown in italics and in blue colour.

1) Referee #2 still has made two remarks. You can choose whether or not you want to add a comment addressing those into the final manuscript.

> The authors addressed well my comments and suggestions in the revised manuscript except for bias-correction of streamflow and scaling aspects of river flow routing.
>
> 1) Given the observed streamflow at the hydrometric stations, i.e., outlet of each river basin, the routed streamflow can be bias-corrected as a post-process to enhance reliability in projected streamflow without calibrating hydrologic and land-surface models.
>
> 2) If spatial resolution in routing is not sensitive to the accuracy in streamflow for a large-scale basin (e.g., Mackenzie River basin), as addressed in the revised manuscript, I still think that a simple aggregation of runoff at each time step within a basin may provide streamflow comparable to those from a routing model. For example, Li et al. (2019) calculated streamflow using the direct aggregation of the runoff and baseflow over the drainage area for each gage as they confirmed that runoff routing vs aggregation differences in both streamflow timing and magnitude at the daily time scale are modest.

We have tried our best to address all reviewers' comments from the past set of reviews, and we are glad that this reviewer is satisfied with our revisions. However, we have decided to not take into account suggestions made in this second round of review because of the reasons discussed below.

First, the bias correction of routed streamflow after-the-fact will not only compensate for routing biases but also biases in CanRCM4 climate, and the biases in the land surface model itself. In addition, streamflow bias correction adapted for the present day cannot be used for bias correction in the future especially for high emissions scenarios. This is because bias correction for the present day climate will not be valid for simulated future streamflow because of the shift in the timing of the peak flow, projected for all basins, and for the shift in flow regime from snow-dominated to hybrid regimes, projected for the Fraser and Columbia basins. We do not think that bias correction for routed streamflow will be scientifically defendable.

Second, aggregating runoff (without routing) as in Li et al. (2019) is not appropriate for our study because the catchments considered in that study are much smaller in size than the *continental scale river basins considered in our study. Based on our tests (not shown) the time difference in the peak runoff and peak streamflow for the Mackenzie River basin, i.e. the delay caused by routing, is of the order of about a month. This is a not a trivial delay. So in our opinion, the suggestion to not route runoff is worse than ignoring the effects of anthropogenic regulation (that we have tried to address for the Columbia River by using naturalized streamflow) and the simple treatment of ice jams in our routing approach.*

2) Line 117 in the revised manuscript with track changes: I believe "that" should be removed.

We have broken this long sentence into two sentence and reworded it for clarity on Page 6 of the revised manuscript.

3) I appreciated the added new discussion in Lines 116-153 and 154-162 (again in the track-changes manuscript), but it could be greatly strengthened by adding some references. Especially after the discussions during the review process, I strongly encourage you to try and find some papers that could back up these statements (if available).

Thank you for this suggestion. We have added a couple of small additional sentences to this paragraph and four new references. This modification is also on page 6.

Best regards,
Authors

The effect of climate change on the simulated streamflow of six Canadian rivers based on the CanRCM4 regional climate model

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Abstract

The effect of climate change on the hydro-climatology, in particular streamflow, of six major Canadian rivers (Mackenzie, Yukon, Columbia, Fraser, Nelson, and St. Lawrence) is investigated by analyzing results from the historical and future simulations (RCP 4.5 and 8.5 scenarios) performed with the Canadian regional climate model (CanRCM4). Streamflow is obtained by routing runoff using river networks at 0.5° resolution. Of these six rivers, Nelson and St. Lawrence are the most regulated. As a result, the streamflow at the mouth of these rivers shows very little seasonality. Additionally, the Great Lakes significantly dampen the seasonality of streamflow for the St. Lawrence River. Mean annual precipitation (P), evaporation (E), runoff (R), and temperature increase for all six river basins in both future scenarios considered here, and the increases are higher for the more fossil fuel-intensive RCP 8.5 scenario. The only exception is the Nelson River basin for which the simulated runoff increases are extremely small. The hydrological response of these rivers to climate warming is characterized by their existing climate states. The northerly Mackenzie and Yukon River basins show a decrease in evaporation ratio (E/P) and an increase in runoff ratio (R/P) since the increase in precipitation is more than enough to offset the increase in evaporation associated with increasing temperature. For the southerly Fraser and Columbia River basins, the E/P ratio increases despite an increase in precipitation, and the R/P ratio decreases due to an already milder climate in the Pacific north-western region. The seasonality of simulated monthly streamflow is also more affected for the southerly Fraser and Columbia Rivers than for the northerly Mackenzie and Yukon Rivers as snow amounts decrease and snowmelt occurs earlier. The streamflow seasonality for the Mackenzie and Yukon rivers is still dominated by snowmelt at the end of the century even in the RCP 8.5 scenario. The simulated streamflow regime for the Fraser and Columbia Rivers shifts from a snow-dominated to a hybrid/rainfall-dominated regime towards the end of this century in the RCP 8.5 scenario. While we expect the climate change signal from CanRCM4 to be higher than other climate models, owing to the higher-than-average climate sensitivity of its parent global climate model, the results presented here provide a consistent overview of hydrological changes across six major Canadian river basins in response to a warmer climate.

1. Introduction

As the global population and the standard of living increases so does the strain on freshwater resources. The natural availability of water is determined by the balance between precipitation (P) and evaporation (E) (this includes both evaporation and transpiration from plants). When precipitation exceeds evaporation, which is determined primarily by available energy, the water that does not evaporate or transpire (either at the surface or after infiltration into the soil) termed runoff (R) is carried by the rivers to the oceans. The seasonality of precipitation, its partitioning into snow and rainfall, and the seasonality of snowmelt and evaporation, all of which are determined by the climate in a given catchment or river basin eventually determine the seasonality of runoff. As anthropogenic climate change progresses, changes in the mean annual amounts and the seasonality of these different water budget components will lead to corresponding changes in runoff (Trenberth et al., 2007). Changes in precipitation extremes are also expected to lead to corresponding changes in the extremes of streamflow. The changes in streamflow have implications for floods and power generation. While runoff is expressed in similar units to precipitation and evaporation (depth of water per unit time, e.g. mm/s or m/year), streamflow is the volume of water generated per unit time (e.g. m^3/s or km^3/year) and requires multiplication with the area over which runoff is generated. Streamflow is also routed down the river network which introduces a time lag and attenuation of the peak runoff.

Output from climate and Earth system models (ESMs) remains the primary source of information for evaluating climate change impacts. Current approaches that rely on information generated by ESMs, to obtain an estimate of how future streamflow may potentially change, may be classified into two broad categories. The first approach uses simulated runoff directly from the land surface component of single or multiple climate models which may be routed downstream to obtain streamflow at the mouths of river basins and at different points along a given river network (Arora and Boer, 2001; Miller and Russell, 1992; Zhang et al., 2014). Using direct runoff output from climate models has the benefit that the calculated changes in runoff are physically consistent with the altered radiative balance of the Earth in response to increases in the concentrations of greenhouse gases (GHGs). The corresponding changes in the general circulation of the atmosphere result in the associated changes in near-surface temperature, precipitation, and the hydrological cycle. However, this approach suffers from three limitations – 1) the biases in the climate simulated by the climate model, 2) the fact that the land surface components of climate models are not calibrated for a given river basin but rather designed to operate in a reasonably realistic way over the whole globe, and 3) the coarse resolution of global climate models (GCMs). The last limitation is partially addressed when data from finer-resolution regional climate models is used. The biases in the simulated climate do affect the simulated runoff for the current climate. Despite this, the approach can effectively capture the effects of climate change including increased evaporative demand (Winter and Eltahir, 2012), reduced snowpack (Salathé et al., 2010; Shrestha et al., 2021a), increased winter streamflow, and earlier snowmelt-driven peak flow (L. Sushama et al., 2006; Poitras et al., 2011). The second approach attempts to overcome these limitations by downscaling and/or bias-correcting climate from climate models for future scenarios and uses that to drive a well-calibrated hydrological model for given catchments or river basins (Gosling et al., 2011; Ismail et al., 2020; Miller et al., 2021; Yoosefdoost et al., 2022). The second approach is more prevalent for watershed to regional scale impacts and adaptation studies. Given the large effort involved in downscaling and bias-correcting raw climate data from climate models, most current impact studies use downscaled and bias-corrected data put together by other groups rather than specifically doing this for their project. Recent examples include the downscaled and bias-corrected climate data for the conterminous United States (Thrasher et al., 2013) based on climate model output from the fifth phase of the Coupled Model Intercomparison Project (CMIP5), and statistically downscaled and bias-corrected data from five CMIP5 models, available at the global scale, tailored to the requirements of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Lange, 2019). Both these data sets have found large applications in the impacts and adaptation community. The processes of downscaling and bias correction are distinct, and they both have their inherent limitations. There are several examples of the limited ability of bias-correction to correct and downscale variability, and that bias-correction can potentially cause implausible climate change signals (Maraun, 2016; Maraun et al., 2017). There are also uncertainties, substantial contradictions, and sensitivity to assumptions between the different downscaling methods (Hewitson et al., 2014).

Finally, while land surface models are typically used within the coupled framework of climate models, hydrological models are typically used as a standalone model for impact studies. While the primary output quantities from hydrological models are runoff and streamflow, land surface models output a range of water, energy, and CO_2 fluxes (Blyth et al., 2021; Fisher and Koven, 2020). The layer of air directly above the land surface, commonly referred to as the atmospheric or planetary boundary layer, is affected by surface-atmosphere exchanges of energy and water and extends upward into the atmosphere. A realistic representation of turbulent fluxes

Formatted: Underline, Font color: Red of energy and water in the planetary boundary layer is essential to the transport of moisture and energy through the atmosphere. As a result, while calibration of hydrological models to reproduce observed streamflow is a routine exercise (Chegwidden et al., 2019; Hattermann et al., 2018; Huang et al., 2020; Hundecha et al., 2020), land surface models cannot be calibrated to reproduce a single or a small subset of quantities. This aspect of land surface versus hydrological models is also addressed briefly in Bolaños Chavarría et al. (2022). A review by Overgaard et al. (2006) also attempts to differentiate land surface models from hydrological models. In contrast to hydrological models, land surface models are expected to reproduce reasonably realistic estimates of a range of energy, water, and CO_2 fluxes over the whole globe. The philosophy behind land surface models, as they are used in the context of climate models, is that given 1) a model's structure and parameterizations, 2) the driving geophysical data for fields such as vegetation cover, soil depth, and soil texture, and 3) the driving meteorological variables, a model is expected to reasonably realistically reproduce various components of the water, energy, and carbon cycle at the global scale. The global scale of land surface models within the framework of climate models precludes tuning of their parameters for individual grid cells or for a region (e.g. a river basin) to reproduce a small subset of model outputs.

While well-calibrated hydrological models are generally suitable for a given catchment or a river basin their application cannot be easily extended to large-scale global or regional hydrologic modelling studies since it is typically not feasible to tune model parameters for all grid cells in a large domain. For a large region like Canada correctly representing anthropogenic regulation using downscaled and bias-corrected climate data from an ensemble of climate models is a challenging task. As a result, this has been done for only a few selected river basins,

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considering only one basin at a time. In the end, both approaches have their strengths and limitations for assessing climate change impacts on hydrology and can be considered complementary to each other.

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Future hydrologic projections using the second approach (hydrological modes driven by statistically downscaled and bias-adjusted climate models) are available for selected river basins in Canada. The results over the Prairies and British Columbia (Shrestha et al., 2021b; Sobie and Murdock, 2022) generally indicate shorter snow cover duration, earlier snowmelt, and reduced annual maximum snow water equivalent as the climate warms. Streamflow projections across Canada generally indicate earlier snowmelt-driven peak flow, increased winter flow, and decreased summer flow (Budhathoki et al., 2022; Dibike et al., 2021; Islam et al., 2019; MacDonald et al., 2018; Shrestha et al., 2019). Annual streamflow is projected to increase, with higher increases in the northern basins (Bonsal et al., 2020; Stadnyk et al., 2021). However, these projections are based on different climate and hydrological models, downscaling methods, emissions scenarios, and future periods, and no consistent set of projections is available across all major river basins of Canada.

Field Code Changed

In this study, we have used the first approach to provide a consistent set of projections across all major river basins of Canada, while being cognizant of its limitations. We investigate the effect of climate change on the annual, monthly, and daily streamflow characteristics of six major Canadian rivers (Mackenzie, Yukon, Columbia, Fraser, Nelson, and St. Lawrence) using runoff output from simulations performed with version 4 of the Canadian Regional Climate Model (CanRCM4) (Scinocca et al. 2016). The river basins of the Yukon and Columbia Rivers cover part of the United States of America as well. We used daily runoff generated from CanRCM4 for