We greatly appreciate input and comments by the reviewers and associate editor. In the new revised version, we have addressed almost all of them. Please find a point by point answer following by a marked up version of the revised manuscript:

Dear authors,

Thank you for your responses to the reviewer comments and for the revision of the manuscript. Both reviewers were positive about the manuscript and recommended to publish it after some considerable revisions. The results showing increases in winter discharge in key watersheds within southern Ontario under future climate are of interest, and the study helps improve understanding of the potential hydrological impacts. However, the revised manuscript suffers from a number of issues of clarity and other problems, and will require further revisions to bring it up to the quality standards for this journal. Both reviewers offered constructive and helpful comments on how this paper needs to be improved, but I find these have not yet been fully addressed. A more careful and thorough effort is required.

Major Issues

1. The model must be more fully explained and justified as to its appropriateness for use in this region and under changing climates. Why is it appropriate for use here and what are its main limitations? Simply referring to the fact that others have used it and citing your earlier paper are not sufficient. The snowmelt routine appears to be a simple temperature index approach (i.e. a snow energy balance approach explicitly accounts for turbulent and radiative energy exchanges), and here the only inputs are temperature and precipitation. So why and how can this be justified under future climates?

PRMS model has been used in this study because of its coupling capability with Modflow. The integrated model (GSFLOW) is planned to be used in this region in future studies (which would improve the results concerning groundwater flow). We added this justification to the manuscript. Temperature and precipitation are simple variables that have a direct impact on streamflow. A model with a greater number of variables will be more time consuming, especially multiplied by 50 members and it would lead to more uncertainties associated to each variable. Moreover, a recent study have shown that the snowmelt routine using temperature works well in the Big Creek watershed (Champagne et al., 2019)**. These explanations were also added to the manuscript.**

2. There needs to be more detail and explanation of the model setup, parameterization, and calibration/validation. Both reviewers were adamant about this. More discussion is needed on model and data uncertainties, especially given the bias in simulated winter flows as noted by reviewer #1. The comments by reviewer #2 included a number of important issues to address

regarding model setup and geofabric. Why is it ok to neglect control structures and reservoirs, especially on the Grand River, where there are a number of flood control dams? (See specific comments further below.)

Model setup and grid structure has been clarified and a figure has been added to the supplementary materials. We added more details of the model structure and the calibration/validation as suggested. Concerning the uncertainties associated to the dams the model has been calibrated and validated using the regulated flow series. Therefore, the dam effect if any should be implicitly accounted for during the model calibration. A more detailed study or analysis of control structure was not the main focus of this study. However, this is an important aspect and we will be exploring these aspects and impacts in a follow up future study

3. The ascending hierarchical classification needs to be better described, and perhaps better illustrated, as it remains quite unclear. The reader needs to understand this. Why focus on runoff response groupings, given the non-linear nature of runoff, as opposed to strictly synoptic climatological patterns?

We have renamed the ascending hierarchical classification as agglomerative hierarchical clustering, which correspond more adequately to the literature. The description of an AHC has been improved and a reference has been included. A runoff response grouping has been used to investigate if a similar change in streamflow can be associated to a similar change in atmospheric circulation. A group of runoff response can be associated to a mean streamflow change and a mean circulation change. It worked well with the extreme groups with clear atmospheric patterns for the largest and lowest increase in streamflow. This approach from the impact (streamflow) to the forcing (atmospheric circulation) may have more application than synoptic climatological patterns. It identifies groups of streamflow change than can be used independently of the atmospheric circulation. A sentence explaining this choice has been added to the manuscript.

Detailed Comments

I refer to page and line numbers for the "clean" (i.e. non marked-up) version of the ms. My comments here are meant to help specifically address some of the reviewer concerns and to flag other issues that need to be dealt with.

P1, L12 and throughout: what is "internal variability of climate"? This term is central to the paper, but it isn't made entirely clear what this actual means. Does it refer to variation among the ensemble of climate model outputs?

The internal variability of climate refers to the variability of climate due to inherently internal processes within the climate system. It is opposed to the variability of climate due to external forcing such as anthropogenic forcing (CO2 increase) or natural forcing (Volcanic eruptions and changes in solar radiation). A more clear definition of internal variability of climate has been added to the manuscript.

P1, L18-22: the short summary of results is very unclear. What is meant by the terms in parentheses? The reader can't understand this by just reading the abstract. How significant is it that 14% of the ensemble members predict a high increase? What about the rest of the ensemble? More importantly, what is the magnitude and variation of projected flow changes?

A clearer explanation of the results has been added to the abstract and especially the percentage change in streamflow for the different classes (and standard deviation).

P1, L22: what does the 16% refer to? This isn't clear.

This 16% corresponded to the number of members in the class HiQHiT (16% of the entire ensemble). This number has been removed to make the abstract clearer.

P1, L22: what is "internal variability of hydrological projections"?

How internal variability of climate will modulate hydrological projections is a more correct formulation. The sentence has been modified accordingly.

P1, L30: the "choices" are really cascading sources of uncertainty throughout the modelling process. And does this link in to the concept of internal variability of climate? There is an opportunity to explain all of this more clearly here.

Internal variability of climate is one of the sources of uncertainty which cascades to the hydrological model simulations. How internal variability contributes to the total uncertainty has been explained more clearly.

P2, L15: "future climate data should not be used…" – do you mean that coarse-scale climate model outputs shouldn't be used directly?

We meant that the coarse scale climate model outputs shouldn’t be used directly. This sentence has been modified to increase clarity.

P2, L29: does a large ensemble assess the entire range of internal variability? Does this not also depend on selection of RCP, GCM, downscaling method, bias correction, hydrological model, parameterization, etc.?

We agree that the total uncertainty depends on all of these factors but the uncertainties due to internal variability of climate (explained more clearly in the new revised of the manuscript) is a very specific type of uncertainty. It can be assessed by modifying the initial conditions of a GCM (model ensembles). The larger is the number of members in the ensemble, the higher is the range of internal variability that can be assessed. The ‘’entire’’ range was perhaps an overstatement. It has been replaced with ‘’large’’ in the revised manuscript.

P2, L30: instead of “processes”, do you mean “responses”?

Responses is more appropriate here and has been used instead of processes.

Introduction section: In general, this section should be a bit more clear on the overall purpose and objectives of this study, and on how it builds on previous work to advance understanding. What is new and how and why is it important?

The objectives of the study section have been improved in the new revised version of the manuscript.

P3, L8-9: What about other urban areas such as Kitchener–Waterloo and others?

Other urban areas such as Guelph, Cambridge and Kitchener-waterloo were added here.

Section 2.1: This section should describe the major landcover types in more detail, and a bit on the climate and the hydrological regime. For example, there is a lot of deciduous forest cover. How much snow is there and when does it melt? What are the key characteristics of regional climate?

The description of the watersheds has been improved by including details about the amount of precipitation and snowfall per year, the spatial variability of precipitation, the type of flood regime as well as a more precise description of the land cover.

P3, L18: Is this daily forcing data? Please indicate in the ms.

It is daily forcing data. This information has been added.

P3, L25: this model is not using a snowmelt energy balance approach, and this needs to be rectified here and also justified.

This model uses the concepts of the energy balance approach but is using temperature as main driver of snow processes. This statement has been removed from the manuscript and more accurate description has been included.

P3, L30-31: The model is really using a grid, which is different than HRUs, so it should say "coarser grid". Also, what is "parameterization computation time"?

Term HRU has been replaced with grouped hydrological units (GRU) in the entire manuscript. The "Parametrization computation time" meant that Arcpy-GSFLOW has not been functional with a large number of GRU's. The sentence has been modified in the revised manuscript.

P3, L31 - P4, L1: There is a need for more detail on the model, what processes are represented, how it is run, etc., and then references can be added for further, more specific details.

A more detailed explanation of the model has been added to the manuscript as suggested.

P4, L4: What is the full reference for the "Natural Resources Canada" data? This is needed.

A full reference has been added to the manuscript.

P4, L11: despite analyzing 30-year average flows, the model simulations and the calibration approach uses daily flows, so the approach to neglect flow controls needs better justification.

The model has been calibrated and validated using the regulated flow series. Therefore, the dam effect, if any, should be implicitly accounted for during the model calibration. We assume that the flow control will not be modified in the future and that the relative change in streamflow will not be impacted by the dams.

Section 2.2: More details are needed on how the how the model was set up and parameterized, following the advice of reviewer #2. It isn't clear how parameters were set, how they varied among basins and HRUs, and how the HRUs were defined. In fact, the approach seems to be more consistent with a grouped response unit approach, where physical landscape groupings and their proportional area are derived from a grid, and parameters are set for the GRUs. Which parameters were important in the calibration and which were the results most sensitive to? Were there ranges that certain parameters were restricted to? Table 2 indicates that 17 parameters were determined by calibration alone, which provides a high potential for model equifinality, and so a more detailed explanation is important.

The word HRU has been replaced by GRU in the entire manuscript. More details of model setup and parametrization have been included. The spatial variability of the parameters has been added in the supplementary materials. A sensitivity analysis of the parameters has been performed for the Big Creek watershed and results has been added in the supplementary material as well.

P4, L5: instead of each HRU, the percentages were determined for each grid cell.

HRU has been replaced by GRU to show that grid cells were used.

P4, L27: Table 3 provides NSE and PBIAS info, not a set of model parameters.

This was a mistake. We were referring to Table 2. This has been modified in the manuscript.

P4, L28: the range is less than -15 to 15%, so why say this and not the actual range?

The reference to -15 to 15% was used because it is considered as a good fit according to Moriasi et al. (2007).

P4, L30-31: What can be said about how well the model represents processes within the watershed, such as snow accumulation and melt, for example? This relates back to the points about physical appropriateness of the model.

More details on the calculations of the snow processes have been added to the manuscript. The representation of snow has been tested in Big Creek watershed (Champagne et al., 2019) **and was satisfactory. A reference to this study has been added to the manuscript.**

Section 2.3: The bias correction procedure is not adequately described. How well did the data compare and what type of correction was necessary? There is not enough information to determine what was done.

The description of the bias correction technique has been improved and the comparison between bias corrected and raw data has been added to the supplementary materials.

Section 2.4: This is still very unclear and there are no further details or reference provided to give more clarity. See comments by reviewer #2. A more clear illustration or some more detail may be needed to clearly explain this to the reader.

This section has been rewritten for clarity. The ascending hierarchical classification has been renamed agglomerative hierarchical clustering which correspond to more references in the literature. A reference has been also added.

P5, L21: What is the Euclidean distance between pairs (i.e. in what space)?

The intraclass variance has been used at each grouping step. The term Euclidean distance has been removed from the manuscript

P6, L5-8: Here is where internal climate variability is defined. So is this essentially the variation in forcing among the ensemble of climate model outputs?

The internal variability of climate is the variability of climate not due to forcing but only due to the chaotic variability of atmospheric circulation. The explanation of internal variability has been improved through the manuscript. It has now been explained earlier in the text.

P6, L11: what qualifies as a high flow? Is there a specific threshold?

High flows are defined as streamflow higher than a threshold corresponding to the average streamflow plus three times the standard deviation using the observation streamflow. The description of the high flows has been added to the revised manuscript.

P6, L22-27: These are important results and should be described in more detail. For instance, what are the magnitude and variability of the changes? How do the results differ among the ensemble members?

The 50-members average changes and standard deviation has been added to the manuscript. This gives information on how the results differ between classes and inside classes.

P6, L30: higher than what? Than the range of air temperature?

Change in precipitation appear more variable between members compare to the change in temperature. This has been described in the revised manuscript

P7, L8: Are you referring to Jan-Feb streamflow? The section heading indicates that, but it isn't specified.

Yes we are referring to January-February. January-February streamflow has been specified in the manuscript

P7, L18: Instead of "majoritarily" it would be better to simply say "mostly" or "for the most part".

We replaced majoritarily by the "most part" in the manuscript as suggested.

P8, L31-32: It is not clear why groundwater shows these differences, and this relates back to the need to explain how the models handles such processes.

Big Creek shows a lower increase in overall streamflow. Therefore, it is likely that change in groundwater flow is also lower. This has been added to the manuscript.

P9, L7-8: monthly resolution of what? And what was the issue with representation of winter processes?

It was mostly lack of ponding and frozen soil in the HydroGeosphere model that may have overestimated streamflow in winter. According to Erler et al., (2018) **frozen soil may delay the streamflow due to more ponding. We have mentioned these aspects in the revised manuscript.**

P9, L11-12: This is not correct. It is not clear how model structure and process representation affect the simulation of internal watershed processes, such as snowmelt and routing.

Not all processes can be compared to observations but Snowpack was satisfactorily simulated by PRMS model using NRCANmet in Big Creek watershed. This statement has been added to the manuscript.

P9, L14-19: How confident can you be about the use of NRCANmet? Just because it is "widely used" isn't justification enough. There should be some indication somewhere about how well the simulations capture other variables (i.e. the internal watershed processes – especially snow accumulation and melt). Also, if measured Q is overestimated, would that not indicate that the problems with the model are even worse? Reviewer #1 raised some important concerns around the evaluation of the model.

Snow accumulation is adequately simulated by PRMS model when forced by NRCANmet as its have been shown by Champagne et al. (2019)**. Measured Q may be overestimated during ice conditions but the model was calibrated using these possibly overestimated values. The actual**

discharge, taking into consideration ice on the river, could be used to calibrate the model, but this is not likely to improve the ability of the model to simulate winter streamflow. The statement on stream ice is aimed to show that measurements can also have errors or uncertainties but not to explain why the model overestimates streamflow.

P9, L27-31: This is unclear and could perhaps be better written.

This part has been rewritten.

P10, L23: high Z500 anomalies enhance what?

The Z500 anomalies are increasing. It has been reformulated to increase the clarity.

Section 4.3: It is not clear what the discussion here is getting at. Is it that variability among the ensemble members still predicts similar local weather patterns? Does this relate to the internal climate variability issue? It could be more clear.

The goal of this paragraph is to discuss the method of classes used in this study. There is a large atmospheric variability between members of the same class that produce similar local conditions. Some sentences were rewritten to increase clarity.

P11, L2-3: Presumably, this is because only T and P data were fed into the model as forcing variables?

The goal of this paragraph is to discuss the role of temperature and precipitation that directly impact streamflow in the same months opposed to delays in the relationships due to snow process and groundwater. The mention of January-February has been added to increase the clarity.

P11, L24: How do you know this correlation isn't an artifact of the model due to the representation of groundwater?

PRMS model is not adapted to answer this question. A surface-groundwater coupled model such as GSFLOW is therefore suggested to be used to confirm this hypothesis.

P11, L26-28: It was presumed that examining the influence of different weather patterns on streamflow regime was a purpose of the study. So what can be said about what the findings of this study suggest?

This study didn't examine the atmospheric conditions that occurred in the previous months (November-December) while they could have an impact in the modulation of streamflow in January-February. The results in the lags between precipitation and January- February suggest that the succession of different atmospheric patterns in the previous months can have an impact on the January-February modulation of streamflow.

P11, L32: When it says "there will be less snow", it isn't clear initially that this isn't entirely a model projection, but that under the current climate the hydrological regime is less dominated by snowmelt runoff than the other basins. This could be rephrased to be more clear, although it becomes clear further into the paragraph.

This sentence has been reformulated to improve clarity.

P12, L23-28: The summary of results needs to be more clear. What do the "small" and "low" in parentheses mean? What are the percentages – just the number of runs that showed a certain category of streamflow change? This should be more clear. What is the threshold for categorizing large or small changes? And more importantly, what is the magnitude and variation of the projected changes? How confident are you in the various ensemble members, and are there some that are more likely than others (i.e. these near the median) which should be given more weight or more consideration? This is something to present more clearly in the results section, and convey briefly in the abstract.

The summary of results has been greatly improved and suggested aspects have been included.

P13, L2: what can be said about high flows from the results of this study? What insight is there into changing flood regimes?

This study did not focus on high flows. We can hypothesize that average change in atmospheric circulation and associated local temperature/precipitation in winter will likely produce more high flows. However, as stated in the conclusion, the day to day variability of atmospheric circulation needs to be studied for an estimation of high flows variability. This has been clarified in the new version of the manuscript.

P13, L12: There is a need to indicate where the data can be found. I think it is mostly publically available, so it should be a matter of identifying the sources.

The data sources were added.

Figure 1: It might be helpful to specify in the legend that the points are for the CRCM5-LE data.

The mention of CRCM5-LE was added to the legend.

Figure 6: is Delta Q annual? It is not clear why it varies between 0 and 2.5 when in the next figure it varies between 0 and 1. Also, to help, it could be made more clear by labelling the four weather classes in the right hand panel.

It varies between -2.5 and 2.5 because it represented the normalized change in streamflow used to classify the members, not the absolute change in streamflow. Normalized data has been replaced by absolute values in the new figure and the four weather classes have been labelled.

Figure 7: Instead of delta flow, this should be delta Q to be consistent with Fig. 6.

Delta flow has been replaced by delta Q in the figure.

Figure 8: Units are needed throughout the figure and the legends. Is part (a) surface temperature?

The units were added to the figure and the word ‘’surface’’ has been added to temperature.

Figure 9: Units are needed throughout the figure and the legends.

The units have been added to the new version of the manuscript

Figure 10: The legend is ambiguous for the different classifications. There are two red, three orange, two green and two blue categories. Although the order seems to be clear, this could be improved. Also, what are the vertical lines and hatches in the figure? Standard deviations? Please clarify.

Different line types have been included for the streamflow classes to improve the clarity. The hatches are the standard deviation for each class. It has been included in the legend.

Table 1: Where does urban landcover fit in? How much is urban?

Urban is counted as barren. Most of barrens are actually urban. This information has been added to the table.

Table 2: The ranges in parameter values do not provide enough information. What are the values for different HRUs (GRUs)?

The average for each parameter has been added as it gives more information. However, the values for the different GRUs cannot be given as there is thousands of GRUs in this watershed. They are shown in maps in the supplementary materials.

Table 4: In the third column, what does the percentage in the top row specify? % of the ensemble? In the fourth to seventh columns, what are the units? mm/day? If so, what do the terms in brackets represent? And why are some missing?

The third column indicates the percentage of the ensemble. This information has been added to the table. The unit was mm/day but has been replaced by percentage of increase as it represents better the relative change of streamflow. The term in parenthesis is the standard deviation. This information has been added in the table. Standard deviation are not available for classes that include only one member.

Grammatical and Technical Issues

P2, L8: “source” should be “sources”

P8, L26: instead of “expecting” it should say “projected”

Changes were done as suggested

P9, L13: “incriminated”? Is there a better word choice?

Incriminated has been changed to “was a source of error”

P9, L16: “wrong measurements” should instead say “measurement uncertainty”

Changed as suggested

P9, L30: “which is conform”? Pease rephrase.

This sentence has been reformulated

P10,L1: “associated to stronger”; replace “to” with “with” and subsequently where the words “associated to” are used.

Associated to has been replaced by associated with in the entire manuscript

P10, L12: “enhance” should say “enhancement”.

P10, L18: capital letter G for “great Lakes”.

P11, L15: replace “in the meanwhile” with “Meanwhile”

P11, L19: either say “if more snow falls” or “if there is more snowfall”

P11, L26: “connexion” should be replaced with “connection” or “link”

P12, L17: the s should be removed from “precipitations”, and where this is written subsequently.

All these changes have been done in the manuscript

Future shift in winter streamflow modulated by internal variability of climate in southern Ontario

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Abstract. Fluvial systems in southern Ontario are regularly affected by widespread early-spring flood events primarily caused by rain-on-snow events. Recent studies have shown an increase in winter floods in this region due to increasing winter temperature and precipitation. Streamflow simulations are associated with uncertainties mainly due to the different scenarios of Greenhouse gases emissions, general circulation models (GCM) or the choice of the hydrological model. ~~tied to~~ T~~t~~he internal variability of climate, defined as the chaotic variability of atmospheric circulation due to natural internal processes within the climate system, is also a source of uncertainties to consider. ~~These~~ Internal variability uncertainties can be assessed using hydrological models fed by downscaled Global Climate Model Large Ensemble (GCM-LE) data, but GCM output have a too coarse scale to be used in hydrological modelling. The Canadian Regional Climate Model Large Ensemble (CRCM5-LE), a 50-member ensemble ~~a dynamically~~ downscaled from the Canadian global climate model version 2 Large Ensemble (CanESM2-LE)~~version of a GCM-LE~~, was developed to simulate local climate variability over northeastern North America under different future climate scenarios. In this study, CRCM5-LE temperature and precipitation projections under RCP 8.5 scenario were used as input in the Precipitation Runoff Modelling System (PRMS) to simulate streamflow at a near future horizon (2026-2055) for four watersheds in southern Ontario. To investigate the role of internal variability of climate in the modulation of streamflow, the 50-members were first grouped in classes of similar projected change in January-February streamflow and temperature-precipitation between 1961-1990 and 2026-2055. Then, the regional change in Geopotential height (Z500) from CanESM2-LE was calculated for each class. Model simulations showed an average January-February increase in streamflow of 18% (±8.7) in Big Creek, 30.5% (±10.8) in Grand River, 29.8% (±10.4) ~~-~~in Thames River and 31.2% (±13.3) in Credit River. ~~that~~ 14% of all ~~the~~ ensemble members projected positive Z500 anomalies in North America's East Coast enhancing ~~project a high (low)~~ rain, snowmelt and ~~increase in~~ streamflow volume in January-February. For these members the increase of streamflow is expected to be as high as 31.6% (±8.1) in Big Creek, 48.3% (±11.1) in Grand River, 47% (±9.6) in Thames River and 53.7% (±15) in Credit River. ~~Streamflow increases may be driven by rain and snowmelt modulation caused by the development of high (low) pressure anomalies in North America's East Coast. Additionally, the streamflow may be enhanced by high pressure circulation patterns directly over the Great Lakes creating warm conditions and increasing snowmelt and rainfall/snowfall ratio (16%).~~ Conversely, 14% of the ensemble projected negative Z500 anomalies

in North America's East Coast and arewere associated with a much lower increase in streamflow: 8.3% (±7.8) in Big Creek, 18.8% (±5.8) in Grand River, 17.8% (±6.4) in Thames River and 18.6% (±6.5) in Credit River. These results provide are important to information to -researchers, managers, policy makers and society about of the expected ranges of -in increased in winter streamflow and to help understandassess the how internal variability of climate is expected to modulate the future streamflow in a highly populated region of Canada, and They will help to understand how internal variability of climate is expected to modulate the future streamflow in this region. hydrological projections and to inform society of increased winter streamflow.

1 Introduction

Increasing atmospheric greenhouse gases (GHG) concentration is projected to increase air temperatures globally and modify the regional precipitation regimes (Hoegh-Guldberg et al., 2018). GHG-driven climate change is projected to impact watershed fluvial hydrological regimes especially in snow dominated regions (Barnett et al., 2005) with serious implications for flood management and water resources (Hamlet and Lettenmaier, 2007; Wu et al., 2015).

The quantification of streamflow and other hydrological processes using hydrological models is becoming an active area of research in various regions of the world. However, the use of hydrological models to project the future hydrology is subject to uncertainties (Clark et al., 2016) that have recently been intensely investigated recently (Leng et al., 2016). Part of the uncertainties are associated with the projections of climate a number of choices such as through the choice of the Global Climate Model (GCM), the -and GHG emission scenario (Kour et al., 2016; Stephens et al., 2010) and, the climate data downscaling method (Fowler et al., 2007; Schoof, 2013). -hydrological model (Boorman et al., 2007; Devia et al., 2015)model calibration technique (Khakbaz et al., 2012; Moriasi et al., 2007). In addition, the future temporal evolution of temperature and precipitation, simulated by the GCMs, patterns will be is modulated by the internal variability of climate due to- inherently chaotic internal processes within the climate system the inherently chaotic characteristic of the atmosphere (Deser et al., 2014; Lorenz, 1963). These uncertainties are cascading to and will also impact the hydrological processes and streamflow (Lafaysse et al., 2014). In addition and -additional uncertainties are associated to the choice of the -hydrological models (Boorman et al., 2007; Devia et al., 2015) and model calibration techniques (Khakbaz et al., 2012; Moriasi et al., 2007). cause are. Therefore, the uncertainties associated with future projections of streamflow and hydrological processes are very high (Clark et al., 2016) and have recently been the subject of intense research (Leng et al., 2016).

The uncertainties due to the internal climate variability is one of the biggest sources of uncertainty for the early 21st century hydrological projections (Harding et al., 2012; Hawkins and Sutton, 2009; Lafaysse et al., 2014). The internal variability of climate is a cause of the hiatus observed in global warming in the 2000s (Dai et al., 2015) and is expected to mask the impact of human-induced climate change on precipitation (Rowell, 2012) and streamflow (Zhuan et al., 2018). –To assess the contribution of internal variability of climate in the overall climate-change projections uncertainty, Single GCM Large Ensembles (GCM-LE), are based on small initial condition variations between members of the ensemble, and have been used recently ~~to assess the contribution of internal variability on the overall uncertainty in climate-change projections~~ (Deser et al., 2014; Kay et al., 2015; Kumar et al., 2015). ~~and~~ This method was used to investigate how these uncertainties are transferred to hydrological processes in large watersheds ~~hydrological processes~~ (Gelfan et al., 2015).

However, such ~~Due to~~ coarse scale GCMs data ~~GCM's coarse spatial resolution, future climate data~~ should ~~not~~ be downscaled to be used ~~directly for~~ in small watersheds~~. They should be hydrological modelling~~ ~~and downscaled~~ ~~ing techniques must be applied first to these climate data~~ (Fowler et al., 2007). Despite the fact that Regional climate models ~~Statistical downscaling methods are generally preferred as Regional Climate Model Large Ensembles (RCM-LEs)~~ are a computationally costly downscaling method (Lafaysse et al., 2014; Thompson et al., 2015), ~~. However,~~ Regional Climate Model Large Ensembles (RCM-LEs) offers the possibility to relate each member of a ~~Regional Climate Model (~~RCM~~)~~ to large scale variability from GCM-LEs. Furthermore, RCM-LEs avoid additional and ambiguous sources of uncertainty caused by ~~from~~ the statistical methods (Gelfan et al., 2015). One such dataset is

t~~T~~he Canadian Regional Climate Model Large Ensemble (CRCM5-LE), ~~, which is~~ a 50-members, high resolution (12 km grids) regional model ensemble ~~at a 12km resolution~~dataset produced over northeastern North America, that has recently been developed as part of ~~in the scope of~~ the Québec-Bavaria international collaboration on climate change project (ClimEx project; ~~(~~Leduc et al., 2019)~~)~~.

In the literature, ~~For the purposes of this study, precipitation and temperature data from CRCM5-LE were used as input in the Precipitation Runoff Modelling System (PRMS), which was applied to four watersheds in southern Ontario~~. ~~The 50-members were then grouped into classes of similar weather and streamflow projections to assess the impact of internal climate variability on future hydrological processes in southern Ontario. Few-member~~ several studies have projected an increase in winter streamflow in the Great Lakes region due to earlier snowmelt and increase in precipitation (Byun et al., 2019; Erler et al., 2018; Grillakis et al., 2011; Kuo et al., 2017) but the role of internal variability of climate was the subject of very few studies. Large e~~E~~nsembles have been ~~used~~ previously used as input in multiple hydrological models in the Au Saumon catchment in southern Québec (Seiller and Anctil,2014) and in the Grand River watershed in southern Ontario (Erler et al., 2018). However, theses studies only used a few ensemble members which removed the possibility ~~. However, using larger ensembles is beneficial to~~of assessing a large ~~the entire~~ range of internal variability ~~and to adopt a probabilistic approach~~ in the projections of the future hydrological responses~~processes~~.

The main goal of this study is to explore the impact of internal variability of climate in the projections of hydrologic processes and winter streamflow in major watersheds in southern Ontario in the Great Lakes region. Great Lakes region contains ~20 per cent of the world's freshwater, while southern Ontario is home to one third of Canadian population and is a major driver of the Canadian economy (Statistics Canada, 2016). The specific objectives of this study are to (i) ~~:~~ Project the future evolution of streamflow in four watersheds in southern Ontario, using the Precipitation Runoff Modelling System (PRMS) forced by a large 50-members Ensemble (CRCM5-LE) under IPCC RCP 8.5 scenario and (ii) Investigate the impact of the future projected changes in the regional atmospheric circulation on the hydrologic processes and winter streamflow in these watersheds.

~~This analysis, therefore, is very relevant to understand the contribution of anthropogenic and natural forcing on the temporal evolution of runoff in southern Ontario and better predict future streamflow for these watersheds.~~

~~This paper is organized as follows: Section 2 presents the PRMS hydrological model, the CRCM5-LE dataset and the classification procedure. Section 3 examines the impact of atmospheric circulation on streamflow projections. Section 4 is dedicated to the discussion of results and the concluding remarks are presented in Section 5.~~

2 ~~Data and m~~Methods

2.1 Study area

Southern Ontario is a humid region according to the Köppen Geiger climate classification (Kottek et al., 2006), with an average annual precipitation of 1000 mm. The precipitation is well distributed throughout the year and about 200 mm falls as snow in the winter (Wang et al., 2015). The amount of rain and snow varies spatially due to the presence of Great Lakes. In winter the amount of snow is enhanced close to Lake Huron and Georgian Bay by lake effects (Suriano and Leathers, 2017) while in summer the precipitation are lower near the lakes because the convection is inhibited (Scott and Huff, 1996). The region is characterized by a mixed flood regime with high flows generated by rain, snowmelt and rain on snow events occurring from late February to early April (Burn and Whitfield, 2015). These events are occurring earlier recently due to a higher contribution of rainfall to the overall winter precipitation (Burn and Whitfield, 2015).

Four watersheds (Big Creek, Credit River, Grand River and Thames River) ~~in southern Ontario~~ were selected for this study considering ~~for~~ their long hydrometric data ~~time series archives~~ and representation of ~~well~~ the diversity of spatial scales, soil type, and land use in this region (Figure 1 and Table 1). Agriculture activity is the largest land use category in all four watersheds, covering more~~.~~ than 80% of the entire surface in Big Creek, Thames River and Grand River. Credit River has the highest proportion of forest (32%), mostly deciduous species. ~~Two~~Several major urban areas~~cities~~ ~~,~~ are located in the study area: Brantford, Cambridge, Kitchener-Waterloo and Guelph in the ~~along the~~ Grand River watershed;~~,~~ and ~~and~~ London in ~~along~~ the Thames River. ~~are located in the study area and a~~Additional urban areas are located in the Credit river watershed in the vicinity of the Greatest Toronto Area while ~~. T~~the Big Creek watershed contains the lowest proportion of urbanization (2%). These watersheds also vary in soil type: sand predominates in Big Creek (79%) and Credit River (43%), but a large area of Credit River is ~~also~~ covered by loamy soil (49%). Grand River has almost an equal proportion of sand (30%), loam (32%) and clay (38%), while Thames River contains more clay (39%). The elevation is also highly variable with the highest altitudes in the North parts of Grand River (531 m) and Credit River (521 m) while the lowest areas are located in the sandplains further south in Grand River (178 m) and Big Creek (179 m).

2.2 PRMS hydrological model

The Precipitation Runoff Modelling System (PRMS), a semi-distributed conceptual hydrological model developed by Leavesley et al. (1983), was applied in all four watersheds to simulate the future evolution of streamflow for each member of a large climate ensemble. PRMS is used in this study because it needs only basic daily forcing climate data (minimum and maximum temperature, and precipitation)~~.~~ The advantage of using a model that need only few data as input is that it reduces uncertainties from multiple variables and reduce the model computational time. A drawback of using temperature is that energy balance is not physically represented. However, in an earlier study in the Big Creek watershed, PRMS represented well the snow processes (Champagne et al., 2019) showing that the use of temperature and precipitation are satisfactory to represent the snow processes in this region. Moreover, PRMS can be coupled with MODFLOW groundwater model (GSFLOW) to study the interaction between surface and groundwater flow (Markstrom and Regan, 2008). While MODFLOW was not activated in this study, having PRMS set up in these watersheds will facilitate the use of GSFLOW in future studies. This model ~~, and~~ has been widely applied in watersheds that experience ~~are affected by~~ periodic snowfall (Dressler et al., 2006; Liao and Zhuang, 2017; Mastin et al., 2011; Surfleet et al., 2012; Teng et al., 2017, 2018). ~~PRMS was used to and study in an earlier study~~ The hydrological calculations in PRMS are based on physical laws and empirical relations between measured and estimated quantities. A series of hydrologic reservoirs ~~are used~~ (plant canopy interception, snowpack, soil zone, subsurface) are used in the model and the water flowing between the reservoirs are computed for each grouped ~~hydrological~~ response units (G~~H~~RUs). In this study the potential evapotranspiration was estimated using the Jensen-Haise formulation (Jensen and Haise, 1963). The interception was calculated separately for summer rain, winter rain and winter snow and was a function of the plant type. The separation between rainfall and snowfall was done by the snow module using temperature thresholds. If a day has a maximum temperature below 0 ºC, all precipitation of the day was considered as snow. If a day has a minimum temperature higher than 0 ºC and a maximum temperature higher than a threshold to calibrate, then all precipitation is considered rain. A mixed precipitation is computed when conditions are between these values. The snowpack dynamics are simulated through estimate of energy and water dynamics. The energy available to melt the snow is based on estimation of shortwave radiation, longwave radiation, convection and condensation. Shortwave solar radiation was estimated using a degree-day method. Longwave radiation is the integration of the longwave radiation from the land cover and from the air depending on the emissivity of air. Convection and condensation are computed together as a function of temperature and a calibrated coefficient. Surface runoff due to infiltration excess (Hortonian runoff) is computed using the antecedent soil moisture content. The amount of water not contributing to Hortonian runoff is infiltrated and directed to the soil zone. The soil zone module computes transpiration, recharge to the groundwater reservoir and three components of the streamflow: saturation excess (Dunnian runoff), subsurface flow through soil cracks, animal borrows or leaf litter (fast interflow) and subsurface flow (slow interflow). These processes are described in more details by Markstrom et al. (2015).~~For more information about the structure of a recent version of PRMS, reader is referred to Markstrom et al., (2015). A major advantage of this model used in a climate change impact study is the representation of snowmelt using an energy balance approach based on temperature and~~

~~precipitation data. This approach uses simple data projections and is a better physical conceptualization of snow processes than a temperature index approach~~. ~~PRMS has satisfactorily simulated snow processes in the Big Creek watershed (Champagne et al., 2019).~~

~~In this study the~~ The model was set up for each watershed using Arcpy-GSFLOW, a series of ARCGIS scripts (Gardner et al., 2018). Arcpy-GSFLOW constructed G~~H~~RUs as surface grid cells of 200m^2 for Big Creek and Credit River watersheds and 400m^2 for Grand River and Thames River. These latter two larger watersheds have coarser G~~H~~RU's ~~to reduce~~ because the parametrization with arcpy-GSFLOW is not functional with an excessive number of GRUs~~computation time~~. An exemple of the GRUs grid is shown for the south part of Big Creek (Supplementary material S1)~~.~~ ~~maximum~~ ~~°Cum °Cum threshold then considered~~ . ~~coefficient. mod sthreesprocessesModules chosen to compute the hydrological processes in these four watersheds have been described by Champagne et al., (2019)~~. ~~Parameter values associated with these processes were spatialized for each HRU's using~~ Arcpy-GSFLOW ~~(Table 2)~~ calculates the physical characteristics of each GRU: ~~according to land use type, elevation, aspect, slope and soil type.~~ Elevation, slope and aspect were derived from the High-Resolution Digital Elevation Model (HRDEM). ~~and the land use data~~ The percentage of each land use type was derived from the Canadian Land Cover CIRCA 2000 (Natural Resources Canada, 2020) and used to calculate the rooting depth. ~~(Natural Resources Canada). Soil type~~Available water content, saturated hydraulic conductivity, and percentage of sand and clay ~~was obtained~~ were estimated using~~from~~the materials from the surficial geology of Southern Ontario (Ontario Ministry of Northern development, Mines and Forestry). From these calculated characteristics the spatialized parameters have been calculated at each GRU: The coefficients used to calculate slow interflow have been estimated using the saturated hydraulic conductivity and the slope. The maximum available water for plants was calculated using the available water content and the root depth and was used to estimate the total soil saturation. Finally, the linear coefficient used to route the water from the soil zone to the groundwater reservoir was estimated using the saturated hydraulic conductivity. ~~For each HRU the percentage of each land use type and soil type was calculated by Arcpy-GSFLOW, and used to estimate some parameter values needed in the interception and soil zone modules~~. The dominant land-use type (bare soil, grassland, shrubs, coniferous trees or deciduous treesforests) and a single dominant soil type (sand, loam or clay) for each GRU were also estimated and used in some PRMS modules. ~~Other PRMS parameters are based on the dominant land-use type (bare soil, grassland, shrubs, coniferous trees or deciduous treesforests) and a single dominant soil type (sand, loam or clay).~~ Arcpy-GSFLOW was also used to define the stream network from the HRDEM. The accumulation flow threshold was determined empirically by matching the ~~created~~ streams with aerial photographs. We then estimated the water cascade between the G~~H~~RU's and the stream network. Control structures or dams were not taken into consideration in this study because of their limited impact on the 30-years average streamflow used in this study. The model was calibrated and validated using the regulated flow series. Therefore, the dam effect should be implicitly accounted for during the model calibration and it is assumed that the reservoir levels will not change significantly in the future period. The lakes represent very small areas of the watersheds and therefore considered of negligible effect on streamflow.

The spatialized parameters estimated by Arcpy-GSFLOW were modified during calibration while keeping their relative spatial variability. Other parameters were lumped to the entire watershed and were calibrated as well (Table 2). ~~Some of the~~

~~parameters used in PRMS were modified during calibration while keeping their relative spatial variability (Table 2).~~ Model calibration was performed with a trial and error approach following three-steps: (1) The calibration of the daily shortwave radiation parameters using satellite data (2002-2008) from Natural resources Canada at 10km resolution (Djebbar et al., 2012); (2) The potential evapotranspiration (PET) parameters adjusted against PET values estimated using the Thornthwaite method (Thornthwaite, 1948) and (3) calibration of 17 parameters using the Normal Root Mean Square Error (NRMSE) between daily and monthly ~~by comparing the daily~~ streamflow simulated by PRMS and daily and monthly observations ~~of mean streamflow~~ measured at each watershed outlet (blue triangles in Figure 1, Environment and Climate Change Canada Historical Hydrometric Data). A sensitivity analysis of the parameters in the Big Creek watershed (supplementary materials) shows that the infiltration in the soil zone is the most important process to accurately simulate the streamflow. The available water threshold as well as the travel time between stream segments are also important factors. For the snow module specifically, the convection/condensation energy coefficient is the most sensitive (Section S3). The simulated streamflow was computed using precipitation, minimum temperature and maximum temperature from NRCANmet, the most commonly used dataset in Canada (Werner et al., 2019). The dataset was produced using station observation data from Environment and Climate Change Canada and Natural Resources Canada. The gridding at 10 km spatial resolution was accomplished using the Australian National University Spline (ANUSPLIN, McKenney et al., 2011). 186 data points were necessary to cover the area of the four watersheds (red markers on Figure 1). For model calculations, each G~~H~~RU used climate data from the closest NRCANmet grid point. Five years were used as the warm-up period (Oct 1984-Sept 1989) to remove any error due to initial conditions. Different simulations with a varying initialization period length were tested in the Big Creek watershed and showed that five years were necessary for the hydrological model to forget the initial conditions of the reservoirs. The calibration period was between Oct 1989 and Sept 2008 and the years 2009 to 2013 were used as the validation period. ~~Further calibration details are described in Champagne et al. (2019).~~

The best sets of parameters retained after calibration are~~is~~ shown in Table 2 ~~3~~. The spatial variability of the parameters estimated for each GRUs can be found in supplementary materials (Section S2).The Nash Sutcliff Efficiency (NSE) values are always higher than 0.65 for both calibration and validation periods (Table 3) which~~.~~ is generally considered a good quantitative fit (Moriasi et al., 2007). A~~The~~ percent bias (PBIAS) ~~is~~ between -15% and +15%, also -considered as a good fit was reached in our study with the exception of ~~except for~~ Credit River for ~~during~~ the validation period. ~~A NSE higher than 0.65 and a PBIAS lower than 15% is generally considered a good quantitative fit (Moriasi et al., 2007).~~ Figure 2 shows the simulation and the observation of the daily streamflow in all four watersheds and confirms visually the goodness of simulation fit. The ability of the best set of parameters to recreate the snow depth in the Big Creek watershed was tested in a previous study (Champagne et al., 2019) and show good agreement with the observations.

2.3 Climate data projections

The set of parameters identified for each watershed during the calibration were used to simulate the future evolution of streamflow for each member of the Canadian Regional Climate Model Large Ensemble (CRCM5-LE). CRCM5-LE is a 50-

member ensemble of climate change projections at 0.11° (~12-km) resolution available at 5-minute time steps over North-eastern North-America (Leduc et al., 2019). Each member of CRCM5-LE was driven by 6-hourly atmospheric and oceanic fields from each member of the Canadian Earth System Model version 2 Large Ensemble (CanESM2-LE) at a 2.8° (~310 km) resolution (Fyfe et al., 2017; Sigmond et al., 2018). The downscaling from CanESM2-LE was performed using the Canadian Regional Climate Model (CRCM5 v3.3.3.1; Martynov et al., 2010; Šeparović et al., 2013) developed by the ESCER Centre at UQAM (Université du Québec à Montréal) with the collaboration of Environment and Climate Change Canada. The ensemble extends from the historical (1954-2005) to the projected (2006-2099) period forced with the RCP8.5 scenario (Meinshausen et al., 2011). The CRCM5-LE Data grid-points the closest to NRCANmet data points were used in this study. Before their use in PRMS, modelled temperature and precipitation from CRCM5-LE were bias-corrected monthly against NRCANmet at each grid point over the historical period (1954-2005)~~ using the method developed by Ines and Hansen (2006)~~. The intensity distribution of temperature was corrected using a normal distribution. For precipitation, a two-steps procedure was applied. The frequency distribution was first adjusted by truncating the modelled frequency. The truncated distribution of precipitation intensity was then corrected with a~~A~~ gamma distribution (Ines and Hansen, 2006).~~ was used for both observed and modelled precipitation intensities while a normal distribution was used for the temperature bias correction~~. The bias correction method gives satisfactory results and was a necessary step before using CRCM5-LE in PRMS (Section S4). These bias-correction calculated from the historical period were ~~then~~ applied at ~~to~~ each~~the~~ CRCM5-LE grid point~~s~~ for the entire period 1954-2099.

2.4 ~~Ascending hierarchical classification~~ Agglomerative hierarchical clustering

An agglomerative hierarchical clustering ~~ascending hierarchical classification~~ (AHC) was used to classify all 50 members into classes of similar change of forcing CRCM5-LE meteorological conditions and streamflow simulated by PRMS. AHC is a bottom-up clustering approach where each observation starts as its own cluster and one pair of clusters is merged at each step, respecting a minimum change of total variance between each step (Ward, 1963). ~~The classification was used to simplify the study of the connections between the future change in large scale atmospheric circulation, local meteorological conditions and streamflow.~~ In a general concept, t~~T~~he AHC calculates first the ~~Euclidean distance~~variance between each pair of observations~~members~~. The pair with the lowest ~~closest Euclidean distance is~~ variance merges~~d~~ into a single class~~. The Euclidean distance of this class is then calculated by averaging the Euclidean distance between each member of this class and all other members~~. In the next step, t~~T~~he ~~next~~ pair of classes or pair of observations ~~members with the smallest Euclidean distance is merged and averaged similarly~~ that would result in the smallest increase of total variance, compared to the previous step, is grouped together. This process is repeated ~~49 times,~~ until all classes of members have been merged into a single class. ~~The classification was used to simplify the study of the connections between the future change in large scale atmospheric circulation, local meteorological conditions and streamflow.~~ In this study, t~~T~~he AHC was applied first to the all four ~~4~~ watershed's ~~s~~ January-February normalized change in ~~of~~ streamflow and then to the ~~4~~ four watershed's~~s~~ average change of temperature and precipitation between the historical (1961-1990) and future ~~2040's periods~~ (2026-2055) periods. The AHC was performed using January-February data because these months correspond to a large change in~~of~~ streamflow during the winter period. For precipitation and temperature, the period from 25 December to 22 February was used to account for the delay between weather conditions and streamflow at the outlet. A delay of six~~6~~ days showed the best correlation between the increase in temperature and precipitation and the increase in streamflow for all four~~4~~ watersheds. The number of classes to retain for change of streamflow and number of classes for change of weather conditions correspond~~s~~ to the highest ~~interclass Euclidean distance~~ change in variance. The classification was used here to simplify the study of the connections between the future change in large scale atmospheric circulation, local meteorological conditions and streamflow. This method using streamflow response classification rather than using a classification of climatological patterns was chosen because is focusing on the impact that can be used in other hydrological application.

The future projection of atmospheric circulation for each class was analysed using climate variables from CanESM2-LE with a geographical domain from 30°N to 60°N latitude and 100°W to 50°W longitude. Climate variables used for analysis included air temperature at 850hPa level (850T), precipitation (PP), sea level pressure (SLP), geopotential height at 500hPa (Z500) and surface winds. These climate variables were separated into internal and forcing contributors. The forcing contribution of the climate variables corresponds to the average change of all ensemble members between the historical period and ~~2040s~~future simulations. The internal contribution associated with~~to~~ each member was calculated by subtracting the original member data from the forcing contribution. This method was previously used by Deser et al. (2014) to assess the internal contribution of future change in temperature and precipitation~~s~~ in North America.

3 Results

3.1 Streamflow projections

Figure 3 shows the average daily streamflow volume and the number of high flows for all members for the historical (HIST) and future (2040s) periods. Observational streamflow measured at each watershed outlet (OBS) and the streamflow simulated by PRMS using observed temperature and precipitation from NRCANmet (CTL for control) are also shown for the historical period. A day is considered a high flow when the streamflow value is higher than the mean plus 3 times the standard deviation, based on observed streamflow. When at least two days in a row satisfy this condition, only one day of the series is considered as a high flow.

In the historical period, average streamflow from OBS, CTL and the 50-member data sets followed similar annual cycles with the first peak of the hydrological year occurring in November-December and the highest peak in March-April. By 2040, a clear peak in streamflow and number of high-flow events are still modelled in March but streamflow is more evenly distributed among winter months. This result suggests a shift from two maximal peaks to one winter peak by the mid-21st Century. The largest increase in streamflow occurred in January-February with a 50-members average increase reaching 18% (±8.7) in Big Creek, 30.5% (±10.8) in Grand River, 29.8% (±10.4) in Thames and 31.2% (±13.3) in Credit River. ~~Lastly,~~ All 50 members depict a streamflow increase in winter, but the simulated range of streamflow volume and the number of high flows is wide among the 50 different members~~ in winter~~.

Daily rainfall, snowmelt, and actual ET are also expected to change by 2040s (Figure 4). The amount of rain is simulated to consistently increase among the 50-member average in winter and early spring in all four watersheds. The 50-members average November-April increase in rainfall is about 29.7% (±8.7) in Big Creek, 37.3% (±10.3) in Grand River, 30.7% (±8.6) in Thames and 40.3% (±11.7) in Credit River. In summer, PRMS simulates future average rainfall to decline between 5 and 8.5% depending on the watershed, but the direction of change is inconsistent between individual members. The amount of snowmelt is expected to shift from high melt volume in March to a volume consistent throughout the winter. ~~In November and i~~In March-April, snowmelt is expected to decline by 61.9% (±11.2) in Big creek, 52.2% (±10.7) in Grand River, 60.5% (±10.5) in Thames River and 42.8% (±11.8) in Credit River, while in January-February, snowmelt is expected to increase by 10.2% (±12.5) in Big creek, 32.2% (±12.7) in Grand River, 23.7% (±11.7) in Thames River and 45.8% (±16.1) in Credit River. Future ET will slightly increase for most months ~~in winter following by dramatic increases in spring period (March and April). In summer ET is simulated to~~ but~~slightly~~ decrease in summer. ~~on average but with a large difference between the member with the highest and the member with the lowest ET amount.~~

Figure 5 shows the 50-member historical and projected bias-corrected temperature and precipitation for all four watersheds. Air temperature is shown to consistently increase for all months while the range of precipitation amounts projected by the 50 members is wider compared to the change in temperature~~higher~~. On average, simulated precipitation increases in November-April and decreases in June-September.

3.2 January-February streamflow projections variability

The 50 members of the ensemble were classified first in classes of similar January-February streamflow change between the historical period and 2040s using the AHC described in the method section. The number of classes to retain was determined using a dendrogram (Figure 6). The dendrogram shows the cumulative total intraclass class variance of normalized streamflow change ~~variance of~~ e~~Euclidean distance~~ for the successive merging, from the first merging that uses all members (bottom) to the last merging creating a single class (top). The highest vertical distance between two successive merging in the Y axis corresponds to the change in number of classes affected by ~~with~~ the highest intra~~er~~class variance increase. The number of weather classes was identified using the same method (Figure 6). Three streamflow classes (HiQ, MoQ and LoQ for high, medium and low increase of streamflow) and four weather classes (HiPT, MoPT, LoPT and HiT) correspond to the ~~the number of~~ classes merged right before the highest change in variance~~with the lowest interclass Euclidean distance variance~~ (Figure 6). Three of the weather classes (HiPT, MoPT and LoPT) show a gradient from high to low increase for both precipitation and temperature while one weather class show a high increase in temperature but low increase in precipitation (HiT) (Figure 6, right panel). The labels High and Low are not refering to absolute values but correspond to higher or lower increase in streamflow and temperature/precipitation relative to the other members.

The streamflow and weather classes were then aggregated, grouping the members that are in the same streamflow and weather classes, giving a total of nine classes (Table 4). The increase in streamflow is similar between watersheds with the exception of Big Creek depicting a lower change. In Big Creek the classes corresponding to HiQ have an average increase comprises between 25% and 32%, MoQ between 18% and 24% and LoQ between 8% and 14%. In the three other watersheds HiQ depicts an average increase comprises between 39% and 54%, MoQ between 28% and 36% and LoQ between 18% and 24% (Table 4). ~~Seven out of the eight members associated with high increase of precipitation and temperature (HiPT) show a large increase of streamflow (HiQHiPT) while one member show a moderate streamflow increase (MoQHiPT). Eight of the thirteen members associated with a large increase of temperature only (HiT) generate a moderate increase of streamflow (MoQHiT) while four have a low increase (LoQHiT) and one has a high increase in streamflow (HiQHiT). The members associated with a moderate increase of precipitation and temperature (MoPT) majoritarly produce a moderate increase of streamflow (MoQMoPT) but eight out of nineteen members demonstrate low increases of streamflow (LoQMoPT). Lastly, the class LoPT consists of members with the lowest change of precipitation and temperature with eight members showing a low increase (LoQLoPT) and three members that show moderate increases of streamflow (MoQLoPT).~~ The interclass variability is also generally consistent between watersheds with the exception of Big Creek. The classes HiQHiT and LoQHiT show a comparatively ~~relatively~~ low streamflow increases as compared to other classes ~~the other three watersheds~~ (Table 4).

The table 4 emphasized that despite a simlar change in precipitation and temperature, the streamflow varies greatly between classes. Figure 7 shows scatter plots of averaged change of streamflow to average change of precipitation, temperature, snowmelt and rain between the historical period and the 2040s period for all nine classes shown in Table 4. HiQHiPT and LoQLoPT classes are associated with the highest (lowest) increases of streamflow due to high (low) increases of snowmelt and rain (Figure 7). The larger increase in rain and snowmelt for HiQHiPT members are likely due a larger warming and increase in precipitation. MoQLoPT demonstrates a larger increase in simulated streamflow compared to LoQLoPT, which is likely due to a larger increase of precipitation amounts despite lower warming. MoQLoPT is especially larger than LoQLoPT in term of snowmelt suggesting more snowfall for MoQLoPT members. The three weather classes associated with a large increase of temperature only (HiT) depict a moderate increase of rain and snowmelt suggesting that these members increase the rain to snow ratio and accelerate the snowmelt. LoQHiT also shows ~~also~~ a strong warming but a low increase of snowmelt explaing the low increase in streamflow (Figure 7). Lastly, MoQMoPT has a higher increase in both rainfall and snowmelt compared to LoQMoPT but both classes demonstrate similar change of precipitation and temperature. These results suggest that alternative factors than average change in temperature and precipitation could explain the change in rainfall, snowmelt and streamflow in january-february. These factors will be described in part 3.4 and discuss in section 4.4. Lastly, the main visual difference between watersheds was a lower increase of snowmelt expected in Big Creek.

3.3 Atmospheric circulation and streamflow projections

The 50 members average change of temperature and precipitation between the historical period and the 2040's is shown in Figure 8. An increase of air temperature at 850hPa (T850) and geopotential height at 500hPa (Z500) is expected to occur within the entire domain with a stronger gradient closer to the Arctic (Figure 8c). Precipitation is also simulated to increase by the 2040s throughout the domain while SLP is expected to decrease (Figure 8d). In the region close to the Great Lakes, the magnitude of warming and variability between members is higher on the northern shorelines as compared to the open water and shorelines south of the Lakes (Figure 8a). Precipitation increases is also projected to be higher on land and on the east side of the Great Lakes and toward the Atlantic coast (Figure 8b and 8d).

The internal contribution of each CanESM2-LE member to the change of climate variables was averaged for each class (Figure 9). The class HiQHiPT is projected to be associated with positive temperature, precipitation, and southwesterly winds change anomalies between high pressure anomalies in the east and low pressure anomalies in west side of the domain (Figure 9a and 9h). LoQLoPT has opposite pressure gradient anomalies and is the only class that show negative precipitation and temperature change anomalies occurring simultaneously (Figure 9g and 9n). LoQMoPT demonstrates a similar pattern to LoQLoPT, but the negative pressure anomalies are attenuated, and precipitation increase is higher (Figure 9e and 9l). MoQHiT and LoQHiT are characterized by positive temperature and pressure change anomalies over southern Ontario, while MoQMoPT and MoQLoPT have an opposite pattern.

3.4 Antecedant conditions and streamflow

Alternative factors than January-February atmospheric conditions are also examined that may help to explain the January-February evolution of streamflow between the historical and the future period. Figure 10 shows the change of precipitation amount in November-December, groundwater flow in January-February and amount of snowpack water equivalent for the first and the last day of the January-February period.

November-December precipitation are projected~~expecting~~ to increase for all classes but a large intraclass and interclass variability is shown. The classes HiHiPT, HiHiT, MoHiT and the two LoPT weather classes show visually a higher increase of November-December precipitation as compared to the other classes. The amount of snowpack water equivalent at the beginning of the January-February period is expected to decrease with low variability between the classes but a large intra-class variability (Figure 10). The snowpack at the end of January-February is expected to decrease significantly for all classes with a low intraclass variability. The groundwater flow shows visually ~~a large difference between watersheds with~~ a lower~~higher~~ increase in Big Creek compared to the other watersheds likely due to a lower overall increase in streamflow. ~~Credit River and Grand River compared to Big Creek and Thames River.~~

4 Discussion

4.1 Historical simulations

The observed seasonal cycle of streamflow was visually well reproduced by the simulated CTL and ensemble data for the historical period (1961-1990) (Figure 3). However, the simulated streamflow from CTL and the ensemble overestimated streamflow between November and February in the Thames and Big Creek watersheds. The overestimation is stronger in January for the ensemble which can be attributed to an overestimation of precipitation (Figure 5). Winter overestimation was previously reported for the Grand River watershed (Erler et al., 2018) and was attributed to ~~the monthly resolution and~~ the lack of ponding or frozen soil process representation in the model ~~of the winter processes~~. Similarly, t~~T~~he version of PRMS used in our study ~~is for example~~ did ~~-~~not represents~~ing~~ the ponding and frozen soil processes. However, a comparison of the observed streamflow during frozen and non-frozen soil periods in the Big creek watershed ~~have~~ showed~~n~~ a small difference (figure n~~N~~ot shown) suggesting a ~~low~~ small impact of frozen soil on ~~to~~ the streamflow in this region. Moreover the streamflow simulations using NRCANmet data performed ~~very~~ well in Grand River (Figure 3). These results suggest that other factors than the hydrological model are ~~structure is not~~ likely responsible for the discrepancies in Thames River and Big Creek. The quality of NRCANmet observations could also be a source of uncertainty~~incriminated~~. The ANNUSPLIN method, used by NRCANmet to interpolate the station-based observations, generally overestimates precipitation in this region (Newlands et al., 2011). Despites these biases, NRCANmet is among the most widely used gridded dataset in Canada (Werner et al., 2019) and the use of NRCANmet~~-~~ to simulate snow processes was satisfactory in the Big Creek watershed (Champagne et al., 2019).~~can be used with confidence, awaiting further improvements~~. The observed streamflow itself can also be affected by ~~wrong~~ measurement~~s~~ uncertainty during ice conditions and especially an overestimation of the discharge. The validation of simulations using other variables such as evapotranspiration or soil moisture would be beneficial to improve the confidence in the results. Evapotranspiration from CRCM5-LE was not available for this work but could be investigated in future works.

4.2 Increase in streamflow amplified or attenuated by Z500 anomalies

Despite the discrepancies highlighted in the last section, the results show a clear increase of streamflow in January-February (Figure 3) which has been previously simulated for other watersheds in the Great Lakes region (Byun et al., 2019; Erler et al., 2018; Grillakis et al., 2011; Kuo et al., 2017). January-February streamflow increases ~~are~~ will likely be caused by temperature and precipitation increases (Figure 5 and 8) that causes rain and snowmelt amounts to rise (Figure 4). Grillakis et al., (2011) used several hydrological models in a small catchment close to Lake Ontario and projected ~~reported that~~ streamflow increases ~~are~~due to rainfall increases in January and snowmelt increases in February. In our study we found an increase of rain and snowmelt for both months (Figure 4). The future increase of January-February rain and snowmelt can be associated with the ~~is due to a~~ warming simulated by CanESM2-LE (Figure 8)~~ that has a global feature (Hoegh-Guldberg et al., 2018)~~. This w~~W~~arming has a similar amplitude~~s projected for southern Ontario with CanESM2-LE are conformed to the~~ compared to other CMIP5 ~~multi-~~model projections ~~with~~ forced with the same RCP8.5 scenario (Zhang et al., 2019). An increase in January-February precipitation, ~~increases are likely to occur~~ projected in a large part of the domain (Figure 8), ~~which is conform~~ is also similar to other climate models simulations (Zhang et al., 2019). Precipitation increase between Lake Ontario/Erie and the East coast (Figure 8) is not expected by the CMIP5 multi-model projections and is likely inherent to CanESM2-LE. This precipitation pattern is probably associated with~~to~~ stronger winds from the east coast (Atlantic Ocean) due to a higher pressure decrease on land (Figure 8).

The 50 members produce a variable increase of streamflow (Figure 3) which is likely due to the variability in atmospheric circulation (Figure 9). 14% of the ensemble showed a high increase of streamflow simultaneously with high geopotential height anomalies near the east coast and southerly winds through the Great Lakes region (Table 4 and Figure 9a and 9h). High geopotential height anomalies located in the eastern United States has been previously found responsible for more precipitation and higher temperature in the Great Lakes region in winter (Mallakpour and Villarini, 2016; Thiombiano et al., 2017), thereby increasing the streamflow and high flow events (Bradbury et al., 2002; Mallakpour and Villarini, 2016). 14% of the ensemble corresponds to the opposite pattern with low geopotential height anomalies in the east coast and northern winds anomalies (Figure 9g and 9n). These atmospheric conditions will attenuate the warming and precipitation amounts and~~ are~~ will be therefore associated with~~to~~ a lower increase of streamflow (Table 4 and Figure 7). 6% of the ensemble (Class MoQLoPT) shows a low warming but a moderate increase in precipitation and snowmelt (Figure 7 and 9f and 9m) suggesting snowfall enhancement. The north-west wind anomalies associated with~~to~~ this class (Figure 9f and 9m) could enhance snowfall in this region through lake effect snow (Suriano and Leathers, 2017). Another 16% of the ensemble shows a moderate increase in streamflow associated with~~to~~ a strong warming (MoQHiT) which may be driven by high-geopotential height anomalies on the Great Lakes (Figure 9b and 9i). This pattern drove~~ived~~ moderate increases of snowmelt and rain-to-snow ratio associated with strong warming (Figure 7, 9b and 9i). Correspondence between high geopotential height and high temperature on the Great Lakes in winter have been previously reported (Ning and Bradley, 2015). Ning and Bradley (2015) suggested that the high geopotential anomalies on the G~~g~~reat Lakes prevent the polar jet-stream and the cold air masses from entering the region.

4.3 Consistency in the weather classes

The weather classes are associated with~~to~~ specific trends in atmospheric conditions (Figure 9) but are composed from an average of members that have their own atmospheric signature despite a similar impact on local conditions. Changes in Z500 ~~anomalies~~ and T850 anomalies for each member are depicted in Figure 11 to investigate the atmospheric variability between members. The members that comprise classes HiPT show a large increase in~~high~~ Z500 anomalies~~ enhance~~ in the east coast consistently for six members while for two members (#13 and #48) the high increase in Z500 anomalies is centered north from the Great Lakes. Eight members of the class LoPT show strong Z500 decrease in the east coast but in two members (#1 and #10) the decline is rather centered in the northern side of the Great Lakes. HiT show generally Z500 increase centered on the Great Lakes but four of the thirteen members depict a different pattern (#2, #20, #31 and #47). Finally, members from MoPT show generally a decrease in Z500 but we observe a high diversity in the change of~~in~~ circulation patterns. Members from MoPT depict a lower Z500 gradient compared to other classes suggesting a lower contribution of internal variability of climate to the total change in atmospheric conditions (Figure 11). These results suggest a large variability in atmospheric circulation change between members of the same ensemble with some members showing very unique change in atmospheric circulation. Despite the atmospheric anomalies differences between members predicting similar local weather, the classes method used in this study gives a good probabilistic overview on how the change in regional atmospheric anomalies will impact local weather.

4.4 Lag between atmospheric circulation shifts, local climate conditions and streamflow

Results show that interclass variability in the increase of January-February streamflow is mostly due to temperature and precipitation variability in the same months. The members with the highest increase in January-February precipitation and temperature (HiPT) are the members associated with the highest January-February streamflow increases, except for MoQHiPT

(Table 4). The members associated with the lowest increase in precipitation and temperature (LoPT) show the lowest streamflow increase (LoQLoPT). Three other members of LoPT are associated with higher streamflow increase (MoQLoPT) which can be due to more precipitation and snowfall despite a lower warming (Figure 7).

Within the other two weather classes, HiT and MoPT, a similar change in January-February weather conditions translates to a large range of streamflow projections. These discrepancies between the evolution of weather conditions and streamflow volume in January-February can be associated with~~to~~ a delay between weather conditions and streamflow. To account for the routing delay between rain/snowmelt events and streamflow observed at the outlet, our analyses used a lag-time of ~~6~~ six days between the precipitation/temperature and the streamflow. Any remaining delay between weather conditions and streamflow could occur due to snowpack remaining from the previous months. Figure 10 shows a low variability between all MoPT members and all HiT members in term of change in starting snowpack volume suggesting a low impact of snowpack remaining at the end of December on change in January-February streamflow.~~ In the~~ M~~m~~eanwhile, snowpack remaining at the end of January-February is decreasing at a higher rate for MoQMoPT members as compared to LoQMoPT members and for MoQHiT members compared to LoQHiT members (Figure 10) which may be associated with a higher increase in snowmelt (Figure 7). However, these two classes show very similar change of temperature and precipitation (Figure 7) suggesting that average weather change obscures intra-seasonal variability change. For example, if more snow falls in the second half of February and temperature stays below the freezing point, this snow is likely to melt in March and is therefore not counted in the January-February streamflow.

The discrepancy between change in weather conditions and streamflow can also be due to groundwater recharge/discharge variability. The lower streamflow increase in LoQHiT is for example associated simultaneously with a lower increase in groundwater flow and a lower increase in November-December precipitation amount (Figure 10). A correlation close to 0.7 between the 50 members November-December change in precipitation amount and the January-February change in groundwater flow confirms the connection~~connexion~~ between fall precipitation and winter groundwater flow. The processes connecting fall precipitation and winter groundwater will need further investigation with the help of a coupled surface and groudwater model, such as GSFLOW (Markstrom et al., 2015). These results emphasize the possible role of processes delaying the streamflow (i.e. Snowpack, Groundwater) ~~-~~and the need to also study the~~-~~ succession of different atmospheric patterns in the previous months before ~~leading to~~ the January-F~~f~~ebruary modulation of streamflow.

4.5 Spatial variability of streamflow change modulation

The changes in the amount of rain and snowmelt between the historical period and the 2040’s are visually similar for three of the watersheds (Figure 7). The Big Creek watershed is distinctly different as it shows a lower snowmelt contribution to streamflow (Figure 7). This suggests ~~that there will be less~~ a thinner snowpack available for melting ~~to be melted~~ in this watershed as it is situated in the southern part of the study area near Lake Erie and experiences the mildest winters (Figure 5). In this watershed, the snowmelt volume is expected to increase only slightly in January (Figure 4). The increase in snowmelt is also expected to occur only in January for Thames River while the increase will be stronger in February for Grand and Credit

River. A similar South-North pattern is observed in previous studies. A high increase in streamflow in December and January followed by a decrease in streamflow in February was simulated for the Canard watershed near Lake Erie (Rahman et al., 2012) while this shift is expected to occur between February and March further north near Lake Ontario (Grillakis et al., 2011; Sultana and Coulibaly, 2011) or Lake Simcoe (Kuo et al., 2017; Oni et al., 2014). These results suggest that the winter increase in streamflow is expected to be lower in the warmest watersheds classically situated further south, in ~~low lands~~lowlands and close to the Great Lakes. In these watersheds the snowpack was already reduced in the historical period and the further warming is not expected to increase the snowmelt contribution to the streamflow. However, similar to previous studies in southern Ontario, the reduced snowpack is not projected to decrease the streamflow in winter because the winter precipitation are also projected to increase as suggested in the majority of the climate models (Zhang et al., 2019).

5 Conclusion

This study used a 50-member ensemble of regional climate data, forced with the IPCC RCP8.5 scenario, as input in the PRMS hydrological model to show how the internal variability of climate is transferred to the near future winter (January-February) projections of streamflow in four diverse watersheds in southern Ontario, ~~in~~ Great Lakes region. An agglomerative~~ascending~~ hierarchical clustering~~classification~~ was used to construct classes of similar change in temperatures/precipitation~~s~~/streamflow and define streamflow change probabilities and associated regional atmospheric drivers. First, the results showed that all members of the ensemble ~~are~~ were associated with a January-February increase in streamflow between 1961-1990 and 2026-2055, with an average increase of 18% (±8.7) in Big Creek, 30.5% (±10.8) in Grand River, 29.8% (±10.4) in Thames river and 31.2% (±13.3) in Credit River. This streamflow increase is due to a strong warming trend and an increase in precipitation projected by the IPCC RCP 8.5 scenario. Second, the results suggested that the future increase of temperature and precipitation in January-February will be modulated by the internal variability of climate with implication for hydrological processes. Specifically, our study showed that: ~~. We projected:~~

(i) ~~(i)~~ One class of CRCM5-LE members, representing 14% of all ~~the~~ ensemble members, ~~show~~depicted~~ing~~ an ~~large (small) increase~~ amplification in the future average~~in the near future~~ streamflow ~~increase~~. The average streamflow change for this class will be~~as~~ as high as +31.6% (±8.1) in Big Creek, +48.3% (±11.1) in Grand River, +47% (±9.6) in Thames river and +53.7% (±15) in Credit River. This amplification will be~~as~~ due to rainfall and snowmelt enhancement ~~the modulation of rain and snowmelt~~ associated with the development of high ~~(low)~~ pressure anomalies in the east coast of North America.

(ii) The opposite pattern, associated with anomalous low pressure in the east coast of north America ~~, also 14% of all ensemble members,~~ showed an attenuation in average streamflow. This class depicted a change in streamflow of only +8.3% (±7.8) in Big Creek, +18.8% (±5.8) in Grand River, +17.8% (±6.4) in Thames river and +18.6% (±6.5) in Credit River.

(iii) Two other classes representing another 24% of all ensemble members showed a moderate attenuation in streamflow increase with ~~:~~ +12.7% (±3.6) in Big Creek, +22.3% (±3.3) in Grand River, +23% (±2.3) in Thames river and +21.1% (±6) in Credit River. This attenuation ~~is expected~~might ~~occur~~occur~~red~~ due to low November-December precipitation and low January-February snow accumulation/melting.

(iv) Almost half of all ensemble members showed a change in temperature and precipitation close to the 50-members average and showed a small contribution of internal variability of climate to the projected variability of streamflow.

~~(ii) 16% of the ensemble showing a moderate streamflow enhancement due to an increase in the rainfall to snowfall ratio associated with warmer conditions driven by high pressure over the Great Lakes region.~~

~~(iv~~ii) ~~38% of the ensemble showing a change of temperature and precipitations close to the 50-members average with a small contribution of internal variability of climate to the long-term trends of temperature and precipitation in southern Ontario.~~

~~The evolution of streamflow in January-February will be also modulated by inter-member variability of groundwater recharge from November-December precipitation and by the evolution of snow accumulation/melting due to the timing in the increase of temperature and precipitation.~~

~~This study~~ These results focussing ~~ed~~ on average change of atmospheric conditions cannot be applied to high flows, ~~while~~ mostly driven by t~~t~~he ~~intra-seasonal~~ day to day variability of atmospheric circulation. ~~may greatly impact the streamflow and especial high flows due to day to day variability. T~~ The use of the same regional ensemble together with a classification of daily atmospheric fields would be useful to assess the future projections of high flows and flood regimes in the region. Despite a large number of regional climate simulations used here to drive a hydrological model, the results are derived from a single model chain (CanESM2, CRCM5 and PRMS). As a result, this ensemble does not consider other important sources of uncertainty from emission scenario and model structure. Future studies could use other global climate models and different scenarios and can be extended to the end of the 21st century. Other hydrological models could also be used to increase the confidence regarding the projections of hydrological processes. This work is important to assess the natural variability of the hydrological projections and help the society to be prepared for large range of future changes in flooding regimes.

Data availability

The historical hydrometric data can be extracted from the Environment and Climate Change Canada Historical Hydrometric Data website (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html, last access: 3 February 2020) (Environment and Climate Change Canada, 2020). PRMS model codes are accessible from the USGS website (https://www.usgs.gov/software/precipitation-runoff-modeling-system-prms, last access: 24 March 2020) (USGS, 2020).

CRCM5-LE data are not publicly available. Martin Leduc should be contacted for any request (leduc.martin@ouranos.ca). Model simulations and sequences of weather regimes are available upon request from M. Altaf Arain (arainm@mcmaster.ca). The research codes and data are available on request.

Authors contribution

OC prepared the figures and performed the analyses. OC prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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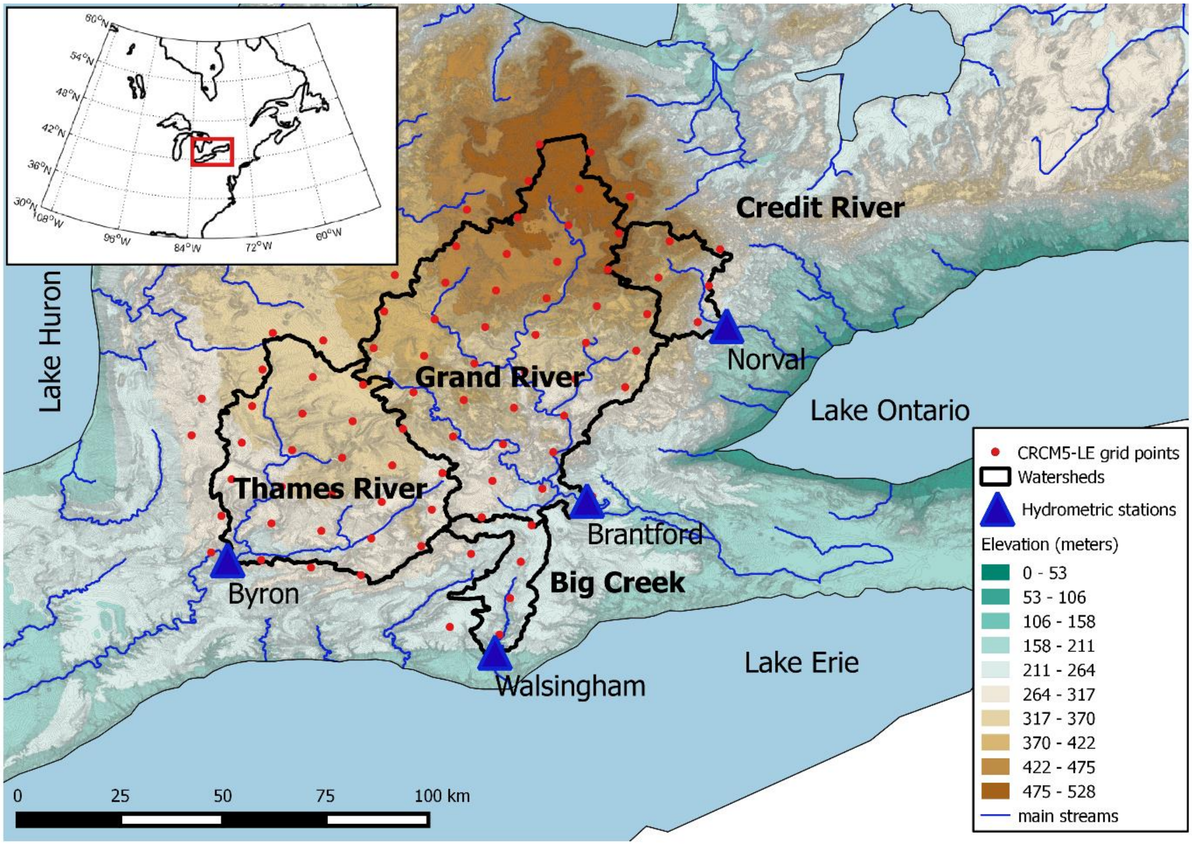

Figure 1: Location map of the four studied watersheds in Southern Ontario. Elevation source: High Resolution Digital Elevation Model (HRDEM, Natural resources Canada).

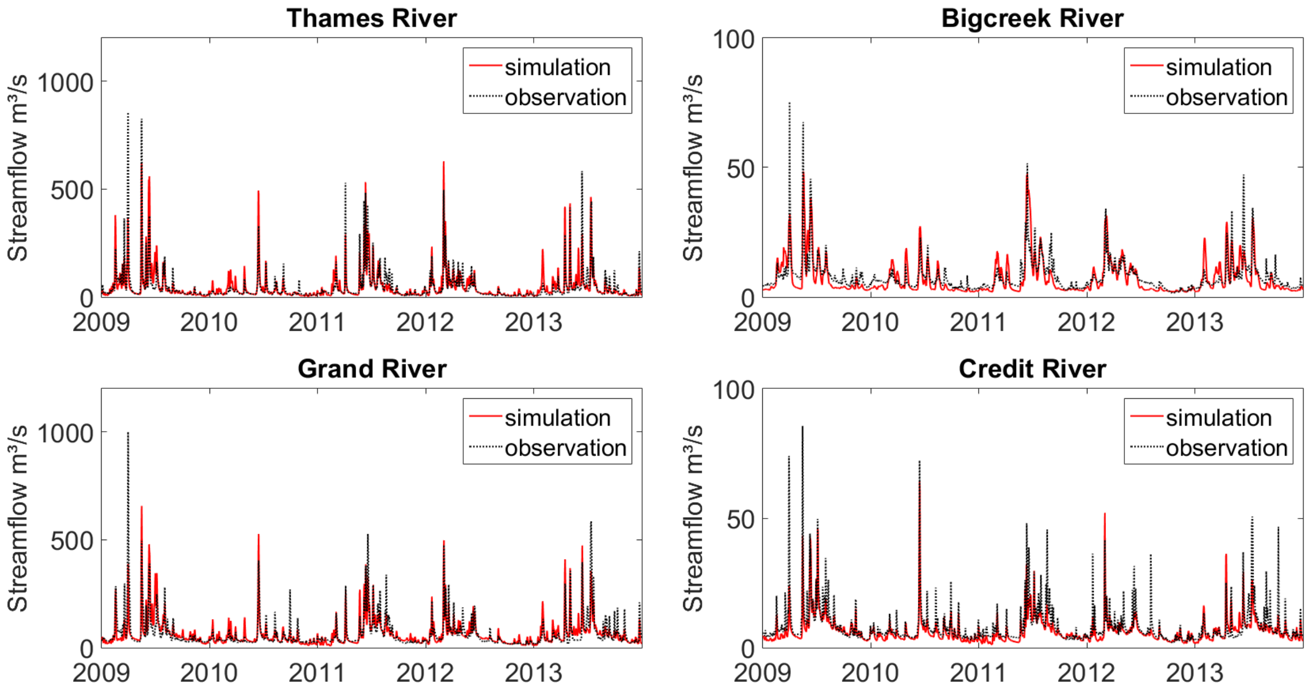

Figure 2: Daily observed (OBS) and simulated (CTL) streamflow during the validation period (2009-2013).

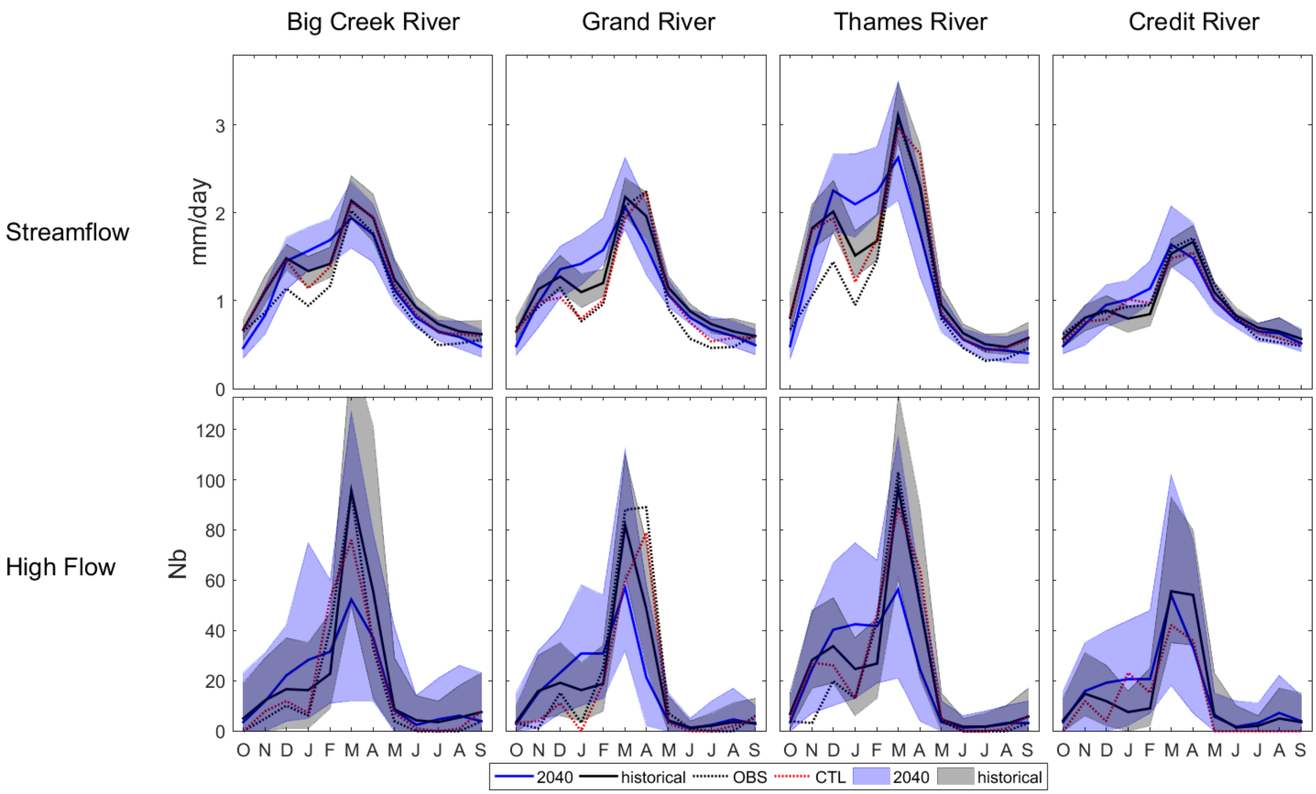

Figure 3: 50-members range and average streamflow and number of high-flows for the historical and the 2040's periods.

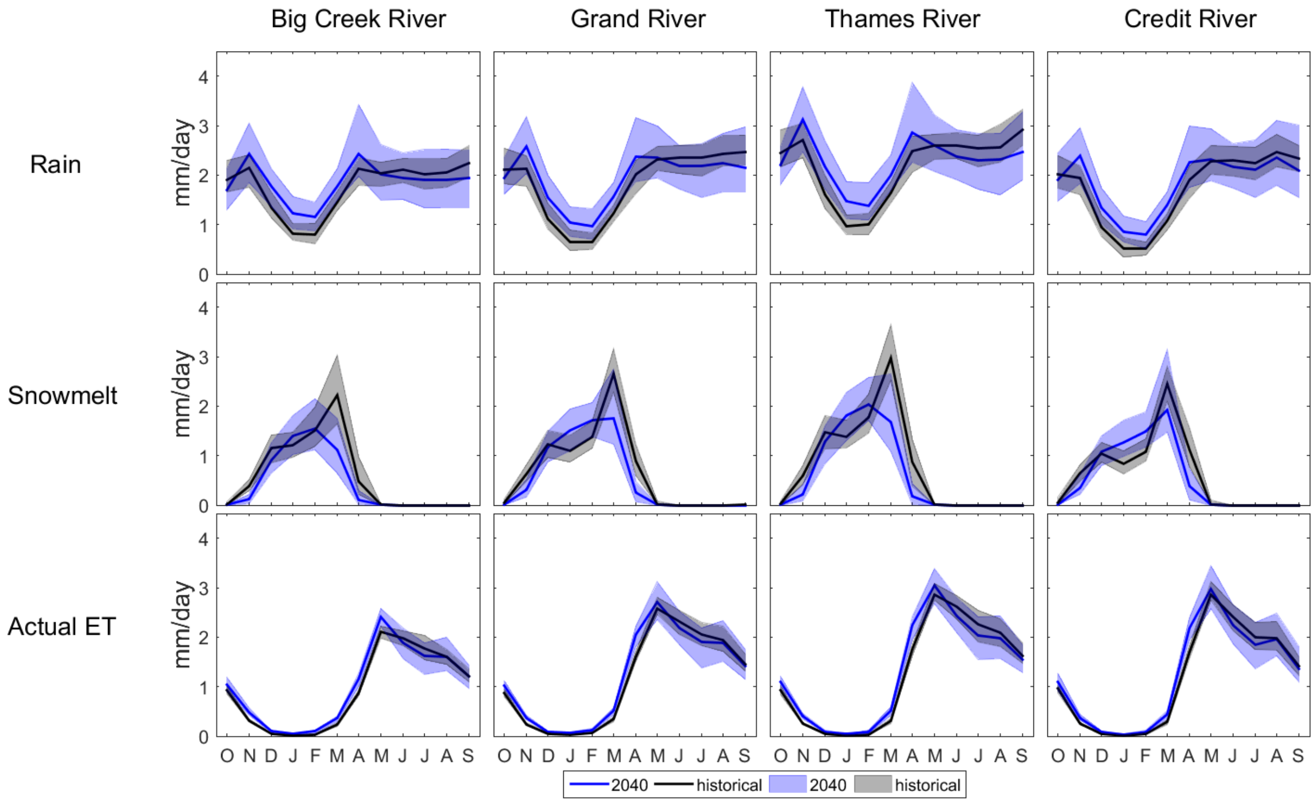

Figure 4: 50-members range and average rain, snowmelt and actual ET amounts for the historical and the 2040's periods.

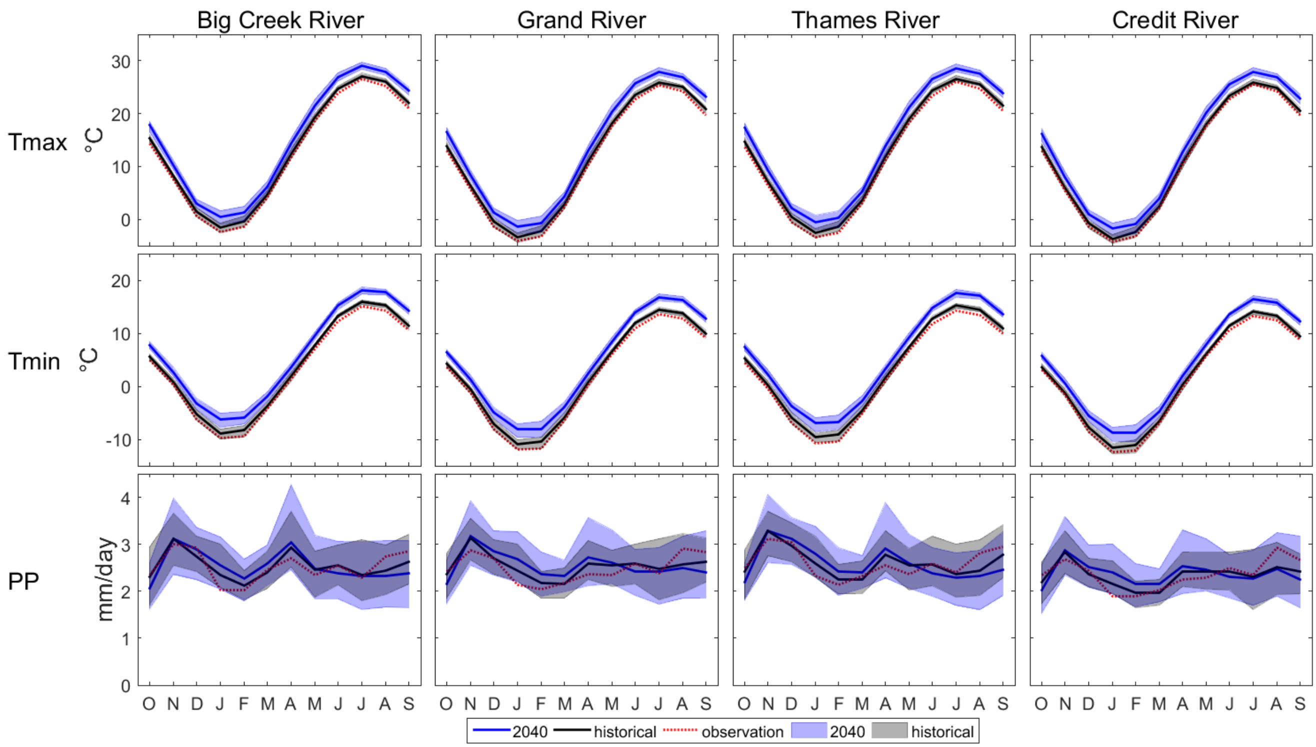

Figure 5: CRCM5 50-members range and average bias-corrected temperature and precipitation amounts for the historical and the 2040's periods, together with the observed temperature and precipitation.

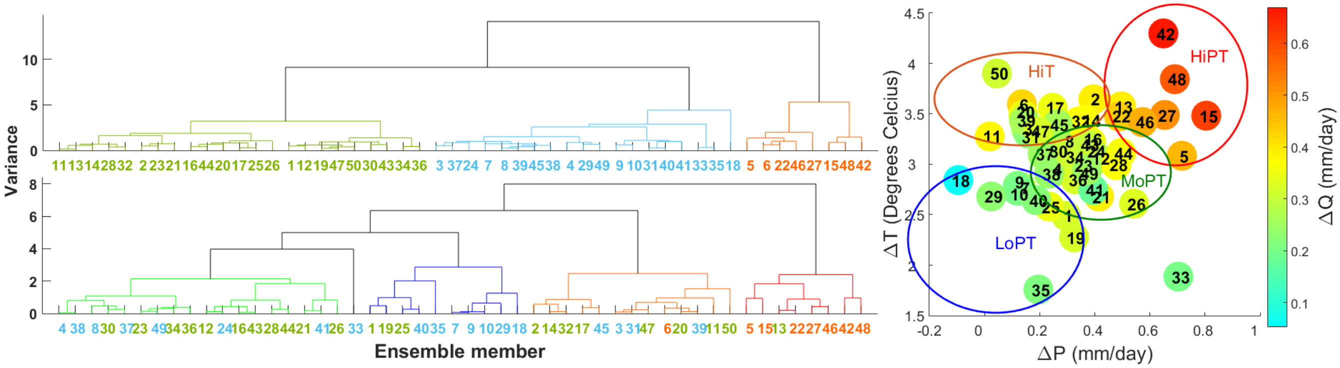

Figure 6 Left: Results of the ~~Ascending~~Agglomerative Hierarchical ~~Classification~~ Clustering (AHC) for the normalized change of streamflow (Q) (above) and normalized change of average Temperature (T) and Precipitation (P) (below). Colored numbers represent Q classes. Right: 4-watersheds average change of streamflow (Q) (Colors) with respect to average change of P and T. Large hollow circles represent the 4 weather classes.

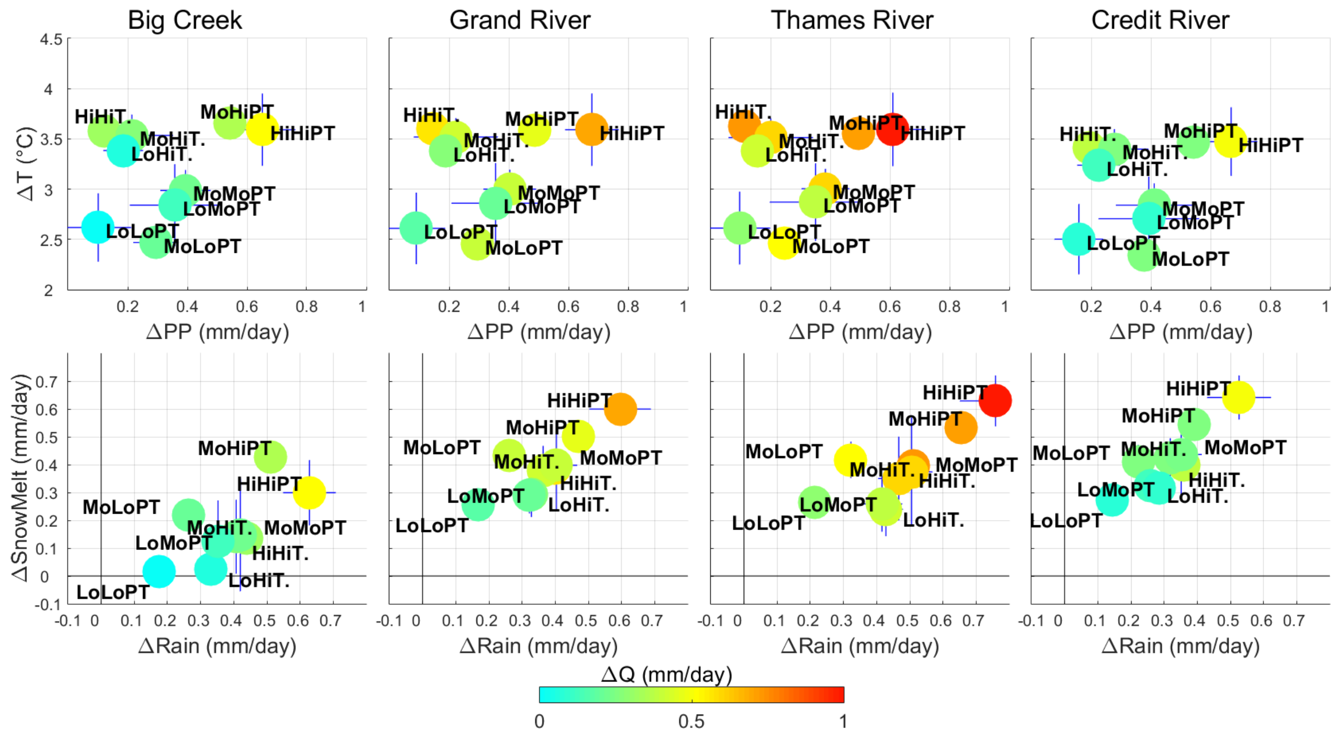

Figure 7: Change of streamflow (Colors) with respect to changes of daily temperature and precipitation amount (above) and snowmelt and rain amounts (Below) between the historical and the 2040's future period in January-February.

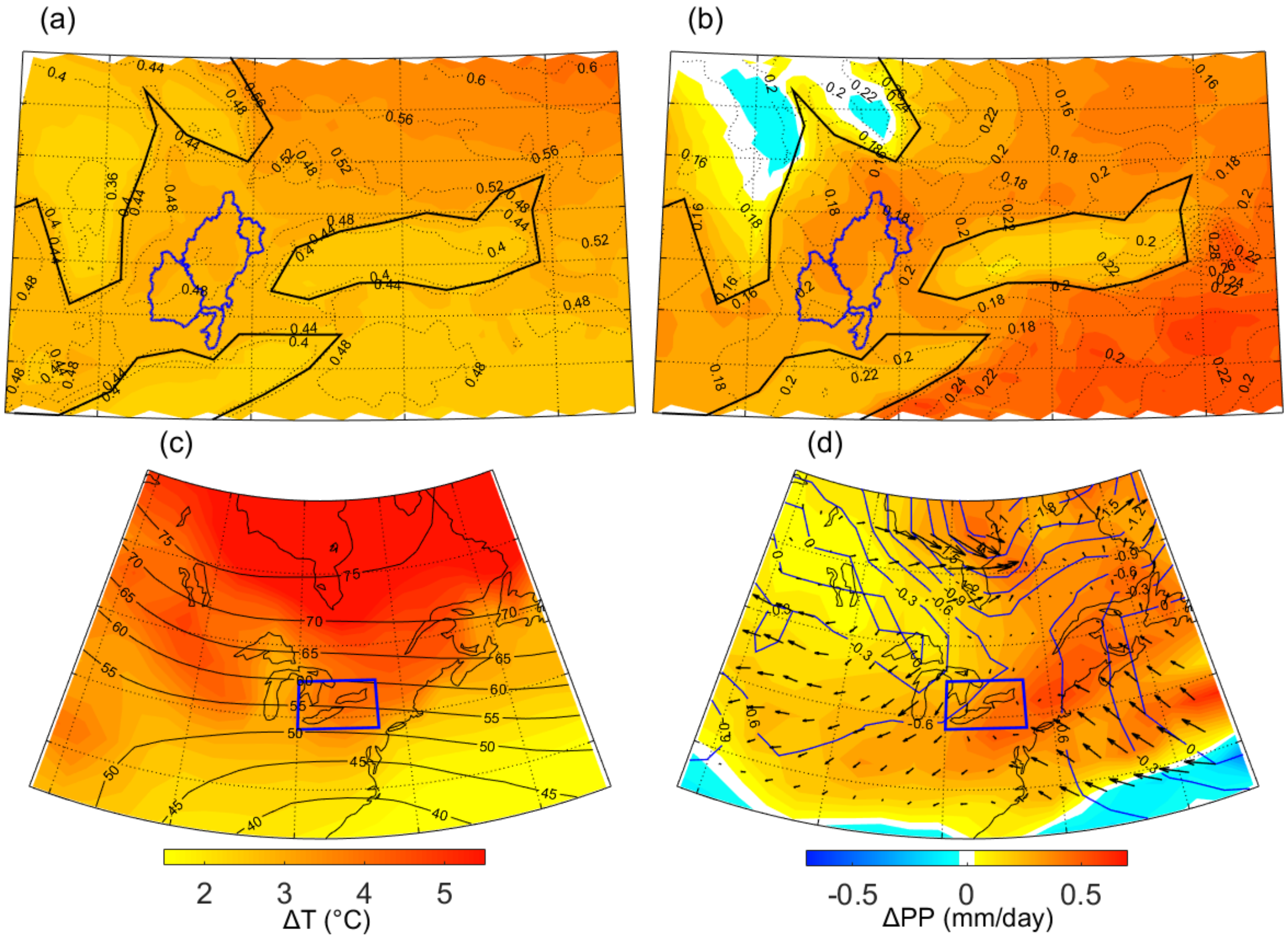

Figure 8. 50-members ensemble average change of atmospheric conditions between the historical and the 2040's period in January-february for a. CRCM5-LE average surface temperature (shade) and standard deviation (black lines), b. CRCM5-LE average daily precipitation (shade) and standard deviation (black lines), c. CanESM2-LE T850 (shade) and Z500 (black lines) and d. CanESM2-LE daily precipitation (shade), SLP (blue lines) and wind (vectors).

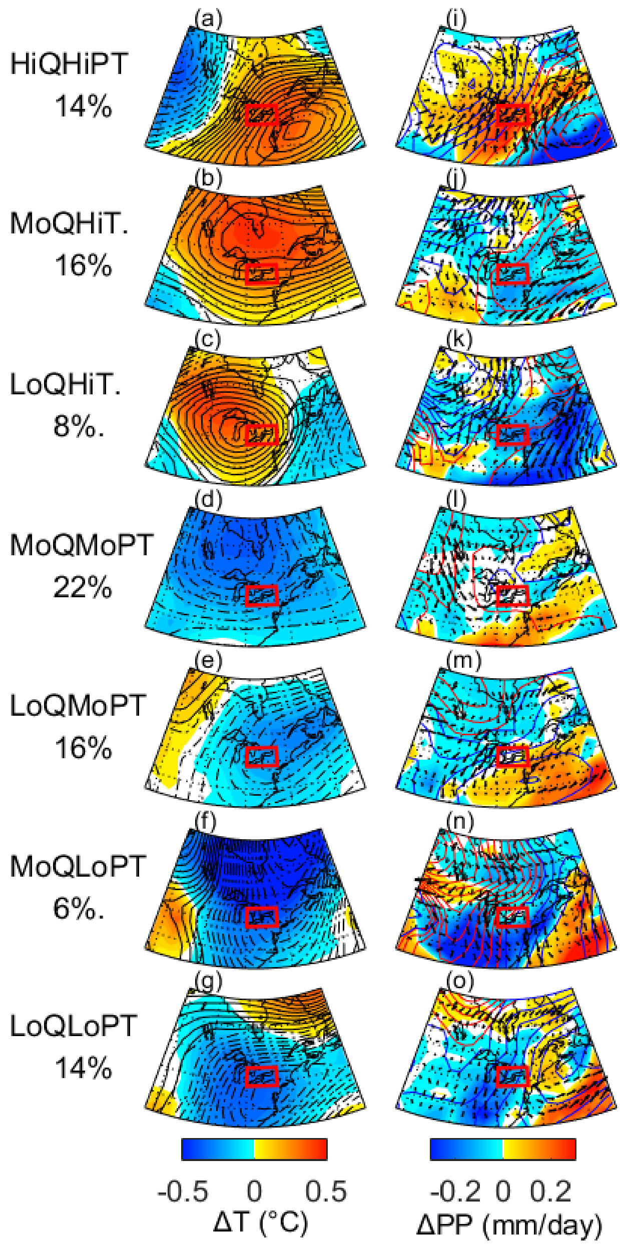

Figure 9: a-g: Classes averaged internal contribution of a-g T850 (shade) and Z500 (black lines, in intervals of 1m) and h-n: Precipitations (shade), SLP (lines, in intervals of 0.1Pa) and wind (vectors) to the 50-members average change between the historical and the 2040's period in January-February.

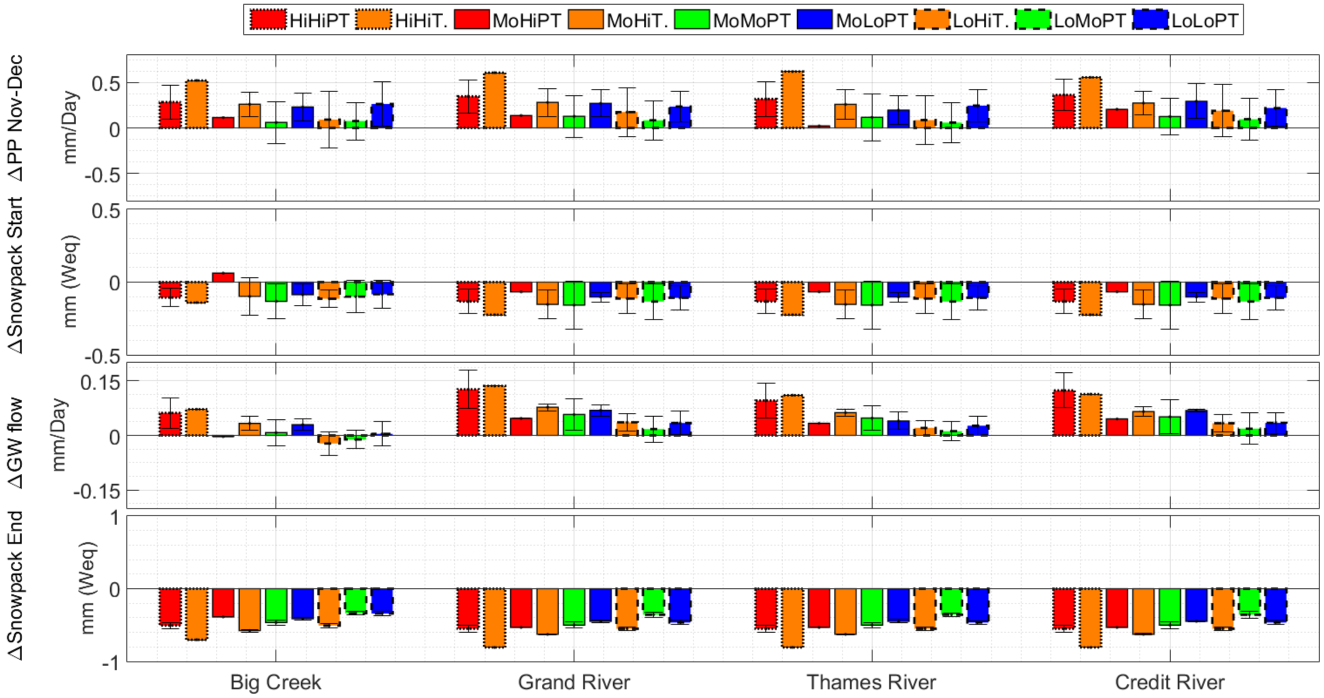

Figure 10: **Classes average (bars) and standard deviation (hatches)Evolution of the change between the historical and 2040's period of for first row: precipitation amount (mm) in November-December, , second row: snowpack amount (mm water-equivalent) in December 25th, third row: Groundwater flow in January-February, , and fourth row: snowpack amount (mm water-equivalent) in February 23th.**

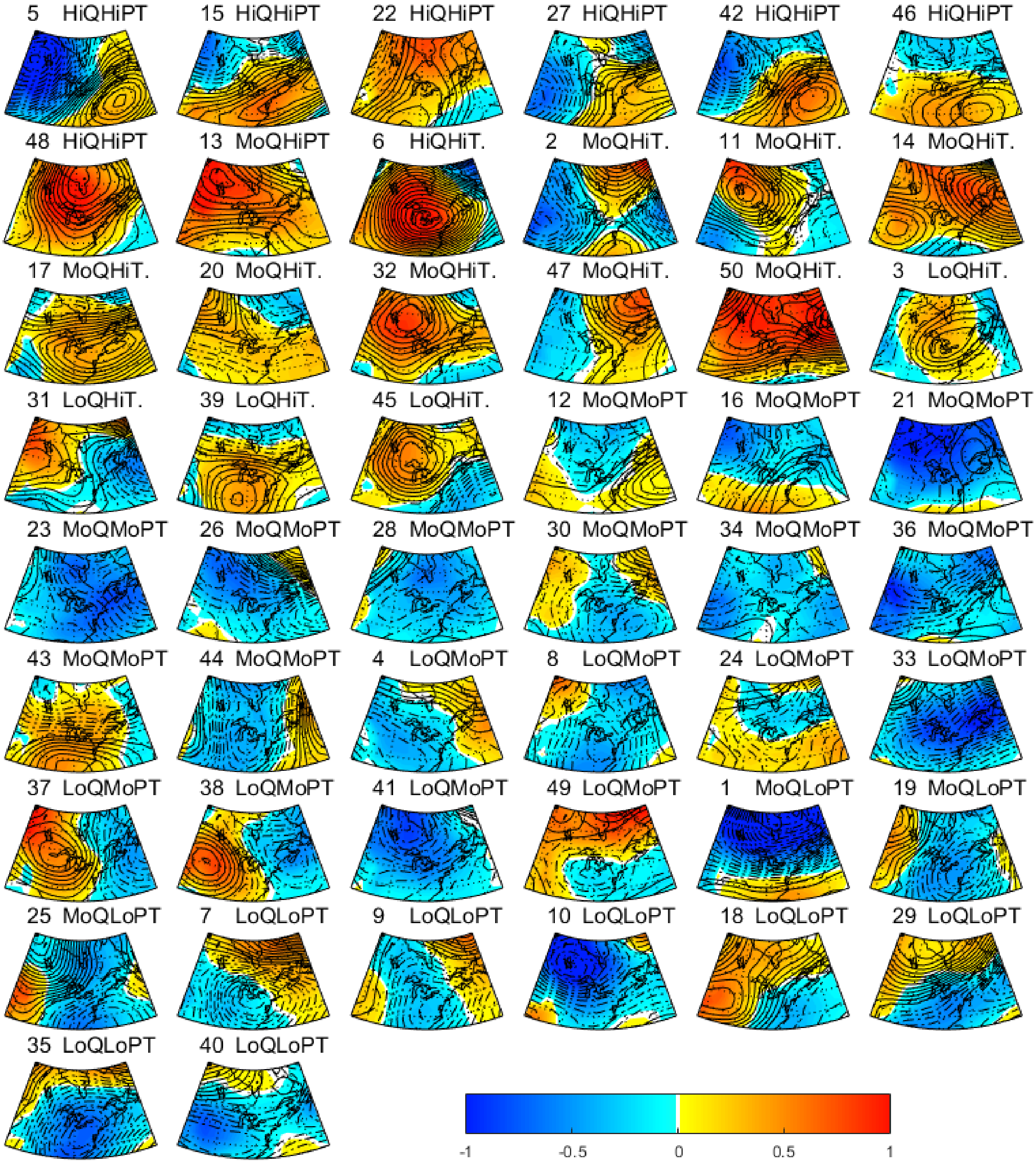

Figure 11: Internal change of T850 (shade) and Z500 (black lines, interval 2m) between the historical and the 2040's period in January-February for each member.

Table 1: Geomorphic, land use, and soil characteristics of the four watersheds examined in this study

	Size (km²)	Altitude (m)	Land use (%)				Soil type (%)		
			Urban/Barren	Forest	Shrub	Crops/Grass	Sand	Loam	Clay
Big Creek	571	179-336	1.9	17	0	81.1	78.6	6.4	15
Grand River	5091	178-531	7.1	11.9	0	80.9	30.4	31.6	38
Thames River	3061	215-423	6.9	5.4	0	87.7	14	46.7	39.4
Credit River	646	190-521	6.6	31.7	0	61.8	42.5	49.1	8.4

Table 2 Parameter values after calibration (C= Calibrated, GIS= estimated by arcpy_GSFLOW)

Parameter	Unit	Big Creek	Grand River	Thames River	Credit River	Spatial and temporal	Source
dday_intcp	Degrees days	-27 – -10	-26 – -9	-26 – -11	-26 – -9	monthly	C
dday_slope	Degrees days / °F	0.38 – 0.41	0.38 – 0.42	0.38 – 0.42	0.38 – 0.42	monthly	C
tmax_index	°F	29.3 – 80	31.2 – 78	29.3 – 80	26.5 – 78.3	monthly	C
jh_coef	per °F	0.005 – 0.021	0.005 – 0.02	0.005 – 0.021	0.003 – 0.02	monthly	C
Jh_coef_hru	per °F	22 – 22.9	20.4 – 21.4	20.7 – 21.3	20.4 – 21.5	~~HRU~~GRU	GIS
Adjmix_rain	Decimal fraction	0	0	1	0	One	C
Cecn_coef	Calories per °C > 0	20	15	10	0	One	C
emis_noppt	Decimal fraction	0.757	0.757	0.757	0.757	One	C
Fastcoef_lin	Fraction / day	0.0~~0~~1	0.2	0.1	0.2	One	C
Fastcoef_sq	none	0.03~~05~~	0.1	0.4	0.5	One	C
Freeh2o_cap	inches	0.07	0.01	0.01	0.01	One	C
Gwflow_coef	Fraction / day	0.05~~1~~	0.05	0.06	0.03	One	C
Potet_sublim	Decimal fraction	0.1	0.75	0.1	0.6	One	C
Smidx_coef	Decimal fraction	0.02~~001~~	0.05	0.04	0.001	One	C
Smidx_exp	1 / inch	0.1~~2~~	0.2	0.2	0.3	One	C
Soil_rechr_max	inches	~~0.24 –~~0.95-~~1.81~~	0.24 – 1.84	0.2 – 1.9	0.71– 5.5	~~HRU~~GRU	GIS+C
Soil_moist_max	inches	~~1.2~~7.2 – ~~9.1~~	~~0.79 – 6.12~~2.9	~~0.8 – 6.3~~3	~~0.79 – 6.1~~3.1	~~HRU~~GRU	GIS
Tmax_allrain	°F	34	35	33	36	One	C
hru_percent_imperv	Decimal fraction	0.1 – 0.6	0.1 – 0.6	0.1 – 0.6	0.1 – 0.6	~~HRU~~GRU	GIS
~~Carea_max~~	~~Decimal fraction~~	~~0.4 – 0.9~~	~~0.4 – 0.9~~	~~0.4 – 0.9~~	~~0.4 – 0.9~~	~~HRU~~	~~GIS~~
Ssr2gw_exp	none	0.4~~3~~	1	1.5	3	One	C
Ssr2gw_rate	Fraction / day	~~0.30 –~~ 0.79~~0.95~~	~~0.02 – 0.66~~0.13	~~0.01 – 0.26~~0.12	~~0.02 – 0.47~~0.11	~~HRU~~GRU	GIS+C
Slowcoef_sq	none	~~0.0004 – 7.6~~0.23	~~0 – 133~~0.37	~~0.002 – 1.97~~0.21	~~0 – 11.9~~0.06	~~HRU~~GRU	GIS+C
Slowcoef_lin	Fraction / day	~~0.02 – 12.3~~0.57	~~0 – 0.07~~0.008	~~0.004 – 0.71~~0.05	~~0 – 0.33~~0.02	~~HRU~~GRU	GIS+C

K_coef	hours	2.8 – 8.4	1.6 – 3.2	1.78 – 3.56	1.35 – 2.68	Segment	GIS+C
Pref_flow_den	Decimal Fraction	0.1	0.1	0.1	0.2	One	C
Rain_adj	Decimal Fraction	0.77 – 0.86	0.69 – 1.12	0.92 – 1.04	0.87 – 0.94	~~HRU~~GRU Monthly	GIS
Snow_adj	Decimal Fraction	0.96 – 1.06	0.69 – 1.12	0.92 – 1.04	0.72 – 0.76	~~HRU~~GRU Monthly	GIS

Table 3: Efficiency of PRMS model for best fit parameters

	Calibration		Validation	
	NSE	PBIAS	NSE	PBIAS
Big Creek	0.75	1.8	0.74	6.7
Grand River	0.71	-5	0.69	1.7
Thames River	0.72	-10.8	0.72	-5.3
Credit River	0.71	-0.1	0.65	18

Table 4: Classes members, percentage of the total member in the class and average January-February increase of streamflow between historical and 2040's period.

Name	Members	%	ΔQ (mm/day)			
			Big Creek	Grand River	Thames River	Credit River
HiQHiPT	5,15,22,27, 42,46,48	14%	0.43 (0.09)	0.55 (0.10)	0.73 (0.11)	0.43 (0.09)
HiQHiT	6	2%	0.32	0.46	0.57	0.35

~~**MoQHiPT**~~	~~13~~	~~2%~~	~~0.33~~	~~0.40~~	~~0.56~~	~~0.29~~
~~**MoQHiT**~~	~~2,11,14,17, 20,32,47,50~~	~~16%~~	~~0.29 (0.05)~~	~~0.37 (0.03)~~	~~0.49 (0.08)~~	~~0.27 (0.02)~~
~~**MoQMoPT**~~	~~12,16,21,23,26,28, 30,34,36,43,46~~	~~22%~~	~~0.25 (0.05)~~	~~0.36 (0.04)~~	~~0.49 (0.06)~~	~~0.26 (0.04)~~
~~**MoQLoPT**~~	~~1,19,25~~	~~6%~~	~~0.25 (0.02)~~	~~0.36 (0.02)~~	~~0.44 (0.02)~~	~~0.28 (0.02)~~
~~**LoQHiT**~~	~~3,31,39,45~~	~~8%~~	~~0.15 (0.03)~~	~~0.29 (0.02)~~	~~0.38 (0.02)~~	~~0.19 (0.04)~~
~~**LoQMoPT**~~	~~4,8,24,33, 37, 38,41,49~~	~~16%~~	~~0.19 (0.06)~~	~~0.25 (0.04)~~	~~0.36 (0.05)~~	~~0.17 (0.06)~~
~~**LoQLoPT**~~	~~7,9,10,18, 29,35,40~~	~~14%~~	~~0.12 (0.11)~~	~~0.23 (0.06)~~	~~0.30 (0.10)~~	~~0.16 (0.05)~~

Table 4: Classes members, percentage of the ensemble in the class and average January-February percentage increase of streamflow between historical and 2040's period. The term in parenthesis indicates the standard deviation when the class has more than two members.

Name	Members	Percentage of the total ensemble	ΔQ (mm/day)			
			Big Creek	Grand River	Thames River	Credit River
HiQHiPT	5,15,22,27, 42,46,48	14%	31.6 (8.1)	48.3 (11.1)	47 (9.6)	53.7 (15)
HiQHiT	6	2%	24.9	44	39.4	46.8
MoQHiPT	13	2%	24	35	35.7	34.1
MoQHiT	2,11,14,17, 20,32,47,50	16%	21.2 (4.4)	33.2 (3.2)	32.2 (5.4)	33.9 (2.8)
MoQMoPT	12,16,21,23,26,28, 30,34,36,43,46	22%	19.3 (5.2)	33.7 (4.8)	32.9 (6.1)	34.1 (5.1)
MoQLoPT	1,19,25	6%	17.8 (1.5)	31.2 (1.3)	27.6 (2.5)	32.7 (0.4)
LoQHiT	3,31,39,45	8%	10.6 (2.7)	24.2 (1.7)	23.5 (1.3)	22 (3.4)
LoQMoPT	4,8,24,33, 37, 38,41,49	16%	13.8 (4)	21.3 (4.1)	22.7 (3.4)	20.6 (7.3)
LoQLoPT	7,9,10,18, 29,35,40	14%	8.3 (7.8)	18.8 (5.8)	17.8 (6.4)	18.6 (6.5)