Winter hydrometeorological extreme events modulated by large scale atmospheric circulation in southern Ontario

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Abstract. Extreme events are widely studied across the world because of their major implications for many aspects of society and especially floods. These events are generally studied in term of precipitation or temperature extreme indices that are often not adapted for regions affected by floods caused by snowmelt. Rain on Snow index has been widely used but it neglects rain only events which are expected to be more frequent in the future. In this study, we identified a new winter compound index and assessed how large-scale atmospheric circulation controls the past and future evolution of these events in the Great Lakes region. The future evolution of this index was projected using temperature and precipitation from the Canadian Regional Climate Model Large Ensemble (CRCM5-LE). These climate data were used as input in PRMS hydrological model to simulate the future evolution of high flows in three watersheds in Southern Ontario. We also used five recurrent large-scale atmospheric circulation patterns in ~~northeastern~~north-eastern North America and identified how they control the past and future variability of the newly created index and high flows. The results show that daily precipitation higher than 10mm and temperature higher than 5°C were ~~a ~~necessary historical conditions to produce high flows in these three watersheds. In the historical period, the occurrences of these heavy rain and warm events as well as high flows were associated with~~to~~ two main patterns characterized by high Z500 anomalies centred on eastern Great Lakes (HP) and the Atlantic Ocean (South). These hydrometeorological extreme events ~~will be more frequent in the near future and ~~will still be associated with~~to~~ the same atmospheric patterns in the near future. The future evolution of the index will be modulated by the internal variability of the climate system as higher Z500 in the east coast will amplify the increase in the number of events, especially the warm events. The relationship between the extreme weather index and high flows will be modified in the future as the snowpack reduces and rain becomes the main component of high flows generation. This study shows the values of CRCM5-LE dataset to simulate hydrometeorological extreme events in Eastern Canada and to better understand the uncertainties associated with~~to~~ internal variability of climate.

1 Introduction

According to the actual pathway of greenhouse gases emissions, temperature will continue to rise in the future with serious implications for society (Hoegh-Guldberg et al., 2018). The amount of precipitation, especially for extreme events, is also projected to increase globally (Kharin et al., 2013), due to the acceleration of the hydrological cycle (Trenberth, 1999). Because extreme precipitation has a great societal impact across the world, internationally coordinated climate indices, built from precipitation and temperature data, are widely used to assess the evolution of different weather extremes (Zhang et al., 2011). Some of these indices such as monthly or annual maximum of precipitation can be used to improve flood management. However, in catchments that receive snowfall, a large number of floods may occur due to a combination of temperature and precipitation extreme events such as Rain on Snow (ROS) (Merz and Blöschl, 2003). The impact of ROS on floods generation have been widely studied in different regions of the world, including Central Europe (Freudiger et al., 2014), the Alps (Würzer et al., 2016), the Rocky mountains (Musselman et al., 2018) or the New York State (Pradhanang et al., 2013). The projections of these events can be a challenge because they depend on the ability of the climate model to project the precipitation extremes and the aerial extent of snowmelt (McCabe et al., 2007). The climate models improvements allowed recent studies to project the future evolution of ROS (Jeong and Sushama, 2018; Musselman et al., 2018; Surfleet and Tullos, 2013)~~(Il Jeong and Sushama, 2018; Musselman et al., 2018; Surfleet and Tullos, 2013)~~. However strong uncertainties in the projections of such events remain~~s~~, especially due to the internal variability of climate (Lafaysse et al., 2014). These uncertainties, even with the perfect climate model, will never be eradicated due to the inherently chaotic characteristic of the atmosphere (Lorenz, 1963, Deser, 2014). ROS are clearly controlled by large scale atmospheric circulation (Cohen et al., 2015) emphasizing the need to include internal climate variability uncertainties in the future evolution of ROS studies.

The Great Lakes region is one of the area of the world highly impacted by ROS events in winter (Buttle et al., 2016; Cohen et al., 2015). In this region, previous studies found correlations between precipitation (rain and snow) and temperature extremes and large-scale circulation indices: The negative phase of the P~~p~~acific North America oscillation (PNA$^-$) brings more heavy precipitation events in the region south of Great Lakes ~~region~~ (Mallakpour and Villarini, 2016; Thiombiano et al., 2017) and more snowfall in the region North of the Great Lakes (Zhao et al., 2013), due to high moisture transport over the region (Mallakpour and Villarini, 2016). Another study showed a negative phase of PNA and positive phase of North Atlantic Oscillation (NAO) associated with warm days (Ning and Bradley, 2015). Temperature and precipitation uncertainties associated with~~to~~ climate internal variability have also been assessed in North America using a global climate model large ensemble (GCM-LE) (Deser et al., 2014). These studies generally separate precipitation and temperature while studying compound events, such as ROS, has been ~~preconized recently~~recommended recently to improve our understanding of extreme impacts (Leonard et al., 2014). However, t~~T~~he definition of ROS index is also subjected to high uncertainties (Kudo et al., 2017) and this index may not be relevant in regions affected by significant rain only events ~~decrease of snowpack~~ (Jeong and Sushama, 2018)~~(Il Jeong and Sushama, 2018)~~. The goal of this study is to ~~These results emphasize the need of new compound climate indices to~~ understand the impact of atmospheric circulation on winter hydrometeorological extreme events in the Great L~~l~~akes region. ~~In this study,~~ W~~w~~e will be using~~ed~~ the Canadian R~~r~~egional C~~c~~limate M~~m~~odel L~~l~~arge E~~e~~nsemble (CRCM5-LE), a 50-member regional model ensemble at a 12km resolution produced over north-eastern North America with the following objectives:~~. The advantage of using a fine resolution large ensemble is that the processes at a local scale are better represented and the impact of the internal variability of climate on these processes can be assessed. Moreover the local processes can be related to atmospheric circulation from each GCM run that forced the regional climate model, will be used with the following objectives:~~

(1) Define a regional precipitation and temperature compound index that explains the variability of ~~contributes to~~ winter high flows in Southern Ontario, which is the most populated area in the Great Lakes region.

(2) Assess the relationship between ~~the occurrence of~~ this index and the recent ~~past~~ large-scale atmospheric circulation.

(3) Investigate the pertinence of the index to explain the future evolution of projected high flows and

(4) Demonstrate how internal variability of climate will modulate the future evolution of atmospheric circulation and number of hydrometeorological extreme events in the region.

2 Data and methods

2.1 Climate data

Observations of precipitation, minimum temperature and maximum temperature for the winter months (DJF) in the 1957-2012 period were taken from NRCANmet ~~the gridded historical weather station data (CanGRD)~~ produced by McKenney *et al.*, (2011). These data were generated from an interpolation of Natural Resources Canada and Environment and Climate Change Canada (ECCC) data archives at 10 km spatial resolution. The simulated evolution of precipitation and temperature are from the Canadian Regional Climate Model Large Ensemble (CRCM5-LE). CRCM5-LE is a 50-member regional model ensemble at 12km resolution produced over north-eastern North America in the scope of the Québec-Bavaria international collaboration on climate change

(ClimEx project; Leduc et al., 2019). CRCM5-LE is the downscaled version of the 310km resolution global Canadian model large ensemble (CanESM2-LE, Fyfe et al., 2017; Sigmond et al., 2018).~~ and offers the possibility to relate each member of CRCM5-LE to its corresponding member in CanESM2-LE.~~ The advantage of using a fine resolution large ensemble is that the processes at a local scale are better represented than a global ensemble and the local climate from each member of CRCM5-LE can be related to atmospheric circulation from CanESM2-LE.~~The~~ Temperature and precipitation from each member of ~~future~~ CRCM5-LE ~~climate data~~ have been bias corrected ~~,~~ following the method of Ines and Hansen (2006) and using the observations and CRCM5-LE ~~historical data~~ in the 1957-2012 period. For each month of the year, the intensity distribution of temperature was corrected using a normal distribution.~~ while~~For the bias correction of precipitation, the frequency and the daily intensity were bias corrected separately: T~~t~~he precipitation frequency was first corrected by truncating the modelled frequency distribution in order to match the observed distribution. ~~and~~and the ~~–~~truncated distribution of precipitation intensity ~~distribution~~ was ~~were~~ then corrected with a gamma distribution (Ines and Hansen, 2006). Each CRCM5-LE grid point has been bias corrected in the 1957-2055 period using the closest ~~CanGRD~~NRCANmet point. Using a unique ~~CanGRD~~NRCANmet point for each CRCM5-LE point is permitted in our study because of low elevation gradients between points, the spatial variability of temperature and precipitation being more dependent on the proximity of the l~~L~~akes than the elevation (Scott and Huff, 1996). The bias corrected CRCM5-LE data are reported at each NRCANmet~~CamGRD~~ point.

2.2 Heavy rain and warm index

Streamflow observations from three watersheds in southern Ontario (Figure 1) were used to define the daily temperature and precipitation threshold needed to generate high flows in winter. A high flow event was defined for each watershed as streamflow higher than the 99th percentile~~ a threshold equal to the mean streamflow plus three times the standard deviation~~. When more than two days in a row were selected~~higher than the high flow threshold~~, the events were~~as~~ considered as a single event and only the day with the highest high flow was considered. Figure 2 shows for each high flow event the distribution of daily temperature and precipitation amounts from all grids of the watersheds. Only events that produced high flows at least in 2 of the 3 watersheds are shown in Figure 2. The precipitation and temperature data are from the day situated three~~two~~ days before the high flow event for Big Creek watershed and two~~three~~ days before the high flow event for Thames and Grand rivers. This lag corresponds to the delay between a rainfall and/or warm event and the peak flow at the outlet. Figure 2 shows a maximum temperature higher than 5°C and precipitation higher than 10mm for most grid points during the high flow events. ~~These temperature and precipitation thresholds are used to create ~~T~~t~~he~~ new~~ index is therefore defined by the number of days with a temperature higher than 5°C and precipitation higher than 10mm. This index~~and~~ defines days with a significant rain and warm event that has the potential to generate a high flow event. The 5°C threshold gives a strong indication that precipitation is in a form of rain, and that the snow in the ground is melting. This index is similar to the Rain on Snow index (ROS) defined by previous studies. The threshold of 10 mm was previously used to define ROS events with floods potential (Cohen et al., 2015; Musselman et al., 2018). Our newly created index can be defined rather as a heavy rain and warm index because snowpack is not integrated in the calculation.

~~2.3 Hydrological modelling~~

~~The future evolution of high flows in the three watersheds have been simulated using the Precipitation Runoff Modeling System (PRMS). PRMS is a semi distributed conceptual hydrological model widely used in snow dominated regions (Dressler et al., 2006; Liao and Zhuang, 2017; Mastin et al., 2011; Surfleet et al., 2012; Teng et al., 2017, 2018). PRMS computes the water flowing between hydrological reservoirs (plan canopy interception, snowpack, soil zone, subsurface) for each hydrological response unit (HRU). For a general description of PRMS the reader is referred to Markstrom *et al.*, (2015). Champagne *et al.*, (2019) previously applied PRMS to these three watersheds and extensively described the parametrization process. PRMS has been calibrated in the 1989-2009 period using Precipitation, minimum temperature and maximun temperature from CanGRD~~t~~. The three step trial-and-error calibration approach applied to each watershed showed satisfactory results (Champagne *et al.*, 2019). The streamflow was simulated for each member of the ensemble in the 1957-2055 period using CMIP5-LE bias corrected data described in the section 2.1.~~

2.~~3~~4 Atmospheric circulation patterns

The recurrent atmospheric patterns in north-eastern North-America were identified by a weather regimes technique computed by a k-means algorithm (Michelangeli et al., 1995). The algorithm used daily geopotential height anomalies at 500hPa level (Z500) from the 20th century reanalyses (20thCR, Compo *et al.*, 2011) and was applied in the 1957-2012 period to the north eastern part of North America (30 N-60 N/110 W-50 W). Prior to the k-means calculations we identified the principal components of the Z500 maps that explain 80% of the spatial variance. These principal components have been decomposed in weather regimes thanks to the k-means algorithm. k-means ~~creates the classes by~~ identifies classes centroids using an iteration method that minimizes intra-regime Euclidean distance and maximize inter–regime Euclidean distance between the principal components of each day. The algorithm is repeated 100 times for each number of class between 2 and 10. The choice of the final class number is decided by a red noise test. This test consists in assessing the significance of the decomposition against weather regimes calculated from 100 randomly generated theoretical datasets that have the same statistical properties than the original dataset. The weather regimes have been previously calculated for the same domain and the red noise test showed~~s~~ five classes as the most robust choice (Champagne et al., 2019a)~~(Champagne et al., 2019)~~.

The eigenvectors of the principal components ~~corresponding to these five classes~~ calculated with 20thCR have been used to calculate the daily principal components for each member of CanESM2. This transformation was applied to the daily Z500 normalized anomalies calculated for periods of 30 years between 1950 and 2099. By calculating the anomalies for periods of 30 years we minimized the low frequency variability and therefore the internal variability of climate through the 50-members can be fully investigated.~~by the k-means algorithm to create similarly five weather regimes for each member of CanESM2-LE.~~ Each day of the principal component dataset was then placed to the closest class centroid among the 5 classes previously identified using the historic 20thCR Z500 anomalies. This process was done for each member of CanESM2-LE. ~~The weather regimes calculated with CanESM2-LE have been calculated in two periods of similar length 1957-2012 and 2013-2068. Z500 anomalies from CanESM2-LE have been calculated separately for these two periods to avoid a large climate change signal in the evolution of regime occurrencesWhen the anomalies are calculated in the entire period, t. By calculating the anomalies for the two periods separately, tThe variability of regime occurrences due to internal variability of climate is therefore fully preserved.~~

2.4~~3~~ Hydrological modelling

The future evolution of high flows in the three watersheds have been simulated using the Precipitation Runoff Modelling System (PRMS). PRMS is a semi distributed conceptual hydrological model widely used in snow dominated regions (Dressler et al., 2006; Liao and Zhuang, 2017; Mastin et al., 2011; Surfleet et al., 2012; Teng et al., 2017, 2018). PRMS computes the water flowing between hydrological reservoirs (plan canopy interception, snowpack, soil zone, subsurface) for each hydrological response unit (HRU). For a general description of PRMS the reader is referred to Markstrom *et al.*~~,~~ (2015). Champagne *et al.*~~,~~ (2019) previously applied PRMS to these three watersheds and extensively described the parametrization process. PRMS has been calibrated in the 1989-2009 period using Precipitation, minimum temperature and maximum~~n~~ temperature from ~~CanGRD~~NRCANmet. The three step trial-and-error calibration approach applied to each watershed showed satisfactory results

(Champagne *et al.*, 2019). The streamflow was simulated for each member of the ensemble in the 1957-2055 period using CRCM~~MIP~~5-LE bias corrected data described in the section 2.1.

To quantify the change in number of high flows due to a change in number of weather extreme events, the theoretical high flows frequency change due to the occurrence change in number of heavy rain and warm events (OCC) have been calculated. For each member of the ensemble, the simulated historical number of high flows events (99th percentile) associated with each weather regime has been multiplied by the change factor between number of rain and warm events in the historical period and in the future period. The difference between this calculated number of high flows and the historical number of high flows corresponds to OCC. The total change in number of high flows simulated by PRMS (TOT) corresponding to each weather regimes is subtracted by OCC for each ensemble member to account for a change in number of high flows not due to a change in number of heavy rain and warm events (DIF).

3 Results

3.1 Weather regimes in northeastern North America

Five weather regimes have been identified in north-eastern North America according to the red noise test and show distinct weather patterns (Figure 3). The weather regimes computed with 20thCR data show two clear opposite patterns characterized by positive (HP) and negative (LP) geopotential height anomalies on the Great Lakes. The regime South was characterized by positive Z500 anomalies in the Atlantic Ocean and negative anomalies in the north-west part of the domain and was associated with southerly winds. The regime North-West had low geopotential height on the Gulf of Saint-Lawrence together with winds from the northwest over the Great Lakes region. Finally, the regime North-East was associated with low geopotential height in the Atlantic Ocean but high geopotential height close to the Arctic that drove northeastern winds over the Great Lakes. The weather regimes calculated with CanESM2-LE data, using the k-means centroids identified with 20thCR anomalies, ~~in the historical period~~ have very similar patterns in the historical period (1961-1990) ~~because were calculating using the eigenvectors identified with 20thCR anomalies~~ (Figure 3). CanESM2 50 members average Z500 anomalies were generally less strong than the 20thCR weather regimes and the anomalies were slightly shifted to the South. Over the Great Lakes, ~~The~~20thCR and CanESM2-LE Z500 anomalies ~~over the Great Lakes~~ were similar for most of the regimes excepted for regime South showing higher Z500 anomalies with CanESM2-LE. In the 2026-2055 period the weather regimes show very similar patterns (Figure 3).

3.2 Validation of heavy rain and warm index and high flows simulated by CRCM5-LE

The ability of the bias corrected CRCM5-LE data to recreate the number of heavy rain and warm events relative to the number of occurrences of each weather regime ~~The ability of CRCM5-LE to simulate the occurrence of heavy rain and warm events~~ is assessed in this section. For the heavy precipitation events the observations show higher number of events during the occurrence of regime~~s~~ HP (10% of all HP days) compared to other regimes, especially in the southern parts of the region (13% of all HP days)~~ and especially in inland areas~~ (Figure 4~~5~~). . The regime South shows the second largest occurrence of heavy precipitation events (7% of all South days) while the regime North-West was associated with the least number of observed heavy precipitation events (2% of all North-west days). The number of precipitation events associated with a regime LP is spatially variable with a large number of events limited to the Lake Huron shoreline (12% of all LP days). The number of heavy precipitation events per winter ~~days~~ was generally well recreated by the regional ensemble in the historical period (Figure 4). The regime South is the exception with much ~~almost twice~~ more events ~~per occurrence of regime~~ with the 50 members average (11% of all South days) compared to the observations (7% of all South days) ~~OBS~~. In southern areas the simulations were also slightly overestimating the number of heavy precipitation events during regime North-West while underestimating during regime HP (Figure 4~~5~~).

Figure 5 shows that t~~T~~he observed number of warm events ~~followed a similar spatial variability with~~ (7.5% of all days) were overall more frequent than the number of heavy rain events (5% of all days, Figure 4). ~~events~~ The number of warm events occurred more frequently in the southern parts, particularly in the Niagara peninsula between Lake Erie and Lake Ontario, where 12-14% of all days were considered as warm days (Figure 5). ~~Concerning~~ The observed warm events~~, they also~~ occurred mostly during regime HP (23% of all HP days) while they were non-existent during regime LP (Figure 5~~6~~). The number of warm events was similar between regimes North-West, North-East and South in a large part of the area. In the Niagara peninsula more events were occurring during a regime South (15% of all South days). The simulated number of warm events -averaged for all members overestimated the observations and represented ~~was~~11% of all days~~ overestimated by all members in the entire area~~ (Figure 5~~Centre~~). This discrepency was -due to an overestimation during regimes North-West~~east~~ and South (Figure 5~~6~~). Specifically, the number of events per occurrence of regime South for the 50 members average (19% of all South days) was twice the number of events calculated with the observations (9%). ~~The simulations recreated well the number of warm events for the regimes HP, LP and North while it~~

The number of compound events, heavy rain and warm temperature was more frequent in the area close to Lake Erie in both observations and simulations if we consider all weather regimes together (Figure 6). The number of events was overestimated by the ensemble mean in the northern parts of the region. In this region, many grid points show all members of the ensemble overestimating the number of events. Close to Lake Erie the overestimation was lower and even non-existent in the Niagara peninsula. These~~e~~ compound index heavy rain and warm events were~~as also~~ more frequent during a regime HP in both observations and simulations (4.5% of all HP days)~~while the occurrences of events were very low for LP and North-West (Figure 7)~~. The simulations show a similar number of events during a regime South (4.5% of all South days) but the results largely overestimated the observations ~~se events by 3 to 4 times for the regime South~~ (1.5% of all Souths days). ~~-~~Finally, the occurrences of events were very low for LP and North-West (Figure 6)~~while it was well recreated for the other regimes (Figure 7).~~

~~The ability of the ensemble to recreate the number of heavy rain and warm events relative to the number of occurrences of each weather regime has been assessed for the heavy precipitation events, the warm events and the compound events. For the heavy precipitation events the observations show high number of events during the occurrence of regimes HP in the southern parts of the region and especially in inland areas (Figure 5). The regime South show the second largest number of heavy precipitation events while the regime North-West was associated with the least number of heavy precipitation events. The number of precipitation events associated to a regime LP is spatially variable with a large number of events limited to the Lake Huron shoreline. The ensemble appeared to recreate with accuracy these number of events per weather regimes. The regime South is the exception with almost twice more events per occurrence of regime with the 50 members average compared to OBS. In southern areas the simulations were also slightly overestimating the number of heavy precipitation events during regime North-West while underestimating during regime HP (Figure 5).~~

~~Concerning the observed warm events, they also occurred mostly during regime HP while they were non-existent during regime LP (Figure 6). The number of warm events was similar between regimes North-West, North-East and South in a large part of the area. In the Niagara peninsula more events were occurring during a regime South. The simulations recreated well the number of warm events for the regimes HP, LP and North-East while it overestimated the number of events for the two other regimes and especially the regime South (Figure 6). The~~

~~number of events per occurrence of regime South for the 50 members average was twice the number of events calculated with the observations.~~

~~The compound index heavy rain and warm events was also more frequent during a regime HP in both observations and simulations while the occurrences of events were very low for LP and North-West (Figure 7). The simulations overestimated these events by 3 to 4 times for the regime South while it was well recreated for the other regimes (Figure 7).~~

The historical distribution of streamflow associated with~~to~~ heavy rain and warm events for the observed streamflow (OBS), streamflow simulated with ~~CanGRD~~NRCANmet (CTL) and streamflow simulated for~~with~~ all~~each~~ CRCM5-LE members (ENS) are depicted~~is shown is~~ in Figure 7~~8~~. The results show an observed streamflow frequently higher than the high flows threshold when the heavy rain and warm events occurred during a regime HP. ~~Few days also show high flows during a regime South especially in Thames River and Big Creek watersheds.~~ The streamflow simulated with ~~CanGRD~~NRCANmet weather data (CTL) is underestimated but show a similar inter-regime variability with higher streamflow during HP heavy rain and warm events compared to events associated with other weather regimes. The 50 simulations from CRCM5-LE show a less strong variability between weather regimes but again~~also~~ higher streamflow when heavy rain and warm events correspond to regimes HP~~or South (Figure 8)~~. High flows are also occurring for other weather regimes especially regime South (Figure 7).

3.3 Future evolution in the number of hydrometeorological extreme events

The ~~total~~ number of heavy precipitation events simulated by CRCM5-LE is expected to increase between 1961-1990 and 2026-2055, with a maximum increase between 1 and 2 events per winter expected close to the Georgian Bay (Figure 8~~9~~). The increase in the number of events is mainly expected during the regime South but also for the regime LP near Lake Huron.~~and HP between the Georgian Bay and Lake Ontario.~~ The increased frequency of warm events is expected to be even higher reaching a total increase of about 10 events close to Lake Erie. The highest increase is expected for HP and South regimes and at a lower rate for regimes ~~South~~ North-east and North-West. The number of compound events is expected to increase by 1 or 2 events per winter with a maximal increase between Lake Erie and Huron. The increase in the number of heavy rain and warm events is expected to concern mainly the regime South and HP (Figure 8~~9~~).

The contribution of the trend in heavy rain and warm events to the trend in number of high flows has been investigated (Figure 9~~10~~). ~~For each member of the ensemble, the historical number of high flows events associated to each weather regime has been multiplied by the change factor between number of Rain and warm events in the historical period and in the future period. The difference between this calculated number of high flows and the historical number of high flows corresponds to the theoretical high flows frequency change due to the occurrence change in number of heavy rain and warm events (OCC). The total change in number of high flows (TOT) corresponding to each weather regimes is subtracted by OCC for each ensemble member to account for a change in number of high flows not due to a change in number of heavy rain and warm events (DIF).~~ Taking all weather regimes events together, the total change in number of high flows simulated by PRMS (TOT)~~TOT~~ is expected to increase in the future. ~~The increase in OCC is similar to the increase in~~ The theoretical high flows frequency increase due to the occurrence change in number of heavy rain and warm events (OCC) ~~TOT even though OCC~~ is slightly lower ~~higher~~ than the increase in TOT for ~~in the Big Creek watershed~~most of the weather regimes (DIF positive). Regime HP shows an opposite result with~~. Considering HP's events only, the increase of~~ higher OCC ~~is higher~~ compared to~~than~~ TOT on average (DIF negative). ~~while for events associated with regime South TOT is higher than OCC.~~

The 50-members distribution change in rainfall and snowfall amounts corresponding to all compound events simulated by PRMS at each watershed outlet have been investigated (Figure 10). The amount of snowmelt and rainfall taken together is generally decreasing but with a large difference between members. A large number of members show an increase in amount of rain and snowmelt especially during regime LP. The change in amount of snowmelt follows a similar decreasing trend for most of the cases but an increase in snowmelt during LP weather extreme days especially in Grand River. The amount of rainfall is slightly increasing for most of the members especially for LP in Thames river and Big Creek river.

3.4 Relationship between change in occurrence of weather regimes and extreme events

Correlations between change in~~of~~ occurrence of weather regimes and change in number of Rain and Warm events between 1961-1990 and 2026-2055 for the 50 members have been calculated for each grid point (Figure 11). The magnitude of the correlations between occurrence of weather regimes and warm events is higher compared to correlations with heavy precipitation events. The results show significant positive correlations (95% confidence) between warm events~~-~~ and the change in occurrence of ~~and~~ regime HP and negative correlations (95% confidence) between warm events and~~–~~ the change in occurrence of regime LP/North-east. ~~in the entire area.~~ For the precipitation events the results varied spatially with few areas showing positive correlations for regime South (Figure 11). ~~The change in number of warm events is also positively correlated to the change in occurrence of regime South but the results are not significance (95% confidence). The correlations with the~~ The compound index ~~are less spatially spread with~~ shows positive correlations between ~~the~~ the number of events~~index~~ and ~~the~~ regime HP close to Lake Erie and negative correlations between the number of events and~~with~~ regime LP near Lake Huron.

Inter-member c~~C~~orrelations between combination of weather regimes change and Rain and warm index change averaged over the entire region have also been investigated (Table 1). The goal is to identify the impact of a combination of two weather patterns on the hydrometeorological events ~~(Table 1).~~ The weather regimes are a discretization of a continuous process and the combination of weather regimes aim to show the impact of weather regimes interactions on local climate. The combinations of weather regimes have been done by summing the change of occurrence from the two regimes of each combination. The correlation~~s~~ between change of any weather regimes combinations and change in number of heavy precipitation events are not significant. The correlations between change in~~of~~ number of warm events and change in occurrence of weather regimes is improved when regime South is associated with~~to~~ regime HP and when regime LP is associated with~~to~~ regime North-East~~E~~ compared to correlations with regimes HP or LP only (Table 1). Concerning the compound index, the number of heavy rain and warm events~~index, the correlations are not significant if the regimes HP and South are correlated separately to the number of events but are~~ is positiv~~e~~ely correlated to a combination of regime South-HP (significant at 95% confidence interval) ~~and significant (95% confidence interval) if the correlation is applied to a combination of regime South-HP~~ and negatively ~~and significant (90% confidence interval)~~ correlated to~~with~~ a combination of North-~~w~~Ea~~e~~st-LP and North-East-LP (significant at 90% confidence interval). The correlation with the change in number of high flows in each of the three watersheds have also been investigated (Table 2) and shows significance ~~only~~ in the Big Creek and Grand River watersheds. In both watersheds ~~A combination of HP-~~ LP ~~is~~ and a combination LP-North-West are negatively correlated to high flows while ~~North-west and~~ a combination North-W~~w~~est-South is~~are~~ positively correlated to high flows. In Grand River the number of high flows is also negatively correlated to a combination of regime HP-LP.

The change of heavy precipitation, warm and compound events frequency in respect to change of occurrence of regimes South, HP, LP and North-west for each member of the ensemble is shown in Figure 12. The correspondence between change in number of heavy precipitations events and change in number of occurrences of weather regimes is not clear, confirming the low correlations in Figure 11 and Table 1. Regarding the warm events, the large increase in occurrence of regime HP-South or large decrease in regimes LP-North-Ea~~W~~est are generally associated to a large increase in number of warm events confirming the results from Figure 11 and Table 1. Concerning the compound index~~, despite the correlations shown in Figure 11 and Table 1~~, a high increase of HP and South occurrences does not systematically lead to a large increase in number of events (Figure 12).

4 Discussion

4.1 Atmospheric circulation and extreme weather events

The extreme weather events investigated in this study were identified from data that have been bias corrected by an univariate method (Ines and Hansen, 2006) that can potentially increase the simulation bias for variables depending equally strongly on more than one climatic driver (Zscheischler et al., 2019). In our study, the number of warm events was clearly overestimated in a large area of the domain (Figure 5) but the bias corrected data satisfactory recreated the number of heavy precipitation and number of compound events (Figure 4 et 6). Despite remaining biases in the simulated data, the bias correction improved the results compared to analysis using raw data (Supplementary material Figure S1 and S2). This univariate bias correction method has been chosen in this study because was satisfactory used in previous works in the region (Champagne et al., 2019b; Wazneh et al., 2017). Future studies should consider using multivariate bias corrected methods to further improve the simulation of compound indices.

~~The results show that~~ T~~t~~he occurrence of heavy rain and warm events calculated from bias corrected temperature and precipitation data are modulated by specific atmospheric patterns in winter which corroborates previous studies in the Great Lakes region. These studies found that heavy precipitation and flooding events are associated with~~to~~ high geopotential height anomalies in the east coast of North America similarly to regimes HP or South (Mallakpour and Villarini, 2016; Zhang and Villarini, 2019; Farnham *et al.*, 2018)~~)~~. Our results found differences between observations and simulations with more heavy precipitation events during regime HP in the observations while the simulations with CRCM5-LE show more precipitation~~s~~ events during regime South (Figure 4~~5~~). The overestimation in~~of~~ the number of precipitation events for regime South can be associated with~~to~~ the difference in pattern between regimes calculated with 20thCR and CanESM2-LE (Figure 3). Regime South calculated with CanESM2-LE shows Z500 anomalies shifted to the west and likely a more meridional flux compared to the regime South from 20thCR. The weather regimes associated with~~to~~ heavy precipitations in the Mid-west defined by Zhang and Villarini~~,~~ (2019) show high pressure anomalies on the east and low pressure on the west sides of the Great lakes similarly to regime South calculated with CanESM2. The regime South calculated with 20thCR shows negative Z500 anomalies with a northern position compared to CanESM2-LE and therefore a stronger zonal flux while the regime South calculated with CanESM2-LE has likely a more meridional flux driving humidity from the Gulf of Mexico (Figure 3). This pattern also brings warm temperature events even though the regime HP brings even more warm events in both the observations and the ensemble average (Figure 5~~6~~). Regime HP has similarities with the positive phase of the NAO, previously ~~clearly~~ associated with warm winter temperature in the Great Lakes region (Ning and Bradley, 2015). The other weather regimes bring generally fewer heavy precipitation or warm events apart from regime LP bringing heavy precipitation close to Lake Huron (Figure 4~~5~~). LP is not associated with warm events (Figure 5~~6~~) suggesting that these extreme precipitations are in form of snow and likely from lake effect snow. Suriano and Leathers, (2017) show that low pressure anomalies north-east from Great lakes brings major lake effects snow in the eastern shores of Lake Huron due to less zonal wind and cold outbreaks from the Arctic. The regime LP shows low geopotential height anomalies right on the Great lakes and the associated north-west winds on the Lake Huron are likely to bring lake effect snowfall in this area.

4.2 Future evolution of rain and warm events

The future increase in~~of~~ winter heavy precipitation~~s~~ events ~~in winter~~ in Southern Ontario was already described in Deng *et al.*, (2016). Compound events such as Rain on Snow (ROS) events have also been investigated by ~~Il~~ Jeong and Sushama (2018). These authors defined ROS events as liquid precipitation and snow cover higher than 1mm and found no significant trend of ROS events in the Great L~~l~~akes region, in continuity to what was observed in the past (Wachowicz et al., 2019). These studies show that the Great Lakes region is located between a region of increase ROS events due to increase of rainfall in the north and a decrease in ROS events due to decrease of snowpack in southern regions. Increase of rainfall and decrease of snowpack are both expected~~likely~~ to occur in Southern Ontario (Figure 10) and are likely to cancel~~ling~~ each other in term of ROS events. Our heavy rain and warm index ~~study~~ does not consider snowpack and is expecting to~~show an increase~~ be more frequent in ~~heavy rain and warm compound events~~ the future (Figure 8~~9~~). The increase of heavy rain and warm events is likely driven by warmer temperature shown by the increase of the compound events and warm events both occurring at a higher extent close to Lake Erie (Figure 8~~9~~). The increase in extreme precipitation events is less significant than the increase in~~of~~ warm events and is occurring mostly in the Northern parts of the area (Figure 8~~9~~).

The future evolution of ROS or heavy rain and warm events corresponding to different weather patterns have not been yet investigated in previous literature. It is interesting to note that the future increase of the heavy rain and warm events are expected to occur only for the regimes HP and South, the number of events remaining very low for the other regimes (Figure 8~~9~~). This result suggests that the global increase of mean temperature and precipitation is not sufficient to reach the 10 mm and 5°C threshold for LP, North-West and North-East regimes. More precipitation events are expected during regimes LP but the temperature stays too low to increase the numbers of heavy rain and warm events (Figure 8~~9~~). Regime North-West and North-East show~~s~~ an increase of warm events but not an increase in precipitation events and therefore the number of rain and warm events is not expected to increase.

4.3 Change in frequency of heavy rain and warm events partially modulated by the occurrence of weather regimes

Despite clear association between regimes HP/South and occurrences of rain and warm events, the uncertainties linked to internal variability of climate are not fully apprehended by the frequency of weather regimes. Members of the ensemble associated with a simultaneous high increase of regime HP and South frequencies are generally associated with higher increase in rainfall and warm events (Table 1) but the association is less straightforward than suggested by the correlation values (Figure 12~~1~~) probably due to poor association between precipitation extremes and occurrence of weather regimes (Table 1 and Figure 11~~0~~). Similar change in occurrences of South-HP weather regimes can lead to variable change in number of heavy rain and warm events (Figure 12~~1~~). This suggests that other scales than the weather regimes calculated in the northeastern North American domain are likely to play a role in weather extreme events and especially the change of heavy rain and warm events and precipitation events. The presence of the Great lakes has a large role in the variability of precipitation at a local scale (Martynov et al., 2012) suggesting that variability of precipitation events depend not so much on the atmospheric circulation over the Great Lakes at the day of the events. The temperature of the lakes and the amount of ice covering the lakes plays a great role in the variability of precipitation (Martynov et al., 2012).

4.4 Non stationarity in the relationship between weather extreme events and high flows

The projections show that the increase in number of high flows associated to a regime HP is expected to be lower than the increase in number of heavy rain and warm events (negative DIF in Figure 9~~10~~). This result suggests that the conditions to produce high flows may change in the future. As the temperature increase, snowmelt is expected to be a less important component in the generation of high flows in the region (Figure 10). In the historical period regimes HP and South produce approximately the same number of high flows in the simulations (Figure 7) but are driving mostly by heavy precipitation for the regime South and warm events for the regime HP (Figure 4~~5~~ and 6~~6~~). More importantly, HP shows a further increase of warm events in the future while South show rather an increase of precipitation (Figure 8~~9~~). In the context of less snow, the importance of precipitation to drive high flows will be higher in the future because warmer conditions do not increase snowmelt in case of a snowpack reduction (Figure 10). Therefore, the increase of weather extreme events associated to the regime South will be associated to an increase of high flows more strenuously than the increase of events associated to HP (Figure 9). The future change in number of high flows is associate to a large inter-member uncertainty (Figure 9~~10~~). The weather extreme events inter-member uncertainty was partly associated to the change in occurrence of weather regimes especially for the warm component (Figure 11 and 12 and Table 1). The association between occurrence of weather regimes and high flows is less clear and shows opposite results (Table 1 and 2). Especially, change of occurrence of regime North-west is positively correlated to the change in number of high flows in Big Creek and Grand river watersheds (Table 2) while it is negatively correlated to the change in number of weather extreme events in this area (Figure 11). The correlation is even ~~also~~ significant when regimes North-west and South are associated (Table 2). This result can be due to ~~the continuous nature of streamflow and~~ the preferential sequence of weather regimes and more snow generated by patterns similar to the regime North-West (Champagne et al., 2019b). ~~Regime North-west shows an increase in number of warm events especially close to Lake Erie (Figure 9) with the potentiality to melt more snow in the future. The amount of precipitation generated by a regime North-west is probably not sufficient to generate high flows (Figure 9), but the increase of snowmelt during the regime North-West likely enhances streamflow that make the high flows threshold easier to reach in a following precipitation event~~. The pattern associated with regime North-west shows anticyclonic systems in the west part of the domain (Figure 3). The meteorological systems have a tendency to move eastward and this anticyclonic system is likely to become a regime South or HP (Champagne *et al.*, 2019, Supplementary material, Table S2). In addition, as already stated in the previous paragraph, regime HP will be less likely to produce a heavy rain event than a regime South in the future. Therefore, members projecting an increase in the combination of the snowy regime North-West and wetter and warmer regime South are more likely to project more high flow events. ~~The combination of the warmer regime North-west following by a wetter and warmer regime South are therefore more likely to produce high flows in the future~~. These results emphasize the need to study not only each hydrometeorological extreme events and relationship with atmospheric circulation independently, but also focusing on the sequence of weather patterns preceding the high flows events.

4.5 Relevance of rain and warm events to explain future evolution of high flows

The relevance of using an index based on daily temperature and precipitation to study the future evolution of high flows is questionable. Even if a heavy rain and warm event is a necessary condition to create a high flow event (Figure 2), such event is not systematically followed by a high flow event (Figure 7). The previous section suggests that snow falling days before the high flow event has an important role in the generation of high flows. Other factors such as multi-days rain events could also contribute to increase the streamflow. This study focused on single day events to introduce first results in the ability of CRCM5-LE to identify extreme events and their associated CanESM2 weather patterns in southern Ontario, but future studies should investigate multi-day events. ~~One of the objectives of this study was mainly to create a new index that explains high flows in Southern Ontario and investigate how this index will change in the near future.~~ Moreover~~However~~, as stated in the previous section, the relationship between the extreme weather events index and high flows is affected by non-stationarity. Applied in the past, the Rain and warm index works well to define the high flows risk in Southern Ontario (Figure 2), the warm component of this index being a condition to trigger snowmelt. In a warming climate, snowpack is reduced, and the rain to snow ratio is increasing (Il Jeong and Sushama, 2018), changing the relationship between extreme weather events and high flows.

To integrate snow processes and reduce the uncertainties from non-stationarity of temperature, Rain on snow index could be used in lieu of our heavy rain and warm index. -However, ~~but~~ this index is not projected to be more frequent in the future in the Great Lakes region, precisely because of less snow in the ground (Jeong and Sushama, 2018)~~(Il Jeong and Sushama, 2018)~~. Moreover, ROS index integrate events with a very small contribution of snowmelt to the high flows while neglecting rainfall only events (Cohen et al., 2015; Jeong and Sushama, 2018; Pradhanang et al., 2013)~~(Cohen et al., 2015; Il Jeong and Sushama, 2018; Pradhanang et al., 2013)~~. The definition of ROS also introduces more uncertainties as it depends on the combination of simulated precipitation and temperature for several days (Kudo et al., 2017). Our heavy rain and warm index minimizes this uncertainty and take into consideration heavy rainfall whatever the amount of snow covering the ground. It is therefore a good tool to assess the potential risk of high flows in Southern Ontario from all ranges of rain events, even though it is important to keep in mind that the flood risk diminished as snowpack decreases. A rain only index could also be used but the impact of snowpack on streamflow would be completely eradicated while snow will still play a role in the future hydrology. ROS events, liquid precipitation events and our heavy rain and warm events, ideally with multi-day events integrated, should be investigated together to fully understand the future evolution of the flood risk due to a shift in weather extreme events.

5 Conclusion

The aim of this study was to assess the ability of the Canadian Regional Climate Model Large Ensemble (CRCM5-LE), a downscaled version of the 50-members global Canadian model Large Ensemble (CanESM2-LE), to simulate winter hydrometeorological extreme events in Southern Ontario and to investigate how the internal variability of climate will modulate the future evolution of these extremes. The winter composite index heavy rain and warm temperature was identified in the past with gridded observation data (~~CanGRD~~NRCANmet) by investigating what conditions of temperature and precipitation are necessary to produce a high flow in three watersheds in Southern Ontario. PRMS model was used to simulate the future evolution of high flows for each member of CRCM-LE in these three watersheds. The large-scale circulation patterns corresponding to these events were assessed by identifying past recurrent weather regimes based on daily Z500 from the 20th century reanalyses and estimating the evolution of the same weather regimes in the future for each member of CanESM2-LE. The results of this study show that CRCM5-LE was able to:

(1) Recreate the historical larger number of events close to Lake Erie despite an overestimation of warm events.
(2) Simulate more heavy rain and warm events as well as high flows during the regimes associated with high pressure anomalies on the Great Lakes (HP) and the Atlantic-Ocean (South).
(3) Project an increase in the future number of heavy rain and warm events and associated high flows especially during the regimes HP and South and in the vicinity of Lake Erie.

These results suggest that depending on the future evolution of natural variability of climate, the increase in the number of events will be amplified or attenuated by the favoured positions of the pressure systems. The natural variability of climate is not expected to greatly modulate the number of high flows due to an increase of the importance of precipitation in generating high flows. The role of more localized processes such as impact of the lakes on precipitation events needs to be further evaluated to improve the ability of the next versions of regional climate models to recreate the precipitation events. The newly created weather index did not integrate snowpack because the uncertainties in the ability of CRCM5-LE to recreate precipitation and temperature extremes at a daily basis would be further increase in snowmelt estimates. However, snowpack variability will have a large impact in the modulation of high flows in the region and future studies should investigate snow processes by taking advantage of rapid improvements in climate regional modelling. Other regional climate models and different scenarios should also be used to improve our understanding of~~in~~ the future evolution of hydrometeorological extreme events in Southern Ontario. Despite these future possible improvements, our study gives a good estimation of what to expect in term of change in number of hydrometeorological events in Southern Ontario and will serve to better estimate the future flood risk in this populated region.

Authors contribution

ML furnished CRCM5-LE data. OC performed the analyses and made the figures. OC prepared the manuscript with contributions from all co-authors.

Competing interest

The authors declare that they have no conflict of interest.

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Zscheischler, J., Fischer, E. M. and Lange, S.: The effect of univariate bias adjustment on multivariate hazard estimates, Earth System Dynamics, 10(1), 31–43, doi:10.5194/esd-10-31-2019, 2019.

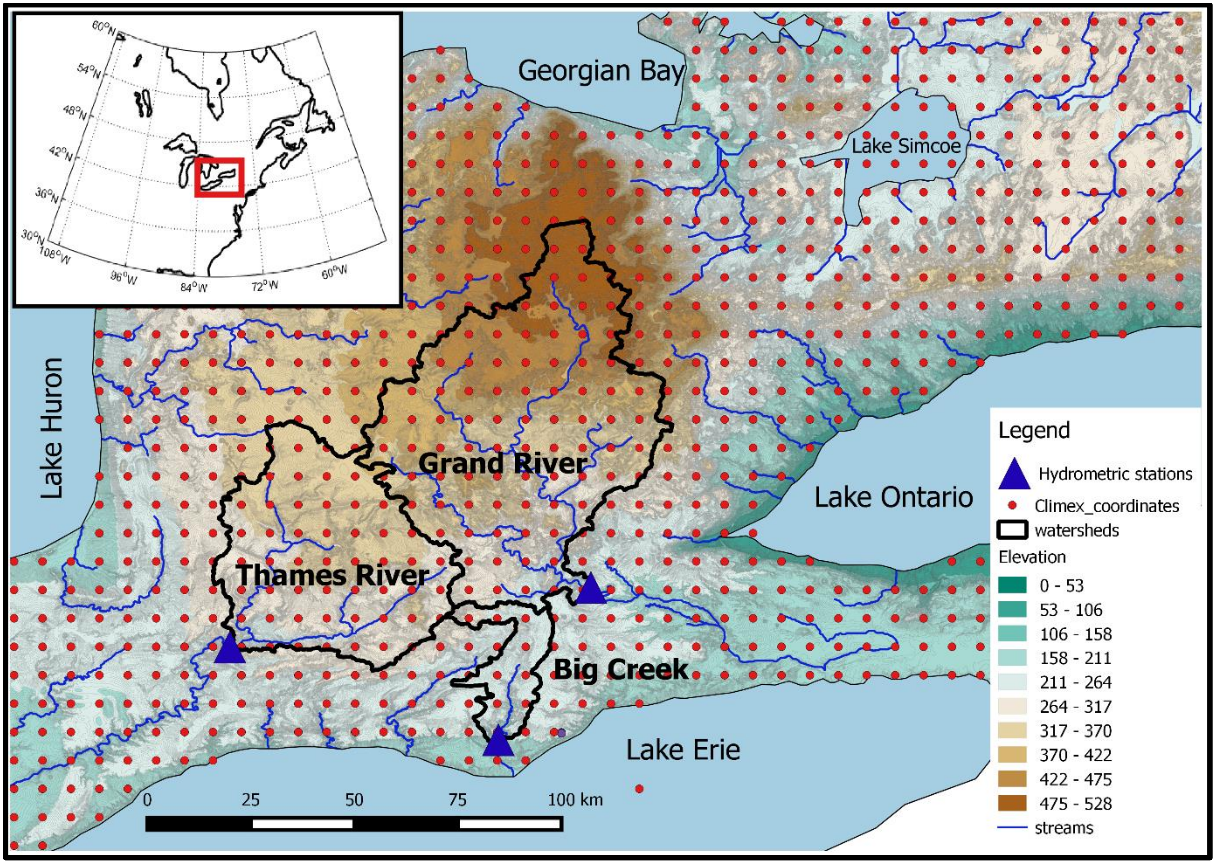

Figure 1: Location of the three watersheds and the ClimEx grid points used in this study and situation in the north-eastern North American domain (Inset).

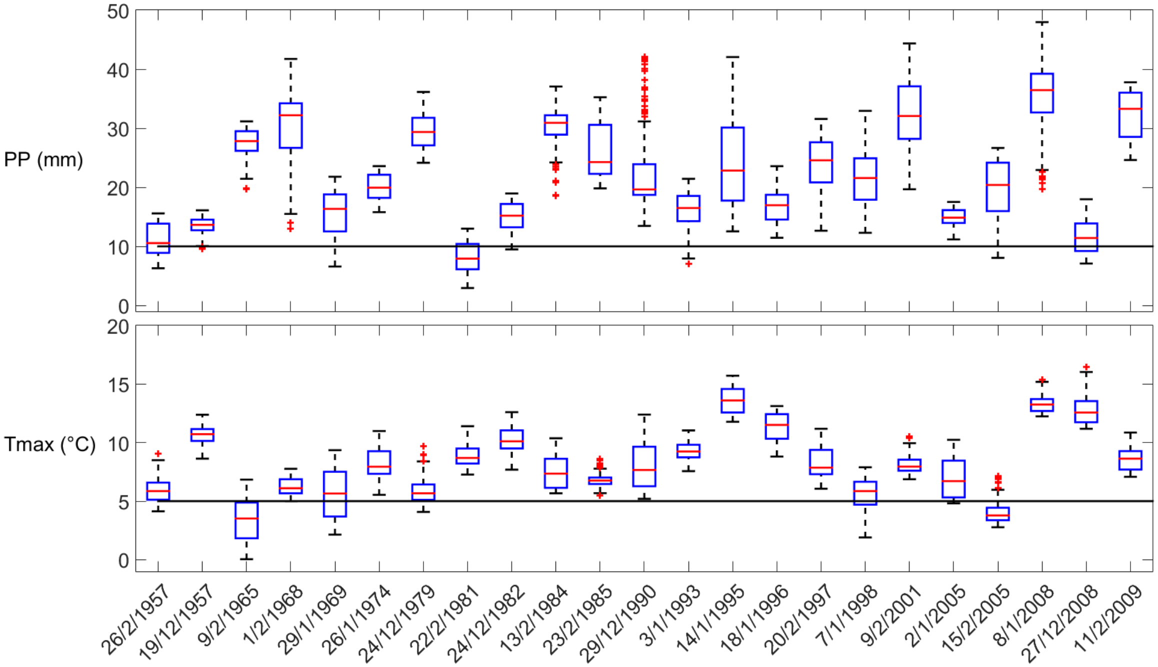

Figure 2: Distribution of ~~CanGRD~~NRCANmet temperature and precipitation from all 3 watersheds grid-points corresponding to each DJF high-flow event. Boxes extend from the 25th to the 75th percentile, with a horizontal red bar showing the median value. The whiskers are lines extending from each end of the box to the 1.5 interquartile range. Plus signs correspond to outliers. ~~The blue lines correspond to high flows (Average streamflow plus 3 times the standard deviation).~~ The horizontal black lines correspond to the thresholds used to define DJF weather extreme events.

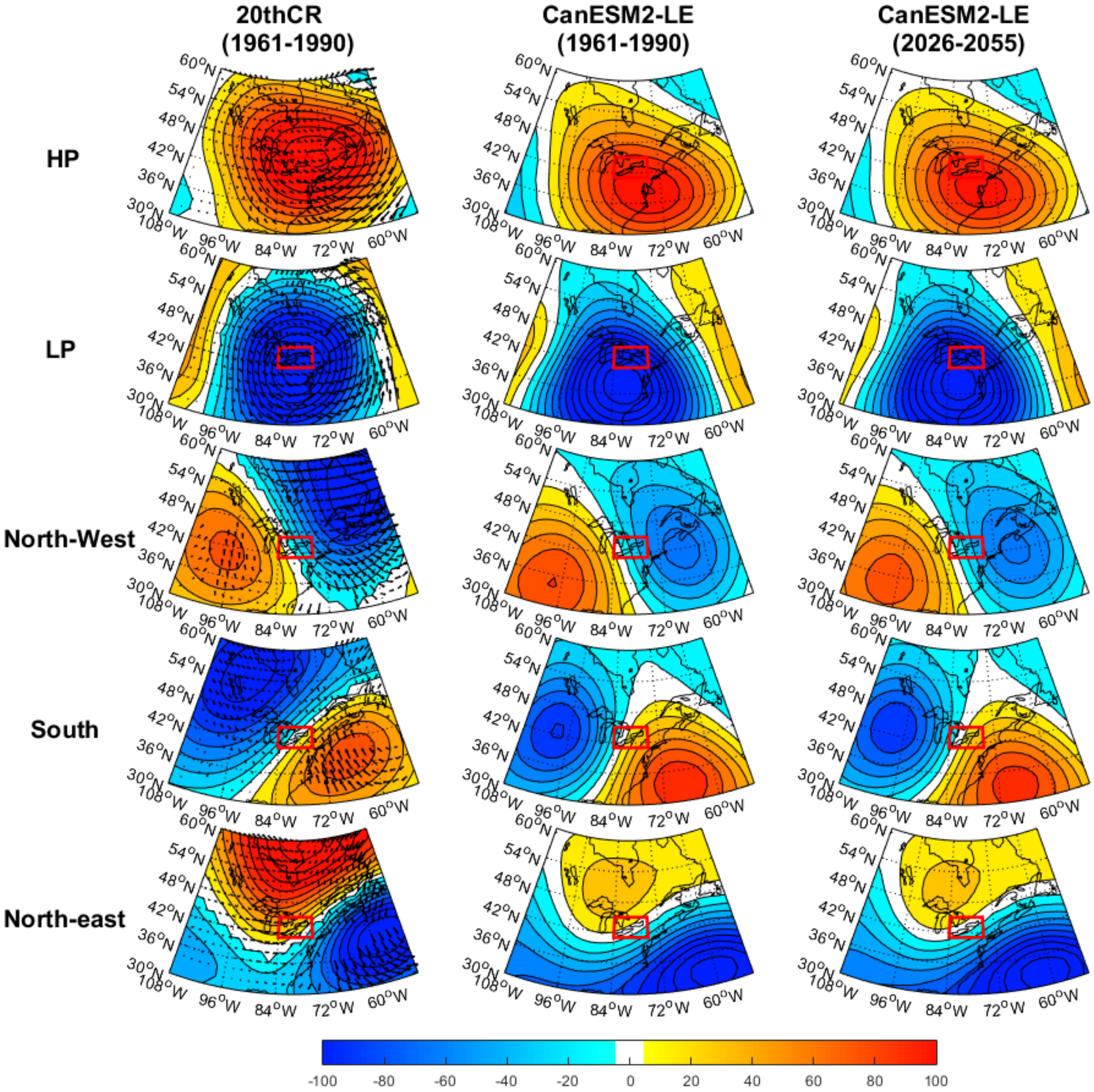

Figure 3: Left panels: DJF Z500 anomalies (colours) and winds (vectors) corresponding to Weather regimes calculated with 20thCR in the 1961-1990 period. Mid panels: DJF 50 members average Z500 anomalies calculated with CanESM2-LE in the 1961-1990 period. Right panels: DJF 50 members average Z500 anomalies calculated with CanESM2-LE in the 2026-2055 period.

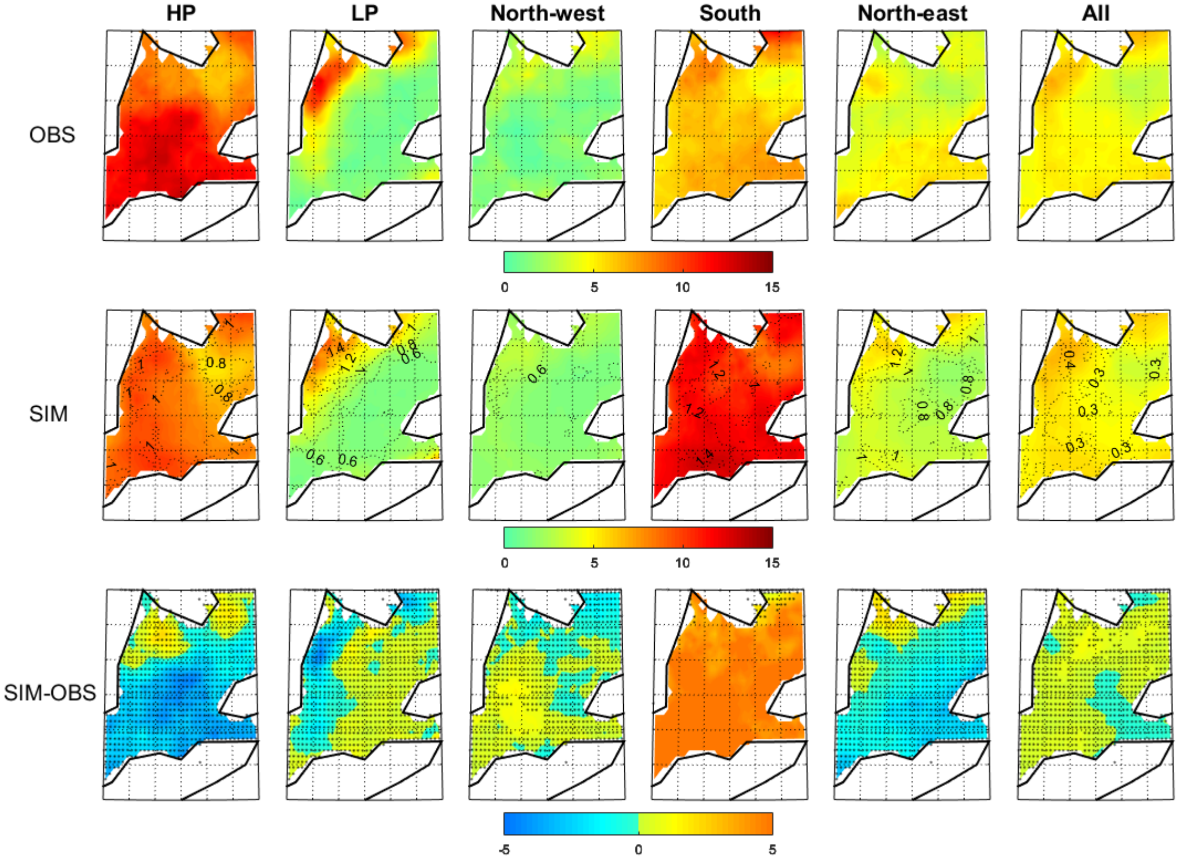

Figure 4: Percentage of DJF number of precipitation events relative to DJF occurrence of weather regimes in the historical period (1961-1990) for the observations (upper panels), simulations from CRCM5-LE 50 members average (mid panels) and simulations minus observations (lower panels)~~for CanGRD (upper panels), 50 members CRCM5-LE average (mid panels) and CanGRD minus CRCM5-LE (right panels)~~. The dotted lines in the mid panels represent the standard deviation of the 50-members CRCM5-LE simulated percentage. Stippled regions in the lower panels indicate where the observations lie within the CRCM5-LE ensemble spread.

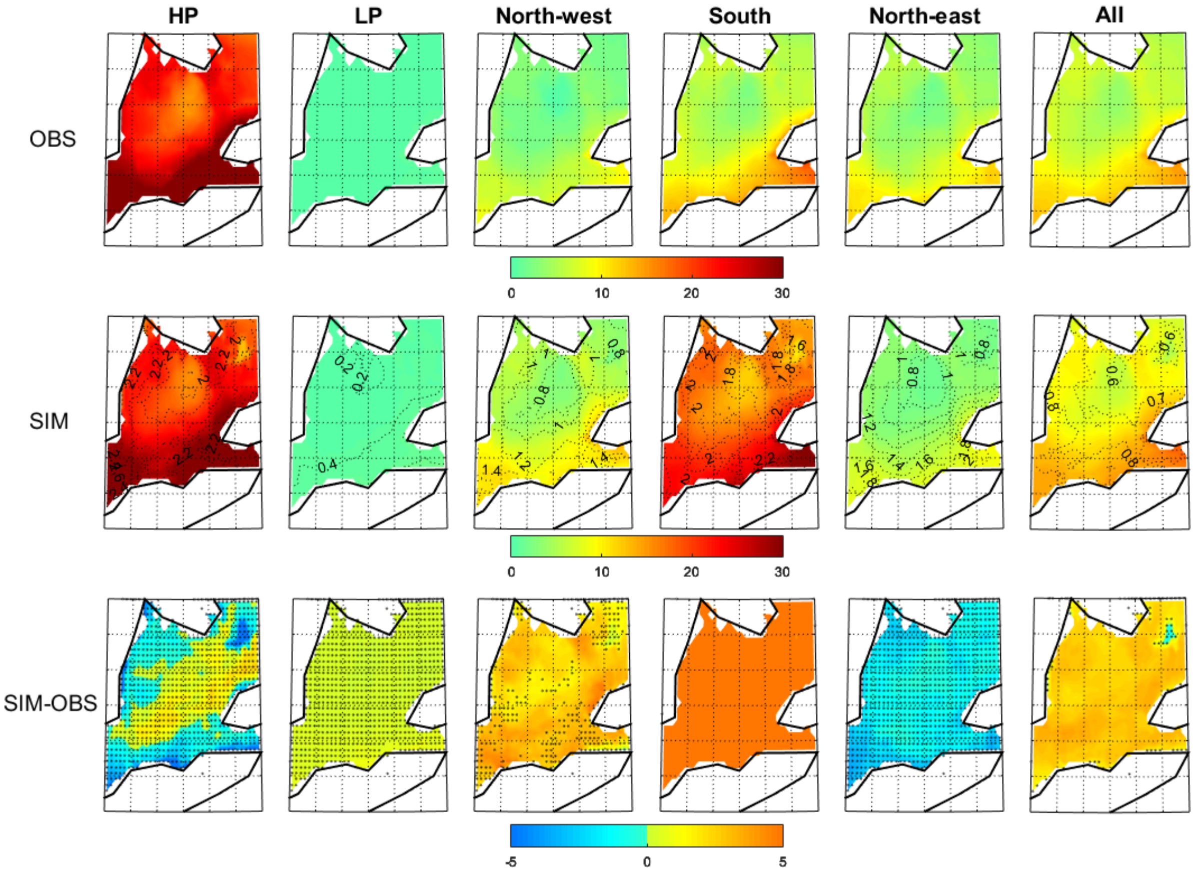

Figure 5: Percentage of DJF number of warm events relative to DJF occurrence of weather regime in the historical period (1961-1990) for the observations (upper panels simulations from CRCM5-LE 50 members average (mid panels) and simulations minus observations (lower panels)~~for CanGRD (upper panels), 50 members CRCM5-LE average (mid panels) and CanGRD minus CRCM5-LE (lower panels~~). The dotted lines in the mid panels represent the standard deviation of the 50-members CRCM5-LE simulated percentage. Stippled regions in the lower panels indicate where the observations lie within the CRCM5-LE ensemble spread.

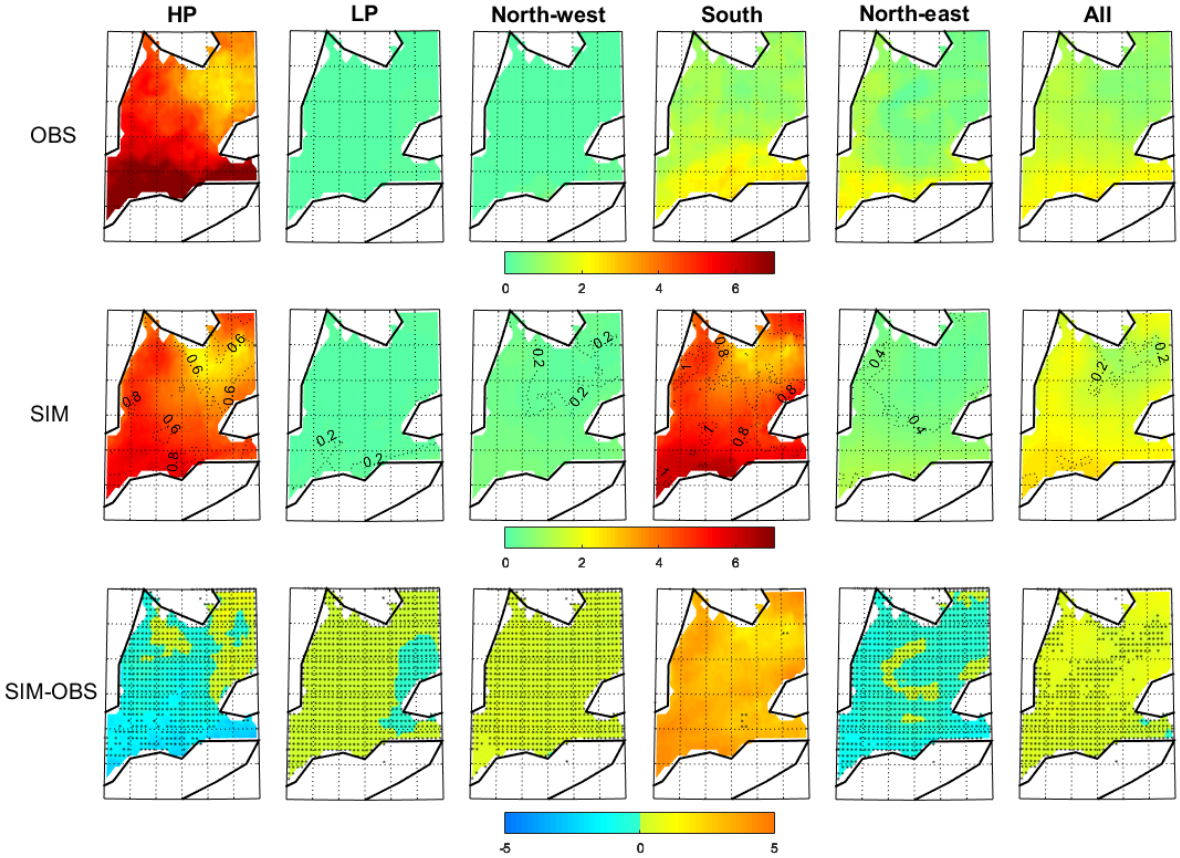

Figure 6: Percentage of DJF number of heavy rain and warm events relative to DJF occurrence of weather regimes in the historical period (1961-1990) for the observations (upper panels), simulations from CRCM5-LE 50 members average (mid panels) and simulations minus observations (lower panels)~~for CanGRD (upper panels), 50 members CRCM5-LE average (mid panels) and CanGRD minus CRCM5-LE (lower panels)~~. The dotted lines in the mid panels represent the standard deviation of the 50-members CRCM5-LE simulated percentage. Stippled regions in the lower panels indicate where the observations lie within the CRCM5-LE ensemble spread.

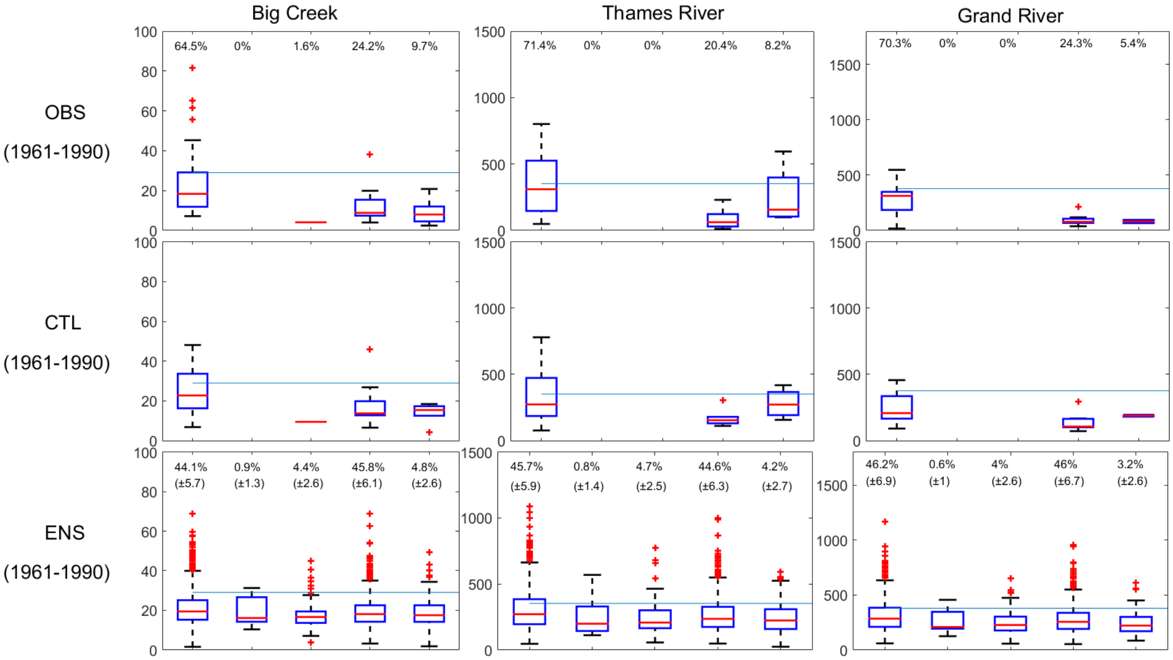

Figure 7: First and second rows: Distribution of observed (OBS) and simulated (CTL) streamflow corresponding to all observed heavy rain and warm events. Two lower rows: Distribution of simulated streamflow corresponding to all simulated heavy rain and warm events pooled from the entire ensemble pooled for all members (ENS)~~ en 1961-1990 and 2026-2055~~. Boxes extend from the 25th to the 75th percentile, with a horizontal red bar showing the median value. The whiskers are lines extending from each end of the box to the 1.5 interquartile range. Plus signs correspond to outliers. The horizontal blue lines correspond to high flows (99% percentile~~Average streamflow plus 3 times the standard deviation~~).

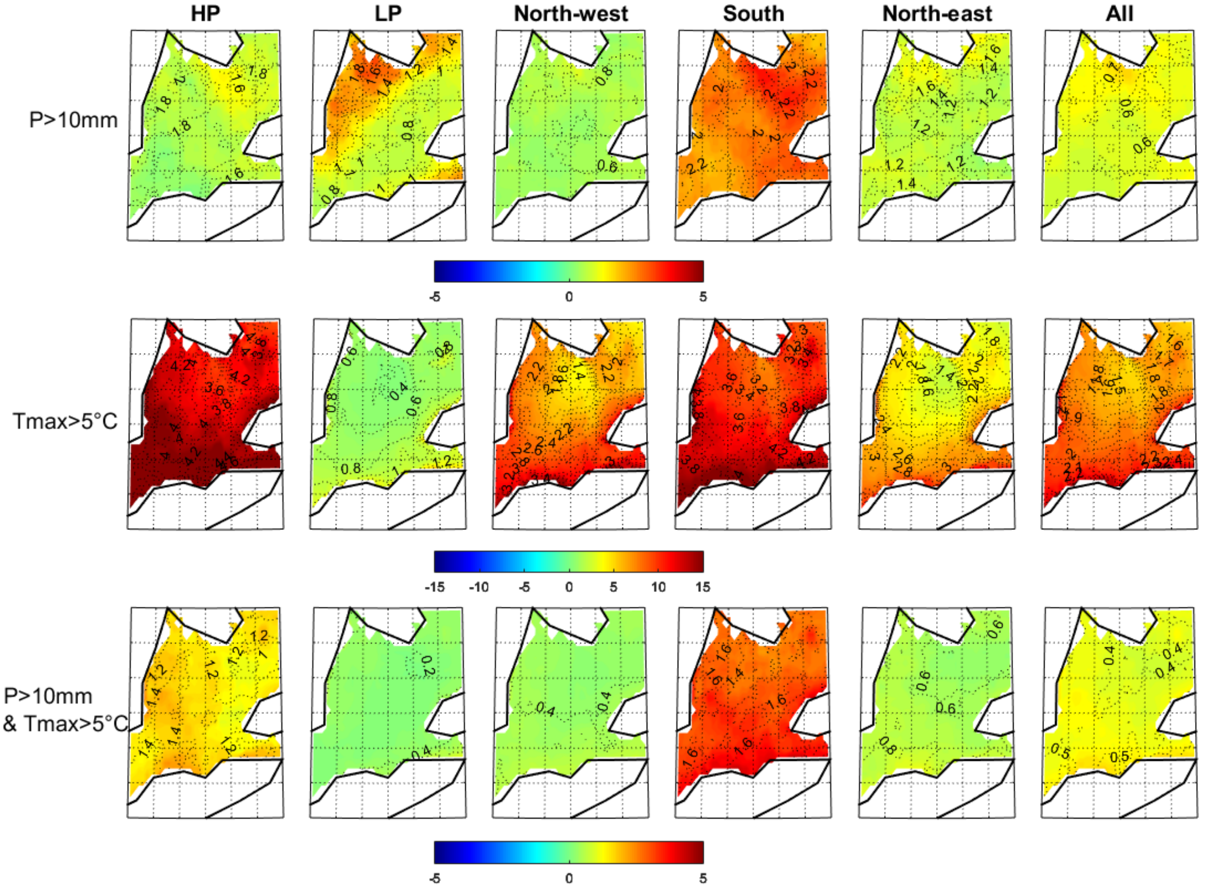

Figure 8 DJF change in : 50-members CRCM5-LE average percentage of DJF number of precipitation and warm events relative to DJF occurrence of weather regimes between the historical (1961-1990) and the future period (2026-2055) for the 50 members CRCM5-LE average. The dotted lines represent the standard deviation of the 50-members CRCM5-LE simulated change.

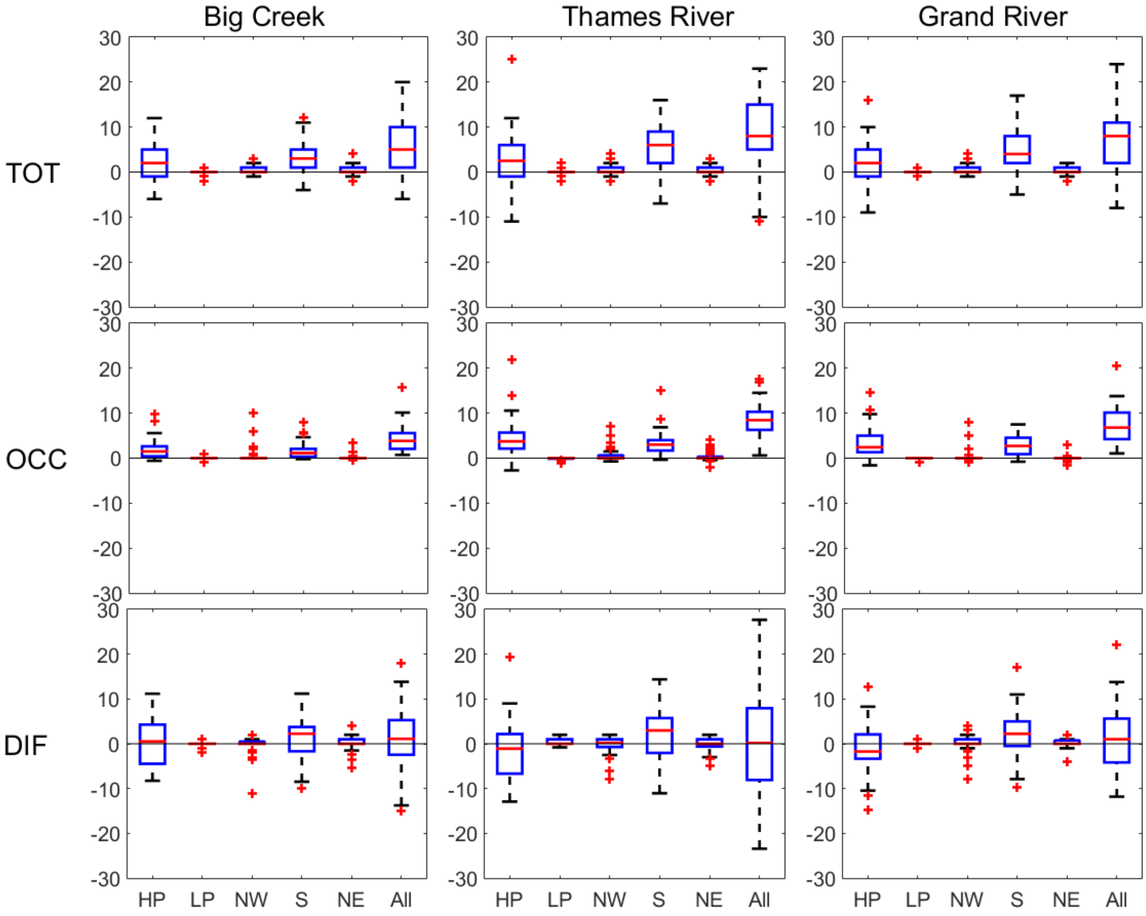

Figure 9~~10~~: upper panels: Distribution of change in number of high flows between 1961-1990 and 2026-2055 simulated from the 50 members of the ensemble (TOT). Mid panels: Distribution of theoretical change in number of high flows using the factor of change in number of heavy rain and warm events between 1961-1990 and 2026-2055 (OCC). Lower panels: TOT minus OCC (DIF). Boxes extend from the 25th to the 75th percentile, with a horizontal red bar showing the median value. The whiskers are lines extending from each end of the box to the 1.5 interquartile range. Plus signs correspond to outliers.

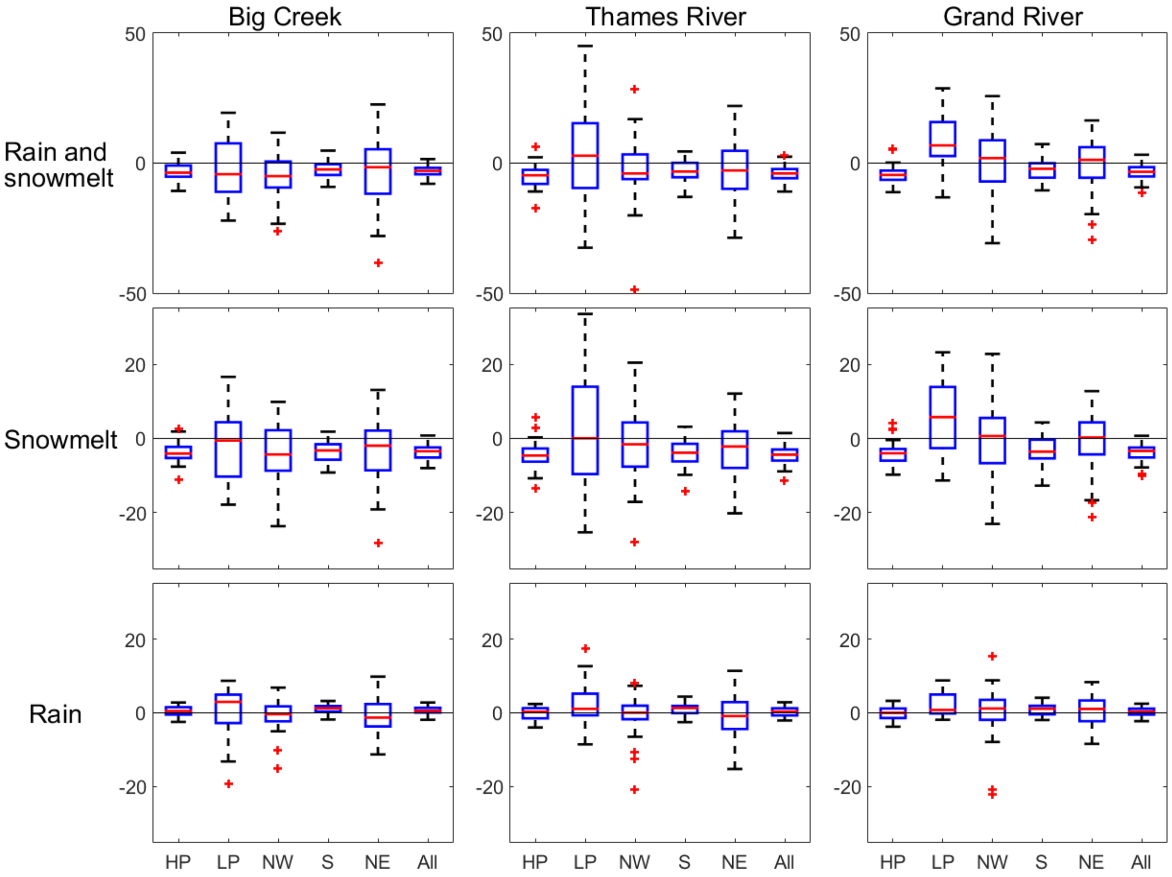

Figure 10 Distribution of simulated change in rain and snowmelt amounts (mm Weq) for all compound's extreme events between 1961-1990 and 2026-2055 from the 50 members of the ensemble.

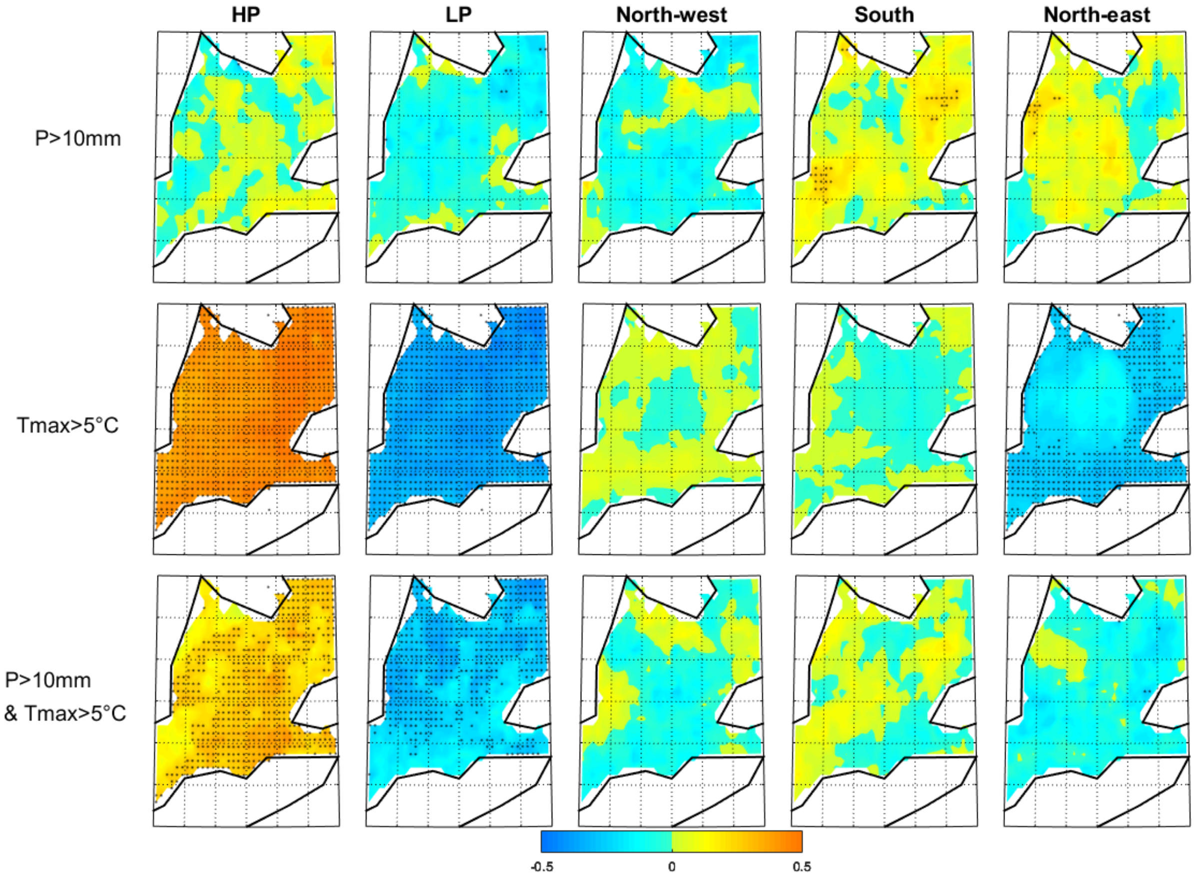

Figure 11: DJF inter-members correlations between change in occurrence of weather regimes and change in number of events between 1961-1990 and 2026-2055. Black points indicate a correlation significant at 95% according to the Pearson's correlation table.

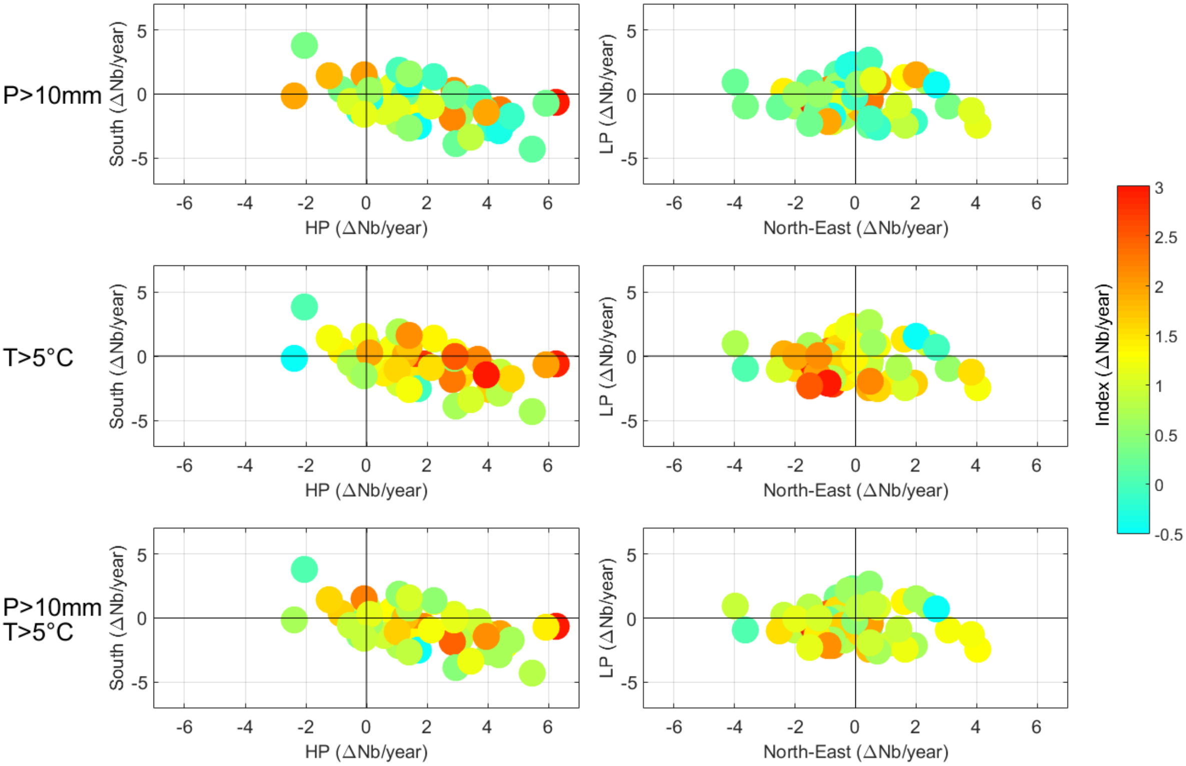

Figure 12: DJF change in occurences of regimes HP-South (left) and LP-north-~~W~~Ea~~e~~st (right) in respect to change in number of precipitation and warm events (Colours) for each member of CRCM5-LE between 1961-1990 and 2026-2055.

Table 1: inter-members correlations between DJF change in occurrence of weather regimes and DJF change in number of events between 1961-1990 and 2026-2055. Bold show correlations significant at 90% confidence level, a single underline significant at 95% and double underline significant at 99% according to the Pearson's correlation table.

	~~**P>10mm**~~					~~**Tmax>5°C**~~					~~**P>10mm & Tmax>5°C**~~				
	~~**HP**~~	~~**LP**~~	~~**NW**~~	~~**S**~~	~~**NE**~~	~~**HP**~~	~~**LP**~~	~~**NW**~~	~~**S**~~	~~**NE**~~	~~**HP**~~	~~**LP**~~	~~**NW**~~	~~**S**~~	~~**NE**~~
~~**HP**~~	~~-0.01~~	~~-0.01~~	~~-0.15~~	~~0.09~~	~~0.06~~	~~**0.43**~~	~~0.15~~	~~**0.32**~~	~~**0.55**~~	~~0.12~~	~~0.21~~	~~0.05~~	~~0.08~~	~~**0.35**~~	~~0.08~~
~~**LP**~~		~~0~~	~~-0.17~~	~~0.09~~	~~0.18~~		~~**-0.38**~~	~~**-0.26**~~	~~-0.13~~	~~**-0.46**~~		~~-0.21~~	~~**-0.23**~~	~~-0.01~~	~~-0.21~~
~~**NW**~~			~~-0.17~~	~~-0.06~~	~~-0.09~~			~~0~~	~~0.09~~	~~**-0.26**~~			~~-0.08~~	~~0.04~~	~~-0.08~~
~~**S**~~				~~0.12~~	~~0.18~~				~~0.13~~	~~-0.16~~				~~0.16~~	~~0.04~~
~~**NE**~~					~~0.10~~					~~**-0.28**~~					~~-0.10~~

	P>10mm					**Tmax>5°C**					**P>10mm & Tmax>5°C**				
	HP	**LP**	**NW**	**S**	**NE**	**HP**	**LP**	**NW**	**S**	**NE**	**HP**	**LP**	**NW**	**S**	**NE**
HP	0.02	-0.04	-0.05	0.10	0.06	**0.45**	0.20	**0.38**	**0.48**	0.20	**0.30**	0.10	0.21	**0.35**	0.18
LP		-0.08	-0.14	0.02	-0.01		**-0.38**	**-0.23**	**-0.25**	**-0.45**		**-0.29**	**-0.23**	-0.17	**-0.27**
NW			-0.08	-0.01	-0.04			0.02	0.01	-0.20			-0.04	-0.02	-0.13
S				0.10	0.12				-0.01	-0.21				0.03	-0.06
NE					0.06					**-0.25**					-0.10

Table 2: inter-members correlations between DJF change in occurrence of weather regimes and DJF change in number of high flows events between 1961-1990 and 2026-2055. Bold show correlations significant at 90% according to the Pearson's correlation table.

	~~**Big Creek**~~					~~**Thames River**~~					~~**Grand River**~~				
	~~**HP**~~	~~**LP**~~	~~**NW**~~	~~**S**~~	~~**NE**~~	~~**HP**~~	~~**LP**~~	~~**NW**~~	~~**S**~~	~~**NE**~~	~~**HP**~~	~~**LP**~~	~~**NW**~~	~~**S**~~	~~**NE**~~
~~**HP**~~	~~-0.13~~	~~**-0.25**~~	~~0.12~~	~~-0.09~~	~~-0.16~~	~~-0.08~~	~~-0.12~~	~~0.02~~	~~-0.02~~	~~-0.09~~	~~-0.10~~	~~-0.19~~	~~0~~	~~0.03~~	~~-0.10~~
~~**LP**~~		~~-0.18~~	~~0.15~~	~~-0.08~~	~~-0.16~~		~~-0.06~~	~~0.05~~	~~0.01~~	~~-0.07~~		~~-0.13~~	~~0~~	~~0.02~~	~~-0.10~~
~~**NW**~~			~~**0.26**~~	~~**0.25**~~	~~0.21~~			~~0.09~~	~~0.12~~	~~0.06~~			~~0.08~~	~~0.15~~	~~0.07~~
~~**S**~~				~~0.04~~	~~-0.03~~				~~0.06~~	~~-0.02~~				~~0.14~~	~~0.10~~
~~**NE**~~					~~-0.08~~					~~-0.04~~					~~-0.02~~

Table 2: inter-members correlations between DJF change in occurrence of weather regimes and DJF change in number of high flows events between 1961-1990 and 2026-2055. Bold show correlations significant at 90% according to the Pearson's correlation table.

	Big Creek					**Thames River**					**Grand River**				
	HP	**LP**	**NW**	**S**	**NE**	**HP**	**LP**	**NW**	**S**	**NE**	**HP**	**LP**	**NW**	**S**	**NE**
HP	0.00	-0.18	0.18	0.04	-0.08	0.06	-0.02	0.11	0.04	0.04	-0.05	**-0.27**	0.13	0.10	-0.10
LP		**-0.24**	0.05	-0.12	**-0.25**		-0.12	-0.02	-0.11	-0.10		-0.31	-0.01	-0.07	**-0.28**
NW			0.22	**0.23**	0.14			0.07	0.03	0.06			0.20	**0.29**	0.14
S				0.05	-0.05				-0.04	-0.05				0.18	0.06
NE					-0.11					-0.02					-0.09

We would like to thank again the reviewers for their constructive comments. Please find our point by point answer as follow:

Response to Reviewer #1:

This manuscript presents an index to describe warm, heavy rain events during winter in southern Ontario. This index is then used to evaluate the occurrence of such events with different large scale circulation patterns and projections for the future. The paper presents a thorough analysis and I appreciate the detailed discussion included in Section 4. Some concerns are listed below.

My main concern is that the authors have not provided sufficient justification for the need to create a new index. The introduction focuses on rain on snow events, but this new index does not consider snow cover. This disconnect needs to be more fully explained. Why is the proposed index better than those used in previous literature?

The main goal of this study was to understand how the frequency of winter weather extreme events (temperature and precipitation), simulated by CRCM5-LE, is modulated by large scale atmospheric circulation. Studying such events are mostly relevant if they have societal implications. A strong shift in high flows occurrence from spring to winter was observed recently in southern Ontario and is expected to continue in the future. Therefore, we decided to define temperature and precipitation thresholds that may explain the generation of high flows in several watersheds in Ontario. Defining an index based also on snow would have been interesting but is not in the scope of this study. A major originality of the study was the calculation of future weather regimes for each member of CanESM2-LE to investigate how the variability of atmospheric circulation will impact the winter weather extremes. The weather pattern of a given day impacts directly local temperature and precipitation conditions and investigating also snowmelt adds a level of complexity. Indeed, snowmelt of a given day depends also on the atmospheric conditions occurring weeks before the extreme events (major snowfalls following by cold conditions keeping the snow on the ground). Therefore, weather regimes of these days would also need to be investigated. The need of studying the sequence of weather regimes occurring prior to a high flow event in future studies was discussed at the end of section 4.3.

Moreover, when using snowmelt in the index (With Rain on snow index (ROS) for example) some questions are arising. ROS index does not take into consideration the rain only events while it can have a significant impact on high flows. The occurrence of ROS

events is decreasing in the Great Lakes region because of an increase in days without snow on the ground (Jeong and Sushama, 2018), but this doesn't lead to a decrease in high flows. Our index takes into consideration rain events even with the absence of snow on the ground, conditions that are expecting to become more frequent in the future. The proposed index is not meant to be better than ROS but is adapted to the study of weather extreme events simulated by CRCM5-LE and how these events are impacted by large scale atmospheric circulation. As stated in the section 4.4, ROS and our index can be studied together to understand the future evolution of different hydrometeorological extreme events (Rain only, rain on snow, snowmelt).

PRMS hydrological model was previously set up in this region (Champagne et al., 2019a) **which gave us the opportunity to discuss the ability of this index to explain high flows events. We used PRMS to investigate how the future evolution of high flows is corelated to the future evolution of weather extreme events. But the objective was not to create an index using snow data from PRMS output. Nevertheless, to strengthen the discussion around snowmelt, we added a figure showing the evolution of snowmelt between 1961-1990 and 2026-2055 corresponding to each weather pattern (Figure 11 of the new manuscript).**

Considering this is a special issue on large ensembles, I think there should be more discussion about how this work is taking advantage of the large ensemble used here.

The main objective of this work was to assess how the internal variability of climate has an impact on the variability of local meteorological extreme events in southern Ontario. To investigate these extreme events in a small region such as southern Ontario, high resolution simulations are required. A regional large ensemble such as CRCM5-LE has the double advantage of simulating the local climate and that each member of CRCM5-LE can be related to large-scale atmospheric circulation from its corresponding CanESM2-LE member. Statistical stochastic methods to downscale GCM data could also represent well the local climate but cannot be related to a corresponding large-scale atmospheric circulation. Few sentences explaining the double advantage of a regional large ensemble was added in the section 2.1.

Specific comments:

Line 52: Is the "precipitation" here referring to rain or snow or both?

Precipitation is referring to both rain and snow. A mention ‘’Rain and snow’’ was added to improve the clarity of the sentence.

Line 84: Was only the future period bias corrected?

The bias correction was applied for the entire period (past included). The mention ‘’Future’’ has been removed to avoid confusions.

Line 87: Is precipitation frequency also modeled with a gamma distribution? This makes more sense for intensity.

The method developed by Ines and Hansen (2006) involves two steps in the bias correction of precipitation. For each month, the first step consists on truncating the distribution of the modelled frequency of daily precipitation in order to match the observed distribution of precipitation frequency. The second step used the truncated distribution of precipitation intensity into a gamma distribution fitted to the observed intensity distribution. For clarity, these explanations on the bias correction method have been added to the manuscript.

Line 138-141: What effect would the trends within these two periods have?

The Z500 anomalies were calculated and normalized for two distinguished period (55 years in the past and 55 years in the future) to avoid the low frequency variability (Here positive trend in Z500) to be disproportionate compare to the high frequency variability. However, this method does not remove all the low frequency Z500 trends. Following this comment, we investigated the change in occurrence of regimes within these two periods and results show a large increase in occurrence of regime HP within the 2026-2055 period. Therefore, the regimes HP are occurring mostly at a period when the conditions are warmer (At the end of the 2026-2055 period), which overestimates HP average temperature and number of warm events. To avoid this artefact, we decided to slightly change our original method and normalize the anomalies in period of 30 years before calculating the regimes. This method minimizes the impact of low frequency on average climate of each regime while keeping sufficient periods length (30 years) for the calculations of the anomalies. The results were not significantly different with this new method and therefore the discussion remains very similar to the first version of the manuscript.

We also modified the figure 9 *(DJF change in number of precipitation and warm events between the historical (1961-1990) and the future period (2026-2055) for the 50 members*

***CRCM5-LE average)* and turned it into change in number of extreme events per occurrence of weather regimes (Figure 8 in the new manuscript). The objective is to remove the impact of the 50-members average change in occurrence of weather regimes on extreme events and study only the variability between members. The goal of this figure is to investigate the stability between the past and the future regarding the number of weather extreme events occurring for each weather regime. The impact of change in occurrence of weather regimes on weather extreme events were anyway investigated in the section 3.4 (Figure 11 and 12, Table 1 and 2).**

Section2.4/Section 3.1: Were the top regimes determined separately for the model and reanalysis? If so, then I think the good agreement warrants more commentary. If not, can you describe more clearly how they are related?

A principal component analysis (PCA) was first applied to the daily 20thCR Z500 anomalies calculated between 1956 and 2012 for each grid of the domain. The principal components explaining 80% of the spatial variance were identified and their eigenvectors were used to transform the original time series into the principal components time series. This daily principal components time series was then classified using the k-means algorithm. The k-means algorithm identifies iteratively classes centroids that maximize the interclass variance and minimize the intraclass variance. To classify the daily Z500 for each member of CanESM2, the same regimes identified with 20thCR were used. First, the same eigenvectors identified in the PCA using 20thCR Z500 were used to calculate the principal components time series for each member of CanESM2. Then, the k-means classes centroids identified with 20thCR were used to classify the principal components time series for each member of CanESM2 large ensemble. For a better understanding of the method, a more accurate description of the CanESM2 regimes identifications were added to the section 2.3.

Section 3.2: Is the modelled and bias-corrected data being compared against the dataset used for the bias correction target? If so, can you add a brief discussion on the implications?

The modelled and bias corrected data have not been explicitly compared in the first version of the manuscript. Following this comment, the extreme events identified from the raw data from CRCM5-LE have been compared to the extremes calculated with the observations and a figure has been included in supplementary materials (Figure S2). This figure show that the difference between simulations and observations is much higher when using the raw data (Figure S2) compared to the bias corrected data (Figure S1 in supplementary materials).

Section 3.3: What does the model bias in the South regime mean for these projections?

The model bias between simulated Z500 and observed Z500 in the regime South in the past is likely to remain similar in the future because the same simulated dataset (CanESM2-LE) is used for the future period. The number of events for a regime South calculated with CanESM2 will likely be overestimated compare to a pattern that would look like the 20thCR regime South. However what is relevant in this study is to understand why the atmospheric circulation of the regime South using CanESM2 anomalies produces weather extreme events and how the change in number of regime South occurrence will modulate the number of extreme events. We added a new column to the figure 3 showing the future evolution of Z500 corresponding to each regime.

How robust are the streamflow projections when they do not account for changes in snowfall/snowpack or associated feedbacks?

The streamflow projections were computed by the model PRMS. PRMS accounts for change in snowfall and snowpack to calculate streamflow.

Line 229: Do you mean the magnitude of the correlations here?

We meant the magnitude of the correlations. This was added to the new version of the manuscript.

Line 237: Can you clarify what is meant by the combination of weather regimes? The value of using these combinations instead of just changes in individual regimes is not clear.

A combination of two weather regimes has been done by summing the seasonal occurrence of these two weather regimes. If for a given winter the regime HP occurs 20 times and the regime South 15 times, there combination will be 35. The goal of using these combinations is to identify the impact of a combination of weather patterns occurring the same winter on weather extremes and high-flows. The weather patterns are linked to each other because are a discretization of a continuous process (Atmospheric circulation). As stated in the discussion, a given pattern recurrently succeed to the same patterns because the systems (cyclones and anticyclones) are following a general direction (West to east). Therefore, the weather regimes are not independent from each other. A combination of weather regimes occurrence shows the impact of a simultaneously large occurrence of two weather regimes on hydrometeorological extremes. It is particularly valuable to understand their impact on high-flows because atmospheric conditions days before the

events are also relevant to explain the generation of high flows events (i.e. Formation of Snowpack). A clearer explanation on what is a combination of weather regimes and its purpose was added to the section 3.4.

Figure 1: I found it very difficult to orient myself in this figure. It is hard to discern the coastlines of the Great Lakes from the contours in the large scale figure and the legend covers the land separating two lakes. It would be very helpful to label the lakes and key places here, especially since so much of the later discussion is very specific about local geography.

This figure was replaced by a new figure with a modified large-scale figure, a clearer separation between Lake Erie and Ontario and the name of the Lakes.

Figure 2: Why is the scale of the horizontal axis nonlinear? With the current spacing and connecting line, this time series is misleading.

The scale of horizontal axis is not linear because represent different high flow events. The connecting lines representing the average have been removed in the new figure as they are confusing and do not give any valuable information.

Figures 4-7: The figure label (“simulations minus observations”) does not agree with the caption (“CanGRD minus CRCM5-LE”)

The words simulations and observations have been added to the legend.

Figure 8: Are the ensemble values pooled or averaged?

The ensemble values are pooled. This information has been added to the manuscript.

Line 462: This paper should be cited as Jeong and Susham

This modification has been done

Response Reviewer #2

The authors investigate the occurrence of rain on snow events with a single model ensemble. Overall this is a very interesting paper with a good application of the bottomup approach that has recently been endorsed for studying compound events.

Using the compound exceedance of a precipitation and temperature threshold seems relatively naive, given that large increases in temperature in the future will lead to very different snow cover patterns, a key determinant of ROS events. A more appropriate variable than temperature seems to me the difference in surface snow amount between consecutive days, which could be used as a proxy for snowmelt. This is available from the model output. With this it should be possible to build a better compound index that should also be more reliable in future projections.

The main goal of this study was to understand how the frequency of winter weather extreme events (temperature and precipitation), simulated by CRCM5-LE, is modulated by large scale atmospheric circulation. Studying such events are mostly relevant if they have societal implications. A strong shift in high flows occurrence from spring to winter was observed recently in southern Ontario and is expected to continue in the future. Therefore, we decided to define temperature and precipitation thresholds that may explain the generation of high flows in several watersheds in Ontario. Defining an index based also on snow would have been interesting but is not in the scope of this study. A major originality of the study was the calculation of future weather regimes for each member of CanESM2-LE to investigate how the variability of atmospheric circulation will impact the winter weather extremes. The weather pattern of a given day impacts directly local temperature and precipitation conditions and investigating also snowmelt adds a level of complexity. Indeed, snowmelt of a given day depends also on the atmospheric conditions occurring weeks before the extreme events (major snowfalls following by cold conditions keeping the snow on the ground). Therefore, weather regimes of these days would also need to be investigated. The need of studying the sequence of weather regimes occurring prior to a high flow event in future studies was discussed at the end of section 4.4.

Moreover, when using snowmelt in the index (With Rain on snow index (ROS) for example) some questions are arising. ROS index does not take into consideration the rain only events while it can have a significant impact on high flows. The occurrence of ROS events is decreasing in the Great Lakes region because of an increase in days without snow on the ground (Jeong and Sushama, 2018), but this doesn't lead to a decrease in

high flows. Our index takes into consideration rain events even with the absence of snow on the ground, conditions that are expecting to become more frequent in the future. The proposed index is not meant to be better than ROS but is adapted to the study of weather extreme events simulated by CRCM5-LE and how these events are impacted by large scale atmospheric circulation. As stated in the section 4.5, ROS and our index can be studied together to understand the future evolution of different hydrometeorological extreme events (Rain only, rain on snow, snowmelt).

PRMS hydrological model was previously set up in this region (Champagne et al., 2019a) **which gave us the opportunity to discuss the ability of this index to explain high flows events. We used PRMS to investigate how the future evolution of high flows is corelated to the future evolution of weather extreme events. But the objective was not to create an index using snow data from PRMS output. Nevertheless, to strengthen the discussion around snowmelt, we added a figure showing the evolution of snowmelt between 1961-1990 and 2026-2055 corresponding to each weather pattern (Figure 11 of the new manuscript).**

I suspect streamflow is very non-gaussian distributed. In particular, it's asymmetric and bounded from below. Taking the mean +3 standard deviations as an indicator for extremes is thus very unintuitive and not really appropriate for such a distribution. I would suggest to use a high percentile (e.g. above the 99th percentile, or something similar, could also be more extreme). This can then also be translated easily into a return period.

The mean +3 standard deviations was changed to 99th percentile in the entire manuscript.

Would it be an option to us only the weather patterns based on the observations and classify the models according to those? This might reduce differences between models and observations with respect to the occurrence rate of heavy precip and warm events (the authors discuss this point in sec 4.1).

The models were classified according to the weather patterns calculated with the observations (20thCR reanalyses). The daily Z500 anomalies from the observations were first transformed by principal component analysis (PCA) keeping 80% of the spatial variance. The principal components identified were then classified into recurrent weather patterns using a k-means algorithm. The eigenvectors of the PCA as well as the k-means centroids of the patterns identified using the observations, are used to identify the weather regimes for each member of CanESM2-LE. The explanations of the method used to calculate the CanESM2 weather regimes was improved in the section 2.3.

Please mention somewhere explicitly how the compound index is defined. Is it just the occurrence of events where both temperature and precipitation exceed a certain threshold? Or the number of such occurrences?

The compound index is simply defined by the number of days with a temperature exceeding 5 degrees and precipitation exceeding 10mm. The information was explicitly added to the method section (Section 2.2).

Minor comments: I would recommend the authors to do a thorough spell check and grammar check. There are a number of minor grammatical errors and typos in the text.

A spell and grammar check will be done for the entire manuscript.

L 49: start new paragraph

L59: “preconized” ?

L67: “contributes to”: maybe better: “explains the variability of”

L69: “occurrence of the index”: an index does not occur, it has a certain value. Better “relationship between the index and recent large-scale atmospheric circulation” (“past” sounds a bit like historical)

These modifications were done as suggested

L84: Univariate bias correction might induce artefacts when studying compound events (Zscheischler et al., 2019), this might be highly relevant here. Consider applying a multivariate bias correction approach.

The bias correction approach used in this study was used in a previous study in the area (Champagne et al., 2019a)**. For consistency with this previous study, the same bias correction technique was applied. We also identified the number of extreme events using the raw data (Supplementary materials Figure S2) and found a higher difference between simulations and observation compared to the bias corrected data (Supplementary materials Figure S1). These results are showing that this bias correction method is satisfactory. A reference to a multivariate bias correction approach was added to the discussion (Section 4.1)**

Please note that the figure S1 was previously in the manuscript (Figure 4 in the first manuscript). This figure was moved to supplementary material for an easy visual comparison between the events calculated from bias corrected data and from raw data. The plots in figure S1 are still in the manuscript and have been added to figure 4, 5 and 6 (Column ’’all’’).

Figure 2: “blue lines correspond to high flows” is unclear. There is one blue line in the precipitation figure and a red line in the temperature figure. It looks as if they would just correspond to the mean of the boxplots. It would be surprised if the highflows would align so well with the precipitation amounts. Please clarify.

These blue and red lines correspond to the mean of the boxplots. These lines are not giving valuable information and were removed for clarity.

Section 3.2: I assume this is after bias correction?

Yes the results are given using bias correction data. This information has been added to the manuscript

Figure 4 and following: are these comparisons on the same spatial grid?

These comparisons are on the same spatial grid because the bias correction was performed at each observed grid point. The modelled grid-point the closest from each observed grid point was identified and the corresponding temperature and precipitation were bias corrected. These bias corrected data are represented at each observed grid point in the figures.

Figure 8: why do so few events result in high streamflow?

Few events result in high flows because even though the index is a condition to produce a high flow event the generation of high flows also needs other conditions (other rain events in the previous days, snowmelt amount). This discussion has been added to the manuscript (Section 4.5).

Consider reporting the events as relative numbers (e.g. sections 3.2, 3.3). This might be more intuitive as it is easier for the reader to put the occurrence probability into context.

The relative numbers have been added to the manuscript.

Some method description appear in the results, e.g. L 215 and following.

These elements of methods were put in the method section.

L220: I assume TOT are the events as simulated with the hydrological model? This should be mentioned somewhere explicitly.

The mention ‘’simulated by PRMS’’ was added to the manuscript

References:

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Jeong, D. and Sushama, L.: Rain-on-snow events over North America based on two Canadian regional climate models, Climate Dynamics, 50(1–2), 303–316, doi:10.1007/s00382-017-3609-x, 2018.

Zscheischler, J., Fischer, E. M. and Lange, S.: The effect of univariate bias adjustment on multivariate hazard estimates, Earth System Dynamics, 10(1), 31–43, doi:10.5194/esd-10-31-2019, 2019.