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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 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 condition 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 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 to the same atmospheric patterns. 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 to internal variability of climate.

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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 (Il Jeong and Sushama, 2018; Musselman et al., 2018; Surfleet and Tullos, 2013). However strong uncertainties in the projections of such events remains, 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 and temperature extremes and large-scale circulation indices: The negative phase of the pacific 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 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 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 to improve our understanding of extreme impacts (Leonard et al., 2014). The

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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 decrease of snowpack (Il Jeong and Sushama, 2018). These results emphasize the need of new compound climate indices to understand the impact of atmospheric circulation on hydrometeorological extreme events in the Great lake region. In this study, CRCM5-LE, a 50-member regional model ensemble at a 12km resolution produced over northeastern North America, will be used with the following objectives:

(1) Define a regional precipitation and temperature compound index that 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 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 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 northeastern 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 global Canadian model large ensemble (CanESM2-LE) at 310km resolution and offers the possibility to relate each member of CRCM5-LE to its corresponding member in CanESM2-LE. The future 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 the precipitation frequency and intensity distribution were corrected with a gamma distribution. Each CRCM5-LE grid point has been bias corrected using the closest CanGRD point. Using a unique CanGRD

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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 Lakes than the elevation (Scott and Huff, 1996).

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 a threshold equal to the mean streamflow plus three times the standard deviation. When more than two days in a row were higher than the high flow threshold, the event was 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. The precipitation and temperature data are from the day situated two days before the high flow event for Big Creek watershed and 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 the new index and define 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. The three step

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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.

2.4 Atmospheric circulation patterns

The recurrent atmospheric patterns in northeastern 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 northeastern 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 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 shows five classes as the most robust choice (Champagne et al., 2019).

The principal components corresponding to these five classes calculated with 20thCR have been used by the k-means algorithm to create similarly five weather regimes 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 occurrences. The variability of regime occurrences due to internal variability of climate is therefore fully preserved.

3 Results

3.1 Weather regimes in northeastern North America

Five weather regimes have been identified in northeastern 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 in the historical period have very similar patterns (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. The Z500 anomalies over the Great Lakes were similar for most of the regime except for regime South showing higher Z500 anomalies.

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

The ability of CRCM5-LE to simulate the occurrence of heavy rain and warm events is assessed in this section. The number of heavy precipitation events per winter was generally well recreated by the regional ensemble in the historical period (Figure 4). These events were generally overestimated in the north and western parts of the region especially in areas close to Lake Huron. In this region, few grid points show all 50 members of the ensemble overestimating the number of events compared to the observations. The number of warm events followed a similar spatial variability with more frequent events in the southern parts, particularly in the Niagara peninsula between Lake Erie and Lake Ontario. The number of warm events was overestimated by all members in the entire area except for the Lake Simcoe Area (Figure 4 Centre-right plot in blue). 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. 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.

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

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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 to heavy rain and warm events for the observed streamflow (OBS), streamflow simulated with CanGRD (CTL) and streamflow simulated with each CRCM5-LE member (ENS) is shown is Figure 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 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 also higher streamflow when heavy rain and warm events correspond to regimes HP or South (Figure 8).

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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 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 regime and at a lower rate for regimes South 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 9).

The contribution of the trend in heavy rain and warm events to the trend in number of high flows has been investigated (Figure 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, TOT is expected to increase in the future. The increase in OCC is similar to the increase in TOT even though OCC is slightly higher than TOT in the Big Creek watershed. Considering HP's events only, the increase of OCC is higher than TOT while for events associated with regime South TOT is higher than OCC.

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

Correlations between change 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 correlations between occurrence of weather regimes and warm events is higher compared to correlations with heavy precipitation events. The results show positive correlations between warm events and regime HP and negative correlations between warm events and regime LP/North-east in the entire area. 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 compound index are less spatially spread with positive

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correlations between the index and the regime HP close to Lake Erie and negative correlations with regime LP near Lake Huron.

Correlations between combination of weather regimes change and Rain and warm index change averaged over the entire region have also been investigated (Table 1). The combinations of weather regimes have been done by summing the change of occurrence from the two regimes of each combination. The correlations between change of any weather regimes combinations and change in number of heavy precipitation events are not significant. The correlations between change of number of warm events and change in occurrence of weather regimes is improved when regime South is associated to regime HP and when regime LP is associated to regime NE compared to correlations with regimes HP or LP only (Table 1). Concerning the heavy rain and warm index the correlations are not significant if the regimes HP and South are correlated separately to the number of events but are positive and significant (95% confidence interval) if the correlation is applied to a combination of regime South-HP and negative and significant (90% confidence interval) with a combination of North-west-LP. The correlation with the high flows in each of the three watersheds have also been investigated (Table 2) and shows significance only in the Big Creek watershed. A combination of HP-LP is negatively correlated to high flows while North-west and a combination North-west-South are positively correlated to high flows.

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-West 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 results show that the occurrence of heavy rain and warm events are modulated by specific atmospheric patterns in winter which corroborates previous studies in the Great Lakes region. These studies found that heavy

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precipitation and flooding events are associated 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 precipitations events during regime South (Figure 5). The overestimation of the number of precipitation events for regime South can be associated 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 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 show 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 6). Regime HP has similarities with the positive phase of the NAO 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 5). LP is not associated with warm events (Figure 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 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 of heavy precipitations 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 lake 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

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southern regions. Increase of rainfall and decrease of snowpack are both likely to occur in Southern Ontario and are cancelling each other in term of ROS events. Our study does not consider snowpack and show an increase in heavy rain and warm compound events (Figure 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 9). The increase in extreme precipitation events is less significant than the increase of warm events and is occurring mostly in the Northern parts of the area (Figure 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 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 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 9). Regime North-West shows 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 11) probably due to poor association between precipitation extremes and occurrence of weather regimes (Table 1 and Figure 10). Similar change in occurrences of South-HP weather regimes can lead to variable change in number of heavy rain and warm events (Figure 11). 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).

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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 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. 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 5 and 6). More importantly, HP shows a further increase of warm events in the future while South show rather an increase of precipitation (Figure 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. 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.

The future change in number of high flows is associate to a large inter-member uncertainty (Figure 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 watershed (Table 2) while it is negatively correlated to the change in number of weather extreme events in this area (Figure 11). The correlation is 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. 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). 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. 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

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. 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. Rain on snow index could be used in lieu of our heavy rain and warm index 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 (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; 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 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) by investigating what

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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 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.

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Competing interest

The authors declare that they have no conflict of interest.

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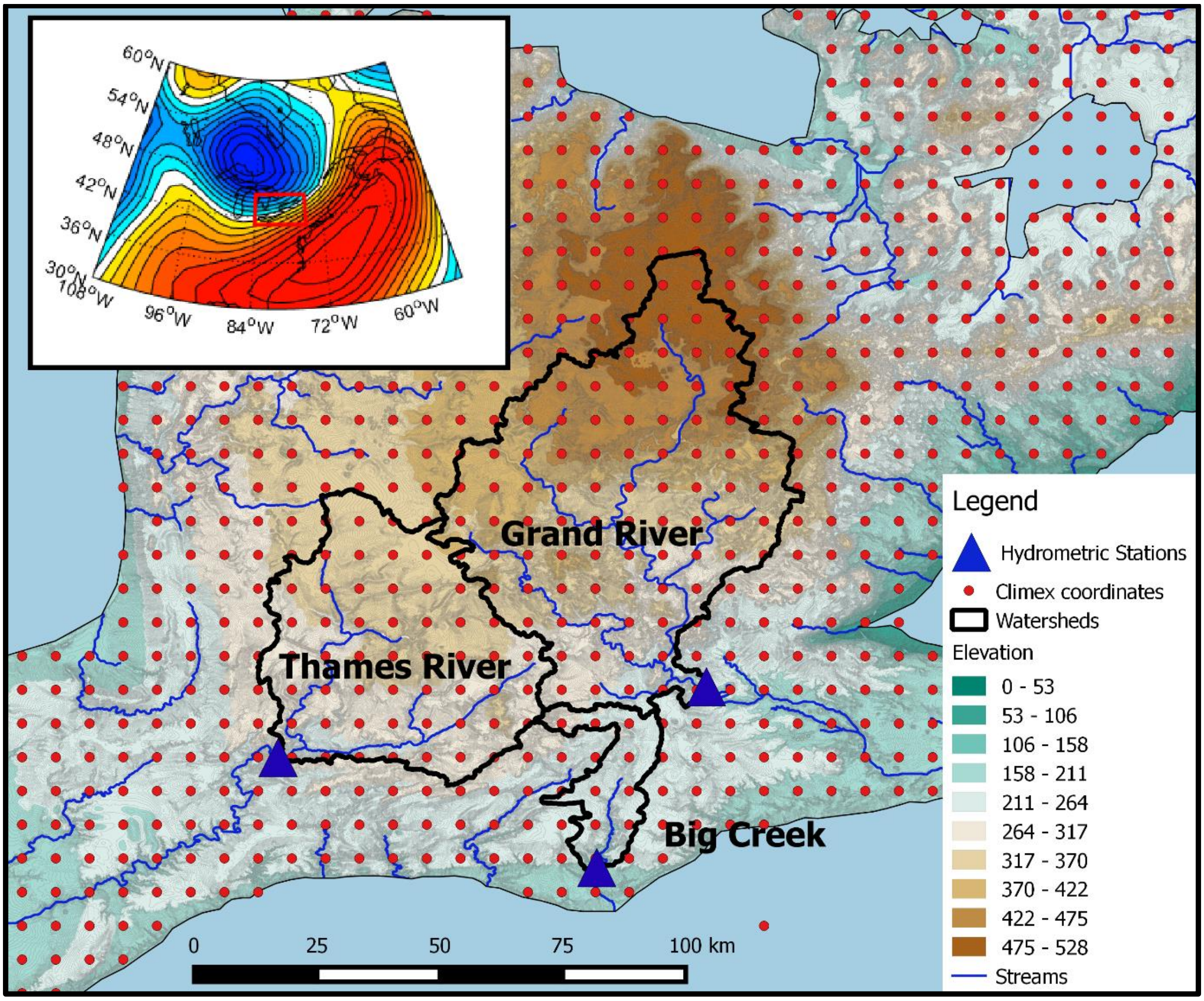

Figure 1: Location of the three watersheds and the ClimEx grid points used in this study and situation in the northeastern North America domain (Inset)

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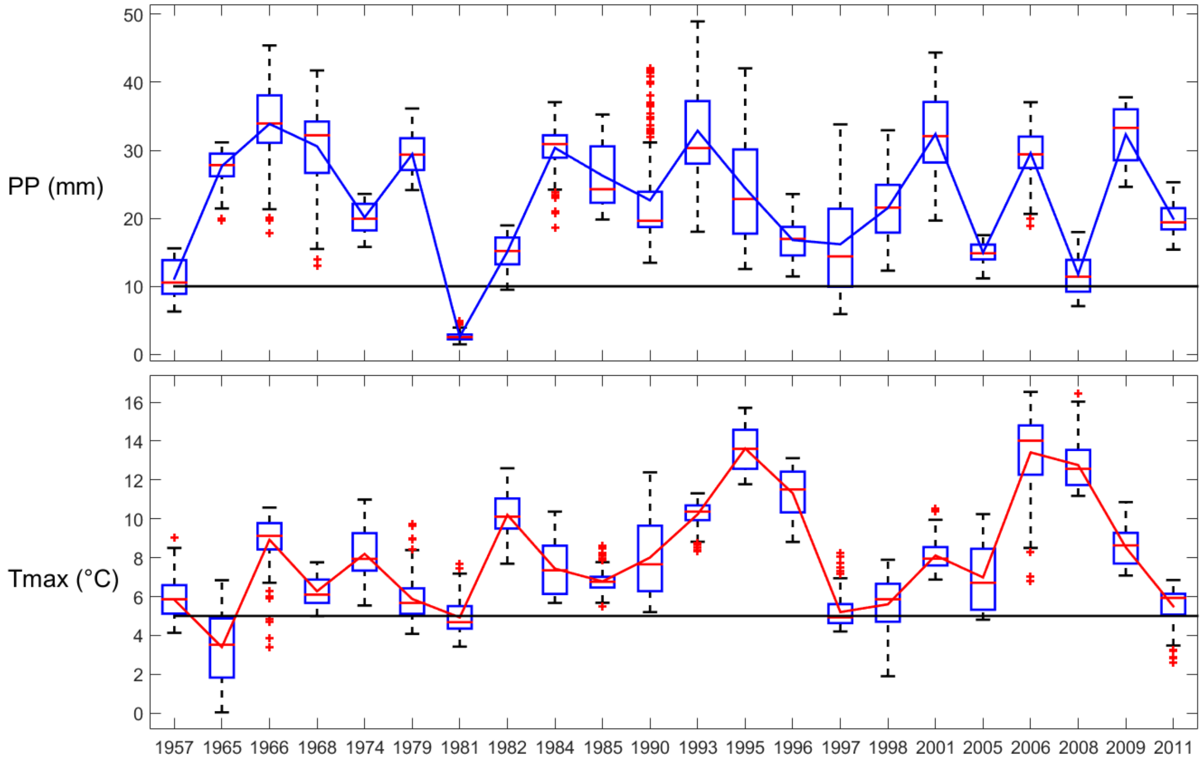

554

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

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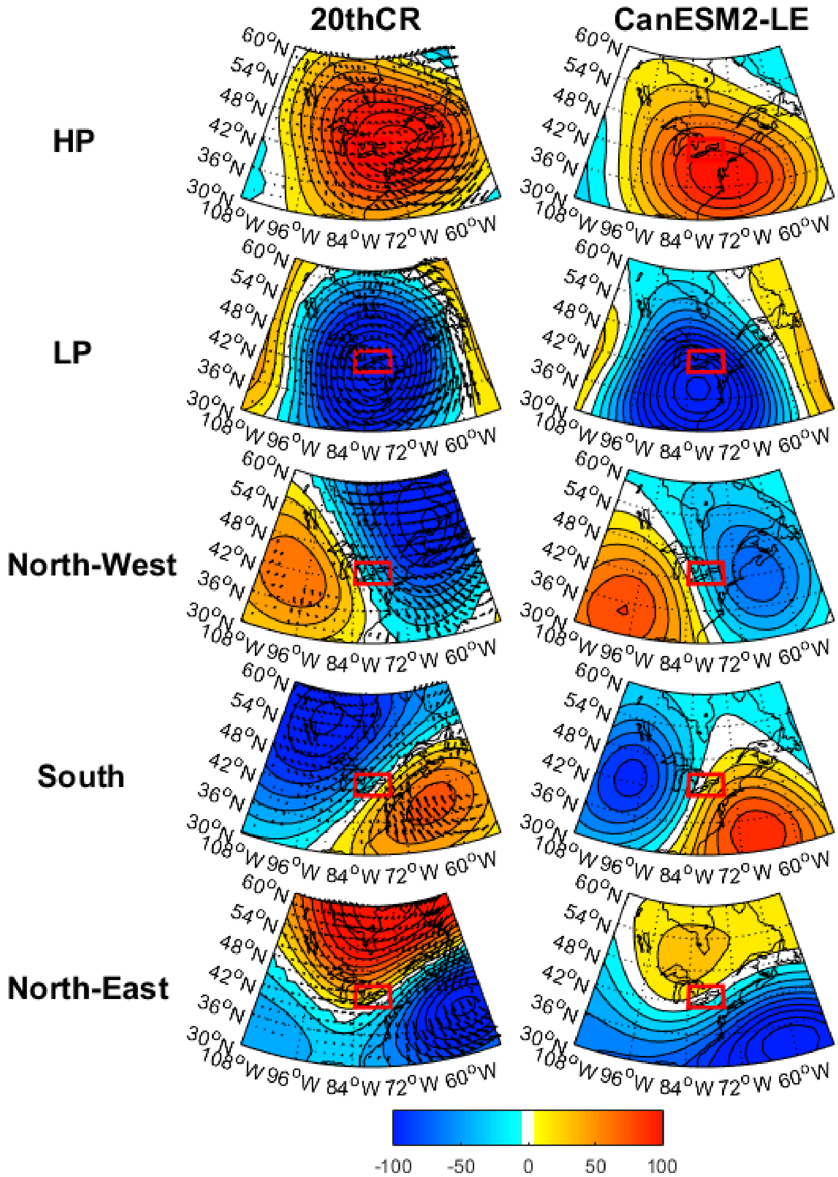

Figure 3: Left: DJF Z500 anomalies (colours) and winds (vectors) corresponding to Weather regimes calculated with 20thCR. Right: DJF 50 members average Z500 anomalies calculated with CanESM2-LE.

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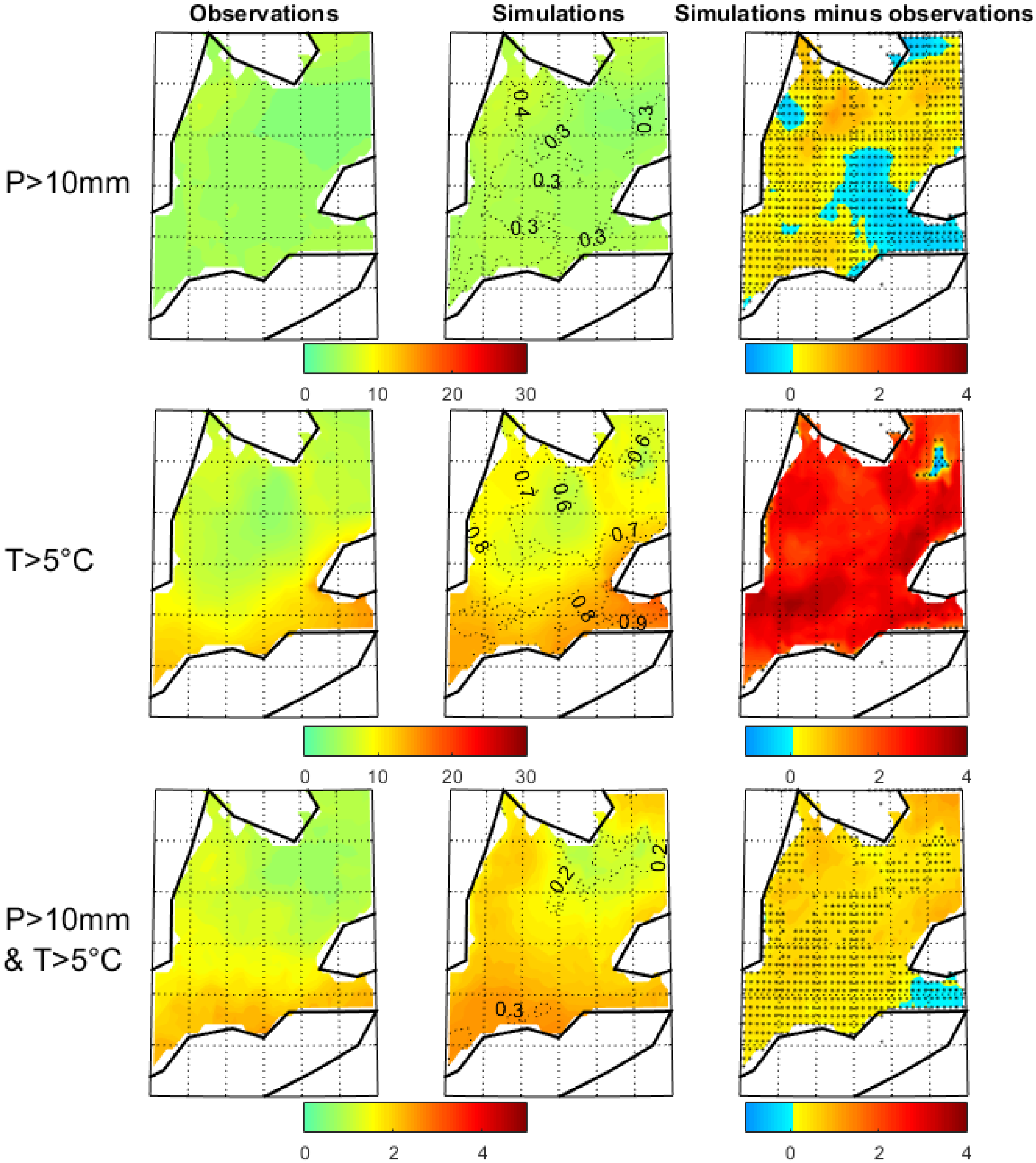

Figure 4: DJF number of precipitation and warm extreme events in the historical period (1961-1990) for CanGRD (left panels), 50 members CRCM5-LE average (mid panels) and CanGRD minus CRCM5-LE (right panels). The dotted lines in the mid panels represent the standard deviation of the 50-members CRCM5-LE simulated number of events. Stippled regions in the right panels indicate where the observations lie within the CRCM5-LE ensemble spread.

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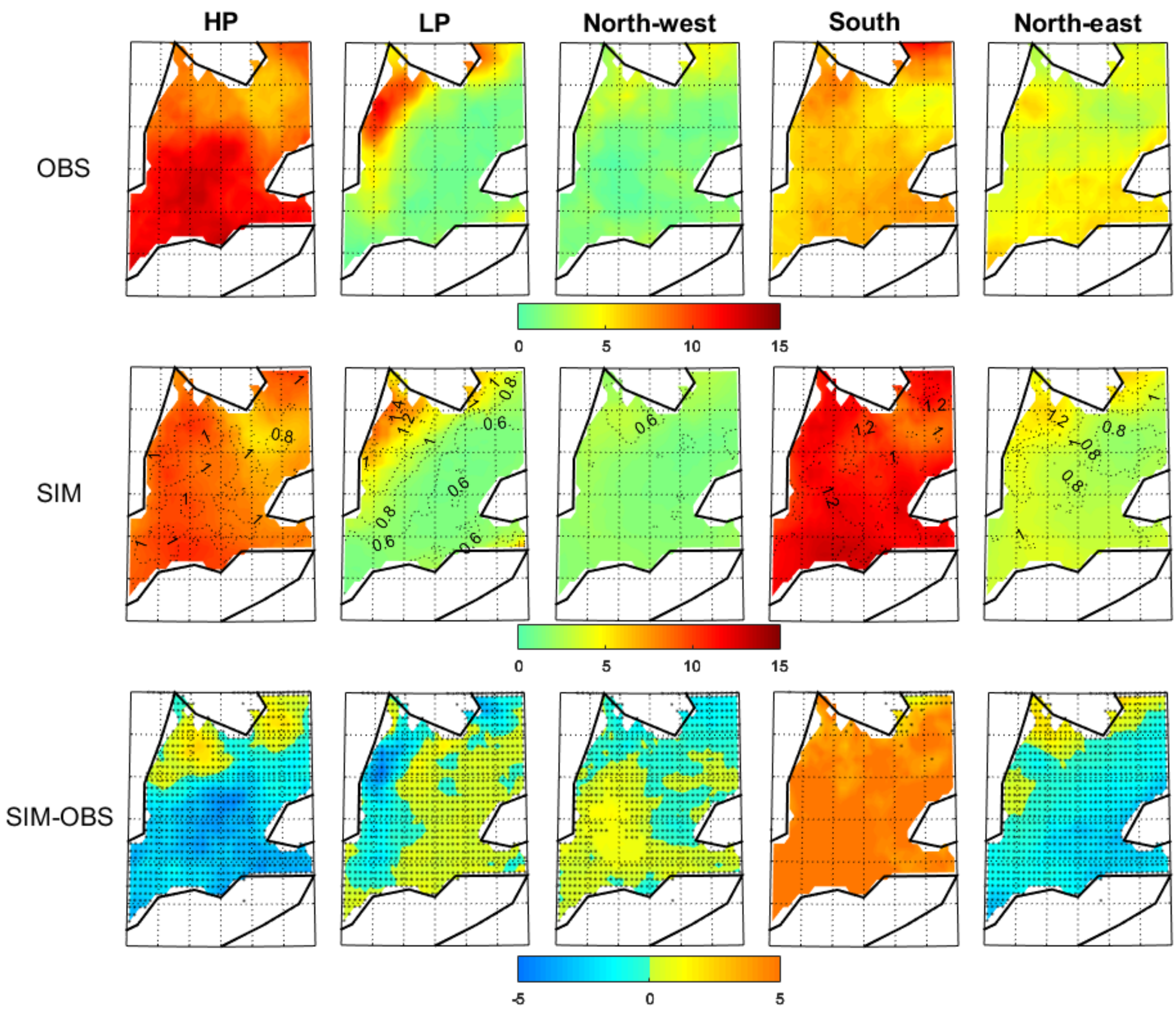

Figure 5: Percentage of DJF number of precipitation events relative to DJF occurrence of weather regimes in the historical period (1961-1990) for CanGRD (upper panels), 50 members CRCM5-LE average (mid panels) and CanGRD minus CRCM5-LE (right panels). The dotted lines in the mid panels represent the 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.

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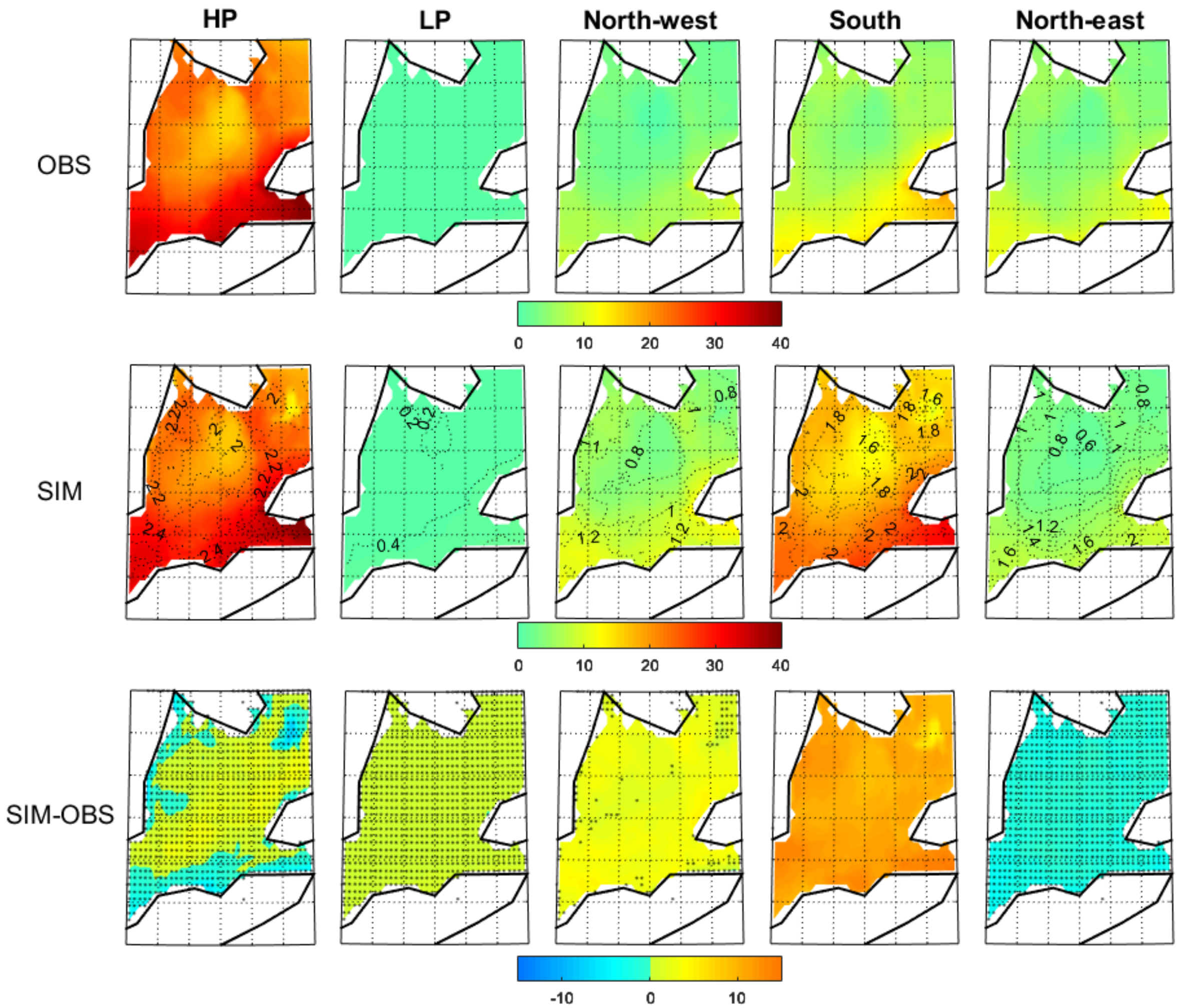

Figure 6: Percentage of DJF number of warm events relative to DJF occurrence of weather regime in the historical period (1961-1990) for CanGRD (upper panels), 50 members CRCM5-LE average (mid panels) and CanGRD minus CRCM5-LE (lower panels). The dotted lines in the mid panels represent the standard deviation 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.

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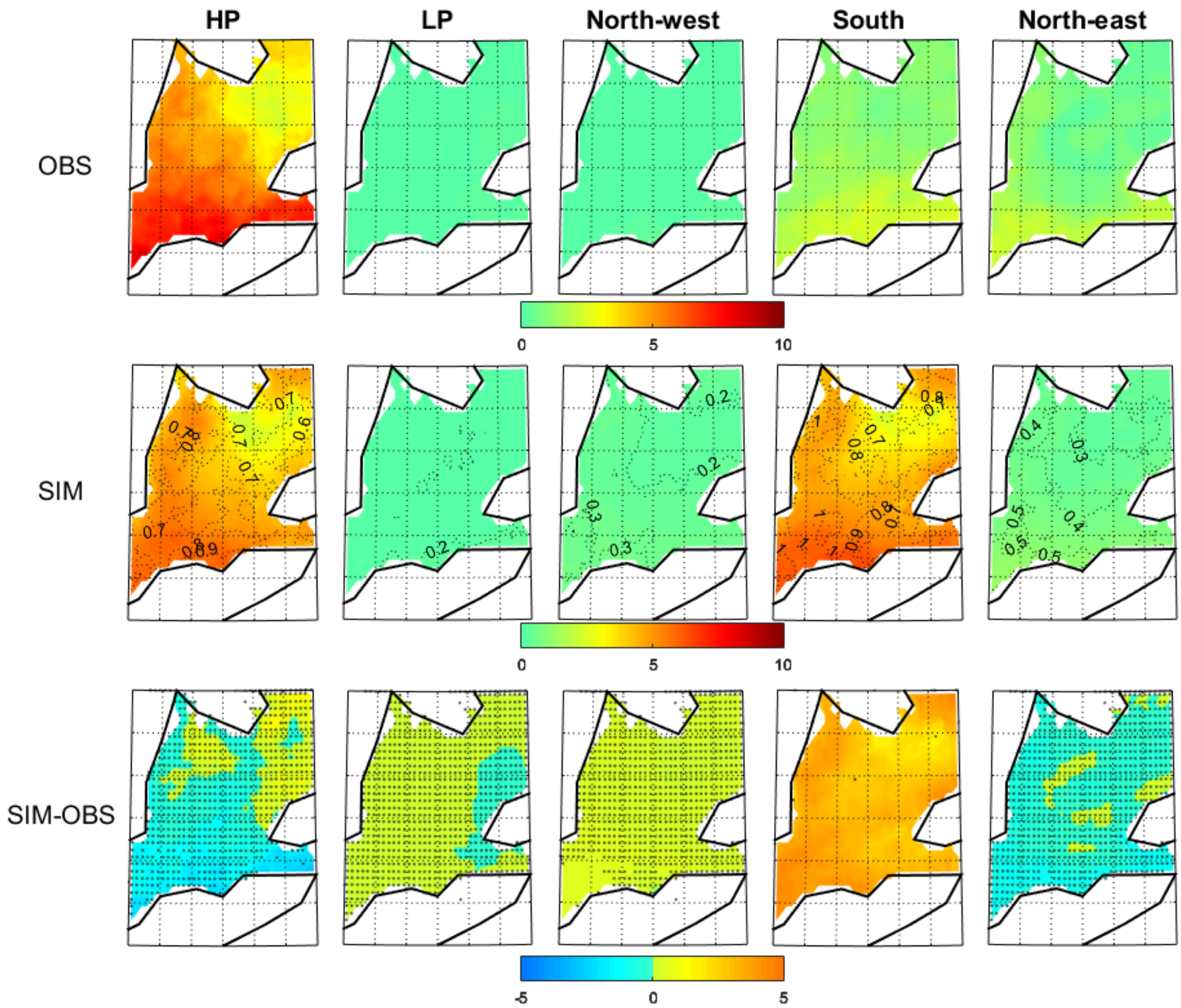

Figure 7: Percentage of DJF number of heavy rain and warm events relative to DJF occurrence of weather regimes in the historical period (1961-1990) for CanGRD (upper panels), 50 members CRCM5-LE average (mid panels) and CanGRD minus CRCM5-LE (lower panels). The dotted lines in the mid panels represent 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.

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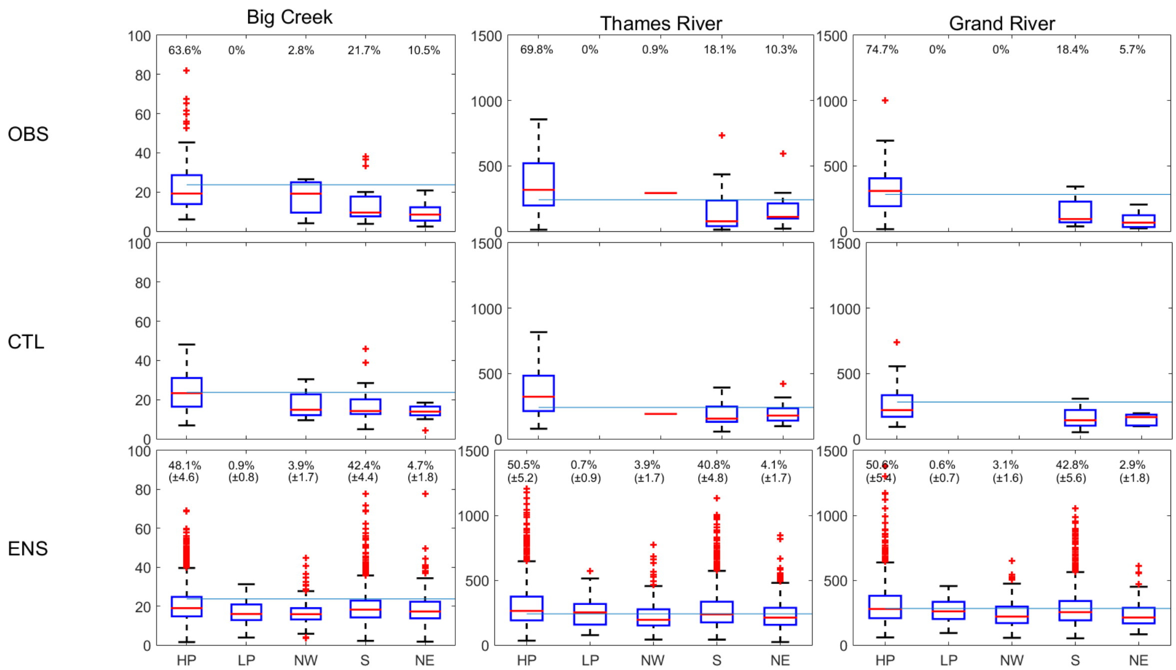

Figure 8: Upper and mid panels: Distribution of observed (OBS) and simulated (CTL) streamflow corresponding to all observed heavy rain and warm events. Lower panels: Distribution of simulated streamflow corresponding to all simulated heavy rain and warm events (ENS). Boxes extend from the 25th to the 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 (Average streamflow plus 3 times the standard deviation).

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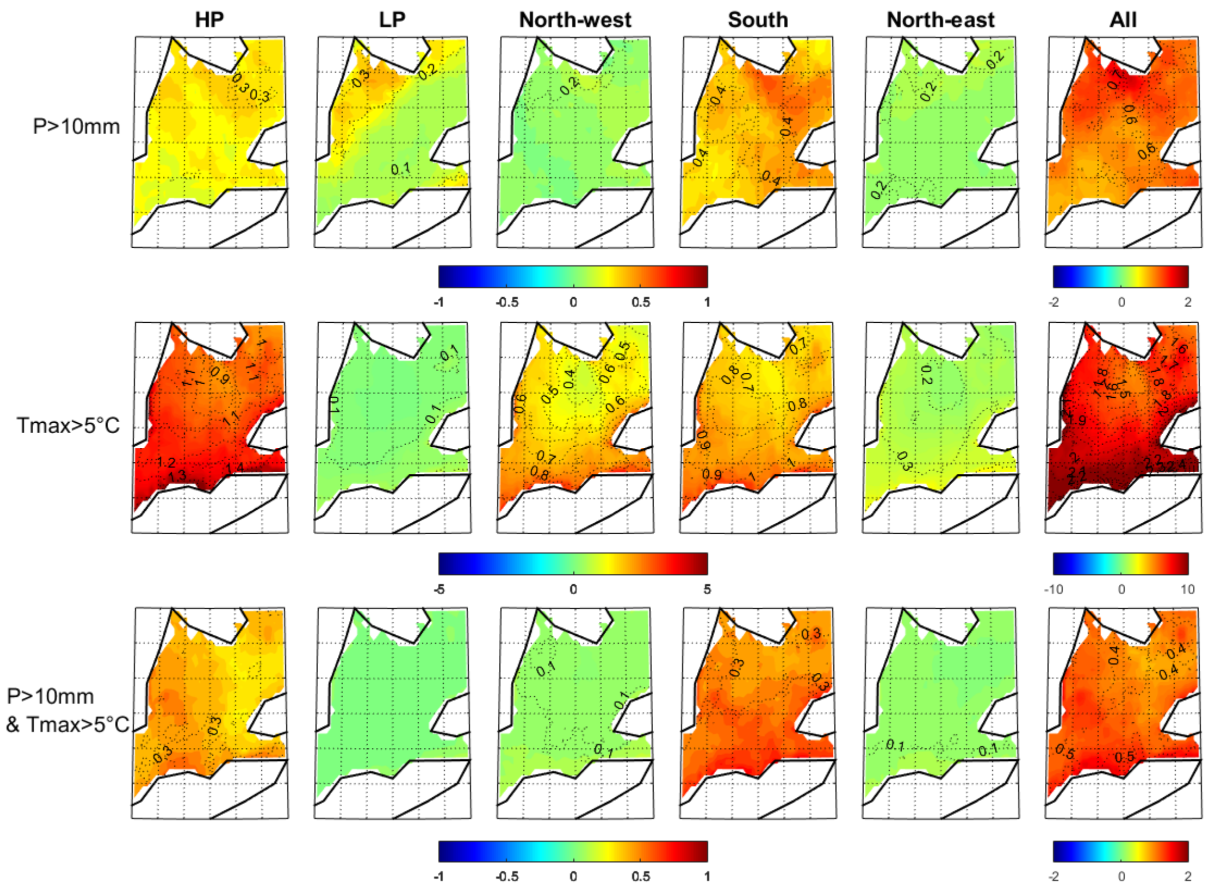

Figure 9: DJF change in number of precipitation and warm events between the historical (1961-1990) and the future period (2026-2055) for the 50 members CRCM5-LE average. The dotted lines represent the standard deviation of the 50-members CRCM5-LE simulated change in number of events.

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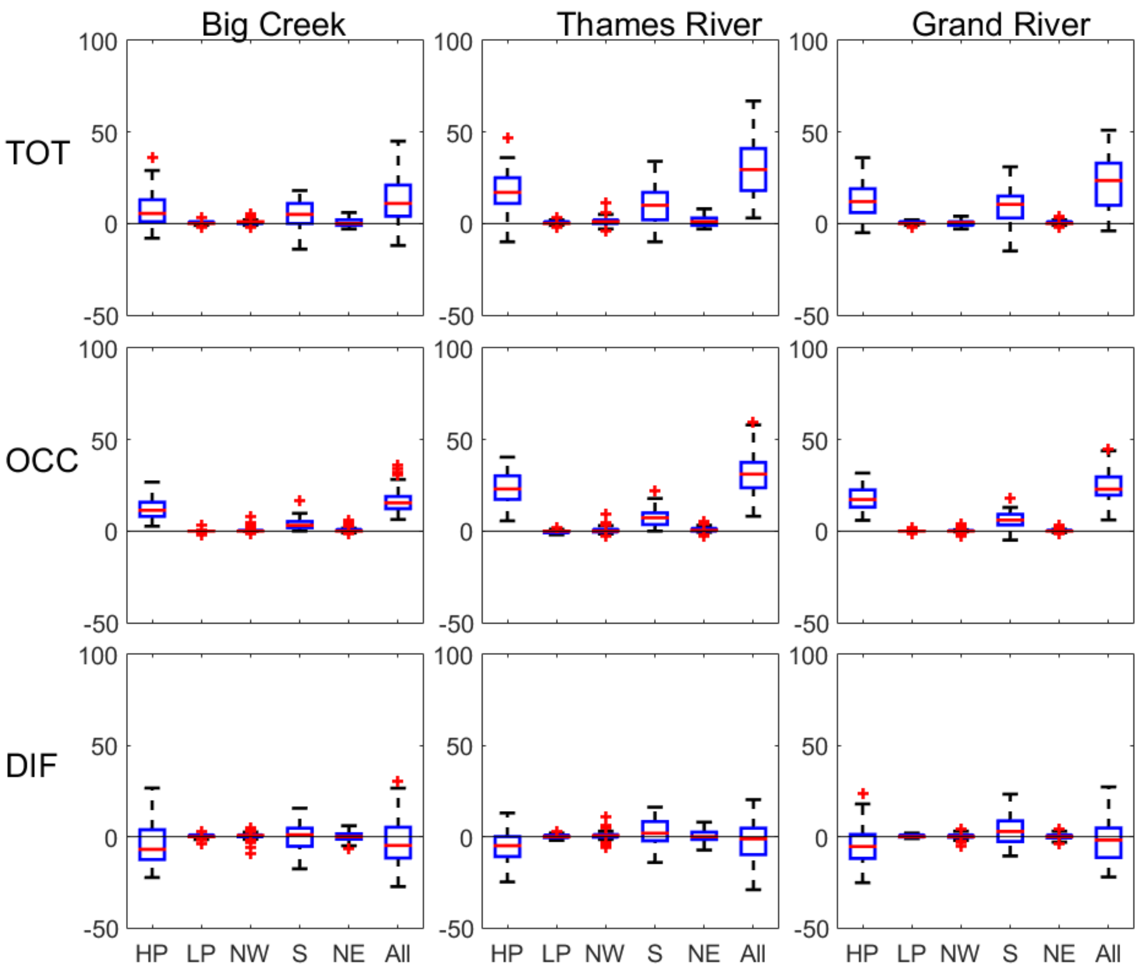

Figure 10: upper panels: Distribution of change in number of high flows between 1961-1990 and 2026-2055 simulated from the 50 members of the ensemble (TOT). Mid panels: Distribution of theoretical change in number of high flows using the factor of change in number of heavy rain and warm events between 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.

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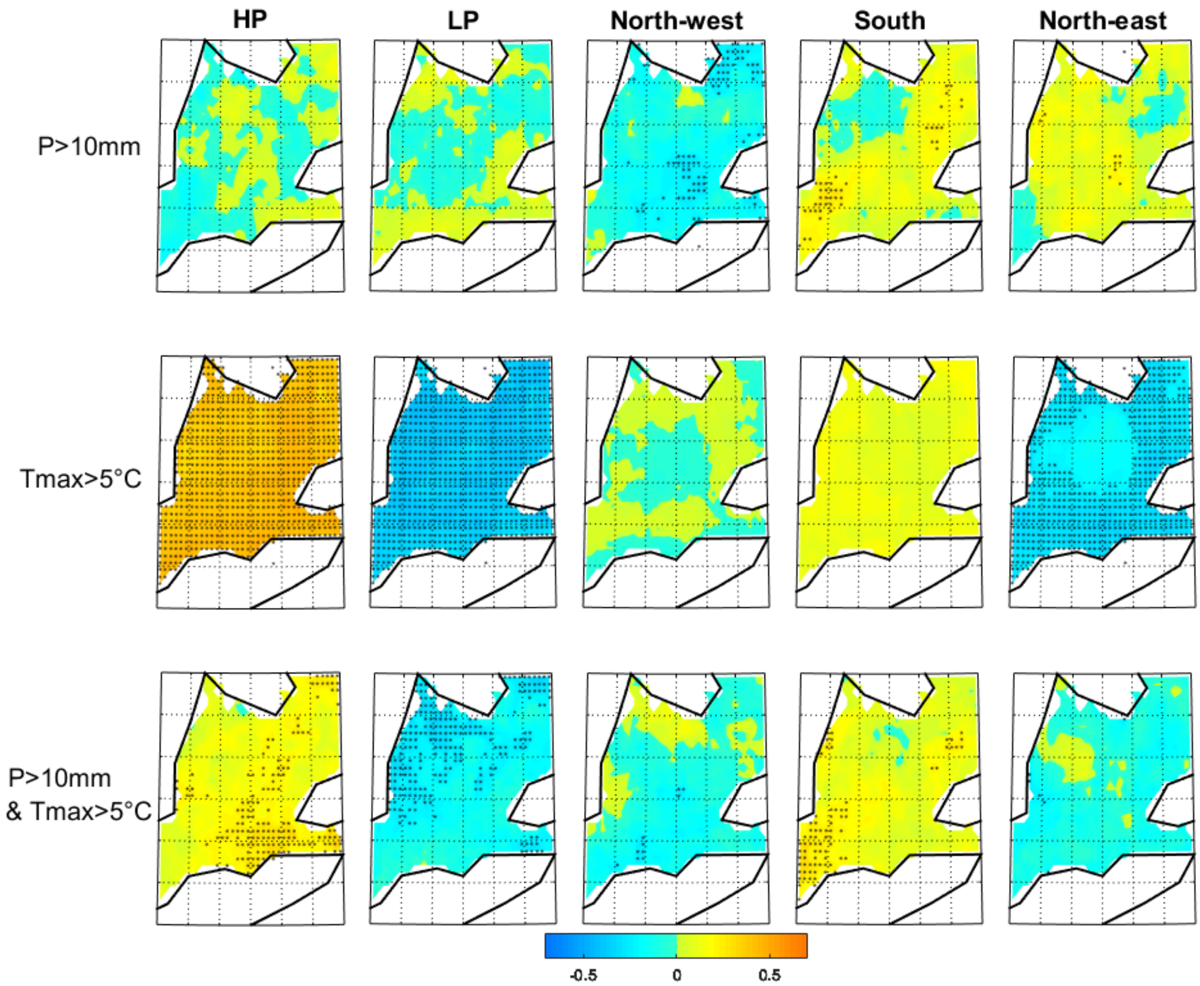

Figure 11: DJF inter-members correlations between change in occurrence of weather regimes and change in number of events between 1961-1990 and 2026-2055. Black points indicate a correlation significant at 95% according the Pearson's correlation table.

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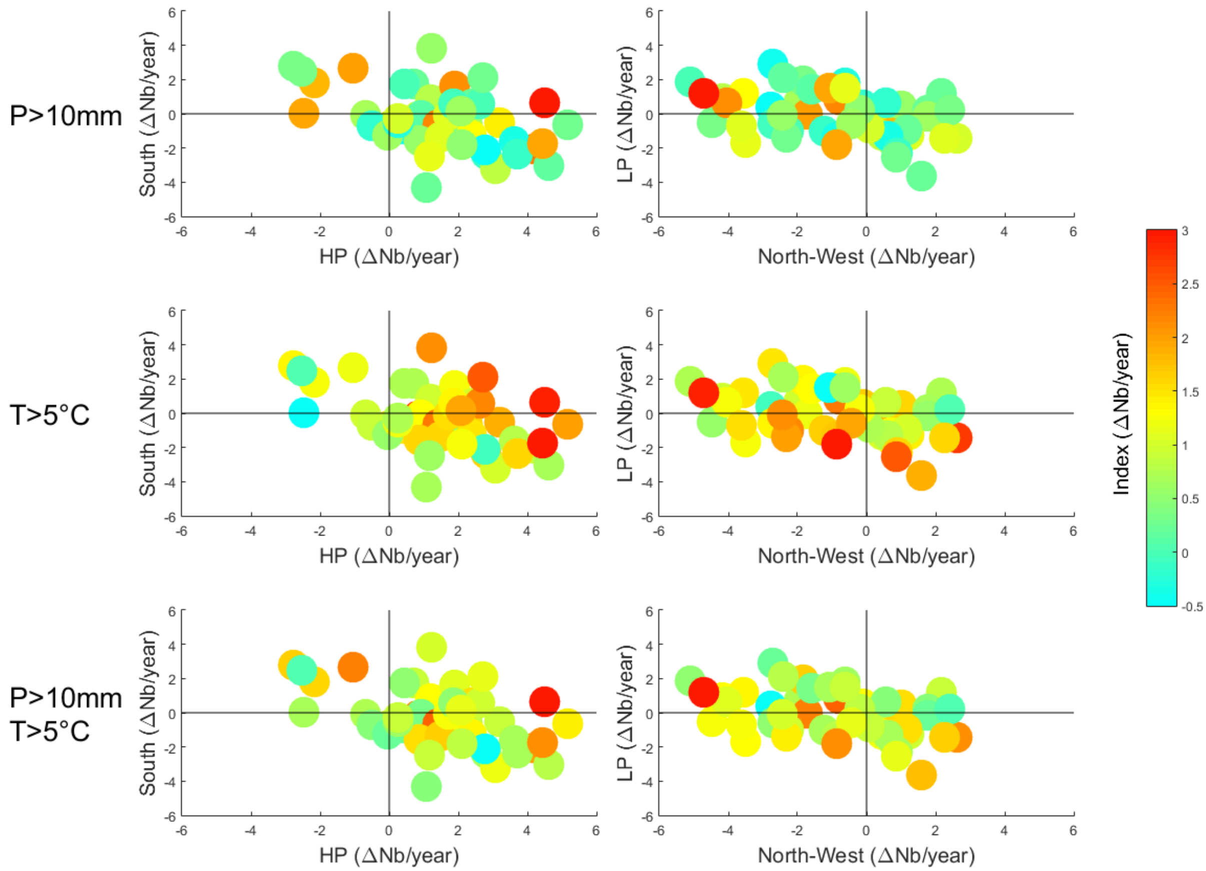

Figure 12: DJF change in occurences of regimes HP-South (left) and LP-north-West (right) in respect to change in number of precipitation and warm events (Colours) for each member of CRCM5-LE between 1961-1990 and 2026-2055.

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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

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