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**CONSTRUCTING INTENSITY-DURATION-FREQUENCY CURVES UNDER
CHANGING CLIMATE ACROSS CANADA USING CMIP5 AND CMIP6 CLIMATE
SIMULATIONS**

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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présenté par : **Vincent CRÉVOLIN**

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DEDICATION

Je dédicace ce mémoire à toutes les personnes m'ayant aidé au cours de la réalisation de ma maîtrise recherche à Polytechnique Montréal. À tous celles qui ont participé au projet, mais également celles qui m'ont soutenu dans mon quotidien, ma famille, mes amis, et également mes collègues de laboratoire de Polytechnique. Je dédicace séparément ma directrice de recherche, Dr. Elmira Hassanzadeh, pour son précieux investissement, particulièrement lors de la rédaction de notre article scientifique. Ses initiatives, sa disponibilité et son écoute ont permis de travailler sous de bonnes conditions.

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RÉSUMÉ

Depuis la fin du 19^{ième} siècle, le monde est soumis au phénomène de réchauffement climatique, étroitement lié aux activités humaines telles que l'industrie, l'agriculture et le transport, émettrices de gaz à effets de serre. Parmi les conséquences de la hausse des températures terrestres, l'augmentation de la capacité de l'atmosphère à emmagasiner de l'eau, ainsi que l'accélération de l'évaporation sont à la base de nouveaux régimes de précipitations. Les pluies extrêmes, plus spécifiquement, deviennent de plus intenses et fréquentes dans de nombreuses régions dans le monde. Le Canada n'est pas une exception, alors qu'il y est prévu un réchauffement plus intense que la moyenne. De plus, la population du pays connaît un fort accroissement, particulièrement dans les villes, qui deviennent plus vulnérables face aux catastrophes naturelles telles que les inondations urbaines. Les courbes Intensité-Durée-Fréquences (IDFs) sont généralement utilisées par les ingénieurs pour estimer statistiquement les caractéristiques de ces pluies sur les lieux d'études. Pour ce faire, les caractéristiques locales des courbes sont souvent utilisées pour le design et la maintenance d'infrastructures. Cependant, le changement climatique affecte les valeurs d'IDF au Canada et il est urgent de les mettre à jour en fonction des projections de pluies extrêmes dans le futur pour assurer la sécurité de projets, mais également afin de réduire la vulnérabilité de la population concentrée en zone urbaine. D'autre part, ces événements extrêmes entraînent des coûts de dédommagement et de réparations en forte croissance sur le territoire.

Ce travail de recherche a pour objectif de construire les courbes IDF sous l'emprise des effets du changement climatique dans 30 villes majeures du Canada, réparties dans toutes les provinces et territoires du Canada. À cet égard, 7 modèles de circulation globales provenant du dernier projet du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) appelé 'Coupled Model Intercomparison Project Phase 6' (CMIP6), ainsi que leur modèles prédécesseurs CMIP5 sont utilisés. Les projections sont réalisées sous deux scénarios de forçage radiatif différents: 4.5 et 8.5 W/m², et deux périodes futures: Court-terme (2021-2050) et long-terme (2071-2100). Du fait de la large résolution spatio-temporelle de ces modèles climatiques, la méthode de réductions d'échelles dites de 'Quantile-Quantile Downscaling' (QQD) transforme les sorties des modèles climatiques à l'échelle locale et pour différentes durées de précipitations extrêmes. Dans cette étude, la sensibilité

de ces courbes IDF est testée selon différents facteurs tels que le projet CMIP, les modèles climatiques, futurs scénarios et horizons.

Ainsi, notre évaluation projette une forte augmentation des intensités et des fréquences d'apparition des pluies extrêmes pour la plupart des villes canadiennes. Néanmoins, les magnitudes d'augmentations sont dépendantes du choix de modèles, du scénario et horizon, ainsi que de la position géographique de la ville considérée. De plus, il est expliqué que les événements plus rares, c'est-à-dire ceux avec une période de retour de 100 ans, devraient avoir lieu sous des augmentations de fréquences d'apparition plus rapides que celles des pluies extrêmes plus fréquentes (avec une période de retour de 2 ans par exemple). De façon plus concrète, les villes peuplées à croissance rapide telles que Montréal, Vancouver et Toronto font face à des précipitations extrêmes de 29 à 53 % plus intenses et environ 4 à 11 fois plus fréquentes pour une période de retour de 100 ans et une durée de 5 minutes, à l'horizon 2071-2100 sous un forçage radiatif de $8,5 \text{ W/m}^2$. Également, des villes du nord du Canada telles que Whitehorse au Yukon et Iqaluit au Nunavut possédant des communautés parfois vulnérables devraient subir des précipitations extrêmes largement supérieures à celles enregistrées dans la période historique, avec une augmentation d'intensité pouvant atteindre 70 %. Dans un scénario plus optimiste de $4,5 \text{ W/m}^2$, les augmentations d'intensité et de fréquence sont plus faibles que les celles sous le scénario de $8,5 \text{ W/m}^2$. Par exemple, les précipitations extrêmes de récurrence 100 ans subissent des augmentations de fréquences jusqu'à deux fois inférieure à celles sous un scénario de $8,5 \text{ W/m}^2$ dans les villes de Brandon, Québec et London. De plus, à l'horizon court-terme, les augmentations d'intensités et de fréquences sont les plus faibles pour toutes les villes. Au sujet des groupes de modèles CMIP6, l'ensemble de projections semble fournir des intensités plus importantes que par les modèles CMIP5 pour la plupart des villes. Cela peut s'expliquer en partie par la présence de deux modèles sur sept sous CMIP6 prouvés comme projetant des températures anormalement élevées associé à une grande sensibilité aux facteurs responsables du changement du climat. Dans notre cas, ces 'modèles chaud' estiment des quantiles de précipitations extrêmes globalement plus élevés que les autres modèles CMIP6/CMIP5. Une étude complémentaire produisant des courbes IDF projetées avec la méthode de Quantile-Delta Mapping montre l'impact du choix de la méthode de réduction d'échelle sur les résultats. Le comportement de cette méthode est moins fiable que la méthode QQD, particulièrement pour reproduire des pluies extrêmes de courtes durées. Cela souligne la nécessité

de travaux préliminaires pour choisir une méthodologie robuste. Pour conclure, nous recommandons de projeter les courbes IDF en ayant connaissance du climat local et de sélectionner des modèles climatiques conformément aux travaux d'évaluation de performances de la communauté scientifique. De ce fait, les ingénieurs doivent maintenant s'appuyer sur ces conseils et résultats afin de projeter des précipitations extrêmes assurant une rentabilité économique adéquate des infrastructures sur le long terme.

ABSTRACT

Global warming is a worldwide growing threat induced by human activities since late 19th century. One of the consequences of increasing air temperature is the augmentation of the atmosphere's water holding capacity and acceleration of evaporation, which affect formation of extreme rainfalls and their spatial and temporal distributions. Specifically, extreme rainfalls are becoming more intense and frequent in many regions of the world. Canada is not an exception as global warming is expected to be more severe than the global average. Larger amounts of annual rainfalls are already observed, accompanied with intensifications of extreme rainfall events. As the population is growing in the country, particularly in the cities, they become more vulnerable to extreme rainfall disasters such as urban flooding. The Intensity-Duration-Frequency (IDF) curves are typically used by engineers to statistically estimate the characteristics of extreme rainfall at a given location. The historical characteristics of IDF curves are often used for design and maintenance of various urban infrastructures. However, changes in climate can modify the IDF curves in Canadian cities. Therefore, it is urgent to update the IDF curves accounting projected precipitation to ensure the safety of future projects and lessen the vulnerability of the urban population. Moreover, these extreme events lead to increasing compensation and repair costs in the regions.

This thesis aims at constructing the IDF curves under changing climate conditions in 30 major cities across Canadian provinces and territories. For this purpose, the outputs of 7 Global Circulation Models (GCMs) from the latest Coupled Model Intercomparison Project Phase 6 (CMIP6) as well as from its predecessor CMIP5 project under 4.5 and 8.5 W/m² radiative forcing during short-term (2021-2050) and long-term (2071-2100) horizons are obtained. Due to large spatiotemporal resolution of GCMs (typically few kilometers and daily scale), a quantile-based downscaling approach, namely Quantile-Quantile Downscaling (QQD) is used to transform their outputs to fine local scale and obtain sub-daily/sub-hourly extreme rainfall quantiles. In this study, the sensitivity of the estimated IDFs to considered CMIP projects, climate models, future scenarios, and horizons are assessed.

Our analyses show increases in intensity and frequency of extreme rainfalls for most of the Canadian cities, particularly during the long-term horizon and under the 8.5W/m² forcing, given

both CMIP5 and CMIP6 projects. However, the magnitude of increase depends on the considered GCM, future scenario and horizon, as well as the geographical location of the considered city. Moreover, results show that rarer events, i.e., those with a 100-year return period are expected to occur more often than the more frequent ones (e.g., with 2-year return period). As an example, during the long-term horizon and under 8.5W/m^2 forcing, fast-growing populated cities such as Montreal, Vancouver, and Toronto would face 29-53 percent more intense and about 4-11 times more frequent extreme rainfall events with a 100-yr return period and 5-min duration. Moreover, northern Canadian cities such as Whitehorse and Iqaluit, which include vulnerable communities, would witness extreme rainfalls with a greater intensity of up to 70%. Strikingly, under a milder scenario of 4.5 W/m^2 , the increases of intensity and frequency are smaller than high radiative forcing. For example, 100-yr extreme rainfalls are expected to occur up to two times less than those for the 8.5W/m^2 forcing for Brandon, Quebec, and London. Moreover, increases of intensity and frequency are the lowest during the short-term horizon and under the 4.5 W/m^2 scenarios for all the cities. Considering the CMIP projects, the CMIP6 models generally estimate a higher intensity and frequency than CMIP5 ones for most cities. This can be partly related to the fact that two out of 7 GCMs under CMIP6 are considered as too hot models, i.e., producing excessively higher global temperature values than the expected range, that estimate larger extreme rainfall quantiles than other CMIP6/CMIP5 models. Lastly, a bias correction method, the Quantile-Delta Mapping (QDM) is implemented to construct projected IDF curves. The behavior of this method for reproducing future extreme rainfall quantiles is analyzed. Large uncertainties in the projections are observed and most importantly, the method fails to represent IDF values for short duration extreme rainfalls. This highlights the need to carefully select the downscaling method. Moreover, future IDF curves need to be constructed after analyzing the local climate and selecting climate model in accordance with peer assessment works. Thus, guidelines for engineers must be updated accordingly to these findings to ensure that engineers optimize the economic viability of the infrastructures over the long term.

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LIST OF SYMBOLS AND ABBREVIATIONS

AMP	Annual Maximum Precipitation
AMT	Annual Maximum Temperature
BIC	Bayesian Information Criterion
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
ECS	Equilibrium Climate Sensitivity
EQM	Equidistant Quantile Matching
GCM	Global Circulation Model
GEV	Generalized Extreme Value
IDF	Intensity-Duration-Frequency
IPCC	Intergovernmental Panel on Climate Change
QQD	Quantile-Quantile Downscaling
RCM	Regional Circulation Model
RCP	Representative concentration pathway
SSP	Shared socioeconomic pathway

TCR Transient Climate Response

QDM Quantile-Delta Mapping

ε Shape parameter

μ Location parameter

σ Scale parameter

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CHAPITRE 1 INTRODUCTION

1.1 Context

The rainfall Intensity-Duration-Frequency (IDF) curves are one of the most commonly used tools for design and operation of various water management infrastructure such as pipes, retention ponds, manholes, and culverts (Koutsoyiannis et al., 1998). The interest in understanding and extracting the precipitation IDFs have emerged since early 20th century in particular to advance flood frequency analysis (e.g. Bernard, 1932). The IDF relationships, developed if long data of precipitation are available at the location of interest, present the intensity of an extreme rainfall event for a given return period and duration. For this purpose, first the Annual Maximum Precipitation (AMPs) are obtained for rainfall with different durations e.g., for 5min, 30-min, 1h, to 24 h or even longer) based on the historical records. Then, probability distribution functions that can represent extreme values are fitted to the AMPs with different durations. Accordingly extreme rainfall quantiles corresponding to the return period of interest can be extracted and summarized on IDF graphs. However, human activities since the industrial revolution have caused considerable increases in heat trapping gasses such as CO₂, which has led to increases in the global air temperature by around 1 degree above pre-industrial levels and is currently increasing around 0.2°C per decade (IPCC, Global Warming of 1.5°C, 2018). As a result of this anthropogenic climate change, alterations in the form, distribution, magnitude, duration, and frequency of precipitation have been observed in many parts of the world (Martel et al., 2018) and IDF curves have become outdated.

In Canada, although large-scale atmospheric and oceanic oscillations such as Pacific North America (PNA), Atlantic Oscillation (NAO), and Arctic Oscillation (AO), are several external forcings that have a significant effect on the climate (Thiombiano et al., 2016; Tan et al., 2019), global warming has been responsible for increases in intensity and frequency of regional extreme precipitations in the country (Kirchmeier-Young and Zhang, 2020). For instance, total amounts of precipitation per year follow upward trends (Yagouti et al., 2008; Mekis and Vincent, 2011; Nalley et al., 2012;). Meanwhile, characteristics of extreme rainfalls have been disrupted (Groisman et al., 2005; Berg et al., 2013, Burn and Taleghani, 2013, Mailhot et al., 2007), exposing the reliability

of infrastructures and human-based systems (agriculture, economy, social...). Depending on the location and the storm duration, Shephard et al. (2014) estimate that at least two-thirds of the climate regions in Canada have already witnessed increasing (up to 33%) trends in extreme rainfall amounts. Moreover, data from Public Safety Canada point out important upward trends in weather-related disasters in Canada, as there are two times more natural disasters on average today than in 1970 and their total average cost has risen to be 5-6% of annual GDP growth in Canada. Among those catastrophic events, floods and thunderstorms caused by extreme rainfall events are the most frequently reported climate-related disasters in Canada (Sawyer et al., 2020), with 58% of the reported events (Public Safety Canada, 2022). The Canadian Standards Association (2019) explains that extreme rainfalls can result from four atmospheric processes (or their combinations): synoptic also called frontal events, convective rainfalls, tropical storms, hurricanes or their remnants events, and regional orographic processes. Each is associated with specific characteristic of extreme rainfall patterns. Convective storms influence extreme rainfall for durations shorter than 6 hours, synoptic events dominate events longer than 12 hours, and it is observed a combination of synoptic and convective rainfall for events lasting between 6 and 12 hours. As further explained in the following chapters, extreme rainfall characteristics will continue to change, hence the importance of understanding their behavior in the future. According to the IPCC Working Group I Interactive Atlas (2022), Canada is expected to have higher amounts of annual rainfalls under every different level of warming from 1.5°C to 4°C. The exacerbated extreme rainfalls can be partly explained by the Claudius Clapeyron law, indicating that the air holding water capacity increase while the global temperature increase.

1.2 Study area

These changes in climate are projected to be unequally spread across the country and depend on the local atmospheric processes taking place. Figure 1.1 represents the location of the climate zones in Canada: Mackenzie District, Yukon and North British Columbia Mountains, Prairies, Northwestern Forest, Pacific Coast, South British Columbia Mountains, Artic Tundra, Northeastern Forest, Great Lakes and Saint Lawrence, Atlantic Canada and Arctic Mountains and Fiords (Environment Canada, 1998). These regions are defined based on various variables such as temperature and precipitation, as well as land and vegetation cover (Sanderson, 2013).

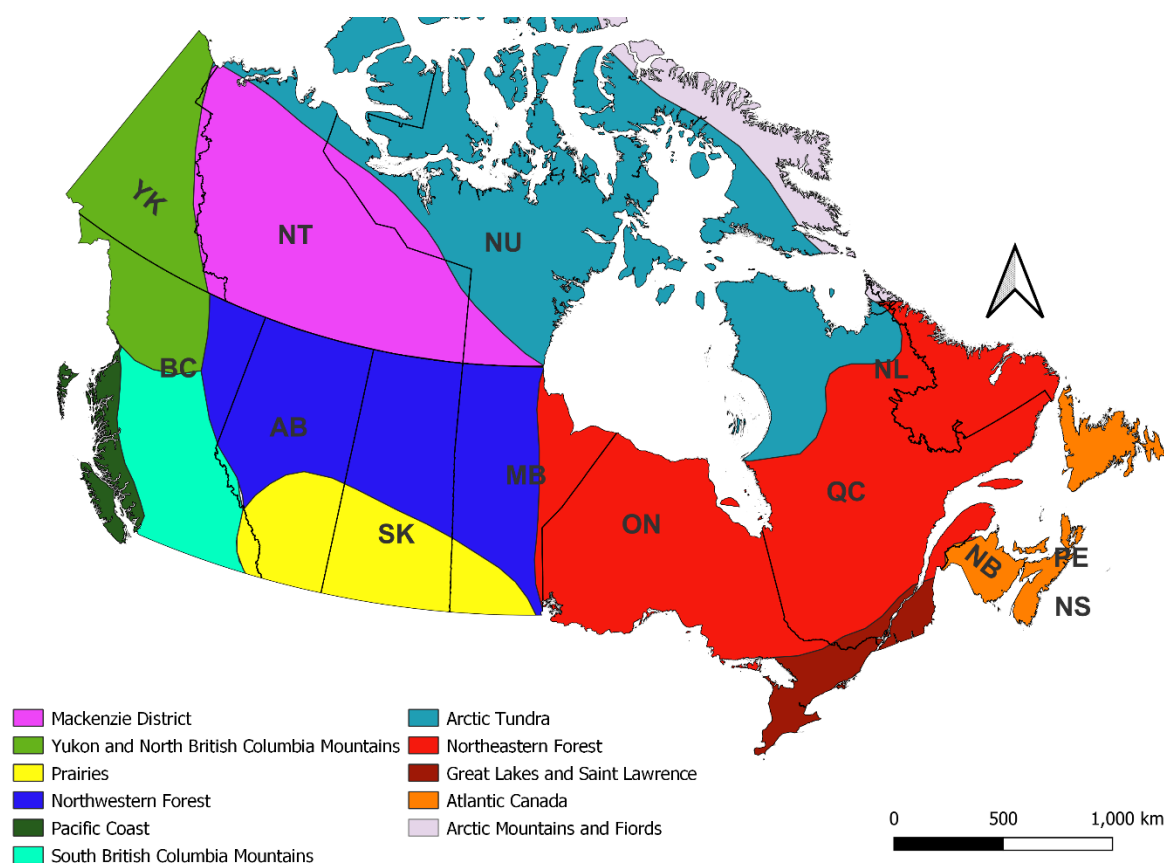


Figure 1.1. Climate zones in Canada over the different Provinces and Territories.

When IDF curves are constructed, practitioners must be aware of the local atmospheric processes manifesting in the region of interest. Various regional atmospheric processes are observable depending on the climate zone, largely impacting the magnitude of the local extreme rainfalls. The dissimilarities are particularly obvious while looking at the duration of their extreme events. Therefore, an understanding of the dominant atmospheric process in the study region is important when estimating IDF curves. The highest extreme rainfalls stem from shorter time duration rainfall resulting from convective processes. In Canada, typically, small regions from Prairies through Ontario witness this process. On the contrary, the highest 6-24 hr rainfall (long durations) amounts have been observed on the Pacific coast of British Columbia, under the influence of combination of synoptic, orographic, and topographical processes. For example, Table 1.1 shows that the highest ever recorded 5-min rainfall in Canada belongs to Winnipeg (387 mm/hr) in Manitoba and was a convective-based rain. Reversely, for a 24-hr duration, the maximum rainfall has been recorded in

Moresby Island (14.3 mm/hr) in British Columbia, which was a mix between synoptic and orographic-based rain.

Table 1.1. Maximum intensity of extreme rainfalls recorded for different durations, with their respective dominant atmospheric processes. Table from the Canadian Standards Association (2019) based on Environment Canada's National Climate Archive for each region in Canada (with data up to 2008).

DURATION	LOCATION	MAX INTENSITY (MM/HR)	DOMINANT ATMOSPHERIC PROCESS
5 MIN	Winnipeg, MB	387.6	Convective
10 MIN	Toronto North York, ON	268.2	Convective
15 MIN	Toronto North York, ON	265.2	Convective
30 MIN	Toronto North York, ON	180.4	Convective
60 MIN	Tobermory Cyprus Lake, ON	112.0	Convective
2 HR	Toronto North York, ON	65.9	Convective
6 HR	Jordan River, BC	25.2	Synoptic
12 HR	Moresby Island, BC	18.6	Synoptic and Orographic
24 HR	Moresby Island, BC	14.3	Synoptic and Orographic

Table 1.2 presents the range of maximum rainfall recorded (in mm) between 1 h duration and 24 hr duration for each province and territories. Overall, the Arctic region see the lowest extreme precipitation for all durations, British Columbia is subject to the highest long duration extreme rainfalls, whereas the Prairies and Ontario witness the highest short duration events of convective type.

Therefore, the aim of this study is to investigate the impact of climate change on extreme rainfall events in Canada using the most credible climate models. In this context, stormwater infrastructure built with the up-to-date IDF curves are still at risk being under-designed and vulnerable to climate change consequences (Tousi et al., 2021). From now on, guidelines and open data are slowly getting accessible for practitioners to properly includes IDF curves in their projects, considering the impact of climate change, see for example <https://idf-cc-uwo.ca/>. In this thesis, the literature on extreme events in Canada, current usage of IDF curves, climate models and their projects, as well

as downscaling methods are reviewed. Chapter 3 presents the organization of this thesis, identifies the gap in the knowledge, research questions, and objectives. Chapter 4 is the research article covering the analysis of impact assessment using one downscaling approach. Lastly, a general discussion on the best practices to construct the IDF curves, limitations of this study, and further research works are provided.

Table 1.2. Maximum recorded rainfall for 1-hr and 24-hr durations, for different group of climate-like provinces and territories. Table from the Canadian Standards Association (2019) based on Environment Canada's National Climate Archive for each region in Canada (with data up to 2008).

REGION OF CANADA	MAX 1 HR INTENSITY (MM/HR)	MAX 24 HR INTENSITY(MM)
BRITISH COLUMBIA (BC)	48.8	14.3
PRAIRIES (AB, SK, MB)	96.3	6.4
ONTARIO (ON)	112	11.0
QUEBEC (QC)	84	5.8
ATLANTIC MARITIMES (NS, NB, PE, NL)	64.8	10.0
ARCTIC (NT, NU, YT)	27.9	3.6

CHAPITRE 2 LITERATURE REVIEW

This literature review gathers key components of this thesis. Extreme events in Canada are first briefly studied. Then, climate projections using General Circulation Models from the CMIP5 and CMIP6 projects are discussed. Finally, a review of downscaling methods is provided.

2.1 Extreme events in Canada

Canada is the second larger country in the world covering 6.7% of the Earth's surface area (Wikipedia, 2022), and is consequently prone to various internal climate (Environment Canada, 1998). As a result, the country's provinces and territories undergo a variety of meteorological hazards which are responsible of severe disasters such as droughts, floods, heat waves, tornados and thunderstorms, and wildfires. Through federal programs, more than \$6 billion disaster financial assistance has been allocated in response and recovery costs amid natural disasters since 1970. The cost of such disasters reaches \$35 billion if uninsured catastrophic losses are also accounted (Public Safety Canada, 2022). Moreover, \$1.3 out of 6 billion were distributed solely in three recent years, between 2016 and 2019. The insurance Bureau of Canada (IBC, 2019) confirms \$31 billion insured and uninsured cost from 1983 to 2019 for 271 weather-related catastrophic loss events. According to Canadian Institute for Climate Choices (2020), there are two times more natural disasters on average today than in 1970. Meanwhile, the average losses per event, including private and public costs, increased from \$8.3 million in the 1970s to \$112 million between 2010-2019, that is a 1250% change. They also indicate that the astronomic average cost of weather-related disasters and catastrophic losses each year has risen to be 5-6% of annual GDP growth in Canada. Climate change could cost to Canadian economy \$139 billions by 2050 (Aquanomics, 2022). These extreme events affect all sectors, ranging from the economy to ecosystem, as well as human health. Although it is widely proved that climate change and variability are the main drivers of the climate imbalance today (IPCC, 2021), impacts of anthropogenic activities at the local and regional scale should not be ignored (Canadian Institute for Climate Choices, 2020). For instance, existence of limited and old drainage systems, construction of building in flood prone areas, as well as expansion of impermeable surfaces can contribute to urban flooding, which soar our vulnerability facing rainfall-related disasters.

In Canada, extreme rainfalls occur under various meteorological forms such as thunderstorm, prolonged rainfall, and even hurricanes in some Eastern regions. One of the costliest and more spread consequences of extreme events are floods. Although floods can occur as a result of different individual and compound phenomena, here our focus is on those that occur as a result of heavy rainfall during ice-free season. In the cities, these events can considerably damage infrastructure and cause death or injuries. For instance, in October 1954, heavy rains following the Hazel Hurricane caused major flooding in Toronto and resulted in more than 80 deaths and severe damages (The Canadian Encyclopedia, 2021). Since then, development on this flood plain have been restricted. Unfortunately, even though developments on lands were assumed to be protected against extreme rainfall events in Saguenay, intense summer storms associated with inadequate storage capacity of some dams, led to floods throughout the region in 1996 (The Canadian Encyclopedia, 2021). This well-known rare disaster took 10 lives and 16,000 people were evacuated. Other events such as these could be reported in Calgary in spring 2013 reaching total cost of damages as high as 6\$ billions or in more vulnerable cities such as Iqaluit in 2016 when a record rainfall flooded parts of the city.

In parallel with the risks of floods related to human life and goods, extreme precipitations threat sectors well beyond the risk of infrastructure failure. Indeed, the performance and operation of hydraulic and hydroelectrical plants can be modified, power may be cut too, impacting the energy sector, and once again threatening population with malfunctioning systems. Engineers usually consider these hazards in the design of infrastructures.

2.2 IDF curves in engineering

Nowadays, IDF curves are utilized routinely by engineers for the design of water resource management infrastructures. Different return periods are chosen to define design storms standards. A choice of safety level is made accordingly to risk assessment studies accounting for vulnerability but is also related to financial constraints. There is always a risk of these infrastructure being under-sized or oversized or experiencing reduced service life as the result of more frequent stresses (more frequent functioning under surcharged conditions for example). For instance, conveyance

infrastructures are draining systems such as underground sewers and overland storm water pathways. These pathways can require the construction of roadside ditch and culvert (Canadian Standards Association, 2019). Oppositely, temporary storage facilities aim to fill a pound upstream, to reduce downstream peak flow thus controlling the impact of severe storms inside urban areas. For all these types of infrastructure, the design return period is selected considering different risk levels, up to 10 years for low risk (catchment area inferior to 100 ha), up to 50 for medium risk (catchment area superior to 100 ha), and from 50 to 100 for high risks urban drainage network (more than 1,000 ha) (Ponce, 2008). Nowadays, 2-yr return period design storm can be selected for green infrastructures engineering, aiming to reproduce a natural response to rainwater management, by improving water quality and limiting large discharge downstream, i.e., infiltration swales or pervious pavement (Dupras et al., 2015). Although the return period considered for a project can go beyond 10,000 years for large dam design, our interest is only for urban system design having a range of return period from 2 years to 100 years. Design and Development Standards Manual of the city of Saskatoon (Section 6 - Storm Water Drainage System (saskatoon.ca)) is an example of guidelines and considerations for engineers to build different storm water drainage systems. Various service lives, ranging from 25 years for some urban temporary storage systems, to a century or more for major sewer infrastructures, stormwater detention ponds, make the choice of this design storm critical (Canadian Standards Association, 2019), particularly under the effect of climate change. In this context, there are still significant infrastructures used well past their originally planned lifespan putting the safety of population in jeopardy.

Another way of using IDF curves for engineering is while realizing analytical techniques such as hydrological modelling. Widely used techniques or more complex hydrological modelling processes often required standard intensities found with IDF curves as inputs. In hydrology, models of river discharges can be built under different levels of extreme rainfall events. For instance, extreme rainfall values are typically used to estimate peak flow discharge in small watersheds using the rational method (Wang and Wang, 2018). Equation 2-1 shows this relationship between Q_p the maximum discharge at basin outlet, i the rainfall intensity, and A the basin area. C is an empirical factor that depends on basin soil (Campos et al., 2020).

$$Q_p = C \times i \times A \quad 2-1$$

Such information is not only used for design purposes but also for urban flood analysis, to mitigate the risks induced by floods on the population and urban infrastructures (Oubennaceur et al., 2019), as well as to go toward resilient urban development (Heinzlef et al., 2020). Climate change impact must therefore be incorporated inside IDF curves to handle the upcoming increases in rainfall extremes intensity and frequency during the projects' lifespan. Larger investment costs and thus oversizing the initial construction can lead to lower total cost over the lifespan of the infrastructure element (Martel et al., 2021). Difficult financial decisions must be made in the short term for futureproofing.

2.3 Climate projections based on General Circulation Models

Global Climate models (GCMs) aim at simulating the Earth's climatic response to external forcings such as increase of Green-House Gases (GHG) emissions or aerosols in the atmosphere. Using principles of fluid dynamics and thermodynamics, they aim to reproduce physical processes and dynamics, not only in the atmosphere but also within and between ocean, cryosphere, and land surface (IPCC, 2021). The models use a three-dimensional grid over the globe with a typical resolution of 100- 250 km horizontally, 30-40 km vertically in the atmosphere, and 3- 10 vertical layers in the soil and bedrock, as well as 40 to 50 vertical layers in the ocean (Canadian Standards Association, 2019). GCMs' projections have been widely used by the scientific community in many branches for impact assessments and most importantly, the Intergovernmental Panel on Climate Change (IPCC) uses them in their CMIP experiments. IPCC is an international organization established by the United Nation General Assembly in 1988. It provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation (IPCC,2021). Six assessment reports have been published so far, in 1990, 1995, 2001, 2007, 2014, and 2021. These Assessment Reports (AR) are extensive literature research based on studies from vast ranges of fields and are major international multi model activities. Climate Model Intercomparison Project Phase 4 (CMIP3), 2006 and 5 (CMIP5), 2013 are the groups of simulations at the root of the 4th and 5th report of the IPCC, respectively. One of

their experiments, Scenario Model Intercomparison Project (ScenarioMIP), required the participation of climate centers around the world, for which each GCM model runs standard simulations under several realizations (members) having different initialization parameters. This enables results to be directly comparable across different models and scenarios, to see where models agree and disagree on future changes. As technology improves and scientific knowledge about these physical processes increase, the performance of the models in presenting climate conditions is improved. The numerous climate centers around the world develop their GCMs based on the same basic physical processes, but may have different initialization, feedback mechanisms, parametrizations, simplifications, etc (IPCC, 2021). Therefore, their projections can be different from each other (Lehner et al., 2020). CMIP5 projections have been generated using more than 30 GCMs since 2013, under Representative Concentration Pathways (RCPs) scenarios considering population growth, energy flux, economic activities, and other socioeconomic factors. These scenarios correspond to different radiative forcing by the end of the century. The radiative forcings are measures of Earth's heating per surface, in comparison with pre-industrial levels and drive the changes between the scenarios. They are derived following different increase of energy flux by the end of the century. Classically, scenarios from CMIP target forcings of 2.6, 4.5, 6.0, or 8.5 W/m². For instance, the most ambitious scenario of 2.6 W/m² is design to align with the low end of global temperature goal based on Paris Agreement, meaning keeping the increase in global temperature to well below 2 degrees above the pre-industrial levels by the end of the century, pursuing the efforts to limit the increase to 1.5 degrees (Government of Canada., 2022).

Oppositely, CMIP6 results became initially public after 2019, noting substantial expansions of CMIP6 models over CMIP5 with higher number of modelling groups participating (more than 50), higher number of GCMs, higher number of future scenarios available, or else the number of experiments conducted (23 experiments) (Eyring et al., 2016). Additionally, CMIP6 models follow scenarios called Socio-Economic Pathways (SSP). They represent simultaneously factors included in CMIP5 scenarios, with additional challenges such political issues, share and access to resources, etc. Moreover, SSPs are ranked from one to five according to their difficulty or success in addressing the challenges of implementing any global policies, or mitigation or adaptation strategies (Riahi et al., 2017). More precisely, SSP 1-2.6 represents sustainability (low challenges), SSP24.5 reflects the middle of the road (medium challenges), SSP3-4.5 shows a regional rivalry

(high challenges), SSP4-6.0 is marked by inequality and a divided road (low challenges to mitigation, high challenges to adaptation), and finally SSP5-8.5 is based on a fossil-fueled developments and represent a world pushed economically to growth (high challenges to mitigation, low challenges to adaptation) (IPCC, 2021). Some SSPs were established to work in combination with the RCPs scenarios of CMIP5. Indeed, SSP 1-2.6, SSP2-4.5, SSP3-4.5, SSP4-6.0, and SSP5-8.5 correspond to RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. Overall, some improvements are noticed using CMIP6 models rather than CMIP5 ones, although projections are often comparable, see the first volume of the 6th report from the working group 1: Physical Science Basis (IPCC, 2021). According to Meehl et al., (2020), the equilibrium climate sensitivity, a hypothetical value of global warming at equilibrium for a doubling of CO₂ is 1.8 °C to 5.6 °C, larger than CMIP5 range. Additionally, the transient climate response, the surface temperature warming around the time of CO₂ doubling in a 1% per year CO₂ increase simulation is 1.7 °C, slightly larger than its CMIP3 and CMIP5 predecessors.

Today, CMIP5 is commonly used for impact assessment and estimation of IDFs, in Canada and in the world. However, there are limited studies using CMIP6 data, particularly for projecting IDF curves, presented in Chapter 4. The difference of CMIP5 and CMIP6 in reproducing extremes rainfalls in Canada are not known to the best of our knowledge. Although Bourdeau-Claude et al., (2021) commented on AMPs in Canada at large scale, no analysis of the choice of CMIP5 or CMIP6 projects or their individual models has been done to point scale locations in the country, regarding their projections of extreme rainfall events. Here, IDF curves are derived based on daily precipitation data from CMIP5 and CMIP6 models, further spatially and temporally downscaled at the cities' locations.

2.4 Downscaling methods for constructing IDF curves in the future

As above noted, the spatial resolution of GCMs are typically few hundred kilometers, therefore, their projections cannot be immediately used for local scale analysis, in particular to construct the IDF curves. Regional Circulation Models (RCMs) belong to the category of dynamical downscaling and allow to make projections with finer scale resolutions (approximately 25-50 kilometers). Although it has been used directly to construct IDFs, various studies suggest to even

downscale RCMs to the point of interest too (Xu and Yang, 2019; Fowler et al., 2021a). Indeed, RCMs may not still be able to present local processes such as convective rainfalls. Therefore, statistical downscaling is widely used to project IDF curves under the impact of climate change and are mainly based on climate projections from GCMs. Then, these projections are further spatially downscaled to a specific location of interest and temporally downscaled from daily to different sub-daily durations using various algorithms. Classical methods such as Shifting mean, Bias correction, Delta method or Change factor (Fowler, 2007) are the basis to more advanced statistical downscaling processes. They are continuous downscaling methods, meaning that they are applied on the entire set of model-based time series along the future period and use observed time series to correct them. They involve coefficients, e.g., Bias correction, or linear regressions, e.g., Shifting mean to project a downscaled series. More advanced regression-based frameworks, such as typing approaches and stochastic weather generators are methods that can process daily GCM precipitations to daily local rainfall series (Solaiman et al., 2011; Tareghian and Rasmussen, 2013). Nonetheless, their performances remain limited (Camici et al., 2012; Bi et al., 2017).

Another category of methods based on quantiles breaks free with modifying all the time series to only focus on certain rainfall quantiles to reduce the propagation of errors (Hassanzadeh et al., 2019). This approach builds mathematical relationships between observed extreme rainfall quantiles and model-based historical quantiles to map changes for future projections. To the best of our knowledge, the QQD (Hassanzadeh et al., 2014), the Equidistance Quantile Matching (EQM) (Srivastav et al., 2014) and the Scale Invariance Method (SIM) (Nguyen et al., 2007) are the only generic parametric quantile-based approaches and have already been recognized to be parsimonious and simple to use. Thus, the focus in this study is on the QQD quantile-based method. In Chapter 4, QQD is selected to construct IDF curves under the impact of climate change for 30 Canadian cities. Complementarily, a bias-correction method, Quantile-Delta Mapping, is implemented in Chapter 5 and is compared to QQD.

CHAPITRE 3 APPROACH TO THE ENTIRE RESEARCH WORK AND ORGANISATION OF THE WORK

As Canada is warming under climate change effects, characteristics of precipitations and most notably characteristics of extreme rainfalls are changing. IDF curves is an engineering tool indispensable to design most of the water-related infrastructures, characterizing extreme rainfall associating the intensity of an event, with its duration and frequency. Usually, these curves are constructed using historical extreme precipitation records. Since using them in the future can cause underestimation of the severity of these weather phenomena, they need to be updated accordingly. Among the most reliable tools available to estimate future climatic conditions, GCMs are widely used around the world. Different scenarios mainly based on greenhouse gas emissions allow to consider many imaginable pathways. So far in various studies, GCMs based on CMIP5 project are used to study IDF curves in individual or a series of cities. Recently, the newest versions of models based on CMIP6 project have become available; however, these new projections of precipitation have not been compared with CMIP6 ones on projecting IDF curves in Canada yet. Therefore, there is a need to investigate on the reliability of the IDF curves based on CMIP6 models.

Therefore, the main goal of this thesis is to understand the impact of climate change on IDF curves in major Canadian cities in the future under different horizons and scenarios. Corresponding to noted gaps in the knowledge, the secondary objective is to compare the projected IDF curves in the future based on CMIP5 and CMIP6 projects and using Quantile-Quantile Downscaling approach.

Chapter 4 presents the scientific paper corresponding to the first noted specific objective. The paper has been submitted in August 2022 in Journal of Hydrology (Impact factor of 6.708). In brief, we used 389 simulations of precipitation from seven CMIP6 and seven CMIP5 GCMs to construct the IDF curves in Canadian cities for different horizons, and scenarios. Our benchmark period is 1961-1990, depending on the availability of the data for every city. Two horizons are considered, the short-term period (2021-2050) and the long-term period (2071-2100). The considered radiative forcing scenarios are RCPs 4.5 and 8.5 for CMIP5 and SSP 2-4.5 and SSP 5-8.5 for CMIP6. In this article, the AMPs per CMIPs and their individual models at the grid scale and daily resolution are studies. The performance of two probability distributions typically fitted to extremes are assessed.

Moreover, the performance of QQD downscaling method in reproducing local scale and fine temporal resolution extreme rainfall quantiles during the historical period is evaluated. Accordingly, IDF curves are updated given CMIP5/6 models for Canadian cities, impact of different CMIP projects, and future scenarios are also discussed. Particular attention is given to understand the changes in frequency of design storms. Finally, impacts of inclusion/exclusion of two ‘hot models’ from the CMIP6 project on the constructed IDFs are discussed.

Chapter 5 uses a different downscaling method, based on bias correction, called Quantile-Delta Mapping. The behavior of this method for projecting IDF curves is analyzed for the different CMIP5 and CMIP6 models. The goal is to realize a comparison of the expected IDF curves based on QDM relatively to those from QQD, to understand the impact of the choice of the downscaling method on the IDF curves.

Finally, a general discussion on projecting IDF curves for engineering design is presented. Uncertainties in the process are described and several recommendations are presented. Finally, alternative methods for engineers to project IDF curves under climate change are explained.

CHAPITRE 4 ARTICLE 1: CONSTRUCTING INTENSITY-DURATION-FREQUENCY CURVES ACROSS CANADA UNDER CHANGING CLIMATE USING CMIP5 AND CMIP6 MODEL PROJECTIONS

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4.1 Contribution of the Master Student

The master student obtained observed data and did their curation, as well as the curation of model-based data provided by Sarah-Claude Bourdeau Goulet. The student did the formal analysis and visualizations as well as writing the original draft. Dr. Elmira Hassanzadeh with the master student did the investigation, conceptualization, methodology, validation, reviewing and editing. Dr. Hassanzadeh oversaw the funding acquisition as well as the project administration.

4.2 Abstract

Extreme rainfall events can cause catastrophic floods in urban areas. The characteristics of extreme rainfalls are often presented by the Intensity-Duration-Frequency (IDF) curves, which are commonly used for urban infrastructure design. The impact of climate change on IDF curves has been studied using the projections of the Climate Model Intercomparison Project Phase 5, called CMIP5 models. However, the simulations of CMIP6 models have recently become available, which offer better process representation at the smaller scale and more realistic scenarios than their

precedent CMIP5 models. In this study, we update the IDF curves across Canadian cities using the projections of 7 CMIP6 models under Shared Socioeconomic Pathways (SSPs) 2 and 5 as well as their counterpart CMIP5 models under Representative Concentration Pathways (RCPs) 4.5 and 8.5. Quantile-Quantile Downscaling is utilized to estimate extreme rainfall quantiles at fine spatiotemporal scale. Results show that the characteristics of extreme rainfall events will change unequally across Canadian regions. The estimated rate of change in extreme rainfall values for each city depends on the considered climate model, CMIP project, as well as future scenario. Nevertheless, the intensity and frequency of extreme rainfalls are expected to increase in majority of cities, particularly under 8.5 W/m². For instance, under this scenario, the fast-growing cities such as Vancouver, Toronto, and Montreal could expect around 29-53% more intense and between 4 to 11 times more frequent rainfalls with 100-year return period and 5-min duration in 2071-2100. Moreover, cities in provinces of Atlantic Maritimes, such as Halifax, Stephenville, and Saint John, as well as vulnerable Northern cities such as Iqaluit in Nunavut and Whitehorse in Yukon would witness dramatical changes in their extreme rainfall characteristics. Furthermore, although IDF curves based on CMIP5 and CMIP6 individual models diverge in particular under 8.5 W/m² and 2071-2100, the expected IDF curves based on multi-model ensemble mean of these projects are somewhat similar if the too hot models based on CMIP6 are excluded from the analysis. This study calls for action to update the IDF curves across Canadian cities under changing climate conditions.

Keywords: Extreme rainfall; IDF curves; Climate change; CMIP5 and CMIP6 projections; Quantile-Quantile downscaling; Canada

4.3 Introduction

Human activities since the last century have altered climate conditions across various scales (IPCC, 2021). Most notably, the water holding capacity of the atmosphere and convective available potential energy have been increased (Kuo et al., 2021) and changes in precipitation patterns have been observed worldwide (Martel et al., 2018; Du et al., 2022). In particular, the characteristics of extreme rainfall events, which are often presented using the Intensity-Duration-Frequency (IDF) curves, have been changed across various regions (Groisman et al., 2005; Berg et al., 2013; Kourtis et al., 2022). For instance, more frequent and heavier rainfall events have been observed in different

cities in North America (Mailhot et al., 2007; Burn and Taleghani, 2013; Ganguli, and Coulibaly, 2019; Barlow et al., 2019). Such changes in extreme rainfall can be problematic for design, maintenance, and upgrade of urban infrastructure, for which the historical characteristics of IDF curves are often considered (Cosgrove and Loucks, 2015; Tousi et al., 2021; Zhou et al., 2019; He et al., 2021). Hence, there is a need to better understand the changes in the IDF curves to inform engineering design in the future (Peck et al., 2012; Cook et al., 2020; Martel et al., 2021).

The changes in the IDF curves are classically estimated using the outputs of General Circulation Models (GCMs), which should be further downscaled to the spatial and temporal resolution of interest (Yan et al., 2021; Tayşi., and Özger, 2022). The GCMs aim at representing the physical processes in the atmosphere, ocean, cryosphere, and land surface, and are the most advanced tools currently available to simulate the response of the global climate system to increasing greenhouse gas concentrations (IPCC, 2021). The group of simulations from the Climate Model Intercomparison Project Phase 4 (CMIP3; 2006) and 5 (CMIP5; 2013) used in the 4th and 5th report of the IPCC has been widely used to investigate the behavior of extreme precipitation in the future (Kharin et al., 2013; Jones, and Carvalho, 2013; Freychet et al., 2015). Their projections show intensifications of extreme rainfall events in numerous locations around the world (Westra et al., 2014; Donat et al., 2016). Recently, the state-of-the-art simulations of CMIP6 models from the 6th report of the IPCC have become available with new sets of future scenarios, called Shared Socioeconomic Pathways (SSP). The SSPs are based on new socioeconomic trajectories in comparison to CMIP5 analogous scenarios called Representative Concentration Pathways (RCPs) (Hausfather, 2020). Furthermore, the pledges of CMIP6 are to overcome the limitations identified in CMIP5, e.g., to better represent land use and land management changes and aerosol forcing as well as to reduce the systematic errors in process simulations (Eyring et al., 2016; Akinsanola et al., 2021). Indeed, general improvements in the simulation of precipitation have been observed in CMIP6 models compared to their predecessor across the world (Du et al., 2022), and in the simulation of extreme rainfall with smaller model spread, especially for regions in high northern latitudes (Chen et al., 2020). Considering multi-mean ensemble of CMIP6 models, a better estimation of extreme precipitations is found for Western North Pacific and East Asia (Chen et al., 2021), India for monsoon rainfall (Gusain et al., 2020), China (Luo et al., 2021; Zhu et al., 2020; Xu et al., 2022), and East Africa (Ayugi et al., 2021). In contrast, no substantial improvements of

CMIP6 over CMIP5 models have been found in Northeast U.S according to a regional precipitation metric considering one simulation per 16 models (Agel and Barlow, 2020).

IDF curves are commonly used for infrastructure design in Canadian cities. Several studies using CMIP3 models, e.g., in Southern Québec (Mailhot et al., 2007), Ontario (Peck et al., 2012), and in Alberta and Saskatchewan (Burn and Taleghani, 2013; Hassanzadeh et al., 2014; Kuo et al., 2015) have already indicated substantial modifications in the characteristics of extreme precipitation and IDF curves. Recently, IDF curves in Canadian cities have been updated using CMIP5 models (Srivastav et al., 2015 and 2017; Switzman, et al., 2017; Nguyen et al., 2018). For instance, increases of extreme rainfall are projected for Calgary, London, Vancouver, Moncton, Winnipeg, and Hamilton (Schardong et al., 2020; Silva et al., 2021), as well as in Saskatoon (Elshorbagy et al., 2015) and in central Alberta (Alam et al., 2015; Kuo et al., 2015, 2021) for short duration and long return periods. Jaramillo and Nazemi (2018) use CMIP5 models and find increases of typical design storms under a changing climate in the city of Montréal. Masud et al. (2021) present that CMIP6 models still do not fully represent convective precipitations in Alberta's mountainous regions. Bourdeau-Goulet and Hassanzadeh (2021) show that while no solid superiority of CMIP6 over CMIP5 is found in representing a series of climatic indices across Canada in comparison to NCEP and NOAA reanalysis, the range of Annual Maximum Precipitations (AMPs) based on ensemble of CMIP6 models is slightly greater than CMIP5 ones during the historical period. Moreover, they indicate that projected AMPs based on CMIP5 and CMIP6 models diverge depending on the considered region, climate model, and forcing scenarios. As these models do not fully reproduce AMPs, it is suggested to use simulations of both CMIP projects for estimation of extreme rainfall quantiles in Canada. Indeed, using CMIP6 models, Simonovic et al. (2021) have recently upgraded their interactive webtool for IDF curve in Canada, considering the Equidistant quantile mapping as a method of downscaling. However, the differences between extreme rainfall values and IDF curves based on CMIP5 and CMIP6 simulations per individual models and model ensembles have not been comprehensively analyzed over Canada.

This study aims at estimating the impact of climate change on the IDF curves in 30 major cities in Canada using the simulations of a set of CMIP6 and CMIP5 models. Due to the large spatiotemporal resolutions of GCMs (Willems et al. 2012), and their poor representation of

convective processes affecting sub-daily scales (Berg et al., 2018), Quantile-Quantile Downscaling (QQD; Hassanzadeh et al., 2014) is used to statically downscale daily climate model simulations to sub-daily and sub-hourly scales at local points. While typical statistical downscaling approaches aim to spatially downscale the model-based daily time series and then disaggregate them into sub-daily/hourly values (Requena et al., 2021b; Feitoza Silva et al., 2021), using the QQD, the propagation of error in the cascade downscaling can be reduced. This is because the focus of this technique is on spatiotemporally downscaling of rainfall quantiles rather than the entire time series (see Hassanzadeh et al., 2019). Moreover, the methodology is simple and computationally inexpensive, which is its clear advantage to apply in practice. The performance of the QQD has been compared with other quantile-based and continuous downscaling techniques and is found promising (Alam et al., 2015; Hassanzadeh et al., 2019 and 2021). The structure of the paper is as follows. The CMIP5 and CMIP6 climate models, applied downscaling technique, and parametric probability distributions utilized in this study are explained in Section 2. Section 3 provides a set of information about considered Canadian cities. In Section 4, the performance of the QQD method during the historical period, as well as the constructed IDF curves in the future using CMIP5/6 models are presented and intercompared. Moreover, the changes in frequency of design storms as well as sensitivity of analyses to employed climate models is further discussed in Section 5. Section 6 summarizes the key findings and provides some concluding remarks.

4.4 Materials and Methods

4.4.1 CMIP5 and CMIP6 models

The daily precipitation data of 7 CMIP5 and 7 CMIP6 models, in total 389 simulations, over Canada are obtained from the Earth System Grid Federation (2022) for the baseline as well as the short-term (2021-2050) and long-term (2071-2100) horizons. Table 4.1 presents these models and their associated number of simulations. These models are selected due to their previous application in Canada by Bourdeau-Goulet and Hassanzadeh (2021) and substantial number of simulations. The data under RCPs 4.5 and 8.5 for CMIP5 and SSPs 2-4.5 and 5-8.5 radiative forcing for CMIP6 models are considered. These radiative forcings are measures of Earth's heating per surface, in

comparison to pre-industrial levels, which tend to gradually increase because of natural and anthropogenic perturbations (Smith et al., 2020).

Table 4.1. Considered climate models and their grid resolutions as well as the number of simulations during the baseline and future periods, along with the future scenarios.

Climate center	Country	CMI P	Model	Spatial resolution (degree)	Number of simulations per period	
					Baseline	Future
Canadian Centre for Climate Modelling and Analysis (CanESM)	Canada	5	CanESM2	2.8×2.8	5	5
		6	CanESM5	2.8×2.8	50	50
National Centre for Meteorological Research (CNRM)	France	5	CNRM-CM5	1.4×1.4	10	1
		6	CNRM-CM6-1	1.4×1.5	30	1
Hadley Centre (Had/UK)	United Kingdom	5	HadGEM2-ES	1.9×1.2	5	4
		6	UKESM1.0-LL	1.9×1.3	19	5
Institut Pierre-Simon Laplace (IPSL)	France	5	IPSL-CM5A-LR	3.8×1.9	6	4
		6	IPSL-CM6A-LR	2.5×1.3	32	6
Model for Interdisciplinary Research On Climate (Miroc)	Japan	5	MIROC5	1.4×1.5	5	3
		6	MIROC6	1.4×1.4	10	3
Max Planck Institute for Meteorology	Germany	5	MPI-ESM-LR	1.9×1.9	3	3
		6	MPI-ESM1-2-LR	1.9×1.9	10	10
Meteorological Research Institute (MRI)	Japan	5	MRI-CGCM3	1.1×1.1	5	1
		6	MRI-ESM2.0	1.1×1.1	6	1

The RCP 4.5 and SSP 2-4.5 are built with a same end of century forcing of 4.5 W/m^2 , whereas the RCP 8.5 and SSP 5-8.5 follow 8.5 W/m^2 forcing. SSP 2-4.5 starts with a higher emission than RCP 4.5 but ends up slower declining than RCP 4.5 by the end of century, whereas SSP 5-8.5 possesses around 20% higher values of greenhouse gasses emission than RCP 8.5 (Hausfather, 2019).

4.4.2 Quantile-Quantile downscaling

The QQD method is inspired by the quantile-quantile relationship between daily rainfall extremes at a large scale, and the corresponding daily and sub-daily rainfall extremes at a local scale (Hassanzadeh et al., 2014). Figure 4.1 shows the procedure for the estimation of extreme rainfall values at finer spatiotemporal scales. The first step consists of fitting a probability distribution to (i) daily and sub-daily observed AMPs, (ii, iii) daily model-based (GCM-based) AMPs during the same baseline period and (iv) daily model-based AMPs in future periods. Second, linear regression relationships are found between each model-based daily extreme rainfall quantiles and corresponding local rainfall quantiles at daily and sub-daily scales during the baseline period and for each GCM (v). Third, by assuming that the extracted quantile-quantile relationships during the baseline period remain unchanged in time, the relationships are used to downscale model-based daily AMPs into sub-daily and daily projections in the future (vi).

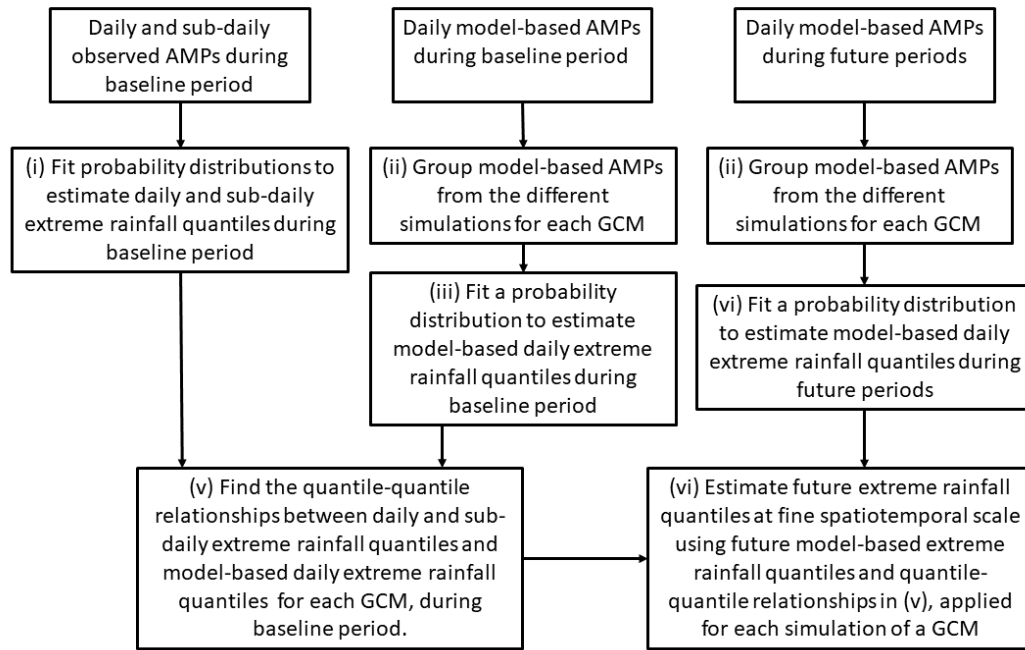


Figure 4.1. Workflow of the Quantile-Quantile downscaling for estimating future extreme rainfall quantiles at fine spatiotemporal scales.

Considering that here we have more than one simulation for most of CMIP5/6 models and even the number of simulations per models in the historical and future periods are not necessarily similar,

we have found daily AMPs per each simulation and then complied them for each model to fit the GEV distribution to extract model-based daily extreme rainfall quantiles. The quantile-quantile relationships for each GCM in the historical periods are then found between these model-based and observed quantiles. In the future period, similarly model-based daily extreme rainfall quantiles are found by fitting GEV to AMPs based on all simulation per each model, which are further plugged into quantile-quantile relationships to find extreme rainfall quantiles at daily and sub-daily scales locally.

4.4.3 Parametric distribution

The Generalized Extreme Value (GEV) distribution is commonly used to construct the IDF curves in Canada at different scales and regions (e.g., Sarhadi, 2017; Silva, 2021). GEV distribution is presented in Equation 4-1, where $F \in [0,1]$ is the non-exceedance probability (i.e., the percentile) of the random variable x (i.e., quantile); $\mu \in \mathbb{R}$ is the location parameter; $\sigma > 0$ is the scale parameter; and $\varepsilon \in \mathbb{R}$ is the shape parameter.

$$F(x; \mu, \sigma, \varepsilon) = e^{-\left(1 - \varepsilon \times \left(\frac{x - \mu}{\sigma}\right)\right)^{\frac{-1}{\varepsilon}}} \quad (4-1)$$

Due to its upper tail behavior, GEV can sufficiently present values of long return periods (Nguyen, 2016). Indeed, GEV distribution is recommended for the analysis of AMPs because of its solid theoretical basis and property (Nguyen, and Nguyen, 2008). It is noted that the GEV distribution is more suited for data with at least 20 to 30 points length (Requena et al., 2021). In Canada, Gumbel distribution, GEV where the shape parameter is equal to zero, is also used for IDF analysis, e.g., see Ouali, and Cannon (2018) and Cannon and Innocenti (2019). However, Gumbel may underestimate extreme rainfall quantiles relative to GEV distribution that has a heavier tail (Papalexiou, and Koutsoyiannis, 2013; Burn, 2014). Indeed, the shape parameter in the GEV distribution provides a supplementary local information as it depends on dominating precipitation systems and changes in elevation (Ragulina and Reitan, 2017). Although Gumbel distribution shows a smaller variance than GEV, it has more biases for longer return periods (Cannon, 2015). All this makes the GEV distribution a useful tool for modelling sub daily and daily extreme rainfall quantiles under changing climate (Nguyen, and Nguyen, 2017, 2019).

In this study, using the Bayesian Information Criterion (BIC; Equation 4-2), we have evaluated the goodness-of-fit of a range of probability distributions, including GEV and Gumbel, for the Canadian cities.

$$BIC = k \times \ln(n) - 2 \times \ln(\hat{L}) \quad (4-2)$$

where k is the number of parameters estimated by the models, n is the number of data points in the set of data, and $\hat{L}$ is the maximum value of the likelihood function of the distribution. This measure is selected due to its computational simplicity and performance (Neath, and Cavanaugh, 2012) and that it considers the sparsity of the distributions with their number of parameters. Considering the BIC, Figure A1 in the Supplementary Materials compares the performance of GEV and Gumbel and shows the superiority of GEV to replicate extreme rainfall values in most of Canadian cities. Therefore, in this study, GEV distribution is fitted to AMPs. The parameters of this distribution are estimated using the Maximum Likelihood Estimation method (Katz, and Brown, 1992).

4.5 Case Study

Canada is experiencing an intense rise of temperature, twice the global average rate (Stadnyk et al., 2021). Indeed, changes in mean precipitation and increases in intensity and frequency of regional extreme rainfall have been observed in Canada (Shephard et al., 2014; Martel et al., 2018; Kirchmeier-Young, and Zhang, 2020). For instance, intensity of extreme rainfall events has increased decennially for 30-min and 24-hr design storms between 1960 and 2010 in Ontario (Soulis et al., 2016). Similarly, considering 233 stations, Tan et al. (2017) show that AMPs have increased in the Pacific Maritime, central Boreal regions, and Atlantic Maritime between early 20th century to 2010. Henceforth, it is important to understand how changes in climate can affect extreme rainfalls in the future. For this purpose, 30 cities are selected based on the availability of historical data and fair representation of Canadian Provinces and Territories. Four provinces of Ontario, Quebec, British Columbia, and Alberta, share more than 85% of the Canadian population (Statistics Canada, 2021). For these densely populated provinces, the most populous cities are

selected. Table 4.2 shows these cities and their corresponding population, climate stations, and coordinates. A map of Canada representing the locations of the cities is provided in Figure A2.

Table 4.2. Selected Canadian cities and their corresponding population, climate station, and coordinates

Province	City	Population (2021) ¹	Climate station	Longitude	Latitude
Alberta (AB)	Calgary	1,306,784	CALGARY INT'L CS	-114.02	51.11
	Edmonton	1,010,899	EDMONTON INTERNATIONAL CS	-113.58	53.32
	Lethbridge	98,406	LETHBRIDGE CDA	-112.8	49.63
	Red Deer	100,844	RED DEER REGIONAL A	-113.89	52.18
British-Columbia (BC)	Abbotsford	153,524	ABBOTSFORD A	-122.36	49.03
	Kelowna	144,576	KELOWNA A	-119.38	49.96
	Vancouver	662,248	VANCOUVER INTL A	-123.18	49.2
Manitoba (MB)	Brandon	51,313	BRANDON RCS	-99.95	49.91
	Winnipeg	749,607	WINNIPEG A CS	-97.23	49.92
New Brunswick (NB)	Moncton	79,470	MONCTON INTL A	-64.68	46.11
	Saint John	69,895	SAINT JOHN A	-65.89	45.32
Newfoundland (NL)	Saint John's	173,757	ST JOHN'S A	-52.74	47.62
	Stephenville	6,540	STEPHENVILLE RCS	-58.55	48.53
Northwest territories (NT)	Yellowknife	20,340	YELLOWKNIFE A	-114.44	62.46
Nova Scotia (NS)	Halifax	439,819	HALIFAX INTL A	-63.5	44.88
	Sydney	30,960	SYDNEY CS	-60.05	46.17
Nunavut (NU)	Iqaluit	7,429	IQALUIT CLIMATE	-68.54	63.75
Ontario (ON)	Hamilton	569,353	HAMILTON A	-79.93	43.17
	London	422,324	LONDON CS	-81.15	43.03
	Ottawa	1,017,449	OTTAWA MACDONALD-CARTIER INT'L A	-75.67	45.32
	Sudbury	166,004	SUDBURY A	-80.8	46.63
	Toronto	2,794,356	TORONTO INTL A	-79.63	43.68
Prince Edward Island (PE)	Charlottetown	38,809	CHARLOTTETOWN A	-63.13	46.29
	Summerside	16,001	SUMMERSIDE	-63.83	46.44
Québec (QC)	Montréal	1,762,949	MONTREAL PIERRE ELLIOTT TRUDEAU INTL	-73.75	45.47
	Québec	549,459	QUEBEC	-71.38	46.8
	Saguenay	144,723	BAGOTVILLE A	-71.0	48.33
Saskatchewan (SK)	Regina	226,404	REGINA RCS	-104.67	50.43
	Saskatoon	266,141	SASKATOON RCS	-106.43	52.1
Yukon (YT)	Whitehorse	28,201	WHITEHORSE AUTO	-135.07	60.71

¹The most recent population data are obtained from Statistics Canada (<https://www12.statcan.gc.ca/>).

The historical AMP values for these cities are obtained from Climate Data (2022). For most cities the rainfall data are available in our considered benchmark period of 1961-1990 (30 years). For the cities with missing data, such as Halifax and Abbotsford a slightly smaller period is considered, see Table A1 in the Supplementary Materials. Overall, the origin of precipitation varies across Canada. For instance, the highest 6-24 hr rainfall (long durations) amounts can be often observed over the Pacific coast of British Columbia, under the influence of combination of synoptic, orographic, and topographical processes (Canadian Standards Association, 2019). The Prairie Provinces and even Ontario often witness heavy rainfalls in a very short duration, resulting from convective processes (Canadian Standards Association, 2019). Although all these regions would face severe climate change impacts (IPCC, 2021), representing such local climate processes, e.g., by CMIP5/6 models, is still challenging (Abdelmoaty et al., 2021). Therefore, the IDF projections at the local scale should be manipulated carefully.

4.6 Results

This section evaluates the impact of climate change on extreme rainfall characteristics in Canadian cities. For this purpose, first the observed as well as simulated AMPs based on CMIP5 and CMIP6 climate models are compared. Then the QQD's performance in representing local scale extreme values at fine temporal resolution is assessed during the baseline period. Accordingly, extreme rainfall values in the future are estimated and intercompared using 14 GCMs, 7 model per each project, under 4.5 and 8.5 W/m² radiative forcing for the 2021-2050 and 2071-2100 periods. For the sake of simplicity, the results in the following section are only presented for 5-min, 1-hr, and 24-hr durations and 2-, 25-, and 100- year return periods.

4.6.1 Overview of the model-based AMPs and performance of the downscaling technique

Here, the raw AMPs, obtained based on each simulation of CMIP5 and CMIP6 models for the grids covering the considered Canadian cities, are compared with the observed values at the daily scale during the historical period. Figure 4.2 shows the AMPs per individual CMIP5 (blue) and CMIP6 (red) models, their multi-model ensembles, containing values per CMIPs, as well as the observed

ones (grey). As expected, the range of model-based AMPs is not necessarily similar to the observed values, especially for the maximum and minimum values, e.g., see Montreal and Sydney. Similarly, having higher numbers of simulations in multi-model ensembles do not guarantee covering observed AMPs. Indeed, most models underestimate the local scale AMPs, see Quebec, Saskatoon, and Yellowknife. The smallest and largest difference between the model-based and observed median is found for Iqaluit and Abbotsford, respectively. Moreover, it can be seen that the range of AMPs based on CMIP6 are larger than CMIP5. In addition, median AMPs based on CMIP6 are higher and closer to the observed values than CMIP5 for almost all cities, e.g., see Charlottetown, Saskatoon, and Stephenville.

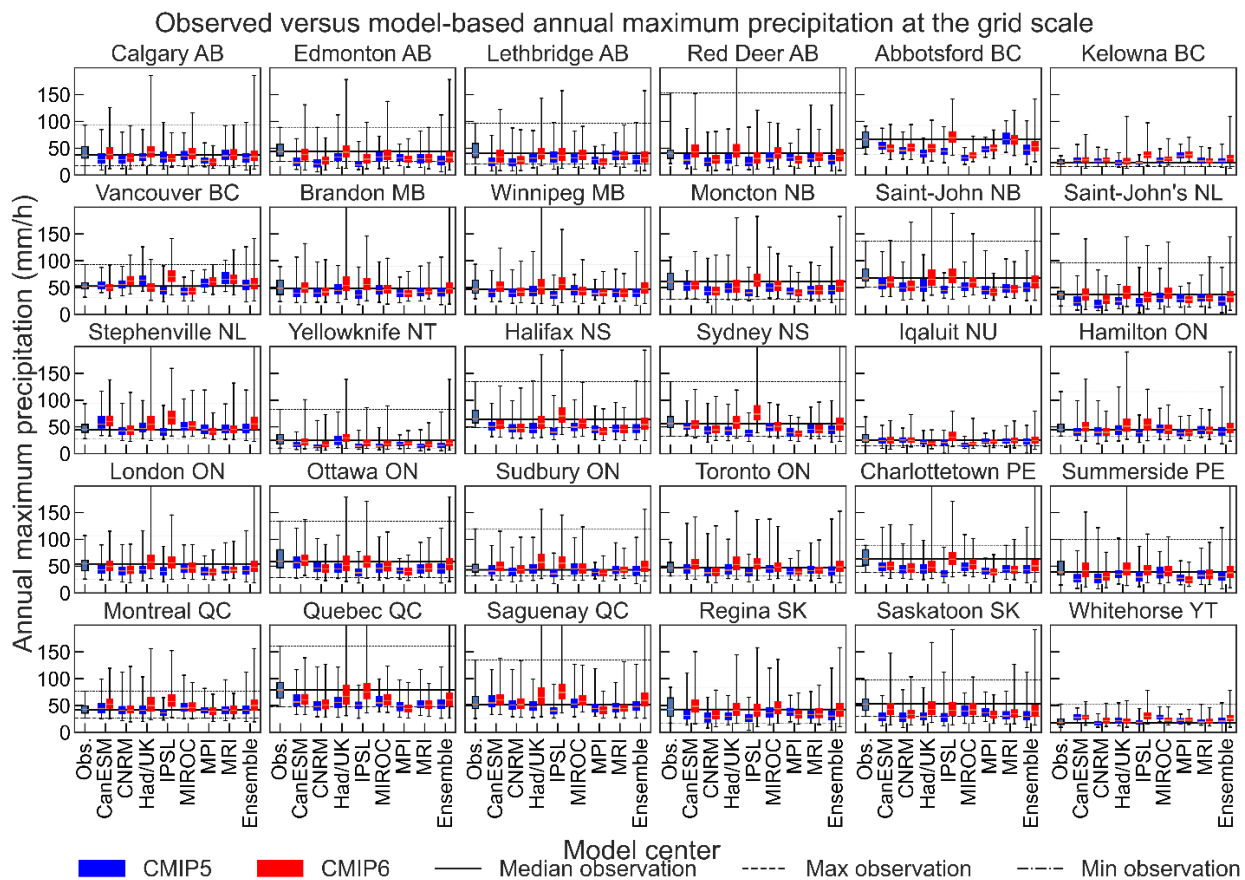


Figure 4.2. Daily observed and model-based AMPs (mm/h), obtained using CMIP5 (blue) and CMIP6 (red) simulations during the historical period over Canadian cities.

Considering the individual models, while the MPI, MRI and CNRM show the narrowest, the IPSL, Had/UK, and CanESM climate centers present the widest range of estimation. Particularly, the UKESM1-0-LL and IPSL-CM6A-LR based on CMIP6 consistently show larger ranges of AMPs than observed values, see Brandon and Saguenay. Similar to multi-model ensembles, the individual models often present smaller median than observed values, especially given the MPI climate center, see Calgary, and London. Moreover, extreme AMP values are often underestimated per models. For example, simulations from CNRM and MPI model centers have consistently lower maximum AMPs than observed ones, meaning that they might not be able to present large values in the future too. This is particularly obvious for all cities given CMIP5 individual models. Indeed, for the same modeling center, it is apparent that the CMIP6 and CMIP5 estimations are different, except for MRI. Nevertheless, as noted the differences between raw model-based and observed AMPs are somewhat logical due to the large spatial resolution of the GCMs, which accentuates the need for spatial downscaling (Martel and Brissette, 2021).

Here the QQD is applied to downscale the model-based daily extreme rainfall quantiles into daily and sub-daily values at the local scale. As previously noted, for each city, a single relationship is found to downscale daily extreme rainfall quantiles based on all simulations per each GCM to the duration of interest. For instance, Table A2 shows the regression equations to downscale quantiles based on CanESM2 and CanESM5 models, in 30 Canadian cities to 5-min, 1-hr, and 24 hr duration values. Here, the performance of these equations in representing the point scale values at fine temporal resolutions is assessed during the baseline period prior to using them for downscaling future model-based values. Figures 4.3 and 4.4 show the percentage of relative error between the estimated (downscaled) model-based and observed extreme rainfall values for the Canadian cities during the historical period. Each boxplot contains 7 values corresponding to 7 models per CMIP and the results for CMIP5 and CMIP6 are shown with blue and red colors, respectively. Figures A3 to A9 in the Supplementary Materials show the relative errors calculated for each of the climate models during the historical period for the Canadian cities.

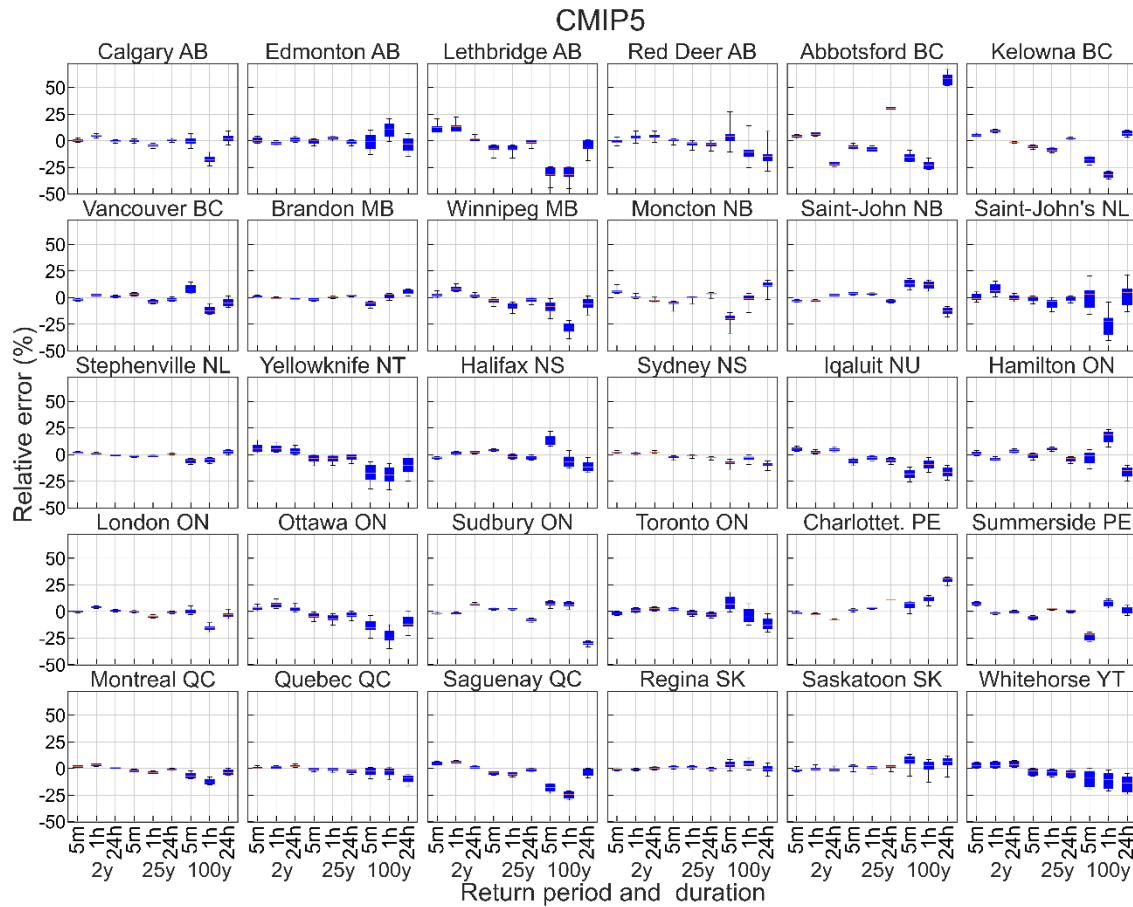


Figure 4.3. Percentage of relative error between the downscaled extreme rainfall quantiles based on 7 CMIP5 models and observed values during the historical periods over 30 Canadian cities.

The small error values in the figures imply that downscaling sufficiently reduces the discrepancy between the model-based and observed extreme rainfall quantiles. Most importantly for all durations and 2- and 25- year return periods, the error is smaller than 15% and, in most cases, close to zero, except for Abbotsford and Lethbridge. However, for 100 years return period, the errors are larger, and can exceed 25 percent, e.g., see Saint John's. It is clear that such great errors for 100-year return period can be somewhat expected due to the length of utilized baseline data, i.e., 30 years, and uncertainties associated with the fitted distribution to them (Hassanzadeh et al., 2019). Reversely, the performance of the downscaling process is good for cities such as Montreal, Quebec, Regina, Stephenville, and Brandon. Further comparisons reveal that the errors are slightly larger for CMIP5 than CMIP6 models for most cities, e.g., in Whitehorse, Montreal, and Saskatoon in Figure 4.3 and 4.4. This can be logical due to the larger differences between raw CMIP5 and

observed values, as seen in Figure 4.2. Figures A3 to A9 shed light on the errors of downscaling per individual CMIP5 and CMIP6 models.

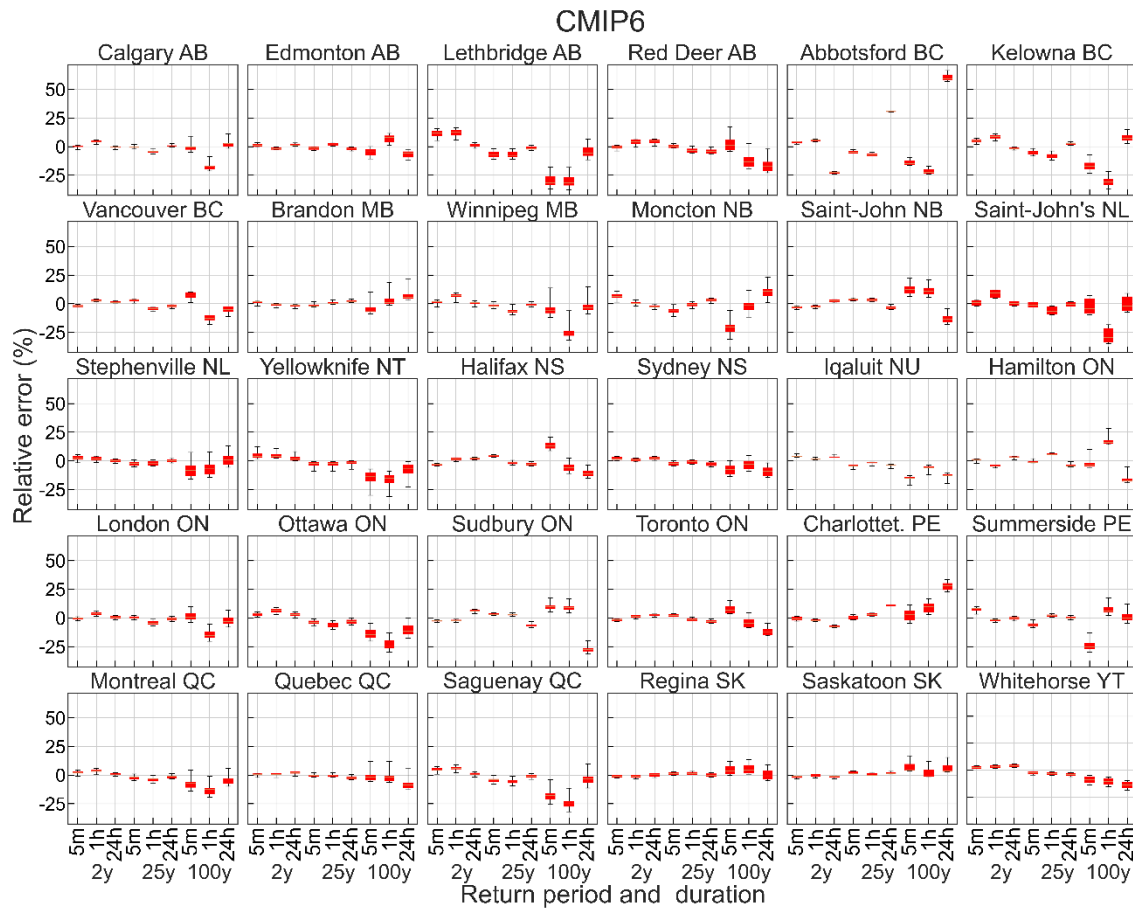


Figure 4.4. Percentage of relative error between the downscaled extreme rainfall quantiles based on 7 CMIP6 models and observed values during the historical periods over 30 Canadian cities.

The magnitude of the error not only depends on the considered GCM but also the target city. For instance, the error of downscaling quantiles based on CanESM5 model is small in the city of Regina, but it is large for Saguenay. Another example is that for Montreal and Ottawa, the errors based on downscaled CNRM-CM5 and CNRM-CM6-1 are almost similar, whereas for Saint John's there is more than 25% difference between these two models' error values. Further analysis of individual models reveal that no model seems to have better results than others, which shows the need to use multi-model ensemble projections. Furthermore, as previously noted, the higher number of simulations per individual model or modeling center does not imply better coverage of

observed values. Overall, although the performance of the QQD depends on the given city, climate model, return period and duration, it clearly helps reducing the errors.

4.6.2 Extreme rainfall quantiles in the future

IDF values for the Canadian cities in the future are estimated based on the downscaling equations identified in the previous section, as well as daily extreme rainfall quantiles based on all simulations given each GCM in short-term and long-term horizons under two radiative forcing 4.5 and 8.5 W/m². Therefore, for each GCM, one set of IDF curves are found. Figures 4.5 and 4.6, as well as Figure A10 in Supplementary Materials show these local scale extreme rainfall quantiles for 5-min, 1-hr, and 24-hr durations, respectively, under 2-, 25-, and 100-year return periods in the Canadian cities, which are estimated using CMIP5 (blue) and CMIP6 (red) models under 8.5 W/m² radiative forcing during 2071-2100. Similar figures are provided for 4.5 W/m² radiative forcing during 2071-2100 as well as under both forcings during the short-term horizon, see Figures A11 to A19 in the Supplementary Materials. Observed extreme rainfall quantiles are shown in these figures as well.

As it can be seen extreme rainfall values will change in the future. Indeed, median of projected extreme rainfall values are significantly higher than the observed ones for most of the cities. Under 8.5 W/m² and long-term horizon, the lowest model-based projections are even higher than observed values for some cities in Ontario such as Sudbury, Brandon, and Hamilton for all duration. Same behavior is observed for Eastern cities, for example, Montreal, Saint-John, Charlottetown, Sydney, and Halifax, especially for short duration events. Nevertheless, some reductions in rainfall intensity are projected, solely for 100-years return period and for 1-hr duration at Saint John's, Lethbridge, and Kelowna and for 24-hr duration at Sudbury. In general, the estimated magnitude of change in extreme values depends on the considered duration, return period, city, as well as CMIP project. Moreover, the spread of projections is wider for rainfalls with longer than shorter return periods, as an example see Ottawa.

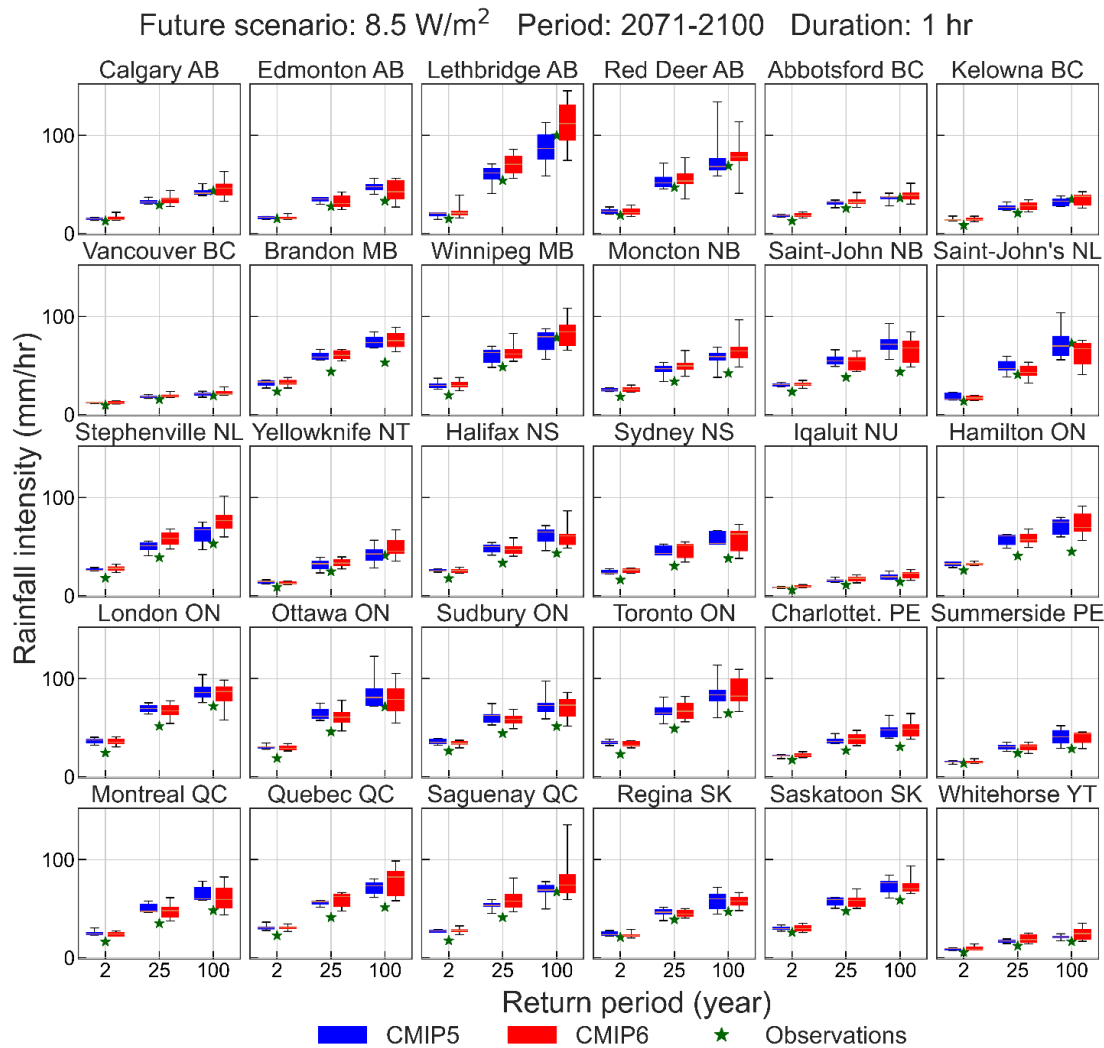


Figure 4.5. Boxplots of extreme rainfall quantiles for 1-hr duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 8.5 W/m² radiative forcing during 2071-2100. The observed values during the historical period are shown with green stars.

Similarly, the difference between projections of CMIP5 and CMIP6 models is more obvious for rainfalls with longer than shorter return periods. In most cases, CMIP6 models estimate slightly larger median extreme values than CMIP5 ones, e.g., see the results for Moncton in Figure 4.5. Moreover, as expected CMIP6 projections do not necessarily overlap CMIP5 values or vice versa, see the results for Charlottetown versus Stephenville. It is also noted that the spread of projected values and rates of change in extreme rainfall are more significant under 8.5 W/m² forcing during 2071-2100 than other horizons and forcing. Figures A11 to A13 present extreme rainfall quantiles

under 4.5 W/m² radiative forcing and the period 2071-2100. The projected quantiles under this scenario are slightly larger than observed ones for all duration, see Regina and Edmonton. Some cities in Ontario such as for Sudbury or Toronto for example, seem to undergo significant changes under this milder forcing for 5-min and 1-hr durations. Despite some discrepancies in CMIP5 and CMIP6 ranges of projections, see Summerside or Yellowknife, models under the 4.5 W/m² radiative forcing have higher agreement than under 8.5 W/m².

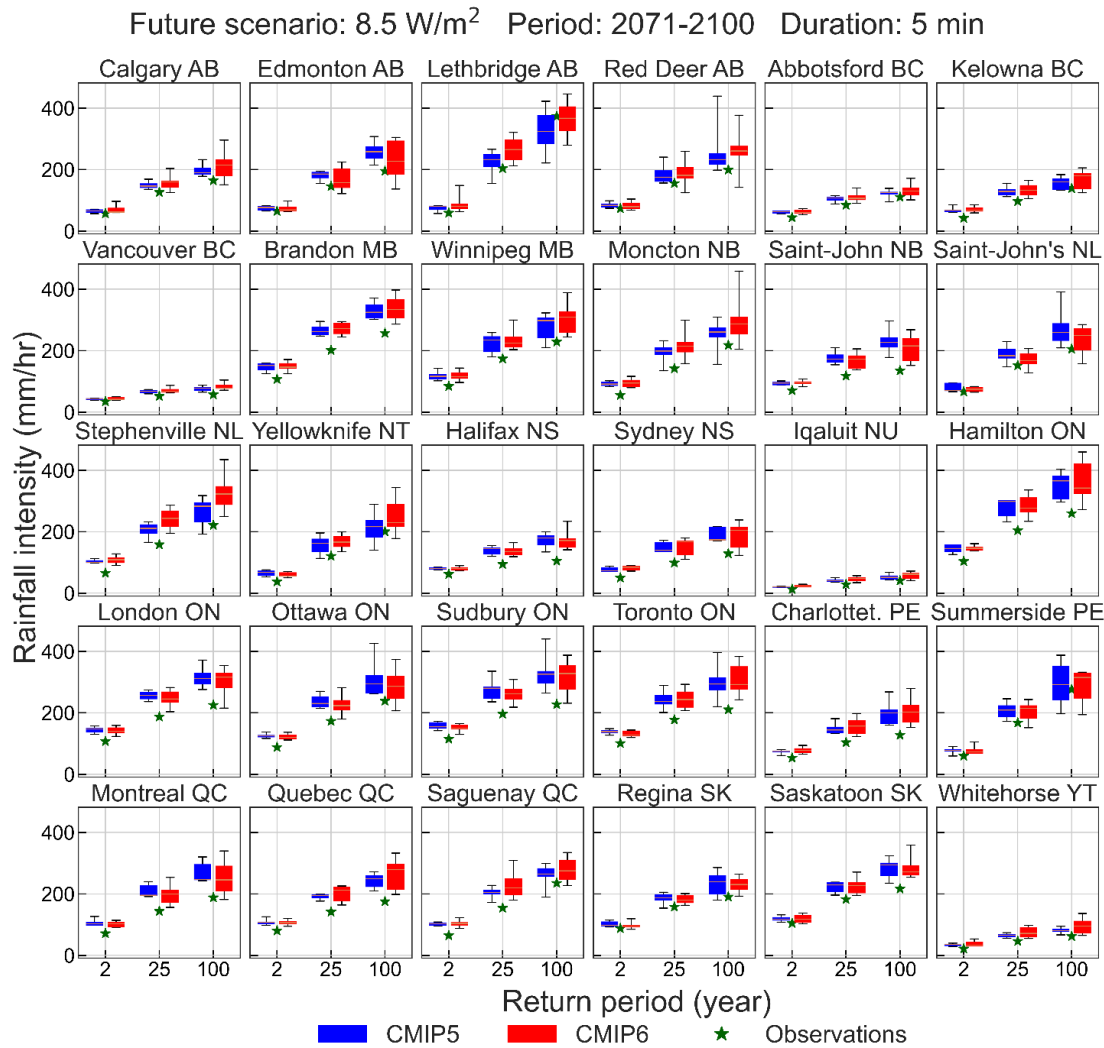


Figure 4.6. Boxplots of extreme rainfall quantiles for 5-min duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 8.5 W/m² radiative forcing during 2071-2100. The observed values during the historical period are shown with green stars.

Considering Figures A14 to A16, it is evident that the projected changes in extreme rainfall values under the 8.5 W/m² radiative forcing during the short-term horizon are somewhat similar to those under 4.5 W/m² during 2071-2100. Moreover, the smallest difference between the observed and projections are found under 4.5 W/m² radiative forcing for the short-term horizon (Figures A17 to A19), see Ottawa or Vancouver.

To better understand the changes in extreme rainfall values spatially across Canada, we find “expected IDF curves” per CMIP projects, i.e., average of 7 model-based IDF values. The relative differences between these expected IDF curve values based on CMIP5 and CMIP6 projects under 8.5 W/m² during the long-term horizon and their corresponding values during the baseline period are shown in Figures A20 and A21, respectively in the Supplementary Materials. At the first glance, the changes in expected IDFs based on CMIP5 and CMIP6 projections are roughly alike. At the region scale, the smallest changes e.g., by less than 30% in expected IDFs can be observed in Alberta for Calgary, Red Deer, and Edmonton, as well as in Saskatchewan for Saskatoon and Regina for all durations and return periods. In contrast, an increase of more than 70% is projected for Iqaluit in Nunavut and Whitehorse in Yukon for small return period rainfall. The largest increases are expected in Northern cities (e.g., Whitehorse), Ontario (e.g., Ottawa), and Quebec (e.g., Saguenay) for short return period events, as well as Nova Scotia (e.g., Halifax) and New Brunswick (e.g., Saint John) for long return periods events. Such extraordinary increases of extreme rainfall values in Northern cities, whatever the CMIP project, alert on the reliability of existing infrastructures to serve the already vulnerable indigenous communities in these areas (Medeiros et al., 2017). Generally, the rate of increase is slightly greater for extreme rainfalls with shorter than longer return periods. In this scenario, increases in extreme rainfall intensity in populous cities of Toronto in Ontario and Montreal in Quebec are 51% and 49% for short and 42% and 57% for long return periods for 1-hr durations. Such increases call for action regarding the design of infrastructure in these fast-growing Canadian cities in the future.

Here, we aim to understand the differences between the expected IDF curve values in the future based on CMIP6 and CMIP5 models. Figures 4.7 and 4.8 show these relative differences under 8.5 W/m² during 2021-2050 and 2071-2100, respectively. Similar results are provided under 4.5 W/m² during short- and long-term horizons in Figures A22 and A23, respectively. Clearly, Figure 4.7

reveals a small difference between the expected IDF curve quantiles (see the green dots) during 2021-2050, which is around 5% except in two cities of Stephenville and Sydney, in which the difference can be as much as 20%. This illustrates a high consensus between both two projects in most cities considering their multi-model mean values in short-term horizon.

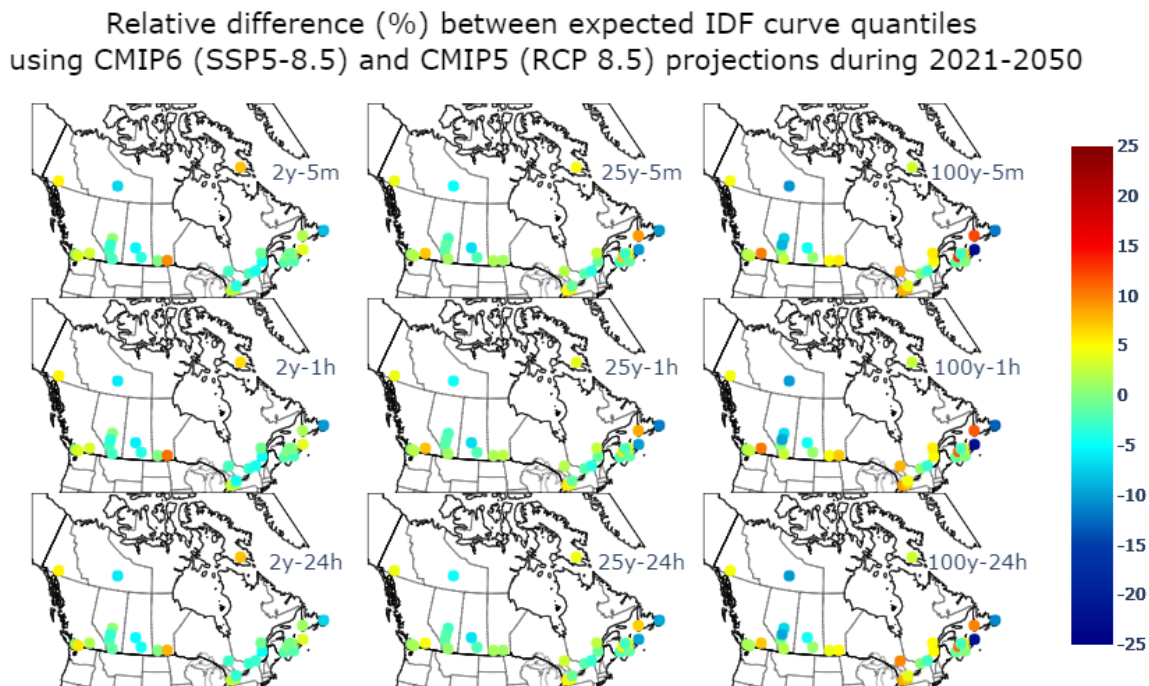


Figure 4.7. Relative difference between the expected IDF curves quantiles by CMIP6 and CMIP5 projects under 8.5 W/m² during 2021-2050.

The differences between the expected IDF curve quantiles based on CMIP6 and CMIP5 projects are larger during 2071-2100 than 2021-2050 under 8.5 W/m², e.g., compare Figures 4.7 and 4.8. Depending on the city, this relative difference can be as high as +25% for Lethbridge and -15% for Saint John's or as small as $\pm 5\%$ e.g., for Red Deer, Toronto, and cities in Saskatchewan. This is because, inter alia, 8.5 W/m² scenarios follow different trajectories under CMIP5 or CMIP6 towards the end of century. It is noted that given each horizon, the differences between expected IDF quantiles by CMIP6 and CMIP5 projects are roughly similar for all durations. The relative difference between expected IDF values based on CMIP6 and CMIP5 projects under 4.5 W/m² during 2021-2050 and 2071-2100 are displayed in Figures A22 and A23, respectively. The

dissimilarities between CMIPs' projections can be as high as $\pm 25\%$ under this scenario too, which is even more obvious for quantiles with longer return periods. For both future horizons, it seems that both CMIPs have a higher consensus (more green dots) for projection of rainfalls with 2-year return periods under 4.5 W/m^2 , see the cities of Vancouver, Hamilton, and Regina as examples. Higher disagreements can be seen for projection of rainfalls with 100-year return periods under 4.5 W/m^2 , most notably for the long-term horizon, see the cities of Whitehorse, or Ottawa.

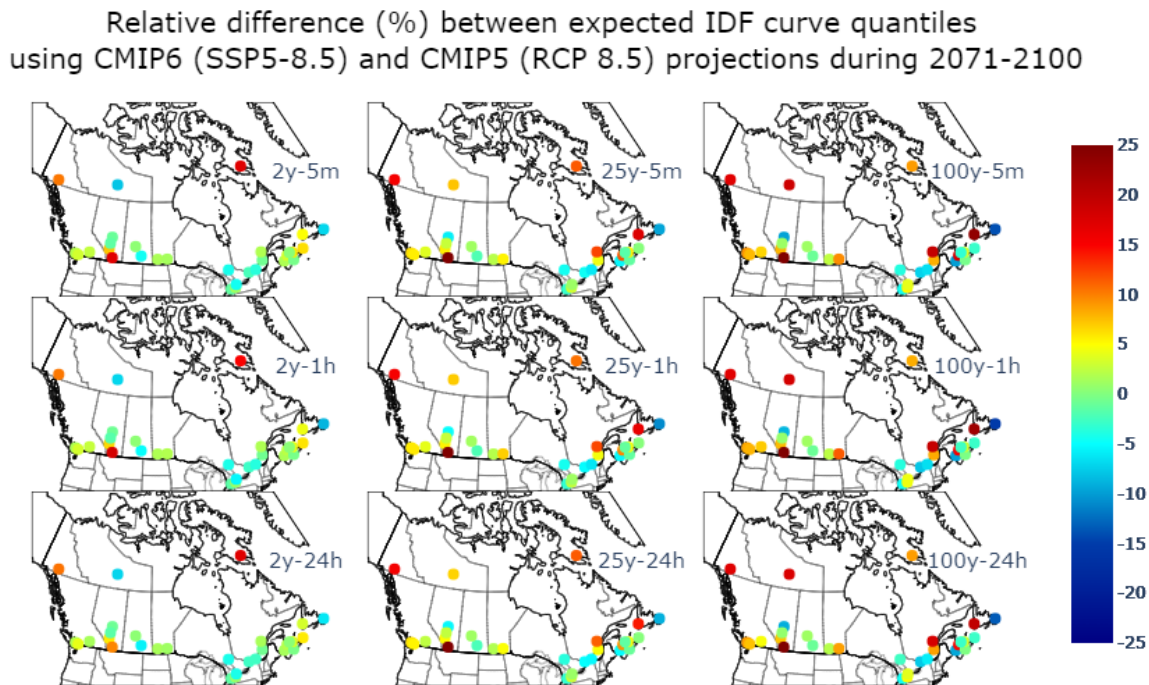


Figure 4.8. Relative difference between the expected IDF curve quantiles based CMIP6 and CMIP5 projects under 8.5 W/m^2 during 2071-2100.

4.7 Discussions

4.7.1 Changes in design storm frequencies

Although infrastructures are typically designed using several conservative engineering assumptions (Watt and Marsalek, 2013; Jean et al., 2018), increase of design storm frequency can be critical for the safety of projects (Amponsah, et al., 2019; Canadian Standards Association,

2019). Signs of higher occurrence of design storms in Canada have been noted in the literature (Watt and Marsalek, 2013; Fortier, and Mailhot, 2015; Nguyen, 2020). For example, Mailhot et al. (2007) estimate that the return period of 2- and 6-hr design storms in Quebec may be halved due to climate change. Adamowski et al. (2010) identify smaller return periods for the design storms in different locations in Ontario. Here, the changes in frequency of design storms given CMIP projects are further analyzed. For instance, what is the new return period of an observed 100-year storm with 5-min duration in the future? To this end, the magnitude of expected IDF curve quantiles in the historical period are compared with the quantiles in the future for each CMIP project. Accordingly, a ratio of historical over future return period corresponding to the same rainfall intensity is estimated for each CMIP project. For example, considering the expected IDF curves based on CMIP5, a storm with 100-year return period in the historical period in Calgary would have a 43-year return period in the long-term future under RCP8.5; therefore, the ratio is equal to 2.3 (100 over 43). Figures 4.9, A24, and A25 present these ratios for 5-min, 1-hr, and 24-hr extreme rainfall events, respectively, considering future horizons and scenarios, as well as CMIP5/6 models. High ratio values above 25 are represented with a white cell, especially for Abbotsford and Summerside ratios for 1-hr and 24-hr durations showing a high sensitivity using this approach.

Ratios greater than one in almost all cases under 4.5 and 8.5 W/m² given both CMIPs signify more frequent storms are projected for all durations and return periods, particularly under 8.5 W/m² for the long-term period. In the near future, the rate of increase in design storms' frequency is somewhat similar between 4.5 W/m² and 8.5 W/m² forcings and the divergence among them increases during the long-term horizon. It also worth noting that the increase of storm frequencies based on 8.5 W/m² scenario in 2021-2050 are lower to those under 4.5 W/m² in 2071-2100. Moreover, the magnitude of the ratios reveals that rare events (e.g., 100-year storms) would become more frequent than other ones (e.g., 2-year storm) for most cities in future horizons and scenarios. Such observation is inline with findings in other studies, e.g., see Wang et al. (2014) and Yang et al. (2019). For instance, under 8.5 W/m², results show 2-year extreme rainfalls can occur around 1.6 times more frequently by the end of the century, whereas this ratio is for 100-year extreme rainfalls on around 4 under 8.5 W/m². The longer the return period is, the highest differences are noticeable between cities. In Figure 4.9 for example, 100-yr extreme rainfalls in Vancouver, the ratio is 12 under 8.5 W/m², whereas the cities of Regina and Saskatoon in Saskatchewan have ratios

around 3. More strikingly, the increase in storm frequency for a rainfall with 100-year return period, is more pronounced under 8.5 than 4.5 W/m^2 . Indeed, ratios can even be doubled between these forcings, see Brandon, Quebec, and London.

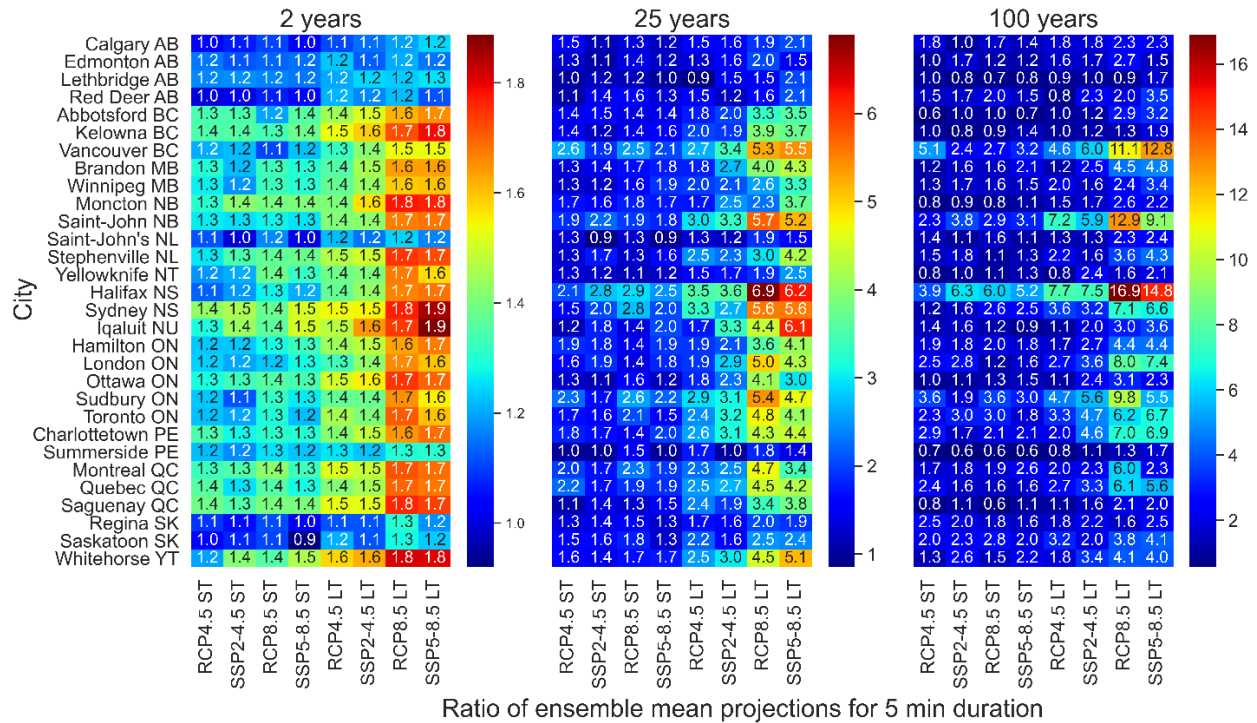


Figure 4.9. Ratio of historical over future period for the 5-min extreme rainfall over 30 Canadian cities. Future return periods correspond to expected IDF curve quantiles that are estimated using CMIP5 (RCPs) and CMIP6 models (SSPs) during short-term period (ST) left four columns and long-term period (LT) right four columns under 4.5 and 8.5 W/m^2 radiative forcing.

The largest increases of storm frequency for all durations and for short return period extreme rainfalls are found in Northern cities, such as in Whitehorse and Iqaluit, Ontario, as well as in Atlantic provinces such as Nova Scotia and New Brunswick. For longer return periods, the largest increases are seen in Vancouver, cities in Atlantic Maritimes and for some cities in Quebec and Ontario such as Sudbury and Quebec. In contrast, smaller increase in storm frequency are shown for most cities of Alberta and Saskatchewan, with ratios under 4.4 for all scenarios, durations, and return periods. The ranges for the ratios during the short-term horizon between CMIP5 and CMIP6 are almost identical. Nevertheless, the ratios can be different between CMIP6 and CMIP5 estimates for the longer return periods during the long-term horizon, which also depend on the considered

city, horizon, and scenario. For instance, the occurrence of a 100-year storm with -min duration is estimated to be two times more frequent given CMIP5 than CMIP6 projections for Montreal under horizon 2071-2100 and 8.5 W/m² forcing. In contrast, for Moncton for 24-hr duration under the same conditions, CMIP6 models project about 2.2 times more frequent 100-year storm than CMIP5 models. When comparing Figures 4.9, A24, and A25, it can be seen that the duration has almost no impact on the ratio for 2-yr extreme rainfalls, even though 25-yr and 100-yr events are affected. The magnitude of the changes for longer return periods depend on the considered city, scenario, and horizon. For example, for a 100-yr extreme rainfall in Toronto under SSP5-8.5 for the long-term period, the ratios decrease from 6.7 for 5-min to 2.5 for 24-hr duration. In this city, convective storm might occur more often in the future than longer duration events, which highlight the importance of knowledges about local atmospheric processes for analysis.

The analyses in this study show that the design storms will become more frequent and more intense in most Canadian cities. Largest changes are seen in the provinces with the highest population e.g., in Ontario, Quebec, and British-Columbia. Interestingly, the cities with the greatest storm frequency such as London and Halifax are expected to have the largest intensity in the future too. These results reveal the significant impact of climate change on design storms, whether under 4.5 W/m² or 8.5 W/m², which can considerably affect standards to construct, maintain and upgrade infrastructures (Sanford et al., 2014; Cannon and Innocenti, 2019; Schwalm et al., 2020; Martel and Brissette, 2021). Additionally, these phenomena can be exacerbated by urbanization and anthropogenic emissions of heat (Marelle et al., 2020). This shows the urgency to prepare Canadian cities to endure the inevitable effects of climate change. The renewal of guidelines related to IDF curves is fostered to address the various challenges that our engineers will contend.

4.7.2 Impact of too hot models on the projected IDF curves

Several studies have presented concerns regarding the high climate sensitivity of CMIP6 models, meaning that they show greater global temperature rise in response to increase of greenhouse gas emissions (e.g., Zelinka et al., 2020; Meehl et al., 2020). As precipitation is related to temperature by the Claudius Clapeyron law, they suggest acknowledging the impact of such climate sensitive models on the precipitation analysis, in particular when multi-model mean ensemble values are

used. Climate sensitivity of the models can be assessed using two standardized metrics of Equilibrium Climate Sensitivity (ECS) and Transient Climate Response (TCR). Hausfather et al. (2022) analyze the climate sensitivity of CMIP6 models using these two metrics. Based on this study, ECS metric has a ‘likely’ range of 2.5 – 4°C and a very ‘likely’ range of 2 – 5 °C, whereas TCR has a ‘likely’ range of 1.4 – 2.2°C and a very likely range of 1.2– 2.4°C. Outside these ranges, ECS and TCR are considered ‘unlikely’. If ECS is greater than 6 °C, this metric can be considered as ‘very unlikely’ (IPCC, 2013; Sherdwood et al., 2020). For the TCR metric, a ‘very unlikely’ threshold could be considered for values above 3°C (Scott and Jones, 2012). In brief, it is found that among considered 7 CMIP6 models the ECS and TCR metrics for CNRM-CM6-1 and IPSL-CM6A-LR are in the very likely range (Hausfather et al., 2022). For MIROC6, MPI-ESM1-2-LR, and MRI-ESM2-0 these metrics are in the likely range. However, ECS and TCR for CanESM5 and UKESM1.0-LL are in the unlikely range, but don’t exceed the ‘very unlikely’ thresholds. It means that their climate sensitivity is high, and they can be considered as ‘hot models’. Therefore, the impact of these two models on the constructed IDF curves over Canadian cities are briefly discussed.

Our analysis shows that raw AMPs based on ‘hot models’ of UKESM1-0-LL and CanESM5 present significantly larger ranges than their CMIP5 counterpart and higher median values than observed records. Nevertheless, their performance is acceptable when they are downscaled in comparison to observed and relative to their predecessor CMIP5 values during the historical period, compare Figure 4.2 with Figures A3 and A5. Indeed, there is no clear evidence of unreliable results for any of downscaled CMIP5 and CMIP6 models during the historical period. However, the impact of inclusion/exclusion of these too hot models are more obvious on the IDF curve quantiles in the future period. As an example, the extreme rainfall quantiles based on these too models versus the rest of GCMs per CMIP6 project is shown for 8.5 W/m² scenario during the long-term horizon and for different durations in Figures 4.10, A26, and A27 in the Supplementary Materials. Indeed, these two climate sensitive models provide generally higher projections than other models for most cities. The ‘hot models’ seem to bias upward CMIP6 projections and might lead to some overestimations of IDF values in some cities. For instance, the highest overestimations are seen in the cities of Saguenay, Stephenville, Sudbury, and Montreal for all durations. For 24-hr duration, the ‘hot models’ show high intensity values compared to other models for Vancouver and

Abbotsfor. Quantile projections from the UKESM1-0-LL are extraordinarily high for the city of Lethbridge. Further analyses also show that expected extreme rainfall quantiles by ‘hot models’ (meaning the average of quantiles based on the two ‘hot models’) are systematically higher than expected extreme rainfalls given other CMIP6 models. Therefore, expected IDF curve quantiles in the future are found again by excluding these two ‘hot models’ to estimate the relative difference between expected IDF curve quantiles in the future and historical periods.

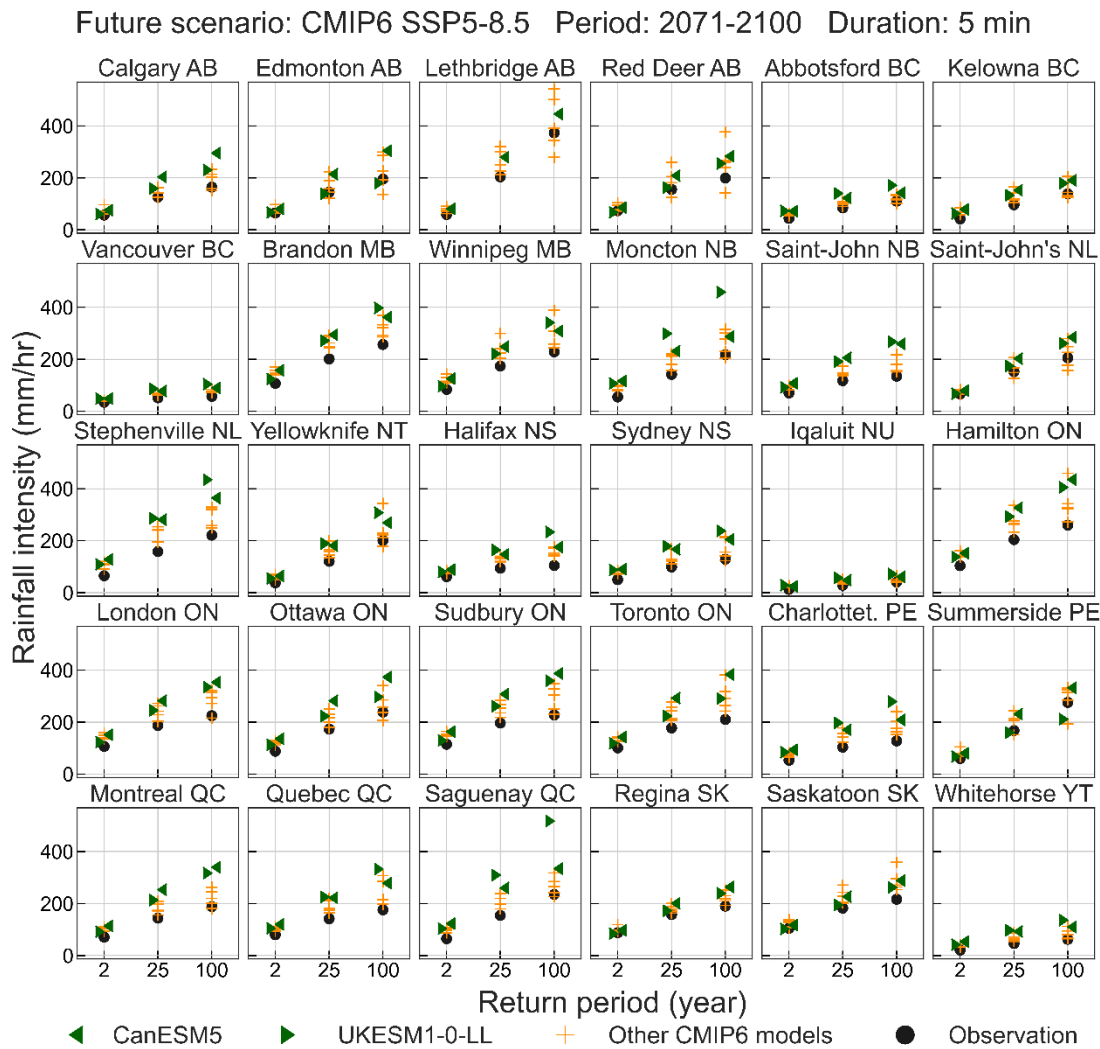


Figure 4.10. Extreme rainfall quantiles for 5-min duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 8.5 W/m^2 radiative forcing during 2071-2100. The two ‘hot models’ CanESM5 and ‘UKESM1-0-LL are represented using green arrow

symbols, the other CMIP6 extreme rainfall quantiles are displayed with orange ‘plus’ marker, and the observed quantiles during the historical period are shown with black dots.

Figure A28 presents the relative differences between these expected IDF curve values based on CMIP5 and CMIP6 projects under 8.5 W/m² during the long-term horizon. When comparing Figure A21 to A28, the impact of excluding two ‘hot models’ can be assessed. Based on this, smaller increase of extreme rainfall in Alberta and Saskatchewan is expected in comparison to other regions in the future. High projections in Atlantic Maritimes are also slightly softened. Finally, the frequency ratios are estimated by exclusion of these two climate sensitive models and the results based on rest of models are shown in Figure 4.11, A29, and A30 for 5-min, 1-hr, and 24-hr durations, respectively.

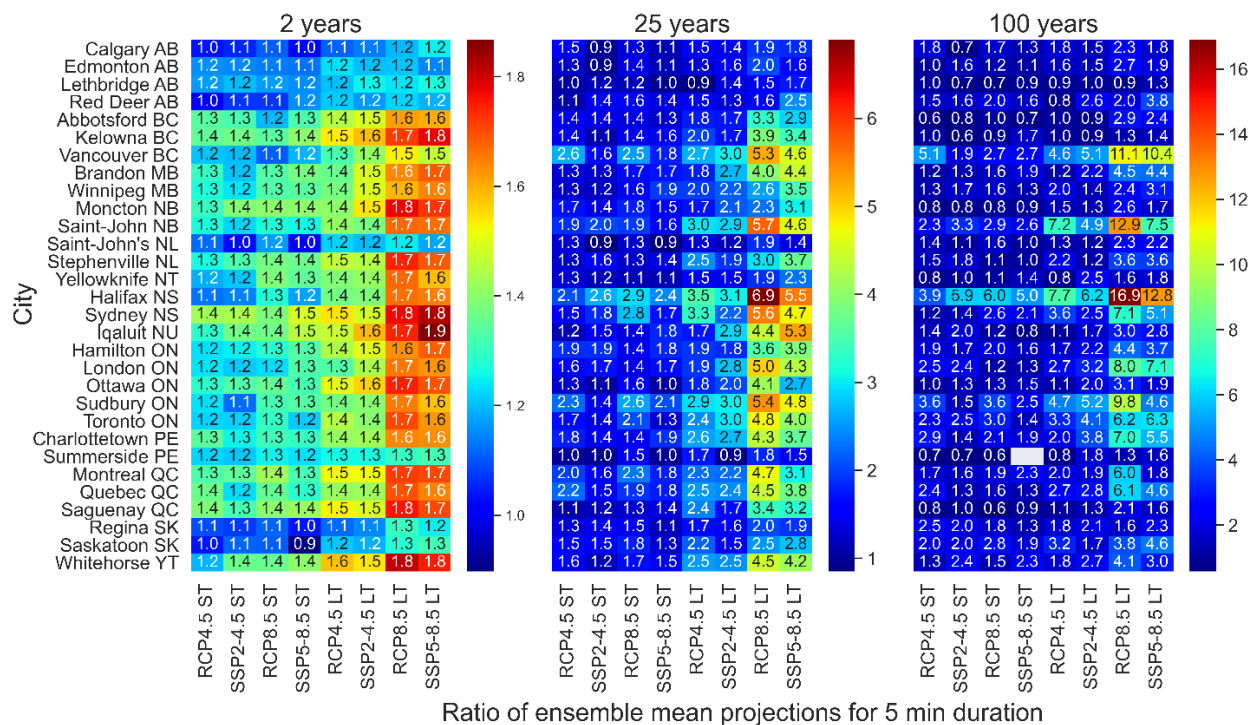


Figure 4.11. Ratio of historical over future return period for the 5-min extreme rainfall over 30 Canadian cities. Future return periods correspond to expected IDF curve quantiles that are estimated using CMIP 5 (RCPs) and CMIP 6 models (SSPs) excluding CanESM5 and UKESM1.0-LL, during short-term period (ST) left four columns and long-term period (LT) right four columns under 4.5 and 8.5 W/m² radiative forcing.

It can be seen that the expected ratios from CMIP5 and CMIP6 projects excluding two hot models are somewhat similar. The largest dissimilarities are still under 8.5 W/m² during the long-term horizon. Therefore, more agreements between IDF curve values based on CMIP5 and CMIP6 models can be seen if sensitive CMIP6 models are removed from the analysis. Nevertheless, there are still some large extreme rainfall projections given the rest of models, see for example Abbotsfort and Charlottetown for a 24-hr duration in Figure A30. These important observations reinforce that IDF curves must be updated considering both CMIP5 and CMIP6 models, knowing the wide range of uncertainties partly created by incorporation of the ‘hot models’ in the analysis and from the considered future scenarios. Nevertheless, screening out these models might be considered for future investigations, following a thorough examination of the selected models.

4.8 Conclusions

Changes in climate have already altered the characteristics of extreme rainfall in various regions in the world. As Canada gets warmer, the credibility of using the existing IDF curves, which are developed based on the historical extreme rainfall conditions, for engineering design purposes becomes questionable. This study evaluates the impact of climate change on the characteristics of extreme rainfall and updates the IDF curves in 30 major Canadian cities using a wide range of simulations based on CMIP5 and CMIP6 projects and the QQD downscaling approach. In particular, the differences among model-based extreme rainfall quantiles and alterations in design storm frequencies based on CMIP5 and CMIP6 projects are explored under different radiative forcing and horizons. Our results show that changes in climate inevitably modify extreme rainfall values. It is estimated that design storms would be more frequent in Canada, particularly for rarer events, i.e., long return period (100 years). Impressively, these long return period events are projected to occur up to twice as much under 8.5 than 4.5 W/m² scenario in some cases of city along the long-term horizon. In addition, under the 8.5 W/m² forcing scenario, increases in extreme rainfall quantiles are observed for almost all cities in comparison to their historical values. Inside fast-growing cities of Vancouver, Montreal, and Toronto in the provinces of British-Columbia, Quebec, and Ontario, considerable increases in the intensity and larger rate of reductions in design storms return periods i.e., more frequent events are found. For these cities, 25-yr extreme rainfalls

along their baseline period might become on average 4 times more frequent under 8.5 W/m² between 2071 and 2100. Under the same conditions, the three cities are projected to have increases of extreme rainfall intensity around 40%. In contrast, smaller changes in intensity and lower rate of decrease in design storm frequency have been found for Alberta and Saskatchewan in the future. Furthermore, while there is no significant difference between 4.5 W/m² and 8.5 W/m² scenario along the short-term horizon, great discrepancies are observed between the projections under the two scenarios for the long-term horizon. Indeed, projections of extreme rainfall quantiles under a 4.5 W/m² forcing during 2071-2100 are only slightly larger than those under 8.5 W/m² forcing during 2021-2050. Meanwhile, CMIP5 models and CMIP6 models are compared and have some differences between their expected extreme rainfall values, with generally larger ranges of projections and median values for CMIP6, especially for 8.5 W/m² scenarios, during the long-term horizon. Moreover, we showcase the impact of CMIP6 ‘hot models’, namely UKESM1-0-LL and CanESM5 on estimated IDF curve values. These models show significantly higher projections of extreme rainfall quantiles in almost all cities in the future in particular under 8.5W/m² scenarios in long-term horizon. Therefore, by screening out those models, expected extreme quantiles based on CMIP5 and CMIP6 projects have somewhat similar values for most cities.

There are several assumptions and limitations in this study that can potentially affect the estimated extreme rainfall values. For instance, GCM even based on CMIP6 are still not able to fully represent rainfall processes in particular the formation of convective storm, which is the dominant rainfall type in several Canadian cities. This can be partly due to GCMs’ coarse spatial and temporal resolution (Cannon, and Innocenti, 2019; Martel, and Brissette, 2021). Moreover, here we only utilized outputs of 14 climate models under 4.5 and 8.5 W/m² radiative forcing. Obviously, higher number of GCMs and under more diverse future scenarios can be considered in future studies. Here we briefly discuss the impact of previously noted ‘hot models’ on the analysis of IDF curve quantiles; further attention to their projections should be given. In addition, there are uncertainties related to properly representing extreme values using probability distributions and estimation of their parameters as well as spatiotemporal downscaling of projections. It is recommended to consider other distributions, parameter estimation methods, and downscaling techniques, and assess the sensitivity of the estimated extreme rainfall values to these factors too. Indeed, scientific

community must be more consistent in these choices to ensure that engineers are accounting for the same type of uncertainties in design (Cook et al., 2020).

Our Canada-wide investigations show that availability of sub-daily precipitation data across many cities is limited. In particular, although Northern communities are vulnerable and already at risk due to changes in climate (Medeiros et al., 2017), not enough data is available for these areas. This prevents performing a comprehensive assessments of extreme rainfall quantiles. At this stage, interpolation/extrapolation of existing IDF curve information to those ungauged locations is suggested (Ouali and Cannon, 2018; Jalbert et al., 2022; Nguyen and Nguyen, 2022). Although analysis of the stationary/non-stationary characteristics of extreme rainfall are important (Koutsoyiannis, et al., 2014; Ganguli and Coulibaly, 2017; Silva et al., 2021; Requena et al., 2021), it has not been investigated in this study as the focus has been more on the comparison of CMIP-based values and also having short data records across the considered Canadian cities. Last but not least, these IDF curves are obtained based on rainfall data during the ice-free season, whereas in cold regions peak runoff causing urban floods can be occurred due to snowmelt, particularly during rain-on-snow events. Therefore, such snow related information should be included in the IDF curves for design purposes in Canadian cities (Yan et al., 2018). Regardless of limitations, this study presents the potential alterations in extreme rainfall quantiles in major Canadian cities and calls for action related to updating design standards. The model-based analysis per CMIPs and comparison of CMIP6 and CMIP5 IDF curve projections based on different future scenarios open a window on understanding the unavoidable uncertainties in climate change impact assessment.

CHAPITRE 5 PROJECTED IDF CURVES WITH QUANTILE-DELTA MAPPING

5.1 Introduction

In the previous chapter, extreme rainfall quantiles are estimated for the historical period and projected in the future using 14 GCMs, see Table 4.1, and using QQD downscaling method. In this Chapter, we want to know if the choice of the downscaling method can have an impact on the projections. The scientific community agrees that this indispensable step for projecting IDF curves based on GCMs is a major source of uncertainties (Martel et al., 2021) and statistical downscaling methods must always be practiced with caution, particularly if only one method is utilized in an impact assessment (Kourtis & Tsihrintzis 2021). Hassanzadeh et al., (2019) already compared QQD with the two other quantile-based approaches EQM and SIM and found that performances of these downscaling methods in reproducing quantiles can be divergent and generate dissimilar future extreme rainfalls. To this end, the focus of the investigations is on a bias correction method called Quantile-Delta Mapping (QDM), which differs largely from QQD and other quantile-based ones. QDM is used considering models from both CMIP5 and CMIP6 projects, 4.5 and 8.5 W/m² radiative forcings, and along previously noted short and long-horizons. The two hot models, CanESM5 and UKESM1.0-LL, are deliberately kept in the analysis to challenge the downscaling method to reproduce too sensitive extremes values. To showcase our analysis and for the sake of simplicity, here the results are only shown for the five cities of Vancouver, Calgary, Winnipeg, Toronto, and Montreal, which are the most populated cities in Canada belonging to different provinces spread across Canada from East to West, see Table 4.2. The changes in extreme rainfalls in these cities are also often studied e.g., see Mailhot (2007), Srivastav (2014), and Silva (2021). Our main objective here is to assess the behavior of the QDM while reproducing extreme rainfall quantiles. The method is first described in Section 5.2. Then, in Section 5.3, the relative difference of model-based projected quantiles versus observed quantiles is represented for the different coupled future horizons and scenarios. Finally, the expected IDF curves values obtained with QDM are compared with the expected IDF values found using QQD method in Chapter 4.

5.2 Methodology of QDM

The literature review Chapter introduces the variety of downscaling methods available to deal with GCMs' large spatial grids, and temporal scales. The focus of this chapter is on bias correction downscaling methods, which modify the time series of AMPs with multiplicative coefficients. Thus, it differs largely of the quantile-based approaches by its modeling assumptions and procedure.

These methods measure the differences between the observed data and historical model-based data for a same baseline period to adjust future model-based projections by the multiplicative factors. This method has the specificity to use quantiles inside the multiplicative factor and has shown a good performance on estimating CMIP5 simulations (Cannon et al., 2015). Contrarily to the quantile-based methods, the edge of this method is to be able to conserve the relative change in future quantiles relatively to historical quantiles. This method relies on the preservation of relative changes in the quantile delta change method as well as the quantile perturbation methods. However, all the quantiles relative changes are considered rather than only modeled mean relative changes (Cannon et al., 2015). This algorithm is implemented in our framework with the help of a package from Ouranos available in their *xclim* platform accessible by the following link: <https://xclim.readthedocs.io/en/stable/sdba.html>. The flowchart of the QDM process is shown in Figure 5.3. GEV distributions are used to be consistent with Chapter 4.

The QDM method is time dependant, meaning that each historical quantile is associated with an observed quantiles during the same year of occurrence, and the non exceedance probability associated with the value at time t is given by Equation 5-1, with $x_{m,p}$ the future model-based series.

$$\tau_{m,p}(t) = F_{m,p}^{(t)}(x_{m,p}(t)), \quad \tau_{m,p}(t) \in [0,1] \quad (5-1)$$

This enables to calculate the factor of relative change in quantiles between the historical and time t , given by Equation 5-2.

$$\Delta_m(t) = \frac{F_{m,p}^{(t)-1}(\tau_{m,p}(t))}{F_{m,h}^{-1}(\tau_{m,p}(t))} = \frac{x_{m,p}(t)}{F_{m,h}^{-1}(\tau_{m,p}(t))} \quad (5-2)$$

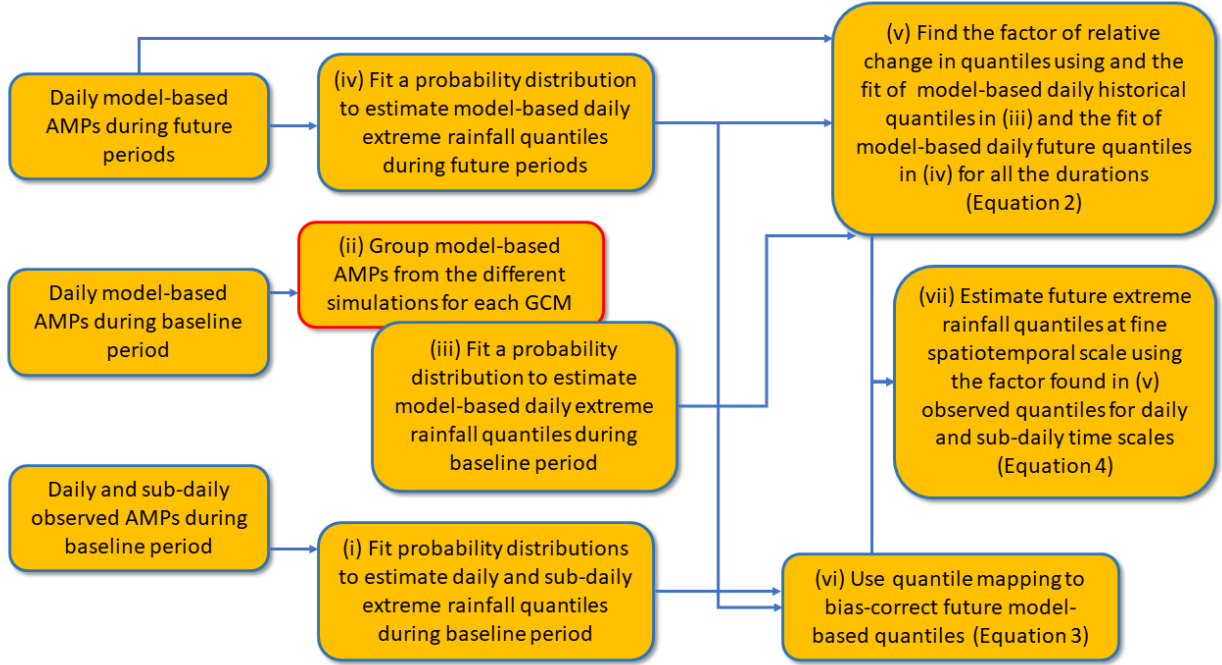


Figure 5.1. Flowchart of the QDM method

Then, the future model-based quantiles are bias corrected with quantile mapping using the inverse distribution of the historical model-based AMPs, see Equation 5-3

$$\hat{x}_{b:m,h;p}(t) = F_{b,h}^{-1}(\tau_{m,p}(t)) \quad (5-3)$$

Finally, the future model-based projections are obtained by multiplying the relative change ratio to the bias corrections obtained in Equation 10, see Equation 5-4.

$$\hat{x}_{m,p}(t) = \hat{x}_{b:m,h;p}(t) \times \Delta_m(t) \quad (5-4)$$

Detrending by quantiles accompanied by quantile mapping takes on the statistical characteristics of the observations to correct bias between projected and observed quantiles (Cannon et al., 2015). The relative changes in modeled quantiles are preserved by multiplying the bias-corrected series. Now, a fitting distribution can be applied on these bias-corrected series to extract quantiles corresponding to a specific return period.

5.3 Results

This section assesses the behavior of QDM to project IDF curves under different scenarios and horizons. For this purpose, the projected model-based quantiles from CMIP5 and CMIP6 are first compared with observed quantiles along the baseline period. Figures 5.2 and 5.3 show the percentage of relative difference between projected IDF curves using QDM based on CMIP5 and CMIP6 models for scenario 4.5 W/m² and 8.5W/m² respectively, considering different future periods and three durations and return periods for the city of Calgary. Likewise, Figures 5.4 and 5.5 are for Montreal, Figures B1 and B2 in Supplementary Materials for Vancouver, Figures B3 and B4 for Winnipeg, and lastly Figures B5 and B6 for Toronto. This close analysis per individual city aims to display projected IDF values for three durations and three return periods, for all scenarios and future periods.

In Figure 5.2 for Calgary, most severe increases of intensity are visible for the long-term period. The range of projections is the largest for short duration return periods. Most noticeably, 5-min extreme rainfall quantiles seem to be abnormally high, see for example along the 2021-2050 period, relative differences go over 200% for a model. Although ranges of projections based on CMIP5 and CMIP6 models are alike, differences in median values are observable. For example, for 1-hr duration, along short-term period, and under a 4.5 W/m² forcing, the 100-yr return period extreme rainfall is produced in a range around -30% to 45%, but the median is around 0% for CMIP6 and 15% for CMIP5. In Figure 5.3, observations are similar to Figure 5.2. However, uncertainties in projections of quantiles are higher for all panels. The poor ability of the bias-correction method to reproduce short duration events is even more pronounced under a forcing of 8.5 W/m². More generally, the medians of these projected IDF values are higher under this more intense forcing. In

addition, uncertainties are lower for 2-yr extreme rainfall quantiles and larger for 100-yr events whatever the future period and duration.

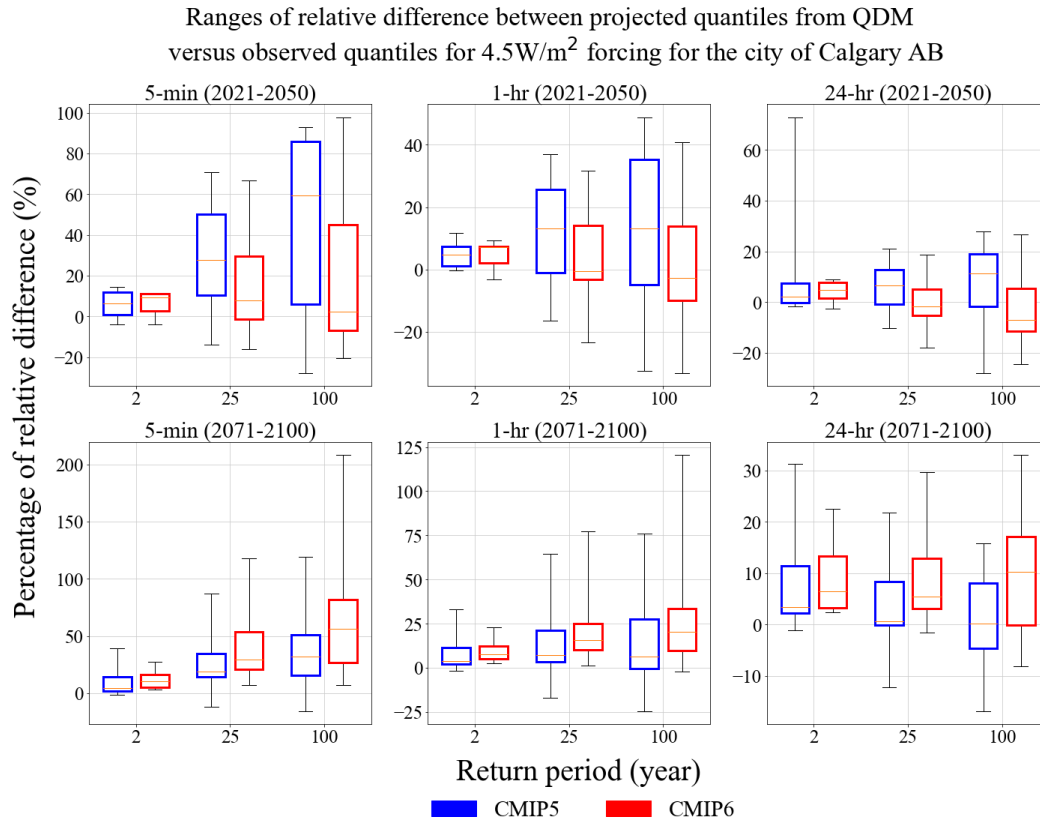


Figure 5.2. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 4.5 W/m², and along different future periods, for the city of Calgary.

For the city of Montreal, in Figures 5.4 and 5.5, the projections for short duration events seem again too high and even reach 400% under 8.5 W/m² forcing, for the long-term period, 5-min duration, and 100-yr return periods. Therefore, the behavior of QDM for the projections of short-duration extreme rainfall events is questioned and looks highly sensitive. Oppositely, for longer durations, the percentage of differences are consistent but CMIP5 ranges remain lower than CMIP6 ones. Further investigations would be necessary to understand if the model responsible of the 400% relative differences in projections of IDF curves and responsible of higher projections in general from CMIP6 are the ‘hot models’ seen in Chapter 4.

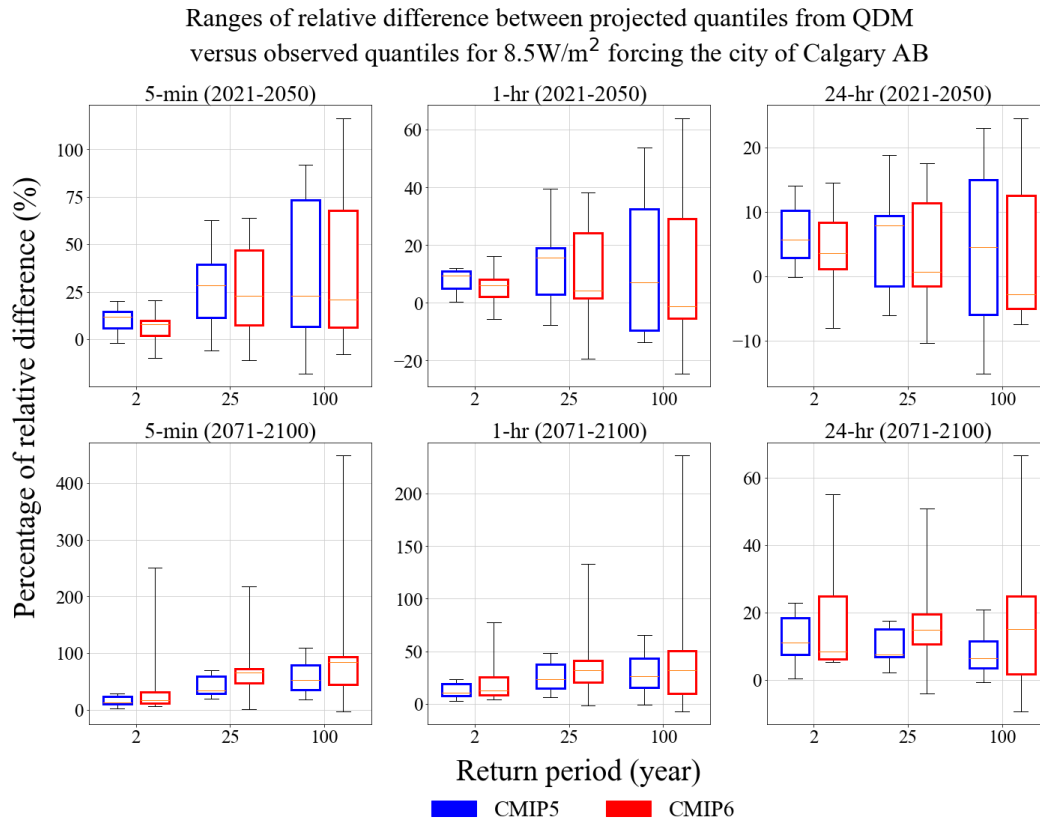


Figure 5.3. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 8.5 W/m^2 , and along different future periods, for the city of Calgary.

For the three other cities in Annexes B, the behavior of the bias corrected method is similar with what is presented so far for Montreal and Calgary, with a few exceptions. For Vancouver, in Figure B1 and B2, QDM is not able to reproduce 5-min and 1-hr duration extreme rainfall quantiles properly and largely over-estimates them. The distribution of quantiles is too wide, this method should particularly not be used for the city. Nevertheless, for 24-hr extreme rainfall quantiles, the outcomes have acceptable ranges of uncertainties. However, for the city of Winnipeg, in Figures B3 and B4, the behavior of the projections for short duration events seems more reliable than for any other city. The percentages of differences are still higher for short-duration extreme rainfalls and few differences are seen between CMIP5 and CMIP6. Lastly, for Toronto, in Figures B5 and

B6, the ranges are large and median values high, even for 1-hr and 24-hr durations, with more than 50% of magnitude for 25-yr and 100-yr extreme rainfall events.

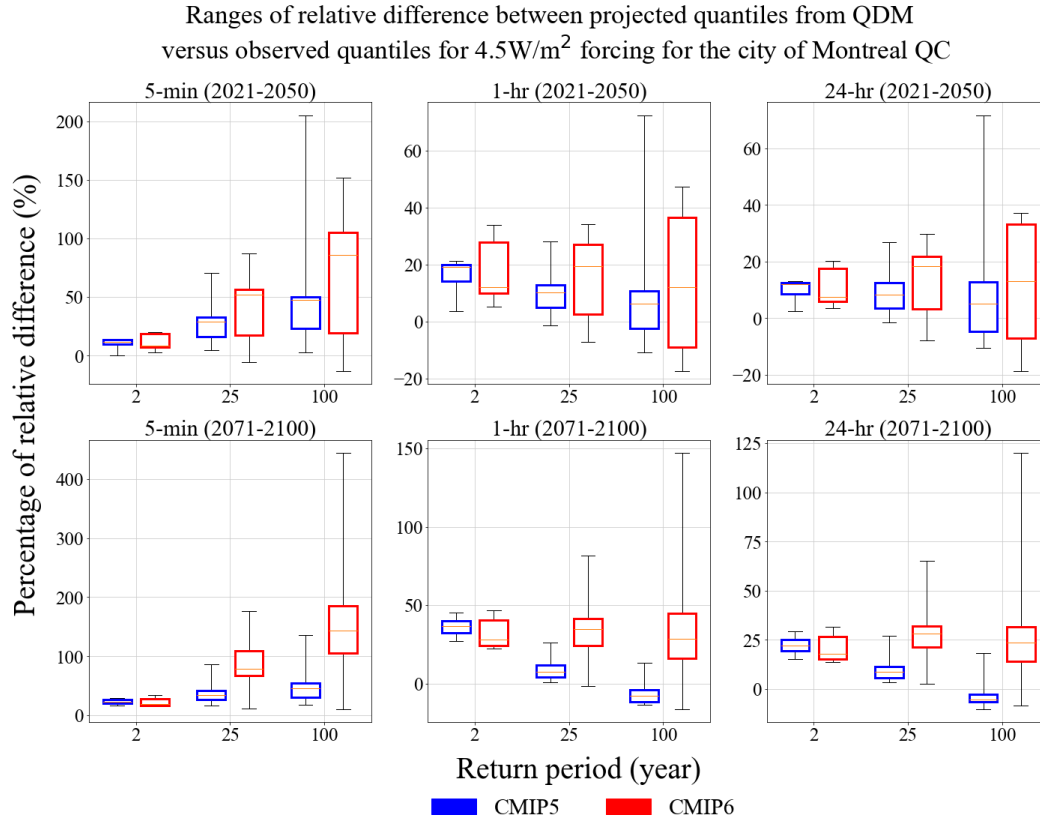


Figure 5.4. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 4.5 W/m², and along different future periods, for the city of Montreal.

To conclude on the projected extreme rainfall quantiles using QDM approach relatively to observed quantiles, the behavior of the downscaling method is heterogeneous. Generally, although we can notice bad projections of quantiles for 5-min duration, IDF values seem to be constructed properly for 1-hr and 24-hr durations. This shows a clear misrepresentation of short-term events of convective type by the downscaling process, leading to major errors and over-evaluations of quantiles, in combination with extremely large uncertainties. This finding is crucial to avert practitioners on the poor representation of short-duration storms by the method. Moreover, uncertainties are often larger for CMIP6 projections, and this might be linked to ‘hot models’ seen

in Chapter 4. Despite the large uncertainties, particularly under CMIP6 projections, the method seems to capture the increase of extreme rainfall intensities under the different future scenario and horizons. Indeed, highest percentages of increase are observed for the long-term period and long return period events. Therefore, it can be interesting to compare the expected quantiles found using QDM with those found in Chapter 4 with QQD, to see where the major dissimilarities are. Expected projected quantiles here are the average of quantiles from each GCM of the same CMIP project, a technique also called multi-model ensemble.

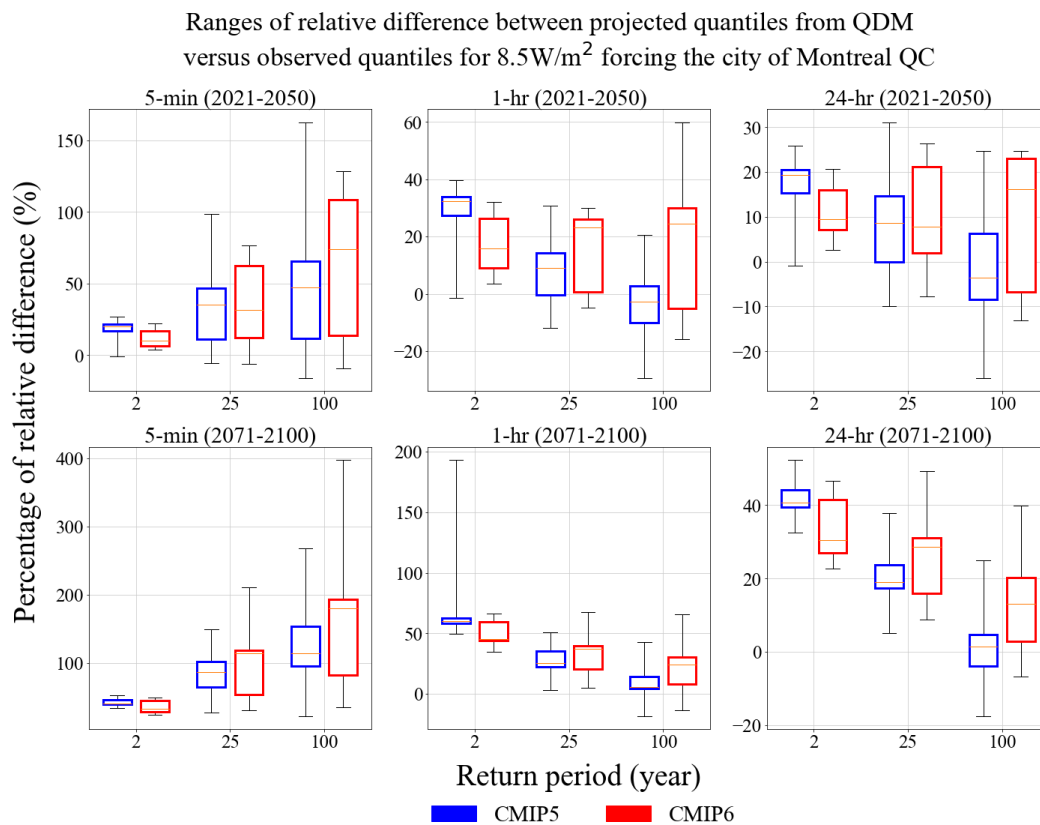


Figure 5.5. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 8.5 W/m^2 , and along different future periods, for the city of Montreal.

Henceforth, it is questioned how closed the expected values of the projections based on QDM to those based on QQD are. Therefore, maps of Canada representing the relative difference between expected IDF values based on QDM versus those based on QQD for the different scenarios and

future periods are represented (expected values from QDM minus expected values from QQD, divided by expected values from QDD). Figure 5.6 shows the relative differences for scenario SSP2-4.5 from CMIP6 models, during 2021-2020, whereas Figure 5.7 present these relative differences for the SSP5-5.5 scenario and for the 2071-2100 period. Comparing these two figures is meaningful, as the two situations are often seen in this thesis as opposite, showing the most discrepancies. In Annexe B, Figures B7 to B12 show the relative difference between expected IDF values using QQD versus QDM for the following situations: For RCP4.5 scenario from CMIP5, along 2021-2050; for RCP 8.5 scenario from CMIP5, along 2021-2050; for SSP5-8.5 scenario from CMIP6, along 2021-2050; for RCP4.5 scenario from CMIP5, along 2071-2100; for SSP2-4.5 scenario from CMIP6, along 2071-2100; and finally, for RCP8.5 scenario from CMIP5, along 2071-2100, respectively.

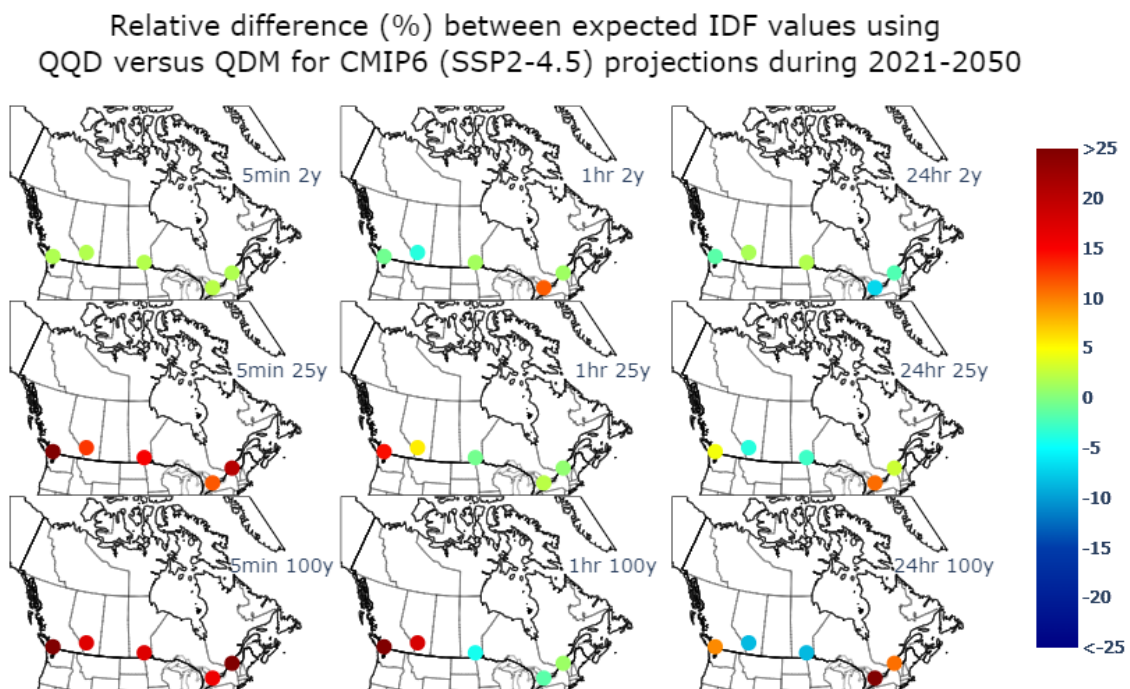


Figure 5.6. Relative difference between expected IDF values using QQD versus QDM for SSP2-4.5 scenario from CMIP6, along 2021-2050, for different durations and return periods.

Even though Figure 5.6 represents the short-term horizon with a mild radiative forcing, it can be observed many divergences between QQD and QDM expected quantiles. Strikingly, the over-

evaluations of projected quantiles relatively to the observed quantiles seen in Figures 5.2, 5.3, B1 to B6 are recognizable under 5-min duration and 25-yr/100-yr return periods for all the considered cities. Indeed, dark red dots signify that QDM expected quantiles are more than 25% higher than those from QQD. Interestingly, for 5-min duration but 2-yr return period, dots are green or yellow, signifying a relative difference close to zero. In our prior findings, projected quantiles with QDM for Toronto are high for 1-hr and 24-hr durations and as it is shown in Figure 5.6, expected quantiles can be even larger than those from QQD, see for example 24-hr and 25-yr/100-yr return period extreme rainfalls. The expected quantiles from the cities of Montreal and Winnipeg seem to be similar using QQD and QDM, excepting for short durations and 25-yr/100-yr return periods extreme rainfalls.

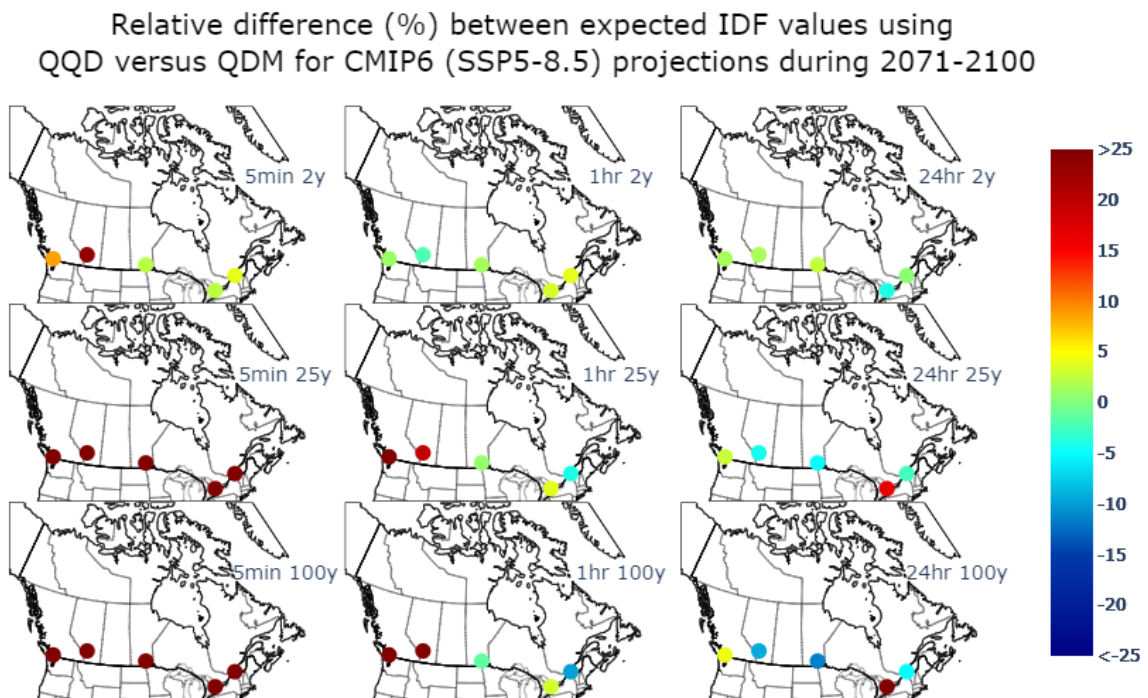


Figure 5.7. Relative difference between expected IDF values using QQD versus QDM for SSP5-8.5 scenario from CMIP6, along 2071-2100, for different durations and return periods.

In Figure 5.7, discrepancies are accentuated relative to Figures 5.6. The type of event with the more similitudes between the methods of downscaling is the 2-yr return period extreme rainfalls.

On contrary, highest discrepancies are observed for long return period extreme events. It can be over-estimations from QDM compares to QQM, e.g., Toronto and Vancouver, or under-estimations from QDM to QQD, e.g., Winnipeg and Calgary. Figures B7 to B12 show scale of colors in between the colors of the dots from Figures 5.6 and 5.7, with more discrepancies under the 8.5W/m² scenario along the long-term horizon. These figures confirm that the two methods of downscaling present large dissimilarities.

5.4 Conclusion

Finally, this analysis makes us understand the behavior of QDM, a bias correction method, under various situations. Extreme rainfall quantiles based on this process are compared considering different durations and return periods but also along several coupled future periods and scenarios. First, it is found that the method poorly represents extreme rainfall quantiles of short duration in the future. In addition, the spread of projected quantiles by the different models shows us large uncertainties, particularly for short duration and long return period events. Once the expected quantiles based on QDM are compared to those from QQD, high discrepancies are observed, most particularly for 5-min duration and long return periods. Kourtis and Tsihrintzis (2022) suggest using at least two statistical downscaling methods in assessment works to incorporate uncertainty associated with these approaches (Kourtis & Tsihrintzis 2022). In our case, merging expected quantiles from QQD and QDM to lessen uncertainties related to the downscaling phase is not recommended. Indeed, QDM is not able to reproduce short-duration extreme events and should not ‘penalize’ QQD projections. This again reinforces the interest in verifying the performance of the considered downscaling method before using it inside future works. As more models have been made available for CMIP6 project, they should be incorporated in future uncertainties assessments to capture the full range of uncertainties. It can be done in a processing phase conjointly with the meticulous selection of climate models recommended in Chapter 5, to avoid selecting too sensitive GCMs.

CHAPITRE 6 GENERAL DISCUSSION: UNCERTAINTIES IN CONSTRUCTED IDF CURVES

This chapter presents a discussion on updating IDF curves under climate change in Canada. Different ways of projecting IDF curves as well as some recommendations for dealing with uncertainties in the analyses are described.

In this thesis, we have presented how warming climate can alter the historical characteristics of extreme rainfall and questioned the validity of using historical IDF curves for design purposes. Our results showcase that the highest ratios for increase of rainfall frequency are often found in provinces with the largest population. Moreover, significant increases of rainfall intensity are observed in Iqaluit or Whitehorse, home to vulnerable communities, where investments for water management can be insufficient and monitoring of data is sparse. The altered properties of short-duration extreme rainfalls can potentially cause different sorts of risk of failure for urban infrastructures during their service period or design life period (Yan et al., 2021) and add supplementary expenses. Nevertheless, we acknowledge the sources of uncertainties in our analysis of IDF curves, ranging from obtaining and processing gauged data to final derivations of the quantile values. Some of these issues are explained here.

The choice of radiative forcing scenario (warming level) can considerably influence the estimated changes in rainfall intensity or frequency Martel et al., (2021). As of today, we are following the business-as-usual 8.5W/m^2 forcing scenario, reflecting a future with no effort in reducing GHG and we will be in this track at least for a decade (IPCC, 2021). However, this is misleading because following the 8.5 W/m^2 scenario until the end of the century would become increasingly implausible with every passing year (Hausfather et al., 2020). It would require an unprecedented raw material extraction even though peak of extraction have been reached already. Meanwhile, scenarios with 4.5 W/m^2 radiative forcing seem to be too optimistic (Sanford et al., 2014; Schwalm et al., 2020). Thus, the future level of warming might be somewhere in between these scenarios. As future IDF curves are presented for 4.5 W/m^2 and 8.5W/m^2 forcing in this research, the lower and upper values for “realistic” future scenario are provided.

Despite improvements in process representation, GCMs still struggle to accurately simulate the magnitude and location of convective storms, thus short duration extreme rainfall events, due to their coarse resolution. A large part of uncertainties in constructing IDF curves are from the model parameters and structures. In this study, the divergence among model outputs have been clearly seen for short-duration events or long return period ones, see Chapter 4. In addition, the parameters of GCMs influence the way they simulate the response to increases of GHG in the atmosphere. In Chapter 4, we have shown how climate sensitive models that simulate greater temperature rises to increase of CO₂ in the atmosphere estimate extreme rainfall values.

Internal climate variability can have a substantial influence on uncertainty and could mask climate signals (Kay et al., 2015). Large differences among extreme rainfall quantiles provided by simulations of the same GCM can be due to this issue (Aalbers et al., 2018). Therefore, similar to our study, it is often recommended to use multi-simulations ensembles to account the internal climate variability of the model for projections of future extreme rainfalls. Indeed, this has motivated us to use several models from CMIP5 and CMIP6. Nevertheless, improvements are seen across generation of models as GCMs gain in popularity and become more robust (Fasullo et al., 2020).

In addition to GCMs, spatial downscaling and temporal disaggregation can add large uncertainties to IDF analysis too. The sensitivity of the projections to the choice of downscaling technique is critical. Further assessments should be done to understand the impact of the choice of the downscaling method to the expected IDF curves and extreme rainfall quantiles from different models. In Chapter 5, introducing another type of downscaling approach of bias correction makes it possible to see the differences in projections of expected IDF curves with QQD, depending on the duration and return period of the considered events. QDM ranges of projected IDF values are larger than those from QQD in Chapter 4 and expected IDF values different, particularly for short duration and long return period extreme rainfall events. This analysis leads us to reject the use of QDM and showcases the performance of the quantile-based approach QQD in reproducing extreme rainfall quantiles. Therefore, the scientific community must be more consistent in choices of methodology to ensure that engineers are accounting for the same type of uncertainties in design (Cook et al., 2020). Further comparison assessments of downscaling methods should emerge.

Some recommendations for assessing the climate change impact on the IDF curves using GCMs are provided below. First, it is necessary to understand the local atmospheric processes taking place at the locations of interest to better interpret and analyze changes in IDF curves e.g., given climate zones. Second, if models from different projects are used, it is recommended to consider corresponding forcing scenarios, e.g., RCP8.5 for CMIP5 with SSP5-8.5 for CMIP6 to compare the groups of models accordingly. Third, prior to using climate models, a meticulous investigation should be performed to evaluate their sensitivity. As shown in this research, although selecting a wide set of GCMs is recommended to limit internal climate variability, some ‘hot models’ based on CMIP6 project may overestimate projections of extreme rainfall quantiles. Lastly, analysis based on different levels of warming can be done to complete the analysis presented in this study based on scenarios of radiative forcings.

It is acknowledged that some governmental agencies and practitioners across the globe might not be willing to consider the climate change impacts and might continue using the existing IDFs. This can be due to various reasons ranging from not availability of certain technical skills to obtain and analyze big climate data to existence of large uncertainties in top-down impact assessment, i.e., based on using GCMs and downscaling approaches (Yan et al., 2020)). In some other studies, regional safety factors or percentage of increase in rainfall intensity are considered for design purposes, e.g., 20-30% in Europe (Madsen et al., 2014), 18% in Quebec (MDDELCC, 2017), 20% in Moncton, New Brunswick (EPWDR, 2011). Some European countries are one step ahead and used adaptative percentages of increase, based on factors such as the return periods, regional area, and future time horizon (Gregersen et al., 2014; Madsen et al., 2014; UK department of structure, 2020). Another easy way that has been used to include climate change impact in a project is inclusion of a percentage increase on the Clausius-Clapeyron relationship (Canadian Standard Association, 2019). This approach aims at estimating intensity of extreme rainfalls in the future as a function of their historical values and the projected changes in local temperature. Martel et al., (2021) consider other adjustment factors inside the noted Claudius Clapeyron relationship to reflect the intensification of extreme rainfall of shorter duration and of longer return periods. Nevertheless, these alternative estimations might have larger uncertainties created by various simplifications and assumptions and might under- or over-estimate future design values. Therefore, updating IDF

curves based on using the most advanced projections of climate models is still highly valuable and informative.

CHAPITRE 7 CONCLUSIONS AND RECOMMANDATIONS

The characteristics of extreme rainfall have changed globally as a result of warming climate. Therefore, constructing IDF curves given changes in climate has become necessary to update design storms standards for economical and safety purposes. Changes in extreme rainfall values (and IDF curves) can be estimated using the projections of GCMs and spatiotemporally downscaling them to the location and temporal resolution of interest. As previously noted, climate models based on CMIP5 project are used to estimate changes in IDF curves Canada-wide. However, as CMIP6 simulations have become recently available, the IDF curves based on CMIP6 and CMIP5 have not been compared comprehensively so far to the best of our knowledge. In this study, we have estimated IDF curves for 30 cities in Canada using 14 climate models based on CMIP5 and CMIP6 projects under mild and high radiative forcing. In addition to comparisons based on CMIP projects.

Our analyses show increases of intensity and frequency of extreme rainfalls for almost all Canadian cities. Nevertheless, the rates of increase depend on the considered city, radiative forcing, future time horizon, climate model, and CMIP project. Among different rainfall durations and frequencies, it is expected that extreme rainfalls with short durations and long return periods have the largest increases. However, it should be noted that the projections for long return periods have high uncertainties, and the spread of projections is wide. This can be due to do to the compounding effect of the choice of the climate models and their poor representation of extreme events, to the choice of the downscaling method, and to higher internal climate variability for longer return periods. In addition, the highest intensifications of extreme events take place in populous and vulnerable cities, which can potentially rise the risks of urban floods and infrastructure failures. Interestingly, for the cities in Alberta and Saskatchewan small increases of intensity and frequency in the future are observed. CMIP6 historical quantiles are generally higher and present larger range of estimation than CMIP5 ones. While projecting expected IDF curves, the projections are generally higher using CMIP6, with larger differences under the long-term horizon and the 8.5W/m^2 forcing scenario. It is found out that two out of seven of our CMIP6 models are too sensitive to climate changes and project too hot temperatures. An analysis shows that they are responsible of overevaluation future extreme rainfall quantiles and are then removed from the set

of models. As a result, CMIP6 and CMIP5 expected IDF curves have stronger agreements on the changes of extreme rainfall intensity and frequency for all future scenario and horizon. In addition, another method of downscaling QDM is implemented to analyze its behavior in reproducing extreme rainfall quantiles based on projections of GCMs. This method seems to enlarge the uncertainties in projected IDF curves and poorly represents short duration events. Moreover, expected IDF values obtained through this method remain different relative to the ones found using QQD. Such comparison assessment is important to guide practitioners in their choice of methodology.

Finally, updating IDF curves in Canada using GCMs is highly valuable as these models aim at presenting the Earth's physical processes. However, the technical skills to obtain and analyze big climate data and the existence of large uncertainties, partly explain why practitioners across the globe might not be willing to consider the climate change impacts and might continue using the existing IDFs. In this study, we have discussed the various sources of uncertainties, ranging from the choice of radiative forcing, the internal climate variability, the poor representation of convective storm events, and obviously from the choice of downscaling. Nevertheless, the consensus among all models is that extreme events will increase in Canada, and this is alarming. Therefore, updating IDF curves using projections for various scenarios and horizons is paramount.

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ANNEXES

ANNEXE A – SUPPLEMENTARY MATERIAL OF CHAPTER 4

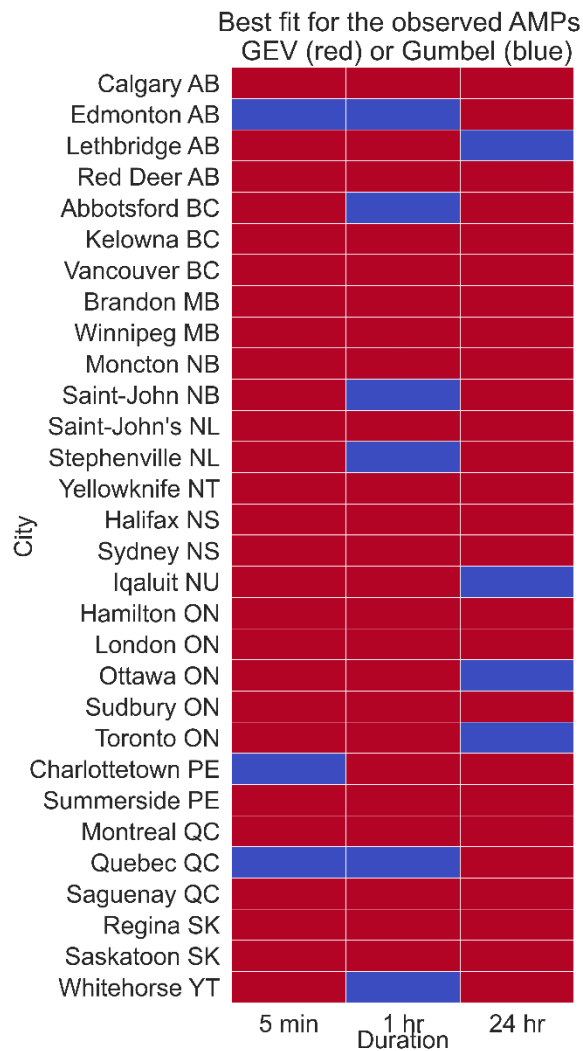


Figure A1. Representation of the best distribution fitted to the observed annual maximum precipitations. The GEV (red) and Gumbel (blue) distributions are selected based on their performance for different durations in 30 Canadian cities

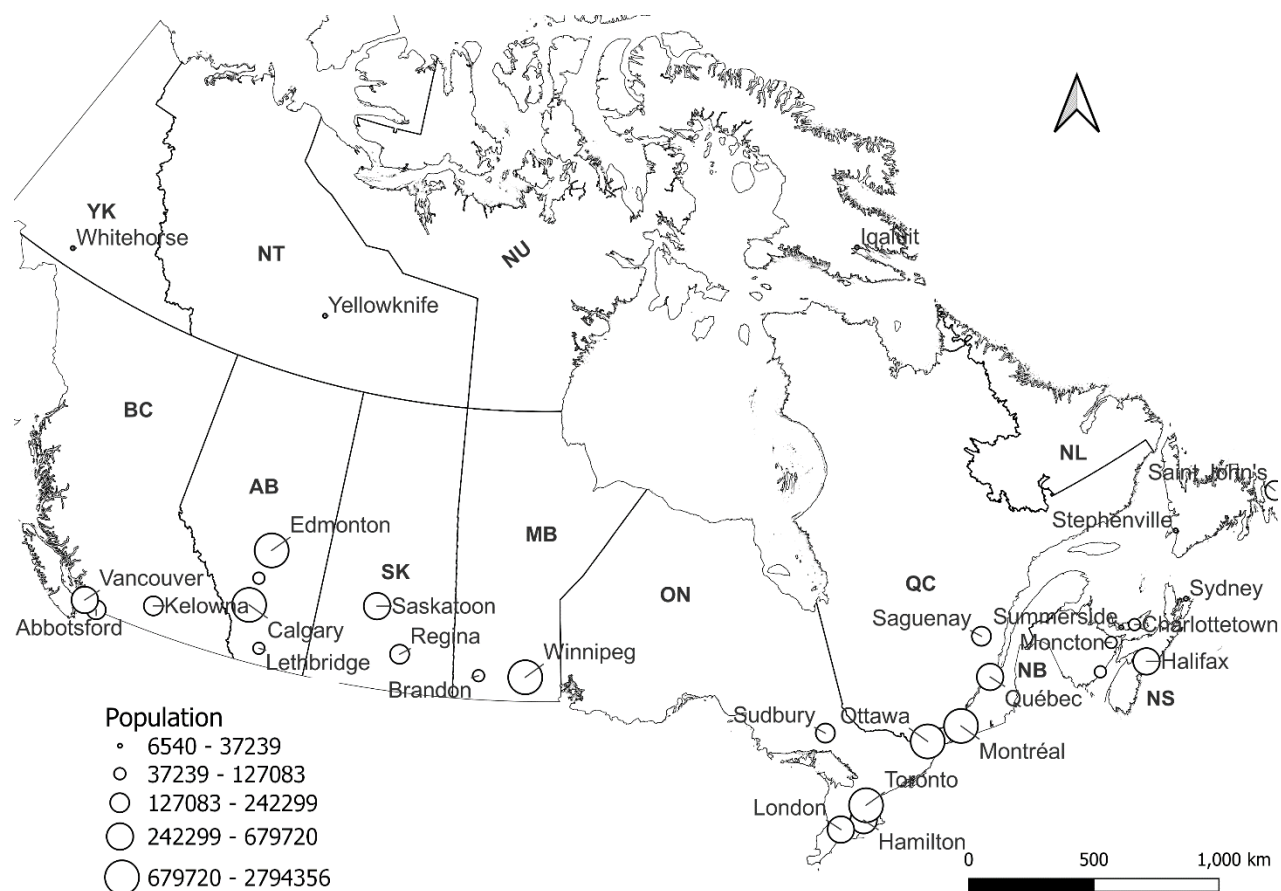


Figure A2. Location of the selected 30 cities in Canada and their corresponding province or territory

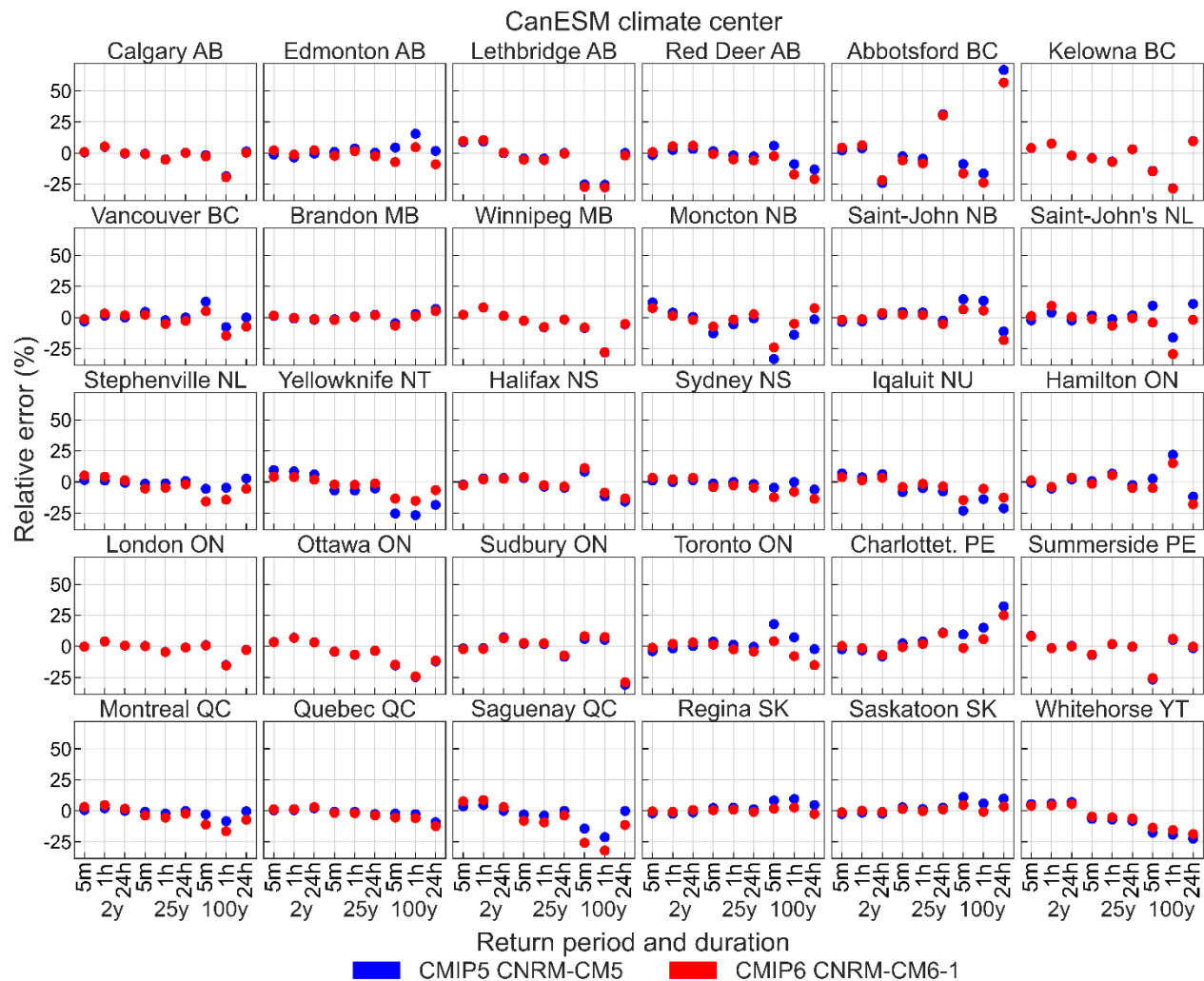


Figure A3. Percentage of relative error between the downscaled extreme rainfall quantiles based on the ensemble of CanESM simulations under CMIP5 (blue) and CMIP6 (red) projects with respective to the observed values during the baseline periods

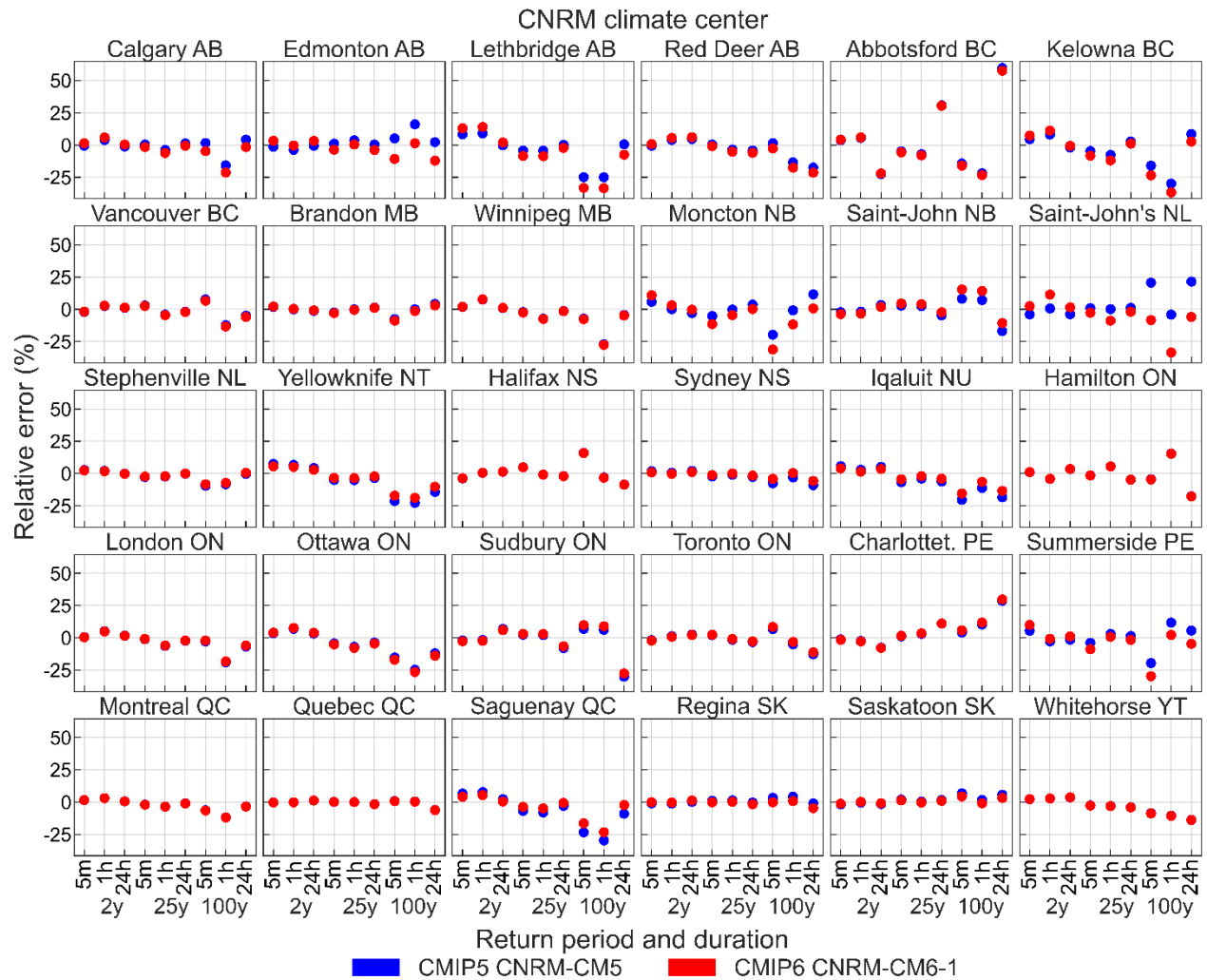


Figure A4. Percentage of relative error between the downscaled extreme rainfall quantiles based on the ensemble of CNRM simulations under CMIP5 (blue) and CMIP6 (red) projects with respect to the observed values during the baseline periods

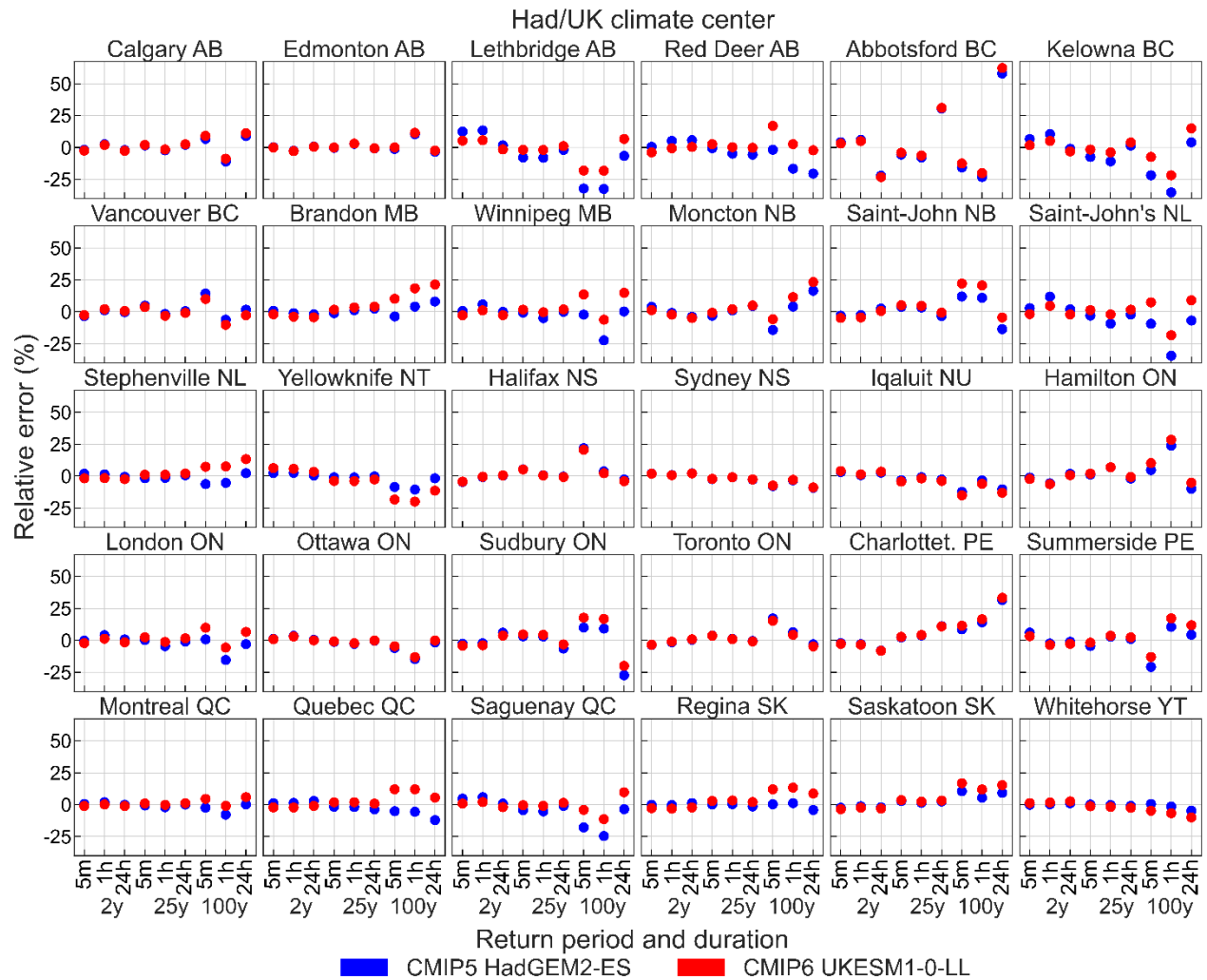


Figure A5. Percentage of relative error between the downscaled extreme rainfall quantiles based on the ensemble of Had/UK simulations under CMIP5 (blue) and CMIP6 (red) projects with respective to the observed values during the baseline periods

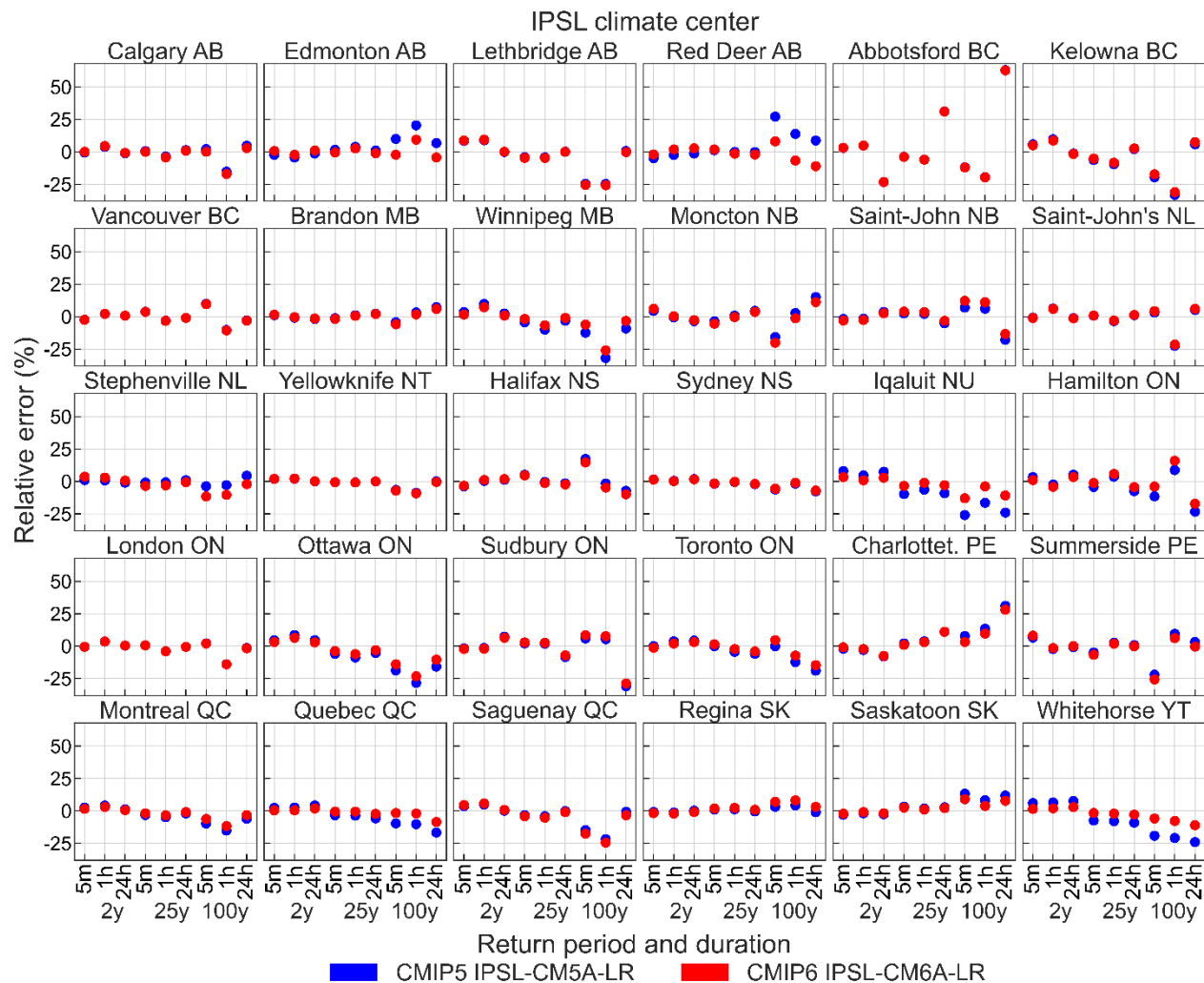


Figure A6. Percentage of relative error between the downscaled extreme rainfall quantiles based on the ensemble of IPSL simulations under CMIP5 (blue) and CMIP6 (red) projects with respective to the observed values during the baseline periods

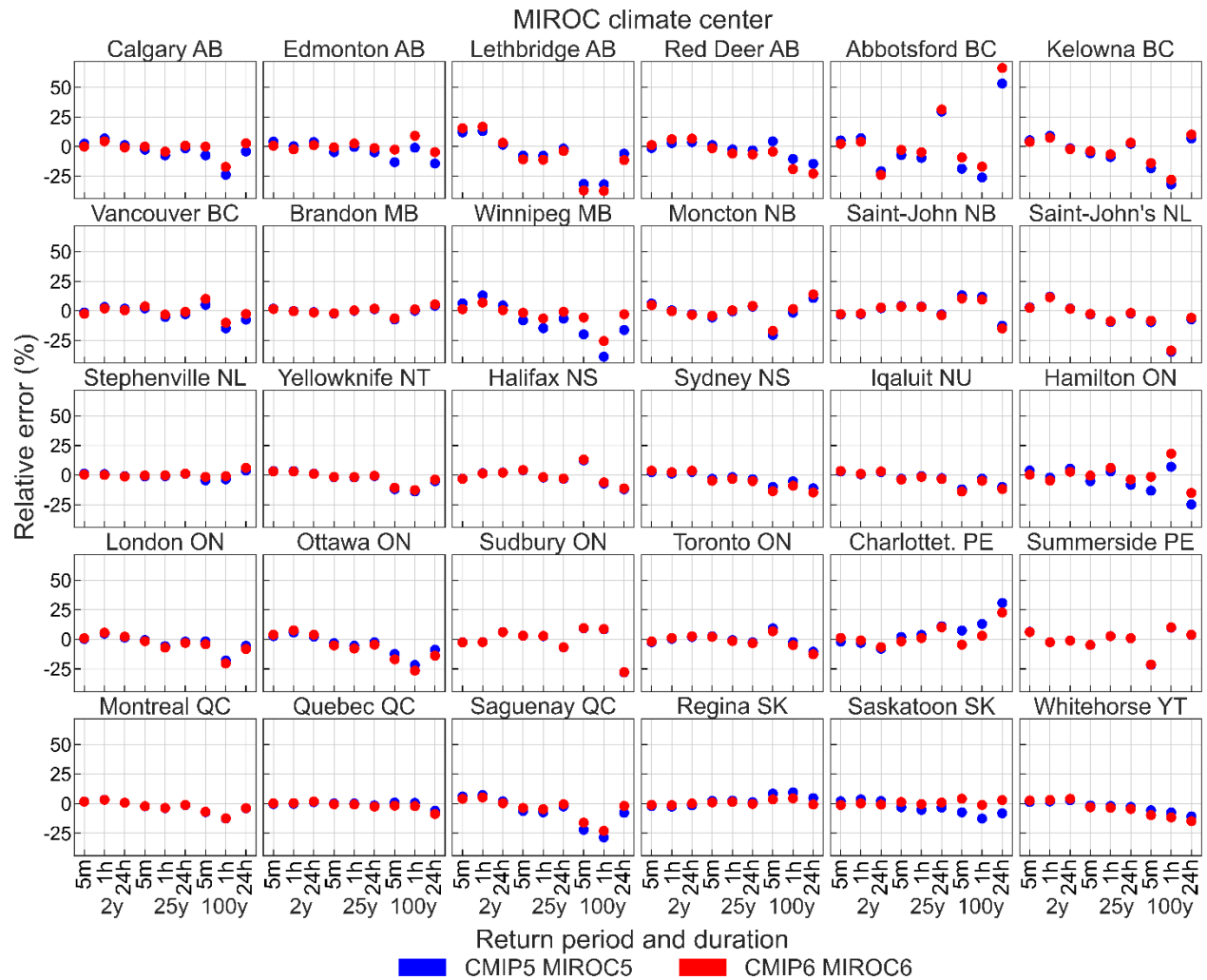


Figure A7. Percentage of relative error between the downscaled extreme rainfall quantiles based on the ensemble of MIROC simulations under CMIP5 (blue) and CMIP6 (red) projects with respective to the observed values during the baseline periods

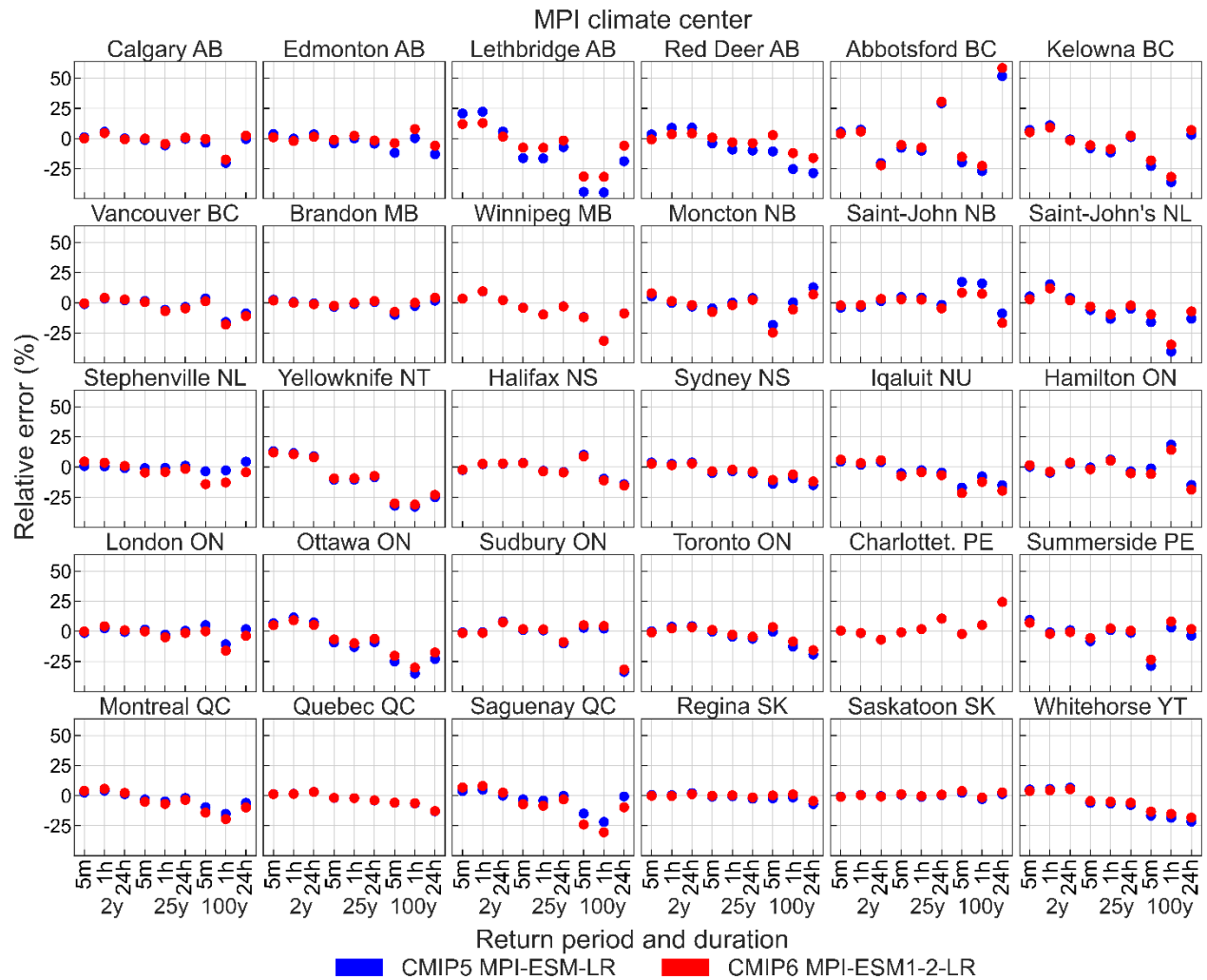


Figure A8. Percentage of relative error between the downscaled extreme rainfall quantiles based on the ensemble of MPI simulations under CMIP5 (blue) and CMIP6 (red) projects with respect to the observed values during the baseline periods

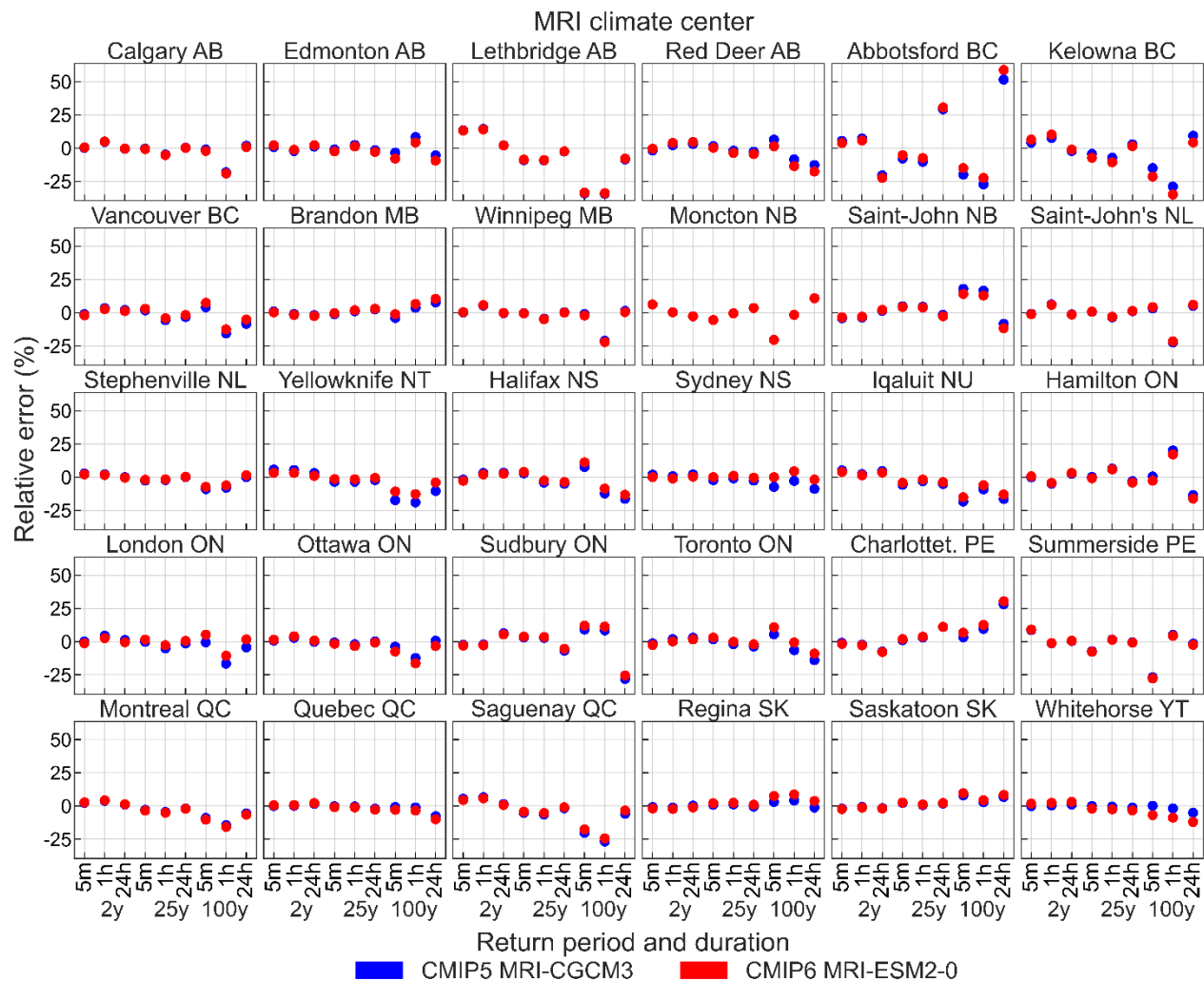


Figure A9. Percentage of relative error between the downscaled extreme rainfall quantiles based on the ensemble of MRI simulations under CMIP5 (blue) and CMIP6 (red) projects with respective to the observed values during the baseline periods

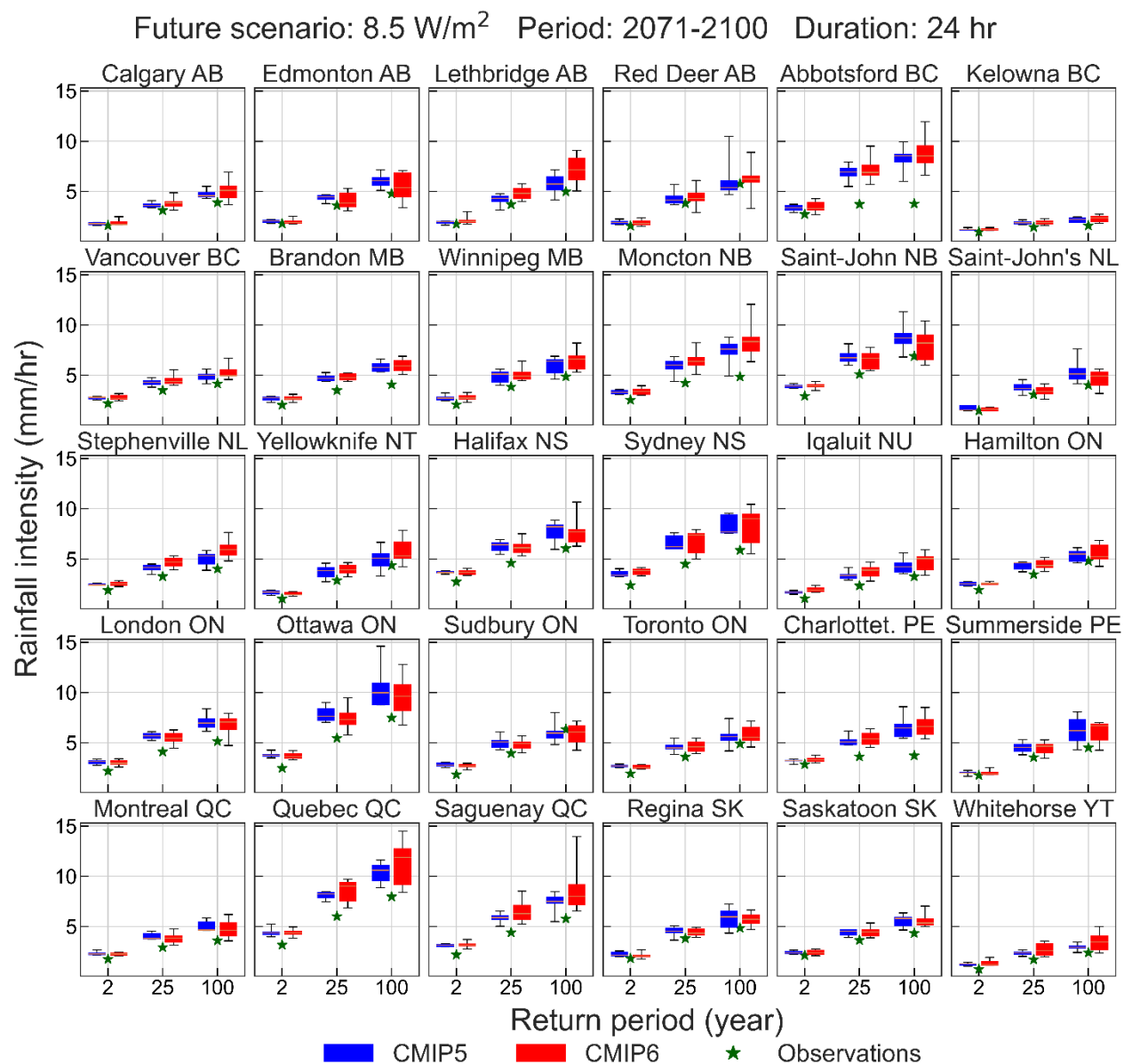


Figure A10. Boxplots of extreme rainfall quantiles for 24-hr duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 8.5 W/m^2 radiative forcing during 2071-2100. The observed values during the historical period are shown with green stars.

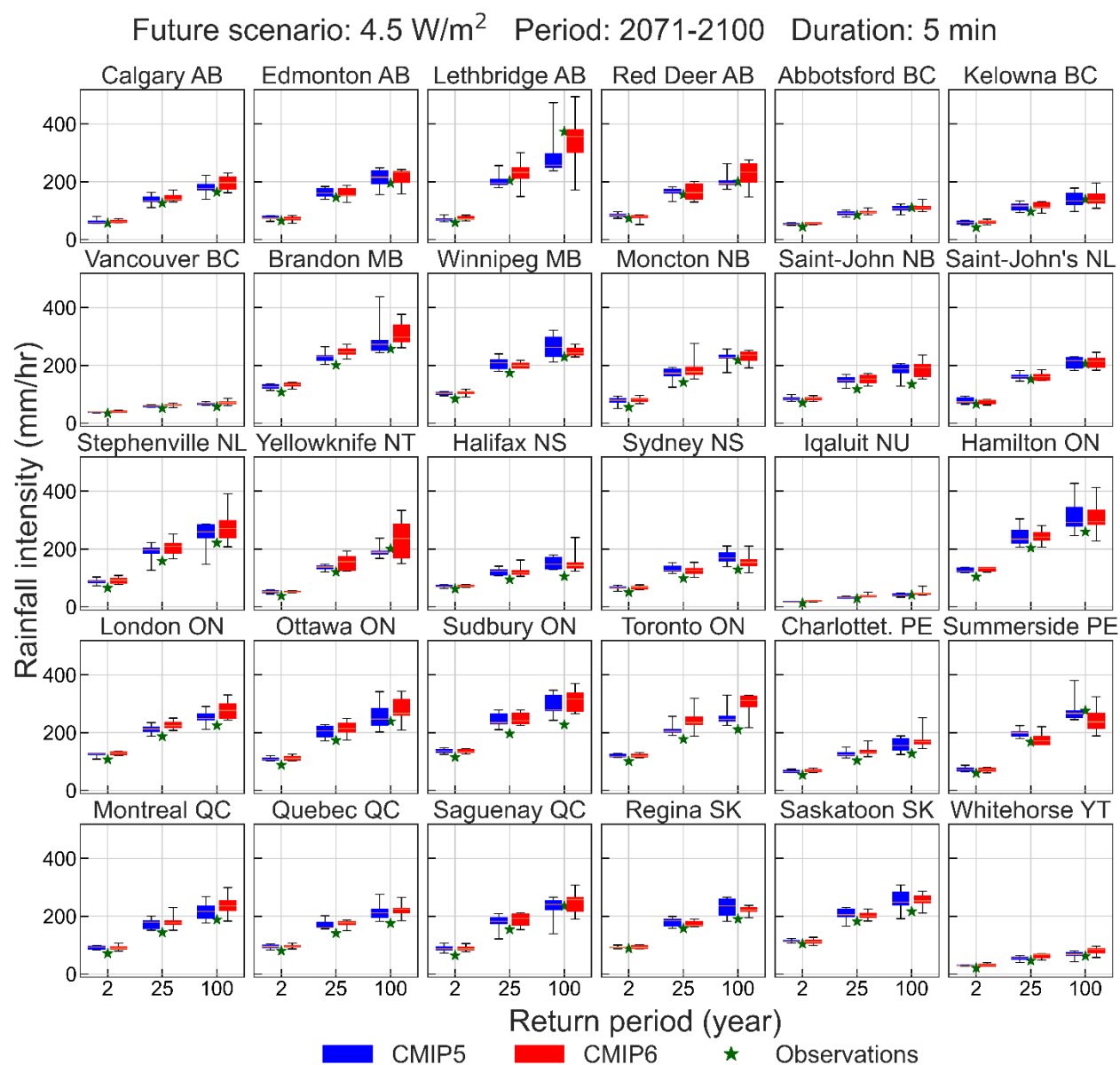


Figure A11. Boxplots of extreme rainfall quantiles for 5-min duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 4.5 W/m² radiative forcing during 2071-2100. The observed values during the historical period are shown with green stars.

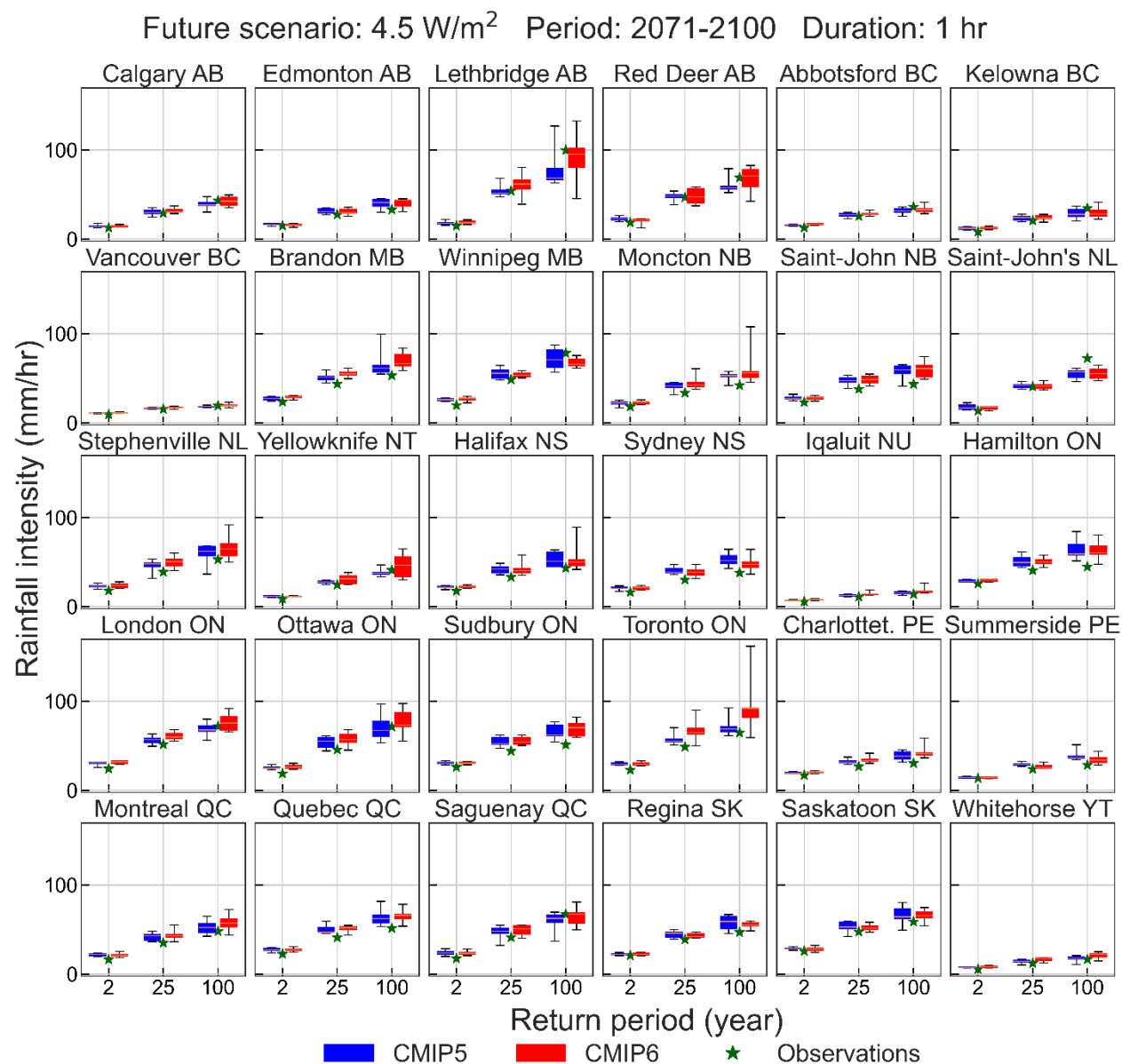


Figure A12. Boxplots of extreme rainfall quantiles for 1-hr duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 4.5 W/m² radiative forcing during 2071-2100. The observed values during the historical period are shown with green stars.

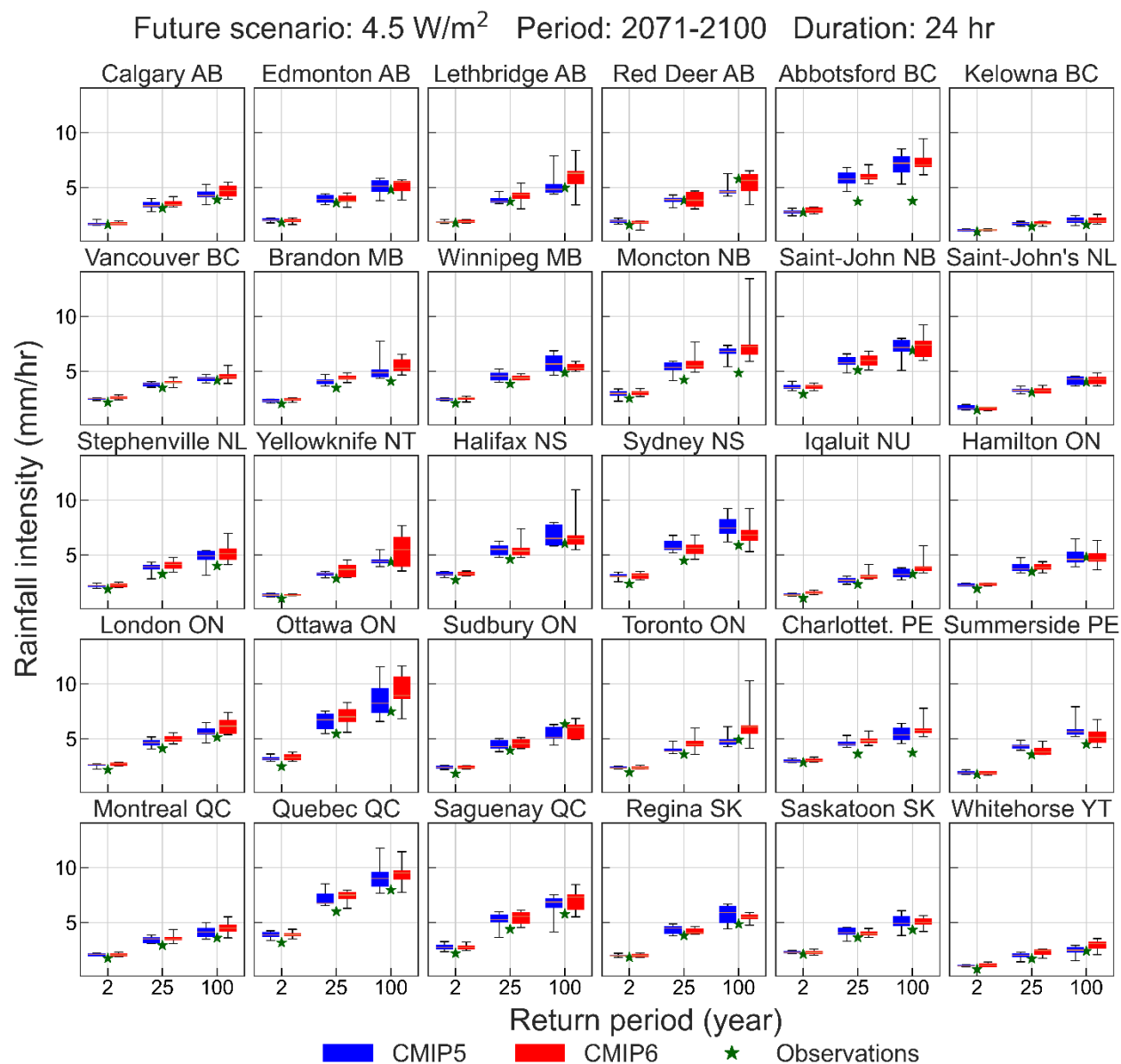


Figure A13. Boxplots of extreme rainfall quantiles for 24-hr duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 4.5 W/m^2 radiative forcing during 2071-2100. The observed values during the historical period are shown with green stars.

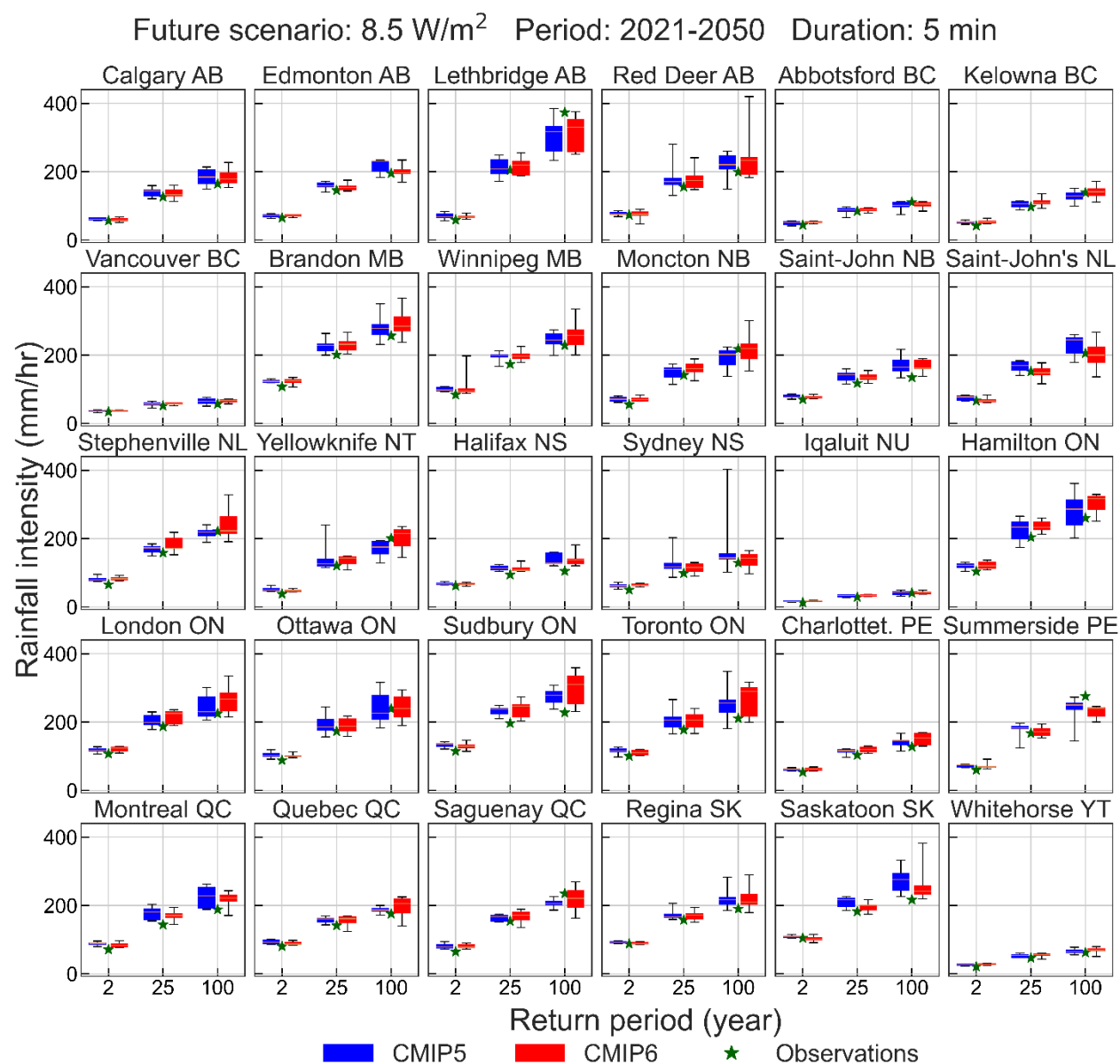


Figure A14. Boxplots of extreme rainfall quantiles for 5-min duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 8.5 W/m² radiative forcing during 2021-2050. The observed values during the historical period are shown with green stars.

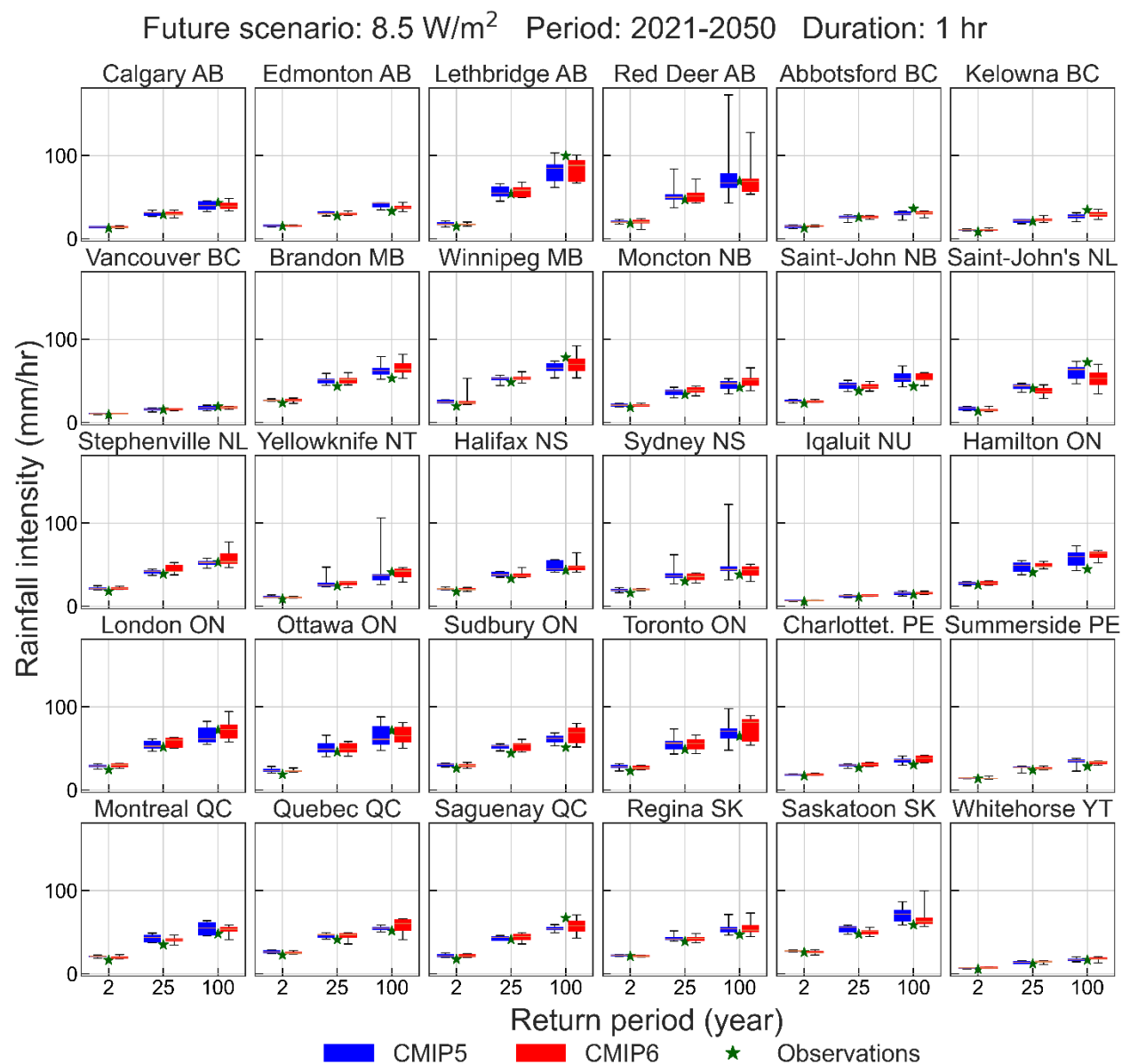


Figure A15. Boxplots of extreme rainfall quantiles for 1-hr duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 8.5 W/m² radiative forcing during 2021-2050. The observed values during the historical period are shown with green stars.

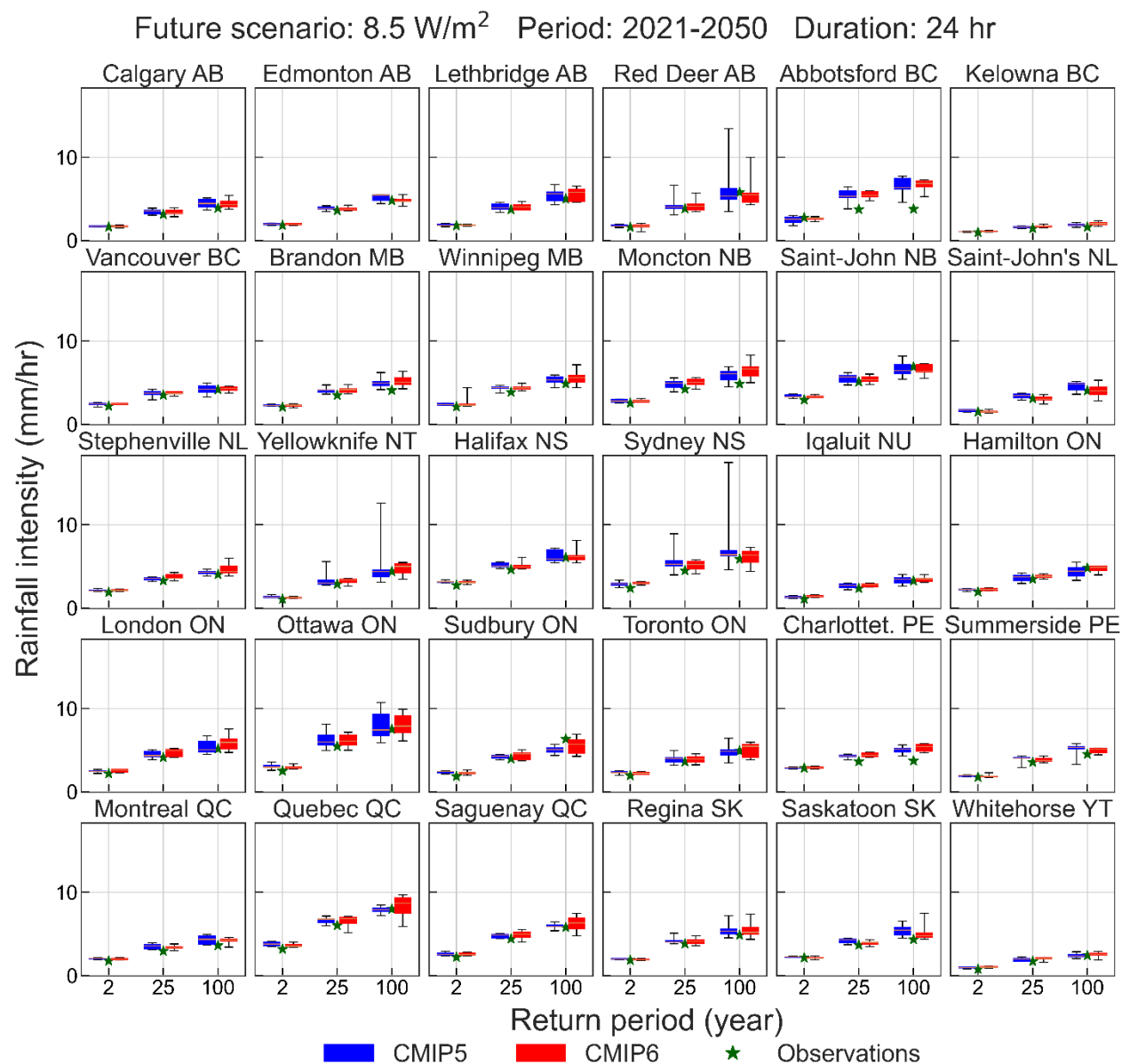


Figure A16. Boxplots of extreme rainfall quantiles for 24-hr duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 8.5 W/m² radiative forcing during 2021-2050. The observed values during the historical period are shown with green stars.

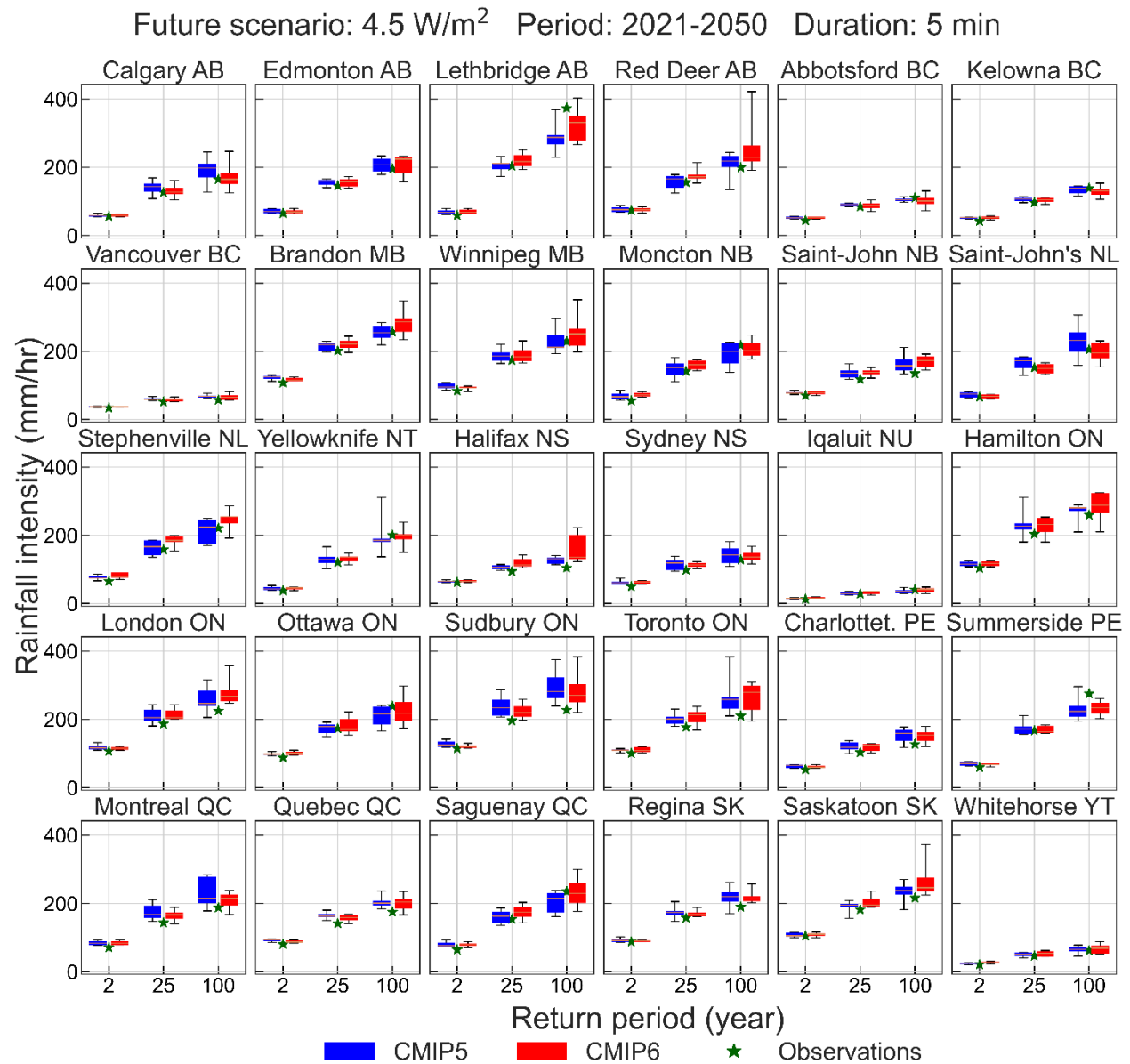


Figure A17. Boxplots of extreme rainfall quantiles for 5-min duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 4.5 W/m^2 radiative forcing during 2021-2050. The observed values during the historical period are shown with green stars.

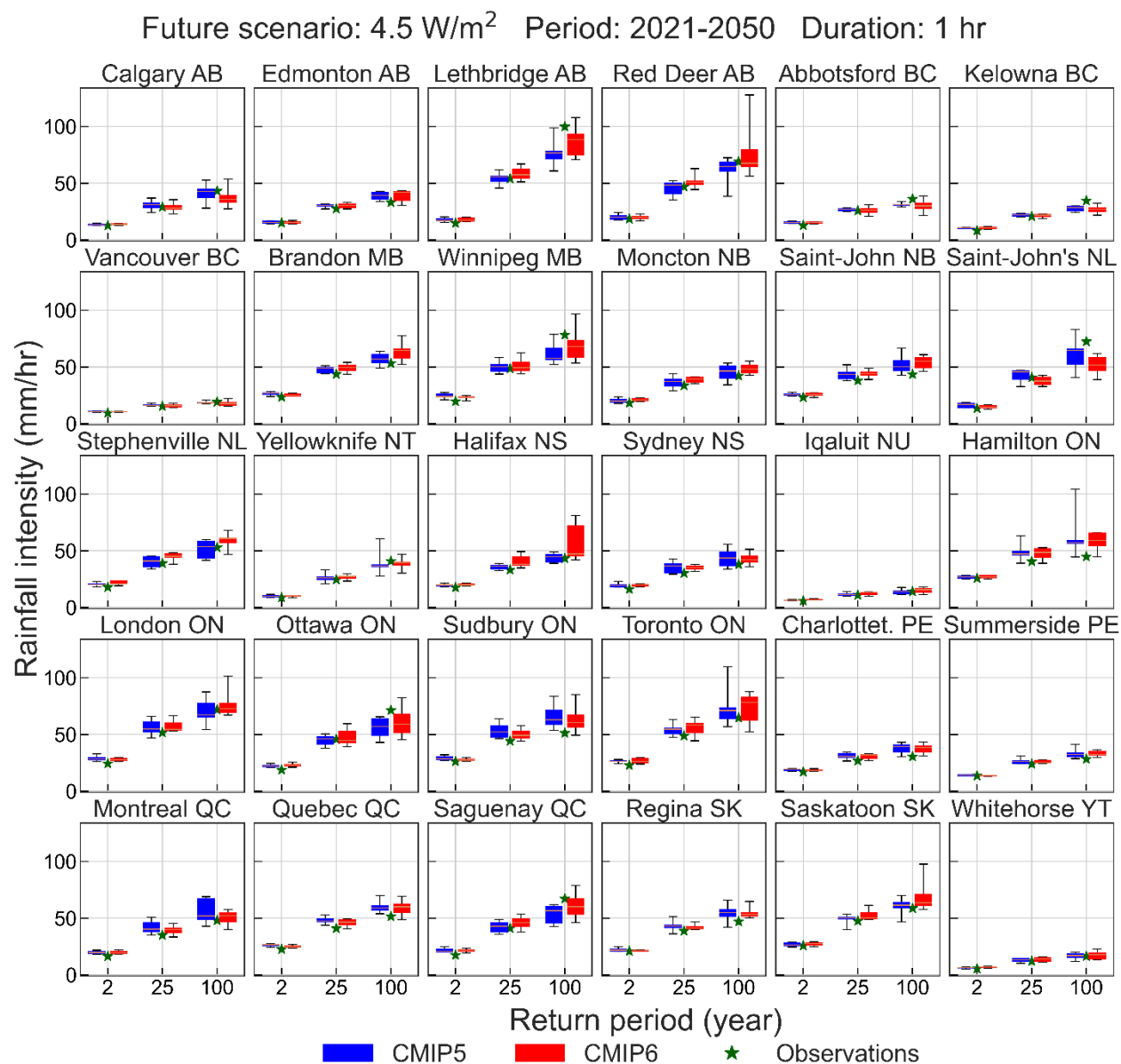


Figure A18. Boxplots of extreme rainfall quantiles for 1-hr duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 4.5 W/m² radiative forcing during 2021-2050. The observed values during the historical period are shown with green stars.

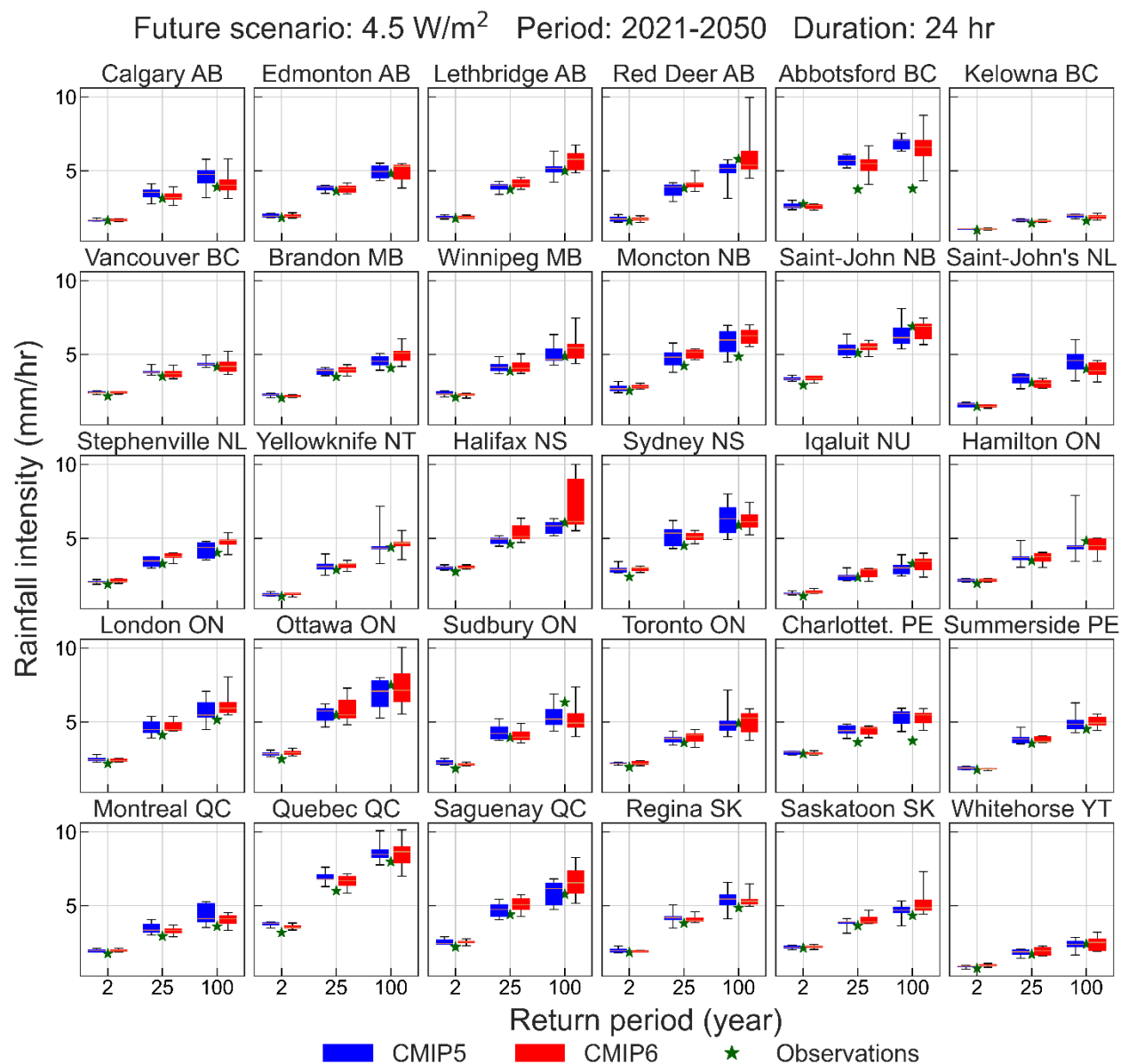


Figure A19. Boxplots of extreme rainfall quantiles for 24-hr duration in 30 Canadian cities, containing values based on 7 CMIP5 (blue) and 7 CMIP6 (red) models under 4.5 W/m^2 radiative forcing during 2021-2050. The observed values during the historical period are shown with green stars.

Relative difference (%) between the expected IDF curve quantiles in the future and historical period based on CMIP5 models Scenario: RCP8.5 Period: 2071-2100

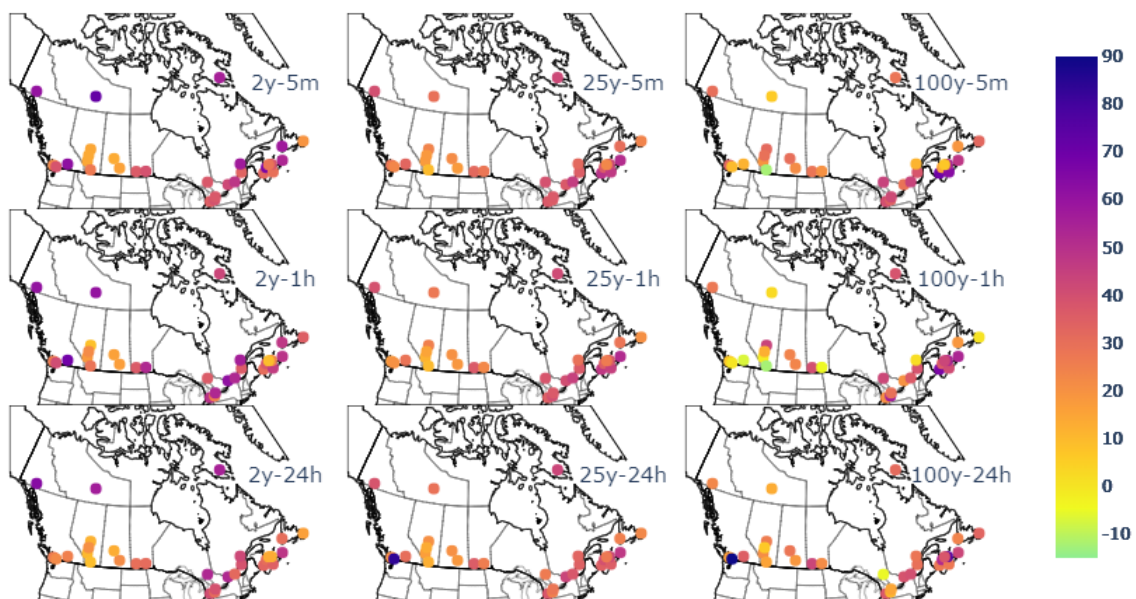


Figure A20. Relative difference between the expected IDF quantiles based on CMIP5 project under RCP8.5 for 2071-2100 with respect to the observed quantiles during the baseline period

Relative difference (%) between the expected IDF curve quantiles in the future and historical period based on CMIP6 models Scenario: SSP5-8.5 Period: 2071-2100

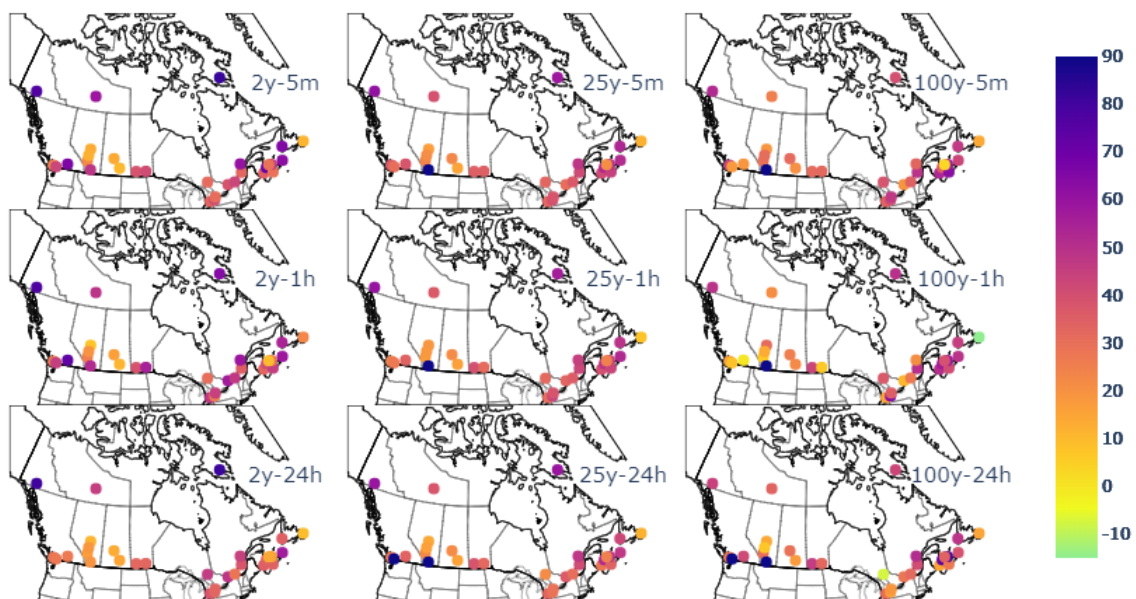


Figure A21. Relative difference between the expected IDF curve quantiles based on CMIP6 project under 8.5 W/m^2 for 2071-2100 with respect to the observed quantiles during the baseline period

Relative difference (%) between expected IDF curve quantiles
using CMIP6 (SSP2-4.5) and CMIP5 (RCP 4.5) projections during 2021-2050

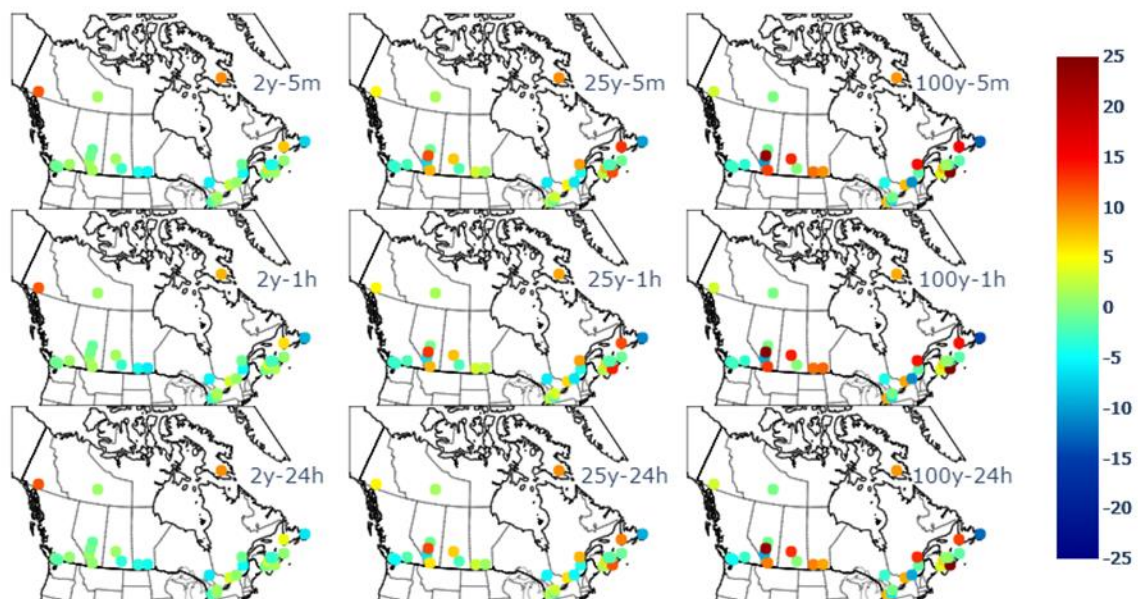


Figure A22. Relative difference between the expected IDF curve quantiles based on CMIP6 and CMIP5 projects under 4.5 W/m^2 during 2021-2050.

Relative difference (%) between expected IDF curve quantiles
using CMIP6 (SSP5-8.5) and CMIP5 (RCP 8.5) projections during 2021-2050

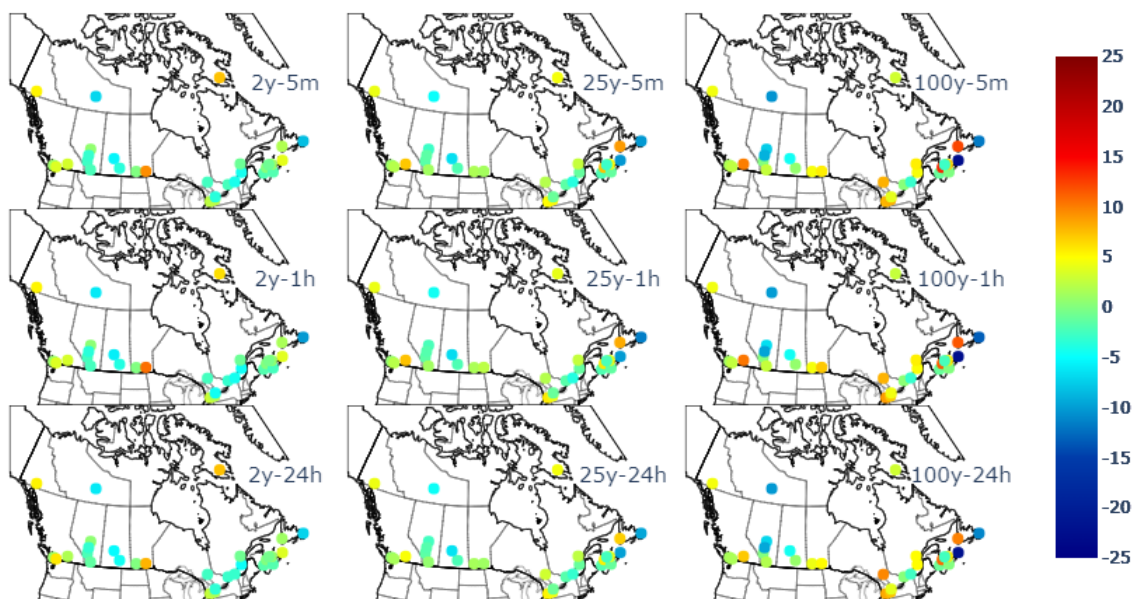


Figure A23. Relative difference between the expected IDF curve quantiles based on CMIP6 and CMIP5 projects under 4.5 W/m^2 during 2071-2100.

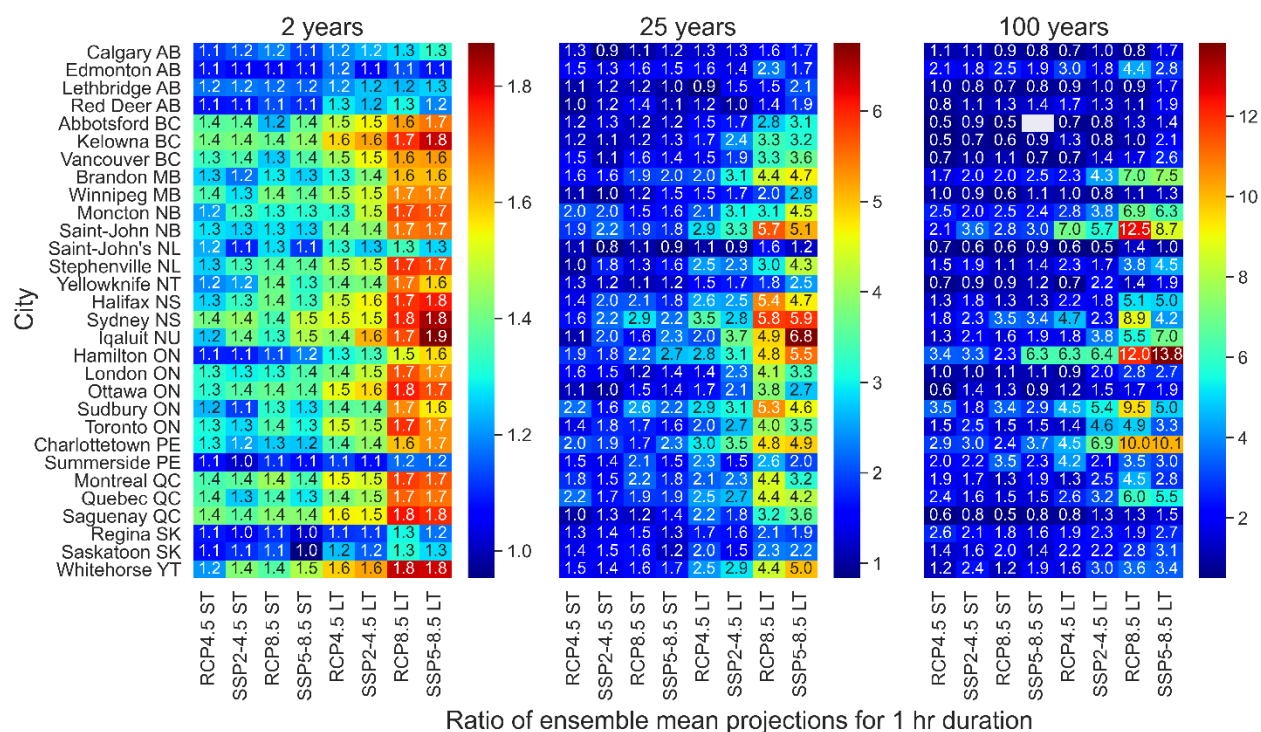


Figure A24. Ratio of historical over future return period for the 1-hr extreme rainfall over Canadian cities. Future return periods correspond to expected IDF curve quantiles that are estimated using CMIP 5 (RCPs) and CMIP 6 models (SSPs) during short-term (ST) and long-term (LT) horizons under 4.5 and 8.5 W/m².

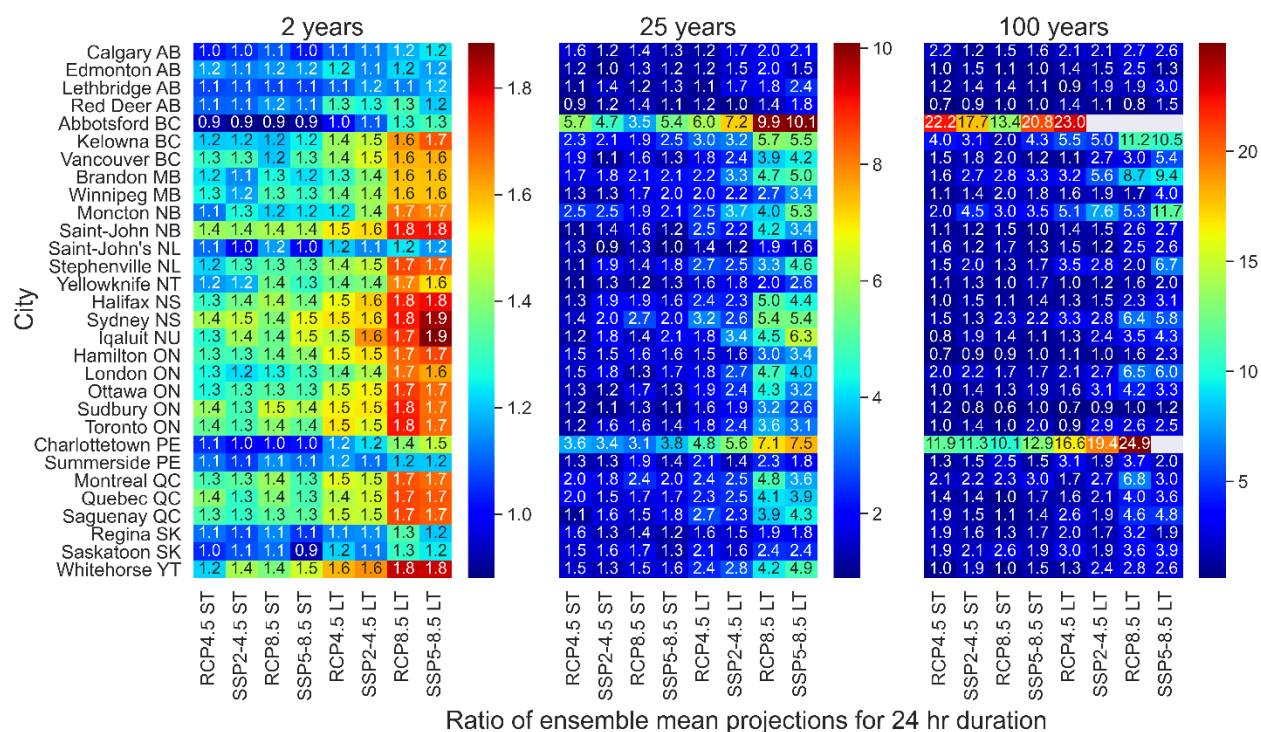


Figure A25. Ratio of historical over future return period for the 24-hr extreme rainfall over Canadian cities. Future return periods correspond to expected IDF curve quantiles that are estimated using CMIP 5 (RCPs) and CMIP 6 models (SSPs) during short-term (ST) and long-term (LT) horizons under 4.5 and 8.5 W/m².

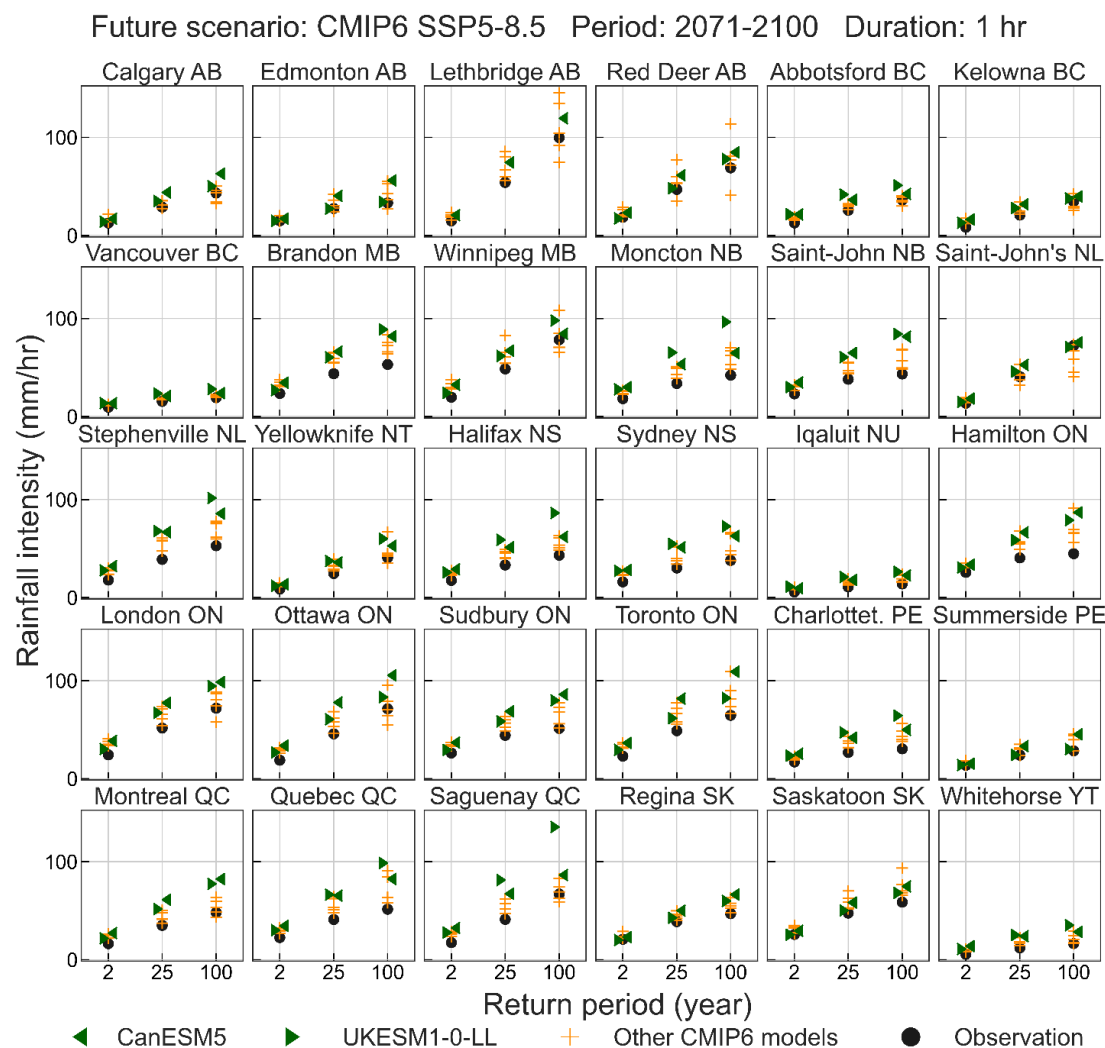


Figure A26. Extreme rainfall quantiles for 1-hr duration based on two ‘hot models’ CanESM5 and ‘UKESM1-0-LL (green arrows) and other 5 CMIP6 models (cross) under 8.5 W/m^2 radiative forcing during 2071-2100. Black dots show observed quantiles during the historical period.

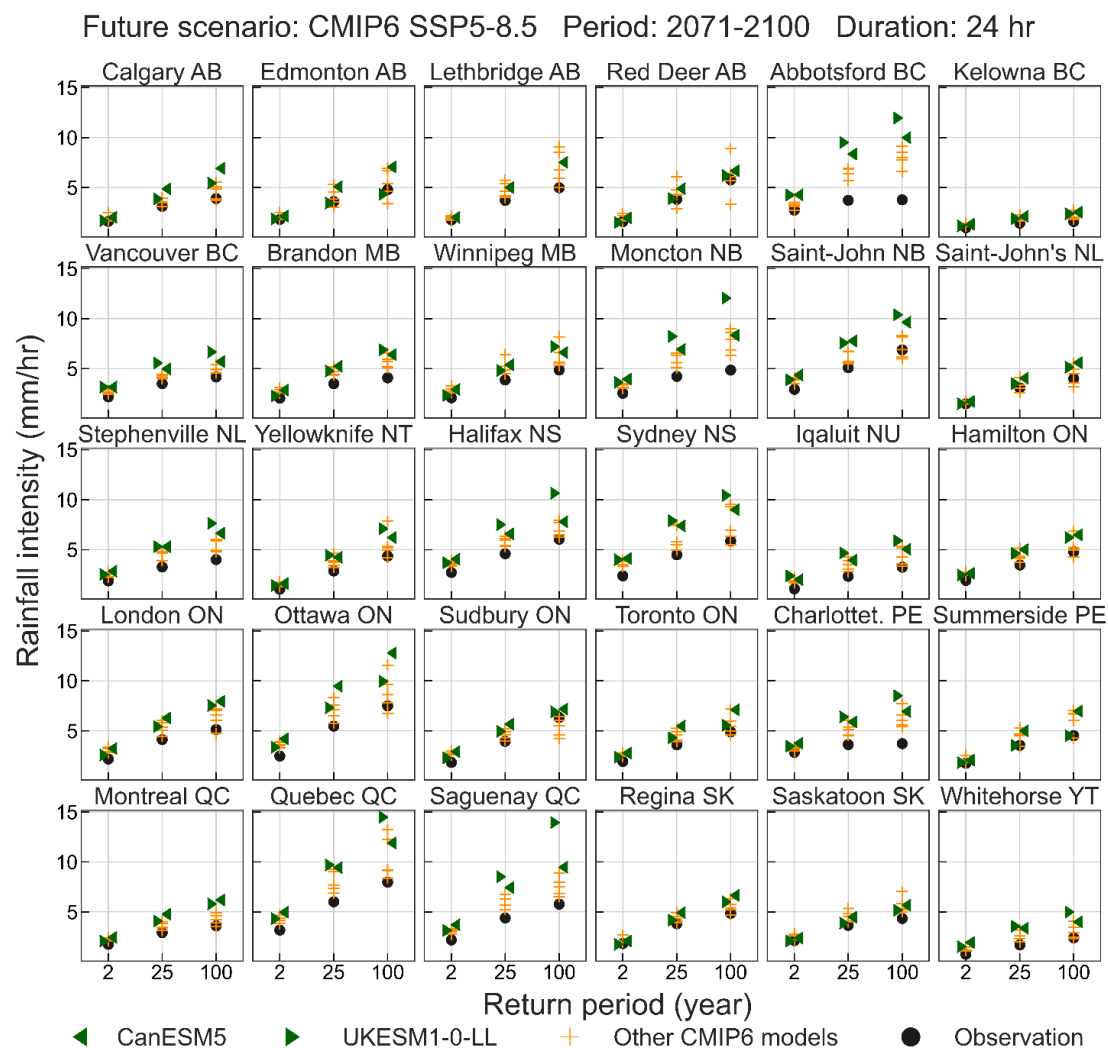


Figure A27. Extreme rainfall quantiles for 24-hr duration based on two ‘hot models’ CanESM5 and ‘UKESM1-0-LL (green arrows) and other 5 CMIP6 models (cross) under 8.5 W/m^2 radiative forcing during 2071-2100. Black dots show observed quantiles during the historical period.

Relative difference (%) between the expected IDF curve quantiles in the future and historical period based on CMIP6 models Scenario: SSP5-8.5 Period: 2071-2100

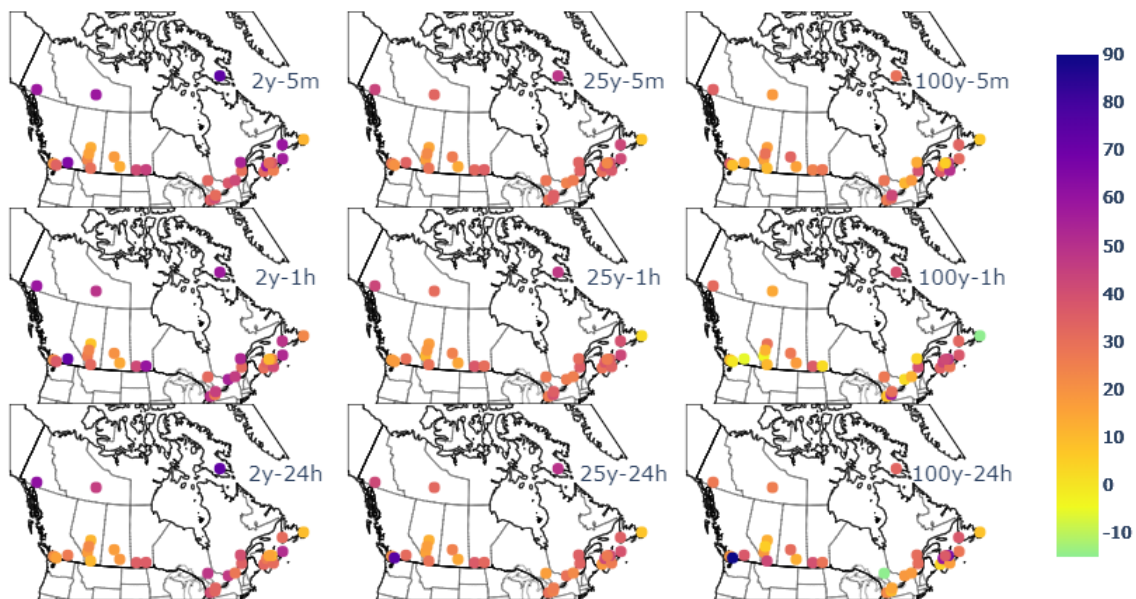


Figure A28. Relative difference between the expected IDF quantiles based on five CMIP6 models excluding CanESM5 and UKESM1.0-LL under RCP8.5 for 2071-2100 with respect to the observed quantiles during the baseline period.

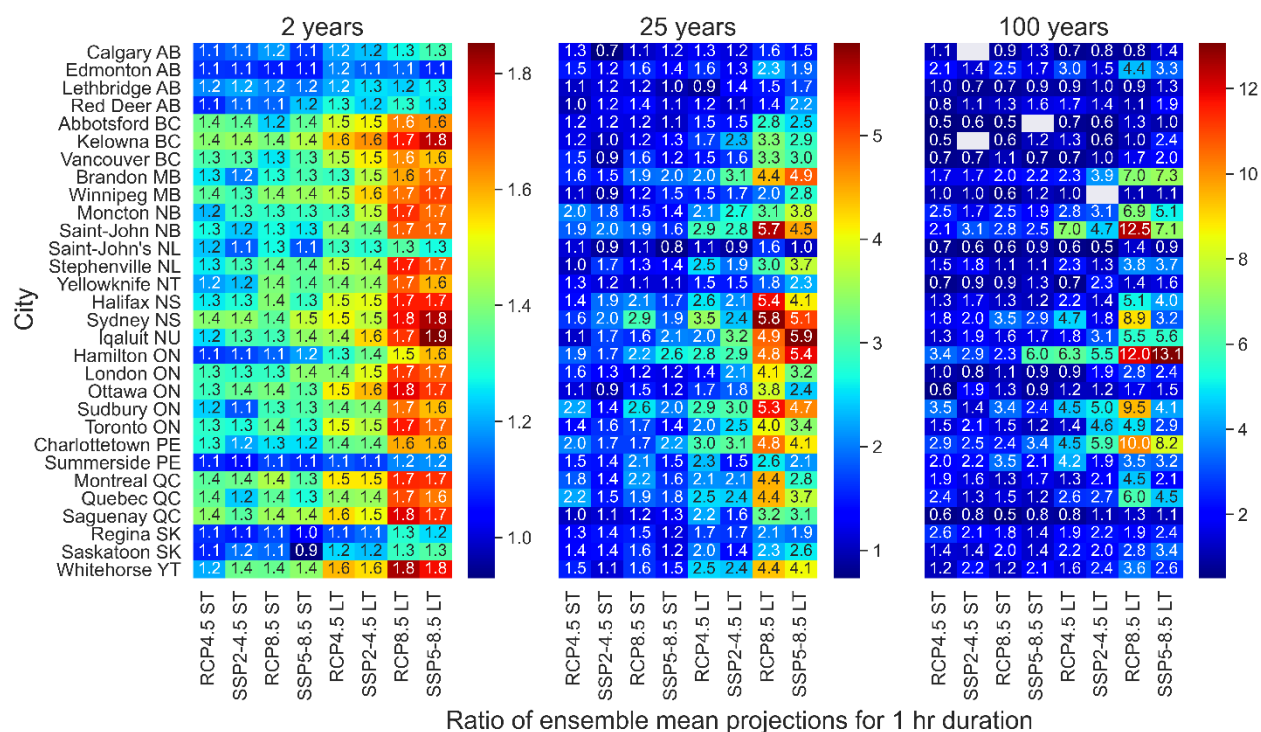


Figure A29. Ratio of historical over future return period for the 1-hr extreme rainfall over Canadian cities. Future return periods correspond to expected IDF curve quantiles that are estimated using CMIP 5 (RCPs) and CMIP 6 (SSPs) models excluding CanESM5 and UKESM1.0-LL, during short-term (ST) and long-term (LT) horizons under 4.5 and 8.5 W/m².

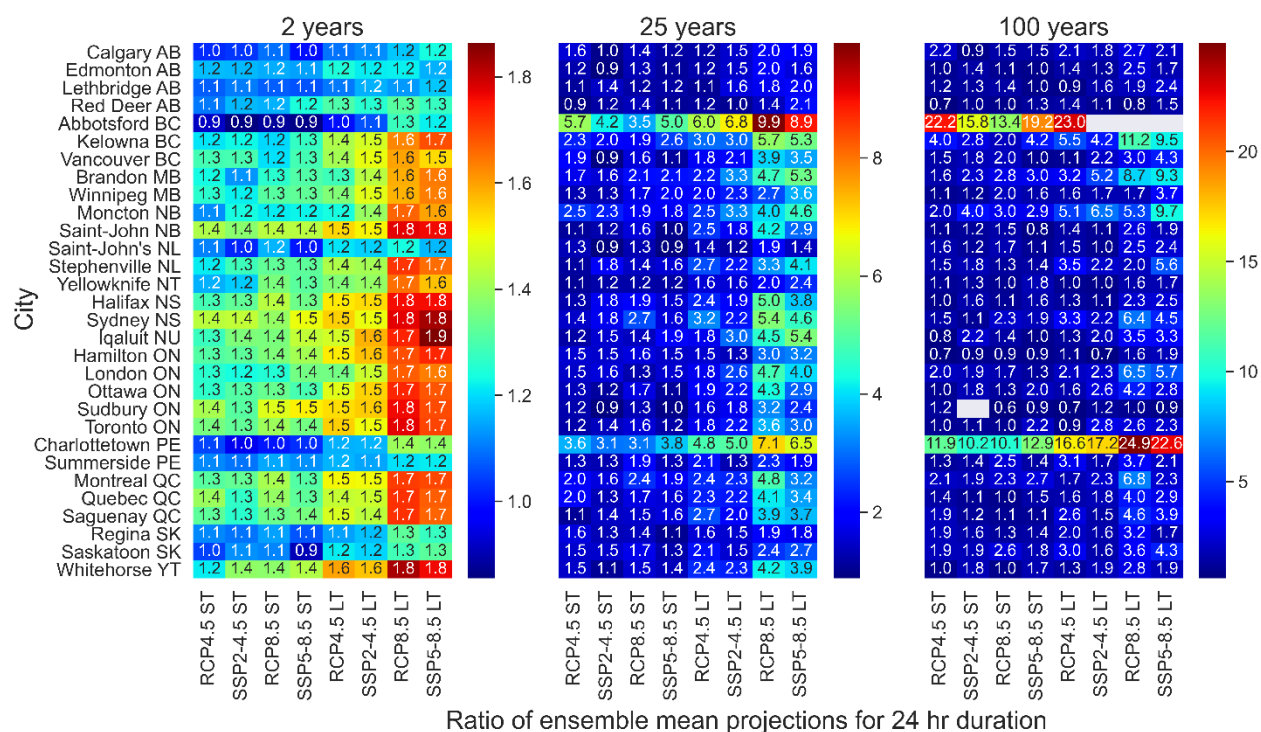


Figure A30. Ratio of historical over future return period for the 24-hr extreme rainfall over Canadian cities. Future return periods correspond to expected IDF curve quantiles that are estimated using CMIP 5 (RCPs) and CMIP 6 (SSPs) models excluding CanESM5 and UKESM1.0-LL, during short-term (ST) and long-term (LT) horizons under 4.5 and 8.5 W/m².

Table A1. Selection of the baseline period for every city, regarding data availability.

Province	City	Baseline period	Number of considered years
Alberta (AB)	Calgary	1962-1992	30
	Edmonton	1961-1991	30
	Lethbridge	1961-1990	30
	Red Deer	1961-1995	30
British-Columbia (BC)	Abbotsford	1977-2001	25
	Kelowna	1969-1998	30
	Vancouver	1961-1990	30
Manitoba (MB)	Brandon	1970-2003	30
	Winnipeg	1961-1990	30
New Brunswick (NB)	Moncton	1961-1992	30
	Saint John	1961-1992	30
Newfoundland (NL)	Saint John's	1961-1990	30
	Stephenville	1967-1998	30
Northwest territories (NT)	Yellowknife	1963-1992	30
Nova Scotia (NS)	Halifax	1977-2017	24
	Sydney	1961-1990	30
Nunavut (NU)	Iqaluit	1982-2017	27
Ontario (ON)	Hamilton	1971-2000	30
	London	1961-1991	30
	Ottawa	1967-1996	30
	Sudbury	1971-2000	30
	Toronto	1961-1990	30
Prince Edward Island (PE)	Charlottetown	1967-2015	30
	Summerside	1964-2006	30
Québec (QC)	Montréal	1961-1990	30
	Québec	1914-1943	30
	Saguenay	1961-1991	30
Saskatchewan (SK)	Regina	1961-1991	30
	Saskatoon	1962-1992	30
Yukon (YT)	Whitehorse	1961-1992	30

Table A2. First degree polynomial relationships between the historical model-based and observed quantiles for 5 min, 1 hr and 24 hr durations and for the CanESM climate center. Q represents the observed quantiles and x the historical model-based quantiles.

Province	City	CMIP5			CMIP6		
		5 min	1 hr	24 hr	5 min	1 hr	24 hr
Alberta	Calgary	$Q(x) = 0.43x + 7.04$	$1.94x + 5.73$	$19.11x + 0.43$	$Q(x) = 0.5x + 6.37$	$2.28x + 4.49$	$22.22x - 1.25$
	Edmonton	$Q(x) = 0.37x + 1.35$	$2.13x - 5.49$	$16.91x - 5.3$	$Q(x) = 0.44x + 4.04$	$2.52x - 4.07$	$20.0x - 3.82$
	Lethbridge	$Q(x) = 0.23x + 13.33$	$0.84x + 14.28$	$16.68x - 1.78$	$Q(x) = 0.28x + 14.68$	$1.04x + 15.85$	$20.21x - 3.31$
	Red Deer	$Q(x) = 0.36x + 1.01$	$1.12x + 5.75$	$14.28x + 3.42$	$Q(x) = 0.49x - 0.3$	$1.55x + 6.06$	$19.92x + 2.74$
British-Columbia	Abbotsford	$Q(x) = 0.8x + 9.93$	$2.59x + 11.65$	$7.25x + 31.67$	$Q(x) = 0.89x + 12.62$	$2.87x + 14.37$	$7.81x + 37.16$
	Kelowna	$Q(x) = 0.3x + 13.11$	$1.28x + 14.71$	$28.0x - 0.91$	$Q(x) = 0.39x + 13.32$	$1.67x + 15.45$	$36.65x - 5.09$
	Vancouver	$Q(x) = 1.45x + 5.43$	$5.53x + 0.88$	$23.14x + 3.57$	$Q(x) = 1.58x + 3.17$	$6.09x - 2.59$	$25.34x + 0.68$
	Brandon	$Q(x) = 0.29x + 8.99$	$1.26x + 11.1$	$16.74x + 6.87$	$Q(x) = 0.39x + 5.66$	$1.69x + 8.8$	$22.26x + 3.32$
Manitoba	Winnipeg	$Q(x) = 0.31x + 12.83$	$1.0x + 18.74$	$15.61x + 6.68$	$Q(x) = 0.44x + 10.66$	$1.44x + 18.42$	$21.99x + 2.08$
New Brunswick	Moncton	$Q(x) = 0.36x + 23.72$	$1.89x + 10.29$	$14.8x + 8.38$	$Q(x) = 0.47x + 24.57$	$2.48x + 6.6$	$19.57x + 3.63$
	Saint John	$Q(x) = 0.55x + 11.87$	$1.78x + 9.27$	$15.22x + 3.75$	$Q(x) = 0.79x + 4.68$	$2.57x + 0.93$	$21.95x - 7.07$
	Saint John's	$Q(x) = 0.36x - 0.05$	$1.16x + 7.0$	$18.89x - 4.13$	$Q(x) = 0.45x + 2.19$	$1.48x + 11.14$	$123.99x - 2.98$
Newfoundland	St. John's	$Q(x) = 0.35x + 21.88$	$1.55x + 17.17$	$22.25x + 3.61$	$Q(x) = 0.49x + 22.3$	$2.15x + 15.76$	$30.93x - 3.2$
Northwest territories	Yellowknife	$Q(x) = 0.23x + 6.05$	$1.22x + 4.31$	$10.6x + 3.83$	$Q(x) = 0.3x + 7.9$	$1.55x + 5.68$	$13.5x + 5.07$
Nova Scotia	Halifax	$Q(x) = 0.68x + 5.25$	$1.83x + 13.67$	$15.75x + 2.22$	$Q(x) = 1.01x - 5.32$	$2.72x + 6.64$	$23.53x - 10.62$
	Sydney	$Q(x) = 0.54x + 15.79$	$1.8x + 14.14$	$12.56x + 12.76$	$Q(x) = 0.9x + 8.42$	$3.0x + 5.85$	$21.0x + 3.3$
Nunavut	Iqaluit	$Q(x) = 1.08x + 7.48$	$3.17x + 3.73$	$13.26x + 7.4$	$Q(x) = 1.44x + 5.1$	$4.19x + 0.44$	$17.68x + 5.07$
	Hamilton	$Q(x) = 0.26x + 13.34$	$1.34x + 7.94$	$18.3x + 4.44$	$Q(x) = 0.34x + 11.13$	$1.73x + 4.64$	$24.08x - 0.95$
Ontario	London	$Q(x) = 0.31x + 8.72$	$1.01x + 16.33$	$13.28x + 12.59$	$Q(x) = 0.43x + 3.4$	$1.41x + 13.37$	$18.32x + 8.61$
	Ottawa	$Q(x) = 0.4x + 8.56$	$1.28x + 19.69$	$11.34x + 16.22$	$Q(x) = 0.49x + 8.35$	$1.57x + 22.04$	$13.89x + 17.66$
	Sudbury	$Q(x) = 0.28x + 9.06$	$1.28x + 7.82$	$12.96x + 15.41$	$Q(x) = 0.38x + 5.99$	$1.73x + 4.29$	$18.1x + 13.32$
	Toronto	$Q(x) = 0.33x + 7.63$	$1.11x + 15.01$	$18.17x + 4.61$	$Q(x) = 0.43x + 5.86$	$1.43x + 15.5$	$23.29x + 2.29$
	Charlottetown	$Q(x) = 0.52x + 15.53$	$2.42x + 2.84$	$15.69x + 2.16$	$Q(x) = 0.69x + 13.92$	$3.21x - 2.85$	$20.67x - 3.31$
Prince Edward Island	Summerside	$Q(x) = 0.3x + 11.15$	$2.68x - 5.89$	$16.49x + 1.07$	$Q(x) = 0.39x + 12.67$	$3.53x - 9.33$	$21.75x - 0.31$
	Montréal	$Q(x) = 0.37x + 14.47$	$1.48x + 16.07$	$22.35x + 1.6$	$Q(x) = 0.51x + 13.03$	$2.04x + 15.25$	$30.73x - 4.67$
Québec	Québec	$Q(x) = 0.52x + 9.37$	$1.74x + 12.1$	$11.77x + 13.48$	$Q(x) = 0.78x - 2.68$	$2.6x + 1.39$	$17.71x + 3.14$
	Saguenay	$Q(x) = 0.38x + 22.41$	$1.41x + 22.15$	$14.81x + 15.05$	$Q(x) = 0.58x + 20.74$	$2.15x + 20.2$	$22.43x + 9.84$
Saskatchewan	Regina	$Q(x) = 0.4x - 4.4$	$1.53x - 1.67$	$14.56x + 3.25$	$Q(x) = 0.56x - 8.36$	$2.18x - 4.45$	$20.81x + 2.46$
	Saskatoon	$Q(x) = 0.35x - 5.67$	$1.31x - 3.85$	$17.98x - 7.94$	$Q(x) = 0.47x - 8.72$	$1.79x - 6.41$	$24.42x - 11.84$
Yukon	Whitehorse	$Q(x) = 0.67x + 6.26$	$2.57x + 6.32$	$17.9x + 6.84$	$Q(x) = 0.74x + 9.31$	$2.83x + 9.37$	$19.78x + 9.94$

ANNEXE B –SUPPLEMENTARY MATERIAL OF CHAPTER 5

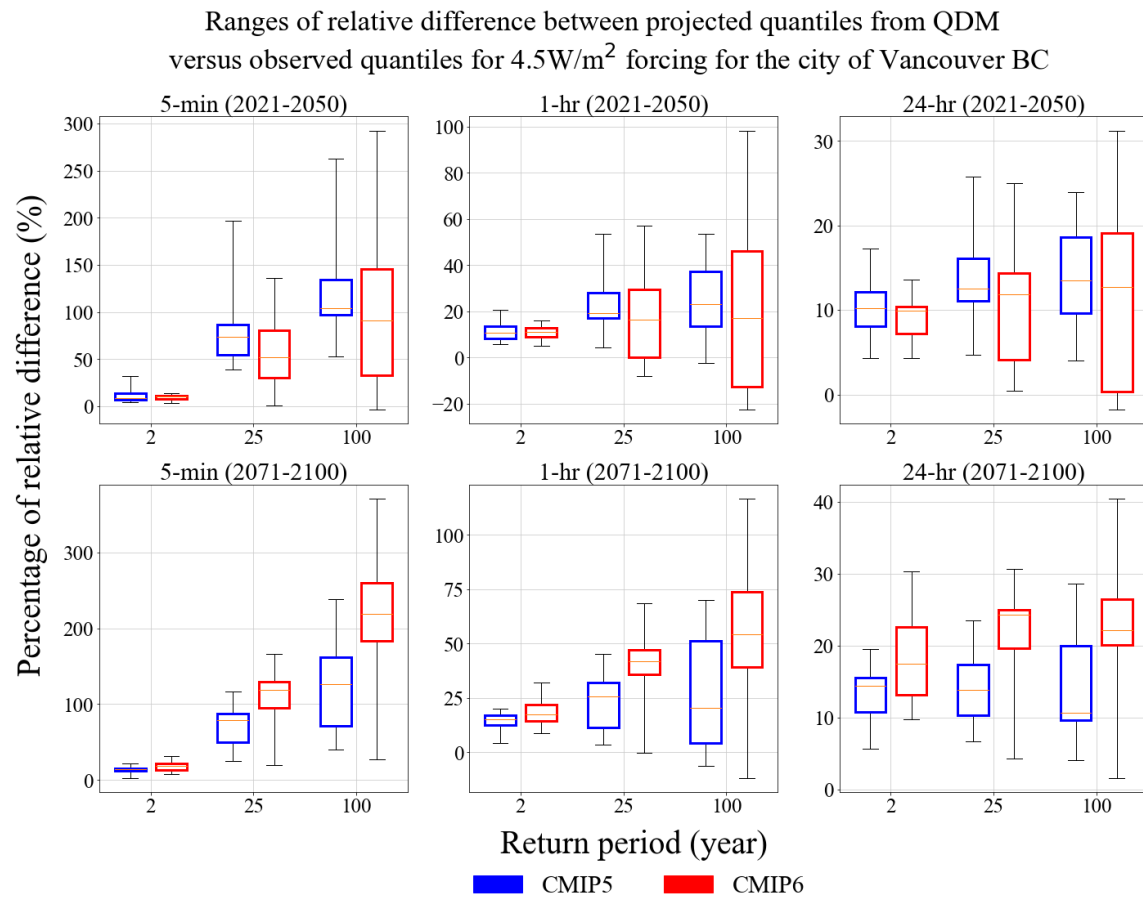


Figure B1. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 4.5 W/m², and along different future periods, for the city of Vancouver.

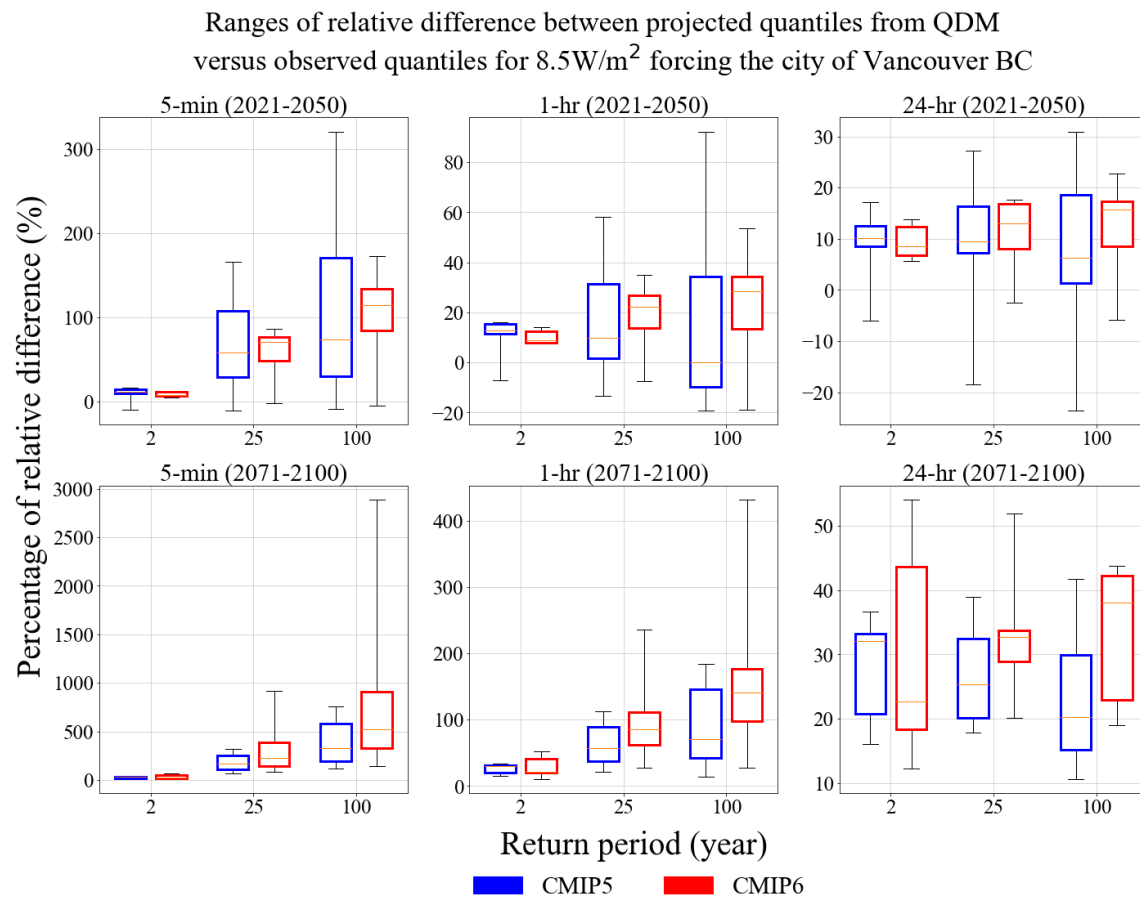


Figure B2. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 8.5 W/m^2 , and along different future periods, for the city of Vancouver.

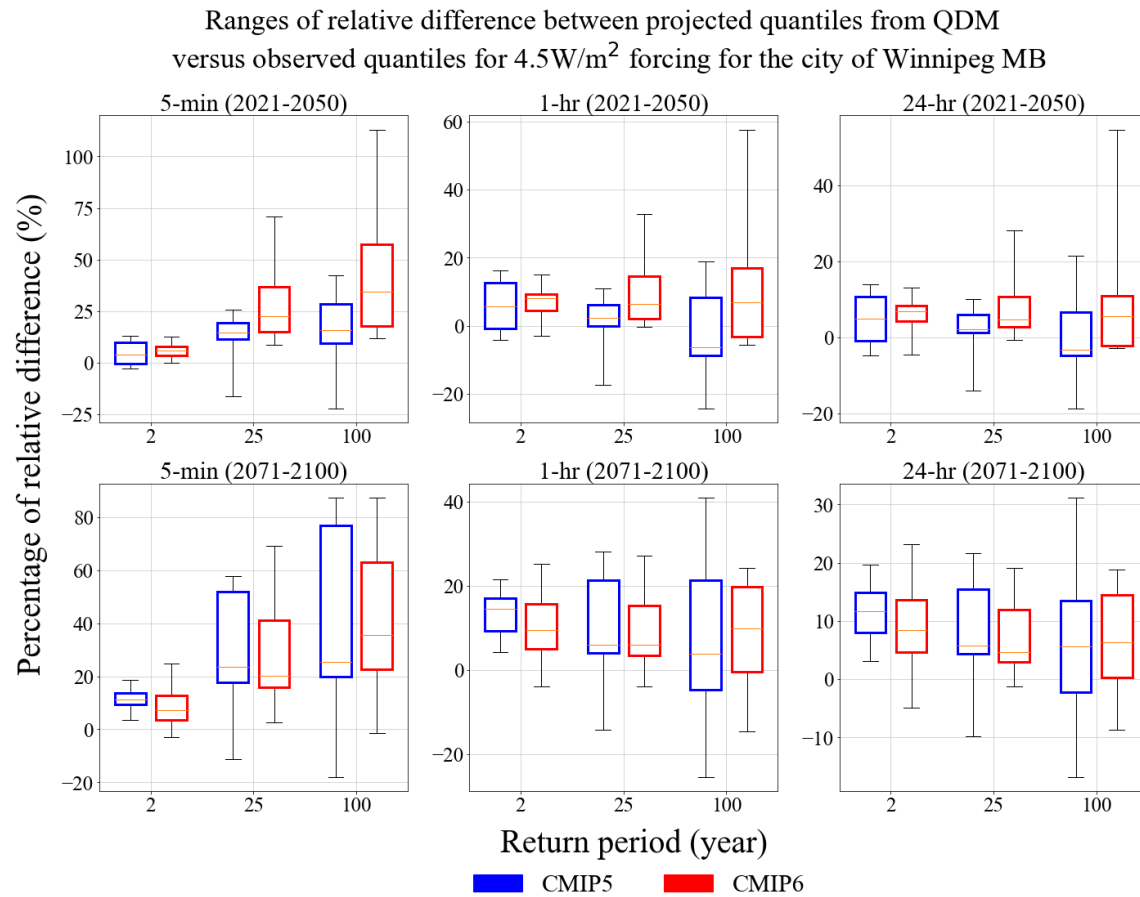


Figure B3. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 4.5 W/m², and along different future periods, for the city of Winnipeg.

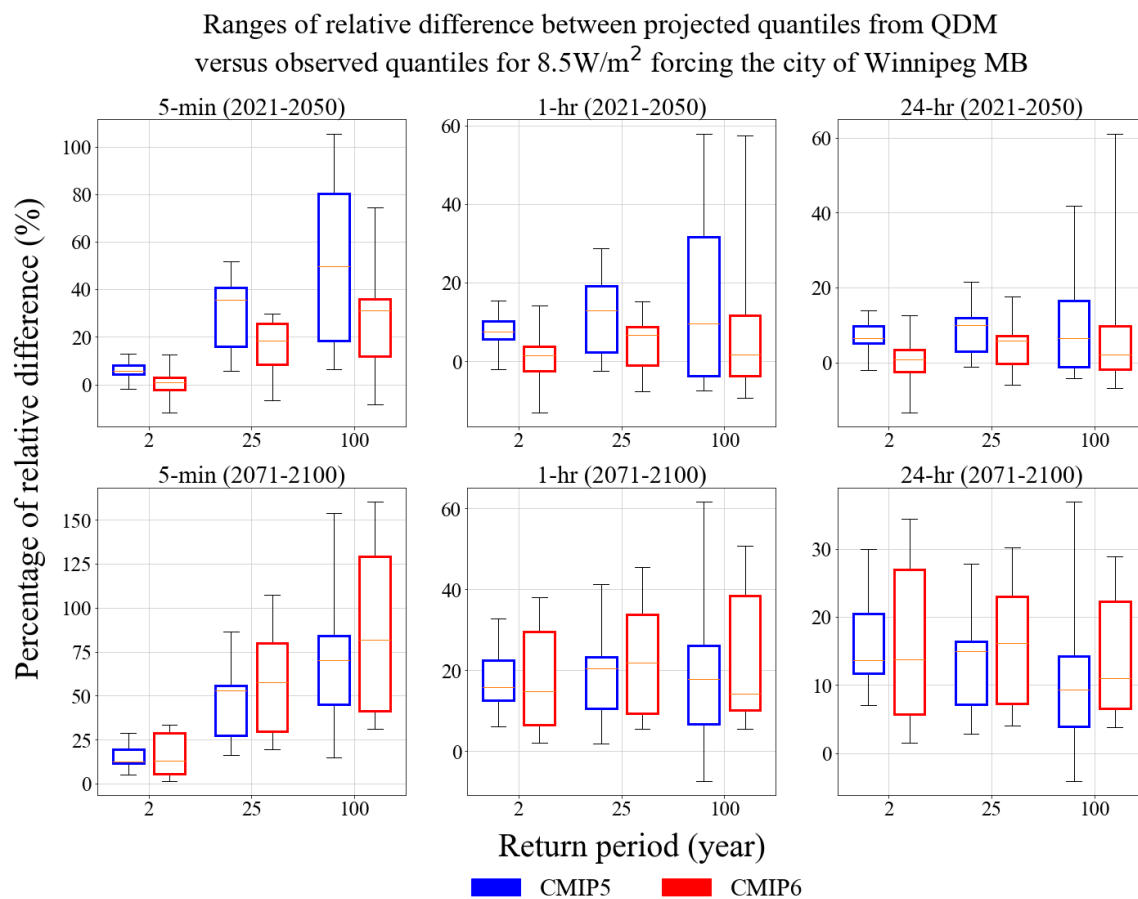


Figure B4. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 8.5 W/m², and along different future periods, for the city of Winnipeg.

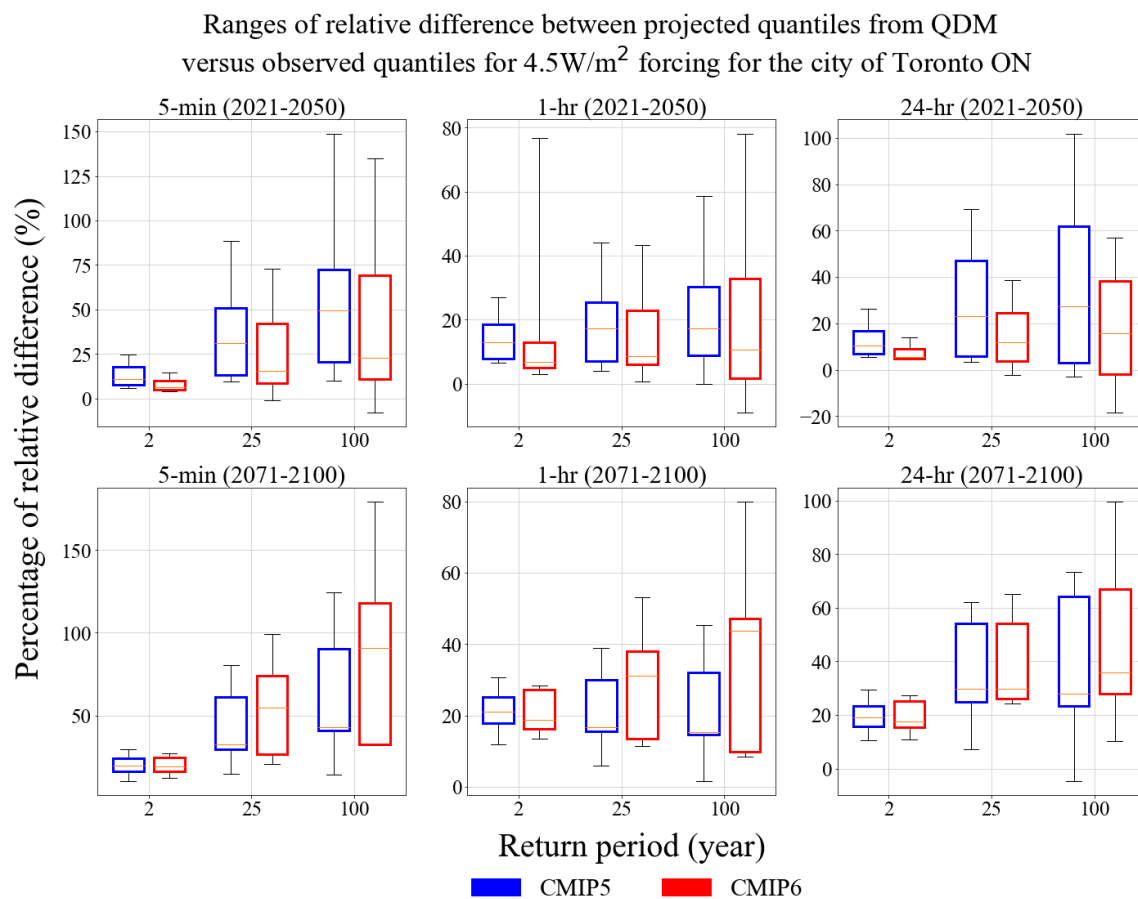


Figure B5. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 4.5 W/m^2 , and along different future periods, for the city of Toronto.

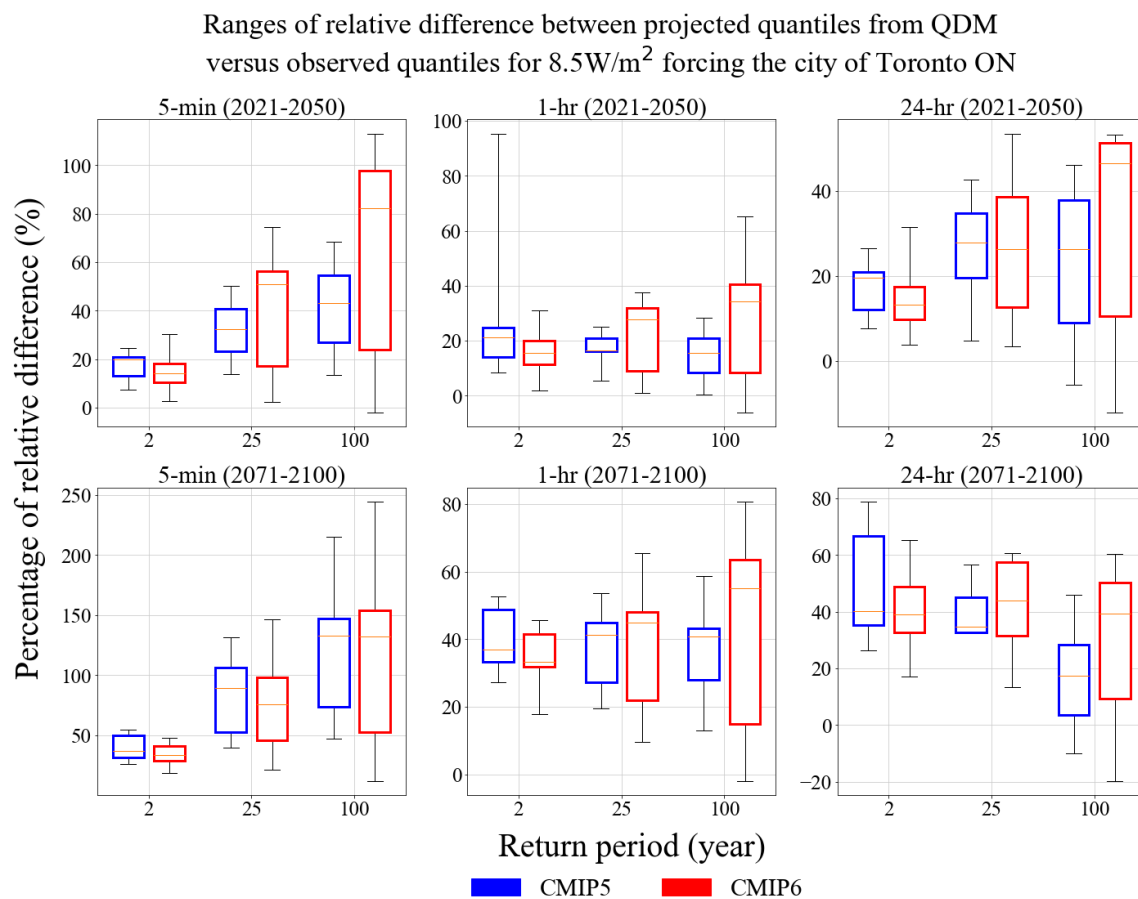


Figure B6. Comparison of the relative difference between projected IDF values using QDM versus observed IDF values for CMIP5 and CMIP6 models, 8.5 W/m², and along different future periods, for the city of Toronto.

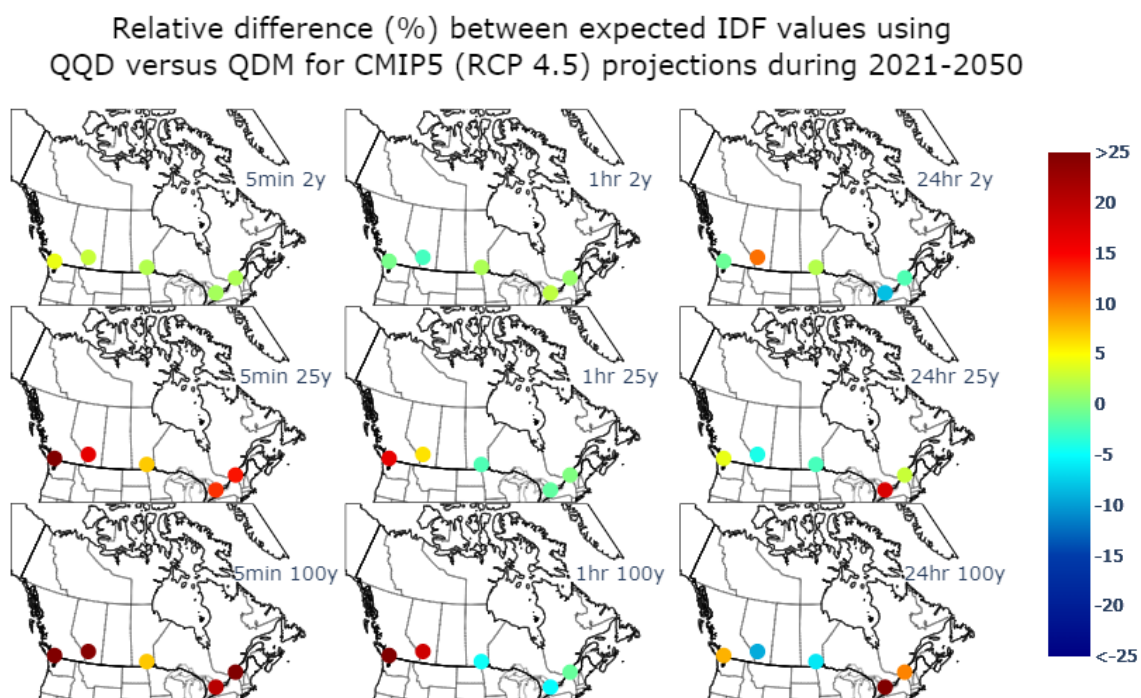


Figure B7. Relative difference between expected IDF values using QQD versus QDM for RCP4.5 scenario from CMIP5, along 2021-2050, for different durations and return periods.

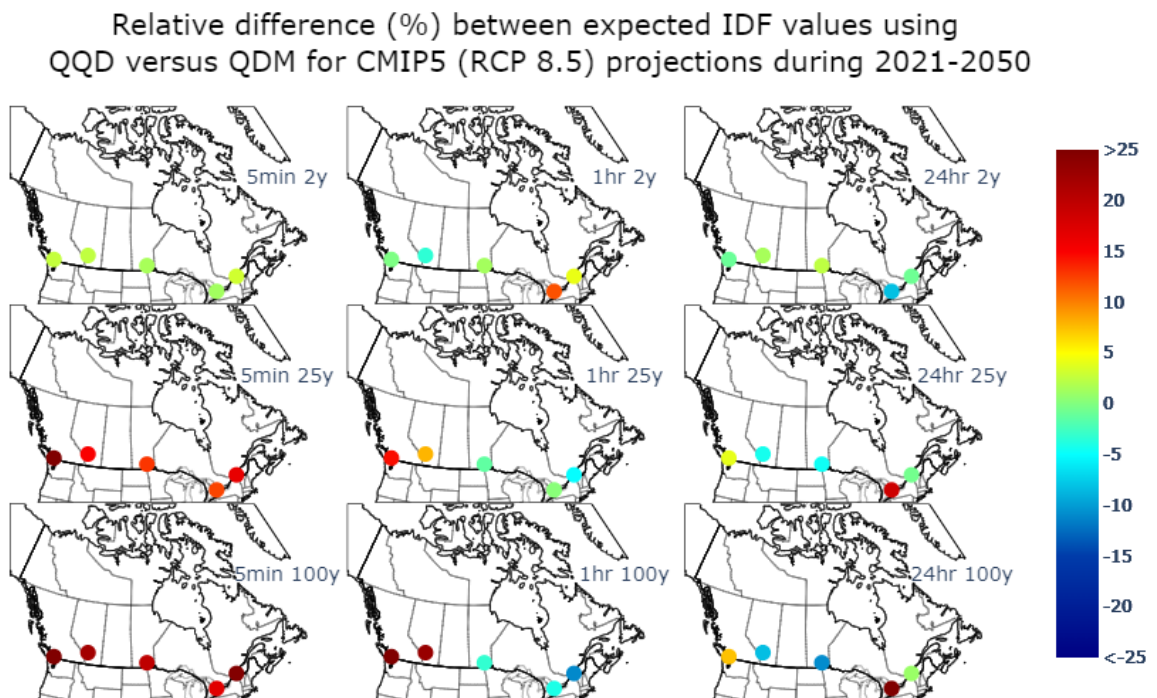


Figure B8. Relative difference between expected IDF values using QQD versus QDM for RCP 8.5 scenario from CMIP5, along 2021-2050, for different durations and return periods.

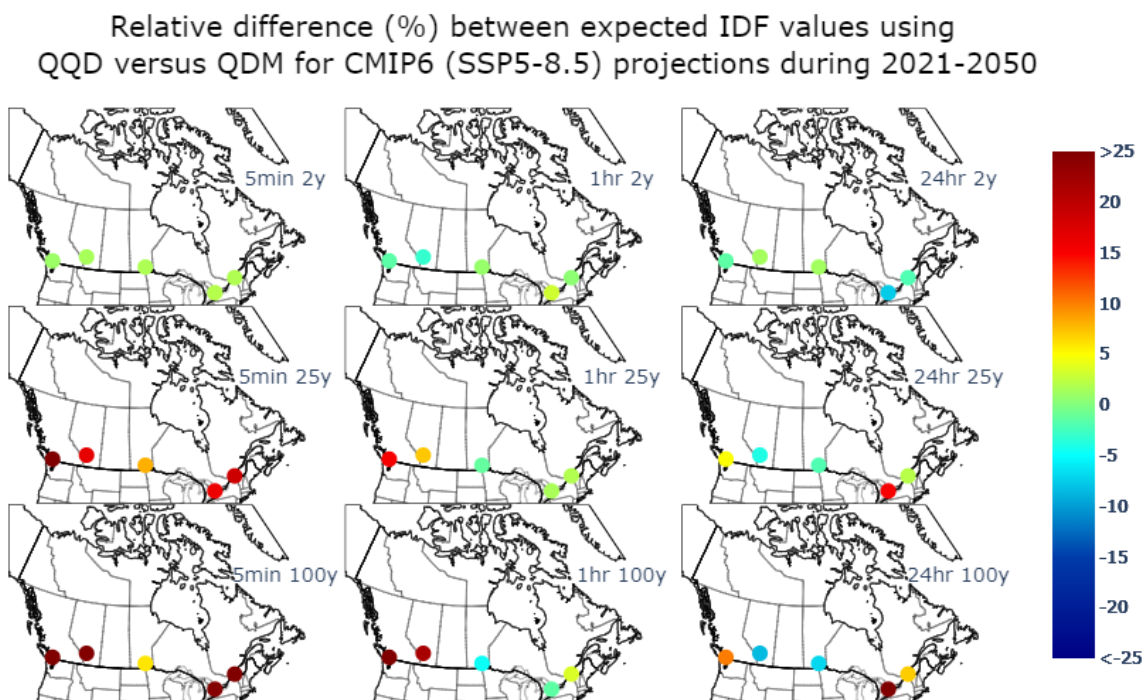


Figure B9. Relative difference between expected IDF values using QQD versus QDM for SSP5-8.5 scenario from CMIP6, along 2021-2050, for different durations and return periods.

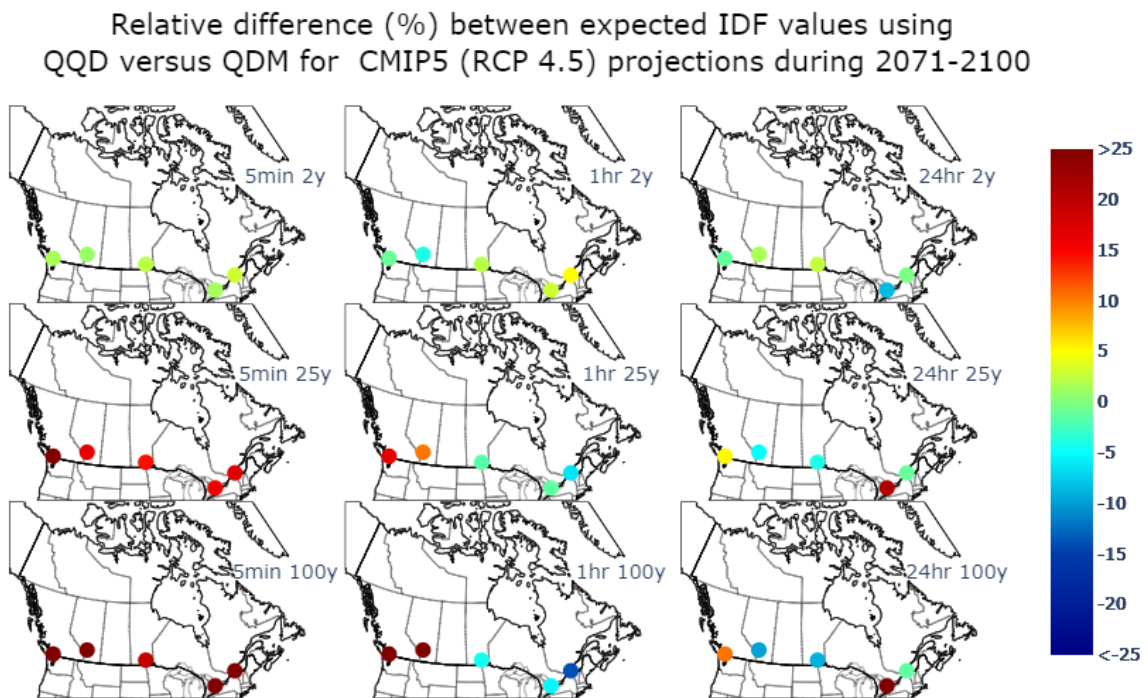


Figure B10. Relative difference between expected IDF values using QQD versus QDM for RCP4.5 scenario from CMIP5, along 2071-2100, for different durations and return periods.

Relative difference (%) between expected IDF values using
QQD versus QDM for CMIP6 (SSP2-4.5) projections during 2071-2100

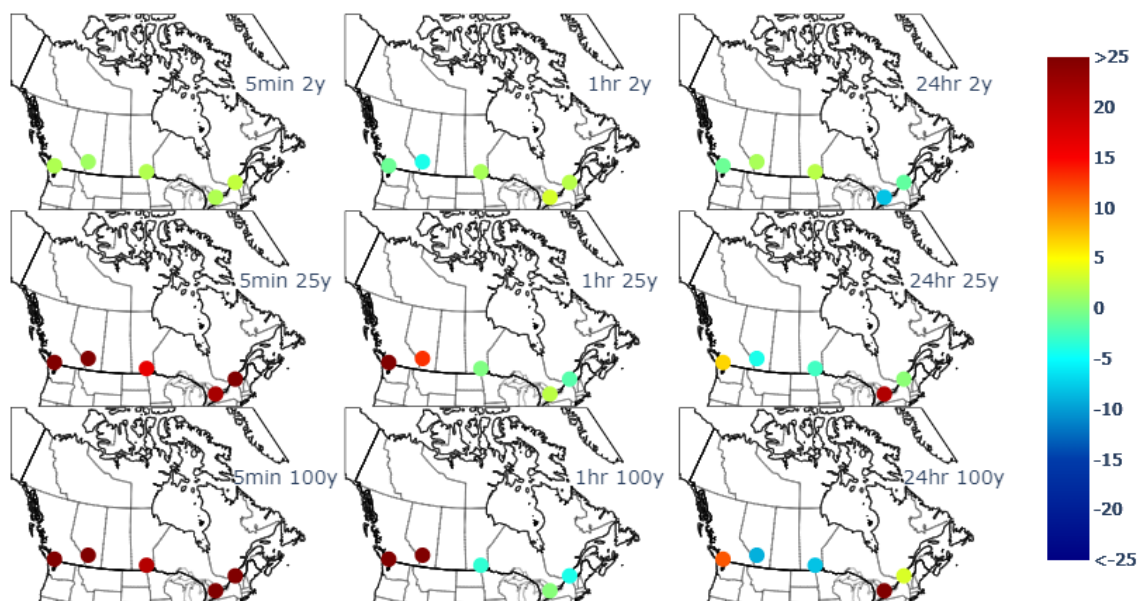


Figure B11. Relative difference between expected IDF values using QQD versus QDM for SSP2-4.5 scenario from CMIP6, along 2071-2100, for different durations and return periods.

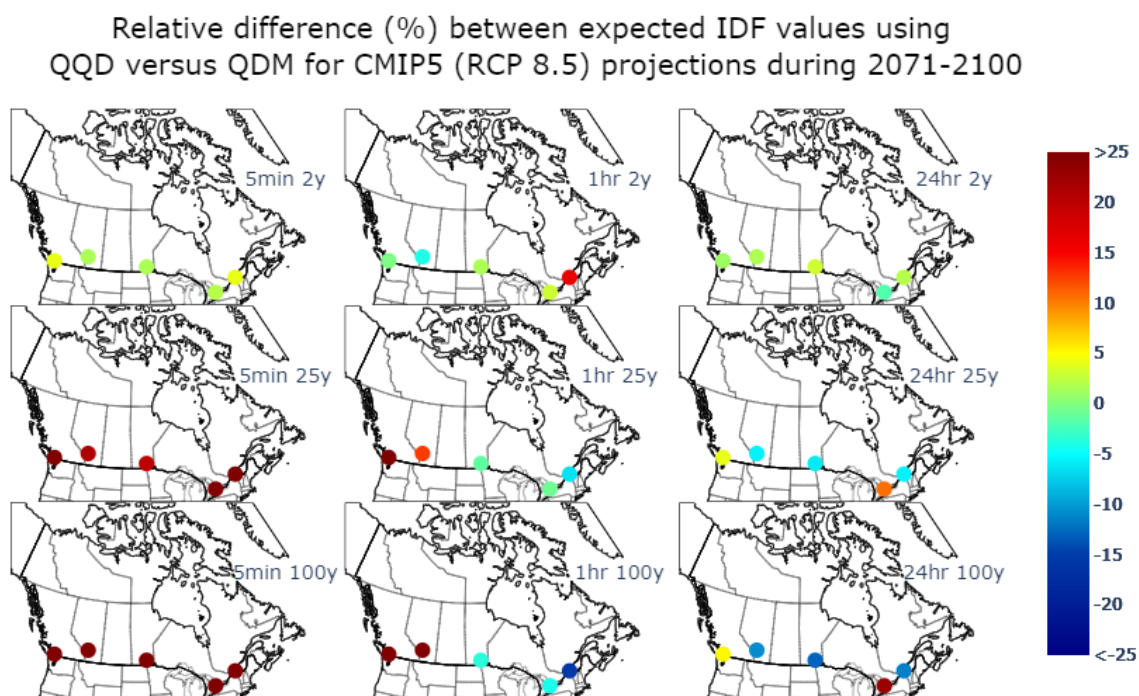


Figure B12. Relative difference between expected IDF values using QQD versus QDM for RCP8.5 scenario from CMIP5, along 2071-2100, for different durations and return periods.

