Mémoire

Auteur : Gauthier, Émilie
Promoteur(s) : Fettweis, Xavier; 24157
Faculté : Faculté des Sciences
Diplôme : Master en sciences géographiques, orientation global change, à finalité approfondie
Année académique : 2023-2024
URI/URL : http://hdl.handle.net/2268.2/20364

Faculté des sciences
Département de géographie

The Percentile Method in Assessing Episodes of Extreme Precipitation: Reanalyses and Future Scenarios

Mémoire présenté par : **Émilie GAUTHIER**

pour l'obtention du titre de

Master en sciences géographiques,
orientation Global Change

Année académique :	**2023-2024**
Date de défense :	**28 juin 2024**

Président de jury :	Pr. Xavier **FETTWEIS**
Promoteur :	Pr. Xavier **FETTWEIS**
Co-promoteur :	Diane **CHAUMONT**
	Dominique **PAQUIN**
Jury de lecture :	Diane **CHAUMONT**
	Pr. Sébastien **DOUTRELOUP**
	Jean **VAN CAMPENHOUT**

Acknowledgment

Choosing a topic for a master thesis is always a delicate step; it not only defines the work to be done the following year, but the chosen subject also has the potential to influence the student's academic career. First and foremost, I would like to thank my supervisors and advisors: Professor Xavier Fettweis from the Université de Liège and Diane Chaumont, Dominique Paquin and Chantal Quintin from the Ouranos team in Montréal. Thank you for giving me the opportunity to write my own project proposal and for your guidance, involvement, and technical advice throughout this journey.

Special thanks to Pascal Bourgault, Nathalie Bleau, and Gabriel Rondeau-Genesse from Ouranos for the server training, access to AQUARISC data, and assistance with the literature on extreme events.

Thanks to the reading committee for their time and interest in this research project.

I also thank Ouranos for generating and providing the CRCM data used in this study. Data access and analysis environment was provided through the Power Analytics and Visualization for Climate Science (PAVICS) platform (Ouranos and CRIM, 2018-2024). PAVICS is funded through Ouranos, the Computer Research Institute of Montreal (CRIM), Environment and Climate Change Canada (ECCC), CANARIE, the Fonds Vert and the Fonds d'électrification et de changements climatiques, the Canadian Foundation for Innovation (CFI), and the Fonds de Recherche du Québec (FRQ). Version 5 of the Canadian Regional Climate Model (CRCM5; Martynov et al. 2013, Separovic et al. 2013) was developed by the Centre pour l'étude et la simulation du climat à l'échelle régionale (ESCER) at the Université du Québec à Montréal (UQAM) in collaboration with Environment and Climate Change Canada (ECCC).

CRCM5 calculations were performed on the narval and beluga supercomputers of Calcul Québec and The Digital Research Alliance of Canada. Operating these supercomputers is funded by the Canada Foundation for Innovation (CFI) and the Ministère de l'Économie et de l'Innovation du Québec.

Résumé

Les événements de précipitation extrême peuvent avoir de nombreuses conséquences au Québec ; il suffit d'évoquer le déluge de Montréal de 1987 ou les inondations du Saguenay de 1996. Ces précipitations peuvent causer de nombreux dégâts et provoquer des crues éclairs, des débordements d'égout et des glissements de terrain (Van de Vyver *et al.,* 2021). Dans un contexte de changements climatiques, il est prévu que les pluies extrêmes seront de plus en plus fréquentes et intenses au Québec (Zhang *et al.*, 2019). C'est le cas également dans de nombreuses régions du monde, conséquence directe de la relation de Clausius-Clapeyron qui stipule que l'air plus chaud peut contenir plus de vapeur d'eau (Westra *et al.,* 2014).

Bien que le besoin d'une meilleure compréhension des événements de précipitations extrêmes sur le territoire soit très présent dans un contexte d'adaptation, le lien entre exposition à une forte pluie et inondations ou crues éclairs n'est pas toujours facile à évaluer. Comment repérer ces événements dans les séries climatiques du passé, et quels seront les changements prévus dans la fréquence et l'intensité des pluies extrêmes au Québec ? Comment informer le public et les décideurs des changements projetés des événements de précipitations extrêmes pour favoriser leur adaptation ?

Le présent projet de recherche a pour objectif de se pencher sur ces questions en appliquant la méthode des percentiles à différents indicateurs de précipitation extrême, tant sur les données de réanalyses que pour les projections climatiques. L'objectif est ainsi de faire le pont entre les événements passés repérés sur une série temporelle et les événements virtuels futurs basés sur différentes simulations climatiques.

La première étape consistera donc à choisir les meilleurs ensembles de données parmi ceux disponibles pour le Québec. La seconde étape consistera à définir les indicateurs de précipitation extrêmes. Dans le cadre de cette analyse seront retenues les quantités maximales aux 3 heures, aux 6 heures, aux 12 heures et aux 24 heures à une fréquence annuelle – donc une donnée par indicateur, par point de grille, par année. Les résultats seront ensuite comparés aux événements extrêmes passés grâce aux séries temporelles résultantes. Peut-on identifier les événements de précipitations extrêmes par les pics de ces séries temporelles ? Quel(s) indicateur(s) permettent le mieux d'identifier les événements extrêmes ?

Une fois que les indicateurs extrêmes permettant d'identifier les crues et inondations éclairs seront définis, il sera possible d'évaluer leur évolution dans le futur jusqu'à l'horizon 2100 par la méthode des percentiles. Est-ce que ces événements deviendront plus fréquents ou plus

intenses dans le futur, est-ce que l'on pourrait voir des changements dans les périodes de retour des événements extrêmes ? Comparer les changements projetés pour divers horizons et scénarios permettra ainsi de mettre en application différentes techniques de représentation pour rendre les conclusions de l'étude accessible pour le public. Sur base de la littérature et de l'analyse de différents sites webs d'information climatique, une réflexion sera également entamée pour intégrer les conclusions de l'étude au site Portraits climatiques d'Ouranos, de même que différentes pistes pour l'amélioration de la plateforme dans le but d'accompagner au mieux les usagers face aux changements projetés des événements de précipitations extrêmes.

Abstract

Extreme precipitation events can have numerous consequences in the province of Québec, Canada; the Montréal deluge of 1987 or the 1996 Saguenay floods are two examples among many. These precipitation events can cause significant damage and lead to flash floods, sewer overflows, and landslides (Van de Vyver *et al.*, 2021). In the context of climate change, it is anticipated that extreme rainfalls will become more frequent and intense in Québec (Zhang *et al.*, 2019). This is also the case in many regions of the world, a direct consequence of the Clausius-Clapeyron relationship, which states that warmer air can hold more water vapor (Westra *et al.*, 2014).

While the need for a better understanding of extreme precipitation events is very present in the context of adaptation measures, the link between heavy rainfall and floods or flash floods is not always easy to assess. How to identify these events in past climate series, and what are the expected changes in the frequency and intensity of extreme rains in Québec? How to inform the public and decision-makers about the projected changes in extreme precipitation events to promote their adaptation and resilience?

The present research project aims to address these questions by discussing the future evolution of the percentiles to different indicators of extreme precipitation, both on reanalysis data and for future scenarios. The objective is to bridge the gap between past events identified on a time series and future virtual events based on different simulations.

The first step will therefore be to choose the best dataset among those available for Québec. The second step will be to define extreme precipitation indicators. In this analysis, the maximum quantities at 3 hours, 6 hours, 12 hours, and 24 hours on an annual frequency will be retained – thus one data per indicator, per grid point, per year. The results will then be compared to past extreme events through the resulting time series. Can extreme precipitation events be identified by the peaks of these time series? Which indicator(s) best identify extreme events?

Once the extreme indicators allowing for the identification of floods are defined, it will be possible to evaluate their evolution in the future until the year 2100 using the percentiles method. Will they become more frequent or intense in the future, could changes be observed in the return periods of extreme events? Comparing the projected changes for various horizons and scenarios and applying different representation techniques will help to make the conclusions of the study accessible to the public.

Based on the literature and the analysis of different climate information websites, a reflection will also be initiated on how to best integrate the conclusions of the study into the Ouranos Climate Portraits site, as well as different suggestions to improve the platform. Consideration will also be given to supporting users’ comprehension regarding projected changes in extreme precipitation events.

Contents

List of Figures

List of Tables

Acronymes

Acronyms	Definition
AQUARISC	Apport Québécois pour l'Anticipation des Risques d'Inondation et des Sécheresses au Canada
CaLDAS	Canadian Land Data Assimilation System
CaPA	Canadian Precipitation Analysis
CC	Clausius-Clapeyron
CFI	Canada Foundation for Innovation
CLASS	Canadian Land Surface Scheme
CMIP6	Coupled Model Intercomparison Project Phase 6
CRCM5	Canadian Regional Climate Model version 5
ECCC	Environment and Climate Change Canada
ECMWF	European Centre for Medium-Range Weather Forecasts
ESCER	Centre pour l'étude et la simulation du climat à l'échelle régionale
ESM	Earth system model
GCM	Global Climate Model
GDRS	Global Deterministic Reforecast System
GEM	Global Environmental Multiscale
IDF	Intensity Duration Frequency
IPCC	Intergovernmental Panel on Climate Change
IRM	Institut Royal Météorologique de Belgique
MSC	Meteorological Service of Canada
MPI	Max Planck Institute
PAVICS	Power Analytics and Visualization for Climate Science
RCM	Regional Climate Model
RDRS	Regional Deterministic Reforecast System
SSP	Shared Socioeconomic Pathways
UQÀM	Université du Québec À Montréal
WMO	World Meteorological Organization

CHAPTER I. GENERAL INTRODUCTION

There is now consensus among the scientific community that climate change will have numerous impacts on ecosystems, including its effects on the hydrological cycle (IPCC, 2021). Extreme precipitation events are especially sensitive to temperature variations; indeed, the Clausius-Clapeyron relationship predicts that for every degree of warming, the atmosphere can hold approximately 7% more water vapor (Lenderink & Van Meijgaard, 2008; Westra *et al*., 2014). With this additional water vapor, extreme events have the potential to become increasingly intense and devastating. These extreme precipitation events can lead to dramatic repercussions on the territory, especially considering the increasing populations in urban areas (Gimeno *et al.*, 2022).

Québec is a region impacted by these episodes of extreme precipitation, and throughout its history, Montréal has frequently been the scene of major precipitation events. The Montréal deluge of July 14, 1987, is a striking example, with dramatic consequences: 40,000 residences flooded, 350,000 subscribers without electricity, major impacts on transportation systems, 2 fatalities, and an estimated costs of $64,216,681 (Government of Canada, 2023).

To study past extreme precipitation events and gain a better understanding of their future evolution, different data sources can be used. Climate reanalyses and Earth System Models (ESMs) are examples. Using hourly data of historical and future simulated precipitation accumulation, it is possible to study the intensity and dynamics of these extreme precipitation events. In this way, knowledge can be gained on how climate change will affect these strong precipitations, and which type of events (short or long-duration event) will be most affected by the increase of atmospheric temperature. In this study, on top of the data analysis, different approaches will be explored to facilitate the communication of complex results and statistics to users of climate information websites.

Problem definition and objectives

The present research project has three distinct goals. The first is to assess the capability of different data sources (reanalyses and regional climate models) to identify extreme precipitation events in past time series. To achieve this, maximum intensity temporal indicators (3 hours, 6 hours, 12 hours, and 24 hours) will be applied to hourly reanalyses data series to identify high precipitation peaks for the city of Montréal. These peaks will then be documented to assess if they are indeed the cause of flooding events.

The second objective is to evaluate the future evolution of extreme precipitation events by applying temporal indicators to future projections from a regional climate model (CRCM5) driven by different data sources (ERA5-LAND reanalysis, and two ESMs, the CanESM5 and MPI-ESM1.2-LR) for two emission scenarios. As the future development of climate change is still uncertain and strongly depends on greenhouse gas emissions released in the atmosphere, the IPCC has defined different scenarios known as Shared Socioeconomic Pathways (SSP). As part of this study, two emission scenarios will be considered in future simulations, namely SSP1-2.6 and SSP3-7.0. The analysis by percentiles will allow for the assessment of the overall trend in the intensity of these events up to 2100, and in that way, verify the approximation of the Clausius-Clapeyron relationship (+7%/°C) at a local scale. Will the intensity of extreme precipitation events increase in the future, and if so, is this increase consistent with the Clausius-Clapeyron relationship? Is the trend in maximum quantity the same for different simulations and event types?

Extreme precipitation events lead to major impacts on the territory, and as such, it appears essential for users and decision-makers to understand the upcoming changes of this hazard to facilitate better adaptation. However, communicating complex climate information in an adaptation context is not always straightforward (Charron, 2016). The final objective of this work is therefore to discuss possible avenues and propose approaches to vulgarize the scientific findings of this study in a way that is understandable for users. Different popularization techniques and formats for climate information websites (such as storyline, temporal analogs, Intensity Duration Frequency (IDF) curve and dynamic and interactive visualization tools) will be presented, along with their applicability regarding the conclusions of this study.

Approach

The next chapters of this report are structured as follows:

2. Literature Review will provide the general context of the project and lay the foundations of the theory.

3. The Methodology and Data section will present the different data sources and the basic methodology applied to detect extreme events, draw time series, and compute the percentiles.

4. The Results section will provide a detailed account of the findings and sets the stage for their interpretation.

5. The Discussion section will further analyze the results in relation with the Clausius-Clapeyron relationship.

6. The Popularizing Science in Climate Information Websites chapter will explore avenues to present the results of the study in the context of popularization and knowledge transfer.

7. The Conclusion section will summarize the study's results, as well as proposals and suggestions for future research and development.

CHAPTER II. BACKGROUND

II.1. Extreme precipitation events in Montreal

With more than 1.7 million inhabitants over an area of 498 km^2, Montréal is the main city of Québec, and the largest French-speaking city in America. Island metropolis located on the St. Lawrence River, it is an important economic, commercial, and financial center.

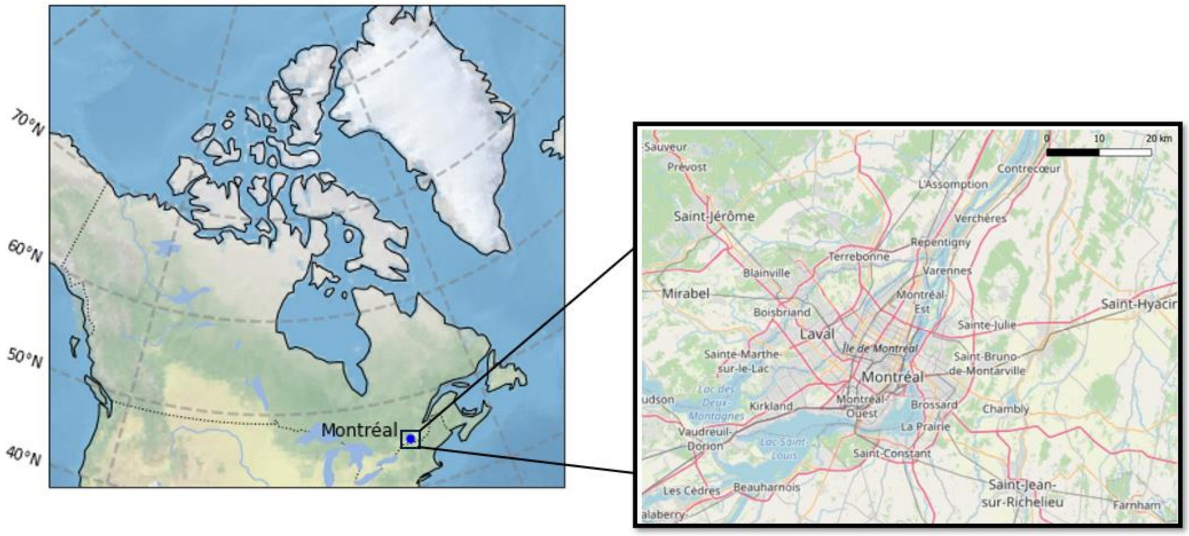


Figure 1: Localization and geography of Montréal, Canada

However, with its humid continental climate (Dfb in the Köppen classification), Montréal is known to experience heavy rainfall events, mostly during the summer. Like much of North America, Montréal suffers many consequences of climate change; increase in temperature, heat waves, droughts, to name a few of them (Bush & Lemmen, 2019).

Annual amounts of precipitation in Montréal total on average 1000 mm, including 175 cm of snow during the winter. Precipitation received is greater than 55 millimeters on average every month and exceeds 100 millimeters during the summer months (Gouvernement du Québec, 2024). However, with climate change, annual rainfall amounts are expected to increase in future years, as illustrated in Figure 2 below:

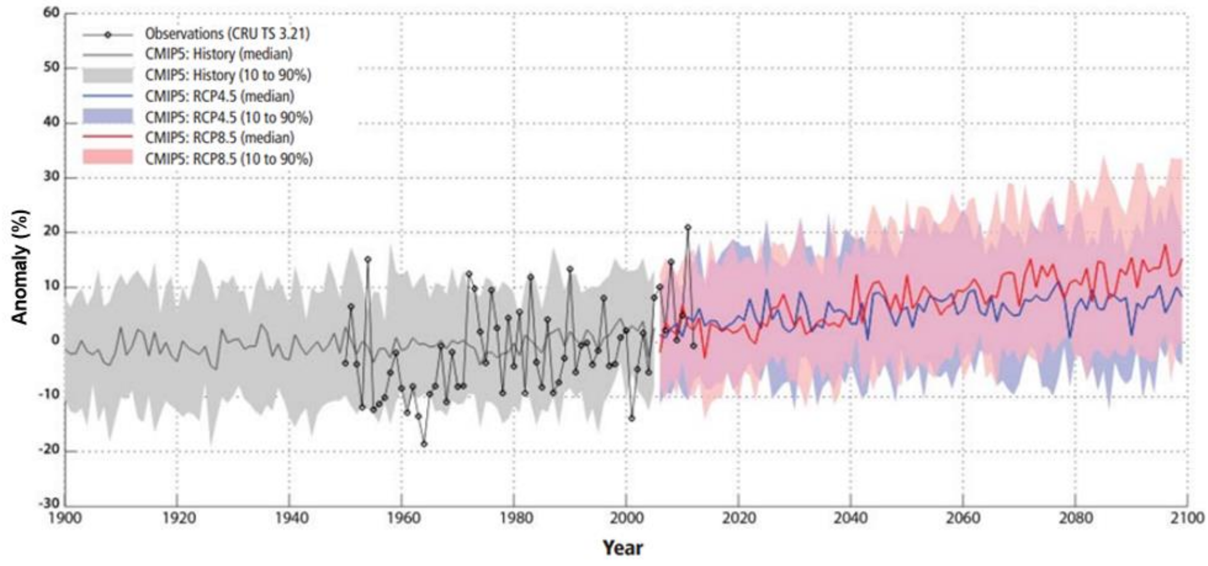


Figure 2: Evolution of anomalies (%) in total annual precipitation, recorded (1950-2012) and simulated (1900-2100), for the southern Québec region including Montréal (City of Montréal, 2017).

As for extreme precipitation events, a report from the city indicates not only a rising trend in the frequency of rainy days in the meteorological data, but also in the quantities of the rainiest days of the year, as shown in the Figure 3 below:

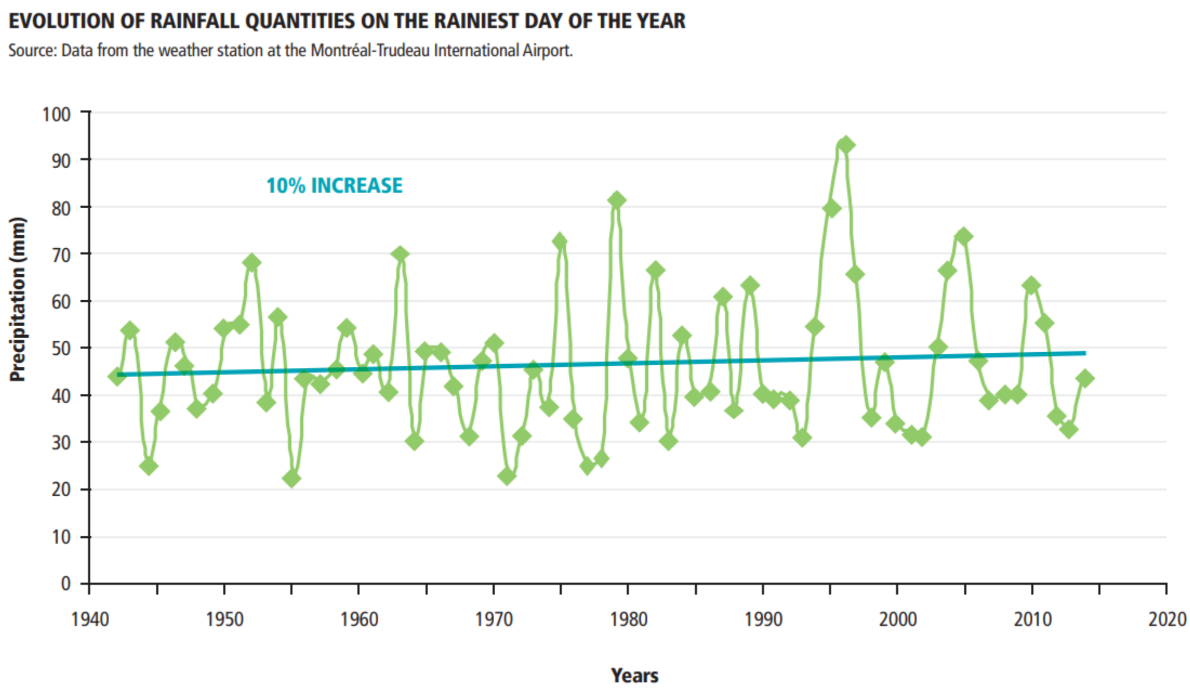


Figure 3: Evolution of rainfall quantities on the rainiest day of the year from 1942 to 2014 for the weather station at the Montréal-Trudeau International Airport (City of Montreal, 2017).

These extreme events can lead to devastating effects in urban areas like Montréal. Flooding, sewer backflows, loss of electric power, major economic impacts and even loss of lives are some of the consequences that can be linked to these events (Van de Vyver *et al*., 2021). One example of these major events is the flooding of 14th July 1987, that will be presented in the next section.

II.1.1. The flood of 14th July 1987

On July 14th, 1987, a thunderstorm line (associated with a mesoscale convective system) left over 100 mm of rain in two hours on the island of Montréal. The McGill station recorded 101.2 mm of rain in 2 hours and 86 mm in 1 hour, while the Lafontaine Park station measured 103 mm of rain over the day (Bergeron *et al*., 1997). These amounts equate to the average rainfall for an entire July month in just a few hours. Since the sewer system could only handle 40 millimeters of rain per hour at that time, the city quickly experienced major flooding.

The consequences were dramatic: 40,000 residences were flooded, and 350,000 subscribers were left without electricity. Transportation was severely impacted: the Décarie Highway was flooded up to 3.6 meters high, thousands of vehicles were stranded on the roads, and almost all subway lines ceased operation. Two deaths were reported, and the estimated cost of the floods amounted to $64,216,681 (Gouvernement du Canada, 2023).

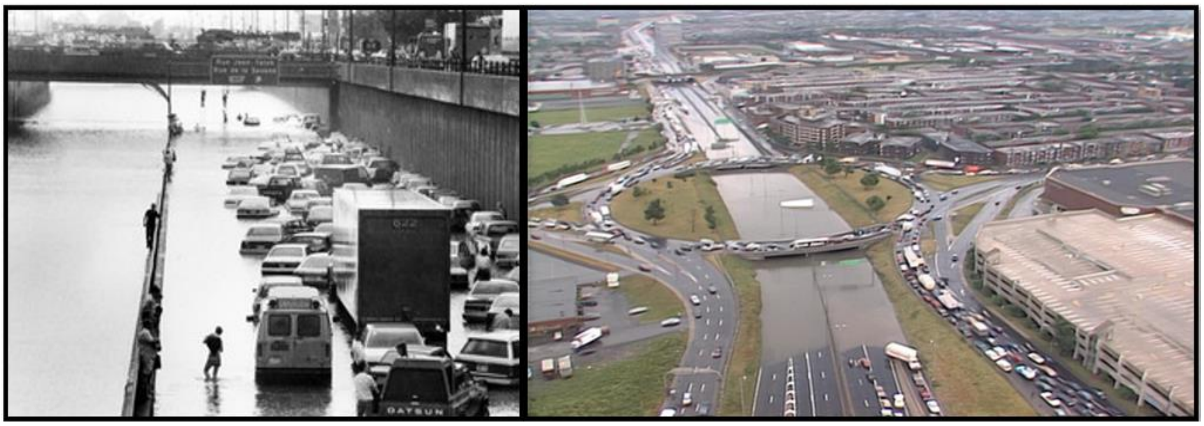


Figure 4: View of the Décarie Highway during the flooding on July 14, 1987. Adapted from Montreal Gazette (2019) and Radio-Canada (2017).

It is expected that these events would become more intense and frequent in a warming climate (IPCC, 2021). But what are the climatic causes of these changes?

II.2. The Clausius-Clapeyron relationship

One of the main drivers of the changes in extreme precipitation events is the Clausius-Clapeyron relationship. The Clausius-Clapeyron equation helps predict changes in the maximum water vapor content of the atmosphere following temperature, and is written as follow:

$$\frac{\partial e_s}{\partial T} = \frac{I_v * e_s}{R_v * T^2}$$

Where l_v is the enthalpy of vaporization (about 2.5 x 10^6 J kg^{-1}), R_v is the gas constant for water vapor (461.5 J kg^{-1} K^{-1}), and T is the absolute temperature (Westra *et al.*, 2014). The right-hand part of this equation being always positive, the saturation pressure always increases with temperature ($\frac{\partial e_s}{\partial T} > 0$). This equation gives proof that a warmer atmosphere has a greater capacity to hold water vapor. Under certain assumptions (such as no change in circulation patterns), this rate of water holding capacity is expected to increase by roughly 7 % for each degree of warming (Lenderink & Van Meijgaard, 2008, Pérez Bello *et al.,* 2021).

The increase in atmospheric water vapor significantly influences short duration extreme precipitation events, especially those of convective origin. This additional water vapor contributes to the increased precipitation quantity during heavy rainfall, an increase that has also been observed in practice.

In a study by Pérez Bello, Mailhot, and Paquin (2021), the outputs of the CRCM5 large ensemble were used to investigate the link between rising temperatures and extreme precipitation events. The analysis was conducted at both daily and sub-daily scales over the Northeastern North America domain for the period 1956-2099. Their results show that the response of extreme precipitation events to temperature changes was more pronounced for short-duration events (1h) than for longer events (24h). While the domain-wide median was consistent with the expected increase of 7%/°C, as stated by the Clausius-Clapeyron relationship, the results varied depending on the studied area and the use of surface air temperature or dew point temperature. A second study by Pérez Bello *et al.,* (2022) for the same domain and period supports this conclusion and emphasizes the importance of considering the precipitation type (convective or stratiform) in studying the impacts of temperature increase on extreme precipitation events.

A study conducted by Kirchmeier-Young and Zhang (2020) using three large ESM based ensembles (CanESM2, CanRCM4 and CESM1) and the RCP8.5 scenario also observed an increase in annual maximum precipitation events over North America over the period 1950-2100. However, the coarser spatial resolution (nine spatial domains covering all North

America) and lack of sub-daily analysis do not allow for more precise conclusions about Québec and the Montréal area for this publication.

On a broader scale, a paper by Sun *et al.* (2020), noted an increase in the amounts of annual maximum precipitation events at a daily scale using meteorological station data from HadEX2 for the period 1900-2018. This increase is particularly pronounced in Asia, Europe, and North America. Another study by Westra *et al.* (2014), synthesizes all available empirical data linking temperature and extreme precipitation. The authors emphasize that the change ratio is not constant and varies depending on temperatures and event type, as presented in Figure 5 below. A ratio exceeding the Clausius-Clapeyron law (super CC) is observed for temperatures between 12 and 22 °C, which could be explained by a shift from stratiform to convective events.

Other studies have linked this super CC scaling to the convective events, the reason being an excess of latent heat released during these events. With rising temperatures, an additional amount of latent heat is released, which enhances convection, leading to higher precipitation quantity (Papadopoulos-Zachos & Anagnostopoulou, 2023).

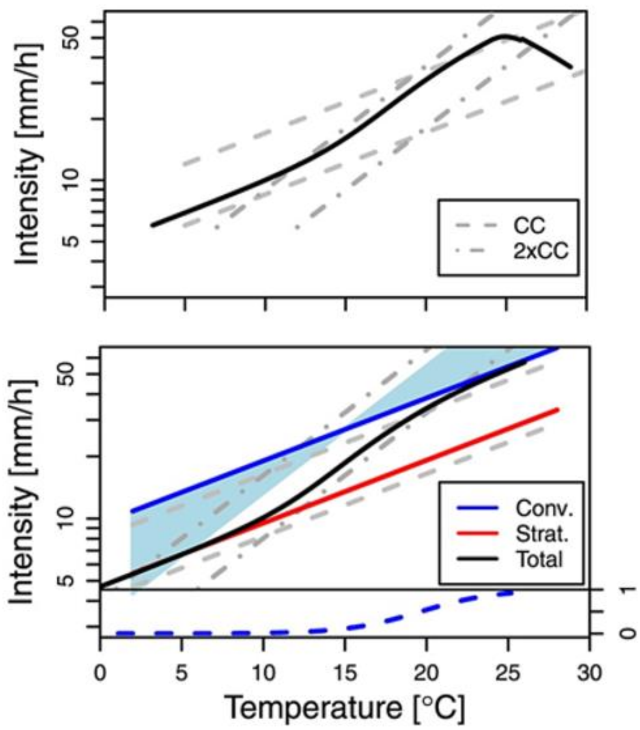


Figure 5: Conceptual diagram of the observed relationship between temperature and extreme rainfall intensity. The black line represents the basic behavior of higher rainfall intensity percentiles. On the bottom panel is illustrated the shift from stratiform to convective events, a hypothesis explaining the super CC-scaling, the dash blue line showing the relative contribution of convective rainfall to total rainfall. Adapted from Westra et al., 2014.

II.3. Popularizing climate information for users

There is now consensus among the scientific community that climate change will have numerous impacts on the territory. It's especially true for extreme precipitation events, given the anticipated increase in their intensity in the future. However, despite the increasing development of knowledge about climate change and its impacts, concrete adaptation measures are far from keeping pace, and this can be linked in part to the difficulties in communicating climate information to users (Dryzek *et al*., 2011).

The challenges associated with communicating climate science to users are numerous. One of them is the need to present data and results in a way that is meaningful to users, thus helping support decision-making and adaptation (Hewitson *et al.*, 2017). It is therefore essential to understand the user's need and the context in which the information will be utilized. Another challenge to communication is inherent to the nature of climate change itself: dealing with uncertainties. Indeed, it is impossible to predict with certainty how climate change will manifest locally (Nerlich *et al*., 2010), just as it is impossible to predict exactly when and with which intensity the next extreme precipitation event will occur.

It has been proven that risk perception is an essential concept, often emphasized as a prerequisite for adaptation. Risk perception is defined as the process by which an individual receives information from their environment and consciously transforms it into actions (Koguia *et al.*, 2021). Several studies have shown direct links between concerns about climate change and personal behaviors (Brosch, 2021). It is therefore essential to implement ways to make climate information interesting and meaningful to the public, and various techniques are applicable for this purpose.

The following subsections will briefly present some useful formats for presenting climate information to users on climate information websites. In Chapter 6 - Popularizing Science in Climate Information Websites, critical feedback will be made on the advantages and disadvantages of these different techniques and climate information websites in relation to the literature. Recommendations will also be made on how to best integrate the results of this study onto the Ouranos Portraits Climatiques website.

II.2.1. Climate Information Website

The number of climate information websites has seen a significant increase in the past decade. Although there is a wide variety of formats, their objective remains the same: to build a bridge between complex climate data and users to facilitate their understanding and support their adaptation (Hewitson *et al.,* 2017). The information available on those websites covers a wide range of climate-related topics: climate projections, case studies, popularized information, etc. These platforms therefore provide new opportunities in sharing visuals and in reaching a vaster and more diverse public (Newell *et al*., 2016).

A few examples of such platforms at a global and local scale include the Climate Change Knowledge Portal (World Bank Group), the IPCC WGI Interactive Atlas (IPCC), the Global Climate Change (NASA), the Attributing extreme events to climate change portal (CarbonBrief), the Climate Atlas of Canada (Prairie Climate Center), ClimateData (Canadian Centre for Climate Services) and PAVICS (Ouranos). Ouranos, the research consortium on climate change in Québec, also operates its own climate information portal called Portraits climatiques. Through this portal, users can visualize several climatic variables such as temperatures, precipitation, and climate indices. These variables are available at different temporal scales, including past and future scenarios, as well at different spatial scales covering the Québec province.

II.2.2. Storylines

Storylines are scenarios based on coherent narrative of past events or plausible future events (Sillmann *et al.,* 2021). In the case of extreme weather events, storylines are narratives that relate the physical hazard and its impacts on the territory. One well-known example of a storyline is the new emission scenarios developed by the IPCC, the SSP scenarios. These scenarios combine economic, social, and environmental trends to represent plausible future trajectories in the form of narratives, resulting in logical storylines of multiple possible futures (O'Neill *et al.,* 2013).

Narratives that report on impacts and damages are an avenue to increase users' emotional engagement regarding the risk (Brosch, 2021). A study published by Vasileiadou and Botzen (2014) supports that individuals who have experienced an extreme weather event endangering their lives have a much higher level of concern than those who have not experienced such an event. From a communication standpoint, linking climate change to extreme events reduces the complexity of the subject by simplifying it into a target that is easy for users to understand (Janković & Schultz, 2016). The storyline technique has the potential to illustrate a more coherent and clear vision of what future climatic conditions could look like. It's a tool especially useful in describing local manifestations of climate change (Bukovsky *et al.*, 2023), allowing for a more concrete visualization of the potential impacts of climate change for users.

II.2.3. Temporal Analogues

Temporal analogues are a popularization technique used to compare past events with those projected for the future in terms of intensity or frequency. By establishing connections between real events from the past and those of the future, temporal analogues help make the impacts of climate change on these events more tangible by simplifying the statistics and uncertainties associated with climate projections (Smith & Lawson, 2011). Temporal analogues should not be confused with spatial analogues, also often applied in climatology, which aim to compare the simulated future climate of one region with the climate of another region.

Figure 6 below, adapted from the latest IPCC report, provides an example of the application of both intensity and frequency temporal analogue techniques in the case of extreme temperature events:

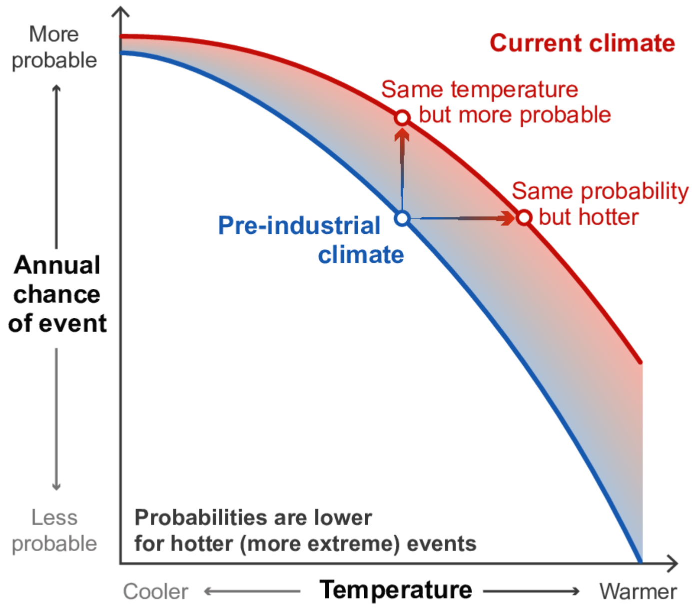


Figure 6: Changes in climate result in changes in the magnitude and probability of extremes. Temporal analogs, example for temperature extremes (Seneviratne et al.*, 2021).*

For example, the heatwave that struck Europe in 2003 was an extreme event as it exceeded the 90th percentile for historical data but could become a median event in 2071-2100 according to some climate projections (Smith & Lawson, 2011). By comparing past conditions that have significantly impacted the territory with possible future events, temporal analogues help translate sometimes complex statistics and aid in understanding the potential impacts of future events.

II.2.4. IDF Curves

The IDF curves (Intensity-Duration-Frequency) are a graphical representation that illustrates the relationship between the intensity of extreme precipitation (usually in mm/hour), their duration, and their return period for a specific area. This type of graph allows visualizing the links between those variables at the local level and is frequently used in the design of hydraulics infrastructures (Martel *et al.,* 2021). This graphical tool can also be applied to compare the characteristics of past extreme precipitation events to those of the future, and in that way highlights the expected changes in rainfall amounts. For example, Figure 7 illustrates the IDF curves simulated by a regional climate model (CRCM driven by CGCM3#4) for the periods 1961-2000 and 2041-2070.

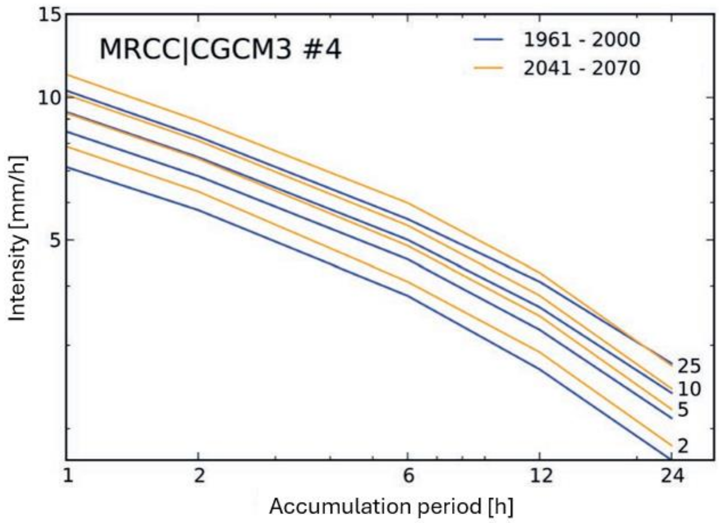


Figure 7: IDF curves for the St-Laurent valley (Québec, Canada) as simulated by CRCM driven by MCCG3#4 for return periods of 2, 5, 10 and 25 years. Adapted from Charron, 2016.

II.2.5. Dynamic and interactive visualization tools

With the proliferation of climate information websites, new visualization techniques are emerging, making possible the creation of figures (time series, maps, diagrams, etc.) that are both dynamic and interactive. A dynamic figure is a method of representing data that includes movement, often over time (Cook, 2009). In climatology, this representation technique is frequently used to illustrate changes over time, for example with animated maps showing year-to-year temperature changes, or dynamic time series of a phenomenon.

A second technique is the use of interactive interfaces, which allow users to interact with the visualization tool, for example by enabling them to select, zoom, or filter options directly on the interface (Terrado *et al.,* 2022). Dynamic and interactive visualization tools have the potential to engage diverse audiences and contribute to their learning by maintaining their interest and promoting the retention of information. However, these techniques are generally more complex to implement (Newell *et al.*, 2016).

CHAPTER III. METHODOLOGY AND DATA

The following section will present the different databases and simulations used in this analysis, along with the reasons behind their integration within this project. Additionally, the foundations of the methodology used to select the area and identify extreme precipitation events will be detailed.

III.1.1. Reanalyses

Data from two climate reanalyses are used in this project, namely ERA5-Land hourly and RDRS (Regional Deterministic Reforecast System). A climate reanalysis is a product that assimilates past meteorological data observations (from various sources) to model to generate continuous databases over time and space for several atmospheric variables (Reichler & Kim, 2008). The advantage of these products lies in their ability to address a primary limitation of the meteorological observation network, which is its inability to always cover the entire globe comprehensively at all times. However, the use of statistical models and averaging over the area of a grid point tends to underestimate the intensity of very localized extreme events, which is especially true in the case of precipitation events (Zolina *et al.*, 2004), as we will discuss further.

The ERA5-Land stands as one of ECMWF's flagship reanalysis products. This reanalysis, available freely on the Copernicus Climate Data Store website, spans from 1950 to the present day (with a 2 to 3 months lag) for all land surfaces on a global scale. With hourly temporal resolution and a spatial resolution of 0.1° by 0.1° (equivalent to grid points of about 11 km by 8 km for Montréal, Canada), this reanalysis gives information on numerous climatic variables, including hourly precipitation (ECMWF, 2024).

The RDRS is a North American reanalysis managed by Environment and Climate Change Canada. Covering the period from 1980 to 2018 with a resolution of 10 km, this reanalysis provides several variables describing the atmospheric state, such as temperature, precipitation, surface pressure, relative humidity, etc. This product is a combination of several models: initially, simulations at a 39 km resolution are generated by the Global Deterministic Reforecast System (GDRS) initiated by ERA-Interim. Subsequently, dynamic downscaling to 10 km resolution is conducted by RDRS, which is coupled with the Canadian Land Data Assimilation System (CaLDAS) and Canadian Precipitation Analysis (CaPA) to produce precipitation and surface data (Gasset *et al.*, 2021). The scheme depicted in Figure 8 below illustrates the applied method in more detail.

Those two reanalyses were used in the scale of this study, the reasons being that ERA5-Land is one of the most used reanalysis products, while RDRS is a Canadian reanalysis specifically developed for the North American domain, thus potentially better adapted to the study area. Furthermore, precipitation is assimilated in RDRS (Gasset *et al.*, 2021), while it is not the case for ERA5-Land. The use of two reanalyses also allows for results inter-comparison and a more robust analysis of past extreme events.

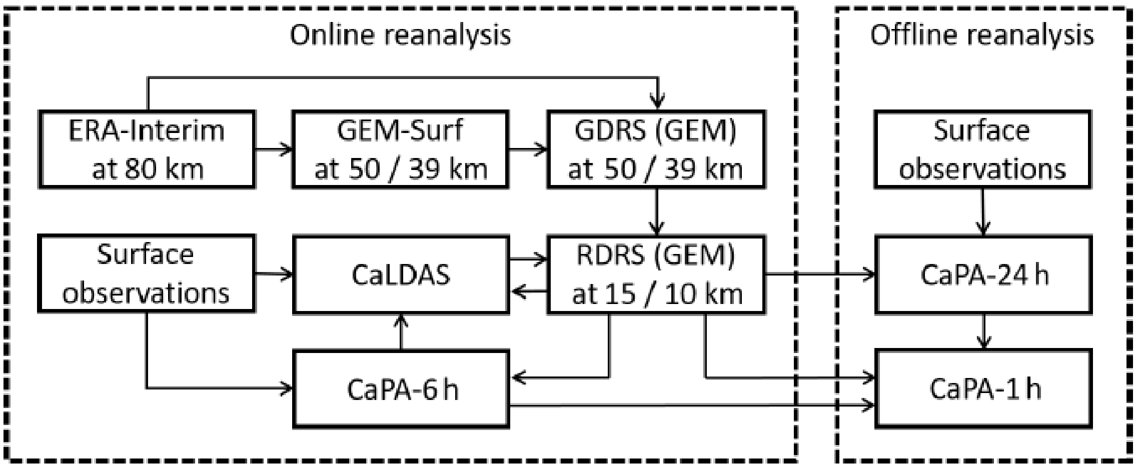


Figure 8 : Main components of the method followed to produce RDRS results (Gasset et al., 2021)

III.1.2. Regional climate model – CRCM5

The CRCM5 (Canadian Regional Climate Model) (Martinov *et al.*, 2013; Separovic *et al.*, 2013) is a regional climate model (RCM) developed by the ESCER center at the Université du Québec à Montréal (UQAM), in partnership with Environment Canada, and Ouranos. This RCM is based on the GEM 3.3.3.1 (Global Environmental Multiscale) model, a numerical weather prediction model (Zadra *et al.*, 2008). The model uses semi-implicit semi-Lagrangian dynamics on a regular grid with a resolution of approximately 12 km over the North American domain, following the CORDEX protocol. The timestep of the model is five minutes, and a light spectral nudging is used for winds above 500 hPa. The surface scheme is given by the Canadian Land Surface Scheme version 3.5 (CLASS 3.5). The precipitation is computed either from the Kain-Fritsch scheme (convection) or following the Sundquist scheme (large-scale)

(Martinov *et al.,* 2013). This model is used, among other purposes, to generate a set of 50 simulations integrated into the ClimEx project (Leduc, 2019).

To generate results, an RCM must be boundary-forced by an external data source. In this study, three drivers are used for boundary forcing, namely a reanalysis (ERA5-Land) and two CMIP6 generation ESMs (CanESM5 and MPI-ESM1.2-LR). The Canadian Earth System Model version 5 (CanESM5) is developed by the Canadian Centre for Climate Modelling and Analysis, a branch of Environment and Climate Change Canada (Swart *et al.*, 2019), while MPI-ESM1.2-LR is developed by the Max Planck Institute (MPI) (Mauritsen, 2019). The use of more than one GCMs allows an evaluation of uncertainties in the RCM simulations. At the time of the beginning of this project, only the MPI-ESM1.2-LR and CanESM5 CRCM5 driven simulations were publicly available.

The GCMs driven simulations cover the period 1950-2100: for the future simulations, two emission scenarios were used, namely SSP1-2.6 and SSP3-7.0. The acronym SSP stands for Shared Socioeconomic Pathway scenarios, which are emission scenarios used in the last IPCC assessment report (Ara Begum *et al.*, 2022). These scenarios are narratives that consider different socio-economic assumptions, allowing for the integration of population growth, land use, and adaptation measures into emission scenarios. The SSP1-2.6 scenario describes a future where greenhouse gas emissions would decrease drastically to limit global warming to + 1.5°C at the end of the century. The SSP3-7.0 scenario presents a continuous increase in greenhouse gas emissions and is currently the most likely following the political engagements taken until now. Figure 9 below illustrates the process of generating climate projections. The concentration derived from emission scenarios is integrated into climate models, which allows for the generation of climate projections in terms of temperature increase at the global scale with respect to historical period.

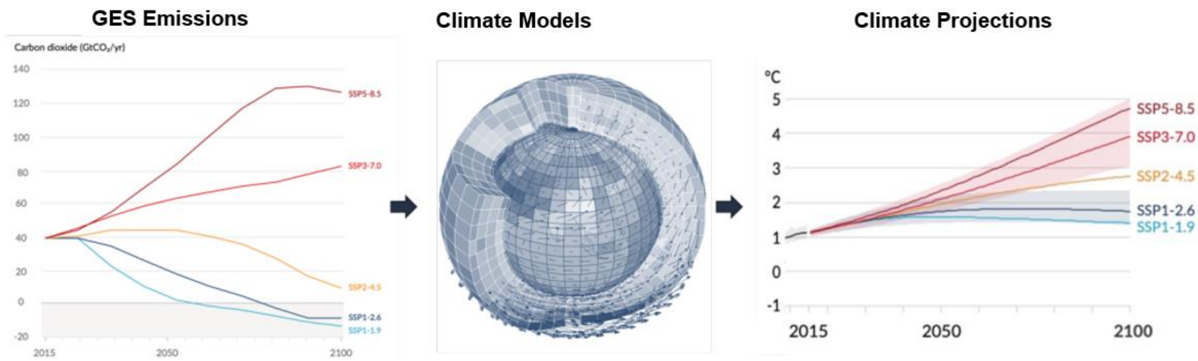
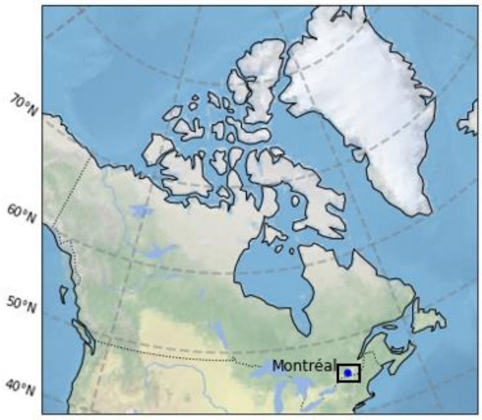


Figure 9: Steps of generating climate projections (adapted from Lepoussez & Aboukrat, 2022).

III.2 Methods

As part of this project, the analyses were initialized on the Montréal region. This choice was prompted by the significant impacts of high precipitation events on the city, as described in the literature. Furthermore, being a major metropolis, Montréal has several weather stations and well-documented resources, making it a prime case for the development of the current methodology.

To detect extreme precipitation events on the simulation data, a region of 4 by 3 grid points (an area of roughly 1 449 km^2) was chosen, as shown on Figure 10 below. The selection of this domain proved most suitable for this study, as a 4 x 3 domain adequately covers the city's surface and structures the data to prevent heavy importation and computation times.



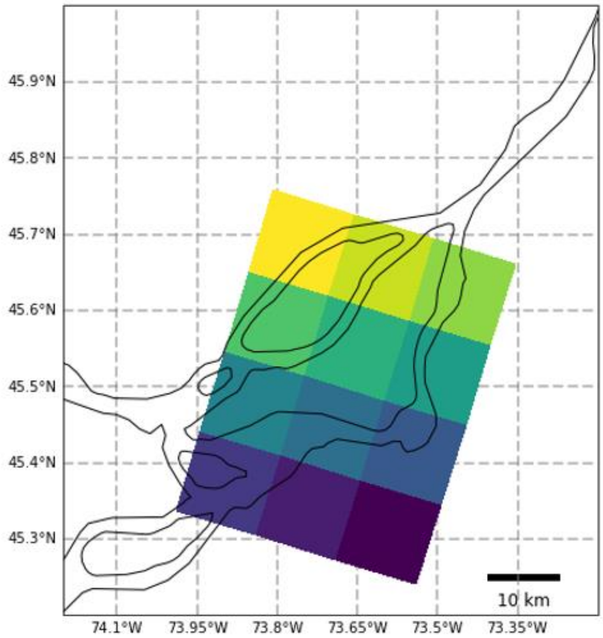


Figure 10: Location of the study domain of 4 x 3 grid points over Montréal.

Once the spatial domain was chosen, the analyses were made using four different temporal indicators to detect and analyze extreme events: maximum precipitation amounts at 3 hours, 6 hours, 12 hours, and 24 hours. Working with four time steps enables the differentiation between very short-duration precipitations, typically convective, and longer-duration precipitations, generally more synoptic (Lenderink & Van Meijgaard, 2008).

To select the maximum annual precipitation event, a mobile summation is applied on all hourly precipitation data for the study year at all grid points within the domain. Only the most significant event (the highest quantity) over all 12 grid points is retained. In this way, only the maximum event corresponding to the chosen year and time step is retained, allowing for the creation of annual time series where each point corresponds to the yearly maximum precipitation event. Figure 11 shows an example of an annual maximum time series for the historical period of CRCM5-MPI-ESM1.2-LR computed for a 3-hour time step:

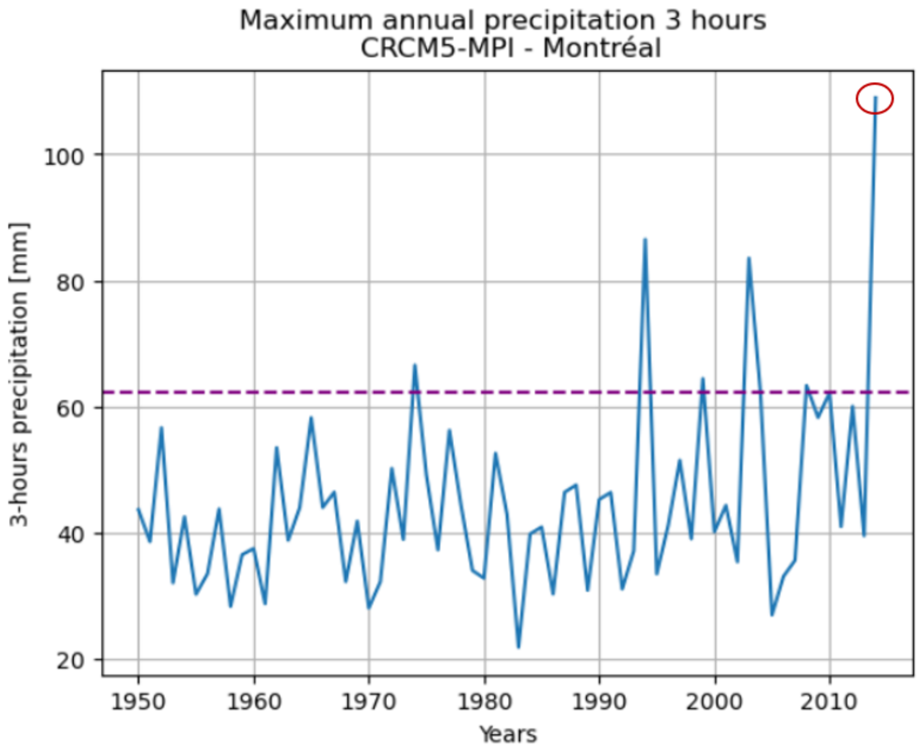


Figure 11: Time series of maximum precipitation events for 3 hours timestep CRCM5-MPI-ESMI-2-LR historical simulation over Montréal. The purple dash line shows the value of the 90th percentile, and the red circle highlights the maximum precipitation event of the series.

Time series allows for a rapid overview of the general data distribution, peaks, and overall trend. However, it's also possible to further analyze these results by conducting a percentile analysis, that can be applied either on the maximum events time series or on all precipitation events of a selected year. The first step of a percentile analysis is to rank the data in ascending order, with the lowest value being the first percentile and the highest, the hundredth. This technique provides a quick and clear insight into data distribution and is particularly useful in extreme event analysis.

The mathematical definition of extreme events states that they are events with percentile values above the 90th percentile or below the 10th percentile of the data distribution (Seneviratne *et al.*, 2021). Percentiles also facilitate simplified comparisons between distributions. For example, in the results section, variations in percentiles across different time periods and simulations will be analyzed. In Figure 11 above, the purple dashed line indicates the value of the 90^{th} percentile of the distribution, while the red circle highlights the maximum value of the distribution (i.e., the most extreme precipitation event). As part of this master thesis, the results for the 90^{th}, 95^{th} and 99^{th} will be displayed and analyzed.

To enable comparisons across different time periods, the data were further structured into 30-year climatic means. Consequently, following the availability of simulations, analyses will be conducted for two historical time spans (1950-1979 and 1980-2009) and three future (2010-2039, 2040-2069, and 2070-2099).

All calculations are performed using PAVICS, Ouranos' virtual laboratory and internal server. All data are imported using the server, on a Python programming environment (Jupyer Lab). Some of the plug-ins used for the analysis of data and generation of figures are xarray, numpy and cartopy, among others.

CHAPTER IV. RESULTS

III.1 – Detecting past precipitation events

Despite their impact on urban areas, it's not always easy to assess the causality relationship between heavy rainfall and flooding. Although the literature on the impacts of these events mentions several heavy rainfalls in Montréal in recent decades, the question arises as to whether climate past databases such as reanalysis are suitable tools for identifying these extreme events.

For the exploratory step of this analysis, a comparison was made between the accumulation data from Montréal weather stations and the reanalysis data for three events from the literature. These chosen events are July 14, 1987, November 8 and 9, 1996, and July 5, 2005. Those events were retained due to the important quantities of rain recorded at the stations, and because they each are the causes of urban flooding.

Although hourly data is available for some weather variables on Environment Canada's public weather portal, this is not the case for precipitation accumulations at the chosen stations and periods. The hourly precipitation data from the reanalyses were therefore summed up daily (summing for both days for the November 1996 event). Table 1 below summarizes the information on the weather stations used in this study and Figure 12 shows the location of the different weather stations on the island of Montréal and in the surrounding area. Although all five stations have data for the 1987 event, only the three airports (Mirabel, Pierre Elliot Trudeau, and St-Hubert) have records for the 1996 and 2005 events. All weather data are imported from the Environment and Climate Change Canada historical weather data webpage (https://climat.meteo.gc.ca/).

Table 1: Summary table of meteorological stations used, with MSC (Meteorological Service of Canada) and WMO (World Meteorological Organization) corresponding ID

Name	Coordinates (lat/lon)	Altitude (m)	ID MSC	ID WMO
Lafontaine	45°31'00" N / 73°34'00" O	41.10	7025267	X
McGill	45°30'00" N / 73°35'00" O	56.90	7025280	X
Mirabel Airport	45°40'00" N / 74°02'00" O	82.60	7035290	X
Pierre Elliott Trudeau Airport	45°28'00" N / 73°45'00" O	36.00	7025250	71627
St-Hubert Airport	45°31'00" N / 73°25'00" O	27.40	7027320	71371

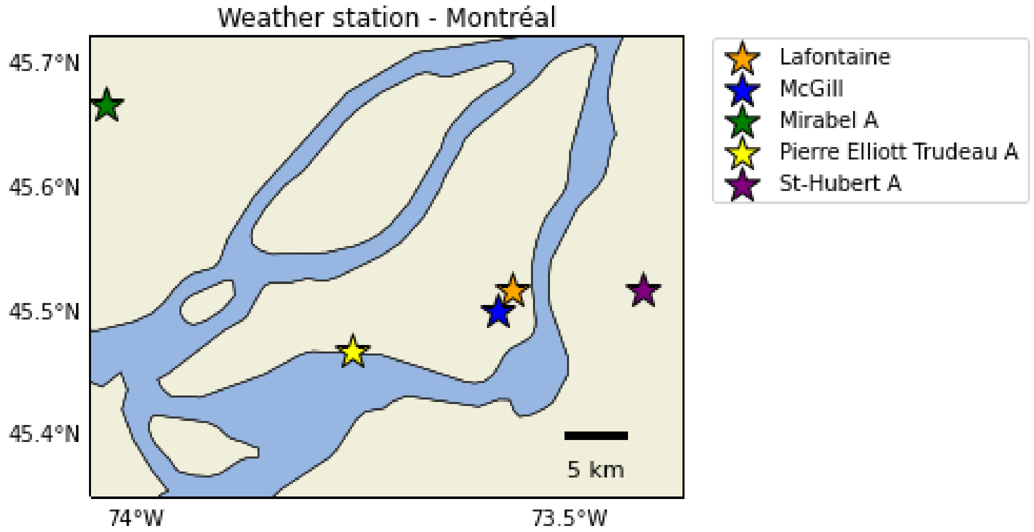


Figure 12: Map of the weather stations on Montréal Island and surrounding area used in this study

A comparison between station data was carried out for the two reanalyses, ERA5-Land and RDRS. The following table summarizes the results, with daily accumulations at the stations and their equivalent in the data from reanalysis. Percentage differences between station data and reanalysis quantities are highlighted in parentheses, with values in blue corresponding to the smallest difference.

Table 2: Comparison of weather station and reanalysis data for three extreme precipitation events. Percentage differences are shown in parenthesis. Values in blue indicate the smallest difference.

Weather station	**Accumulation at the station (mm)**	**ERA5-LAND (mm)**	**RDRS (mm)**
14th July 1987			
Lafontaine	103.0	20.8 (- 80 %)	82.6 **(- 20 %)**
McGill	102.2	20.8 (- 80 %)	82.6 **(- 19 %)**
Mirabel	40.0	22.4 (- 44 %)	34.9 **(- 13 %)**
Pierre Elliott Trudeau	57.4	20.3 (- 65 %)	52.5 **(- 9 %)**
St-Hubert	9.9	24.2 **(+ 144 %)**	96.0 (+ 870 %)
8-9th Novembre 1996			
Mirabel	77.4	72.5 **(- 6 %)**	62.5 (- 19 %)
Pierre-Elliot-Trudeau	134.0	66.9 (- 50 %)	119.9 **(- 11 %)**
St-Hubert	147.6	68.1 (- 54 %)	124.4 **(- 16 %)**
5th July 2005			
Mirabel	10.8	6.4 **(- 41 %)**	17.8 (+ 65 %)
Pierre-Elliot-Trudeau	63.6	8.2 (- 87 %)	15.5 **(- 76 %)**
St-Hubert	26.5	10.2 (- 64 %)	30.0 **(+ 13 %)**

Different conclusions can be drawn from these results. First and foremost, we can observe the highly localized aspect that is characteristic of extreme precipitation events. The case of July 1987 is a good example, with accumulations of 103.0 mm at Lafontaine while the St-Hubert station, located less than 15 km away, recorded only 9.9 mm. This localized aspect is particularly pronounced with convective rains, which often exhibit significant variations in quantity depending on the location., as they are often triggered by the passage of localized thunderstorm cells (Berg *et al.*, 2013).

This spatial variability is hard to capture by reanalyses, as evidenced in Table 2 above. Although error percentages vary widely, it appears that reanalyses tend to globally underestimate the precipitation amounts from these events. This discrepancy can be explained by one main characteristic of reanalyses; they are averaged over grid points (approximately 10 km by 10 km in this case), whereas weather stations correspond to points within these grid points. Precipitation amounts are therefore averaged over the grid point, which reduces the magnitude of extreme events. In this regard, reanalyses are not fundamentally well-suited tools for quantifying complex, highly localized events such as extreme precipitation episodes (Zhang *et al.*, 2022). However, comparing the respective error percentages, RDRS seems to perform better in identifying accumulations related to these events. One of the reasons that could explain this difference is the fact that precipitations are assimilated in RDRS, while it's not the case for ERA5-Land. Despite a few exceptions, RDRS has the lowest error for all events.

Although reanalyses are not well suited to report precipitation quantities associated with extreme events, is it still possible to use them to identify events from the past? To investigate this aspect, 3-hour and 24-hour moving summation were applied to the RDRS data for the grid points corresponding to the Lafontaine and McGill stations (the most central stations on the island). The distance between the weather station and the center of the grid point is 1.7 km. For each year, the maximum value for the indicator was retained, resulting in the Figures 13 and 14 below:

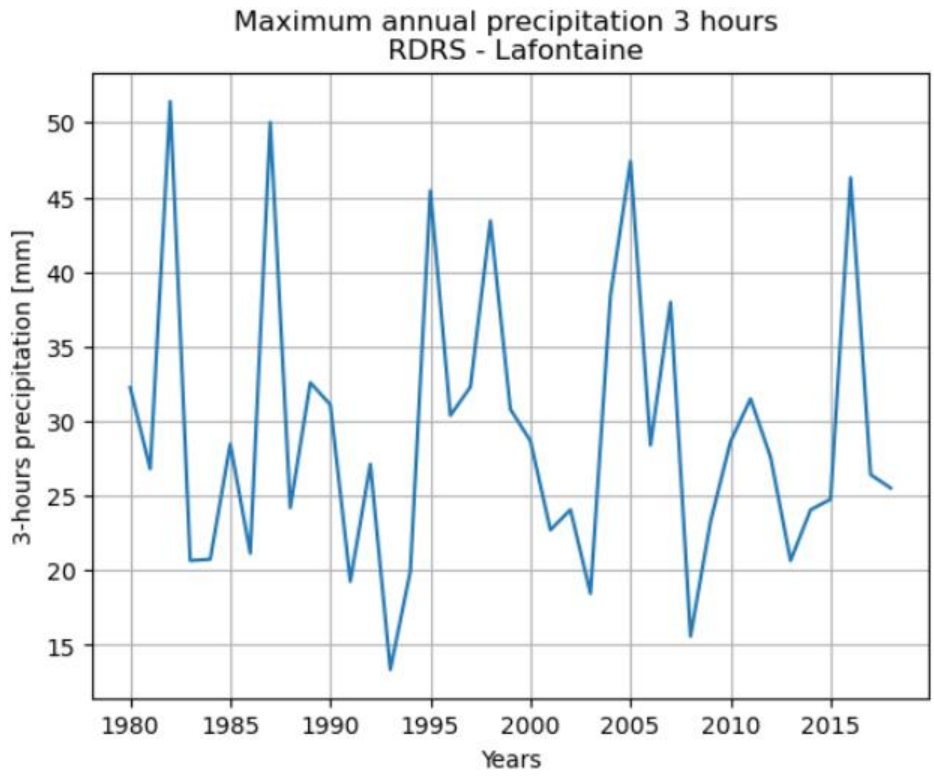


Figure 13: RDRS 3-hours maximal accumulation by year on Lafontaine gridpoint

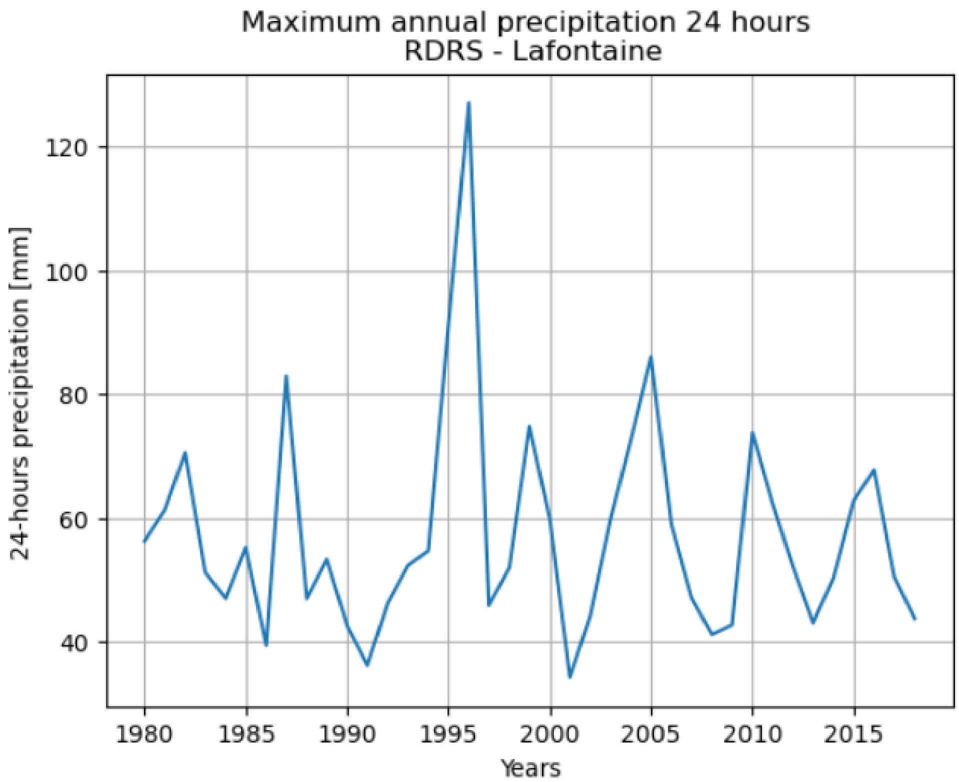


Figure 14: RDRS 24-hours maximal accumulation by year on Lafontaine gridpoint

One can notice that for short-duration events with 3 hours maximum precipitation, the three most significant peaks correspond to the years 1982, 1987, and 2005. As detailed earlier, the events of 1987 and 2005 are indeed associated with impacts and flooding. Following a brief literature review, 1982 (specifically on August 25th) is also an event, although with little impact (only some flooded basements in Montréal following the heavy rainfall) (La Presse, 1982).

For longer-duration accumulations as shown in Figure 14, we note that the most significant peak corresponds to the 1996 event, which aligns with information from the literature. The other two peaks exceeding 80 mm in 24 hours are 1987 and 2005, which also aligns with the analysis made earlier.

These results are proof that it is possible to identify past events through time series of maximum accumulations over a certain period. Even though reanalyses like RDRS and ERA5-Land tend to underestimate actual event precipitation and are not suitable in identifying very localized precipitation variations (as for convective events), these databases still allow for identifying precipitation events impacting the territory in past time series. However, it is important to keep in mind that these conclusions are valid for the case of Montréal only. An analysis of other cities or grid points could lead to different results.

III.2 - Extreme precipitation events in the future

As discussed in the previous section, extreme precipitation events can have major consequences on the territory and infrastructure. We know that the Clausius-Clapeyron relationship predicts an increase in the intensity of these events in the future; but is this hypothesis validated by climate simulations at a local scale?

To answer these questions, the percentile method was applied to all simulations described before (one can refer to the Chapter 3 - Method section III.1.2 for more details and Chapter 9 - Annexe for all results). The following section will detail the CRCM5 simulations driven by two global climate models (CanESM5 and MPI-ESM1.2-LR), to gain insight on future extreme precipitation events. The following two tables present the results obtained for the 90th percentile of the four temporal indicators for the CRCM5-CanESM5 and CRCM5-MPI-ESM1.2-LR simulations:

Table 3: Results for the 90th percentile of yearly maximum event for 3, 6, 12 and 24h accumulated precipitation simulated by CRCM5-CanESM5

Time indicator	**1950-1979**	**1980-2009**	**2010-2039**		**2040-2070**		**2070-2099**		**% changes between 1950-1979 and 2070-2099**	
			SSP 1-2.6	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**
3 hours	63.0	80.7	69.6	77.0	79.2	94.3	97.8	89.3	+ 55	+ 42
6 hours	84.6	90.6	97.7	87.1	95.2	123.9	102.0	120.9	+ 21	+ 43
12 hours	103.4	101.7	121.3	115.9	104.1	130.4	107.8	131.6	+ 4	+ 27
24 hours	114.7	122.1	124.6	142.7	114.1	159.8	132.5	145.5	+ 16	+ 27

Table 4: Same as Table 3 but for CRCM5-MPI-ESM1.2-LR

Time indicator	**1950-1979**	**1980-2009**	**2010-2039**		**2040-2070**		**2070-2099**		**% changes between 1950-1979 and 2070-2099**	
			SSP 1-2.6	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**
3 hours	56.3	63.5	69.6	72.1	72.1	78.8	68.1	94.4	+ 21	+ 68
6 hours	74.7	76.9	78.5	103.5	81.0	80.2	80.0	122.3	+ 7	+ 64
12 hours	104.8	90.2	92.9	117.6	98.3	96.8	86.8	125.1	- 17	+ 19
24 hours	118.5	105.9	103.3	131.5	108.6	108.5	112.0	139.1	- 5	+ 17

We first notice a significant increase in the quantities of precipitation for short-duration events (3 hours and 6 hours) for all simulations in Tables 3 and 4. However, this increase appears to diminish for longer time steps. Indeed, the results for maximum 24-hour precipitation show lesser variation compared to the historical period for the simulation driven by CanESM5.

For CRCM5-MPI-ESM1.2-LR, significant differences are observed following the emission scenario. Results with SSP3-7.0 all show an increase in extreme precipitation, regardless of the duration of the event. Conversely, when considering the SSP1-2.6 scenario, there is a slight decrease in quantities for long-duration events. This decrease associated with the SSP1-2.6 scenario can be partly explained by the emissions curve. As one can observed in Figure 9, the greenhouse gas emissions associated with the SSP1-2.6 scenario increase, reach a plateau, then show a decrease at the end of the century, unlike the emissions of the SSP 3-7.0, which are constantly increasing. It is therefore not surprising to observe significant differences between the results for these two scenarios.

These are the results for the 90th percentile; but what about the most extreme events in the distribution? Is this trend observed in the increase of short-duration events also appears for the 99th percentile? Tables 5 and 6 below show the results obtained for the study of the 99th percentile for the two simulations driven by the global models. Results for the 95th percentile can be found in Appendix 1.

Table 5: Same as Table 3 but for 99th percentile

Time indicator	**1950-1979**	**1980-2009**	**2010-2039**		**2040-2070**		**2070-2099**		**% changes between 1950-1979 and 2070-2099**	
			SSP 1-2.6	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**
3 hours	102.8	107.1	92.0	102.4	107.5	142.5	114.4	218.5	+ 11	+ 113
6 hours	114.1	123.8	117.0	120.7	116.9	160.2	156.6	233.6	+ 37	+ 105
12 hours	125.0	130.3	151.7	149.3	127.7	175.5	167.8	235.2	+ 34	+ 88
24 hours	130.7	145.1	167.1	174.2	141.5	189.2	177.0	242.2	+ 35	+ 85

Table 6: Same as Table 4 but for 99th percentile

Time indicator	1950-1979	1980-2009	2010-2039		2040-2070		2070-2099		% changes between 1950-1979 and 2070-2099	
			SSP 1-2.6	SSP 3-7.0	SSP 1-2.6	SSP 3-7.0	SSP 1-2.6	SSP 3-7.0	SSP 1-2.6	SSP 3-7.0
3 hours	64.1	85.6	98.1	111.6	82.6	95.4	88.9	135.4	+ 39	+ 111
6 hours	90.8	87.6	112.0	118.6	120.3	162.3	93.9	151.9	+ 3	+ 67
12 hours	125.7	101.8	120.0	144.5	123.8	178.0	112.7	154.3	- 10	+ 23
24 hours	155.4	123.8	128.8	158.4	132.6	179.7	129.4	155.7	- 17	+ 0.2

The results for the 99th percentile seem to confirm a significant increase in the quantities for short-duration extreme events for all scenarios and simulations, an increase exceeding in most cases the standard deviation of these events for the 1950-1979 period. This trend is even more important when considering the SSP3-7.0 scenario. One can observe increases of 113% and 105% for the CanESM5-driven simulation, and 111% and 67% for the MPI-ESM1.2-LR-driven simulation, which are significant considering the intensity of these events.

For the 99th percentile, the results of CRCM5 piloted by CanESM5 show an increase regardless of the event duration or emission scenario considered. To summarize, the most extreme events in the distribution show a trend towards increased precipitation quantities. Similar to the 90th percentile results, the trends for MPI-ESM1.2-LR are strongly correlated with the emission scenario. Thus, the results for SSP3-7.0 show an increase regardless of the event duration, although it is smaller for longer-duration events. For the SSP1-2.6 scenario, the trends are also very similar to the 90th percentile, with a slight increase in short-duration events and a slight decrease for longer-duration events.

These results highlight the importance of considering the event duration and the greenhouse gas emission scenario while interpreting the results. Figures 15 and 16 below illustrate the effect of the emission scenario on the trend of the results for 3-hours maximum precipitation.

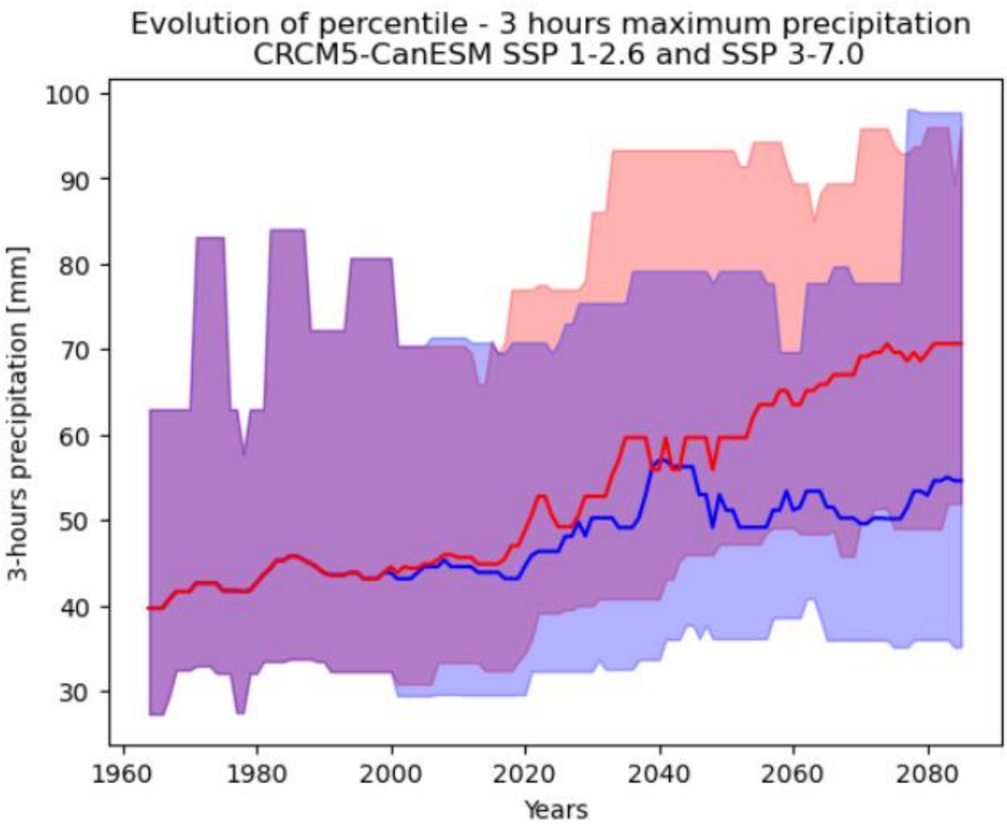


Figure 15: Evolution of percentile 90th of the 3 hours maximum precipitation simulated by CRCM5-CanESM5 using SSP1-2.6 (in blue) and SSP3-7.0 (in red). The shaded blue and pale red areas correspond to the interval between the 10th and 90th percentiles for the SSP1-2.6 and SSP3-7.0 scenarios, respectively. The blue and red curves represent the median (50th percentile) of the event distribution, computed considering the fifteen events before and after the study year (30-year distribution).

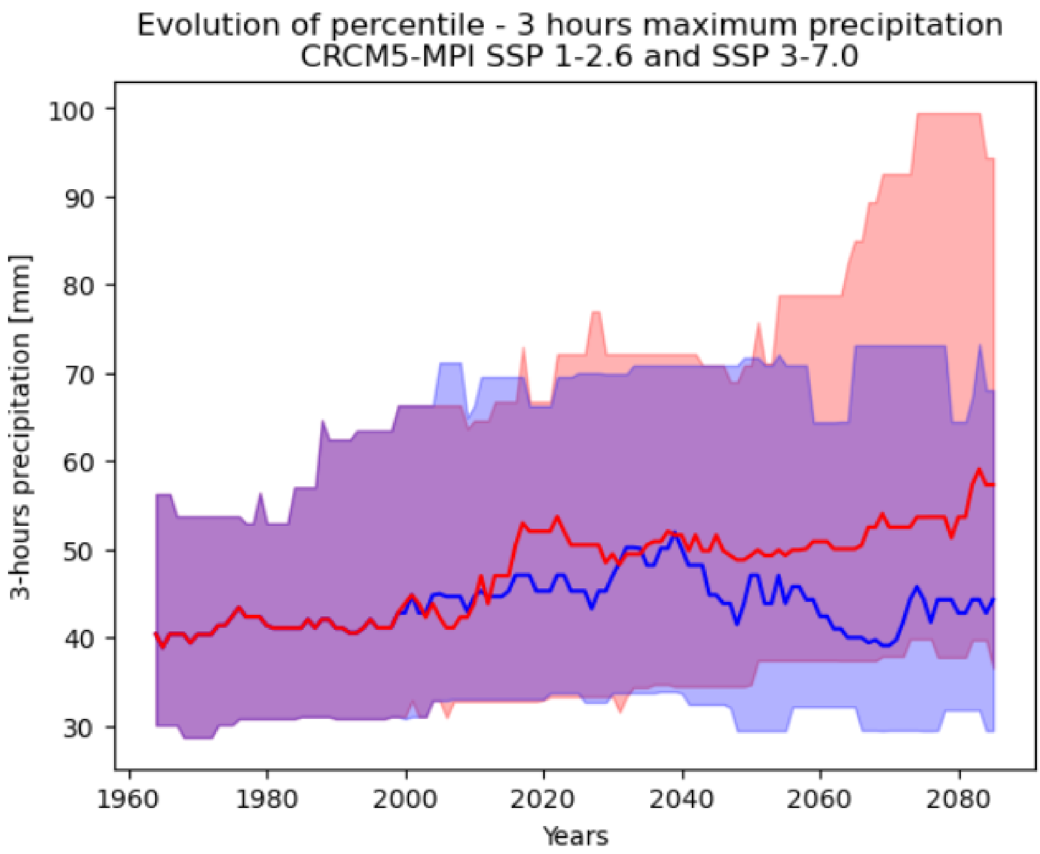


Figure 16: Same as Figure 15 but for CRCM5-MPI-ESM1.2-LR

Although the ranges between the 10th and 90th percentiles can be significant, the median provides a clear indication of trends across scenarios, with increasing disparity between the two simulations as we move forward into the future.

The rather wide distribution of the ensemble serves as a reminder that it is impossible to predict with exactitude the intensity of the next extreme precipitation event. However, a clear signal emerges from the results. For all simulations and scenarios, precipitation amounts for short-duration events (3 hours and 6 hours) are significantly increasing, with a growth ranging from 7 to 68% for the 90th percentile and from 3 to 113% for the 99th percentile between the historical period (1950-1979) and the future (2070-2099). Unfortunately, these conclusions suggest more and more intense and damaging short-duration events in the future.

IV.1.1. Time Series and Extreme Events

A visual analysis of the time series of extreme events reveals the presence of significant peaks in some distributions, which appear to be linked to events that deviate strongly from the data trends. Figure 17 presents an example of a time series for CRCM5-CanESM5 SSP3-7.0 with a peak of very high intensity in the year 2080, highlighted by the red circle:

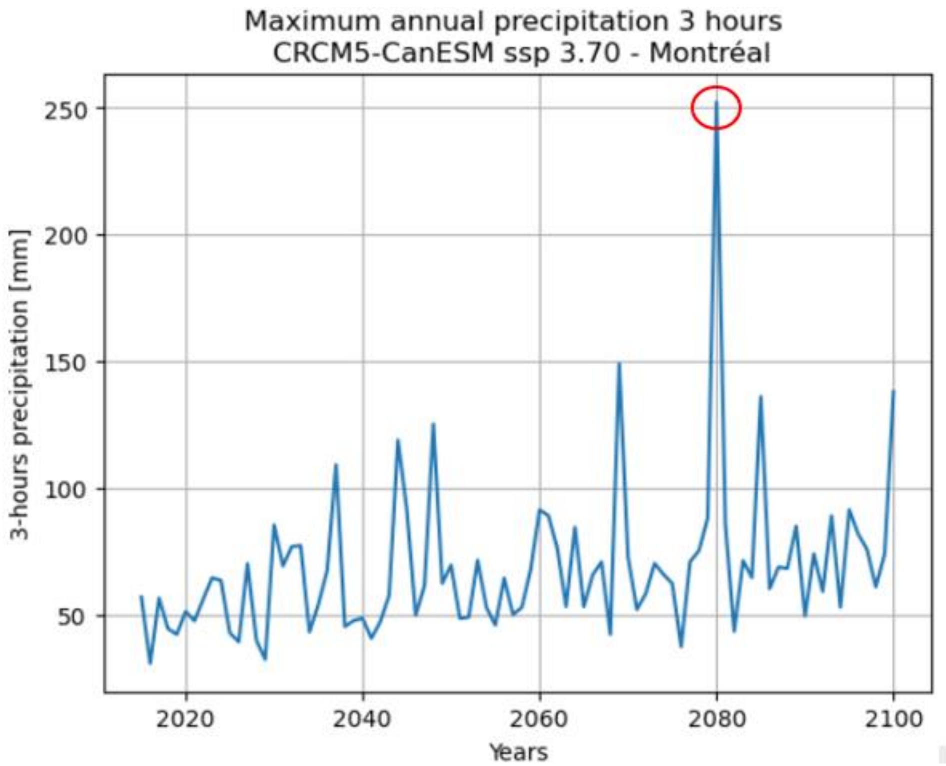


Figure 17: Time series of extreme events, 3 hours maximal annual precipitation CRCM5-CanESM5 SSP3-7.0. The red circle highlights the most extreme event of the serie.

This peak, with a value of 252 mm of rain in 3 hours, stands out significantly from the distribution of events. As a comparison, the floods of July 1987 reported 101.2 mm in two hours (City of Montréal, 2017), and those in July 2021 in Belgium led to accumulations of 271.5 mm in 48 hours in Jalhay (IRM, 2024). In this context, the question arises as to whether such an event is "real" or the result of numerical instability.

To address this question, some simulations were conducted using the data currently available on the server. Maps showing the evolution of surface pressure, winds, and relative humidity were generated for the Québec region. However, these maps provide limited information on the type of depression system and precipitation dynamics, as surface pressure is strongly correlated with topography and relative humidity (although related to precipitation) is not a precursor variable to it.

The system's dynamics were therefore studied in more detail by the Simulations and Climate Analysis group at Ouranos, using climate variables currently inaccessible on the Pavics public server. It was confirmed that the heavy precipitation recorded is indeed caused by a real precipitation system and is not a numerical anomaly of the model. Figure 18 below illustrates the hourly precipitation associated with the passage of the weather system:

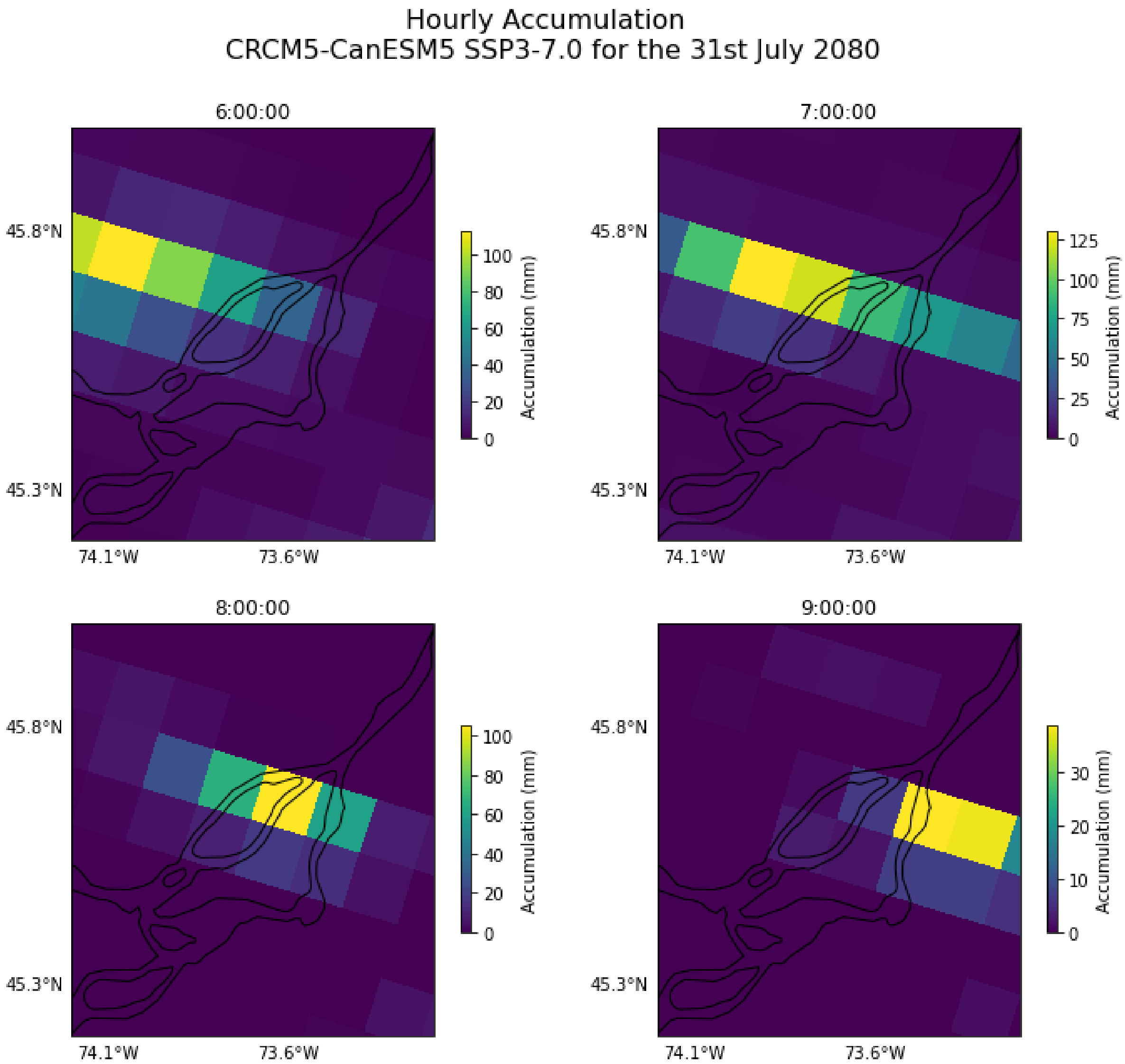


Figure 18: Hourly precipitation for the simulated event of 31st July 2080 by CRCM5-CanESM5 SSP3-7.0

It can be observed that this event appears to be associated with a very intense and localized precipitation system crossing the island from West to East. From a meteorological standpoint, this can be linked to the passage of a very active thunderstorm or a squall line, which would cause very intense and localized precipitation. The accumulated value of 252 mm in 3 hours is therefore consistent in this context.

IV.1.2. Temporal Analogues

As mentioned before, temporal analogs are an interesting tool for communication as they allow future extreme events to be compared with those of the past in terms of frequency or intensity. Will an event classified extreme in historical data still be considered extreme in the future?

The method of percentiles can be applied to study this question. For example, we can compare the evolution of the 90th percentile value of historical data over time and simulate at which percentile this same precipitation value would fall in the future. By applying the same method as for Figures 15 and 16 (i.e., a 30-year window centered on the study year), we can determine the percentile corresponding to the historical value (from Tables 3 and 4) for each time step in the future. Figures 19 and 20 show the evolution of the 90th percentile value for each time step accumulations:

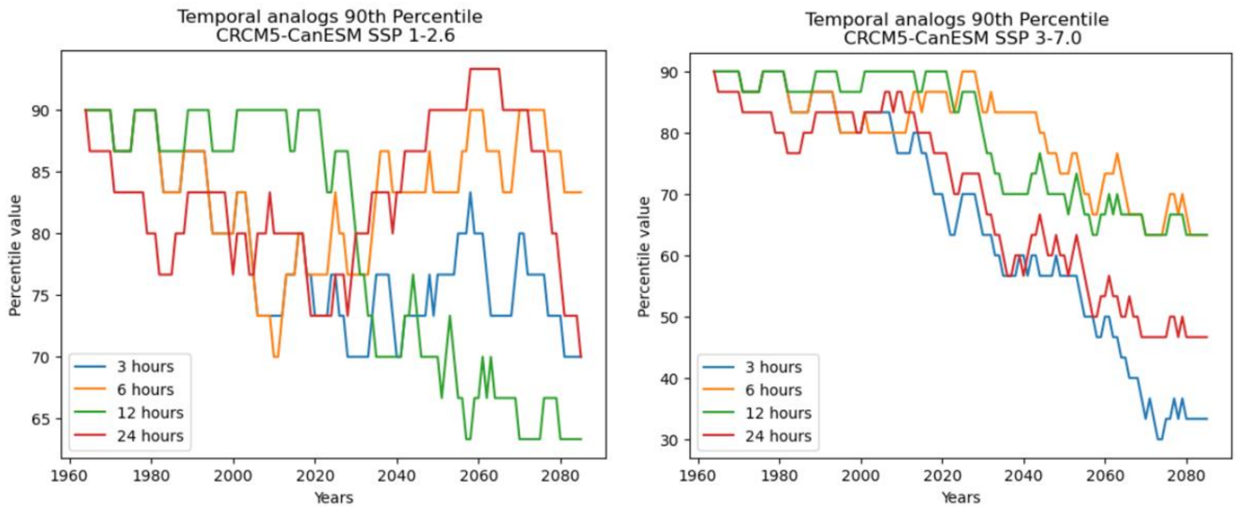


Figure 19: Temporal analogues for the 90th percentile CRCM5-CanESM5. The panel on the left is for SSP1-2.6 scenario and the panel on the right for SSP3-7.0 scenario. Blue line corresponds to events of 3-hours accumulation, orange line to events of 6-hours, green for 12 hours and red for 24 hours.

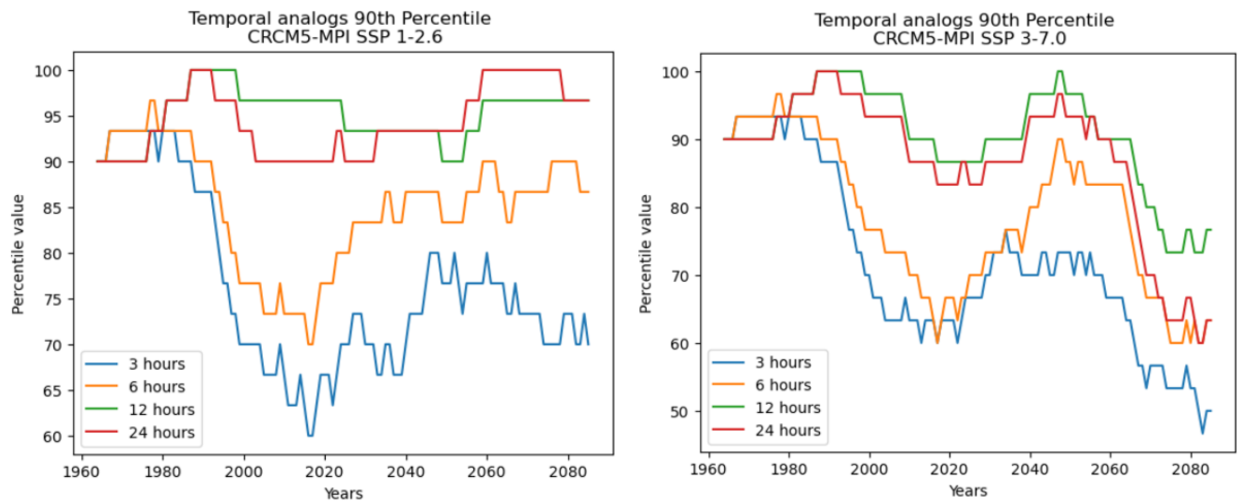


Figure 20: Same as Figure 19 but for CRCM5-MPI-ESM1.2-LR

One can observe that the curves differ significantly depending on the time step and the scenario considered, which is consistent with the results obtained in Tables 3 and 4. For simulations driven by CanESM5, the variations in percentiles are much less pronounced for the SSP1-2.6 scenario than for the SSP3-7.0 scenario. Indeed, for warmer scenario, the values of the percentiles decrease progressively over time. This means, for example, that for 3-hours accumulation, an event considered extreme (90^{th} percentile) in the historical period will become rather common (33^{rd} percentile) by 2085.

For the simulations driven by MPI-ESM1.2-LR with the SSP1-2.6 scenario, the occurrence of long-duration events varies very little in the future, whereas short-duration events show a significant decrease before rising to higher percentile values. This aspect of the curves can be explained by the greenhouse gas emissions of this scenario, which increase before decreasing as getting closer to the year 2100. For the SSP3-7.0 scenario, characterized by higher warming, there is a much more significant decrease in the percentiles associated with extreme events, particularly for short-duration events, although not reaching values as low as those in the simulations driven by CanESM5.

It is important to note that this analysis is based on a limited number of simulations and data. To obtain a more comprehensive overview of the evolution of extreme events, it would be necessary to work with a large ensemble of simulations (CMIP6 or CORDEX as examples), which includes multiple simulations for different scenarios. It would be premature to assert that these results are robust for the future. Nevertheless, a clear trend emerges from the current results, although further analysis and a larger sample of simulations are needed for more robust conclusions.

IV.1.3. IDF Curves

The IDF curves are a representation method that enlightens relationships between precipitation intensity, event duration, and return period. Precipitation intensity can be expressed in mm/hour (as in the example in Figure 7) or in accumulated mm for each time step. This representation technique is frequently used by engineers in the design of hydrological structures such as bridges or dams (DeGaetano & Castellano, 2017).

The IDF curve method was applied to the study results by comparing events for two 60-year timeframes: one historical period from 1950-2009 and one future period from 2040-2099 based on the SSP3-7.0 scenario. Three return periods were chosen, namely extreme rains for 2, 10, and 50 years. The IDF curves for the SSP1-2.6 scenario can be found in Chapter 9 - Annexe section. Figure 21 below illustrates these results for the CanESM5-driven simulation:

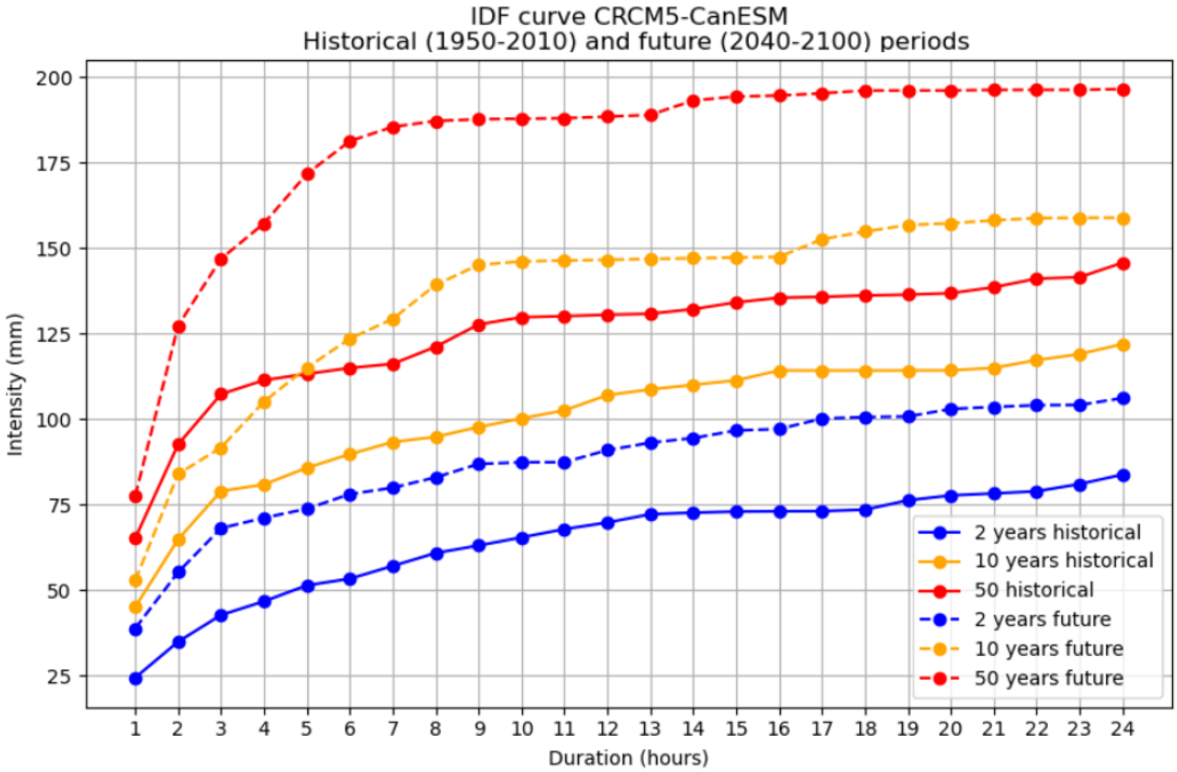


Figure 21: IDF curve for CRCM5-CanESM5 simulation historical (1950-2009, plain lines) and future (2040-2099, dashed lines) periods using the SSP3-7.0 emission scenario.

Reading the IDF curves, one can first notice that for all return periods and time steps, the data generated by the future simulation based on the SSP3-7.0 emission scenario exceeds that corresponding to the historical simulation. It is also observed that the slope of the curve varies depending on the type of event studied, with steeper slopes between short-duration events and shallower slopes for longer-duration events. The gap between historical and future periods is also more significant for events with a return period of 50 years (i.e., the 98th percentile of the distribution) than for those with shorter return periods.

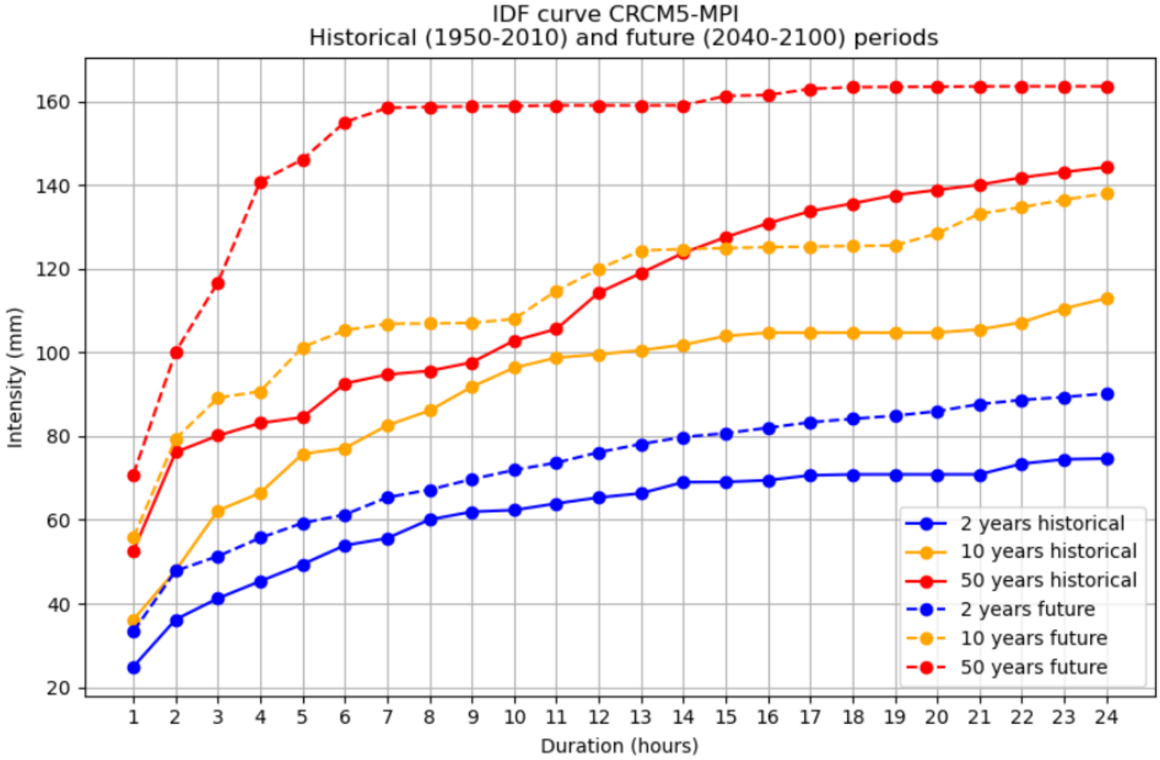


Figure 22: Same as Figure 21 but for CRCM5-MPI-ESM1.2-LR

In the case of the results for the CRCM5-MPI-ESM1.2-LR simulations, one can observe trends that are generally similar to the IDF curves generated by CRCM5-CanESM5, with the intensity of future events higher than that of historical events for all durations and return periods. There is also a small difference between the two curves for events with a 2-year return period, while the difference is significantly larger for the 50-year return period, especially at shorter time steps.

These figures provide another perspective on the results as shown previously in Tables 3 to 6. Indeed, the simulated results for the SSP3-7.0 scenario all show an increase in precipitation intensity, regardless of the time step or simulation considered. This method of representation emphasizes the impact of event duration on accumulated quantities, while highlighting the difference between historical and future simulations. However, their interpretation may be less instinctive for some users.

CHAPTER V. DISCUSSION

V.1.1. Clausius-Clapeyron Relationship

The results of this analysis point towards a clear signal: an increase in the intensity of short-duration extreme events. But is this trend consistent with the Clausius-Clapeyron relationship, or are we instead in presence of a super CC scaling?

As a reminder, the Clausius-Clapeyron relationship predicts an increase in the intensity of extreme precipitation events of around 7% per degree of warming (Pérez Bello *et al.*, 2021). In this study, two warming scenarios are used, SSP1-2.6 and SSP3-7.0. To determine the warming associated with each of these scenarios in the study area, the CRCM5 simulations were used to calculate the projected warming between the periods 1950-1979 and 2070-2099.

The average temperatures were computed annually over the domain corresponding to Montréal as shown in Figure 10. This allows us to obtain the projected local warming values for Montréal: by multiplying these temperatures by 7%/°C as predicted by the Clausius-Clapeyron law, we obtain an estimate of the theoretical increase in extreme precipitation events. The following table presents the projected temperature increases between the historical and future climatic periods, as well as the associated theoretical increase in precipitation:

Table 7: CRCM5 projected temperature increase between 1950-1979 and 2070-2099, with corresponding theoretical increase in precipitation from Clausius-Clapeyron relationship

Climate model and emission scenario	Simulated warming between 1950-1979 and 2070-2099 (°C)	Theoretical precipitation increases (Clausius-Clapeyron) (%)
CanESM5 SSP 1-2.6	+ 4.75	+ 33.25
CanESM5 SSP 3-7.0	+ 9.16	+ 64.12
MPI SSP 1-2.6	+ 2.42	+ 16.94
MPI SSP 3-7.0	+ 5.08	+ 35.56

These rates can be compared to the changes in the percentiles values as simulated by CRCM5. Table 8 summarizes the results obtained in the percentage of change between the historical (1950-1979) and future (2070-2099) periods for the 90th percentile, as shown previously in Tables 3 and 4:

Table 8: Change in the 90th percentile value between historical period (1950-1979) and future (2070-2099)

Time indicator	CRCM5-CanESM5		CRCM5-MPI	
	SSP 1-2.6	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**
3 hours	+ 55 %	+ 42 %	+ 21 %	+ 68 %
6 hours	+ 21 %	+ 43 %	+ 7 %	+ 64 %
12 hours	+ 4 %	+ 27 %	- 17 %	+ 19 %
24 hours	+16 %	+ 27 %	- 5 %	+ 17 %

One can notice that for short-duration events (3 hours), the simulated increase globally exceeds the range predicted by the Clausius-Clapeyron relationship. The only exception is the CRCM5-CanESM5 SSP 3-7.0, with a value (+ 42 %) under the + 64 % expected by the equation. For the longer time steps, the results are more mixed, globally under what is predicted by Clausius-Clapeyron.

However, the conclusions are somewhat different for events at the 99th percentile, as presented in the Table 9:

Table 9: Same as Table 8 but for the 99th percentile

Time indicator	CRCM5-CanESM5		CRCM5-MPI	
	SSP 1-2.6	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**
3 hours	+ 11	+ 113	+ 39	+ 111
6 hours	+ 37	+ 105	+ 3	+ 67
12 hours	+ 34	+ 88	- 10	+ 23
24 hours	+ 35	+ 85	- 17	+ 0.2

For the simulation driven by CanESM5, for the SSP1-2.6 scenario, the results are very similar to what is predicted by the Clausius-Clapeyron relationship. However, for the SSP3-7.0 scenario, the increases are significantly higher than what is predicted by the relationship. For MPI-ESM1.2-LR, although the SSP1-2.6 results are generally lower than the Clausius-Clapeyron law, the short-duration results for SSP3-7.0 are significantly higher than what is predicted by the equation. We can then conclude that the precipitation amounts associated with the most extreme short-duration events in the distribution seem to be tending towards a significant increase, sometimes higher than what expected by Clausius-Clapeyron relationship.

As discussed in the literature (Westra *et al.,* 2014, Papadopoulos-Zachos & Anagnostopoulou, 2023) it is not uncommon to observe an increase in the intensity of extreme events that exceeds the Clausius-Clapeyron relationship. This phenomenon can be attributed to a shift from stratiform to convective events. On that matter, Lenderink and Van Meijgaard (2008) argue that the different trends for short-duration and long-duration events can be explained by the dominance of convective (short-duration) precipitation for high temperatures, supporting the hypothesis of a switch from stratiform to convective events in a warmer climate.

However, it is essential to keep in mind that these trends are projections from only one regional climate model driven by two drivers and two emission scenarios. Given that precipitation trends (especially extreme events) are subject to uncertainties related to internal climate variability (Deser *et al.*, 2014), it would be essential to produce additional simulations to validate the conclusions of this study. Also, other factors such as changes in atmospheric circulation patterns can have an impact on the results (Pérez Bello *et al.*, 2022), and are not assessed in the scale of this thesis.

CHAPTER VI. POPULARIZING SCIENCE IN CLIMATE INFORMATION WEBSITES

Climate change is a major modern challenge, and in this context, the demand for information on this subject is constantly increasing. Therefore, it is not surprising to observe a proliferation in the number of websites specialized in sharing climate information. However, it's often challenging to translate climate data, which are complex and come with uncertainties, into formats that effectively address the actual needs of users, which often include socio-economic, risk, or vulnerability considerations (Hewitson *et al.*, 2017).

To initiate awareness and implement adaptation measures, it is not enough to simply inform about climate changes. It is essential to favorize user engagement, meaning to support a connection between the user and the problem, which includes cognitive, emotional, and behavioral aspects (Whitmarsh *et al.*, 2012). Climate websites can help achieve this goal by promoting risk perception and understanding; their aim should be to make the information interesting and meaningful to the public (Nerlich *et al.*, 2010).

There is a wide diversity in the forms and functions of these websites. We can take, as first example, the Climate Change Knowledge Portal of the World Bank Group (https://climateknowledgeportal.worldbank.org/). On the same website, there is a global view of climate change, with possible sub-selection by country. For each country, detailed information is provided on key past and future climate variables, extreme events, various risks, as well as articles of scientific popularization covering different subjects. Although some complex graphics would benefit from a more exhaustive description, the site's efficient structure and its interactive and visually accessible approach make it an effective popularization tool, especially since the socio-economic dimension is integrated on the platform.

Another example of a climate platform is the Climate Atlas of Canada of the Prairie Climate Centre (https://climateatlas.ca/prairie-climate-centre). The main feature of this platform is a map illustrating the evolution of essential climate variables (temperature, precipitation) at the scale of the country, as well as several applied specialized indicators such as agricultural variables (degree-days, seasonal freeze dates) or extreme climate events (duration of heatwaves, frost, and icing days, etc.). The site, entirely based on an interactive interface, allows users to select grid points, change the displayed variables, zoom in on the map, etc. Specific analyses for some cities show the evolution of climate variables in time series and allow users to download the data. Users can also select one of the clearly identified icons on the map, which leads to videos vulgarizing climate change or local-scale adaptation solutions and projects. An Indigenous Nations section shows the location of different communities and projects implemented by Indigenous Nations. The visualization techniques used by this platform, which combine dynamic data representations with storylines, make the Climate Atlas of Canada a comprehensive tool oriented towards the user, despite the complexity of the data presented. Figure 23 below is a screenshot of the platform's main page, illustrating the graphical interface and some of the interactive navigation settings.

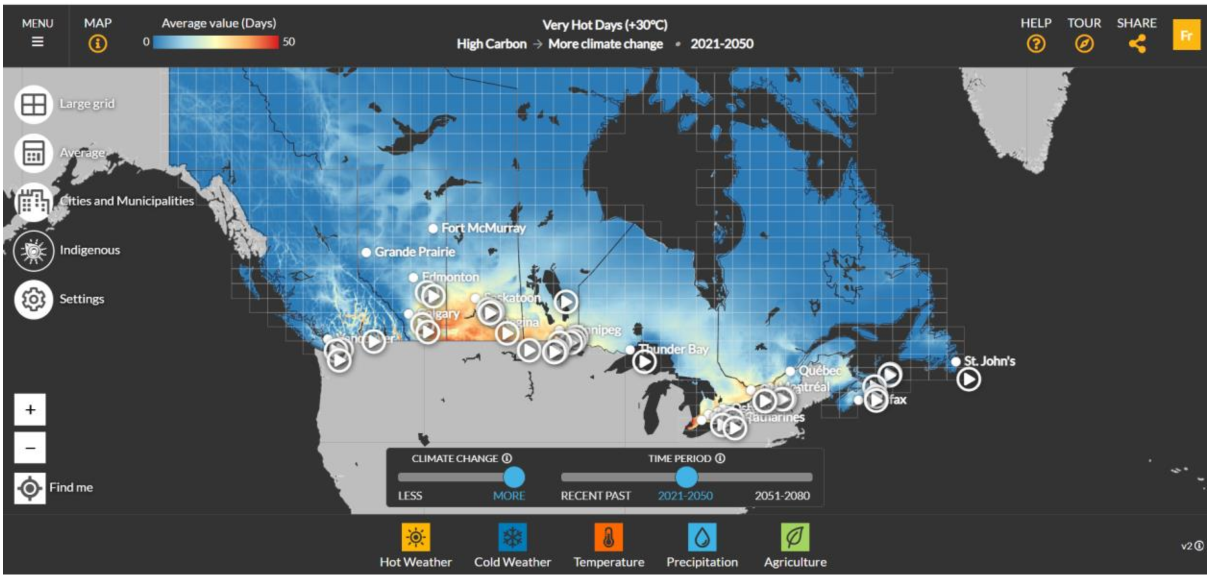


Figure 23: Climate Atlas of Canada webpage, Prairie Climate Centre. Retrieved from https://climateatlas.ca/map/canada/plus30_2030_85#.

More specifically regarding extreme weather events, the "Attributing extreme events to climate change" website by CarbonBrief is also based on an interactive interface. On the displayed world map, users can select various icons representing extreme weather events; the very clear legend effectively distinguishes between event categories, as shown on Figure 24 below. Each icon is linked to an informative card explaining how climate change influences that specific type of event, with each card providing a hyperlink to the scientific article at source. Navigation is very intuitive, and the clean visual design avoids overwhelming the page with information.

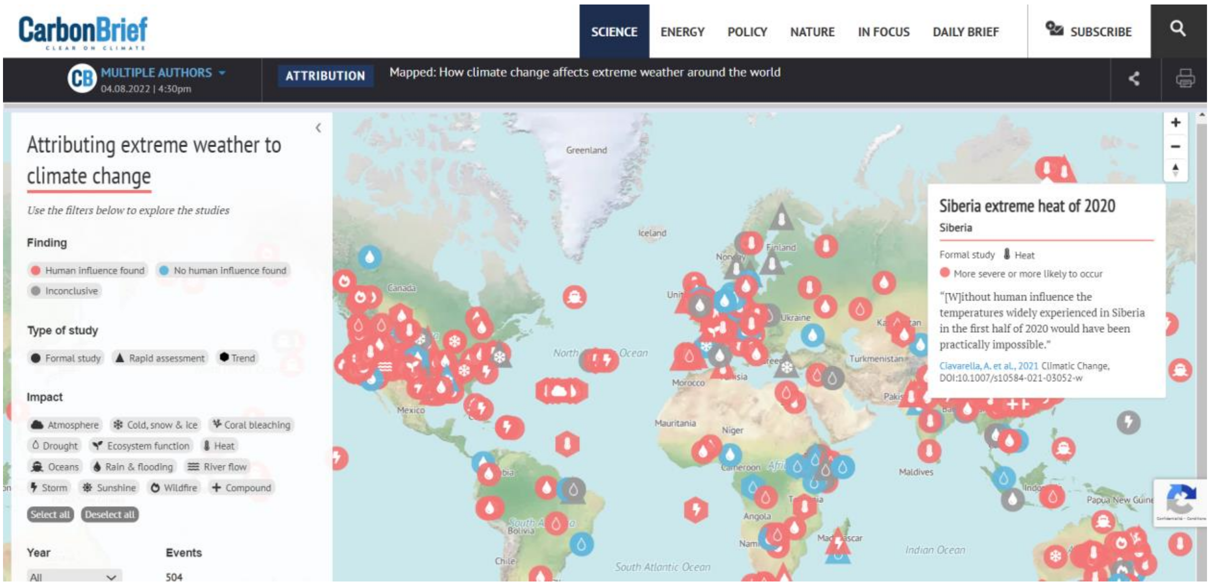


Figure 24: Attributing extreme weather to climate change, CarbonBrief. Retrieved from https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/

These are some examples of formats used in climate information websites to display climate data in a way that is accessible to the public. The choice of the optimal representation mode for scientific information or a series of data is an essential step. The selected method must be aligned with both the study's objective and the user's knowledge and background (Terrado *et al.*, 2022). For example, a map with pictograms (as in the case of the CarbonBrief website) is both a simple representation mode and well-suited for punctual and spatial events such as extreme weather events. On the other hand, time series presenting different simulations, such as those on ClimateData or Portraits climatiques, are very practical for capturing the temporal evolution of a variable. However, their interpretation may require prior knowledge in climatology or statistics. In this context, it is essential to choose the most suitable representation mode to help users understand the data.

VI.1.1. Integrating results to Ouranos's Portraits climatiques website

On the Ouranos' Portraits climatiques platform (https://www.ouranos.ca/fr/portraits-climatiques-introduction), users can visualize projections of several climate variables for different emission scenarios. They can also select specific regions of Québec and visualize the results on time series based on ESPO-G6-R2 and CMIP6 data. Interactive maps and intuitive color palettes allow for a good handling of the evolution of climate characteristic variables.

Figure 25 presents an example of interactive map and Figure 26 an example of time series as seen on Portraits climatiques website:

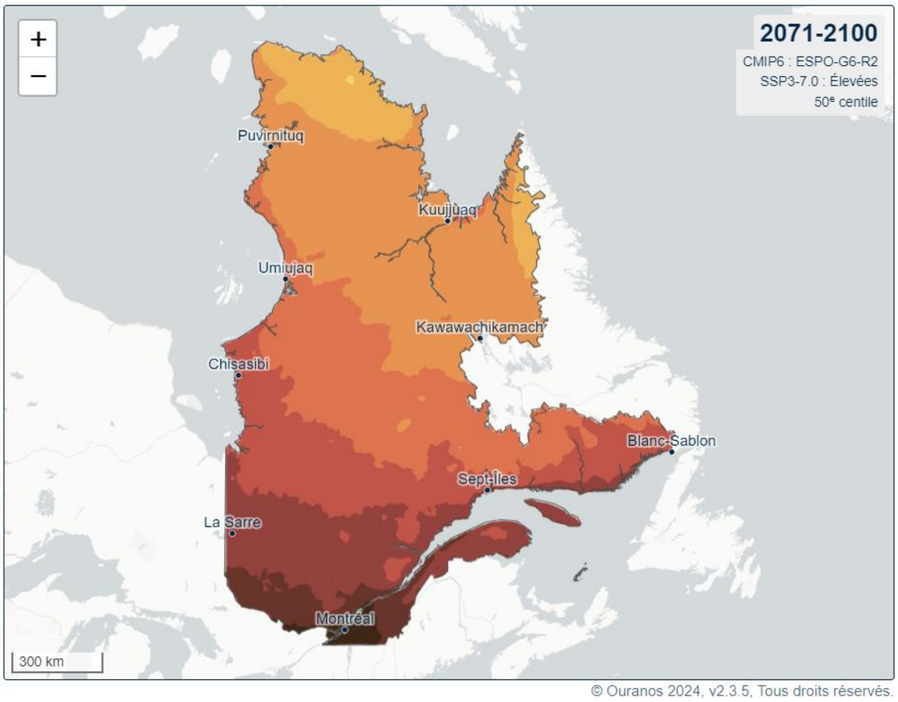


Figure 25: Interactive map displaying 50th percentile future temperature in Québec province for SSP3-7.0 scenario. Retrieved from https://portraits.ouranos.ca/fr/spatial?a=0&c=0&discrete=1&e=CMIP6&i=tg_mean&p=50&r=0&s=annual&scen=ssp370&w=0&yr=2071

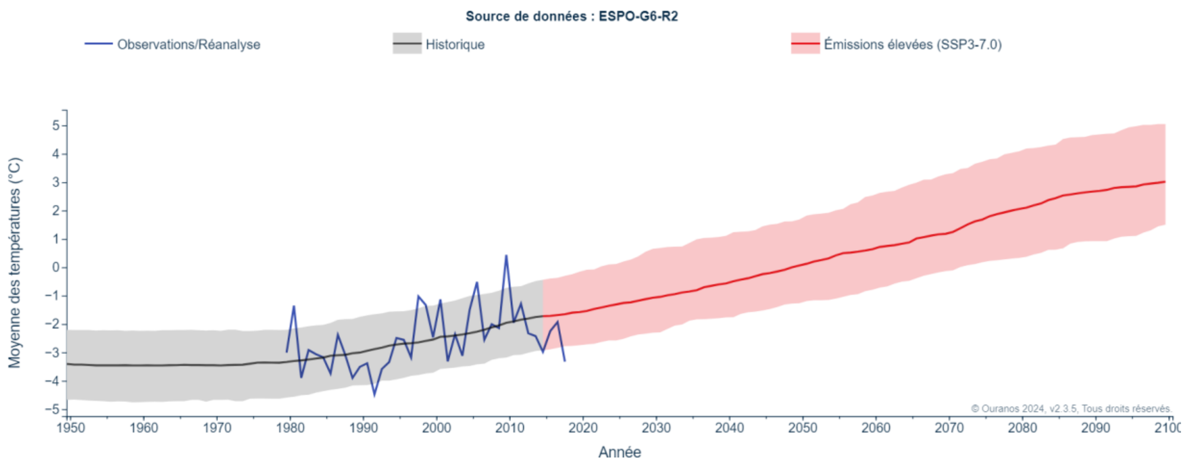


Figure 26: Interactive time series displaying mean temperature evolution for Québec province. Data from ESPO-G6-R2, Retrieved from https://portraits.ouranos.ca/fr/temporal?a=0&e=CMIP6&i=tg_mean&r=0&s=annual&w=0

As there are numerous existing formats for presenting climate data, several approaches could be applied to integrate the study's conclusions into the Portraits climatiques platform. For example, using time series as presented in Figures 13 and 14 would illustrate the variability in precipitation amounts and event distribution. On these time series, it would be possible to add interactive icons allowing users to select an event and view a narrative description of it, with a simplified explanation of its causes and impacts. For instance, a user could select on the time series the peak corresponding to the year 1987 to display a description of the July 14 event, highlighting its impacts and possible options for adaptation measures, as shown on Figure 27 below:

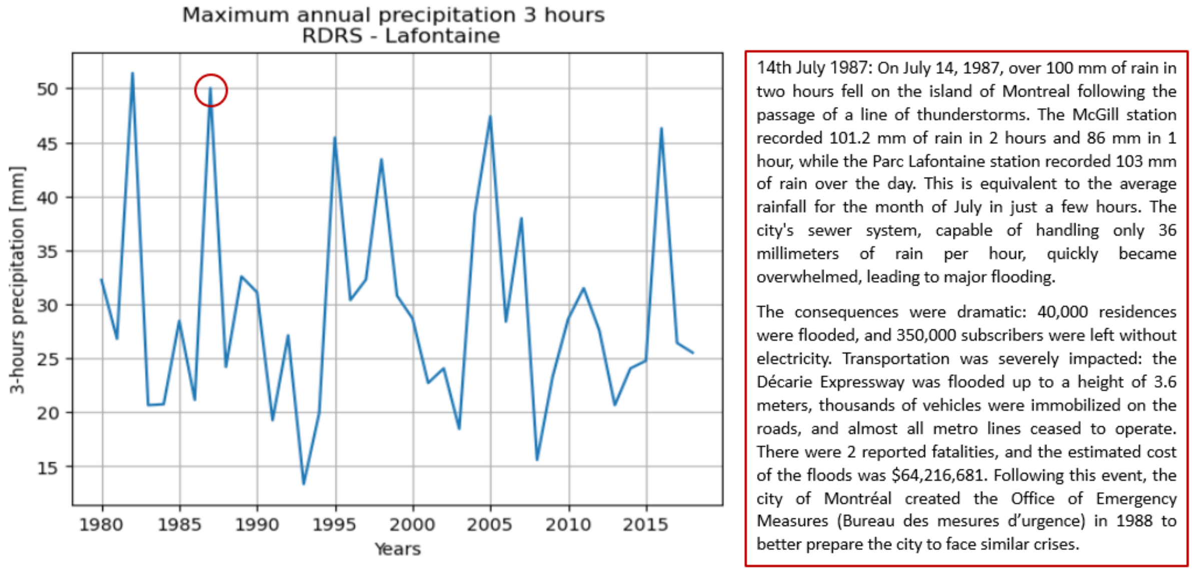


Figure 27: RDRS 3-hours maximal accumulation by year on Lafontaine gridpoint and example of interactive window displaying informations on the event

This approach could help inform users about the phenomenon while supporting their risk perception. Similarly, future simulation results could be integrated in time series format, like presented in Figures 15 and 16. On these figures, the simulated evolution of the percentile corresponding to extreme events is illustrated by integrating the simulation data distribution, emphasizing the uncertainty associated with future climate simulations and the impact of emission scenarios without overloading the figure.

VI.1.2. Recommendations and future developments

After reviewing the literature and analyzing various climate information platforms, it is also possible to make more general recommendations for improving the Portraits climatiques platform. One of these recommendations could be to highlight representations related to reality and the territory. In the case of Portraits climatiques, although maps allow seeing the evolution of climate variables over the territory, it may be challenging for users to understand the consequences of these projected changes on their daily lives. Similarly, for time series, peaks and trends in distributions can be seen, but these are poorly explained in terms of impacts. One way to add this information would be to adopt a strategy similar to the Climate Atlas of Canada or NASA's Global Climate Change (https://science.nasa.gov/climate-change/), by integrating on the platform or through hyperlinks case studies, storylines, or lived experiences on how climate change impacts natural environments, resources, or daily life. These techniques would help integrate climate data into a narrative context, referring to the real world, and in this way making raw data more understandable for users.

Reducing users' psychological distance from climate risk, with the aim of increasing their perception of this risk is another aspect of communication. This is one of the recommendations of the IPCC, which specifies that climate risk should be assessed in relation to other risks (such as economic and societal risks) to facilitate decision-making (IPCC, 2017). This is especially true in the context of extreme events, which have significant visible impacts on the territory. However, very little information on the socio-economic impacts or risks posed by extreme events is currently available on the Portraits climatiques webpage. Although indicators on climate extremes (such as heat waves and freezing rain events) are displayed on the platform, little information is available on the “real” impacts of these events or the risk they pose in a context of climate change. Without necessarily adding the information directly to the Portraits website, it would be possible to add interactive external links leading to the corresponding pages of the main Ouranos site, which already presents vulgarized articles on these subjects.

Since users don’t always have a scientific background, it is essential to simplify navigation, clarify information, and guide them through the interface (Hewitson *et al*., 2017). Regarding the visual design of Portraits climatiques, the clean style of the website emphasizes the data presented by reducing the presence of elements that would distract the user's attention. The color palettes used are also very intuitive and follow IPCC recommendations for data visualization. Interactive navigation is also smooth and allows selecting data on the map, changing the displayed geographic area or type of data, scenarios, and projected percentiles. The presence of legends and simplified explanatory pages makes navigation easier for the user, as does the interactive information tab. Additionally, using the platform on other electronic devices such as phones or tablets is also very seamless and accessible.

Several studies also emphasize the importance of knowledge co-production. In this context, the user should not only be considered as a "receiver" of information but also as a participant in the creation of content for the platform (Beier *et al.*, 2016). It is sometimes possible to find on climate information websites surveys aimed at obtaining user feedback. One example of these surveys can be seen on the IPCC WGI Interactive Atlas webpage (https://interactive-atlas.ipcc.ch/), as shown in Figure 28. Implementing a similar survey on Portraits climatiques would help better understand user requests and needs. It would also help them engage in a participatory approach, providing concrete improvement suggestions for the platform. Setting up discussion forums or exchanges with the user is also an option to achieve this goal, with such exchanges being a great opportunity for co-learning (Bojovic *et al.*, 2021).

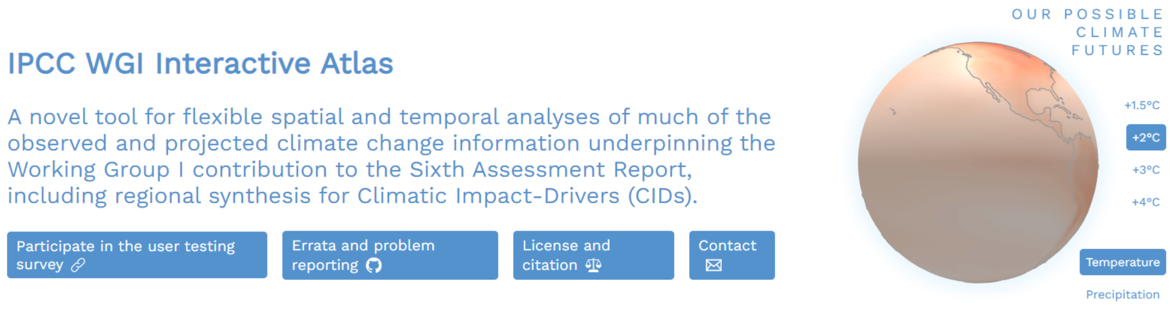


Figure 28: Presence of surveys in a Climate Information Website, example of IPCC WGI Interactive Atlas. Retrieved from https://interactive-atlas.ipcc.ch/

Some more general techniques are linked to aspects directly related to communication with the public. Examples include the use of clear and simplified vocabulary, metaphors, or comparisons, and adapting decimals to the audience (Hassol, 2008). On Portraits climatiques, even if some more technical words are used (such as emissions scenarios, reanalysis, median and percentiles), information and navigation windows help clarify these more complicated concepts.

In summary, to integrate the conclusions of this study on extreme precipitation events into the existing Ouranos Portraits climatiques website, different representation techniques can be used. However, time series and interactive maps could be preferred tools in this case to illustrate the climate data from the study. These visualization techniques would also be relatively easy to integrate into Portraits climatiques, given that the variables displayed on the website are already in those formats. Guided navigation through the interface, simplified and clear vocabulary, as well as knowledge co-production through feedback survey, would help create a user-friendly tool adapted to their needs.

In the case of more complete spatial analysis (covering, for example, the entire province of Québec), it would be possible to project the expected evolution of extreme events in the form of maps. Following the example of the Climate Atlas of Canada and CarbonBrief's website, an interactive map would allow users to visualize past extreme events as icons on the map, with event cards summarizing the associated storylines. For a pixelated map (corresponding to model grid points), users could individually select each point to display graphs showing, for example, time series, IDF curves, or other graphical representations.

These suggestions are a few examples of techniques that could be applied to represent the results of this study. Recent years have also seen the emergence of many new popularization techniques applicable to the field of climate change and extreme weather events. The use of artificial intelligence to generate images illustrating the impacts of climate change (Tousignant, 2021) or the creation of interactive storylines combining various audiovisual techniques (Climate Adaptation Services, 2023) are some examples. These techniques help reach a wider audience and promote understanding and visualization of the impacts of climate change. By integrating such innovative methods, future studies can enhance public engagement and foster a deeper comprehension of the complex nature of climate change.

CHAPTER VII. CONCLUSION

Extreme precipitation events rank among the costliest natural disasters worldwide, and Québec province of Canada is no exception regarding this hazard. As seen multiple times in the past, extremely intense rainfall can lead to urban flooding: the Montréal deluge of July 14, 1987, is a striking example, both in terms of rainfall intensity and the severity of the flooding that followed.

With rising temperatures due to climate change, the atmosphere can hold more water vapor. This physical principle, known as the Clausius-Clapeyron relationship, has a major impact on the intensity of extreme precipitation events, especially for short-duration events.

In this thesis, hourly data from the RDRS, ERA5-Land reanalyses, and the CRCM5 regional model driven by the CanESM5 and MPI-ESM1.2-LR global climate models were used to study past and future extreme precipitation events in the city of Montréal. The percentiles statistical technique was applied to different simulations and precipitation time steps to study the behavior of events, comparing past and future simulations and studying events that stand out from time series and data distributions.

The results highlight a significant increase in the intensity of short-duration extreme precipitation events in the future in the context of climate change. For all simulations and emission scenarios, short-duration (3 hours and 6 hours) extreme events show an increase in future intensity, most of the time corresponding to what is predicted by the Clausius-Clapeyron law (+7% / °C) and even higher in some cases. For longer-duration events (12 and 24 hours), the results are more mixed and strongly dependent on the model and emission scenario used. The application of different visualization techniques, such as time series, temporal analogues, and IDF curves helps to facilitate understanding of the study's conclusions and visualize the behavior of extreme precipitation events in a warming climate.

It is not always easy to bridge the gap between raw climate data, their implications for the territory, and public outreach. Several formats and modes of representation exist to simplify complex climate data for users. In this context, Climate Information Websites are essential tools for sharing science with the public. Several of these platforms, such as the Climate Change Knowledge Portal (World Bank Group), the IPCC WGI Interactive Atlas, the Global Climate Change (NASA), and the Climate Atlas of Canada (Prairie Climate Center), among others, allow exploration of the evolution of different climate variables, learning about the impacts of climate change on the territory, and exploring adaptation strategies.

Ouranos, the climate change research consortium in Québec, also operates its own specialized climate information platform for the Québec territory. Different options have been explored to integrate the study's conclusions into the platform, in a format that is simplified and easily understandable for users. Recommendations for improving the website have also been discussed based on the literature, with the aim of helping developers of Portraits climatiques make it an even more suitable tool for communicating climate change to a wide audience.

Although this study has adopted a multidisciplinary perspective, further research is needed to improve our understanding of extreme precipitation events in a warming climate. Therefore, it would be highly beneficial to extend the methodology to other cities or regions of Québec and Canada and by using other (regional) climate models. It would also be relevant to study in more detail changes in atmospheric circulation patterns and the link between temperature increase and extreme precipitation events. These additional research efforts would better elucidate the future dynamics of these events and help implement effective adaptation measures.

CHAPTER VIII. REFERENCES

Ara Begum, R., R. Lempert, E. Ali, T.A. Benjaminsen, T. Bernauer, W. Cramer, X. Cui, K. Mach, G. Nagy, N.C. Stenseth, R. Sukumar, and P.Wester, 2022: Point of Departure and Key Concepts. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 121–196, doi:10.1017/9781009325844.003.

Auger, M., & Ducas, M-C. (1987). Après le déluge… Le Devoir, 78(161), Pages 1 et 14. https://numerique.banq.qc.ca/patrimoine/details/52327/2763863

Baulenas, E., Bojović, D., Urquiza, D., Terrado, M., Pickard, S., González, N., & St Clair, A. L. (2023). User Selection and Engagement for Climate Services Coproduction. Weather, Climate, And Society, 15(2), 381-392. https://doi.org/10.1175/wcas-d-22-0112.1

Beier, P., Hansen, L. J., Helbrecht, L., & Béhar, D. (2016). A How-to Guide for Coproduction of Actionable Science. Conservation Letters, 10(3), 288-296. https://doi.org/10.1111/conl.12300

Bergeron, L., Vigeant, G., Lacroix, J. (1997). L'étude pancanadienne sur les impacts et l'adaptation à la variabilité et aux changements climatiques. Environnement Canada, Octobre 1997, https://publications.gc.ca/collections/Collection/En56-119-3-1997F.pdf

Bojović, D., St Clair, A. L., Christel, I., Terrado, M., Stanzel, P., Gonzalez, P., & Palin, E. J. (2021). Engagement, involvement and empowerment : Three realms of a coproduction framework for climate services. Global Environmental Change, 68, 102271. https://doi.org/10.1016/j.gloenvcha.2021.102271

Brosch, T. (2021). Affect and emotions as drivers of climate change perception and action : a review. Current Opinion In Behavioral Sciences, 42, 15-21. https://doi.org/10.1016/j.cobeha.2021.02.001

Bush, E. et Lemmen, D.S., éditeurs.: Rapport sur le climat changeant du Canada, gouvernement du Canada, Ottawa, Ontario, 2019, 446 p

Bukovsky, M., Gutowski, W. J., Mearns, L. O., Paquin, D., & Pryor, S. C. (2023). Climate storylines. Bulletin Of The American Meteorological Society, 104(1), E96-E98. https://doi.org/10.1175/bams-d-22-0224.1

CHARRON, I. (2016) Guide sur les scénarios climatiques : Utilisation de l'information climatique pour guider la recherche et la prise de décision en matière d'adaptation, Édition 2016. Ouranos, 94 p.

City of Montreal (2017). Climate change adaptation plan for the Montréal urban agglomeration 2015-2020, Report, 2017. https://ville.montreal.qc.ca/pls/portal/docs/PAGE/ENVIRO_FR/MEDIA/DOCUMENTS/2017_PACCAM_2015-2020_report.PDF

Climate Adaptation Services (2023). Unseen heat – A story about potential heat extremes in the Netherlands based on scientific insights. CAS. https://unseenheat.com/

Cook, D. (2009). Dynamic Graphics. In: LIU, L., ÖZSU, M.T. (eds) Encyclopedia of Database Systems. Springer, Boston, MA. https://doi.org/10.1007/978-0-387-39940-9_1372

DeGaetano, A. T., & Castellano, C. M. (2017). Future projections of extreme precipitation intensity-duration-frequency curves for climate adaptation planning in New York State. Climate Services, 5, 23-35. https://doi.org/10.1016/j.cliser.2017.03.003.

Deser, C., Phillips, A. S., Alexander, M. A., & Smoliak, B. V. (2014). Projecting North American Climate over the Next 50 Years : Uncertainty due to Internal Variability*. Journal Of Climate, 27(6), 2271-2296. https://doi.org/10.1175/jcli-d-13-00451.1

DRIAS, Les futurs du climat - Accompagnement. (s. d.) Ministère de la transition écologique. https://www.drias-climat.fr/accompagnement/sections/339

Dryzek, J. S., Norgaard, R. B., & Schlosberg, D. (2011). The Oxford Handbook of Climate Change and Society. Dans Oxford University Press eBooks. https://doi.org/10.1093/oxfordhb/9780199566600.001.0001

ECMWF. ERA5-LAND-Land : data documentation - Copernicus Knowledge Base - ECMWF Confluence Wiki. (2024, 27 mars). https://confluence.ecmwf.int/display/CKB/ERA5-LAND-Land%3A+data+documentation

Ford, J. D., Keskitalo, E. C. H., Smith, T. F., Pearce, T., Berrang-Ford, L., Duerden, F., & Smit, B. (2010). Case study and analogue methodologies in climate change vulnerability research.

Wiley Interdisciplinary Reviews. Climate Change, 1(3), 374-392. https://doi.org/10.1002/wcc.48

Gasset, N., Fortin, V., Dimitrijevic, M., Carrera, M. L., Bilodeau, B., Muncaster, R., Gaborit, É., Roy, G., Pentcheva, N., Bulat, M., Wang, X., Pavlovic, R., Lespinas, F., Khedhaouiria, D., & Mai, J. (2021). A 10 km North American precipitation and land-surface reanalysis based on the GEM atmospheric model. Hydrology And Earth System Sciences, 25(9), 4917-4945. https://doi.org/10.5194/hess-25-4917-2021

GIEC, 2013: Glossaire [Planton, S. (coord.)]. In: Changements climatiques 2013: Les éléments scientifiques. Contribution du Groupe de travail I au cinquième Rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex et P.M. Midgley (dir. publ.)]. Cambridge University Press, Cambridge, Royaume-Uni et New York, NY, États-Unis d'Amérique, https://www.ipcc.ch/site/assets/uploads/2018/08/WGI_AR5_glossary_FR.pdf

Gimeno, L., Sorí, R., Vázquez, M., Stojanović, M., Algarra, I., Eiras-Barca, J., Gimeno-Sotelo, L., & Nieto, R. (2022). Extreme precipitation events. WIREs. Water, 9(6). https://doi.org/10.1002/wat2.1611

Gouvernement du Canada (2010). Les inondations au Canada : Québec. Environnement et Changements climatiques Canada, 2 décembre 2010. https://www.canada.ca/fr/environnement-changement-climatique/services/eau-apercu/volume/inondations/quebec.htm

Gouvernement du Canada. Base de données canadienne sur les catastrophes. Consulted on Octobre 21, 2023, from https://bdc.securitepublique.gc.ca/rslts-fra.aspx?cultureCode=fr-Ca&boundingBox=&provinces=11&eventTypes=%27FL%27,%27ST%27&eventStartDate=%2719800101%27,%2720201231%27&injured=&evacuated=&totalCost=&dead=&normalizedCostYear=1&dynamic=false

Gouvernement du Québec (2024). Normales climatiques 1981-2010- Climat du Québec. Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs. Consulted on May 24, 2024, from https://www.environnement.gouv.qc.ca/climat/normales/climat-qc.htm.

Hassol, S. J. (2008). Improving how scientists communicate about climate change. Eos, 89(11), 106-107. https://doi.org/10.1029/2008eo110002

Hazeleger, W., Van Den Hurk, B., Min, E., Van Oldenborgh, G. J., Petersen, A. C., Stainforth, D. A., Vasileiadou, E., & Smith, L. A. (2015). Tales of future weather. Nature Climate Change, 5(2), 107-113. https://doi.org/10.1038/nclimate2450

Hewitson, B., Waagsaether, K. L., Pfenninger, S., Kloppers, K., & Kara, T. (2017). Climate information websites : an evolving landscape. Wiley Interdisciplinary Reviews. Climate Change, 8(5). https://doi.org/10.1002/wcc.470

Hewitt, C., Stone, R., & Tait, A. (2017). Improving the use of climate information in decision-making. Nature Climate Change, 7(9), 614-616. https://doi.org/10.1038/nclimate3378

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press.

IPCC. (2017). Chair's vision paper, Intergovernmental Panel on Climate Change, AR6 Scoping Meeting Addis Ababa. Ethiopia, 1–5 May 2017, AR6-SCOP/Doc. 2. https://www.ipcc.ch/site/assets/uploads/2018/11/AR6-Chair-Vision-Paper.pdf

IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

IRM - Ce que l’on sait sur les pluies exceptionnelles des 14 et 15 juillet 2021. (2024). KMI. https://www.meteo.be/fr/infos/actualite/ce-que-lon-sait-sur-les-pluies-exceptionnelles-des-14-et-15-juillet-2021

Janković, V., & Schultz, D. M. (2016). Atmosfear : Communicating the Effects of Climate Change on Extreme Weather. Weather, Climate, And Society, 9(1), 27-37. https://doi.org/10.1175/wcas-d-16-0030.1

Kain, J. S., & Fritsch, J. M. (1990). A One-Dimensional Entraining/Detraining Plume Model and Its Application in Convective Parameterization. Journal Of The Atmospheric Sciences, 47(23), 2784-2802. https://doi.org/10.1175/1520-0469(1990)047

Kain, J. S. (2004). The Kain–Fritsch Convective Parameterization : An update. Journal Of Applied Meteorology, 43(1), 170-181. https://doi.org/10.1175/1520-0450(2004)043

Kirchmeier-Young, M. C., & Zhang, X. (2020b). Human influence has intensified extreme precipitation in North America. Proceedings Of The National Academy Of Sciences Of The United States Of America, 117(24), 13308-13313. https://doi.org/10.1073/pnas.1921628117

Koguia, W. N., Nonga, F. N., Movafeghi, A., Leblois, A., & Laure, M. T. G. (2021). Perception of Climatic Change and Farmers' Decision to Adapt in the Sudano-sahelian Zone in Cameroon. Journal Of Humanities And Social Sciences Studies, 3(10), 22-33. https://doi.org/10.32996/jhsss.2021.3.10.3

Koks, E.E., Bars, D. L., Essenfelder, A. H., Nirandjan, S., Sayers, P., & Sayers, P. (2022). The impacts of coastal flooding and sea level rise on critical infrastructure: a novel storyline approach. Sustainable And Resilient Infrastructure, 8(sup1), 237-261. https://doi.org/10.1080/23789689.2022.2142741

La Presse (1982, August 26). Un véritable déluge sur l'Ontario et le Québec. *La Presse*. https://numerique.banq.qc.ca/patrimoine/details/52327/2292673

Leduc, M. (2019). Documentation for the ClimEx CRCM5 Large Ensemble (v2.1). Ouranos Consortium on Climatology and Adaptation to Climate Change. June 10, 2019. https://www.climex-project.org/wp-content/uploads/2021/10/ClimEx_CRCM5-LE_documentation_v2.1-1.pdf

Lee, J.-Y., J. Marotzke, G. Bala, L. Cao, S. Corti, J.P. Dunne, F. Engelbrecht, E. Fischer, J.C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal, and T. Zhou, 2021: Future Global Climate: Scenario-Based Projections and NearTerm Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 553–672, doi:10.1017/9781009157896.006

Leimbach, M., Marcolino, M., & Koch, J. (2023). Structural change scenarios within the SSP framework. Futures, 150, 103156. https://doi.org/10.1016/j.futures.2023.103156

Lenderink, G., & Van Meijgaard, E. (2008). Increase in hourly precipitation extremes beyond expectations from temperature changes. Nature Geoscience, 1(8), 511-514. https://doi.org/10.1038/ngeo262

Lepoussez, V and Aboukrat, M. (2022). Les scénarios SSP : décryptage et recommandations d'utilisation pour une démarche d'adaptation aux changements climatiques. Carbone4 - Pôle Résilience et Adaptation aux Impacts du Changement Climatique. Juillet 2022. https://www.carbone4.com/files/Publication_Carbone_4_Decryptage_SSP_et_recommandations.pdf

Lucas-Picher, P., Riboust, P., Somot, S., & Laprise, R. (2015). Reconstruction of the Spring 2011 Richelieu River Flood by Two Regional Climate Models and a Hydrological Model. Journal Of Hydrometeorology, 16(1), 36-54. https://doi.org/10.1175/jhm-d-14-0116.1

Martel, J., Brissette, F., Lucas-Picher, P., Chen, J., & Arsenault, R. (2021). Climate Change and Rainfall Intensity–Duration–Frequency Curves: Overview of Science and Guidelines for Adaptation. Journal Of Hydrologic Engineering, 26(10). https://doi.org/10.1061/(asce)he.1943-5584.0002122

Martynov, A., Laprise, R., Sushama, L., Winger, K., Šeparović, L., & Dugas, B. (2013). Reanalysis-driven climate simulation over CORDEX North America domain using the Canadian Regional Climate Model, version 5 : model performance evaluation. Climate Dynamics, 41(11-12), 2973-3005. https://doi.org/10.1007/s00382-013-1778-9

Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., Brovkin, V., Claußen, M., Crueger, T., Esch, M., Fast, I., Fiedler, S., Fläschner, D., Gayler, V., Giorgetta, M., Goll, D., Haak, H., Hagemann, S., Hedemann, C.,. . . Roeckner, E. (2019). Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO2. Journal Of Advances In Modeling Earth Systems, 11(4), 998-1038. https://doi.org/10.1029/2018ms001400

Montreal Gazette (2019, 14 juillet). History Through Our Eyes: July 14, 1987, flooding on the Décarie. Montrealgazette. https://montrealgazette.com/news/local-news/history-through-our-eyes/history-through-our-eyes-july-14-1987-flooding-on-the-decarie

Nerlich, B., Koteyko, N., & Brown, B. J. (2009). Theory and language of climate change communication. Wiley Interdisciplinary Reviews. Climate Change, 1(1), 97-110. https://doi.org/10.1002/wcc.2

Newell, R., Dale, A., & Winters, C. (2016). A picture is worth a thousand data points : Exploring visualizations as tools for connecting the public to climate change research. Cogent Social Sciences, 2(1), 1201885. https://doi.org/10.1080/23311886.2016.1201885

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R., & Van Vuuren, D. (2013). A new scenario framework for climate change research : the concept of shared socioeconomic pathways. Climatic Change, 122(3), 387-400. https://doi.org/10.1007/s10584-013-0905-2

Pérez Bello, A. P., Mailhot, A., & Paquin, D. (2021b). The Response of Daily and Sub-Daily Extreme Precipitations to Changes in Surface and Dew-Point Temperatures. Journal Of Geophysical Research. Atmospheres, 126(16). https://doi.org/10.1029/2021jd034972

Pérez Bello, A. P., Mailhot, A., Paquin, D., & Paquin-Ricard, D. (2022b). Temperature-Precipitation Scaling Rates : A Rainfall Event-Based perspective. Journal Of Geophysical Research. Atmospheres, 127(22). https://doi.org/10.1029/2022jd037873

Radio-Canada. (2017, 13 juillet). Le 14 juillet 1987, c'était le déluge à Montréal ! Radio-Canada. https://ici.radio-canada.ca/nouvelle/1045083/30-ans-deluge-montreal-pluie-inondations-14-juillet-1987

Reichler, T., & Kim, J. (2008). Uncertainties in the climate mean state of global observations, reanalyses, and the GFDL climate model. Journal Of Geophysical Research, 113(D5). https://doi.org/10.1029/2007jd009278

Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi:10.1017/9781009157896.013.

Separovic L, A Alexandru, R Laprise, A Martynov, L Sushama, K Winger, K Tete, M Valin. 2013. Present climate and climate change over North America as simulated by the fifth-generation Canadian regional climate model. Clim Dyn 41:3167-3201. DOI 10.1007/s00382-013-1737-5.

Shepherd, T. G., Boyd, E., Calel, R., Chapman, S. C., Dessai, S., Dima-West, I., Fowler, H. J., James, R., Maraun, D., Martius, O., A, C., Senior, Sobel, A. H., Stainforth, D. A., Tett, S. F. B., Trenberth, K. E., Van Den Hurk, B., Watkins, N. W., Wilby, R. L., & Zenghelis, D. (2018). Storylines : an alternative approach to representing uncertainty in physical aspects of climate change. Climatic Change, 151(3-4), 555-571. https://doi.org/10.1007/s10584-018-2317-9

Sillmann, J., Shepherd, T. G., Van Den Hurk, B., Hazeleger, W., Martius, O., Slingo, J., & Zscheischler, J. (2021). Event-Based Storylines to Address Climate Risk. Earth’s Future, 9(2). https://doi.org/10.1029/2020ef001783

Smith, C., & Lawson, N. (2011). Identifying extreme event climate thresholds for greater Manchester, UK : examining the past to prepare for the future. Meteorological Applications, 19(1), 26-35. https://doi.org/10.1002/met.252

Steuri, B., Viktor, E., Zohbi, J. E., & Jacob, D. (2022). Fashionable Climate Services : The Hats and Styles of User Engagement. Bulletin Of The American Meteorological Society, 103(10), E2341-E2353. https://doi.org/10.1175/bams-d-22-0009.1

Sun, Q., Zhang, X., Zwiers, F. W., Westra, S., & Alexander, L. V. (2021). A Global, Continental, and Regional Analysis of Changes in Extreme Precipitation. Journal Of Climate, 34(1), 243-258. https://doi.org/10.1175/jcli-d-19-0892.1

Sundqvist, H. (1978). A parameterization scheme for non-convective condensation including prediction of cloud water content. Quarterly Journal Of The Royal Meteorological Society, 104(441), 677-690. https://doi.org/10.1002/qj.49710444110

Swart, N. C., Cole, J. N. S., Kharin, V., Lazare, M., Scinocca, J., Gillett, N. P., Anstey, J., Arora, V. K., Christian, J. R., Hanna, S., Jiao, Y., Lee, W. G., Majaess, F., Saenko, O. A., Seiler, C., Seinen, C., Shao, A., Sigmond, M., Solheim, L.,. . . Winter, B. (2019). The Canadian Earth System Model version 5 (CanESM5.0.3). Geoscientific Model Development, 12(11), 4823-4873. https://doi.org/10.5194/gmd-12-4823-2019

Terrado, M., Calvo, L., & Christel, I. (2022). Towards more effective visualisations in climate services : good practices and recommendations. Climatic Change, 172(1-2). https://doi.org/10.1007/s10584-022-03365-4

Tousignant, B. (2021). Mila | Ce climat n'existe pas : visualiser les impacts de la crise climatique avec l'IA, une adresse à la fois. Mila. https://mila.quebec/fr/article/ce-climat-nexiste-pas-visualiser-les-impacts-de-la-crise-climatique-avec-lia-une-adresse-a

Vasileiadou, E., & Botzen, W. (2014). Communicating adaptation with emotions : the role of intense experiences in raising concern about extreme weather. Ecology And Society, 19(2). https://doi.org/10.5751/es-06474-190236

Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., Kendon, E. J., Lenderink, G., & Roberts, N. (2014). Future changes to the intensity and frequency of short-duration extreme rainfall. Reviews Of Geophysics, 52(3), 522-555. https://doi.org/10.1002/2014rg000464

Whitmarsh, L., Lorenzoni, I., & O'Neill, S. (2012). Engaging the Public with Climate Change. Dans Routledge eBooks, 320 pages. https://doi.org/10.4324/9781849775243

Zadra, A., Caya, D., Côté, J., Dugas, B., Jones, C., Laprise, R., Winger, K., & Caron, L. (2008). THE NEXT CANADIAN REGIONAL CLIMATE MODEL. La Physique Au Canada, 64(2). http://www.diva-portal.org/smash/record.jsf?pid=diva2:1192006

Zhang, L., Chen, X., Lai, R., & Zhu, Z. (2022b). Performance of satellite-based and reanalysis precipitation products under multi-temporal scales and extreme weather in mainland China. Journal Of Hydrology, 605, 127389. https://doi.org/10.1016/j.jhydrol.2021.127389

Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., Rong, R., Fyfe, J., Li, G., Kharin, V.V. (2019): Changes in Temperature and Precipitation Across Canada; Chapter 4 in Bush, E. and Lemmen, D.S. (Eds.) Canada's Changing Climate Report. Government of Canada, Ottawa, Ontario, pp 112-193.

Zolina, O., Kapala, A., Simmer, C., & Gulev, S. (2004). Analysis of extreme precipitation over Europe from different reanalyses : a comparative assessment. Global And Planetary Change (Print), 44(1-4), 129-161. https://doi.org/10.1016/j.gloplacha.2004.06.009

CHAPTER IX. ANNEXE

The Table 10 below presents complete precipitation accumulations in mm for the 90th percentiles in 30-year climatic periods:

Table 10 : 90th percentile values (in mm) for all climatic time periods and simulations

Data source	3 hours	6 hours	12 hours	24 hours
1950-1979				
ERA5-LAND	32.6	45.0	54.1	72.9
CRCM5-MPI	56.3	74.7	104.8	118.5
CRCM5-CanESM5	63.0	84.6	103.4	144.7
1980-2009				
ERA5-LAND	35.7	47.1	55.9	69.4
RDRS	49.3	67.8	84.2	91.5
CRCM5-ERA	73.2	81.3	105.6	115.7
CRCM5-MPI	63.5	76.9	90.2	105.9
CRCM5-CanESM5	80.7	90.6	101.7	122.1
2010-2039				
CRCM5-MPI SSP 1-2.6	69.6	78.5	92.9	103.3
CRCM5-MPI SSP 3-7.0	72.1	103.5	117.6	131.5
CRCM5-CanESM5 SSP 1-2.6	69.6	97.7	121.3	124.6
CRCM5-CanESM5 SSP 3-7.0	77.0	87.1	115.9	142.7
2040-2070				
CRCM5-MPI SSP 1-2.6	72.1	81.0	98.3	108.6
CRCM5-MPI SSP 3-7.0	78.8	80.2	96.8	108.5
CRCM5-CanESM5 SSP 1-2.6	79.2	95.2	104.1	114.1
CRCM5-CanESM5 SSP 3-7.0	94.3	123.9	130.4	159.8
2070-2099				
CRCM5-MPI SSP 1-2.6	68.1	97.7	117.2	134.3
CRCM5-MPI SSP 3-7.0	94.4	122.3	125.1	139.1
CRCM5-CanESM5 SSP 1-2.6	97.8	102.0	107.8	132.5
CRCM5-CanESM5 SSP 3-7.0	89.3	120.9	131.6	145.5

The Table 11 presents complete precipitation accumulations in mm for the 95th percentiles in 30-year climatic periods:

Table 11: 95th percentile value (in mm) for all climatic time periods and simulations

Data source	3 hours	6 hours	12 hours	24 hours
1950-1979				
ERA5-LAND	27.1	38.9	54.5	65.9
CRCM5-MPI	57.4	80.3	111.1	136.0
CRCM5-CanESM5	85.7	101.1	112.8	122.2
1980-2009				
ERA5-LAND	37.2	51.2	67.4	82.7
RDRS	51.4	73.0	83.0	91.9
CRCM5-ERA	85.5	101.5	117.4	133.5
CRCM5-MPI	74.9	81.4	94.2	113.8
CRCM5-CanESM5	99.3	108.5	122.3	133.7
2010-2039				
CRCM5-MPI SSP 1-2.6	78.1	106.5	115.1	128.3
CRCM5-MPI SSP 3-7.0	92.2	115.5	134.4	150.7
CRCM5-CanESM5 SSP 1-2.6	71.9	107.1	138.4	147.9
CRCM5-CanESM5 SSP 3-7.0	81.9	92.9	141.4	156.3
2040-2070				
CRCM5-MPI SSP 1-2.6	75.7	97.5	107.1	123.5
CRCM5-MPI SSP 3-7.0	89.5	125.8	131.7	144.6
CRCM5-CanESM5 SSP 1-2.6	91.7	110.9	122.5	127.7
CRCM5-CanESM5 SSP 3-7.0	122.4	139.7	160.9	170.0
2070-2099				
CRCM5-MPI SSP 1-2.6	81.5	83.6	99.9	115.1
CRCM5-MPI SSP 3-7.0	116.5	136.2	139.6	148.2
CRCM5-CanESM5 SSP 1-2.6	104.1	115.5	122.2	139.9
CRCM5-CanESM5 SSP 3-7.0	116.1	156.7	175.3	179.8

The Table 12 below presents complete precipitation accumulations in mm for the 99th percentiles in 30-year climatic periods:

Table 12: 99th percentile values (in mm) for all climatic time periods and simulations

Data source	3 hours	6 hours	12 hours	24 hours
1950-1979				
ERA5-LAND	29.8	43.8	63.5	68.4
CRCM5-MPI	64.1	90.8	125.7	155.4
CRCM5-CanESM5	102.8	114.1	125.0	130.7
1980-2009				
ERA5-LAND	46.0	74.0	92.2	99.5
RDRS	56.9	75.9	85.5	119.7
CRCM5-ERA	136.4	156.8	185.7	194.5
CRCM5-MPI	85.6	87.6	101.8	123.8
CRCM5-CanESM5	107.1	123.8	130.3	145.1
2010-2039				
CRCM5-MPI SSP 1-2.6	98.1	112.0	120.0	128.8
CRCM5-MPI SSP 3-7.0	111.6	118.6	144.5	158.4
CRCM5-CanESM5 SSP 1-2.6	92.0	117.0	151.7	167.1
CRCM5-CanESM5 SSP 3-7.0	102.4	120.7	149.3	172.4
2040-2070				
CRCM5-MPI SSP 1-2.6	82.6	120.3	123.8	132.6
CRCM5-MPI SSP 3-7.0	95.4	162.3	178.0	179.4
CRCM5-CanESM5 SSP 1-2.6	107.5	116.9	127.7	141.5
CRCM5-CanESM5 SSP 3-7.0	142.1	160.2	175.5	189.2
2070-2099				
CRCM5-MPI SSP 1-2.6	88.9	93.9	112.7	129.4
CRCM5-MPI SSP 3-7.0	135.4	151.9	154.3	155.7
CRCM5-CanESM5 SSP 1-2.6	114.4	156.6	167.8	177.0
CRCM5-CanESM5 SSP 3-7.0	218.5	233.6	235.2	242.2

Table 13 shows result for the 95th percentile simulation by CRCM5-CanESM5 and highlights the changes between historical and future periods:

Table 13: Results for the 95th percentile, CRCM5-CanESM5

Time indicator	**1950-1979**	**1980-2009**	**2010-2039**		**2040-2070**		**2070-2099**		**% changes between 1950-1979 and 2070-2099**	
			SSP 1-2.6	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**
3 hours	85.7	99.3	71.9	81.9	91.7	122.4	104.1	116.1	+ 21	+ 35
6 hours	101.1	108.5	107.1	92.9	110.9	139.7	115.5	156.7	+ 14	+ 55
12 hours	112.8	122.3	138.4	141.4	122.5	160.9	122.2	175.3	+ 8	+ 55
24 hours	122.2	133.7	147.9	156.3	127.7	170.0	139.9	179.8	+ 14	+ 47

Table 14 shows result for the 95th percentile simulation by CRCM5-MPI-ESM1.2-LR and highlights the changes between historical and future periods:

Table 14 : Results for the 95th percentile, CRCM5-MPI-ESM1.2-LR

Time indicator	**1950-1979**	**1980-2009**	**2010-2039**		**2040-2070**		**2070-2099**		**% changes between 1950-1979 and 2070-2099**	
			SSP 1-2.6	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**	**SSP 1-2.6**	**SSP 3-7.0**
3 hours	57.4	74.9	78.1	92.2	75.7	89.5	81.5	116.5	+ 42	+ 103
6 hours	80.3	81.4	106.5	115,5	97.5	125.8	83.6	136.2	+ 4	+ 70
12 hours	111.1	94.2	115.1	134.4	107.1	131.7	99.9	139.6	- 10	+ 26
24 hours	136.0	113.8	128.3	150.7	123.5	144.6	115.1	148.2	- 15	+ 9

Figures 29 and 30 illustrates the evolution of different percentiles values for the 3-hours accumulated precipitation on all data of the year (only where 3-hours precipitation is superior to 0), respectively for the CRCM5-CanESM and CRCM5-MPI-ESM1.2-LR simulations:

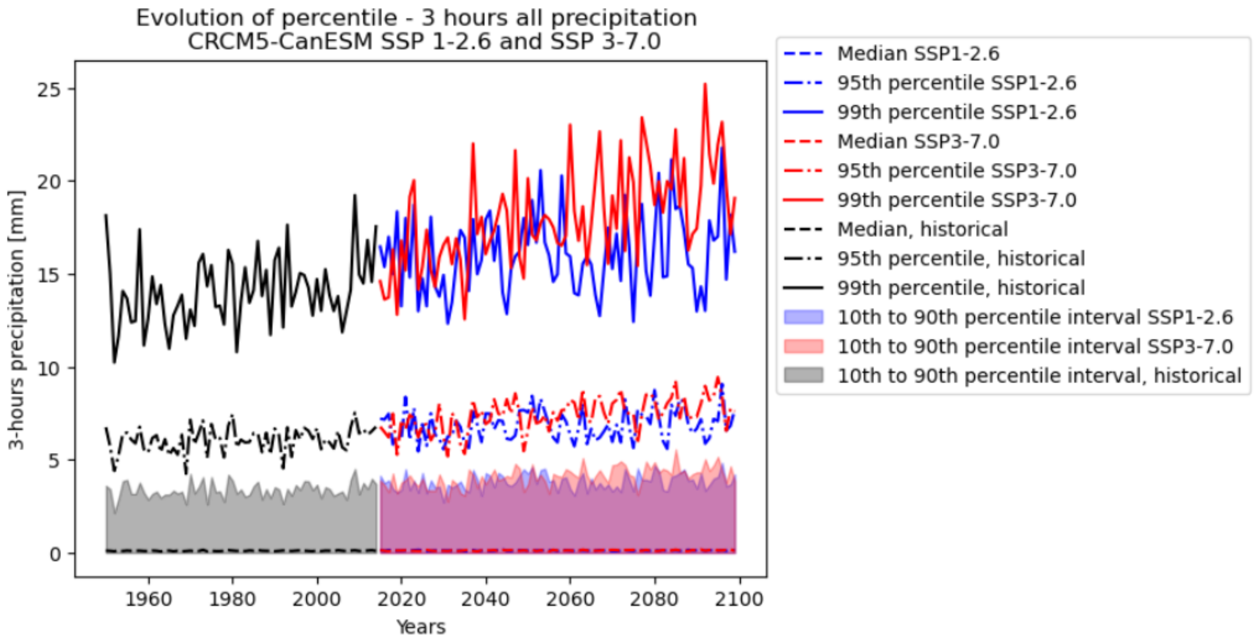


Figure 29: Evolution of percentiles for 3-hour precipitation throughout the year. Data in black is for historical, blue for the SSP1-2.6 scenario and red for the SSP3-7.0 scenario. The dashed line indicates the median, dash-dot line indicates the 95th percentile and plain line indicates the 99th percentile.

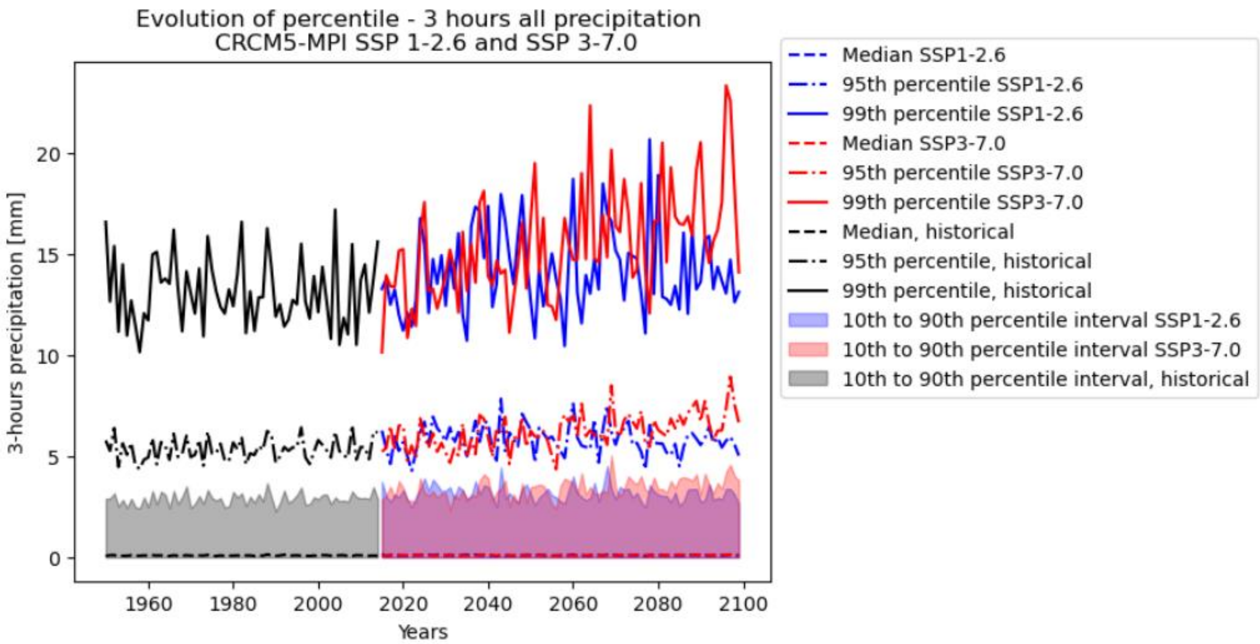


Figure 30: Same as Figure 29 but for CRCM5-MPI-ESM1.2-LR simulation

Figures 31 and 32 illustrates the IDF curves for the SSP1-2.6, respectively for the CRCM5-CanESM and CRCM5-MPI-ESM1.2-LR:

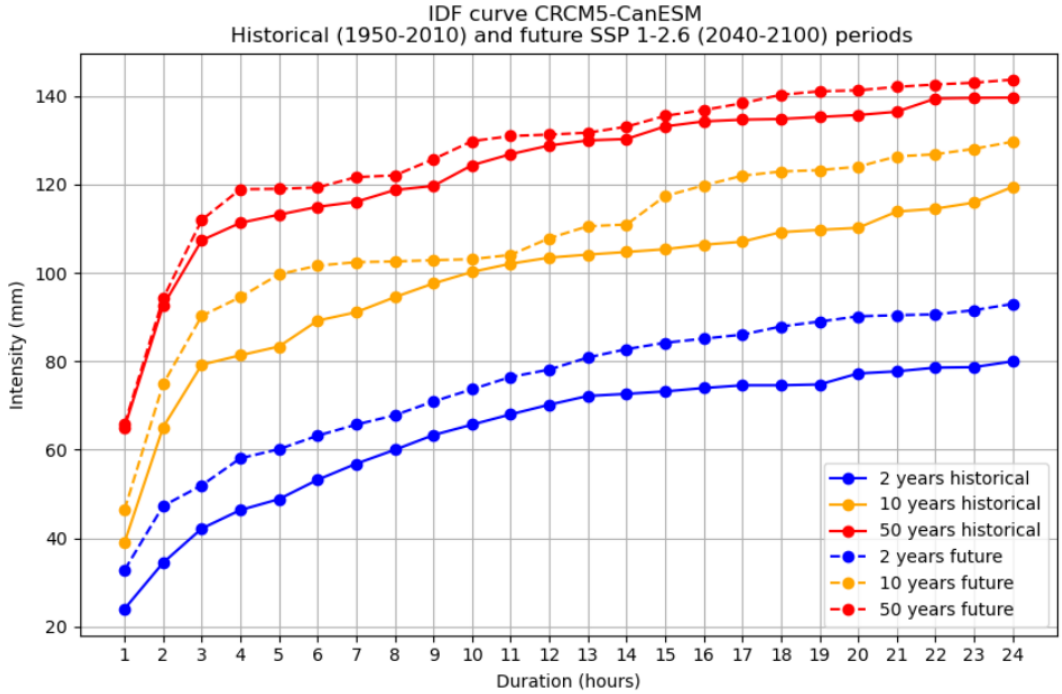


Figure 31: IDF curve for CRCM5-CanESM5 simulation historical (1950-2009, plain lines) and future (2040-2099, dashed lines) periods using the SSP1-2.6 emission scenario.

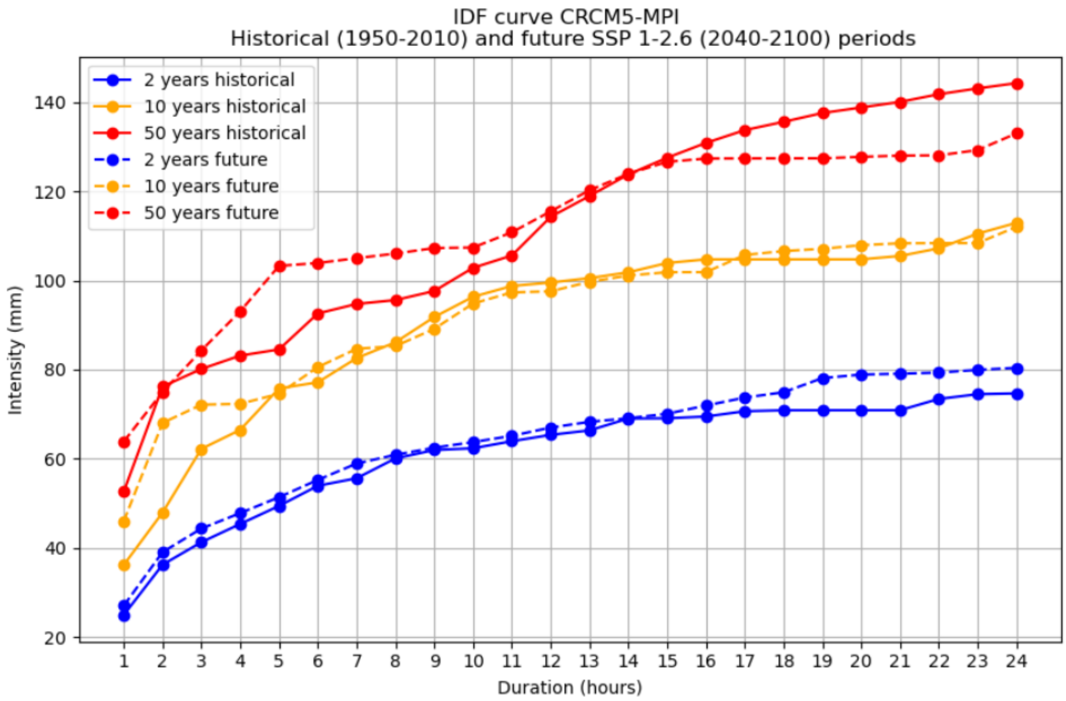


Figure 32: IDF curve for CRCM5-CanESM5 simulation historical (1950-2009, plain lines) and future (2040-2099, dashed lines) periods using the SSP1-2.6 emission scenario.