Climate Projections for the National Capital Region

Volume 1: Results and Interpretation for Key Climate Indices

June 2020

Issue or Revision	***Reviewed By:***	***Date***	***Issued By:***
Final	V. Leys	2020/03/13	L. Braschi L. Wilcott
Draft 3	V. Leys	2020/02/14	L. Braschi L. Wilcott
Draft 2	V. Leys	2020/01/24	L. Braschi L. Wilcott
Draft 1	V. Leys N. Corrin	2019/09/27	L. Braschi L. Wilcott

Report 193600.00

Contents

Volume 1

List of Appendices in Volume 1

Volume 2

List of Appendices in Volume 2

LIST OF FIGURES

List of Tables

Executive Summary

Canada's climate will continue to warm, driven by global greenhouse gas emissions from human activity. Both past and future warming in Canada is, on average, about double the magnitude of warming globally (Canada's Changing Climate Report, NRCan 2019). This poses risks to all sectors of the economy and Canadians' quality of life. Action on climate change mitigation and adaptation is required to limit impacts on people, the economy and natural ecosystems.

The National Capital Commission (NCC) and the City of Ottawa (referred to herein as the Project Partners) commissioned CBCL Limited to undertake a comprehensive climate change projection study for the National Capital Region (NCR). The project used a collaborative and impacts-driven approach that involved iterative feedback from the Project Partners and stakeholders such as the Ville de Gatineau and Conservation Authorities. It relied on data and advice from Environment and Climate Change Canada's (ECCC) Canadian Centre for Climate Services (CCCS). This study complements work being done by the Ville de Gatineau in partnership with Ouranos.

Goals

Climate projections use climate science and modelling to predict future changes in temperature, precipitation, wind and extreme events. Climate projections are used in climate risk assessments and support adaptation and resiliency planning for multiple sectors. The regional approach to developing climate projections encourages consistency across multiple jurisdictions with overlapping climate impacts and adaptation needs. Climate projections from this study (Phase 1) will help decision-makers to understand impacts on communities, infrastructure, economy and the natural environment (Phase 2), and plan for climate resilience and adaptation initiatives (Phase 3). This study builds upon previous studies (Public Services and Procurement Canada, the Ville de Gatineau, and Hydro Ottawa) and is more comprehensive in terms of data coverage and geographical reach, with the intention of reaching the widest user and application base.

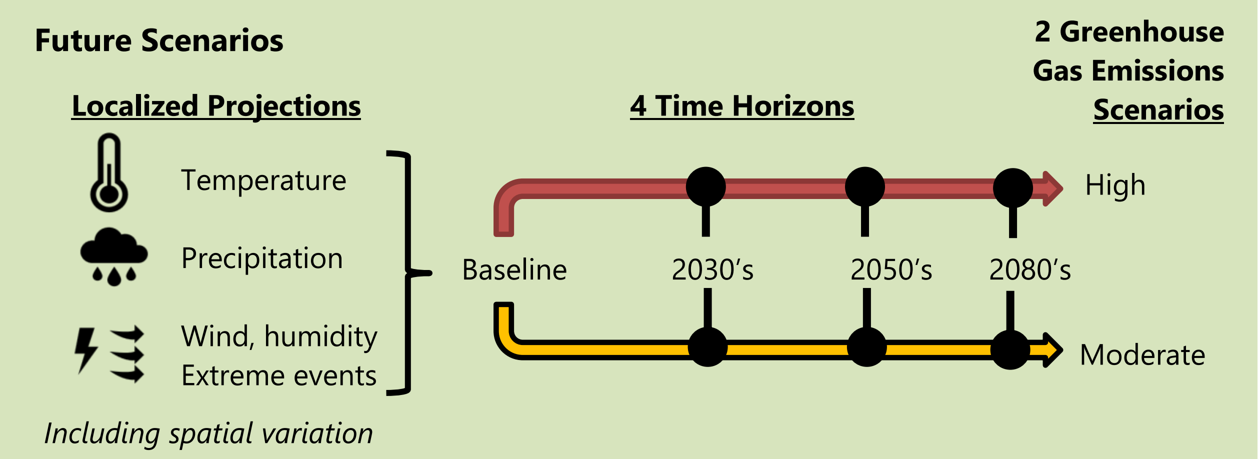
The climate data in this report has been made publicly available to support a common understanding of how the climate in the region is and will continue to change. Stakeholders in the NCR are encouraged to use the results of this climate projections study in climate risk assessments and adaptation planning and projects.

Future Scenarios and Time Horizons

Impact assessment, climate risk management, and policy development today must be informed by a range of emission scenarios, or "Representative Concentration Pathways" (RCPs) used to drive climate models. Scenarios by the Intergovernmental Panel on Climate Change (IPCC Fifth Assessment Report 2013) include low, moderate and high emission scenarios. If global greenhouse gas mitigation objectives from the 2015 Paris Agreement are achieved, the actual emissions will need to fall between the low and moderate scenarios. The rate and magnitude of climate change will depend on future global greenhouse gas emissions; global emissions are currently tracking above the moderate emission scenario.

As the low emission scenario is considered unlikely, this study provides a range of results for the moderate to high emission scenarios (RCP 4.5 and RCP 8.5) for 3 projection horizons, or time slices, when compared to the 1981-2010 baseline:

- **2030s (2021-2050).**
- **2050s (2041-2070).**
- **2080s (2071-2100).**



Climate Projections

The outputs of climate models include parameters like temperature, precipitation, humidity, snow, and wind. Indices, i.e., calculations based on parameters, were selected to provide meaningful projections that can be used by decision-makers.

Overall, it is projected that **the NCR will become warmer and wetter**. Warming is anticipated in all seasons. An increase in precipitation is anticipated in all seasons, except summer. It is expected that **the timing of seasons will shift** and that periods of extreme heat will become more common. Rainfall is expected to increase, both in volume and intensity. Annually, **less snowfall and a shorter snow season** are projected. Conditions favourable for extreme events such as freezing rain, tornadoes and wildfires are projected to become more common.

Temperatures are projected to be warmer under the high emission scenario. In other words, there is a greater difference between the moderate (RCP 4.5) and high emission (RCP 8.5) scenarios for temperature-based indices. Results are more variable for precipitation indices, and some show a negligible difference between moderate (RCP 4.5) and high (RCP 8.5) emission scenarios or between subsequent time horizons.

Temperature and precipitation are the two most typical climate model parameters; hence, a larger ensemble of climate models is available for these parameters, allowing a better characterization. In each of the following key findings (and in the remainder of the report), the two values quoted (e.g., 5-8°C in the 2030s) are **for moderate (RCP 4.5) and high (RCP 8.5) emission scenarios respectively.** These values represent an "average year" for the time period as they are averaged over 30-year time slices.

In this report, the two values reported for each index (e.g., 5-8°C) are not ranges; they represent the mean values for the moderate (RCP 4.5) and high (RCP 8.5) emission scenarios. When a decrease is projected, such as for the amount of snow, the second value will be lower than the first value.

A simplified summary of projections for the high carbon emission scenario RCP 8.5 is provided in the following table, supported by a more detailed summary in the next sub-sections.

Summary of Future Climate in Canada's Capital Region

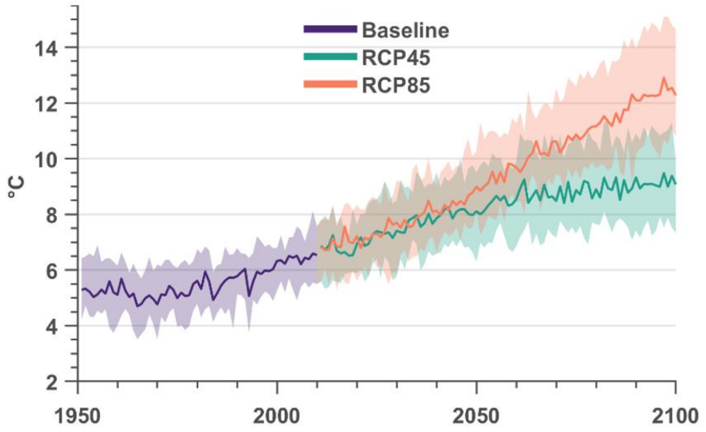
What to expect*	2030s	2050s	2080s
Temperature			
Average temperature	↑ 1.8°C	↑ 3.2°C	↑ 5.3°C
Very hot days (above 30°C)	2.5 times more	4 times more	6.5 times more
Very cold days (below -10°C)	20% less	35% less	65% less
Seasons			
Winters shorter by	4 weeks	5 weeks	8 weeks
Springs earlier by	2 weeks	2 weeks	4 weeks
Winter freeze-thaw	↑ 15%	↑ 35%	↑ 55%
Precipitation			
Fall-winter-spring precipitation	↑ 5%	↑ 8%	↑ 12%
Intense precipitation	↑ 5%	↑ 15%	↑ 20%
Snowfall	↓ 10%	↓ 20%	↓ 45%
Extreme Events			
	Possible increases in freezing rain		
	Warming favours conditions conducive to storms, wildfires		

More certainty ↓ Less certainty

** For high emission Scenario RCP 8.5*

More certainty → Less certainty

Temperature Projections:

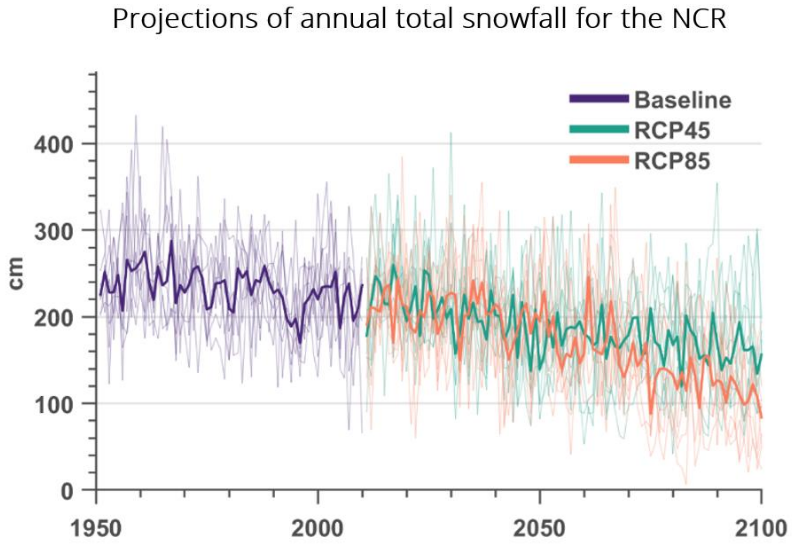

Projections of annual average temperature for the NCR

- **Increase in Average Temperatures (all Seasons)** – The **average annual temperature** is projected to increase from approximately 6.1°C in the baseline to approximately 7.5-7.9°C in the 2030s, 8.2-9.3°C in the 2050s, and 8.8-11.4°C in the 2080s. No single season is projected to warm significantly faster than the others.
- **Less Cold Extremes –** Cold extremes are expected to decrease in intensity and frequency. For example, the number of days per year where the daily minimum temperature is less than -10°C ("**Deep Freeze Events**") is projected to decrease from approximately 71 days in the baseline to approximately 59-57 days in the 2030s, 53-46 days in the 2050s and 48-28 days in the 2080s. Although these projections are for an extreme index, they represent an "average year" since they are averaged over 30-year time slices.
- **More Warm Extremes** – There will be an increase in the frequency and intensity of high-temperature extremes. In the baseline, the NCR experienced approximately 11 days that reached 30°C ("**Hot Days**") per year. Models project an increase to approximately 25-28 days in the 2030s, 32-43 days in the 2050s and 36-72 days in the 2080s. That is twice as many hot days in the 2030s, 3-4 times as many in the 2050s, and 3-6 times as many in the 2080s.
- **Change in Seasonal Characteristics** – The **first day of fall frost** is projected to occur approximately 1-2 weeks later by the 2030s, 2-3 weeks later by the 2050s, and 3-4 weeks later by the 2080s compared to the baseline. The **last day of spring frost** is projected to occur approximately 1-2 weeks earlier in the 2030s and 2050s, and 2-4 weeks earlier in the 2080s.
- **Shift in Freeze-Thaw Cycles** – Models project that winter temperatures will hover around 0°C more frequently in the future. Therefore **winter freeze-thaw cycles** (December–February) are projected to increase, whereas freeze-thaw cycles that occur during spring (March–May) and fall (September–November) are projected to decrease as temperatures warm.

Precipitation Projections:

- **Increase in Total Precipitation (Except Summer)** – The **annual total precipitation** in the NCR (including both rain and snow) is expected to increase from approximately 921 mm/year in the baseline to approximately 949-968 mm in the 2030s, 979-993 mm in the 2050s and 983-1028 mm in the 2080s. Increases will be concentrated in the winter and shoulder seasons with no increases projected for June–September.

- **No change in Frequency of Wet Days** – Although the annual total precipitation is increasing, precipitation is projected to be concentrated within the **same number of wet days** (where precipitation > 1 mm) that occurred in the baseline.
- **More Intense Precipitation** – The **annual maximum precipitation** that falls in one day is expected to increase from approximately 37 mm in the baseline to 39-39 mm in the 2030s, 41-42 mm in the 2050s and 41-44 mm in the 2080s. The increase in precipitation is consistent with a greater amount of total precipitation falling in the same number of wet days (see above). Extreme precipitation (for example the 1 in 100 year event) is projected to increase for multiple durations (sub-daily, daily, and multi-day precipitation events). These projections represent an "average year" (since they are averaged over 30-year time slices), for a 10 km x 10 km area.
- **Decrease in Total Snowfall** – The **annual total snowfall** is projected to decrease from approximately 223 cm in the baseline to 193-201 cm in the 2030s, 184-179 cm in the 2050s and 154-124 cm in the 2080s. This represents a decrease of 31-44% by the 2080s. Due to year-to-year variability, values similar to the baseline are still possible past mid-century.



- **Shorter Snow Season** – The timing of the first snowfall is projected to be later in the year, and the timing of the last snowfall will be earlier. As a result (and due to increasing temperatures), the **number of days with snow cover** is projected to decrease from approximately 115 days in the baseline to approximately 95-94 days in the 2030s, 90-72 days in the 2050s and 78-43 days in the 2080s.
- **High Variability in Extreme Snow** – Projections suggest a decrease in the maximum snow depth and mixed findings for the maximum 1-day snowfall. Average projections suggest that **annual maximum 1-day snowfall** (averaged across the study area) will change from approximately 20 cm in the baseline to 21-20 cm in the 2030s, 22-20 cm in the 2050s and 20-16 cm in the 2080s. There is a decrease by the 2080s for the high emission scenario (RCP 8.5) but not for the moderate emission scenario (RCP 4.5). These projections represent total snow falling over the study area during an "average year" (since they are averaged over 30-year time slices). Due to year-to-year variability, values similar or higher than the baseline are still possible past mid-century.

Humidity, Wind, Extreme Events and Other Phenomena

No trends in average winds and humidity were detected; however, the occurrence of high wind chill is expected to decrease, whereas the number of days with high humidex is expected to increase. Although uncertainty remains high, the occurrence of conditions favourable to extreme weather (such as freezing rain, tornadoes, lightning, hurricanes, and wildfires) is projected to increase.

Prominent Climate Impacts on Key Sectors

This study did not examine specific risks and vulnerabilities, as this will occur in phase 2; however, potential impacts are generally known and can be summarized as follows.

Health and Safety – A warmer and wetter climate conducive to extreme events will have wide-ranging repercussions for public health and safety. For example, flooding, heat waves, and wildfires and extended power outages can have great impacts on those directly affected and put an added strain on emergency services. Wildfires increase the concentration of airborne particulate matter, impacting air quality. Conditions that are favourable for transmission of vector-borne illnesses, such as Lyme disease and West Nile virus, will be more common.

Water Services – More intense precipitation, including winter rain, will increase risks of flooding, erosion, combined sewer overflows and leachate generation at landfills. High winds may increase power outages to water services, requiring back-up power systems. Summer low flows may increase the risk of odours in the wastewater collection system.

Buildings, Real Estate and Planning – Energy demands are expected to shift seasonally, with heating requirements decreasing in the winter months and cooling demands increasing during the summer months. The roof and foundation drainage systems of buildings will be impacted by increases in the frequency and intensity of extreme precipitation events. For new construction, climate change will influence future editions of the National Building Code of Canada. Municipal planning must account for climate impacts, including future flood risks.

Transportation – Climate change will impact both transportation infrastructure (such as life expectancy of roads and flooding) and operations (such as power outages and travel delays). A changing climate could also bring potential opportunities to the transportation sector such as longer construction seasons or reduced winter snow clearing.

Natural Assets, Tourism and Recreation – Shorter winters with less snow, thinner ice and rain-on-snow will negatively impact popular activities such as cross-country skiing in Gatineau Park or skating on the Rideau Canal. Drier and warmer summers may impact plant and animal species, potentially favouring invasive species and agriculture, although variable precipitation may cause additional challenges. Shifting seasons will impact the preferred timing for the tulip festival.

Riverine Flooding – Riverine flooding can occur on all rivers in the NCR, most notably along the Gatineau, Rideau and Ottawa rivers. The NCR has experienced significant flooding along these rivers, including in the springs of 2017 and 2019. There are many factors that contribute to flooding or flood risk, most of which are outside the scope of this study. Spring freshet flooding, for example, is affected by precipitation and snowmelt in the entire Ottawa River watershed, which extends far beyond the present study area.

Managing Uncertainty

Sources of uncertainty in the projections include **natural variability**, **scenario uncertainty,** and **model uncertainty.** The respective significance of the sources of uncertainty changes with the expected remaining useful life of the policy, program, or asset in question. Uncertainty related to natural variability is relatively more significant in the short term whereas predictions associated with each emission scenario diverge over the long term. Strategies for managing uncertainty include:

- Climate Projections (this report) - Using an **ensemble of climate models** and a **range of scenarios.**
- Incorporating the implications of uncertainty into **climate risk assessments** (i.e., Phase 2)
- For planning and adaptation (i.e., Phase 3), where practical to do so, using a **low-regret approach** that accounts for the full range of climate projections can make a project more resilient to future climate and weather extremes, as follows:
    - ✓ Planning/designing for **most probable climate conditions** over the intended lifetime.
    - ✓ **Including flexibility** and/or additional safety factors for alternative courses of action should climate conditions deviate from planning and/or design assumptions.
    - ✓ **Monitoring climate** conditions and project performance over time.
    - ✓ Opting for adaptations that provide a clear **financial or social benefit** regardless of how climate changes in the future.
    - ✓ Implementing design and construction **modifications** in response to observed changes.

Applying the Climate Projections

The climate data in this report can support a wide variety of risk assessments and adaptation planning that build the resilience of people, assets and services to future climate conditions.

In the future, when new models are published, it is worthwhile to monitor new projections and compare them to the results presented within the report on a case by case basis. Risk and impact assessments should not be automatically presumed to be outdated when data becomes available, as new data may not change the outcome of the assessment.

Chapter 1 Introduction

Canada's climate will continue to warm, driven by global greenhouse gas emissions from human activity. Both past and future warming in Canada is, on average, about double the magnitude of global warming (NRCan 2019). This poses risks to all sectors of the economy and Canadians' quality of life. Action on climate change mitigation and adaptation is critically required to limit impacts on people and ecosystems.

The National Capital Commission (NCC) and the City of Ottawa (referred to herein as the Project Partners) are committed to building resilience and adapting to climate change. The services, programs, infrastructure, and assets under the jurisdiction of the NCC and City of Ottawa support the National Capital Region, home to approximately 1.3 million Canadians.

The partnership was formed in 2019 to execute a comprehensive climate change projection study for the National Capital Region (NCR). The project study area includes the National Capital Region (NCR), as defined in the *National Capital Act*, as well as the full extent of the City of Ottawa and the Ville de Gatineau. This study complements work being done by the Ville de Gatineau (in partnership with Ouranos).

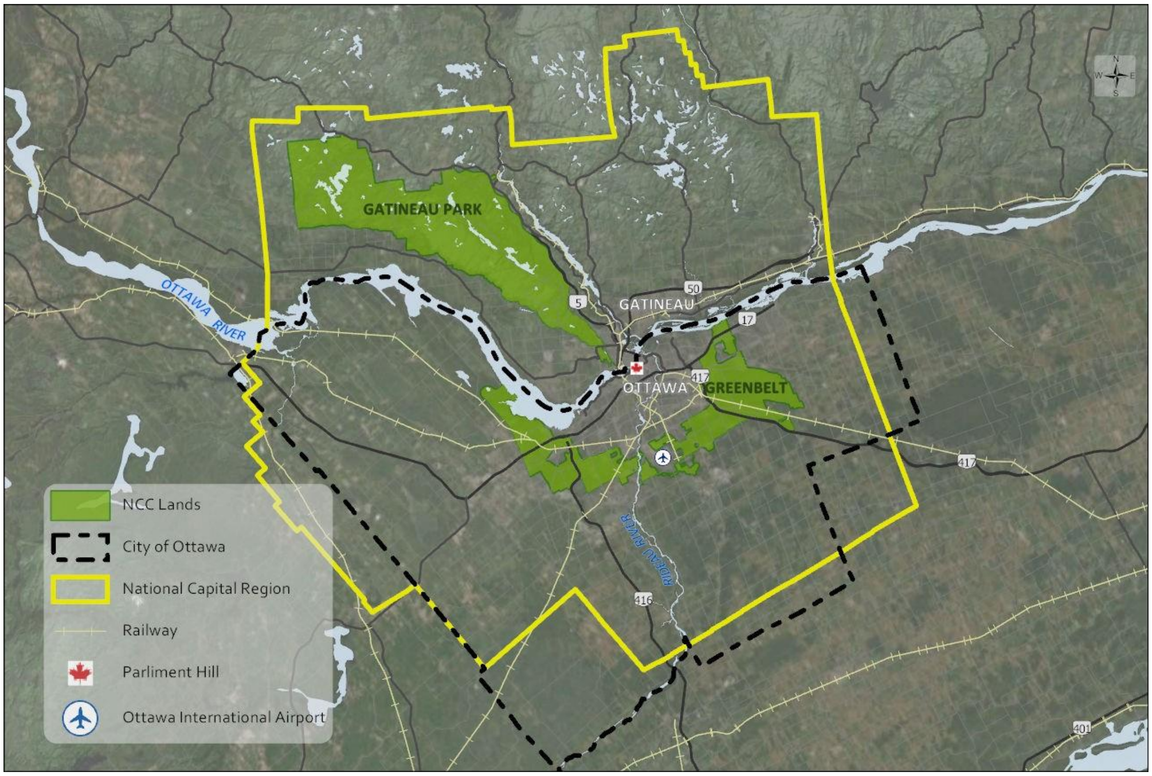


Figure 1.1: Study Area

1.1 Purpose

This project provides the data required to understand how climate is projected to change over the 21st century and assess the overall risks to people, infrastructure, the economy and natural environment.

The regional approach encourages consistency across multiple jurisdictions with overlapping climate impacts and adaptation needs. This is a comprehensive study in terms of data coverage and geographical reach. The intent is to support multiple users with the widest range of needs.

This project represents the first of a multi-phase adaptation initiative for both the NCC and the City of Ottawa. This first project phase includes the collection, analysis, and communication of climate projections for the NCR. Subsequent project phases will include the application of the data. These projections will help decision-makers to understand impacts on communities, infrastructure, economy and the natural environment (Phase 2), and plan for climate resilience and adaptation initiatives (Phase 3).

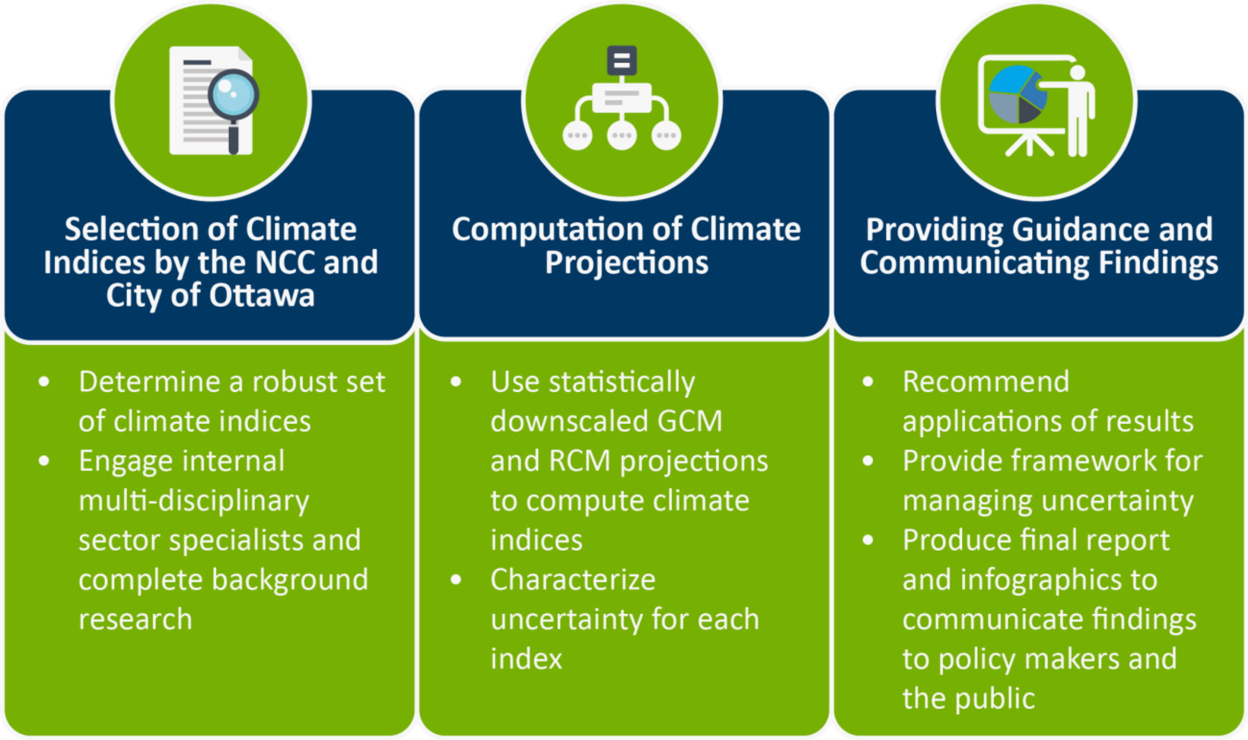
Figure 1.2: Phases of Climate Change Adaptation
The present study constitutes Phase 1.

General climate impacts are referenced broadly throughout this report because they provide important context for the selection of appropriate indices as well as the interpretation of results. A comprehensive vulnerability and impact assessment will be conducted in subsequent phases. Impact and risk assessments can range in scope and scale, from the assessment of a single impact in one sector (e.g., the impact of extreme heat on vulnerable populations) to the assessment of multiple impacts on multiple sectors (e.g., the impacts of climate change on municipal infrastructure). Impact assessments can also be executed across organizations, including collaboration from multiple levels of government. In fact, broad, multi-disciplinary representation on the impact assessment team will strengthen the evaluation of risk, management of uncertainty and identification of effective adaptation mechanisms.

1.2 Project Methodology

This climate projection study uses the most up-to-date climate science and modelling tools available in Canada. The project was approached with a collaborative and impacts-driven lens that involved iterative feedback from the Project Partners at the **NCC and City of Ottawa**, key stakeholder groups as well as data and expert advice from staff at **Environment and Climate Change Canada's (ECCC) Canadian Centre for Climate Services (CCCS).** The CCCS was involved from the beginning in defining the scope of the project, providing input for key decisions, and reviewing the final product.

The methodology for this assessment included the following steps:



Selection of Climate Indices by the NCC and City of Ottawa

- Determine a robust set of climate indices
- Engage internal multi-disciplinary sector specialists and complete background research

Computation of Climate Projections

- Use statistically downscaled GCM and RCM projections to compute climate indices
- Characterize uncertainty for each index

Providing Guidance and Communicating Findings

- Recommend applications of results
- Provide framework for managing uncertainty
- Produce final report and infographics to communicate findings to policy makers and the public

Figure 1.3: Project Methodology

(GCM = Global Climate Model, RCM = Regional Climate Model)

1.3 Future Climate Scenarios

Greenhouse gases (GHGs), such as carbon dioxide and methane, trap the sun's heat within the atmosphere, causing warming of the climate. The future climate will be driven by anthropogenic GHG emissions. Emission scenarios represent possible GHG emission patterns over the 21st century. These scenarios represent different futures based on the amount of anthropogenic GHG emitted globally, which can be affected by population growth and movement, future technology and alternative energy, policies, and conflict. There are currently four industry-standard scenarios, called Representative Concentration Pathways (RCPs) that have been established by the Intergovernmental Panel on Climate Change (IPCC).

Table 1.1: IPCC Emission Scenarios

Emission Scenario	Global GHG Emissions	Global Warming 2081-2100, Mean and Likely Range	Meets 2015 Paris Agreement for 2100 Global Warming <2°C?
Low RCP 2.6	Steep cut starting now to zero by 2070s	1.0°C (0.3 to 1.7)	Yes
Moderate RCP 4.5	Slight rise to 2040s, then drastic cut	1.8°C (1.1 to 2.6)	Possibly
Moderate-High RCP 6.0	Moderate rise to 2070s, then cut	2.2°C (1.4 to 3.1)	Unlikely
High RCP 8.5	Continuous and significant rise	3.7°C (2.6 to 4.8)	No

For this project, the moderate (RCP 4.5) and high (RCP 8.5) emission scenarios were considered. The moderate-high emission scenario (RCP 6.0) was not used, as a smaller number of models have used this RCP. The low emission scenario (RCP 2.6) was not used as it assumes that GHG emissions stay consistent until 2020 and then decline until 2100. Given recent global emission trends, this scenario is considered unrealistic.

Emissions for each scenario are shown in Figure 1.4. Figure 1.5 displays the change in global average temperature for the three RCP emission trajectories, as projected by climate models.

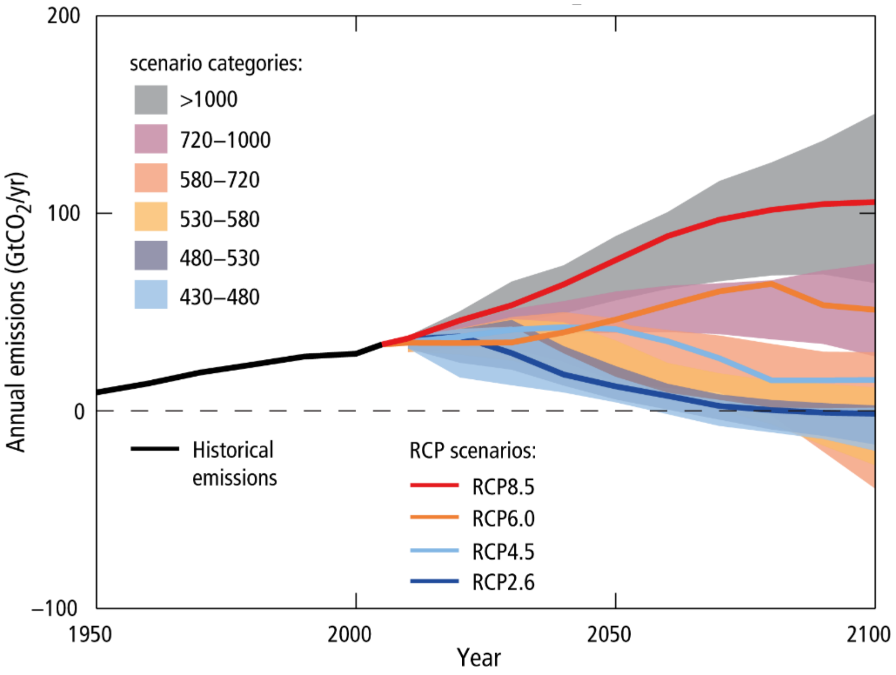


Figure 1.4: Evolution of Global Annual CO_2 Emissions (Historical and with RCP, IPCC 2013)

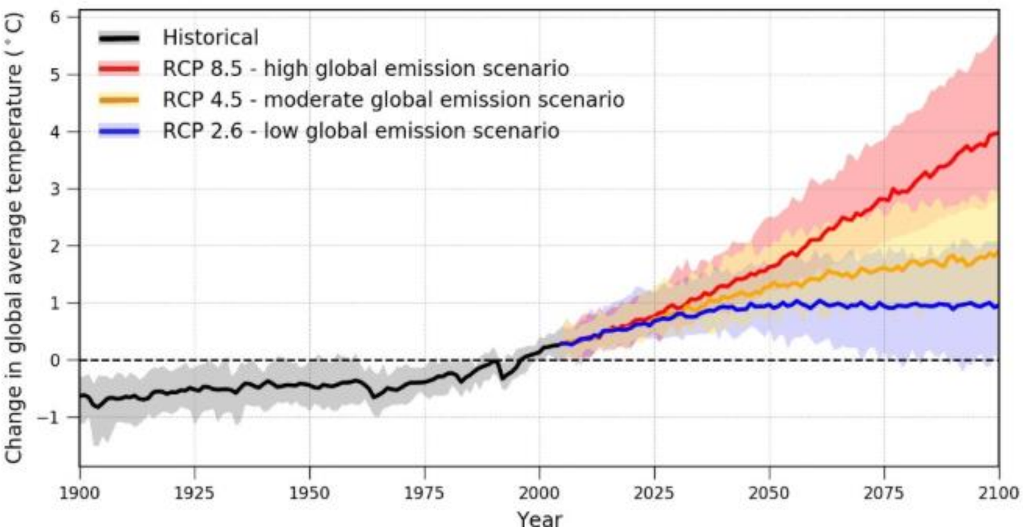


Figure 1.5: Change in Global Average Temperature Relative to the 1986-2005 Reference Period for RCP 2.6, RCP 4.5, and RCP 8.5 (Canadian Centre for Climate Services)

1.4 What is a Climate Model?

Global vs. Regional Climate Models

Climate models divide the earth into 3D cells and use equations to simulate atmospheric, oceanic, and other processes. There are over 30 Global Climate Models (GCMs) which are owned by leading scientific institutions around the world and require significant computational power to run. GCMs use GHG emission scenarios as their inputs.
In general, the cells of GCMs are too large to permit the local details needed for adaptation planning. Precipitation, for example, requires the use of Regional Climate Models (RCMs). RCMs are similar to GCMs except that they have higher spatial resolutions. The GCM outputs can also be focused onto smaller areas by using a process referred to as "downscaling".

This study uses global and regional climate models as described in the following table. Further technical details on models, projections, and uncertainty are provided in APPENDIX A – *Climate Modelling Background*.

Table 1.2: Use of GCMs and RCMs for Different Parameters and Indices

	GCM	RCM
Daily Temperature and Precipitation	x	
Daily Snow, Wind and Humidity		x
Sub-Daily (e.g., hourly) Precipitation and Wind		x
Combined Parameters (e.g., Wind chill, Humidex)	x	x

Certain climate phenomena are not well captured by climate models. These include freezing rain and ice storms; extreme snow and blizzards; extreme winds and gusts; tornadoes; hurricanes; lightning; evapotranspiration, drought and wildfire; air quality (e.g., smog); acid rain; and shortwave (UV) radiation. In this case, we have used a process-based characterization that looks at how the factors that affect these phenomena are changing, in order to understand trends.

Accounting for Model Uncertainty

Climate models use a large number of approximations in their mathematical formulations. These approximations are a practical solution to account for phenomena that occur at a spatial scale smaller than their grid cell. Therefore, models cannot capture the entire complexity of the climate system. As such, one model can overestimate or underestimate the simulated climate parameters. Because different models use different approximations, they will give different solutions, each of these solutions representing one possible future. Therefore, more than one model should be used for climate projections. The range of the models' solutions covers the range of possibilities (to the extent that they can be modelled).

This approach for managing model uncertainty and variability is called ensemble modelling. This study is based on ensemble modelling. The results of ensembles are presented with graphs and plots that indicate the distribution of data so that an assessment can be made with respect to the spread and overall confidence of the modelled result. The plots presented in this report provide the 10th and 90th percentiles of the ensemble as an indication of the uncertainty. The figures presented in the project will show results for the ensemble of models corresponding to the moderate (RCP 4.5) and high (RCP 8.5) emission scenario. More information on how to read plots is presented in APPENDIX B – *Guidelines to Reading and Interpreting the Plots*.

1.5 Time Horizons

The three projection horizons, or time slices, that were selected for this study are:

- 2030s (2021–2050).
- 2050s (2041–2070).
- 2080s (2071–2100).

These projection horizons represent a **mean value over a 30-year period** and are compared to a baseline (1981–2010). The baseline is output from models that have been run in the past (“hindcast”), and it represents the historical climate. Projections presented in these discrete horizons can then be used in risk and vulnerability assessments by matching the remaining useful life of the program or asset with the appropriate horizon. If an asset has an expected life exceeding 2100, it is still encouraged to assess projections for the shorter time horizons (the 2030s and 2050s) as some indices may have greater impacts in the short-term.

These projection horizons were selected for comparability with other work, including the use of standardized time slides where possible (e.g., the 1981–2010 baseline corresponds to ECCC Climate Normals), consistency with other resources available nationally (e.g., Climate Atlas of Canada, Climatedata.ca), and previous and ongoing projects in the region (Public Services and Procurement Canada, the Ville de Gatineau, and Hydro Ottawa).

1.6 Selection of Climate Indices

This study provides projections for 178 climate indices. The list of climate indices is available in Section 1.8, and the formulas for the indices can be found in APPENDIX F – *Plots of Climate Indices*.

Parameters vs. Indices

The outputs of GCMs and RCMs include parameters like temperature, precipitation, humidity, snow, and wind. Indices are then calculated from these parameters to provide detailed and meaningful projections that can be used by decision-makers. The terms climate “parameter” and “index” have different interpretations in climate science and impact science. For the purpose of this study:

- **Parameter** will be used to refer to direct output from models such as temperature, precipitation, snow, and wind.
- **Index** will be used to refer to calculations that are based on parameters, such as “number of freeze-thaw cycles”.

There are many types of indices, such as duration, threshold-based, minimum, maximum, or extreme values. Some indices require a combination of parameters, such as humidex which involves both humidity and temperature. A full list of indices generated in this study is presented in Section 1.8.

Selection of Indices

The selection of climate indices depends on both the specific targeted needs of stakeholders as well as the underlying climate science. In order for the study to be both highly informative and simple to use, climate indices must be impact-driven and established through consultation with the end-users in a broad range of sectors.

A working list of parameters and indices that could be used by stakeholders for future risk and vulnerability assessments was developed based on staff interviews, in-person meetings with select end-users, and input from the Project Partners based on their knowledge of the needs of the NCC and City of Ottawa.

Once the preliminary list of indices was developed, a half-day workshop was held on July 9th, 2019 to gather input from a broader group of internal stakeholders and refine the list of proposed indices. Over 60 people participated in the workshop, largely staff from the NCC and City of Ottawa, as well as representation from the Ville de Gatineau and three Ontario Conservation Authorities. The workshop included a series of presentations on climate change projections and indices, followed by group discussions based on the following sectors:

- Water Services;
- Health and Safety;
- Buildings, Real Estate and Planning;
- Transportation;
- Natural Assets, Tourism and Recreation.

The purpose of these breakout groups was to identify climate processes and impacts relevant to their sector and identify indices that would be useful to them in future risk and vulnerability assessments. The final list of indices included in the study was based on an understanding of the needs of the stakeholders and input from the Project Partners.

Computation of Climate Indices and Projections

The ensemble approach was used in the study, so climate indices were computed for each member of the ensemble. Technical details are provided in APPENDIX C – *Methodology*.

1.7 Interpreting Model Projections

Proper application of the data presented within this report requires the interpretation of results and characterization of uncertainty. There are many sources of uncertainty, from GHG emission scenario uncertainty to model uncertainty, and natural variability (Refer to APPENDIX A - *Climate Modelling Background*, Section A3). The dominant uncertainty depends on the timescale and the parameter or index. Model results are presented for moderate and high GHG emission scenarios (RCP 4.5 and RCP 8.5 respectively), through an ensemble model approach, with the data spread and median presented on graphs and plots (Refer to APPENDIX B - *Guidelines to Reading and Interpreting the Plots*).

Section 2 includes scientific plots, maps and interpretation for key climate indices. Recommendations for how to deal with uncertainty for future climate change assessments as well as the most prominent climate impacts on key sectors are presented in Chapter 3. APPENDIX F – *Plots of Climate Indices* includes scientific data and plots for the full list of climate indices generated in the study. Numerical results for all indices are available in APPENDIX G – *Tables of Climate Indices* in a tabular format. More details on the methodology are available in APPENDIX C – *Methodology*.

1.8 List of Climate Indices

This study provides projections for 178 climate indices. The following tables include index definitions, units, and where in the report each index is discussed. A similar table can be found in APPENDIX F – *Plots of Climate Indices*, which also includes the formulas for each index.

Table 1.3: List of Temperature Indices

	Type of Index	Index Name	Unit	In-Text	App. F Plots	App. G Tables
TEMPERATURE	Maxima and Minima	Warmest Temperature of the Year	°C	2.3.3	F1	G1
		Coldest Temperature of the Year	°C		F1	G1
		Warmest Monthly Temperature	°C		F1	G1
		Monthly Min. of Daily Max. Temperature	°C			G1
		Monthly Max. of Daily Min. Temperature	°C			G1
		Coldest Monthly Temperature	°C	2.3.2	F1	G1
	Thresholds and Ranges	Number of Hot Days (Daily Max. Temperature > 30°C)	# days/year	2.3.3	F1	G1
		Number of Tropical Nights (Daily. Min Temperature > 20°C)	# days/year		F1	G1
		Number of Deep Freeze Events (Daily Min. Temperature < -10°C)	# days/year	2.3.2	F1	G1
		Number of Days Daily Max. Temperature < -34, -5, 0, or > 0, 5, 10, 15, 20, 25, 35°C	# days/season			G1
		Number of Days Daily Min. Temperature < -34, -28, -20, -15, -5, 0°C	# days/season			G1
		Number of Days Daily Max. Temperature is between -20– -10, -10–0, 0–5, 4–10, 10–15, 15–20, 20–25, 18–34, 26–29, 22–30°C	# days/season			G1
		Seasonal Temperature Range	°C			G1
	Averages, Timing and Seasons	Annual Average Temperature	°C	2.3.1	F1	G1
		Seasonal Average Temperature	°C		F1	G1
		Monthly Average Temperature	°C	2.3.1	F1	G1
		Growing Season Length	# days/year		F1	G1
		Frost Season Length	# days/year		F1	G1
		Potato Growing Season Length	# days/year			G1
		Corn Heat Units	units			G1
		Timing of Tulip Emergence and Blooming	day		F1	G1
		Timing of First Fall Frost	day	2.3.4	F1	G1
		Timing of Last Spring Frost	day	2.3.4	F1	G1
		Timing of Warmest Month	month		F1	G1
		Timing of Coldest Month	month		F1	G1
	Winter Melt and Freeze-thaw	Winter Melting Episode	# days/season			G1
		Annual Freeze-Thaw Cycles	# days/year		F1	G1
		Seasonal Freeze-Thaw Cycles	# days/season	2.3.5	F1	G1
	Warm and Cold Spells	Frequency of Warm Spells (Max. Temperature > 32°C for 3 Days)	# periods/year			G1
		Frequency of Warm Spells (Max. Temperature > 31°C and Min. Temperature > 20°C, for 2 Days)	# periods/year	2.3.3	F1	G1
		Frequency of Warm Spells (Max. Temperature > 31°C and Min. Temperature > 20°C)	# days/year			G1
		Frequency of Cold Spells (Max. Temperature ≤ -10°C for 5 Days)	# periods/year		F1	G1
	Design	Heating Degree Days	°C days		F1	G1
		Freezing Degree Days	°C days			G1
		Above Freezing Degree Days	°C days			G1
		Cooling Degree Days (18°C)	°C days		F1	G1
		Winter Melting Degree Days	°C days			G1
		January 2.5% Design Temperature Approximation	°C			G1
		July 2.5% Design Temperature Approximation	°C			G1

Table 1.4: List of Precipitation, Humidity, and Wind Indices

	Type of Index	Index Name	Unit	In-Text	App. F Plots	App. G Tables
PRECIPITATION	Totals	Annual Total Precipitation	mm	2.4.1	F2	G2
		Monthly Total Precipitation	mm	2.4.1	F2	G2
	Return Periods	1 in 100 Year 1-Day Precipitation	mm	2.4.3	F2	G2
		1 in 2, 5, 20, 50, 350 Year 1-Day Precipitation	mm		F2	G2
		1 in 100, 350 Year (2-Day, 5-Day) Precipitation	mm		F2	G2
		1 in 50 Year Hourly Precipitation	mm	2.4.3	F2	G2
		1 in 2, 5, 10, 20, 50, 100 Year (1, 3, 6, 12 -Hourly) Precipitation	mm		F2	G2
	Maxima	Annual Max. 1-Day Precipitation	mm	2.4.3	F2	G2
		Annual Max. (2-Day, 5-Day) Precipitation	mm		F2	G2
		Monthly Max. 1-Day Precipitation	mm	2.4.3	F2	G2
		Monthly Max. (2-Day, 5-Day) Precipitation	mm			G2
	Thresholds	Number of Days Precipitation > 20 mm	# days/year	2.4.3	F2	G2
		Monthly Number of Days Precip > 10 mm	# Days	2.4.3		G2
		Number of Days Precipitation > 1, 10, 25, 50 mm	# days/year		F2	G2
		Number of 2-Day Precipitation > 50 mm	# periods/year		F2	G2
		Number of Hours Precipitation > 25, 50 mm	# hours/year			G2
	Wet and Dry Spells	Max. Length of Dry Spell	# days		F2	G2
		Max. Length of Wet Spell	# days		F2	G2
	Timing	Timing of Wettest Month	month			G2
		Timing of Driest Month	month			G2
PRECIPITATION (SNOW)	Totals and Maxima	Annual Total Snowfall	cm	2.4.4	F2	G2
		Monthly Total Snowfall	cm	2.4.4	F2	G2
		Annual Max. 1-Day Snowfall	cm/day	2.4.6	F2	G2
	Thresholds	Number of Days with Snowfall	# days/year	2.4.5	F2	G2
		Number of Days with Snowfall ≥ 10 cm/day	# days/year		F2	G2
	Snow Depth	Annual Max. Snow Depth	cm	2.4.6	F2	G2
		Number of Days with Snow Depth > 8, 21 cm	# days/year		F2	G2
		Annual Max. 3-Day and 7-Day Snow Melt Water Equivalent	mm		F2	G2
	Duration	Number of Days with Snow Cover	# days/year	2.4.5	F2	G2
		Duration From First to Last Day of Snow	# days		F2	G2
	Timing	Timing of Month with Max. Snowfall	month		F2	G2
		Timing of Month with Max. Snow Depth	month		F2	G2
		Timing of First Snowfall	day	2.4.5	F2	G2
		Timing of Last Snowfall	day	2.4.5	F2	G2
		Timing of Max. 3-Day Snow Melt Water Equivalent	day		F2	G2
HUM. / WIND	Monthly	Monthly Average Wind Speed	m/s	2.5.1	F3	G3
	Extremes	1 in 2, 5, 10, 20, 50, 100 Year 3-Hourly Wind Speed	m/s		F3	G3
		Number of Hours Wind Speed > 10, 20, 40 km/hr	# hours/year			G3
	Averages	Monthly Average Relative Humidity at the Time of Max. Daily Temperature	%	2.6.1	F4	G4

Table 1.5: List of Indices for Other Parameters

	Type of Index	Index Name	Unit	In-Text	App. F Plots	App. G Tables
COMBINED	Winter Precipitation & Melt	Snowfall Approximation (Based on Precipitation and Temperature)	mm			G5
		Winter Rain Approximation (Based on Precipitation From Dec.–Feb. and Temperature)	mm			G5
		Max. 3-Day Sum of Snow Melt and Precipitation	mm		F5	G5
		Winter Rain > 10 mm and Freezing	# days/year			G5
		Snow Melt Water Equivalent > 10 mm and Freezing	# days/year			G5
	Comb. with Winds	Winds > 20 km/hr and Winter Precipitation > 1 mm	# days/year			G5
		Number of Days Wind Chill is between -35°C and -25°C	# days/year	2.5.1	F5	G5
		Number of Days Wind > 10, 20 km/hr and Snowfall > 1, 5 cm	# days/year		F5	G5
	Summer Conditions & Drought	Number of Days Humidex > 30, 35, 40°C	# days/year		F5	G5
		Number of Periods Humidex > 40°C for 2 Days	# periods/year	2.6.2	F5	G5
		Number of Periods Humidex > 30, 35°C for 2 Days	# periods/year		F5	G5
		Number of Days Chandler Burning Index (Fire Index) > 75, 90	# days/year			G5
		Water Scarcity Approximation (Based on Precipitation and Temperature)	# days/year			G5
EXTREME & OTHER	Extreme Events	Freezing Rain & Ice Storms	NA	2.8.1		
		Extreme Snow & Blizzards	NA	2.8.2		
		Extreme Winds & Gusts	NA	2.8.3		
		Tornadoes	NA	2.8.4		
		Hurricanes	NA	2.8.5		
		Lightning	NA	2.8.6		
	Other	Evapotranspiration, Drought, & Wildfire	NA	2.8.7		
		Air Quality	NA	2.8.8		
		Acid Rain	NA	2.8.9		
		Shorwave Radiation (UV)	NA	2.8.10		

Chapter 2 Results

This chapter presents the **main results of the climate projections analysis**. Historical trends are summarized in Section 2.1. Key findings from the future projections are summarized in Section 2.2. Temperature and precipitation are the two most typical climate model parameters; hence, a larger ensemble of climate models is available for these and they are presented first. Snow, wind, and humidity are presented subsequently, as well as projections for combined parameters (e.g., humidex based on temperature and humidity) because a smaller ensemble of climate models is available for these projections. Qualitative projections based on literature reviews are then provided for extreme events and other climate phenomena such as freezing rain and ice storms; extreme snow and blizzards; extreme winds and gusts; tornadoes; hurricanes; lightning; evapotranspiration, drought and wildfire; air quality; acid rain; and shortwave radiation. Lastly, the findings of this project are compared to those of other studies of climate projections in the NCR.

The indices presented and plotted in this chapter were selected to show the main results. **Additional plots and additional indices** are available in APPENDIX F – *Plots of Climate Indices*. Numerical results for all indices are available in APPENDIX G – *Tables of Climate Indices* in a tabular format.

Since different data sources were used for different climate parameters, the interpretation of the projections and the uncertainty for different parameters and indices varies. For example, the snow projections represent “snow that falls over the entire study area”, whereas the precipitation projections represent “precipitation that falls over a 10 km x 10 km area”. These types of distinctions in how to interpret the projections are explained throughout the text.

Other tips on how to read and interpret the various types of plots presented in this Chapter are available in APPENDIX B – *Guidelines to Reading and Interpreting the Plots*. For example, time-series plots differ from other plots because they show year-to-year variations, while box plots and monthly plots show average projections over 30-year time slices. Tips on plot reading are also available throughout the text.

The reader is directed to the following appendices for supplementary materials:

- APPENDIX A – Climate Modelling Background
- APPENDIX B – Guidelines to Reading and Interpreting the Plots
- APPENDIX C – Methodology
- APPENDIX D – Technical Review of Methods for Projections for Extreme Precipitation
- APPENDIX E – References
- APPENDIX F – Plots of Climate Indices
- APPENDIX G – Tables of Climate Indices

2.1 Historical Observations

Analyses of climate station data in the NCR are consistent with regional findings in indicating an **increase in average temperature and total precipitation over the historical record**. According to Canada's Changing Climate Report (NRCan 2019), it is *virtually certain* that Canada's climate has warmed, and significant increases in precipitation have been experienced in parts of southern Canada (Zhang *et al*. 2019). Analyses of climate station data in the NCR also reveal that **variability from year to year is high**, with some years being much warmer (and/or wetter) than others.

2.1.1 Sources of Information

Information on the historical climate in the NCR was obtained from:

- A targeted analysis of several climate station records from Environment and Climate Change Canada (ECCC). Trends in a few major indices (minimum, mean, and maximum temperatures, total precipitation, and maximum 1-day precipitation) were explored on both seasonal and annual timescales.
- A City of Ottawa report from 2011 ("Characterization of Ottawa's Watersheds") which presents plots of data from the Canadian Department of Agriculture Experimental Farm climate station.
- A study by Mudryk *et al*. (2018) on observed and future (modelled) trends for snow across Canada.

Some pre-processing was necessary for the ECCC climate station data. It was found that the inclusion of years missing values, and the length of record chosen for analysis, both impacted the magnitude of the trends. Therefore, several thresholds for data completeness and length were tested. It is cautioned that while general trends are shown in this section, a systematic analysis of historical information was not performed. For instance, the change over time or between stations could be partly due to a combination of factors, including but not limited to:

- Differences over time in measurement methods/instrumentation;
- Station climate influenced by local factors such as land use.

Therefore, the trends should be interpreted as general indications of past changes. Nonetheless, the analyses were sufficient to illustrate that temperature and precipitation have increased in the NCR during the 20th century.

2.1.2 Average Temperature has Increased

ECCC climate station data show an increase in annual average daily mean temperature. This positive trend is shown for four climate stations in Figure 2.1 and Figure 2.2. The rate of increase of average annual daily temperature at the Canadian Department of Agriculture Experimental Farm between the mid-1940s and the mid-2010s is approximately 1.3°C (City of Ottawa 2011).

Winter increase in temperature for the four climate stations is also shown. The winter rate of increase at the Canadian Department of Agriculture Experimental Farm was 2^0C between the mid-1940s and the mid-2010s (City of Ottawa 2011).

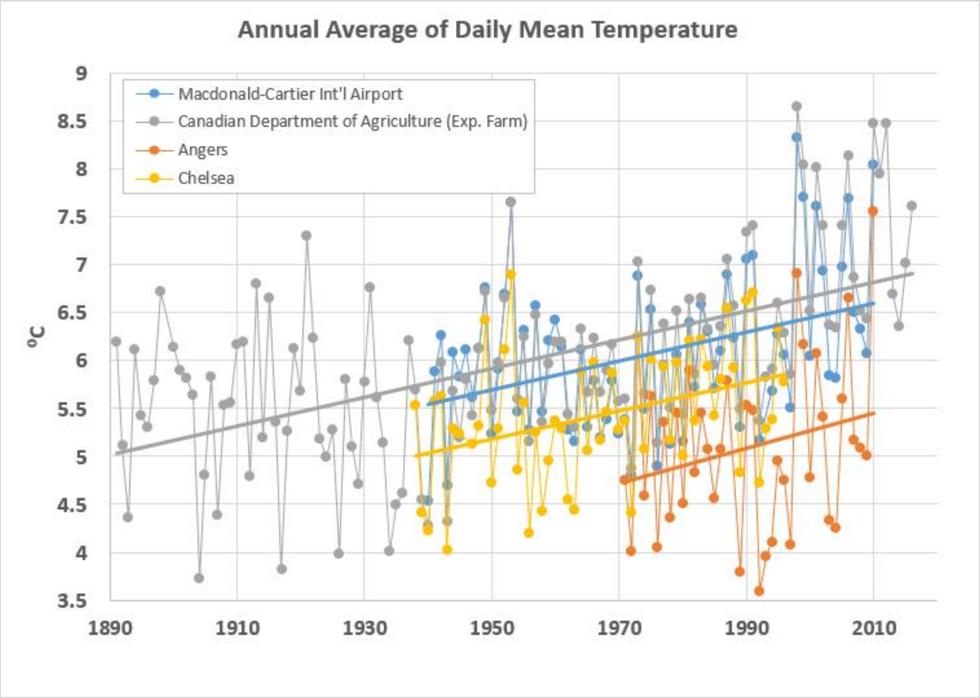


Figure 2.1: **Observed Trends in Annual Average of Daily Mean Temperature for the NCR (ECCC Climate Stations)**

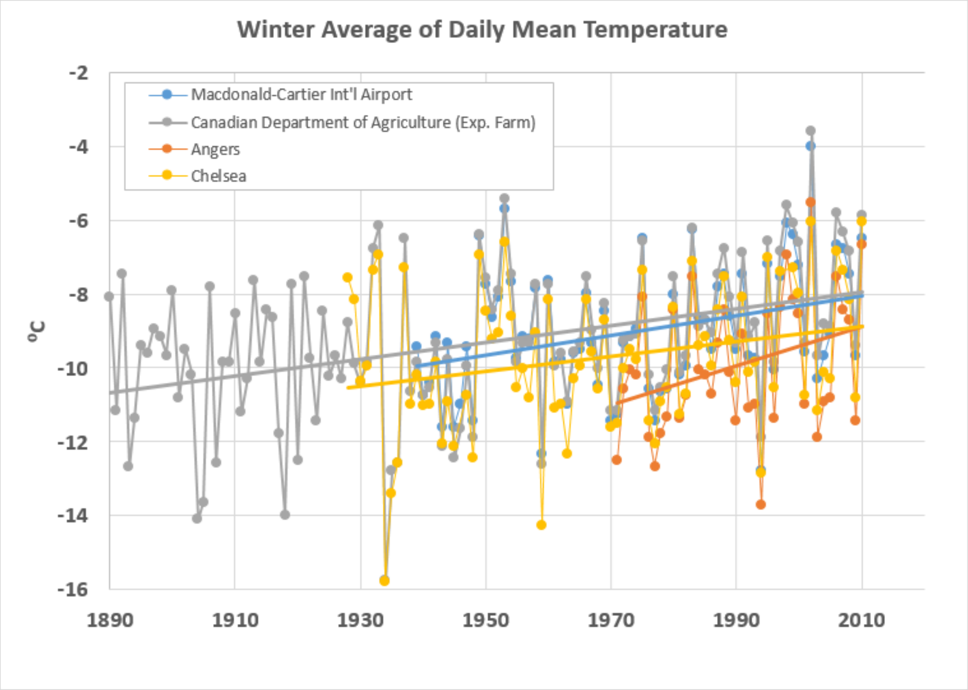


Figure 2.2: **Observed Trends in Winter Average of Daily Mean Temperature for the NCR (ECCC Climate Stations)**

2.1.3 Total Precipitation has Increased

ECCC climate station data show a general increase in total annual precipitation for the four climate stations, as well as high year-to-year variability (Figure 2.3). Correspondingly, the City of Ottawa (2011) reports that at the Experimental Farm, the increase in total annual precipitation since the 1920s has been concentrated during the fall and spring. It is noted that the City of Ottawa (2011) did not detect trends in intense precipitation at the Canadian Department of Agriculture Experimental Farm (annual maximum 1-day precipitation; Figure 2.4). However, the Macdonald-Cartier International Airport climate station has recorded a decrease in the intensity of storms less than 6 hours since 1967 (City of Ottawa Water Resources Group, pers. comm.; historical data analysis was not conducted as part of this project). It is not appropriate to extrapolate from these hourly historical trends to obtain future projections (see Section 2.1.4).

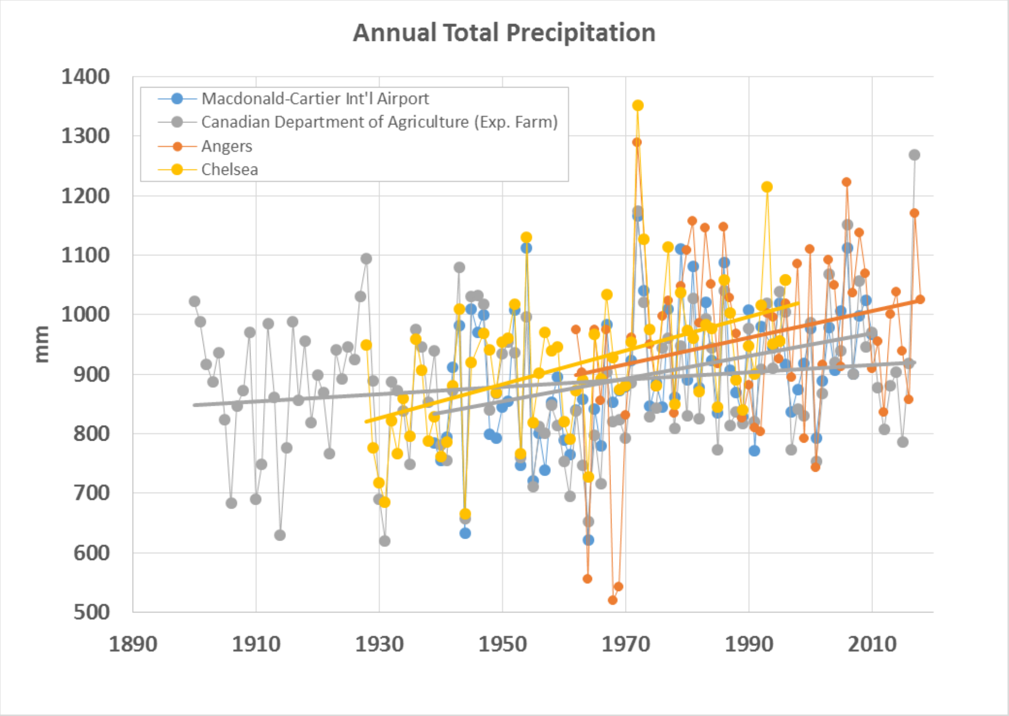


Figure 2.3: Observed Trends in Annual Total Precipitation (ECCC Climate Stations)

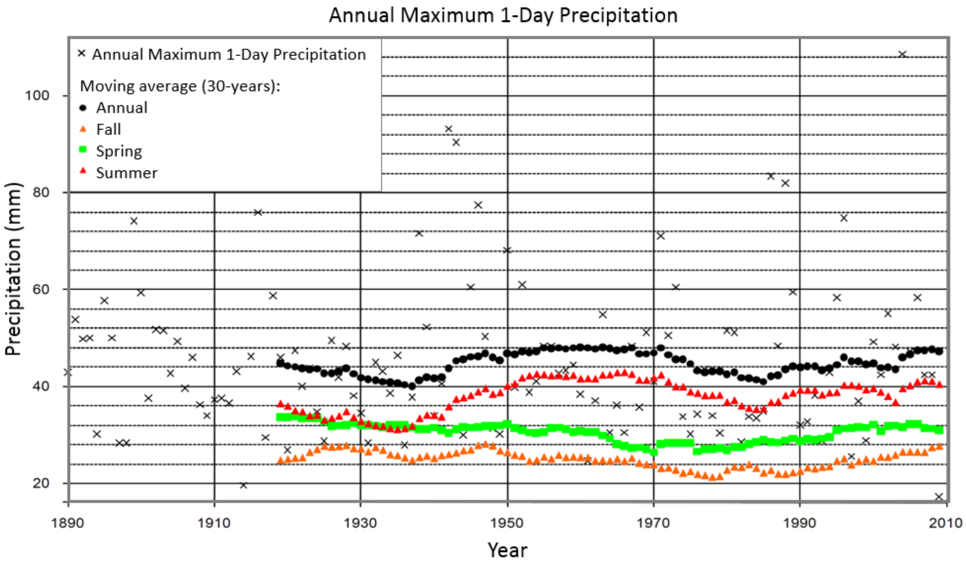


Figure 2.4: Annual Maximum 1-Day Precipitation based on Experimental Farm Climate Station (City of Ottawa, 2011)

In terms of historical trends of snow accumulation, Mudryk *et al*. (2018) suggest a decrease in maximum snow water equivalent from 1981-2010 (Figure 2.5). It is noted that this finding is based on one gridded dataset and that findings may differ depending on the source of information.

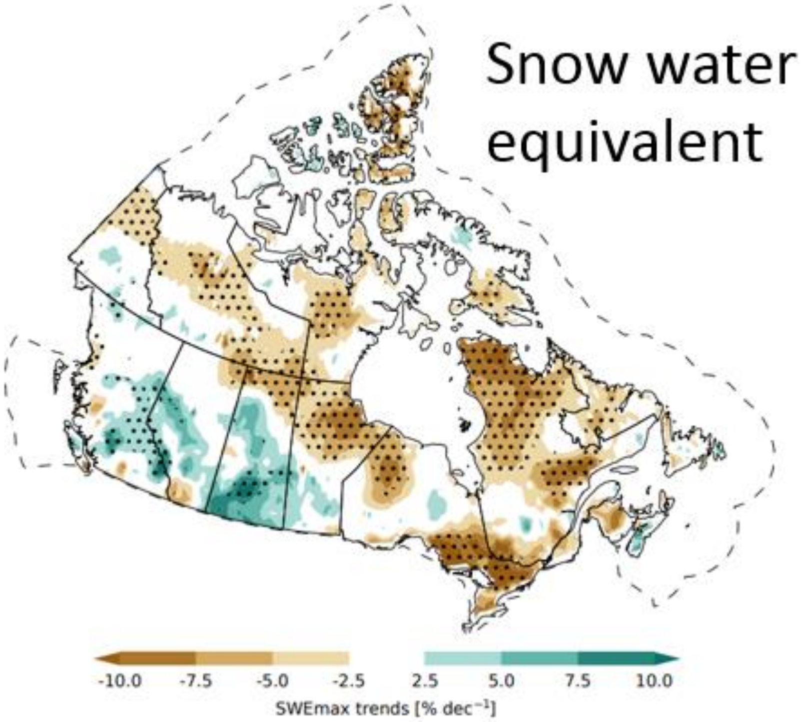


Figure 2.5: Observed Trends in Snow Water Equivalent, CANGRID Dataset 1981-2015 (Mudryk *et al*. 2018)

2.1.4 Models vs. Observations

Models can be used to investigate the future climate; observed trends cannot. This is because the climate system behaves non-linearly (for example, a trend may change once a certain threshold is crossed). Extrapolation of observed trends can only be done in certain situations, over short timescales, when the cause of the trend is well understood. In this context, extrapolation is sometimes cautiously used when there are no other sources of information available.

Model projections need to be compared against observations before they can be used in order to remove model biases. Therefore:

- The model projections for precipitation and temperature, which were provided by the Canadian Center for Climate Services, are bias-corrected using NRCan gridded historical observations. The bias correction was done by the Pacific Climate Impacts Consortium (PCIC) prior to this project.
- The model projections for other parameters (snow, wind, humidity) were bias-corrected as part of this project using climate station data from the Ottawa Airport (see APPENDIX C – *Methodology*).

In other words, the modelling datasets have been compared with historical data as part of the data processing, and the focus of the remainder of the report is on the use of the model projections.

2.2 Key Findings

The following key findings summarize the most important climate projections and findings obtained as part of this project, with more details in subsequent sections. These values represent an "average year" (since they are averaged over 30-year time slices) and the median of the ensemble of models.

In this report, the two values reported for each index (e.g., 5-8°C) are not ranges; they represent the mean values for the moderate (RCP 4.5) and high (RCP 8.5) emission scenarios. When a decrease is projected, such as for the amount of snow, the second value will be lower than the first value.

Temperature Projections:

- **Increase in Average Temperatures (all Seasons)** – The average annual temperature is projected to increase from approximately 6.1°C in the baseline to approximately 7.5-7.9°C in the 2030s, 8.2-9.3°C in the 2050s, and 8.8-11.4°C in the 2080s. No single season is projected to warm significantly faster than the others.
- **Less Cold Extremes** – Cold extremes are expected to decrease in intensity and frequency. The number of days per year where the daily minimum temperature is less than -10°C ("**Deep Freeze Events**") is projected to decrease from approximately 71 days in the baseline to approximately 59-57 days in the 2030s, 53-46 days in the 2050s and 48-28 days in the 2080s. Although these projections are for an extreme index, they represent an "average year" since they are averaged over 30-year time slices.

- **More Warm Extremes** – There will be an increase in the frequency and intensity of high-temperature extremes. In the baseline, the NCR experienced approximately 11 days that reached 30°C ("Hot Days") per year. Models project an increase to approximately 25-28 days in the 2030s, 32-43 days in the 2050s and 36-72 days in the 2080s. That is twice as many hot days in the 2030s, 3-4 times as many in the 2050s, and 3-6 times as many in the 2080s.
- **Change in Seasonal Characteristics** – The first day of fall frost is projected to occur approximately 1-2 weeks later by the 2030s, 2-3 weeks later by the 2050s, and 3-4 weeks later by the 2080s compared to the baseline. The last day of spring frost is projected to occur approximately 1-2 weeks earlier in the 2030s and 2050s, and 2-4 weeks earlier in the 2080s.
- **Shift in Freeze-Thaw Cycles** – Models project that winter temperatures will hover around 0°C more frequently in the future. Therefore winter freeze-thaw cycles (December–February) are projected to increase, whereas freeze-thaw cycles that occur during spring (March–May) and fall (September–November) are projected to decrease as temperatures warm.

Precipitation Projections:

- **Increase in Total Precipitation (Except Summer)** – The annual total precipitation in the NCR is expected to increase from approximately 921 mm/year in the baseline to approximately 949-968 mm in the 2030s, 979-993 mm in the 2050s and 983-1028 mm in the 2080s. Increases will be concentrated in the winter and shoulder seasons with no increases projected for June–September.
- **No change in Frequency of Wet Days** – Although the annual total precipitation is increasing, precipitation is projected to be concentrated within the same number of wet days (where precipitation > 1 mm) that occurred in the baseline.
- **More Intense Precipitation** – The annual maximum precipitation that falls in one day is expected to increase from approximately 37 mm in the baseline to 39-39 mm in the 2030s, 41-42 mm in the 2050s and 41-44 mm in the 2080s. The increase in precipitation is consistent with a greater amount of total precipitation falling in the same number of wet days (see above). Extreme precipitation is projected to increase for multiple durations (sub-daily, daily, and multi-day precipitation events). These projections represent an "average year" (since they are averaged over 30-year time slices), for a 10 km x 10 km area.
- **Decrease in Total Snowfall** – The annual total snowfall is projected to decrease from approximately 223 cm in the baseline to 193-201 cm in the 2030s, 184-179 cm in the 2050s and 154-124 cm in the 2080s. This represents a decrease of 31-44% by the 2080s. Due to year-to-year variability, values similar to the baseline are still possible past mid-century.
- **Shorter Snow Season** – The timing of the first snowfall is projected to be later in the year, and the timing of last snowfall earlier. As a result (and due to increasing temperatures), the number of days with snow cover is projected to decrease from approximately 115 in the baseline to approximately 95-94 days in the 2030s, 90-72 days in the 2050s and 78-43 days in the 2080s.
- **High Variability in Extreme Snow** – Projections suggest a decrease in the maximum snow depth and mixed findings for the maximum 1-day snowfall. Average projections suggest that annual maximum 1-day snowfall (averaged across the study area) will change from approximately 20 cm in the baseline to 21-20 cm in the 2030s, 22-20 cm in the 2050s and 20-16 cm in the 2080s. There is a decrease by the 2080s for the high emission scenario (RCP

8.5) but not for the moderate emission scenario (RCP 4.5). These projections represent total snow falling over the study area during an "average year" (since they are averaged over 30-year time slices). Due to year-to-year variability, values similar or higher than the baseline are still possible past mid-century.

Wind Projections:

- **No Detectable Trends in Averages** – Projections for monthly average wind speed show little to no change. However, only two RCMs with wind projections were available for this study, which reduces the confidence in the findings.
- **Reduced Wind Chill** – Due to warming temperatures, models project that the number of days with wind chill between -35°C and -25°C will decrease from approximately 17 days in the baseline to 11-8 days in the 2030s, 6-5 days in the 2050s and 5-1 days in the 2080s. These values represent an "average year" (since they are averaged over 30-year time slices).

Humidity Projections:

- **No Detectable Trends in Averages** – The projections for daily humidity (occurring during the time of the day that is the warmest) do not show trends. It is noted that projections for humidity (like those for snow and wind) have fewer models available than projections for temperature and precipitation, and hence have lower confidence.
- **Increase in Humidex** – The number of instances with 2 days of humidex > 40 (an important index for public health) is expected to increase from approximately 1 instance in the baseline to 4-4 instances in the 2030s, 5-6 instances in the 2050s, and 6-9 instances in the 2080s. This is an increase of 5-8 instances within a century.

Extreme Events and Other Phenomena

- **Freezing Rain and Ice Storms** – A possible increase of freezing rain during the coldest months is anticipated due to the higher frequency of conditions around 0°C. A decrease or no change is projected during the transition seasons.
- **Extreme Snow and Blizzards** – Models generally project a decrease in average snowfall, but high year-to-year variability makes it difficult to project changes in extremes.
- **Extreme Wind and Gusts** – Increases are possible; however, the supporting literature and models remain inconclusive at this time.
- **Tornadoes** – It is uncertain whether tornado occurrence will change with climate; however, climate change is projected to favour the atmospheric conditions that support their formation.
- **Hurricanes** – The amount of precipitation produced by hurricanes, and the intensities of hurricanes will likely increase on average. Furthermore, the latitude of maximum intensity appears to be moving north, which would increase the NCR's exposure.
- **Lightning** – There is no scientific consensus on how the frequency and intensity of lightning will be impacted by climate change, although increases in convection activity would suggest a possible increase.
- **Wildfires** – It is predicted that the fire season will lengthen and that the number and extent of wildfires will increase, especially in boreal forest types.
- **Air Quality** – It is possible that climate warming could worsen some aspects of air quality; however, there is not enough information to data to draw conclusions.

A simplified summary of projections for the high carbon emission scenario RCP 8.5 is provided in the following table.

Summary of Future Climate in Canada's Capital Region

What to expect*	2030s	2050s	2080s
Temperature			
Average temperature	↑ 1.8°C	↑ 3.2°C	↑ 5.3°C
Very hot days (above 30°C)	2.5 times more	4 times more	6.5 times more
Very cold days (below -10°C)	20% less	35% less	65% less
Seasons			
Winters shorter by	4 weeks	5 weeks	8 weeks
Springs earlier by	2 weeks	2 weeks	4 weeks
Winter freeze-thaw	↑ 15%	↑ 35%	↑ 55%
Precipitation			
Fall-winter-spring precipitation	↑ 5%	↑ 8%	↑ 12%
Intense precipitation	↑ 5%	↑ 15%	↑ 20%
Snowfall	↓ 10%	↓ 20%	↓ 45%
Extreme Events			
	Possible increases in freezing rain		
	Warming favours conditions conducive to storms, wildfires		

More certainty

Less certainty

** For high emission Scenario RCP 8.5*

More certainty

Less certainty

2.3 Temperature Projections

The climate in the NCR is warming. While this may have some benefits, it will have consequences in many sectors and requires careful consideration as to which aspects of the climate are projected to change, and how quickly. The warming is projected to manifest as an increase in average temperatures that is relatively constant throughout the year. Therefore, it is projected that January and February will continue to be the coldest months of the year, and July will continue to be the warmest month of the year. In addition to changes in averages, the warming in the NCR is projected to bring a decrease in cold extremes and an increase in hot extremes, as well as a shift in seasonal characteristics and in the timing of freeze-thaw cycles.

The main cause of the warming is the modification of the energy balance of the earth at different scales. Temperature changes are usually affected by processes that cover a larger area (compared to precipitation). This means that temperature-based indices are typically modelled with higher confidence by climate models with large grid cells (IPCC 2013).

The results presented below are averaged across the project area. Maps for some temperature-based indices (i.e., showing limited variation in projections across the project area) are presented in Section 2.7.

In this report, the two values reported for each index (e.g., 5-8°C) are not ranges; they represent the mean values for the moderate (RCP 4.5) and high (RCP 8.5) emission scenarios. When a decrease is projected, such as for the amount of snow, the second value will be lower than the first value.

2.3.1 Increase in Average Temperature (All Seasons)

The **average annual temperature** (Figure 2.6) is an important index for the NCR because it summarizes the overall degree of warming that is projected. Overall warming will have impacts across most sectors. The average annual temperature in the NCR is expected to increase from approximately 6.1°C in the baseline to approximately 7.5-7.9°C in the 2030s, 8.2-9.3°C in the 2050s, and 8.8-11.4°C in the 2080s. This is a substantial increase of 2.7-5.3°C in less than a century.

The values quoted here are the average conditions over 30-year time slices. Any given year could have average annual temperatures that are higher or lower than these 30-year averages, due to year-to-year variability in the climate. The year-to-year variability is visible (in part) from the ups and downs of the bold lines in the time-series below (although this line is the average of many models and is a smoothed version of the actual variability). The range between the 10th and 90th percentiles of the model ensemble (calculated for each year) is shown in the shaded colours. For more information please see APPENDIX B – *Guidelines to Reading and Interpreting the Plots*.

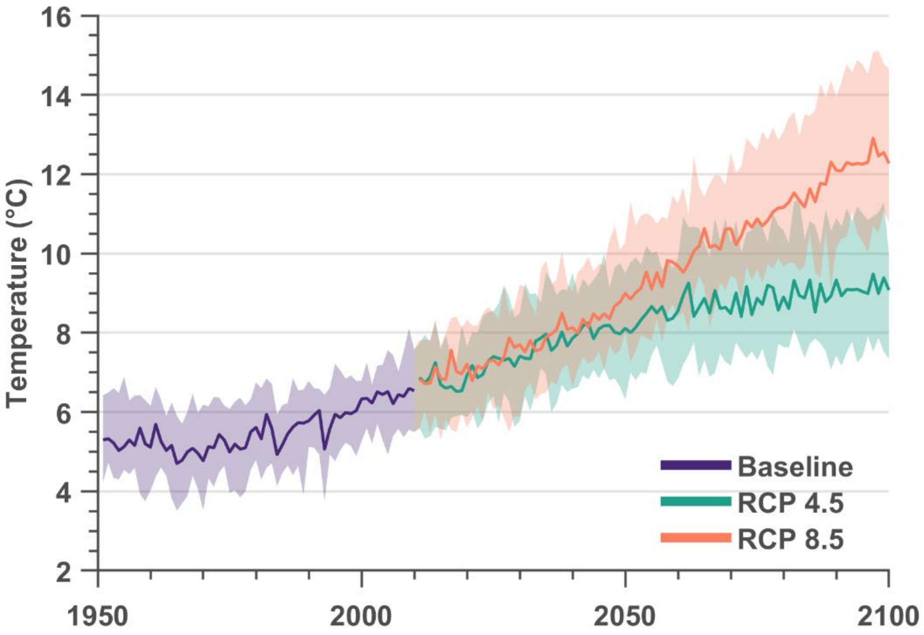


Figure 2.6: Annual Average Temperature

Interestingly, the increase in temperatures in the NCR is projected to be relatively constant throughout the year (no single season is projected to warm significantly faster than the others). The plot of **monthly average temperatures** (Figure 2.7) shows that relatively similar increases in average temperatures are projected for each month (the lines are parallel). This figure only shows the median of the ensemble of statistically downscaled GCMs, and therefore does not give a measure of uncertainty (see APPENDIX F – *Plots of Climate Indices* for the 10th and 90th percentiles of the model ensemble). From this plot, it can also be read that by the 2080s, January average temperatures (blue star) will be approximately that which March average temperatures (red star) would have been during the baseline. Tips on the interpretation of these monthly plots are available in APPENDIX B – *Guidelines to Reading and Interpreting the Plots.*

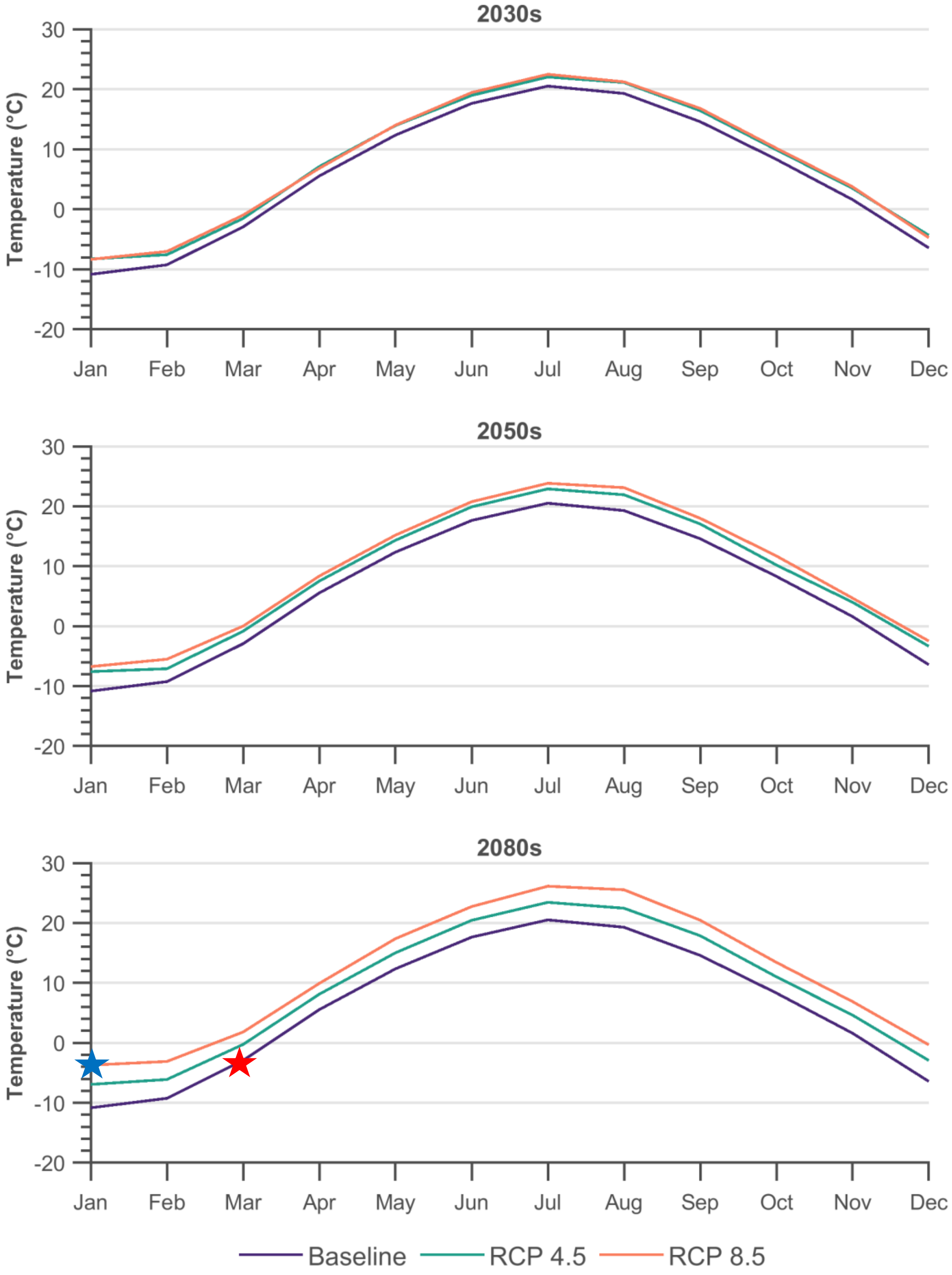


Figure 2.7: Monthly Average Temperature (Only Median is Shown).
Blue star shows January average temperatures (2080s) and red star shows March average temperatures (baseline).

Consistent with warming projected to be fairly constant throughout the year, the **timing of the coldest month** and **timing of the warmest month** are projected to remain the same as during the baseline (January/February will continue to be the coldest months, and July will continue to be the warmest month). These indices are calculated as the month that the greatest number of statistically downscaled GCMs indicate it as the coldest/warmest in each 30-year timeframe.

2.3.2 Less Cold Extremes

All models project daytime high and nighttime low temperatures to rise, but nighttime lows are projected to rise faster. Hence, a decrease in the frequency and intensity of cold extremes, in particular for nighttime lows, are expected. Changing cold extremes have implications for a number of sectors, including but not limited to the Rideau Canal Skateway, the killing of invasive tree pests, and emergency management services.

One approach for investigating cold extremes is to calculate the coldest monthly temperature, which is defined as the minimum nighttime low of a given month. In the baseline, the **coldest monthly temperature for January** (Figure 2.8) was on average approximately -30.0°C. The ensemble of statistically downscaled GCMs projects new values of approximately -26.9 - -26.2°C in the 2030s, -25.2 - -22.9°C in the 2050s and -23.4 - -18.2°C in the 2080s. This is an increase of approximately 6.6-11.8°C by the 2080s. Note that these values do not represent the coldest temperatures that could be experienced in January, but rather the conditions of an "average year" (since they are calculated over 30-year time slices). Hence, this index helps describe the projected "new normal" for the coldest temperature experienced in January in the NCR.

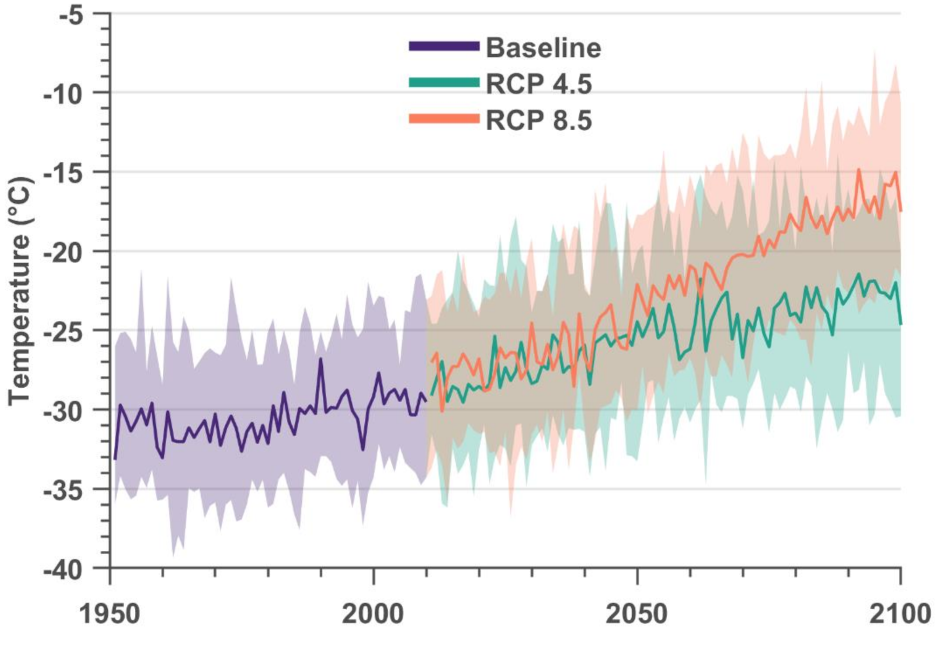


Figure 2.8: Coldest Monthly Temperature – January

Not only are cold temperature extremes projected to be less severe, but they are also projected to be less frequent on average. While the Coldest Monthly Temperature is an index that depicts the severity of cold extremes, the frequency can be depicted by using an index of exceedance over a threshold. For example, the number of days where the daily minimum temperature is less than -10°C ("**Deep Freeze Events**"; Figure 2.9) is projected to decrease from approximately 71 days per year in the baseline to approximately 59-57 days in the 2030s, 53-46 days in the 2050s and 48-28 days in the 2080s.

These findings are represented in the box plots below. To create these box plots, the models are first averaged over the 30-year time slices. The *average* of these values is then shown in the dark line in the center of the box, representing the middle-of-the-range projection for 30-year average conditions. The box and whiskers (lines extending from the box) show the variability between the models and can be interpreted as the uncertainty in the projections; the longer the whisker, the greater the uncertainty (see APPENDIX B – *Guidelines to Reading and Interpreting the Plots*).

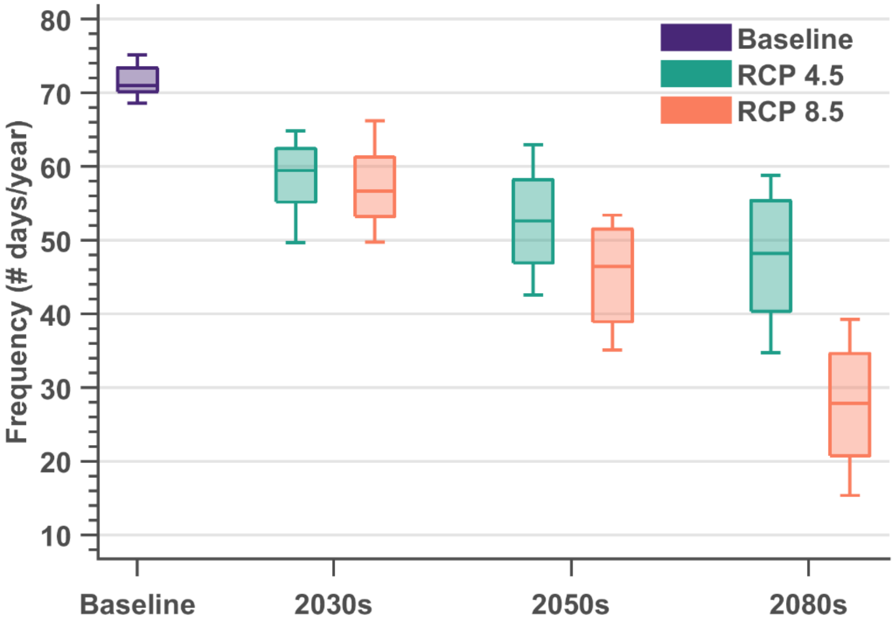


Figure 2.9: Number of Deep Freeze Events (Daily Min. Temp. < -10°C)

2.3.3 More Warm Extremes

Whereas cold extremes are expected to decrease in intensity and frequency, warm extremes are expected to increase in intensity and frequency. One index of warm extremes is the **warmest temperature of the year** (Figure 2.10), which is defined as the highest daytime temperature experienced during any month (usually it would be experienced during the summer months). The warmest temperature of the year is projected to increase from approximately 33.5°C in the baseline to approximately 35.3-35.6°C in the 2030s, 36.2-37.1°C in the 2050s and 36.7-39.7°C in the 2080s. This is an increase of approximately 3.2-6.2°C by the 2080s. As described above, these values represent the conditions of an "average year", during the 30-year time slices.

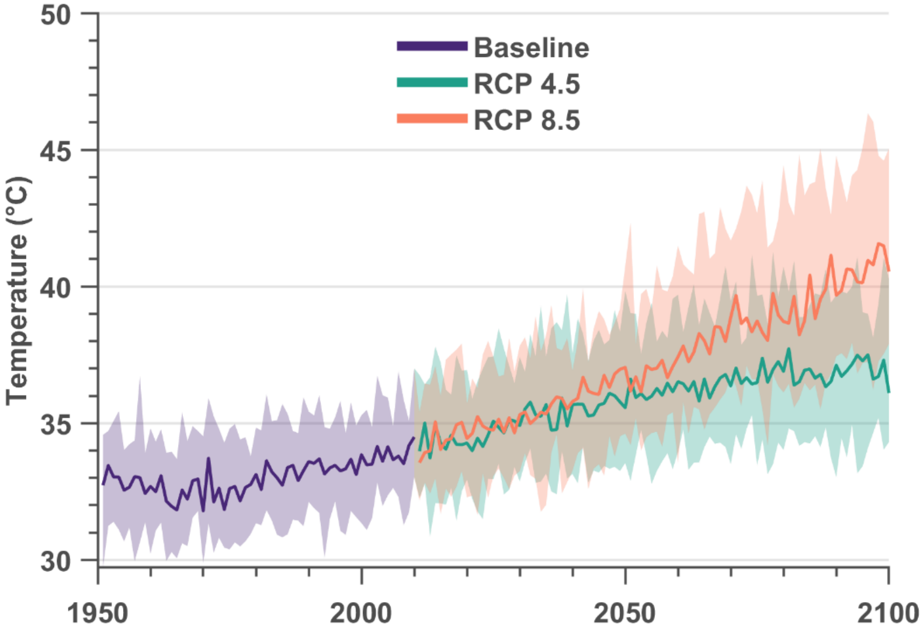


Figure 2.10: Warmest Temperature of the Year

Not only are warm extremes projected to get hotter, but they are also projected to get more frequent. The number of hot days and the number of warm spells are indices that assess the frequency of hot extremes. In the baseline, the NCR experienced approximately 11 days that reach 30°C days per year ("**Hot Days**"; Figure 2.11). The number of hot days is projected to increase to approximately 25-28 days in the 2030s, 32-43 days in the 2050s and 36-72 days in the 2080s (Figure 2.11). This is a drastic change, with (on average) more than twice as many hot days in the 2030s, 3-4 times as many in the 2050s, and 3-6 times as many in the 2080s. This finding has important implications because it represents what is experienced as "summer heat" in the NCR.

The **Frequency of Warm Spells** (Figure 2.12) is a multi-day threshold. It is defined as the number of periods where the maximum daily temperature is >31°C and the minimum daily temperature is > 20°C for at least two consecutive days. The frequency of warm spells is negligible in the baseline (for the "average year" based on a 30-year median). However, they are projected to increase to approximately 1-1 periods in the 2030s, 1-3 periods in the 2050s and 2-6 periods in the 2080s (Figure 2.12). It is noted that the variability between models for this index is high (as indicated by the width of the shaded regions). This high uncertainty is partly because it is more difficult to project an index that has a small numerical value (i.e., it is rarer). Nonetheless, these trends have important implications for the public health sector, and spinoff implications for other sectors such as recreation and emergency management.

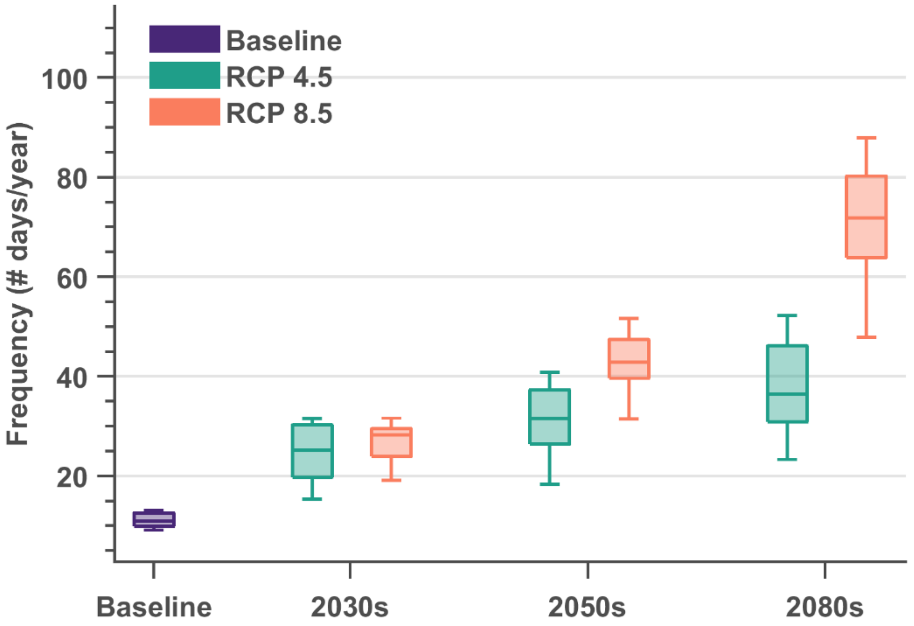


Figure 2.11: Number of Hot Days (Daily Max. Temperature > 30°C)

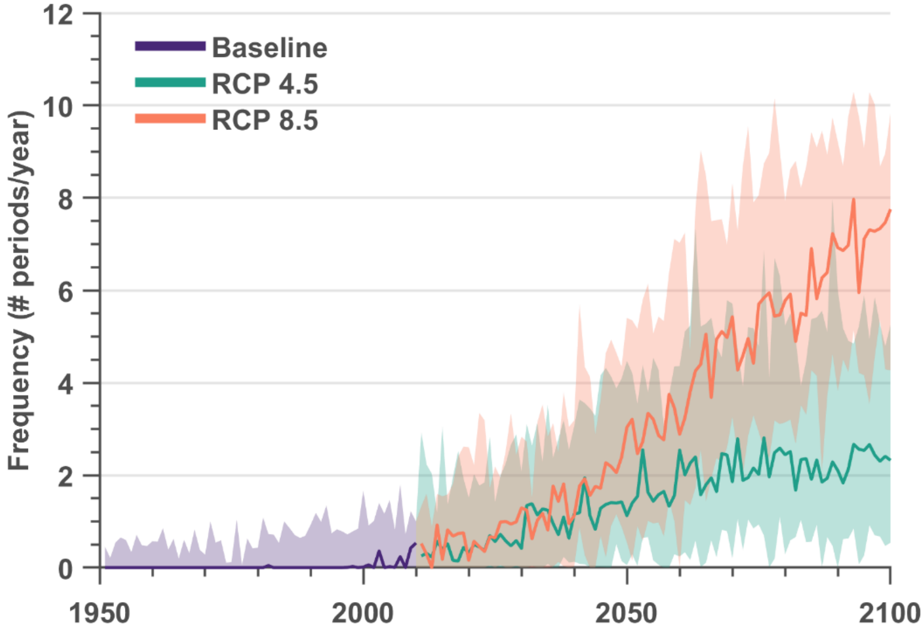


Figure 2.12: Frequency of Warm Spells (2-Day Max. Temperature > 31°C and Min. Temperature > 20°C)

2.3.4 Change in Seasonal Characteristics

The seasons in this study are defined based on months, with winter occurring from December to February, spring from March to May, summer from June to August, and fall from September to November. As temperatures change, so will the average characteristics of these seasons. Some threshold-based indices (such as the timing of the first fall frost) are projected to occur at different times than they would have occurred historically. Seasonal characteristics have implications for vegetation (i.e., landscaping, agriculture, and forest management), as well as recreation and tourism.

The **timing of first fall frost** (Figure 2.13) is defined as the first day when minimum daily temperatures < 0°C. For the baseline, frost starts to occur, on average, in late September or early October. As the century progresses, the first day of fall frost is projected to shift later into October: approximately 1-2 weeks later by the 2030s, 2-3 weeks later by the 2050s, and 3-4 weeks later by the 2080s. The **timing of last spring frost** (the last day when minimum daily temperatures < 0°C; Figure 2.14) is projected to occur approximately 1-2 weeks earlier in the 2030s and 2050s, and 2-4 weeks earlier in the 2080s, compared to the baseline. In other words, the last day of spring frost is projected to shift from early-May to mid- to late-April. Frost-free conditions are projected to be the new normal for September and May.

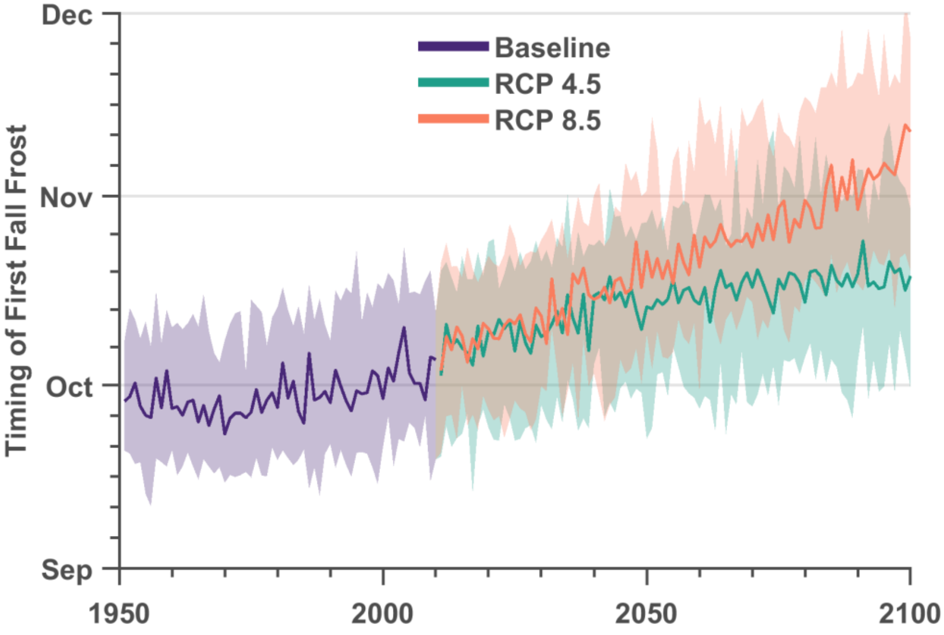


Figure 2.13: Timing of First Fall Frost

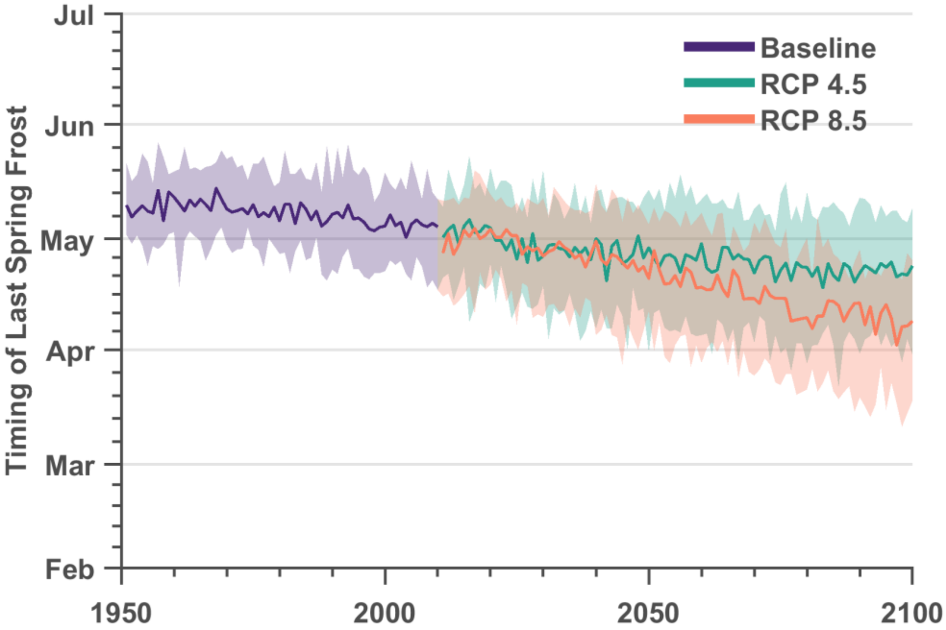


Figure 2.14: Timing of Last Spring Frost

Changes in the characteristics of seasons, and timing of temperature changes in the year, are specifically important for the timing of agricultural activities and landscaping. Additional indices available in APPENDIX E – *Plots of Climate Indices* include growing season length (projected increase), timing of tulip emergence, the timing of tulip blooming, and corn heat units.

2.3.5 Shift in Freeze-Thaw Cycles

Another aspect of seasonal shifts is specific to freeze-thaw cycles. The number of freeze-thaw cycles is an important index, notably for estimating the impact of weathering on construction materials and on winter road operations.

Models project that winter temperatures will hover around 0°C more frequently in the future. Therefore **winter freeze-thaw cycles** (defined as the number of days where the maximum daily temperature > 0°C and the minimum daily temperature < 0°C, from December to February; Figure 2.15) are projected to increase from approximately 24 days in the baseline to approximately 28-27 days in the 2030s, 30-32 days in the 2050s and 32-37 days in the 2080s. These values represent "average conditions" across 30-year time slices. A fairly large range of values is projected for this index (box plots are stretched vertically), which indicates higher uncertainty associated with this index.

Conversely, the **number of freeze-thaw cycles** (that occur during spring (March–May) and fall (September–November) is projected to decrease. As an example, fall freeze-thaw cycles are projected to decrease from approximately 24 days in the baseline to approximately 19-18 days in the 2030s, 17-14 days in the 2050s and 16-8 days in the 2080s. This corresponds to a decrease of approximately 20-25% for the 2030s, 30-40% for the 2050s, and 30-70% for the 2080s. The **annual number of freeze-thaw** cycles (incorporating trends from both winter and shoulder seasons) is projected to decrease overall (not shown here, see APPENDIX F1 – *Plots of Climate Indices*).

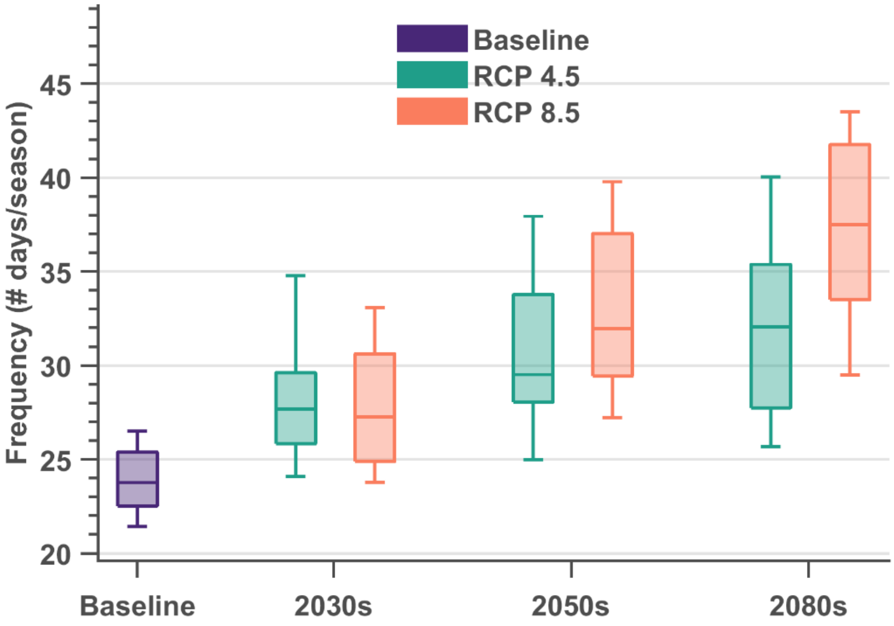


Figure 2.15: Seasonal Freeze-Thaw Cycles – Winter

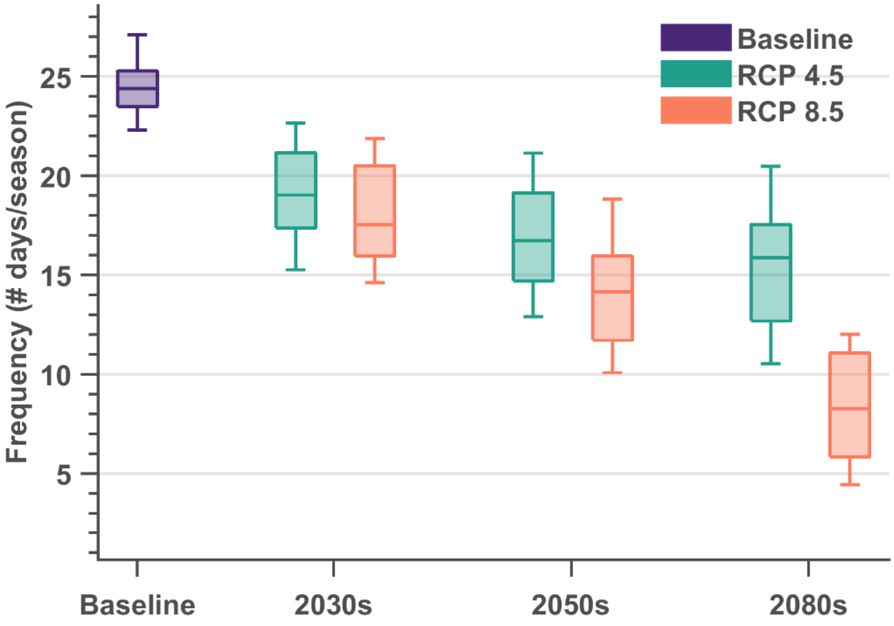


Figure 2.16: Seasonal Freeze-Thaw Cycles – Fall

2.4 Precipitation Projections

Precipitation patterns in the NCR are shifting. An increase in total precipitation (which includes rainfall and snowfall) is expected for the winter and shoulder seasons, with no significant change in summer. Furthermore, more intense precipitation is projected. Precipitation can be more challenging to model than temperature, due to the localized nature of the processes involved (thunderstorms for example). This is why the ensemble of statistically downscaled GCMs presented here provide a range of possible rates of change; however, they do agree about the direction of change for most precipitation indices.

The precipitation projections presented in this section are the average of all the 10 km x 10 km areas within the project area. Maps are also presented in Section 2.7 and APPENDIX F – *Plots of Climate Indices*, although no significant spatial variation was found for precipitation indices. In this project, variation is considered to be significant when variation within the project area is larger than the spread between the models.

The projections for snow (Sections 2.4.4 – 2.4.6) are derived from the ensemble of RCMs instead of the statistically downscaled GCMs and are represented with individual lines (instead of 90th and 10th percentile) and point plots (instead of box plots). There is more uncertainty associated with these projections because the ensemble is smaller. In addition, the projections represent the snow that would fall over the entire project area (rather than a 10 km x 10 km area as for precipitation). This means that values are more representative of the area as a whole, but this also smooths potential spatial variations in values, especially extremes. The decrease in total snowfall, in the snow season duration, and in extreme snow projected by the models is consistent with the scientific understanding that as temperatures increase, more snow should fall as rain. However, while the trends indicate overall decreases, there is high year-to-year variability: and seasons with long duration or depth of snow cover or events with high snowfall could still occur well into the 21st century.

2.4.1 Increase in Total Precipitation (Except Summer)

Total precipitation is the sum of all types of precipitation and includes both rain and snow. Annual total precipitation has implications for a number of sectors, such as water supply, forest management, and river and lake water quality. **Annual total precipitation** demonstrates how precipitation patterns are projected to change, without differentiating between seasons, levels of intensity or types of events (e.g., thunderstorm vs. multi-day event). Total annual precipitation in the NCR is expected to increase from approximately 921 mm/year in the baseline to approximately 949-968 mm in the 2030s, 979-993 mm in the 2050s and 983-1028 mm in the 2080s.

The values quoted here are the average conditions over 30-year time slices. However, year-to-year variability is high, which means that there could be considerably more precipitation falling in some years but not others. The year-to-year variability is visible (in part) from the ups and downs of the bold lines in the time-series below (although this line is the average of many models and is a smoothed version of the actual variability). The range between the 10th and 90th percentiles of the model ensemble (for each year) is shaded.

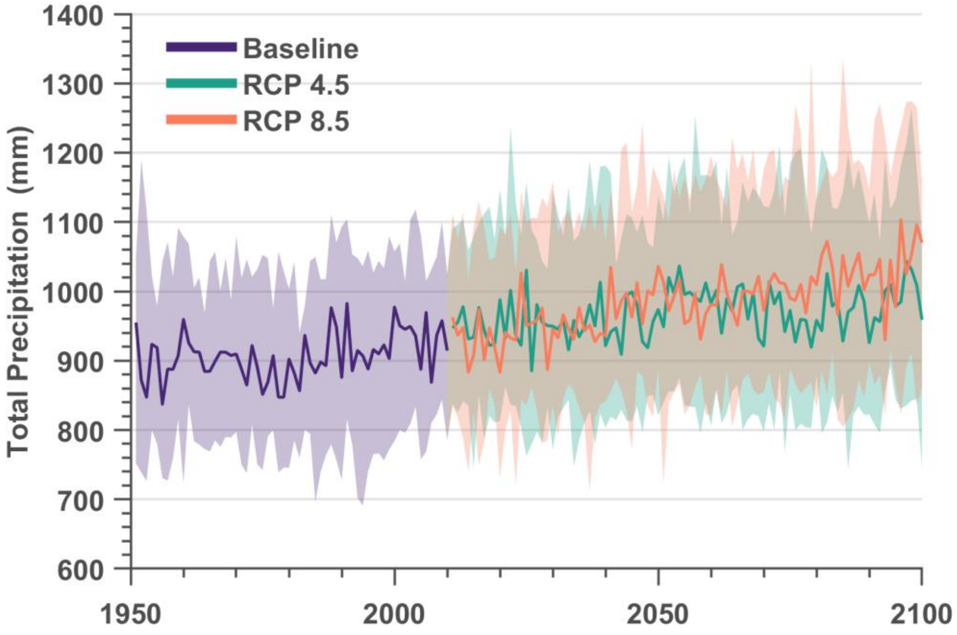


Figure 2.17: Annual Total Precipitation

When projections for total precipitation are examined on a monthly basis, it is apparent that the increase in precipitation is projected to be concentrated in the winter and shoulder seasons with no increases (and in some cases slight decreases) projected for June–September. Although during the baseline the months June to September received the greatest share of the total annual precipitation, projections suggest that by the 2080s, these months may be among those with the smallest share of total annual precipitation. It is cautioned that Figure 2.18 shows only the median of the ensemble of statistically downscaled GCMs and therefore does not give a measure of uncertainty (see APPENDIX D – *Technical Review of Methods for Extreme Precipitation Projections* for the 10th and 90th percentiles of the model ensemble).

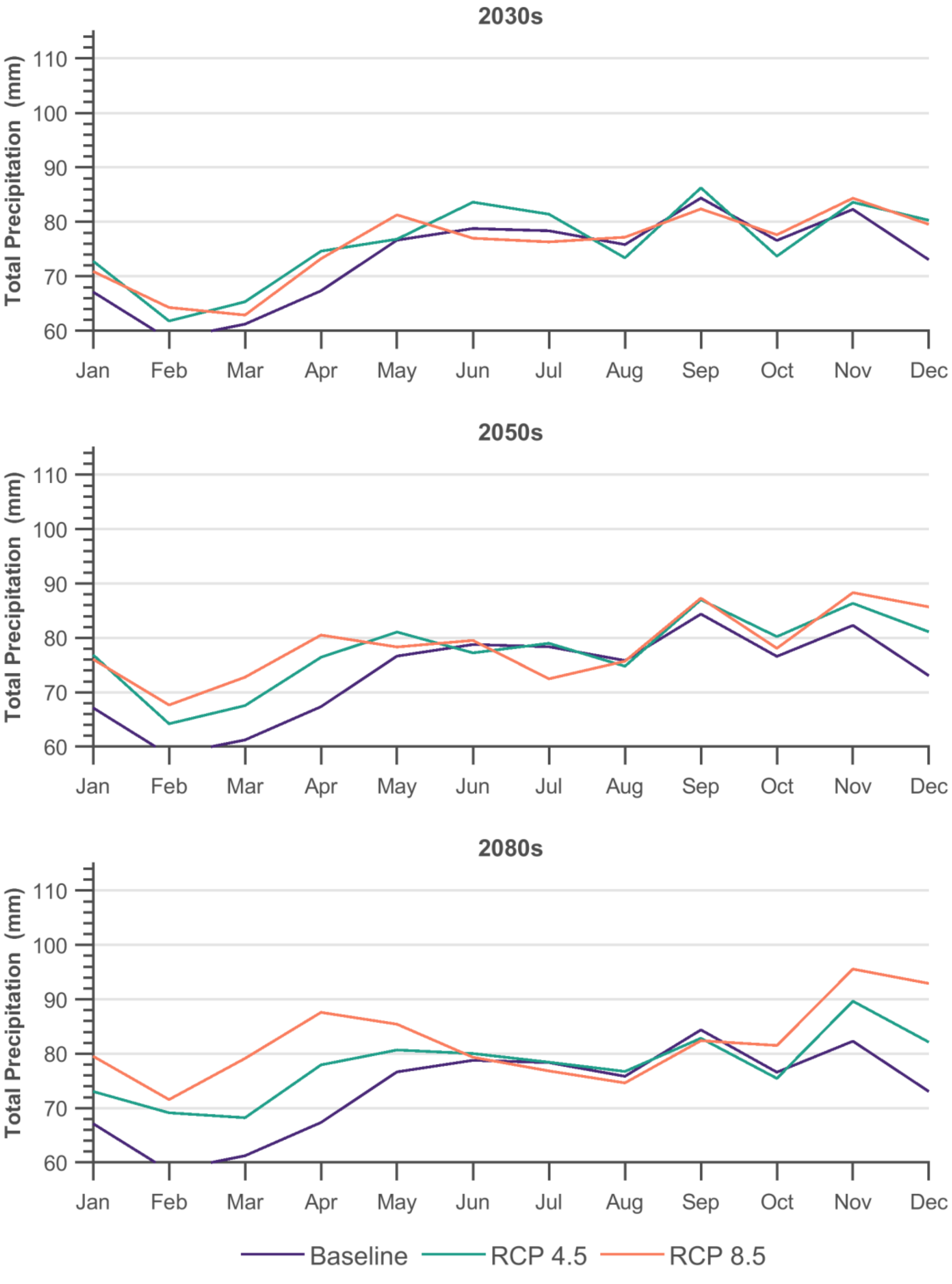


Figure 2.18: Monthly Total Precipitation (Only Median is Shown)

2.4.2 No Change in Frequency of Wet Days

The **frequency of wet days** is an index that represents the number of days when precipitation occurs. It is defined as the number of days where precipitation is > 1 mm and has implications for the weathering of roads and buildings, recreation, tourism, and agriculture. The frequency of wet days in the NCR is not expected to change (not shown here, see APPENDIX F2 - *Plots of Climate Indices*).

Since more precipitation is falling in total, but there is no increase in the number of days with precipitation, it follows that the volume of precipitation on days with precipitation must increase. This is indeed what is found in the projections (discussed in the next section).

The **Maximum Length of Dry spells** is a measure of the number of consecutive days where daily precipitation is < 1 mm. This number does not indicate extreme droughts since it is averaged over the 30-year period. This is an important index because it represents times when precipitation does not supply lakes, trees, crops, and forests. The **Maximum Length of Wet spells** is defined as the number of consecutive days where daily precipitation > 1 mm. Neither the maximum length of dry spells nor the maximum length of wet spells are projected to change (not shown here, see APPENDIX F2 - *Plots of Climate Indices*). However, it is noted that the projections show a large range between the 10th and 90th percentiles of the model ensemble (this is a measure of the uncertainty of these projections), as well as year-to-year variability. There may still continue to be high inter-annual variability leading to some years being drier than others.

2.4.3 More Intense Precipitation

The increase in precipitation intensity (the amount of precipitation that falls during a given rain event) has implications for a number of sectors, for instance, infrastructure (design stormwater flows) and transportation. The indices below examine precipitation both in terms of frequency and intensity. Projections are presented here first annually and then broken down by month. It is noted that these projections are the average of all the 10 km x 10 km grid cells within the study area; this means that any precipitation occurring at spatial scales smaller than the grid cell is smoothed.

The **number of days with precipitation > 20 mm** (an index which measures the frequency of intense precipitation) is projected to increase from approximately 6 days in the baseline to 7-7 days in the 2030s, 8-8 days in the 2050s and 8-9 days in the 2080s.

These findings are represented in the box plots below. To create these box plots, the models are first averaged over the 30-year time slices. The average of these values is then shown in the dark line in the center of the box, representing the middle-of-the-range projection for 30-year average conditions. The box and whiskers (lines extending from the box) show the variability between the models and can be interpreted as the uncertainty in the projections; the longer the whisker, the greater the uncertainty (see APPENDIX F - *Plots of Climate Indices*).

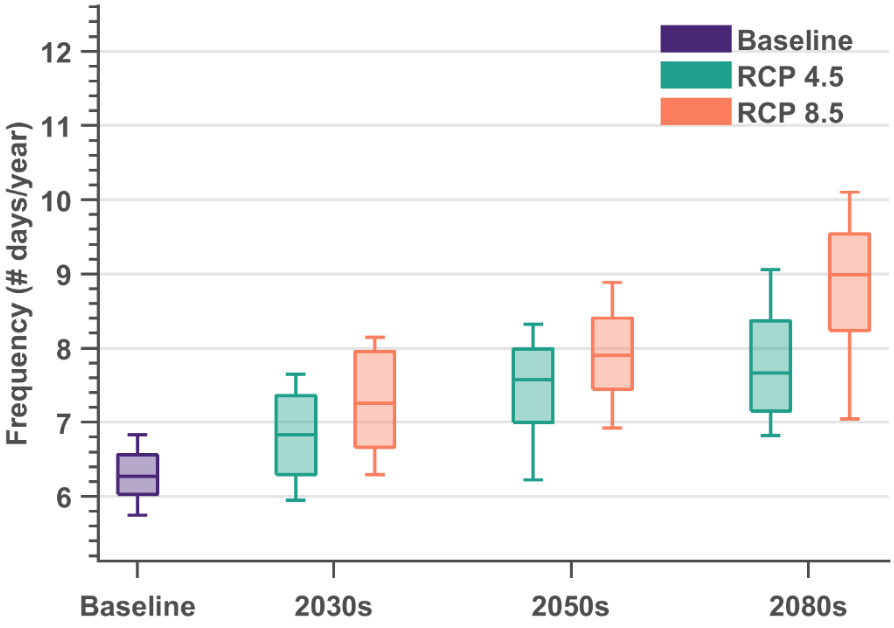


Figure 2.19: Number of Days Precipitation > 20 mm

In addition, the **annual maximum 1-day precipitation** (wettest day of the year) is expected to increase from approximately 37 mm in the baseline to 39-39 mm in the 2030s, 41-42 mm in the 2050s and 41-44 mm in the 2080s. This represents an 11-19% increase by the 2080s, compared to the 7-12% increase that is projected for annual total precipitation. In other words, the projections suggest that 1-day precipitation intensity will increase faster than total precipitation.

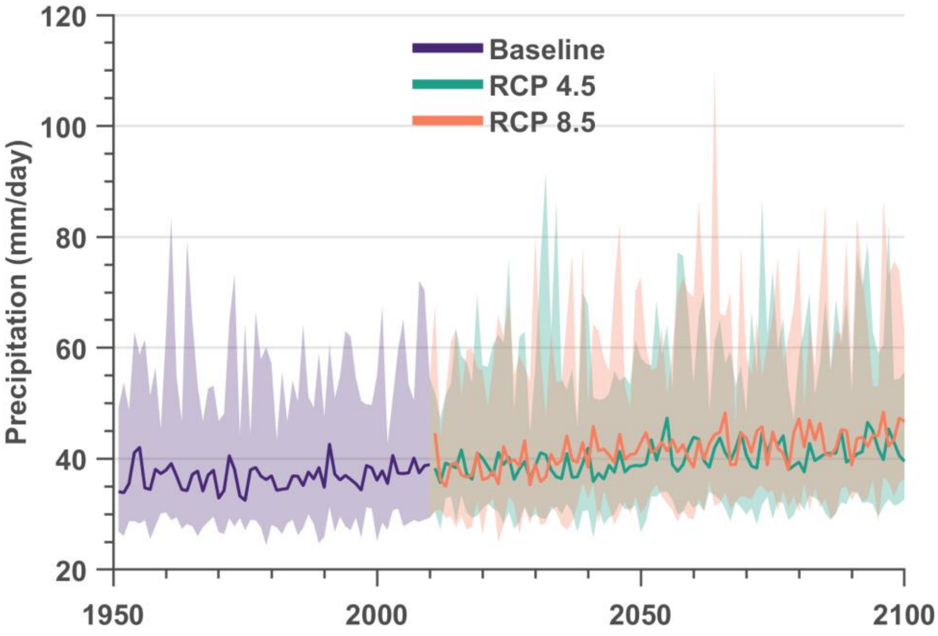


Figure 2.20: Annual Max. 1-Day Precipitation

When these projections are broken down by month, it becomes apparent that the increase in precipitation intensity will be concentrated during the winter and shoulder seasons (i.e., October - May).

The **number of days with precipitation greater than 10 mm** and the **maximum daily precipitation are shown on the monthly plots below.** It is cautioned that these figures show only the median of the ensemble of statistically downscaled GCMs and therefore does not give a measure of uncertainty (see APPENDIX D – *Technical Review of Methods for Extreme Precipitation Projections* for the 10th and 90th percentiles of the model ensemble). Note that the monthly maxima (Figure 2.22) are smaller than the yearly maxima (Figure 2.20) because the annual maximum is calculated from values that occur in any month.

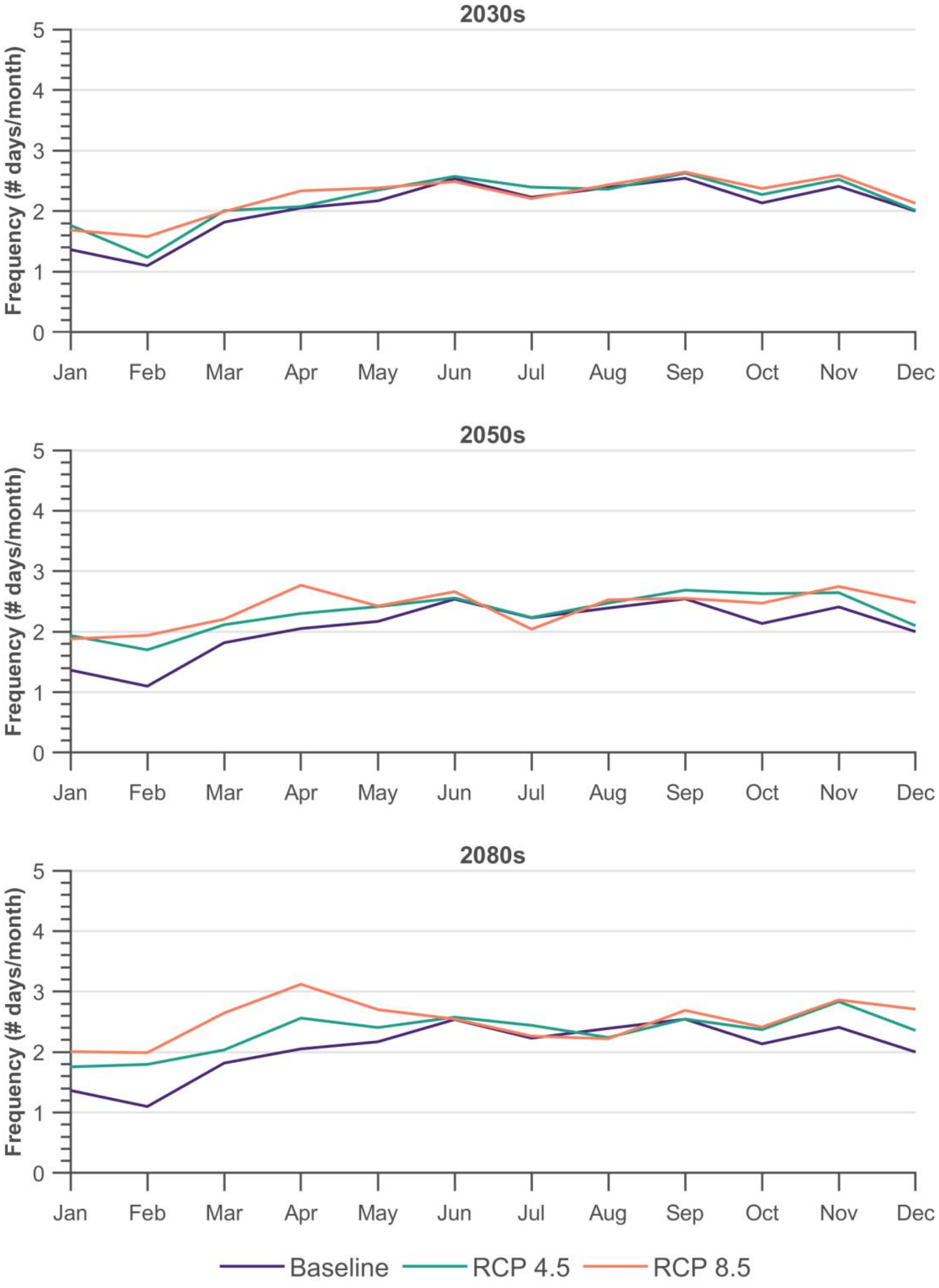


Figure 2.21: Monthly Number of Days Precipitation > 10 mm (Only Median is Shown)

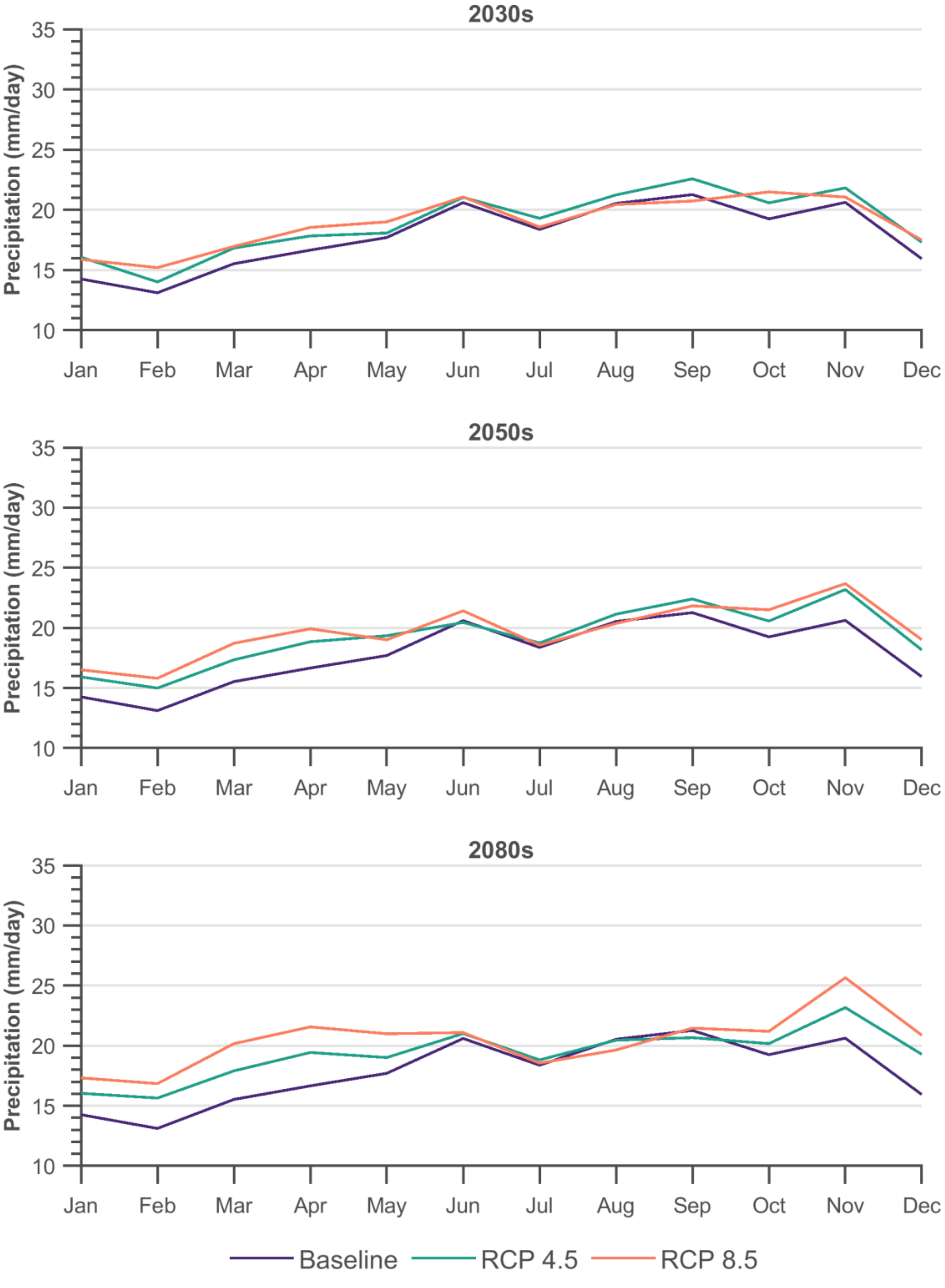


Figure 2.22: Monthly Max. 1-Day Precipitation (Only Median is Shown)

Extreme Precipitation

In this report, precipitation extremes are defined as having a return period of greater than 1 year. Return periods (e.g., 1 in 50 years) are used to describe the probability of occurrence of extreme precipitation events. For example, a 1 in 50 year precipitation event has a 2% chance of occurring each year (1/50 = 0.02). A 1 in 2 year event has a 50% chance of occurring each year. This chance of occurring is the same for any given year (even if an extreme event occurred recently). Different return periods of extreme precipitation are commonly used in the water resources sector, for example for storm sewer design.

Precipitation extremes are particularly challenging to project. Part of the challenge in projecting precipitation extremes is that important precipitation processes occur at small scales, which are difficult to represent in models. For instance, convective updraft cores can be only a few hundred metres to a few kilometres across (Westra *et al*. 2014). Furthermore, even some of the larger-scale precipitation processes pose challenges. For instance, models struggle to resolve the location of jet streams that are also important for precipitation extremes (Trenberth *et al*. 2003, O'Gorman *et al*. 2015).

Therefore, additional analysis was conducted to investigate the strengths and limitations of the methods used and to compare them with other studies available in the literature. The results are summarized below, and the details are provided in APPENDIX D – *Technical Review of Methods for Projections of Extreme Precipitation*.

Overall Findings

- Despite the high natural variability and challenges with projecting precipitation extremes, multiple methods show an increase in precipitation intensity for all durations (sub-daily, daily, and multi-day precipitation events).
- No approach is more reliable or defendable than the others in all situations. Different schools of thought advocate for different methods, but all methods have their faults. The high level of uncertainty cannot be avoided, regardless of the method selected.
- Both the PCIC/CCCS daily projections and the Cordex RCM sub-daily projections underestimate the ECCC Intensity Duration Frequency (IDF) value in the historical period.

Table 2.1: Projections for Extreme Precipitation based on Multiple Methods (2070-2100). The value provided is the median, with the 10th and 90th percentiles provided in the brack4ets. Note that the ECCC Baseline value is 116.5 mm.

	Daily 1 in 100 (mm)		Hourly 1 in 50 (mm)		Main Limitations
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	
GCMs	110 (86-160)	118 (85-185)	N/A		Known to underestimate
RCMs	N/A		38 (36-50)	43 (38-60)	Known to underestimate
IDF-CC	165 (131-188)	183 (137-213)	55 (45-62)	60 (60-71)	Problematic for hourly
Clausius	139 (134-158)	163 (151-185)	58 (55-65)	68 (63-77)	Problematic for hourly
Other	Most suggest an increase		Most suggest an increase		See Appendix D

Using the Projections

- **Considering Projections from Multiple Approaches** – Although other indices can be modelled thorough the use of an ensemble of models (e.g., an ensemble of GCMs or RCMs), for extreme precipitation it is recommended that projections from several approaches be considered, with the context of the strengths and limitations of each (see approaches in APPENDIX D – Technical Review of Methods for Projections of Extreme Precipitation).
- **Projections cannot be ignored** – A clear message from the literature is that the high level of uncertainty does not mean that the information should be ignored (Switzman *et al*. 2017, Coulibaly *et al*. 2016, Charron 2016, CSA 2019). Because of the challenges involved, a robust estimation of rare extremes must make the best use of available information (Li *et al*. 2018, Maraun and Widmann 2018).
- **The importance of risk/vulnerability assessments** – The extreme precipitation projections provided cannot be used directly for infrastructure design or a climate adaptation project without further analysis. A vulnerability/impact assessment and/or risk assessment is needed to determine which values to use from the range of projections provided (see Chapter 3).

2.4.4 Decrease in Total Snowfall

Total snowfall is a measure of the cumulative amount of snow that falls during a winter-centered year (i.e., measured from August to July rather than by the calendar year). Changes in snowfall have implications for a wide range of sectors, including winter recreation, water resources, and snow clearing operations. **Annual total snowfall** (Figure 2.23) demonstrates how snowfall patterns are projected to change, without differentiating between months. A decrease in annual total snowfall is projected in the NCR, from approximately 223 cm in the baseline to 193-201 cm in the 2030s, 184-179 cm in the 2050s and 154-124 cm in the 2080s. This represents a decrease of 31-44% by the 2080s.

In this report, the values reported (e.g., 5-8°C) are not ranges; they represent the mean values for the moderate (RCP 4.5) and high emission (RCP 8.5) scenarios. When a decrease is projected, such as the amount of snow, the second value will be lower than the first value.

Note that these values do not represent the highest or lowest possible annual total snowfall, but rather the conditions of an "average year" (since they are averaged over the 30-year time slice). High interannual variability means that some years may experience more snow than others; values similar to the baseline are still possible past mid-century. The year-to-year variability is visible from the ups and downs of the lines in the time-series below.

While the temperature and precipitation time-series plots showed the range between the 10th and 90th of the models (for each year) as shaded colours, the plot below shows each model projection as a separate line. This is because there are fewer model projections available for snow, so for statistical reasons, it is not recommended to calculate percentiles. See APPENDIX B – *Guidelines to Reading and Interpreting the Plots*.

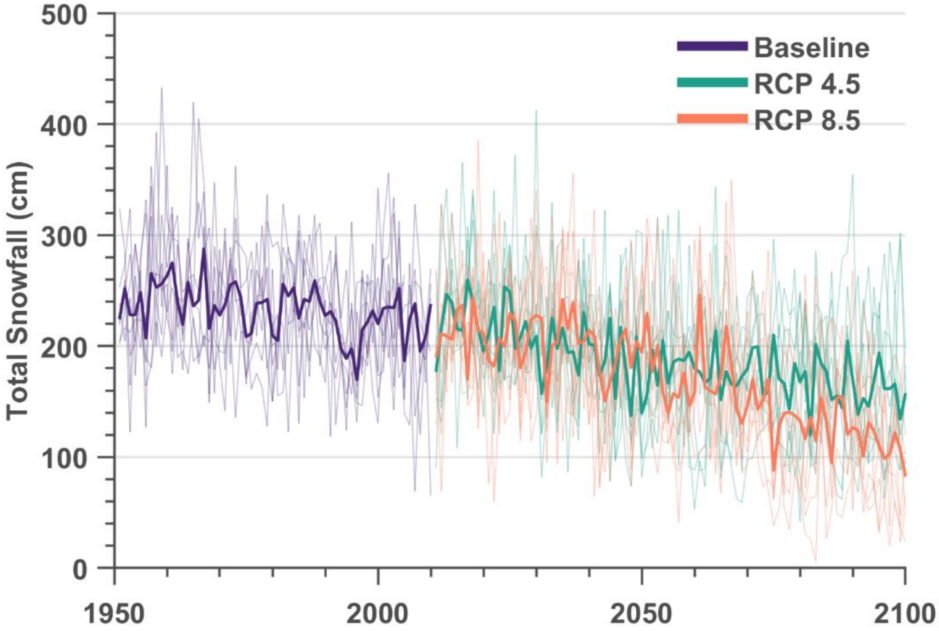


Figure 2.23: Annual Total Snowfall

As shown in the plot of **monthly total snowfall** (Figure 2.24), snowfall is projected to decrease in all months, with the greatest absolute decreases projected to occur in the months that currently have the most snow (December, January, February, and March). Note that a complete loss of snowfall is projected for April by the 2080s under the high emission scenario (RCP 8.5), although this doesn't represent a large decrease in total snow because there wasn't much snow in April in the baseline to begin with. It is cautioned that this figure shows only the median of the ensemble of statistically downscaled RCMs averaged over 30 years and therefore does not give a measure of uncertainty (see APPENDIX F – *Plots of Climate Indices* for the 10th and 90th percentiles of the model ensemble).

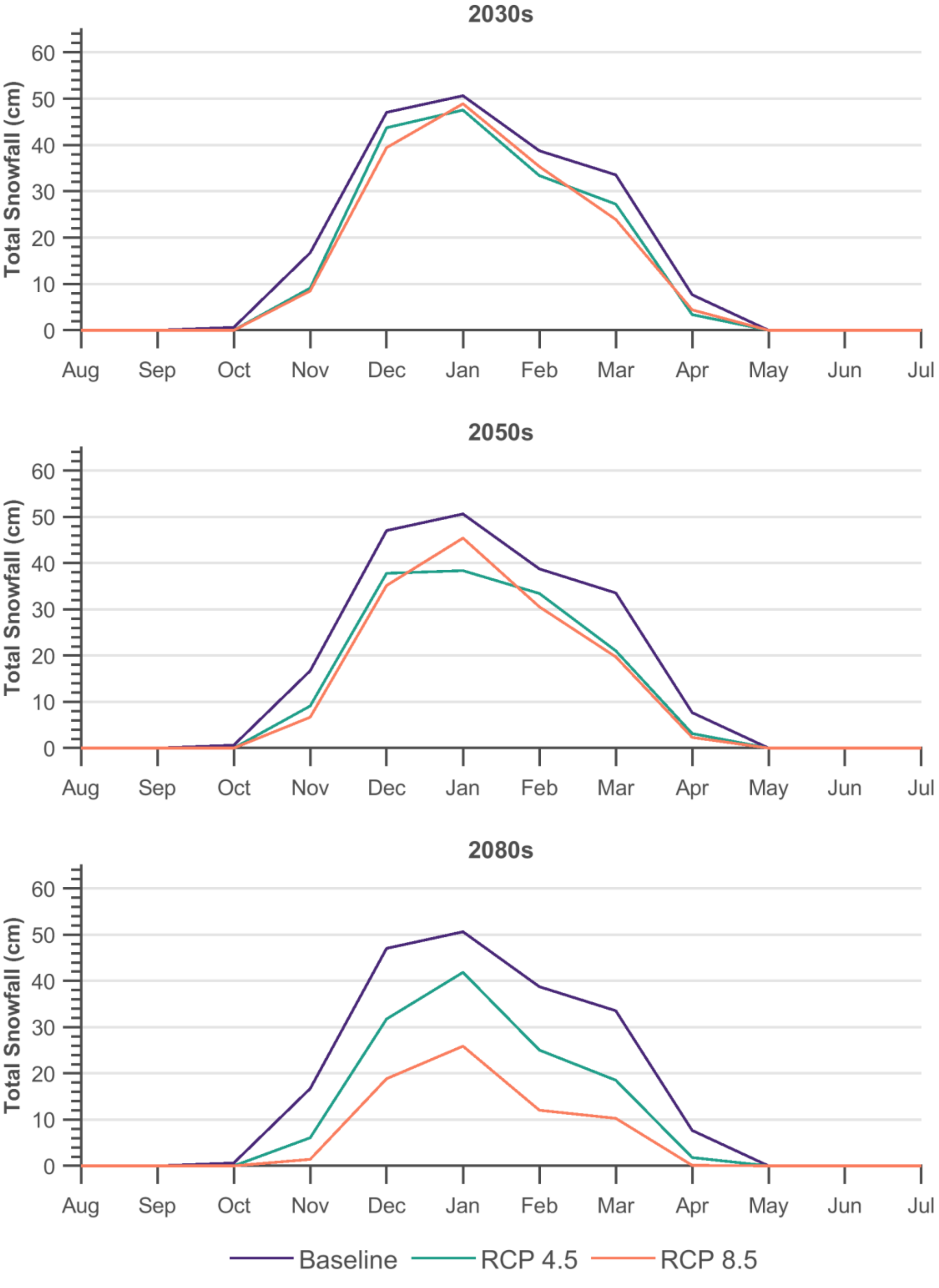


Figure 2.24: Monthly Total Snowfall (Only Median Shown)

2.4.5 Shorter Snow Season

There are different ways of measuring the length of the snow season. It could be measured in terms of the first and last day of snowfall, or in terms of the number of days (not necessarily consecutive) when snowfall occurs, or that have snow cover on the ground. Each of these indices, which are presented below, have different implications for different sectors. For example, the number of days between the first and last days of snowfall may be important for planning snow clearing operations, whereas the number of days with snow cover may be more relevant for planning winter recreation. The uncertainty in these projections is visible based on the range of projections between individual models, as well as from the year-to-year variability.

It is projected that the timing of the snow season will shift. The **timing of first snowfall** (defined as the first date in the fall when snowfall ≥1 cm) is projected to occur approximately 1-1 weeks later in the 2030s, 2-2 weeks later in the 2050s, and 2-3 weeks later in the 2080s compared to the baseline.

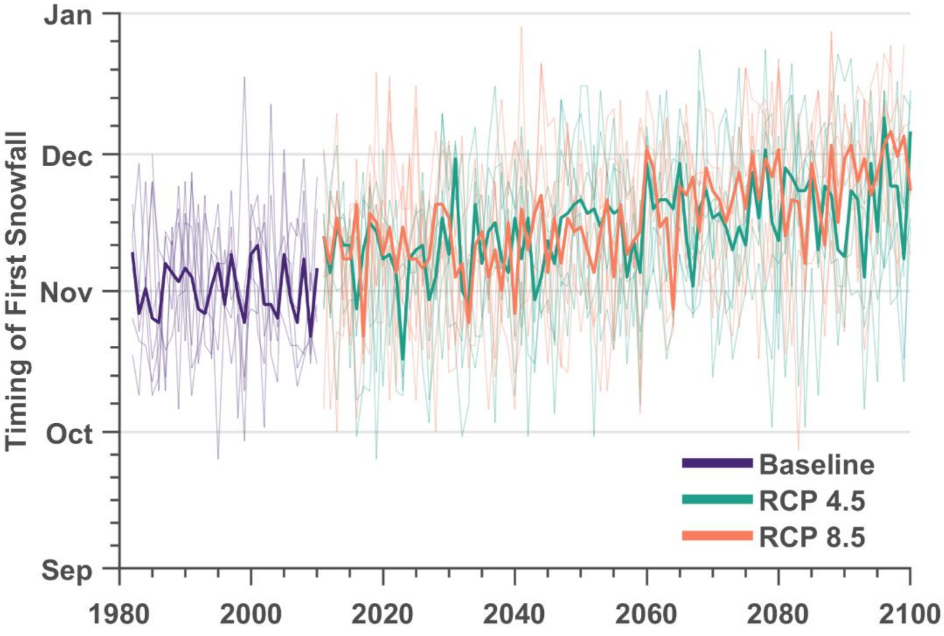


Figure 2.25: Timing of First Snowfall

The **timing of last snowfall** (defined as the last date in the spring when snowfall ≥1 cm) is projected to occur approximately 0-1 weeks earlier in the 2030s, 0-2 weeks earlier in the 2050s, and 1-3 weeks earlier in the 2080s compared to the baseline. As a result, the duration from the first to the last day of snowfall is projected to decrease (not shown here, see APPENDIX F2 - *Plots of Climate Indices*).

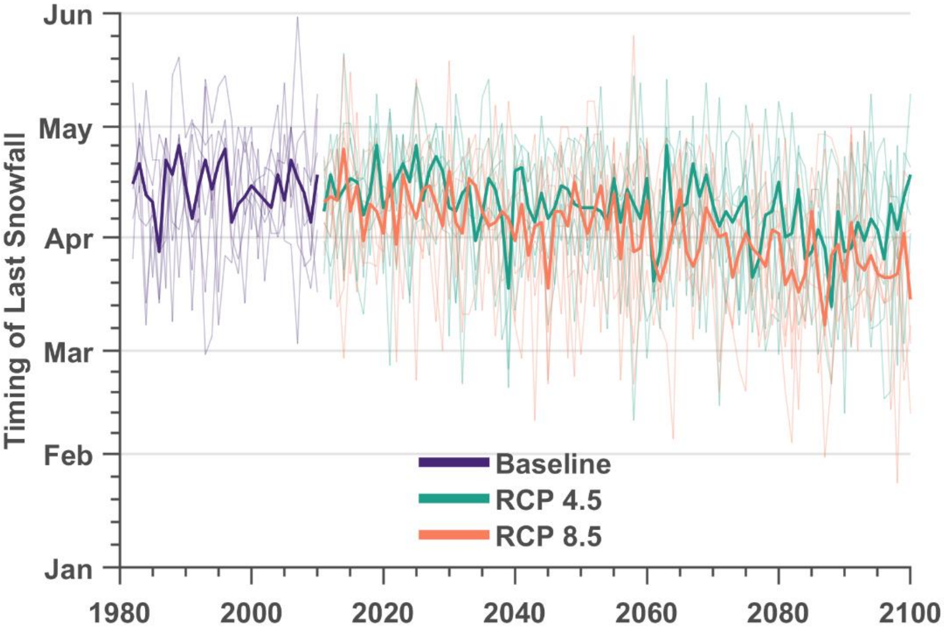


Figure 2.26: Timing of Last Snowfall

The **number of days with snowfall** (defined as the number of days where snowfall ≥ 1 cm occurs) is projected to decrease from approximately 41 days in the baseline to approximately 37-37 days in the 2030s, 33-32 days in the 2050s and 31-22 days in the 2080s (Figure 2.27). It is cautioned that these values are 30-year medians and are thus projections for an "average year".

Changes in snowfall will also translate to changes in snow cover. The **number of days with snow cover** is projected to decrease from approximately 115 days in the baseline to approximately 95-94 days in the 2030s, 90-72 days in the 2050s and 78-43 days in the 2080s (Figure 2.28).

To create the plots in Figure 2.27 and Figure 2.28, the models are first averaged over the 30-year time slices. The average of these values is then shown in the dark circles, representing the middle-of-the-range projection for 30-year average conditions. The hollow circles represent projections from individual models, and the range between hollow circles can be interpreted as the uncertainty in the projections. This plot is different from the box plots used to depict precipitation and temperature because there are fewer model projections available for snow so for statistical reasons it is not recommended to calculate the percentiles shown in earlier box plots. See APPENDIX B – *Guidelines to Reading and Interpreting the Plots.*

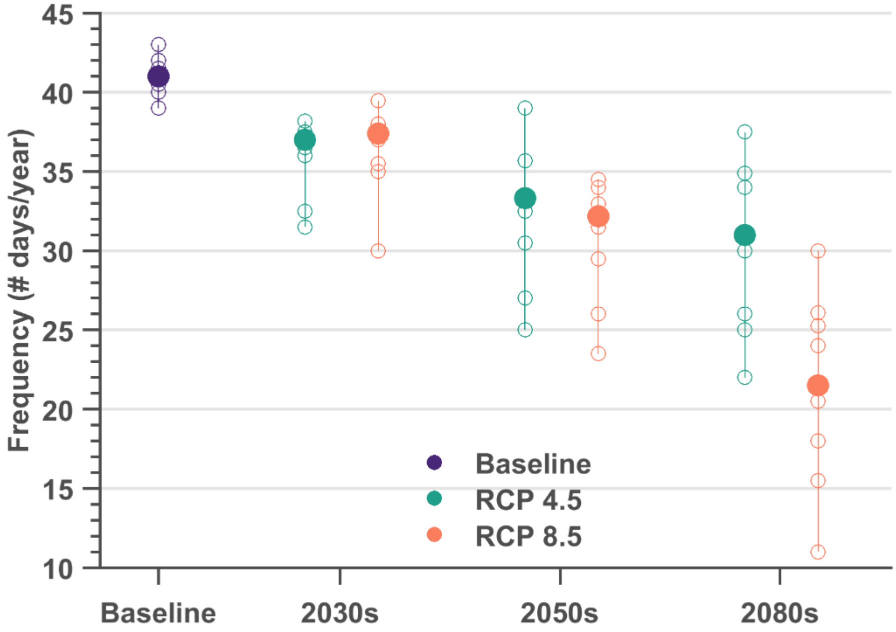


Figure 2.27: Number of Days with Snowfall

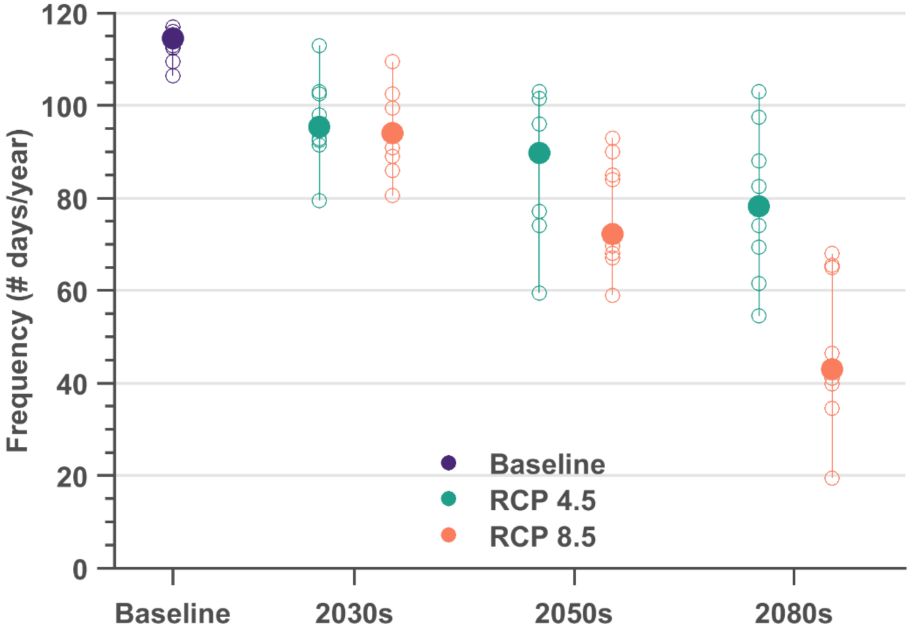


Figure 2.28: Number of Days with Snow Cover

2.4.6 High Variability in Extreme Snow

The ensemble average of RCMs projects a decrease in the maximum snow depth, and mixed findings for the maximum 1-day snowfall. There is high variability between the models, and some RCMs project an increase in snow extremes. For this reason and because of year-to-year variability, it is still possible for extreme snowfall or snow depth to occur both now and in the future. Snow extremes are important because of implications to a number of sectors (e.g., snow clearing, emergency management, flooding, water resources). Refer to Section 2.8.2 on Extreme Snow and Blizzards for additional information from the literature.

Average projections suggest that **annual maximum 1-day snowfall** (averaged across the study area) will change from approximately 20 cm in the baseline to 21-20 cm in the 2030s, 22-20 cm in the 2050s and 20-16 cm in the 2080s. There is a decrease by the 2080s for the high emission scenario (RCP 8.5) but not for the moderate emission scenario (RCP 4.5). Some models project similar or greater values than the baseline median in all future time slices. Furthermore, the findings shown represent maximum snowfall for an "average year" (since they are calculated from 30-year time slices).

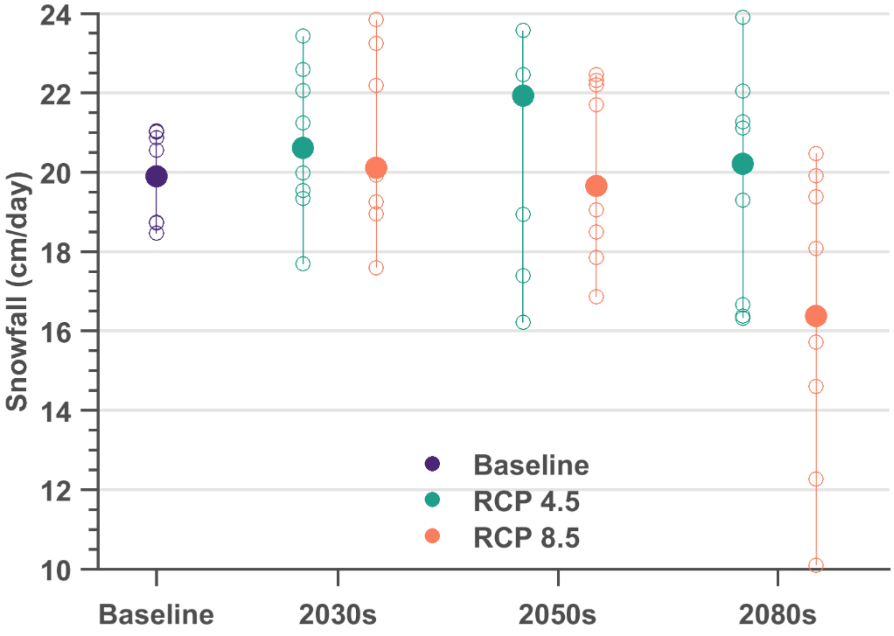


Figure 2.29: Annual Max. 1-Day Snowfall

Annual maximum snow depth (on the ground, averaged across the study area) is expected to decrease from approximately 59 cm in the baseline to 48-50 cm in the 2030s, 45-40 cm in the 2050s and 42-29 cm in the 2080s. It is noted that some models project similar or greater values than the baseline median in the 2030s and 2050s (Figure 2.30). Furthermore, the findings shown represent maximum snow depth for an "average year" (since they are calculated from 30-year time slices).

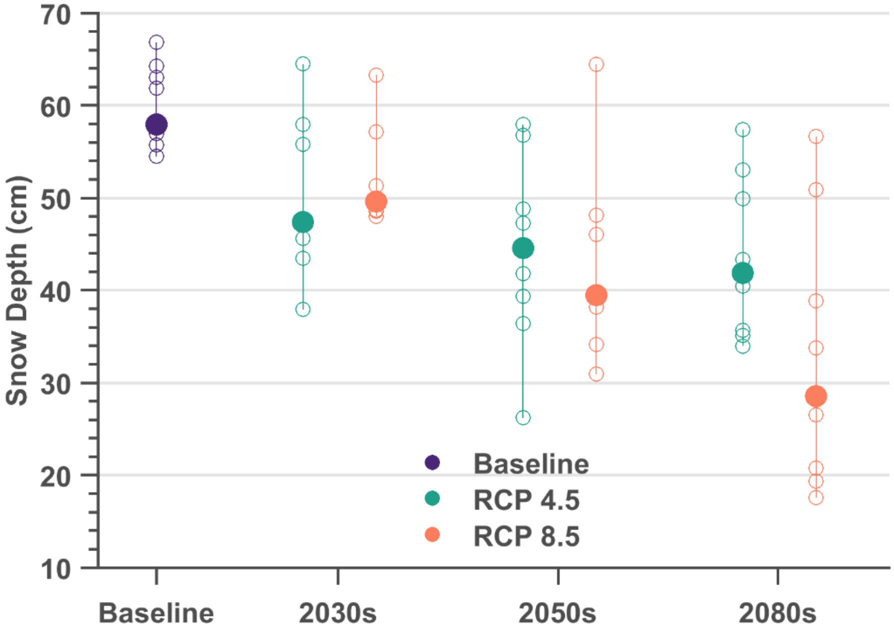


Figure 2.30: Annual Max. Snow Depth

Changes in projected snowpack were used as approximations for “melt” (on days when the snow depth decreased from one day to the next). Several indices based on this proxy for “melt” are available in the APPENDIX F – *Plots of Climate Indices*.

2.5 Wind Projections

Wind speed and direction have implications for a number of sectors, including buildings and other infrastructure, emergency management, air quality, transport of airborne pests, tree damage etc. Wind contributes to wind chill when combined with cold temperature extremes.

It is cautioned that current climate models have limitations with respect to representing wind processes properly. The IPCC (2013) states that winds are modelled with “low confidence.” This is in part because processes impacting winds are complex, with different processes having contrasting effects. Changes are anticipated to be non-linear. The main processes driving potential changes in winds include (a) a possible change in the location of regional storm tracks (e.g., northward movement of extratropical cyclones), (b) the possible displacement of mid-latitude westerlies, and (c) the potential increase in localized convection caused by heating of the ground surface (IPCC 2013).

The plots for wind show much more inter-annual variability than the plots for the previous parameters. This is because the results average only two models, which reduces the confidence in the findings. It is also noted that projections represent average values over the study area. This means that values are more representative of the area as a whole, but that potential spatial variations in values are smoothed. The state of knowledge for wind extremes is addressed separately in Section 2.8.3 on Extreme Winds and Gusts.

2.5.1 No Detectable Trends in Averages

Projections for monthly averaged wind speed show little to no change in the yearly distribution of average wind speeds in the future (APPENDIX F – *Plots of Climate Indices*). The projections suggest no change in average wind speed compared to the baseline (**December average wind speed** is shown as an example).

Like for the plots for snow, the plots for wind use lines for individual models rather than representing the 10th and 90th of the models with a shaded region. This is because there are only two models available for wind speed.

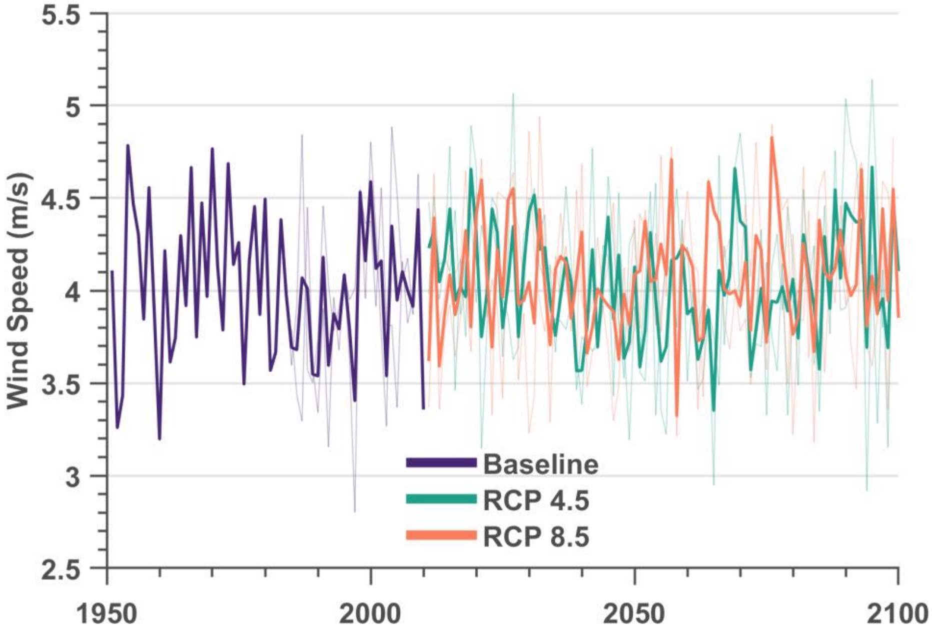


Figure 2.31: Monthly Average Wind Speed – December

2.5.2 Reduced Wind Chill

Projections for changes to wind in combination with other parameters were also investigated. Wind chill is calculated by combining wind speed with cold temperature extremes (see APPENDIX C – *Methodology* for details). For instance, the **number of days with wind chill that is between -35 and -25** is projected to decrease from approximately 17 days in the baseline to 11-8 days in the 2030s, 6-5 days in the 2050s and 5-1 days in the 2080s (Figure 2.32). These values represent an “average year” because they are calculated from the average of 30-year time slices (as well as averaged over the study area). This drastic drop in the projections is caused by the rapid change projected for cold extremes.

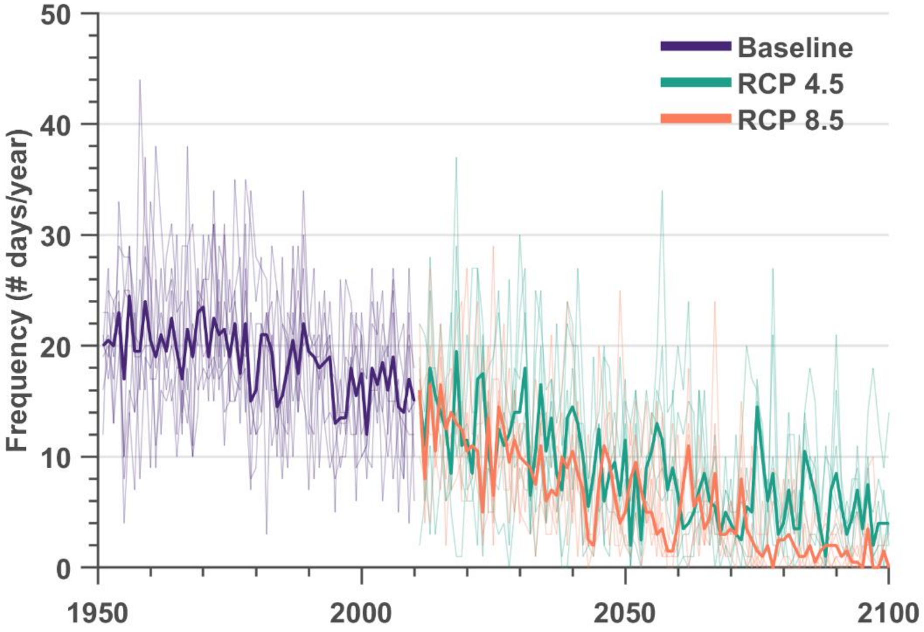


Figure 2.32: Number of Days Wind Chill is between -25°C and -35°C

2.6 Humidity Projections

Humidity is the presence of water vapour in the atmosphere, and it depends on both temperature and precipitation, as well as other factors that affect evapotranspiration (e.g., wind, vegetation, etc.). It is an important parameter because high humidity impairs heat exchange efficiency by reducing the rate of moisture evaporation from skin surfaces. Therefore, humidity projections have implications for wildlife ecology as well as the public health and emergency management sectors.

Humidity has been averaged over the study area. This means that values are more representative of the area as a whole, but also that any spatial variation in values has been smoothed (local extremes could be higher than what is shown here). Like for wind and snow, there are fewer models available for projections of humidity than for projections of precipitation and temperature. Although humidity (from a public health standpoint) is closely tied to temperature through humidex, the findings were purposefully presented separately because of the different sources of data and because the humidity projections have a high degree of uncertainty.

2.6.1 No Detectable Trends in Averages

No trends were found for monthly average humidity in the NCR. The monthly average humidity is the average, over each day of the month, of the approximate “relative humidity at the time of maximum temperature” (details presented in APPENDIX C – *Methodology*). The plot for the **Monthly Average Humidity in September** is shown as an example).

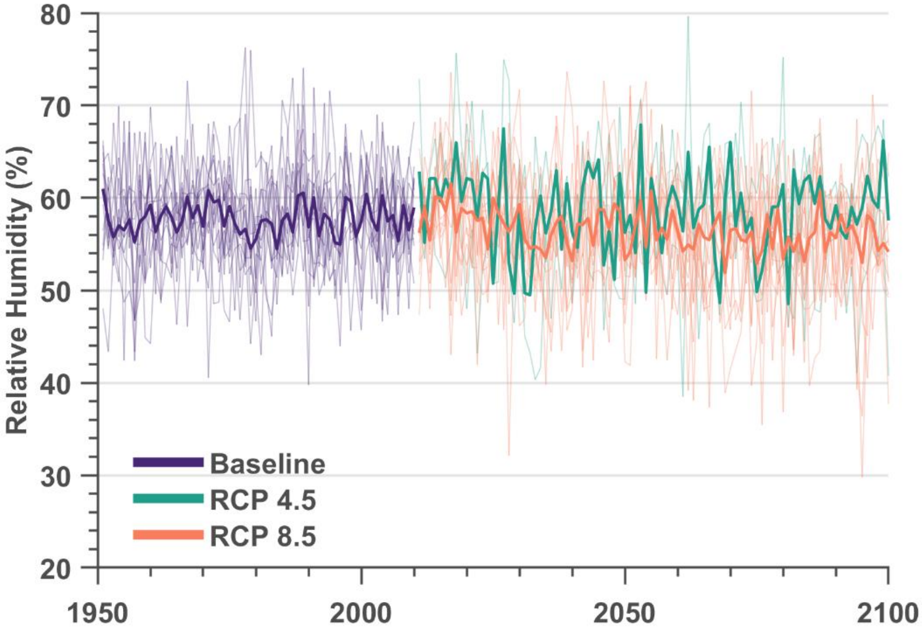


Figure 2.33: Monthly Average Relative Humidity at the Time of Max. Daily Temp. – September

2.6.2 Increase in Humidex

High humidity can exacerbate the effects of high temperatures, and thus has implications for the public health and emergency management sectors. **Humidex** is an index calculation based on both temperature and humidity (see details in APPENDIX C – *Methodology*). An increase in either temperature or humidity results in an increase of the humidex.

Projections averaged over the NCR show that the **number of instances with 2 days of humidex > 40** is expected to increase from approximately 1 day in the baseline to approximately 4-4 days in the 2030s, 5-6 days in the 2050s, and 6-9 days in the 2080s (Figure 2.34). This is an increase of 5-8 days within a century.

These values represent an “average year” because they are calculated from the average of 30-year time slices (as well as averaged over the study area). The 30-year average projections for each model are shown as hollow circles. The dark circles are the middle-of-the-range projections. It is noted that the actual values being projected are small, which makes the projections more uncertain (depicted in part by the large range between model results).

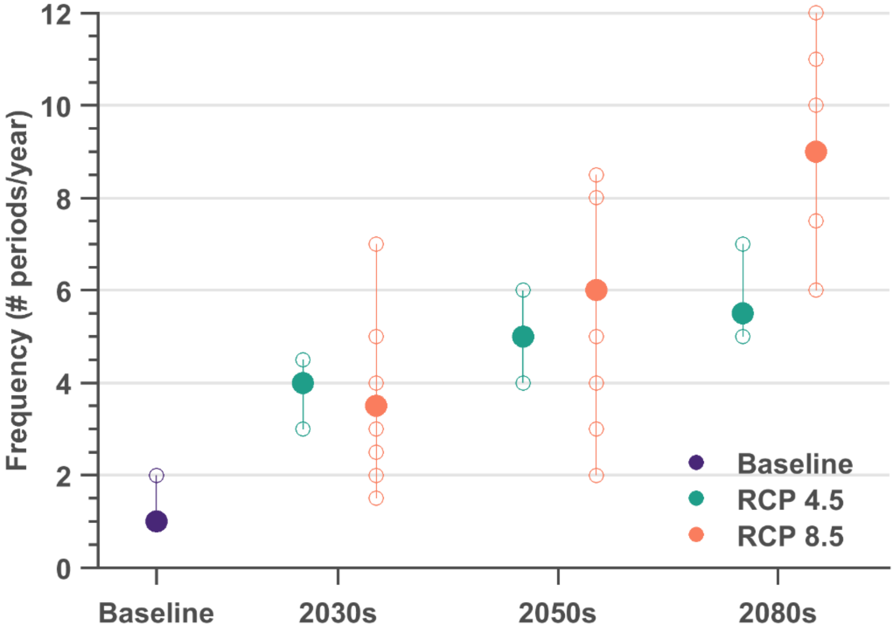


Figure 2.34: Number of Days Humidex > 40°C for 2 Days

2.7 Spatial Variation in the Project Area

The climate projections presented in the previous sections show the spatial mean of the climate indices over the NCR. Although the NCR is fairly homogenous (i.e., no mountains or coasts), there is the potential for topography and land use variability (e.g., Gatineau hills, urban heat island effect, Ottawa River) to cause spatial gradients in the climate index projections. Spatial variations in the projections could be an important consideration for risk and vulnerability assessments.

One of the unique aspects of this study is that the indices for temperature and precipitation were calculated on a 10 km x 10 km grid across the project area, allowing for an investigation of the potential spatial variation of climate index projections.

When evaluating whether a spatial pattern is significant, it is important to also consider the spread between the models (as a measure of uncertainty), which increases with the projection horizon. Therefore, the two types of variation to consider are:

1. **Spatial variation** (e.g., for the median between models, the difference between the grid cell with the highest value and grid cell with the lowest value).
2. **Model variation** (e.g., for one grid cell, the difference between the model with the highest value and model with the lowest value).

In this project, if the spread between models was found to be much larger than the variation within the project area, then the variation was not considered to be significant (i.e., no formal statistical tests were conducted).

Two types of spatial variation were investigated:

- Spatial variation in the climate (Section 2.7.1) – Investigated for one time slice.
- Spatial variation in the projected changes (Section 2.7.2) – Investigated for a difference between two time slices.

The main findings are that:

- Although the study area is relatively small (< 100 km between any two grid cells), several temperature- and precipitation-based indices show spatial variation within one time slice. The climate is generally colder and wetter to the north (Section 2.7.1).
- Changes are projected to occur at similar rates throughout the study area. An exception is shown in Section 2.7.2.

2.7.1 Spatial Variation in Baseline Climate Indices

Some of the temperature-based indices show a north-south gradient or a concentric pattern near the center of the study area. This may be due to regional topography, airflow patterns, and/or land use (e.g., possibly an urban heat island effect). For example, maps of the **coldest temperature of the year** and **timing of first fall frost** are shown below. These maps depict the median of the model ensemble for each grid cell, for the baseline. Grid cells shown on the map are 10 km x 10 km.

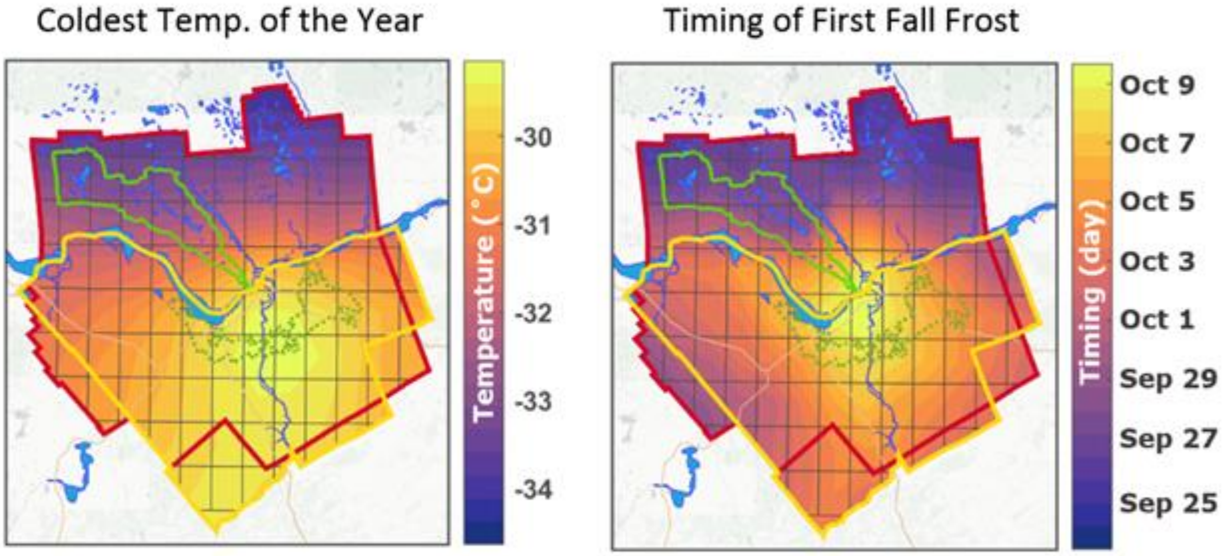


Figure 2.35: Sample Maps of Temperature Indices (1981–2010 Baseline Shown).
Left: example of a North-South gradient; Right: example of a concentric gradient.

Several of the precipitation-based indices also show spatial variation across the study area, generally with higher precipitation values in the north or north-east (Figure 2.36). The indices that show spatial variation include annual (and some monthly) total precipitation, annual (and some monthly) extreme indices, some of the threshold indices, and dry and wet spells. Maps of **annual total precipitation** and **annual maximum 1-day precipitation** are shown as examples below and the full set of plots are in APPENDIX F – *Plots of Climate Indices*.

It is difficult to interpret the cause of a consistent gradient across the study area, which could be due to regional climate influences and more local influences captured by the bias correction, including topography, water bodies, and land use. Alternatively, gradients could be due to model "artifacts" (anomalies or errors resulting from the modelling or data processing). See APPENDIX D – *Technical Review of Methods for Extreme Precipitation Projections* for more information on model artifacts.

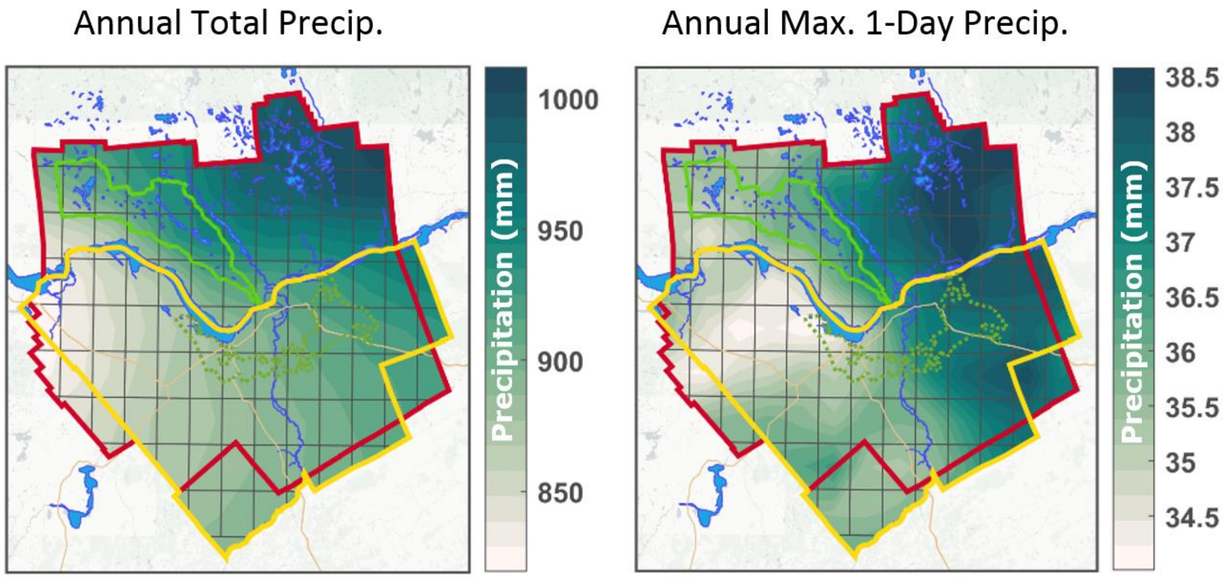


Figure 2.36: Sample Maps of Precipitation Indices (1981-2010 Baseline Shown). Example of a northeast-southeast gradient.

2.7.2 Spatial Variation in Projected Climate Indices

The future changes for most indices are not projected to vary significantly across the study area. In other words, changes are projected to occur at similar rates throughout the study area, and the values for the mean over the domain are representative for the entire region.
In practice, this means that the spread between the models is greater than any spatial gradients (or, the spatial gradients are incoherent and possibly due to model artifacts).

One exception, **number of tropical nights**, does show spatial variation in projections that is greater than model variation. The "difference" maps show the difference between the median of the ensemble at each grid cell. These maps show that:

- The southeast of the NCR is projected to experience a greater increase in the number of tropical nights (nighttime low > 20°C), compared to the northern part of the NCR (see Figure 2.37).
- In other words, the difference in the # of days between the projection horizon and baseline is greater in the southeast.
- It is also noted that the spatial gradient is constant across different timeframes under moderate emission scenarios (RCP 4.5). However, under the high emission scenario (RCP 8.5), there is more spatial gradient initially (baseline to 2030s) followed by less spatial gradient (2050s, then 2080s).

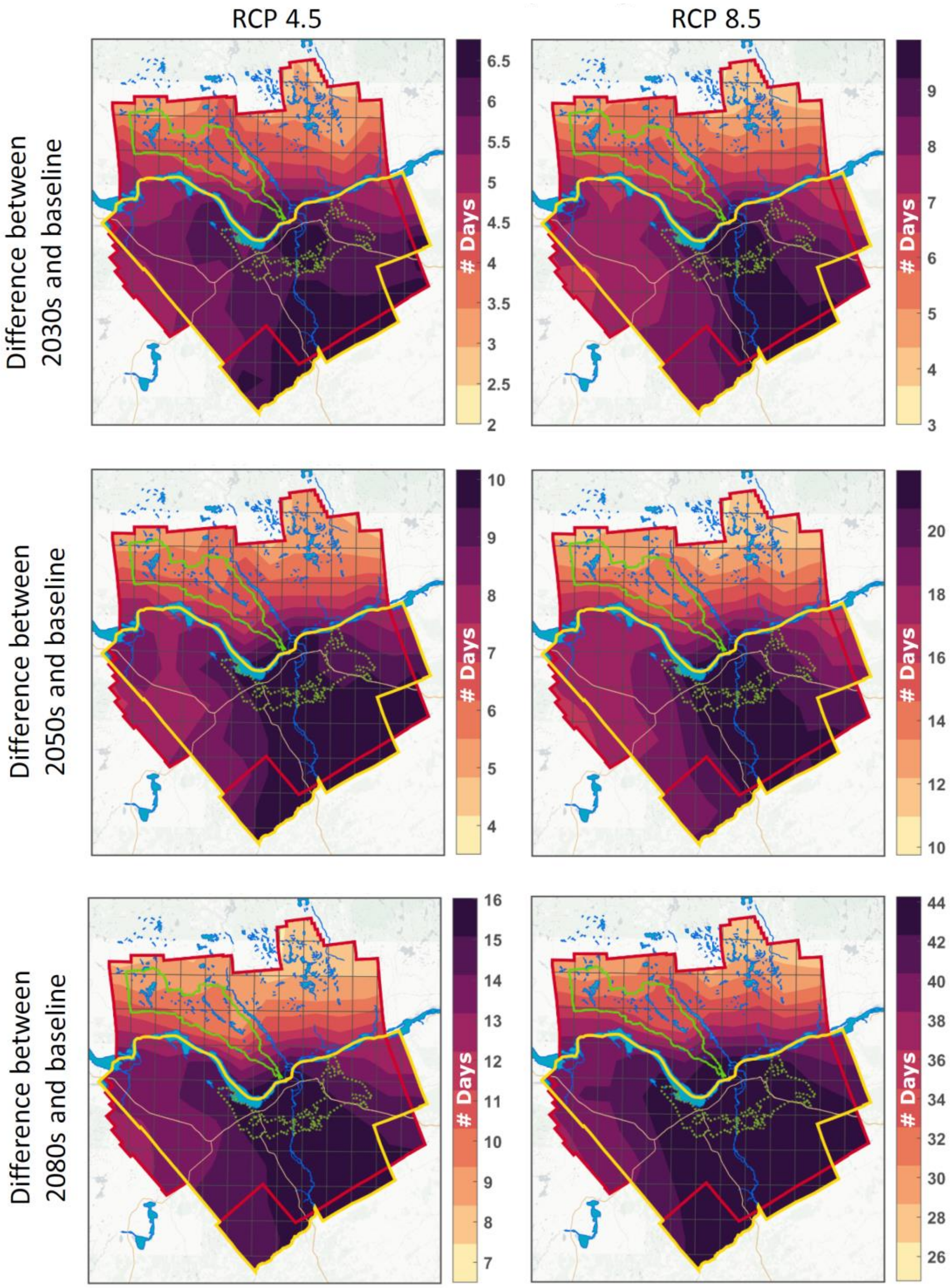


Figure 2.37: Difference Maps for the Number of Tropical Nights

2.8 Extreme Events and Other Climate Phenomena

Some extreme events (such as tornadoes, ice storms, and wildfire) are either not represented in climate models, or not well represented (for instance due to limitations on the current understanding of scientific processes, natural variability, or computation capabilities). Many occur at spatial or temporal scales below the resolution of climate models. Nonetheless, these events/phenomena have implications for a number of sectors, so it is important to investigate whether there is an indication of them changing in the future using qualitative methods.

Qualitative projections were gathered based on targeted reviews of both the peer-reviewed literature (scientific articles) and grey literature (e.g., government reports), with a focus on studies encompassing the NCR region. In this section, the main outcomes are summarized, emphasizing what is projected about future trends (where available) as well as a characterization of uncertainty.

2.8.1 Freezing Rain and Ice Storms

Freezing rain and ice storms can have major impacts on society by causing power outages and disruptions to transportation networks. Even at low intensities, these events can cause damage to trees, housing, communication lines, and other infrastructure. Freezing rain forms if liquid raindrops fall from a warm layer through a layer of cold air (whose temperature is below freezing) that is too thin for the drops to have time to freeze. Water then freezes on contact with the surface.

The St. Lawrence River Valley is prone to freezing precipitation because of wind channelling effects (Carrera *et al*. 2009). The NCR, located in this corridor, has been hit by several major ice storms. In December of 1942, Eastern Ontario's Freezing Rain Storm had ice "as thick as a person's wrist" covering telephone wires, trees and railway tracks (ECCC 2017, "Top Weather 20th Century"). The 1998 Ice Storm (see Figure 2.38) was a combination of five smaller successive ice storms and caused massive damage to trees and electrical infrastructure, leading to a shutdown of activities in the NCR for weeks (Rice 2015).

Projection of freezing rain can be approached from a theoretical standpoint, or through modelling studies.

From a theoretical standpoint, the increase in water vapour in the atmosphere (see extreme snow section) is likely to lead to increased intense precipitation including freezing rain under the right conditions. Furthermore, an increase in freezing rain could occur from an increase in near-freezing temperatures due to the northern movement of the 0°C temperature boundary (Lambert and Hansen 2011, Matte *et al*. 2019), or the location of the jet stream (Francis and Vavrus 2012).

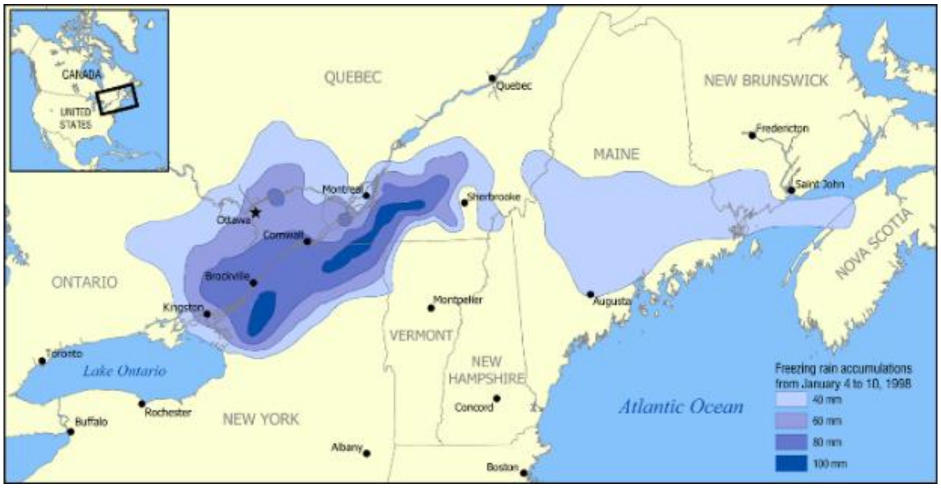


Figure 2.38: Reach of the 1998 Ice Storm (Rice 2015)

A modelling study by Cheng (2011) used a technique called "weather typing" to downscale region-specific freezing rain predictions using eight GCMs. Klima and Morgan (2015) performed an idealized experiment using vertical historical temperature profiles on which they applied several warming scenarios. Both studies found a projected increase in freezing rain in the NCR region during the coldest months, and a decrease or no change during the shoulder seasons.

In summary, the projected increase in near-freezing temperatures in the NCR would suggest an increase in freezing rain occurrence. Modelling studies suggest that this is most likely to occur during the winter, with no change or a decrease during shoulder seasons. It would be prudent to continue preparing for freezing rain extremes in the future.

2.8.2 Extreme Snow and Blizzards

Extreme accumulation of snowfall affects the environment, flooding, and can pose risks to human life and property, by causing power outages, disrupting transportation, and impeding emergency services. According to CBC, on Feb 16, 2018, just over 50 centimetres of snow fell on Ottawa – setting a new record for the biggest single-day snowfall.

Projection of extreme snow can be approached from a theoretical standpoint, or through modelling studies. From a theoretical standpoint:

- A warmer atmosphere can hold more moisture, which drives heavier precipitation, including heavier snowfall if the conditions are right. Therefore, climate change could theoretically result in higher snowfall extremes.
- However, the theoretical increase in snowfall from increased atmospheric moisture will likely be moderated by rising surface temperatures, which cause more snow to fall as rain.

Modelling studies project that mean snowfall will decrease throughout North America; extreme snowfall, however, shows a more inconsistent pattern, with some areas (such as the Arctic) experiencing increases in the frequency of extreme-snowfall events, but not other areas (Janoski *et al*. 2018). A study from 2018 concludes that models do not agree on whether snow is projected to increase or decrease (Jeong and Shushama 2018).

Part of the challenge is that snow experiences major year-to-year variability. The inter-annual variability is partly caused by atmospheric phenomena known as “teleconnections” (e.g., the El Niño-Southern Oscillation cycle; NOAA 2010).

In summary, although a warmer atmosphere can hold more moisture, more snow is expected to fall as rain, so it is unclear what the impact will be on snow extremes. Models generally project a decrease in average snowfall, but high year-to-year variability makes it difficult to project changes in extremes. It would be prudent to continue to prepare for snow extremes in the future.

2.8.3 Extreme Winds and Gusts

Extreme winds can cause considerable economic and social costs, including damage to properties, infrastructure, agriculture, power lines, and trees. Winds are also connected to many other processes such as evaporation, drought, visibility, aerosols (air pollution), and air quality.

From a theoretical standpoint, processes impacting winds are complex, with different processes having contrasting effects. In Ontario, extreme wind events result both from intense synoptic storms, convective activity, or combinations of both (Cheng *et al*. 2011). In addition, changes in driving forces, like temperature gradients, are accompanied by changes in drag forces, like land use (Wu *et al*. 2018).

Studies that have tried to quantify climate change impacts on wind gusts have either looked for trends in past records or have downscaled global or regional climate model projections. A couple of studies project an increase in wind extremes: in Eastern North America (Klink 2015) and in Southern Canada, including the NCR (Cheng *et al*. 2011). Other studies found no change in wind gusts or even decreases in both mean and extreme winds on land globally (Huryn 2016, Wu *et al*. 2018).

The lack of a clear trend between these studies may be due to insufficient and/or deficient observations in Canada (Jeong and Sushama 2018). This is also a challenge for some other climate parameters, but in the case of winds, the assessment method affects not only the magnitude of projected changes but also the direction of change (increase or decrease).

In conclusion, we cannot exclude the possibility that the NCR could receive more wind gust events late this century than has historically been experienced, but there is insufficient information to confirm this.

2.8.4 Tornadoes

A tornado is a narrow, violently rotating column of air that extends from the base of a thunderstorm to the ground. Tornadoes can be extremely damaging and can result in loss of life. Tornadoes are fresh in the collective memory in the National Capital Region, which has experienced several tornadoes in 2018 and 2019 (Ottawa Citizen 2019).

Because tornadoes are localized, short-lived phenomenon, they are difficult to detect and predict. Therefore, to understand whether climate change is impacting tornadoes, it is necessary to (1) investigate the observational record, (2) understand the factors that are necessary for tornado formation and how they are predicted to change.

Figure 2.39: View of Tornado from Highway 17 Near the East-Ottawa Neighbourhood of Cumberland on June 2, 2019 (CBC News)

Canada has experienced significant losses caused by tornado activity, though to a lesser degree than the United States. Ontario has averaged more than 12 tornadoes each year for the past three decades, with most of those touching down in "tornado alley," an informal name for a corridor of land in southern Ontario (Sills *et al*. 2012). The observational records have a number of uncertainties, such as an overrepresentation of events in populated areas, and a change over time in how events are rated. Nonetheless, some studies show some increasing trends in Ontario (e.g., Cao and Cai 2008). It is cautioned however that historical trends should not be directly extrapolated into the future.

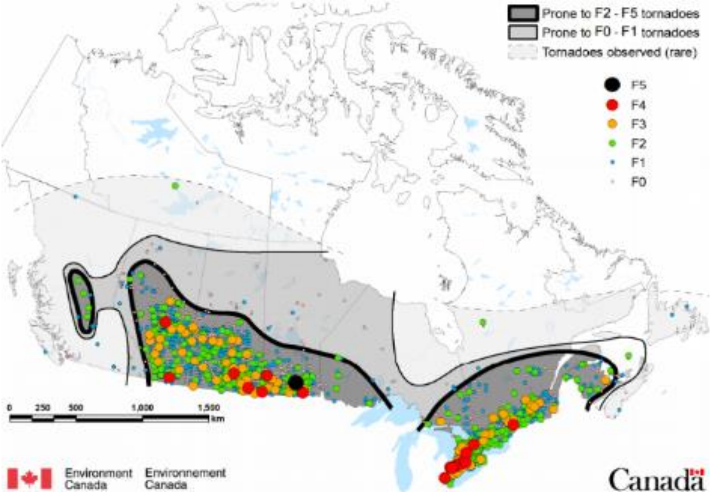


Figure 2.40: Map of Tornadoes from 1972-2009 and Tornado-prone Areas (Sills *et al*. 2012)

Two factors that are important for tornado formation are Convective Available Potential Energy (CAPE), which provides buoyant energy needed for developing updrafts, vertical wind shear (changes in wind speed with altitude). Future climate simulations show an increase in days with high CAPE (because of an increase of low-level moisture and temperature; Brooks 2013). However, vertical wind shear is projected to decrease as the equator-to-pole temperature gradient decreases with climate change (Brooks 2013).

In summary, the interpretation of how tornadoes will change is open to question; Brooks (2013) suggests that it is possible that the occurrence of tornadoes will increase in the future, based on the increasing likelihood of atmospheric conditions favourable for tornadoes. Communities should consider preparing for the possibility of increased tornado activity.

2.8.5 Hurricanes

Hurricanes and tropical storms are made up of masses of warm, humid tropical air with high winds and torrential rains. According to the National Hurricane Center (2017), 163 hurricanes have passed over Canada between 1900 and 2014 (see Figure 2.41). Although many of these storms lose strength as they move over land, areas of central Canada, like Ontario and Québec, can be affected by gusty winds and torrential rain causing damage.

For example, in 1954, Hurricane Hazel, the deadliest inland storm of tropical origin in Canadian history, ripped through southern Ontario (ECCC 2013). More than 200 millimetres of rain fell in 24 hours in Toronto, causing unprecedented flooding. More recently in 2011, the post-tropical storm Irene had a significant impact on Québec. Irene's winds topped 113 km/h east of Québec City and precipitation amounts approached 170 millimetres in just a few hours.

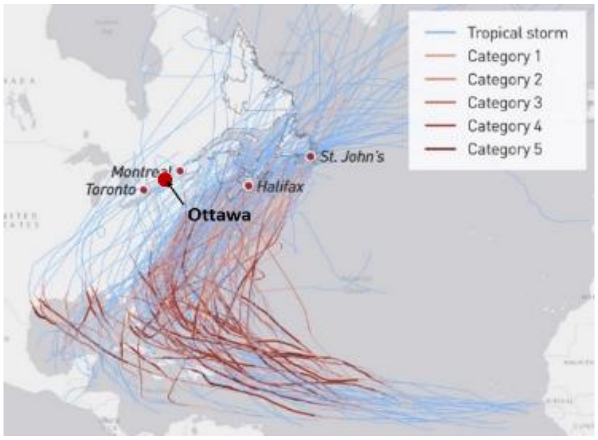


Figure 2.41: Historical Hurricane Tracks (National Hurricane Center 2017)

From a process-based perspective, warmer oceans mean that hurricanes will have more energy. According to new summaries of the state of knowledge by NOAA (Knutson *et al*. 2019), tropical cyclone precipitation and intensities will likely increase on average. Furthermore, the latitude of maximum intensity in the North Atlantic appears to be moving north.

In summary, although hurricanes are not the most immediate threat for the NCR, their future impacts to the region may increase.

2.8.6 Lightning

Lightning is the product of positive and negative charges in clouds making contact with the positive charges on the ground. Lightning can be deadly and destructive on short timescales and has important climatic effects on longer timescales (through the production of nitrogen oxides and forest fire ignition; Huryn *et al*. 2016). Lightning is affected by land use and land cover change, which in turn affect temperature and convection through the "urban heat island effect"; therefore, the NCR is vulnerable as an urbanized region.

A number of processes may impact future lightning occurrence:

- Lightning occurs in convective environments which are also prone to heavy precipitation, hail, lightning, tornadoes, violent downdrafts (Huryn *et al*. 2016). Therefore, the projected increase in Convective Available Potential Energy (CAPE, discussed in the tornado section), may result in conditions favourable to lightning (Brooks 2013).
- In addition, it is projected that climate change will allow clouds to have a larger vertical dimension, a property known to be strongly correlated with a higher flash rate (Agard and Emanuel 2017).
- Other changes that may impact lightning processes include changes in global circulation which may alter the location and frequency of large-scale storms (Sillmann *et al*. 2017), changes in humidity (Sillmann *et al*. 2017), frequency and intensity of tropical storms (especially over warmer oceans), and the El Niño-Southern Oscillation cycle (Yair 2018).

Figure 2.42: Lightning from the Storm on July 21st, 2010. Taken from 200 Rideau Street (Ottawa Citizen)

In summary, lightning occurrence could increase under climate change due to an increase in the conditions favourable to lightning occurrence, and preparations should be made accordingly. It is noted that there is no scientific consensus at this point as to whether these processes will actually translate to a change in the frequency and intensity of lightning occurrence.

2.8.7 Evapotranspiration, Drought and Wildfire

Evapotranspiration – Evapotranspiration is an important parameter for agricultural and ecological applications. *Potential evapotranspiration* is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration, assuming no control on water supply. *Actual evapotranspiration* is the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration; it depends not only on temperature but also on water availability, wind, cloud cover, and other factors (Girardin *et al*. 2004).

Evapotranspiration is closely linked to drought because it is a component of the water balance (and therefore affects drought), and because, in turn, periods of drought result in higher potential evapotranspiration (atmosphere is able to evaporate) and lower actual evapotranspiration (less is actually evaporated).

Drought – A drought is defined as a prolonged period of abnormally dry weather that depletes water resources for human and environmental needs (MSC Drought Study Group 1986). Droughts differ from other disasters (e.g., floods) since they have longer durations and lack easily identified onsets and terminations. Since human activities and ecosystem health are dependent on adequate, reliable water supplies, droughts pose a serious threat to society and the environment (Bonsal *et al*. 2011). Large-area, prolonged droughts have been among Canada's costliest natural disasters, and have major impacts on a wide range of sectors including agriculture, forestry, industry, municipalities, recreation, public health, and aquatic ecosystems (Bonsal *et al*. 2011).

Trend analyses indicate that historical drought severity has seen little change in eastern and central Canada (Girardin *et al*. 2004). However, in the future, it is generally projected that increases in temperature and potential evapotranspiration will not be balanced by projected changes to precipitation (Cook *et al*. 2014). Hence, climate change is projected to cause drier conditions in most of Canada (NRCAN 2019).

Wildfire – Short- and long-term droughts influence several aspects of fire regimes such as the intensity, severity, extent, and frequency of fires. Wildfires occur in the NCR's green spaces and can affect nearby communities (e.g., Ottawa Citizen 2016). Climate change drivers that influence fires include changes to temperature, precipitation (including drought), snowmelt, wind, and groundwater flow patterns (Littell *et al*. 2016). These climate drivers can cause changes to vegetation assemblages (affecting the amount of fuel available to burn), flammability (moisture state of the soil and vegetation), and disturbances (insect outbreaks and trees uprooted or broken by wind). The forest water balance is complex (e.g., more or less precipitation can be intercepted by the canopy; Littell *et al*. 2016). Seasonal timing and geographic heterogeneity of changes are also important in terms of the consequences of fires (Stocks *et al*. 2013).

It is predicted that the fire season will lengthen and that the number and extent of wildfires will increase, especially in boreal forest types (NRCan 2019). Flannigan *et al*. (2013) examined the potential influence of global climate change on fire season severity and length using three GCMs. Their results suggest that fire seasons will be three times more severe and fire season lengths will increase by 20 days in the Northern Hemisphere (particularly at high latitudes) by the end of this century. Wotton *et al*. (2010) projected changes in fire occurrence based on the relationship to moisture variables and found an increase in most of Canada including the NCR (see Figure 2.43).

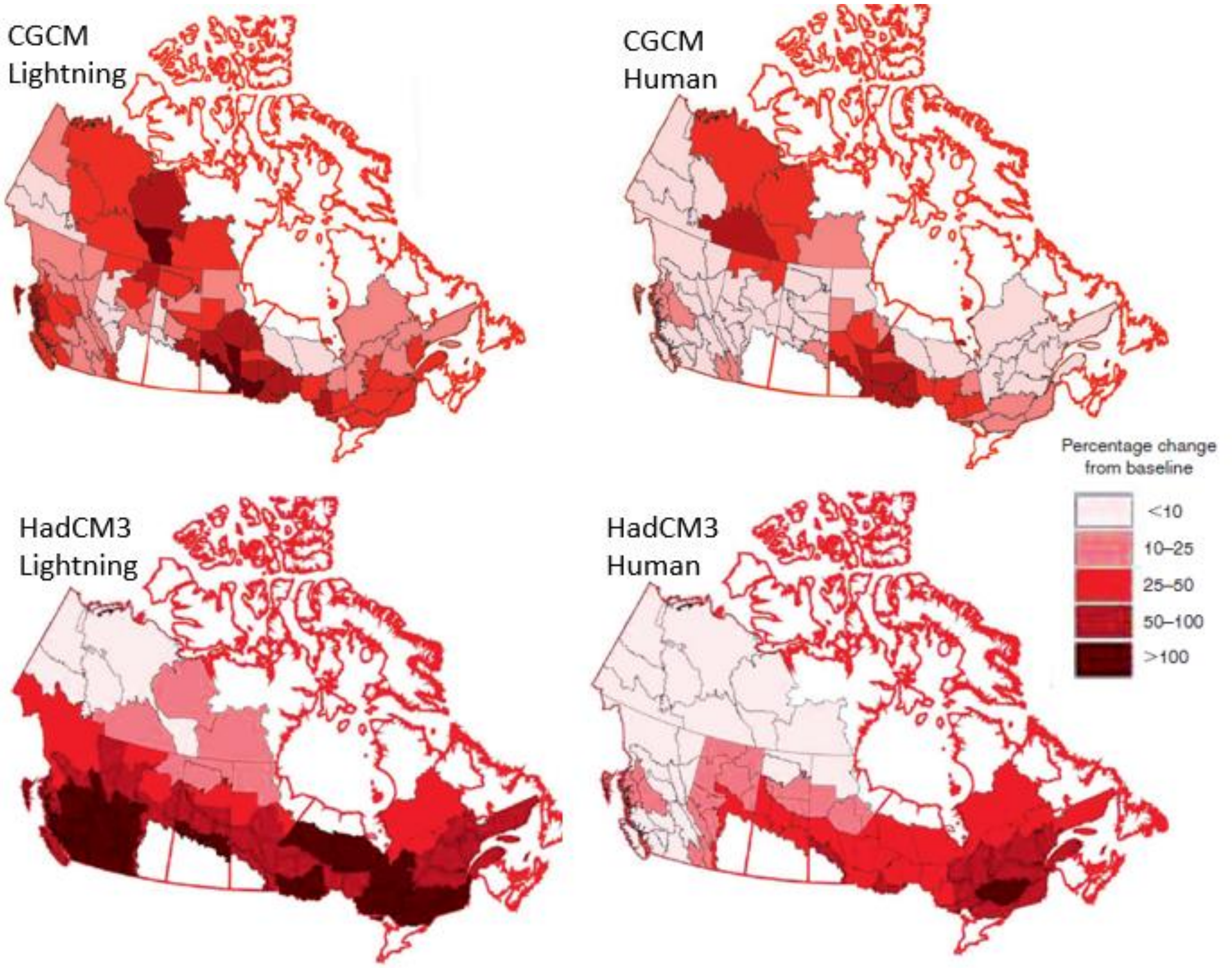


Figure 2.43: Projected Changes in Fire Occurrence from Lightning and Human Ignition, from Two GCMs (Wotton *et al*. 2010).

Modelled Based on Known Relationship to Moisture Variables.

Relative change shown between current and future (3 x CO2) climate scenarios.

Finally, it is noted that climate factors interact with several other controls to affect fires (land use, management activities, and initiation factors from human behaviour). For example, the increased number of dwellings in or near forest environments and wildfire suppression also contribute to changes in fire risk (Bracmort 2013).

2.8.8 Air Quality

Air quality problems such as smog result in large part from the release of pollutants into the atmosphere. Because air pollutants have impacts on public health and the environment, substantial efforts have been made to improve air quality in Canada over the last few decades, and the concentrations of many air pollutants have been decreasing (Environment and Climate Change Canada 2018). However, there are still issues; for example, the estimated percentage of deaths attributable to ground-level ozone exposure has increased from 1984 to 2012.

It is possible that climate warming could worsen some aspects of air quality, even in the absence of changes in human activities (Fu and Tian 2019), for example with changes to:

- The duration of pollen seasons, and pollen production (Poole *et al*. 2019).
- Microbial and mould growth following flooding (Poole *et al*. 2019).
- Weather types that relate to different air pollution concentrations. For example, Cheng et al. (2007) found that the number of days with high ground-level ozone levels (which depends on complex meteorological, chemical, and biological processes and feedbacks) could increase 50% and 100% by the 2050s and 2080s, respectively).

Recent studies have generally projected an increase in pollution from ground-level ozone. However, it is cautioned ground-level ozone is governed by complex meteorological, chemical, and biological processes and feedback systems that are not well understood (Fu and Tian 2019).

In summary, it is possible that climate warming could worsen some aspects of air quality, but uncertainty remains high.

2.8.9 Acid Rain

The deposition of acid rain accelerates corrosion of materials including rocks, mortar, and metals, and can damage natural systems, such as lakes, rivers, forests, soil, fish, and wildlife.

Emissions of sulfate and nitrate have been increasing since the industrial revolution, which is an issue when the amount of acidity exceeds the natural buffering capacity of the ecosystem. In the 1970s legislation controlling acid emissions resulted in acid rain led to a 40% decrease in these emissions from 1970 to 2000 in Canada (Driscoll *et al*. 2001).

The problematic emissions causing acid rain (sulfate and nitrate) are not the same gases that cause the most global warming (carbon dioxide and methane), so it is not strictly considered a climate change process. That said, carbon dioxide can still cause some acid rain (a weaker acid) and increasing concentrations may increase rain acidity in the future. Furthermore, climate change affects precipitation characteristics, and this will change acid rain impacts (e.g., changes to timing, and more acid snow falling as acid rain).

Overall, due to the combination of many changing processes, the assessment of climate change impacts on acid rain is inconclusive.

2.8.10 Shortwave Solar Radiation

Exposure to shortwave solar radiation is important for a number of reasons, including (1) impacts on the durability of common building materials, (2) impacts on solar power production, and (3) impacts on living things, including human health (UV radiation).

Future changes are unclear because shortwave radiation depends on cloud cover, aerosols (air pollution), and ozone, which are some of the most difficult processes to represent accurately in global climate models (Lucas *et al*. 2019). For cloud-free conditions, climate models are largely consistent in projecting an increase in solar radiation over Ontario because of a decrease in certain types of aerosols, as well as a global upper-level ozone recovery since the Montreal Protocol of 1987 (Wild *et al*. 2015).

When it comes to trends in cloud cover, however, these are very uncertain, differ for different types of clouds, vary regionally, and have been shown to have multi-decadal variability that coincides with natural variability in the climate (Sillmann *et al*. 2017). The patterns in multi-decadal variability have been detected from long term worldwide observational networks of shortwave radiation as well. There are coherent periods and regions with prevailing declines (known as "global dimming") and inclines (known as "brightening"; Wild *et al*. 2015).

In summary, there are different trends in shortwave radiation, but it is difficult to link changes to climate change as of yet, due to complications from factors such as clouds.

2.9 Comparison with Other Studies

Climate data is increasingly available through varied data portals and studies. The range of climate modelling methodologies can produce different results and it can be challenging for technical users and policy makers to decide which results to use. This section of the report compares the methodologies and findings from the climate modelling results used in this study with other relevant studies and datasets and offers explanations for any significant differences.

Additional climate projection studies in the NCR have been prepared for Public Services and Procurement Canada (PSPC), the Ville de Gatineau, and Hydro Ottawa to support their respective vulnerability and risk assessments. PSPC has identified climate-related hazards for real property assets mainly focusing on buildings, central heating and cooling plants, bridges, and road infrastructure. The Ville de Gatineau has completed climate projections for a series of indicators on its territory, for the purpose of supporting vulnerability assessments and adaptation plans. Hydro Ottawa has completed a vulnerability and risk assessment for its key infrastructure in the NCR.

In addition to these targeted regional studies, climate projections for the NCR are available through the Climate Atlas of Canada (climateatlas.ca) and the national climate data portal (climatedata.ca), two online tools among others, supported by the Canadian Centre for Climate Services. Both portals provide projections for temperature- and precipitation-based indices based on an ensemble of downscaled GCMs.

The methodologies used in the regional and national studies align with the methodology used in this project in many ways. However, there are several key differences:

- **This study calculated a long list of indices** (178), including "combined indices" which are based on more than one parameter. For example, more sector-specific indices are available in this study than currently accessible on climatedata.ca.
- **This study used an ensemble of GCMs (24 models) with a distribution-based (as opposed to mean-based) downscaling method**. The other studies differ slightly in the sources of model projections used and how post-processing was conducted. For example, the Hydro Ottawa study used the CMIP5 GCMs but applied a more basic mean-based bias correction called the "delta method". The Ville de Gatineau study used a subset of the CMIP5 GCMs and downscaled them with a different distribution-based method (1D quantile mapping by Gennaretti *et al*. 2015 with some modifications), although the same observation dataset was used for downscaling as in this study (10 km; McKenney *et al*. 2011).
- **This study reports the median as well as the 10th/90th percentiles for every index in order to characterize uncertainty.** The other studies report uncertainty (range of projections) to differing degrees, with some focussing on the median only.
- **This study calculated indices separately for every grid cell in the NCR, to investigate potential spatial variation in the projections.** This means that results can be shown as a map (also possible with climatedata.ca), which is not the case for studies that used projections that are downscaled to a point measurement or averaged over the area. Hence, the geographic scope of the study is more extensive.
- **This study used an ensemble of RCMs to obtain projections for snow, humidity, and wind (in addition to temperature and precipitation).** The other studies that do address these parameters used the extrapolation of historical measurements or analyses from the literature.

Findings from this study and those mentioned above (PSPC, Hydro Ottawa, Climate Atlas, etc.) can only be compared for overlapping indices. Findings are broadly similar, with differences expected due to the differences in methodologies mentioned above.

In terms of the **temperature findings**:

- There are slight differences (up to 1.2°C) in the baseline average annual temperatures reported in each study. This may be in part due to differences in the extent of the study areas and the meteorological stations used for the baseline data (e.g., according to the ECCC Climate Normals, the Ottawa MacDonald-Cartier Airport has an annual mean temperature that is 1.4°C warmer than that of Masson-Angers, Québec).
- There is general agreement for temperature-based indices, such as the Number of Hot Days (> 30°C), with less than 5% difference between the median projections across the studies.

In terms of the **precipitation findings**:

- There is general agreement for the total annual precipitation, with less than a 5% difference between the median projections across the studies.
- There is also general agreement in terms of precipitation intensity, with the annual maximum 5-day precipitation having less than 5% difference between the median projections; the annual maximum 1-day precipitation is slightly lower in this study, with still less than 10%

difference. It is noted that this difference is likely because of the different spatial scales used for projections among the different studies (e.g., the values presented here are means over the entire NCC regions, whereas values presented in the Climate Atlas are just one grid cell value, 10x10km).

In terms of extreme events (tornadoes, lightning, etc.), the findings are broadly consistent. Riverine flooding was not assessed in this study because it depends on water management, hydraulic structures, and other factors not captured by water level measurements.

In summary, this study confirms and expands upon previous studies, by providing a greater number and variety of indices, characterizing uncertainty with confidence intervals, and covering a larger geographic area.

Chapter 3 Implications for the National Capital Region

Climate change poses risks to all sectors of the economy and people’s quality of life. Action on climate change mitigation and adaptation is required to limit impacts on people and ecosystems.

This chapter summarizes some key regional impacts of climate change, including those discussed during the July 2019 stakeholder workshop, with a brief discussion on the processes that drive riverine flooding. The examples presented in this chapter are by no means exhaustive and will be explored in greater detail in subsequent risk and vulnerability assessments. The chapter includes a discussion on the use of projection data and how to mitigate uncertainty in impact assessments and adaptation planning.

3.1 Regional Climate Impacts on Key Sectors

This section provides preliminary discussions on impacts on the following key sectors:

- **Health and Safety**, including increased stresses on emergency services and public health systems, as well as impacts on human health.
- **Water Services**, including sewer and stormwater collection and management, water distribution, solid waste management, riverine flooding, and erosion, as well as water quality.
- **Buildings, Real Estate and Planning**, including historic and new buildings, monuments, and land use planning.
- **Transportation**, including the planning, operation and maintenance of roads, public transit, and active transportation networks.
- **Natural Assets, Tourism and Recreation**, including Gatineau Park, the Greenbelt, the Rideau Canal Skateway, the Tulip Festival, agriculture, trees and forests, biodiversity and invasive species, as well as summer and winter recreation.

3.1.1 Health and Safety

The warmest temperature of the year is projected to increase for all time horizons in the NCR. Not only are warm extremes projected to get hotter, but they are also projected to become more frequent. The number of “hot days” is projected to increase from the current average frequency of 11 days per year, up to twice as many in the 2030s and 3-4 times as many in the 2050s. Heat warnings will likely occur much more often than they have historically. Heat stress is a public health concern for everyone, and particularly for vulnerable populations such as children, seniors, people who work outside, and those with health conditions.

Incidents of vector-borne illnesses are anticipated to increase with higher temperatures and changing seasons. Ngonghala *et al*. (2019) determined that the transmission of the Zika virus occurs between an optimal temperature range which may become more common as the average annual temperature in the NCR is expected to increase. Ticks are found any time of year when temperatures are above freezing but are most active in Ontario during the spring and summer months (Government of Ontario, 2019). The last day of spring frost is projected to shift from early-May to mid- to late-April. Frost-free conditions are projected to be the new normal for September and May. With the changing seasons, including earlier onset of spring and later onset of fall, extended contact with ticks is possible.

Extreme weather, such as tornadoes, ice storms, and wildfires may increase in the future. Uncertainty remains high for these events, therefore planning for changes will require careful consideration of risk. Changing climate and extreme weather events such as flooding, heatwaves, fires and storms greatly affect the mental, physical and financial health of those directly affected and put an added strain on emergency services. Wildfires are known to increase the concentration of airborne particulate matter which, when inhaled, can cause adverse health risks.

3.1.2 Water Services

Climate change impacts to the water services sector in the NCR are largely driven by changes in the volume and intensity of precipitation and snowmelt events. Intense precipitation is expected to increase. Seasonally, the most drastic change is projected to occur in the winter where precipitation is expected to increase. Impacts of changing precipitation may include riverine and sewer flooding, erosive rainfall events, increased number and volume of combined sewer overflows, and intensified generation of leachate at solid waste facilities.

Warmer summer temperatures paired with periods of low rainfall may cause low flows in the wastewater collection system which can lead to odours. A universal impact on all mechanically powered systems is the impact of high winds and freezing rain on power outages. Water and wastewater treatment facilities and collection and distribution systems all rely on power for operation. Disruptions may lead to reduced pressures in the water distribution system or untreated combined sewer overflows. Fortunately, the City of Ottawa maintains a number of back-up power systems including permanent and portable generators which can reduce the severity of power outages.

3.1.3 Buildings, Real Estate and Planning

Climate change will have a variety of impacts on the building, real estate and planning sectors. Most notably, energy demands are expected to shift seasonally, with heating requirements decreasing in the wintertime and cooling demands increasing during the summer months.

Building roof and foundation drainage systems may be impacted by increases in the frequency and intensity of extreme precipitation events. For new construction, climate change will influence future editions of the National Building Code of Canada (NBCC). Adaptation may involve raising building lots and selecting building materials that are designed to structurally withstand increased exposure to extreme weather conditions. Climate change may also impact planning and policy, particularly municipal development plans, urban growth strategies, stormwater drainage criteria, land-use planning, as well as master plans and strategic plans.

3.1.4 Transportation

The transportation sector (air, road and rail, public, and active transportation network) is vulnerable to damage and disruptions from a changing climate and extreme weather. This poses risks to all sectors of the economy and the user's quality of life (Palko and Lemmen 2017). Climate change will impact both:

- **Transportation Infrastructure -** Impacts for road infrastructure include flooding and washout, reduced vehicle traction, asphalt deterioration, road closures, and reduced visibility. Many of these impacts would also apply to urban public transportation systems, with the added impact of power outages.
- **Transportation Operations -** Climate and weather-related delays and disruptions to passenger travel could become more frequent in the future, particularly with the projected increase of freezing rain events in the winter. Redundancies in transportation systems (allowing multiple methods of travel) are one method to reduce these impacts.

A changing climate could bring potential opportunities to the sector such as longer construction seasons and a longer summer active transportation season.

3.1.5 Natural Assets, Tourism and Recreation

Changes in temperature and precipitation will have broad impacts on trees, forests, wetlands and other natural areas, as well as agriculture, tourism and recreation.

During hot summer months with low precipitation, vegetation can suspend growth until favourable conditions are reinstated. This process impacts trees, landscaping, and invasive species. It also affects agriculture, through a combination of potentially longer growing season with the added stresses of shifting seasons. New plant species may need to be investigated which are more heat tolerant and can withstand heavy ice loads or high wind gusts.

Conditions may be more favourable for invasive species and species may be at risk due to loss of habitat. Increases in invasive species and pests, such as ticks, may discourage hikers and recreational users of green spaces. As there are many health benefits from being active and enjoying the outdoors, awareness of simple protective and preventive measures will be needed.

Winter recreation is impacted by changes in snow generation and accumulation, ice formation, and temperature. Cross country skiing and snowshoeing in Gatineau Park, the Greenbelt, other ski areas (such as Mooney's Bay and SJAM skiway), as well as skating on community rinks in parks or on the Rideau Canal, generate immense value for locals, tourists and the economy. Snowmelt and rain-on-snow will affect spring freshet levels as well as the Rideau Canal Skateway ice thickness.

3.2 Riverine Flooding

Riverine flooding can occur on any watercourse in the NCR, and most notably along the Gatineau, Rideau and Ottawa rivers. The NCR has experienced significant flooding along these rivers, most recently in the spring of 2017 and 2019. Severe flooding along the Ottawa River also occurred in the 1920s, 1950s and 1970s (Ottawa River Regulation Planning Board - 2019 Spring Flood Frequently Asked Questions Bulletin, Oct 24, 2019).

There are many factors that contribute to flooding or flood risk, most of which are outside the scope of this study. Spring freshet flooding is primarily caused by rainfall and snowmelt. These, in turn, depend on the amount and duration of precipitation, mass of snow cover, and temperature fluctuations. Land use and cover are also factors, such as the amount of pervious areas in the watershed, or the presence of water regulating structures such as dams or reservoirs. River levels are also affected by the timing of the spring freshet, as more water flows into watercourses when the ground is frozen or already saturated. Ice jamming is another consideration, particularly on the Rideau River where seasonal ice clearing programs are implemented as a preventative measure.

The climate projection results presented in Chapter 2 provide information on how some environmental drivers of flooding (i.e., snow, rainfall, temperature) are expected to change in the future. However, riverine flooding is affected by changes in the entire watershed. Figure 3.1 depicts the extents of the Ottawa River watershed, which includes the Gatineau and Rideau River watersheds. The Ottawa River watershed is 23 times larger than the study area boundary, which represents the area covered by the projections presented in this report. In order to properly assess how changes to temperature, precipitation and snowpack may impact flooding, watershed-scale projections would be required.

Several flood risk management tools exist to protect people and property from flooding. Floodplain mapping is used to map areas along a river that are at risk of flooding under varied river levels. In the NCR, development is restricted in areas prone to flooding in a 1 in 100 year flow event; meaning a flood level that has a 1% chance of happening each year (based on historical flows). Additional flood risk maps can assess potential impacts of a less frequent, higher flow event, such as a 1 in 350 year event, to guide emergency planning and response. Many authorities are involved in flood risk forecasting, monitoring and warning in the NCR, including the Ottawa River Regulation Planning Board and Ontario's Conservation Authorities (see www.ottawariver.ca for more information).

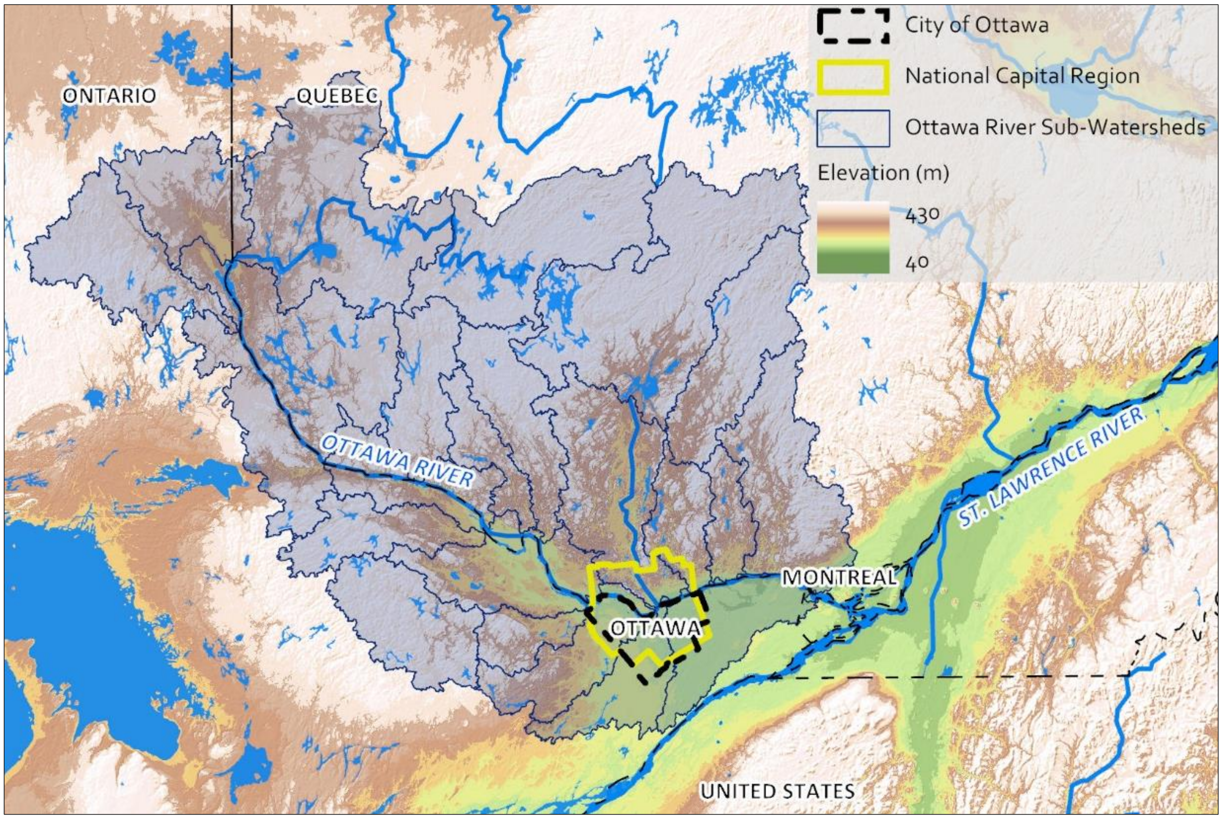


Figure 3.1: Ottawa River Watershed

Projecting the impacts of climate change on future riverine flooding would require complex riverine modelling that integrates factors such as land-use, soil type, topography, river bathymetry (land profile beneath the water's surface), and hydraulic structures (such as bridges, culverts, and dams). This is further complicated by the size of the Ottawa River watershed and the range of local, provincial and federal authorities involved. In the absence of comprehensive river modelling, alternate flood risk management tools should be considered.

3.3 Managing Uncertainty in Impact Assessments and Adaptation

The uncertainties associated with climate projections should be factored into, and not against, the use of future climate information. There is no one certain future for any given climate parameter, and therefore managing uncertainty through the application of the data over the full range (from lowest to highest future value) of the projections is recommended.

Climate data, including the data presented in this report, should be applied in risk and vulnerability assessments to support adaptation planning, impact assessments, and others. A risk assessment provides context over the full range of climate projections by factoring the probability of occurrence with the severity of the climate event. This process assists in determining what future scenario is appropriate for further application, such as:

- Adaptation planning.
- Resilience assessment.
- Health impact assessments.
- Design standards.
- Environmental assessments.
- Asset Management.
- Land use planning.
- Guidelines and best practices.

The most appropriate future scenario for a particular climate parameter may differ for each application of the data. This is due to the fact that each project, asset, program or service area has a unique relative risk tolerance and expected lifespan. For example, it would be too conservative to use temperature projections at year 2100 to assess the capacity of a cooling system that is expected to be taken out of service in the 2030s. It may however, be appropriate to use shorter term projections to assess the capacity of a project with a long-term planning horizon as the project will still experience changes over the short term. This is particularly true for projections which suggest an increase on the short-term and then a decrease in the long-term, such as for snow.

3.3.1 Sources of Uncertainty

There are several sources of uncertainty within the projections: natural variability, scenario uncertainty (i.e., which global emission scenarios will occur), and scientific uncertainty (including uncertainty from the models themselves and the post-processing of model output). The relative significance of these sources of uncertainty changes with the expected remaining useful life of the policy, program, or asset. Uncertainty related to natural variability is significant in the short term whereas predictions associated with each emission scenario diverge over the long term, lessening the significance of uncertainty associated with natural variability. Therefore, the relevance of each source of uncertainty depends on the time horizon of interest. Also, the confidence in temperature projections is typically greater than for other parameters such as precipitation or winds. Discussions on the sources of uncertainty are presented in APPENDIX A – *Climate Modelling Background* (Section A3).

Using an ensemble of climate models, as done with this study, characterizes uncertainty in climate projections. This uncertainty is then framed within the presentation of the data plots and graphs, for decision-makers to consider when using the climate projections. Uncertainty in climate projections cannot be avoided. The “best available information” is therefore obtained not based on the projections of one particular model, but rather from a comparison of the full range of projections.

3.3.2 Mitigating Uncertainty Through Risk Assessment

Decision-makers are already equipped to deal with uncertainty. Weather variability and extreme weather unpredictability is a fact that engineers, planners, health and emergency service providers, and policymakers have learned to accept and respond to appropriately.

A climate risk assessment is a method for identifying vulnerabilities through a function of severity (or consequence) and probability (or likelihood). They consider exposure, or who/ what is most vulnerable. Scoring these functions on a numeric scale allows for a quantitative comparison of various climate impacts to prioritize adaptation measures. There are various established methodologies available for climate risk assessments, such as the:

- Engineers Canada **Public Infrastructure Engineering Vulnerability Committee** (PIEVC) Protocol.
- **Climate Change Planning Tools for First Nations Guidebook 3** (Centre for Indigenous Environmental Resources (CIER), 2006).
- **Integrating Climate Change into Invasive Species Risk Assessment/ Risk Management** – Workshop Report (Government of Canada, 2008).
- **Envision** (Institute for Sustainable Infrastructure).
- **Tools for Climate Change Vulnerability Assessments for Watersheds** (CCMA, 2013).
- **Building Adaptive and Resilient Communities** (BARC) Program (ICLEI Canada, 2017).
- **A Practitioner's Guide to Climate Change Adaptation in Ontario's Ecosystems V1** (Province of Ontario and the Ontario Centre for Climate Impacts and Adaptation Resources, 2011).
- **Adapting to Climate Change: A Risk-based Guide for Local Governments V1 and V2** (Summit Enterprises International (S.E.I.) Inc., 2010).
- **Climate Change and Sustainable Forest Management in Canada: A Guidebook for Assessing Vulnerability and Mainstreaming Adaptation into Decision Making** (Canadian Council of Forest Ministers, 2015)
- Ontario Vulnerability and Adaptation Assessment Guideline under the **Climate Change and Health Toolkit** (Ministry of Health and Long-Term Care, 2016).

The Climate Risk Institute (https://climateriskinstitute.ca/) is an excellent resource for climate impact assessment tools. These assessment frameworks benefit from multi-disciplinary and multi-sectoral participation.

A team with climate projection expertise can filter the sometimes overwhelming volume of available climate information down to a short list of information that must be considered in the decision-making process. Climate scientists working with impact assessors can also provide guidance on the interpretation of climate projection data and plots to ensure that both the strengths and limitations in the climate information are properly accounted for. Ultimately the owner's tolerance for risk will play a central role in how uncertainty is dealt with, along with other non-climatic considerations such as economic, political, and social influences. Typically, decisions are not made based on climate projection information alone. Tools for quantifying cost-benefit, such as return on investment (ROI) or Loss Estimation Analysis (LEA) calculations can help to provide context for the overall project feasibility. Once climate change projections become one piece of a larger decision-making framework that focuses on practical applications, the overall uncertainty becomes less daunting.

Although it is generally easier to understand, ascertaining one value (typically the mean or median value) for future conditions that are selected from a range of possible futures is not advisable. This is because the selection of one number can imply a level of confidence and certainty that simply does not exist in projection modelling. Instead, a better way to represent future conditions could be to provide a range of values that characterize potential changes over a given timeframe. An example of this includes replacing headline statements such as "Temperature will rise by 5°C by the end of the century" with "Average annual temperatures are projected to increase between 3°C and 7°C by the end of the century". The range could represent the low-to-high estimates calculated from both moderate and high emission scenario projections for that time period and therefore is a quantitative representation of the uncertainty. This range of values provides decision-makers with a best- and worst-case scenario which may need to be accounted for in determining the preferred way forward.

3.3.3 Best Practices for New Infrastructure

For new infrastructure, in cases where it is practical to do so, using a low-regret design that accounts for the full range of climate projections can make a project more resilient to future climate and weather extremes. Low-regret actions are relatively low-cost design options to add climate resiliency. This includes:

- Basing plans/designs on the **most probable climate condition**.
- **Including flexibility** and/or additional safety factors for alternative courses of action should climate conditions deviate from the design basis.
- **Monitoring climate** conditions and project performance over time.
- Opting for adaptations that provide a clear **financial or social benefit** regardless of how climate changes in the future.
- Implementing design and construction **modifications** in response to observed changes.

For example, the City of Ottawa currently applies a 20% stress test to the peak rainfall intensity applied in the design of new sewer infrastructure. The 20% stress test may account for a suite of unknown factors such as climate change, future development, or unknown sources of inflow and infiltration. Going forward, the 20% stress test may be combined with the climate projections provided in this report. Particular care should be given to high-uncertainty situations (e.g., precipitation extremes). It is important that sensitivity testing and risk analysis make the best use of the information available.

Infrastructure design and asset management will be further guided by codes and standards that are currently being updated to include climate change. For example, changes to the National Building Code of Canada are expected to be introduced in 2025 to account for climate change. Methodologies presented in codes, standards, and best practices will provide great insight into the management of uncertainty in the application of climate projections for the design of infrastructure as well as programs and policies.

3.3.4 Implications for Adaptation

An adaptation strategy that accounts for the full range of potential outcomes is ideal; however, not always possible or feasible. Sensitivity analyses, a type of what-if analysis, applied to adaptation measures over the full range of potential outcomes is one way to measure resiliency to climate impacts. A sensitivity analysis assesses the response of a study subject to varying scales of future climate, such as monitoring the response of crop production to a range of future temperature projections. This is typically done using models that define the relationship between the climatic parameter and the test subject.

Acting on the best-case scenario over the short-term and leaving space for flexibility in the adaptation or policy, to be expanded or built upon at a later time, is another approach for managing uncertainty. As new information becomes available, and projection models improve, the strategy can be adjusted. For example, a land use approach to climate change adaptation could involve setting aside a percentage of green space for community use. According to the Food and Agriculture Organization (FAO), the strategic placement of trees in cities can help urban communities adapt to the effects of climate change by acting as a wind break and providing cooling. Urban tree planting may also reduce peak stormwater runoff on undeveloped properties. In the future, if the green space isn't required for climate change adaptation, it could be developed at that time to support another need.

Evolving uncertainty in climate projections should be used to balance the costs and potential consequences of failure. Notably, for critical infrastructure, an engineering-economic evaluation of costs and benefits of adaptation measures should be done, with emphasis on the highest risks to help planning efforts.

For projections where a confident trend cannot yet be recognised, or where studies show conflicting results (such as for wind), monitoring advancements in the science more closely are recommended. Based on currently available information, proactive planning for potentially higher wind gusts should be considered.

3.4 Responding to Changes in the Science

Improvements in the scientific community's understanding of climate processes, the development of models, and an increase in computational power are ongoing. APPENDIX A – *Climate Modelling Background* (Section A4) describes some of the anticipated changes in the coming years, including a new generation of models (CMIP6) that should be available in 2021. The capacity of models to represent multiple climate and ocean processes has significantly improved since the 2000s. As models continue to resolve a higher number of processes more accurately, new datasets, better post-processing of climate projections (e.g., downscaling), and new data portals will become available.

When new models are published, the projections in this report should not be presumed outdated without comparison and review. Climate science is fast-moving and uncertainties in climate data, such as GHG emission trends, are evolving. For this reason, it is worthwhile to monitor new projections and compare them to the results presented within the report on a case by case basis. If new projections differ substantially from those presented in this report, revisiting the risk assessment or adaptive capacity of infrastructure, policies, or programs may be warranted. For most parameters, new models are not anticipated to drastically change the trends presented in this report.

There are some sources of uncertainty that are "irreducible" (e.g., uncertainty due to natural climate variability) and will not be eliminated by new climate models. Many impact and risk assessments do not directly apply precise climate information, but rather interpret and act on trends that are less likely to change drastically. For this reason, risk and impact assessments should not be automatically presumed to be outdated when data becomes available as new data may not change the outcome of the assessment.

Regular review of the projections is good practice, this can be done, for example when the new Climate Model Intercomparison Project (CMIP) framework is updated, new RCP scenarios are defined, or when other significant advancements in the climate science are achieved. The data portal ClimateData.ca facilitates access to climate information from various sources for a range of audiences, from the general public, the media, policy analysts, and decision-makers, as well as researchers and scientists. It is expected to be updated as new information becomes available. Future updates would include for example (but are not limited to) the sixth phase of the Climate Model Intercomparison Project (CMIP6) along with the IPCC 6th Assessment Report (Physical Science Basis), which is expected to be released in April 2021. For details on these updates please see Appendix A4 – Climate Modelling Background.

Chapter 4 Conclusion

This study presents projected climate changes in the National Capital Region. It provides the data required to assess the impacts of climate change on multiple sectors and guide climate adaptation and resiliency planning.

It is projected that the NCR will become warmer in all seasons, and wetter during fall, winter and spring. It is expected that the timing of seasons will shift, with later fall and earlier spring. Periods of extreme heat will become more common. Winters are expected to become shorter, with less snowfall. Precipitation is expected to increase, both in volume and intensity. Although uncertainty remains high, the occurrence of extreme weather such as tornadoes, lightning, extreme wind, hurricanes, and wildfires may increase.

The localized climate projections provided in this report can support proactive planning and action in the NCR. Communities and stakeholder groups in the NCR are encouraged to use the results to understand and prepare for future climate conditions.

In the future, as climate science evolves and new data or models become available, the projections in this report should be reviewed to determine if updates are required. While for most parameters, new models are not anticipated to drastically change the trends presented in this report, new projections should be monitored to assess for risk implications.

APPENDIX A – Climate Modelling Background

The purpose of this appendix is to provide high-level background information on several of the climate science concepts mentioned in the main report. Additional detail can be found in the reports of the Intergovernmental Panel on Climate Change (e.g., IPCC 2013).

A.1 Climate Models

Global Climate Models (GCMs) represent the planet by dividing the earth into cells that are approximately 100–300 km wide. Regional (or local) projections are sometimes required to complete a climate impact assessment. Because GCM projections are coarse (large grid size), they require dynamical or statistical downscaling to obtain regional projections.

Statistical downscaling uses statistical relationships between local climate variables and large-scale predictors, which are then applied to GCM outputs to approximate local climate projections. Statistical downscaling is typically less time-consuming but more simplistic than dynamical downscaling.

Dynamical downscaling uses **Regional Climate Models (RCMs),** which are driven by outputs of GCMs. RCMs are higher-resolution (smaller grid size) and include more detailed information on regional conditions (e.g., mountains or water bodies) in accordance with physical laws and mathematical equations, which increases accuracy.

Spatial resolution is important for some processes to be properly modelled. Precipitation, for example, is better resolved with higher resolution models. The resolution of GCMs is too coarse to properly resolve certain processes, which is why downscaling is required (statistical downscaling or dynamic downscaling with RCMs). RCMs generally have 10-50 km resolutions as displayed in Figure A1.

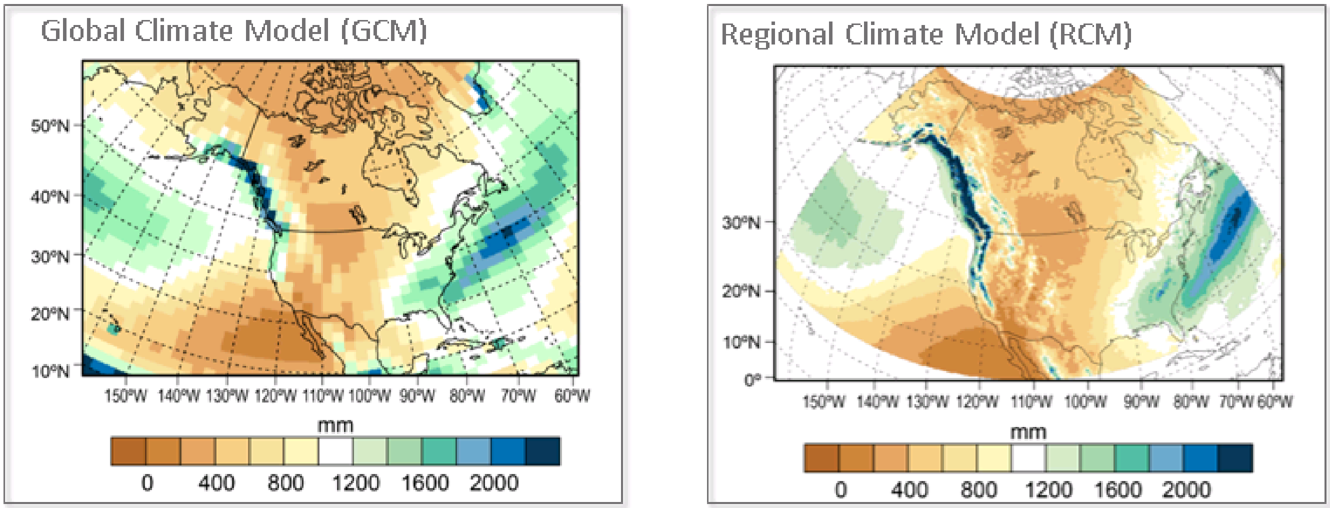


Figure A1: Compared Precipitation Output Field of a GCM (Left) and an RCM (Right) Over a Similar Area of North America – Note the Difference in Spatial Resolution, i.e., Granularity (figure from https://science2017.globalchange.gov/chapter/4/)

The output from GCMs consists of **parameters** like temperature, precipitation, humidity, snow, and wind. **Indices** are then calculated from these parameters so that projections can be applied to determine the overall likelihood of occurrence. The process of applying a risk lens, through the assignment of probability, is a process for dealing with the inherent uncertainty of model predictions (see Section A3 on Sources of Uncertainty below). Some models favour certain processes over others, and therefore the models themselves are a source of uncertainty. The capacity of models to represent multiple climate and ocean processes has significantly improved since the 2000s, as represented in Figure A2. As models continue to resolve a higher number of processes more accurately, the quality of model outputs will also improve.

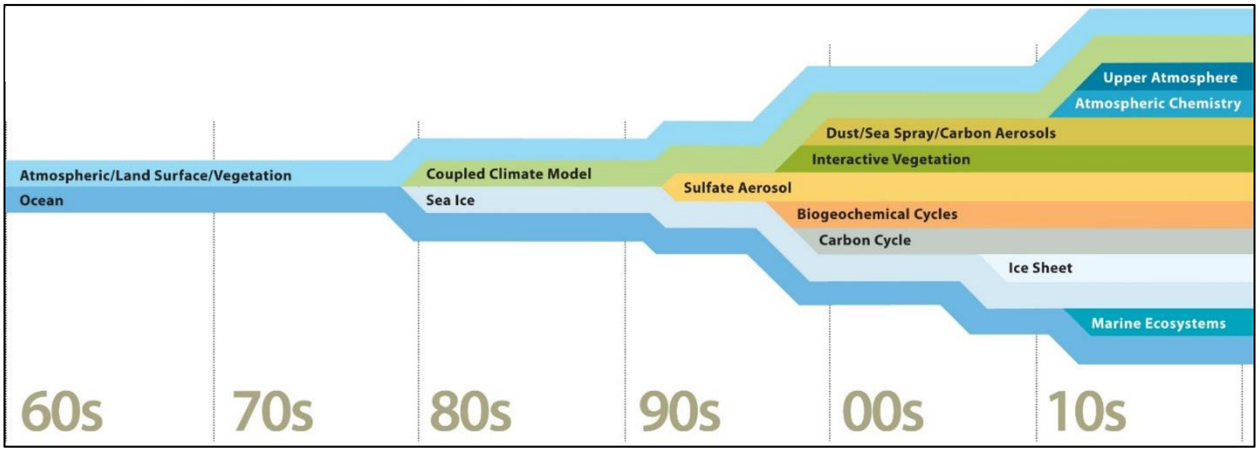


Figure A2: Growth of Processes Included in Climate Models (figure from https://news.ucar.edu/sites/default/files/news/2011/predictFlow2.jpg)

A.2 Projection Horizons

The study baseline is 1981–2010. The three projection horizons, or time slices, that were selected for this study are:

- 2030s (2021–2050).
- 2050s (2041–2070).
- 2080s (2071–2100).

Climate change projections are typically averaged over 20-year or 30-year means in order to smooth out shorter-term changes in the climate caused by natural variability. The 30-year means used in this study are consistent with those used by Environment and Climate Change Canada (ECCC), although not with the Intergovernmental Panel on Climate Change (IPCC) 2013 (where 20-year means were used). In order to use the 30-year means, the baseline had to include the 5-year period of 2006–2010 that is technically part of the "projections", i.e., under the influence of an emission scenario. However, the emission scenarios are considered to have minimum influence on the model outputs for such a short period and it was deemed acceptable to use 1981–2010 as the baseline.

The 2030s (2021–2050) were selected instead of the 2020s (2011–2040) because the 2020s "projection" is confusing for readers because it straddles the present day. It was considered more straight-forward to keep all projection horizons in the future.

The lead times for these projections horizons (10, 30, and 60 years from now) were selected to reflect the planning horizons of impact studies and risk assessments in various sectors (policy, program development, infrastructure rehabilitation and design, etc.). For example, a 30-year lead time is often used in policy planning. The projections could not be extended beyond 2100 because most currently available models have simulations that end in 2100.

In summary, **the projection horizons were selected for maximum comparability with other work**, including the use of standardized time slides where possible (e.g., the 1981–2010 baseline corresponds to ECCC Climate Normals), consistency with other resources available nationally (e.g., Climate Atlas of Canada, Climatedata.ca), and previous and ongoing projects in the region (Public Services and Procurement Canada, Ville de Gatineau, and Hydro Ottawa).

A.3 Sources of Uncertainty

The climate projections produced as part of this project have several sources of uncertainty:

1. **Internal variability** – There are unpredictable natural fluctuations in the climate system that occur even without any changes in greenhouse gas concentrations. Some of this uncertainty is considered "irreducible" (i.e., chaotic) and cannot be removed from climate projections (even with future generations of models).
2. **Scenario uncertainty** – The evolution of greenhouse gas emissions is highly uncertain. It is not considered possible to determine the likelihood of the different emission scenarios. The use of more than one emission scenario mitigates this uncertainty by presenting a range of possibilities.
3. **Scientific uncertainty** – Although climate models are the best tools available to study projections, there is inherent uncertainty in predictive models. Bias correction[1] and statistical downscaling processes are affected by uncertainties in the observation datasets used and uncertainties in the statistical transformations. They rely on assumptions that the corrections made will still hold in the future (this is called the "stationarity assumption"). Lastly, some climate parameters are predicted with more confidence than others. For example, predictions of wind speeds are highly uncertain at present.

The relative importance of each source of uncertainty depends on the timescale considered. Figure A3 (adapted from Hawkins and Sutton 2009) shows how different sources of uncertainty change over time. Note that total uncertainty increases with time, but this figure shows the relative importance of different uncertainties. Over the timescale of a few decades, natural variability dominates and can even hide the climate change signal in the short term. However, over longer time horizons, the choice of the emission scenario becomes very important. The model uncertainty remains fairly large irrespective of the timescale over which decisions are made (Charon 2016). Sources of uncertainty depend on the geography, climate, and variable being projected.

---

[1] The correction of the raw climate model output using the differences between model and observations over a reference period (typically the baseline)

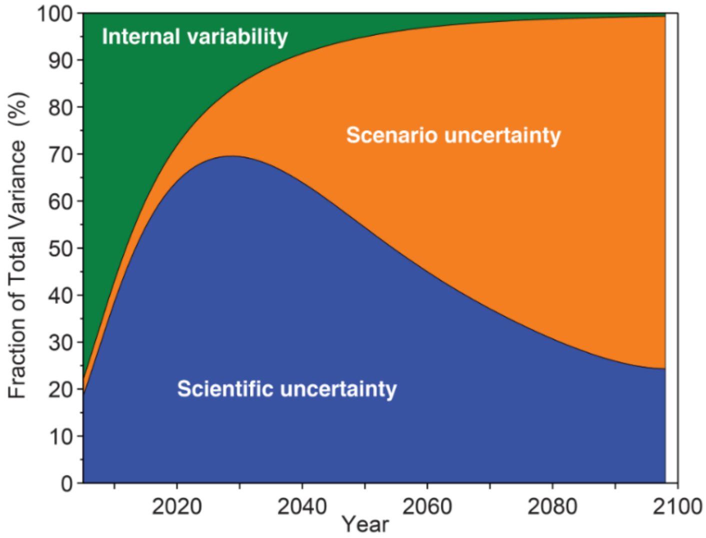


Figure A3: Expected Relative Contribution of Uncertainty Sources in Climate Modelling Over Time (Adapted from Hawkins and Sutton 2009)

A.4 Future Improvements to Models and Methods

The sixth phase of the Climate Model Intercomparison Project (CMIP) project is already ongoing (simulation period 2017–2020; Eyring *et al*. 2016), and **the IPCC 6th Assessment Report (Physical Science Basis) is expected in April 2021**. Emission pathways for the CMIP6 future climate projections will update the four RCP scenarios from CMIP5, to fill the gaps that have not previously been studied by the RCPs. There will also be a new version of the Coordinated Regional Climate Downscaling Experiment (CORDEX), and a newly created High-Resolution Model Inter-comparison Project (HighResMIP).

The main improvements that will come with future generations of models are increases in spatial resolution (made possible due to an increase in computing power). Climate models are also incorporating more and more processes and reduce systematic biases, and there will be more models available, forming a larger ensemble (11 new modelling groups in CMIP6). Improvements in CMIP6 include better representation of aerosols, cloud processes, and ice sheet feedbacks.

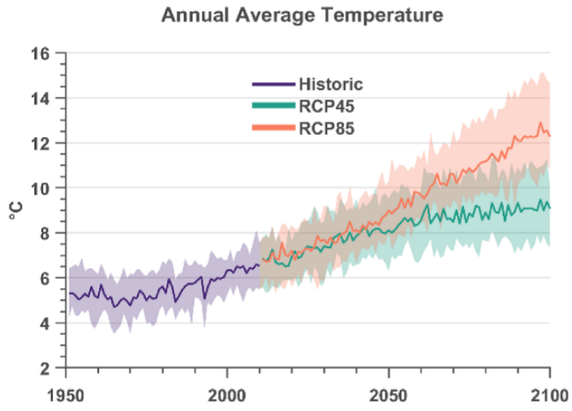
However, some processes will remain very difficult to represent in models, and some will still be smaller than the grid resolution (e.g., cloud microphysics). Lastly, uncertainty will remain from natural variability ("irreducible uncertainty").

APPENDIX B – Guidelines to Reading and Interpreting the Plots

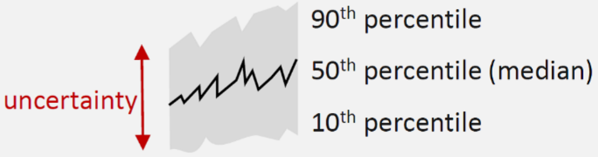
The purpose of this Appendix is to provide a guideline on the reading and interpreting of the various plot types used in this report.

Timeseries plots are mostly used to show change of a continuous variable over time (but can also show discrete variables, e.g., # days over time).

(1) Timeseries Plot with 10th, 50th (median), and 90th Percentiles

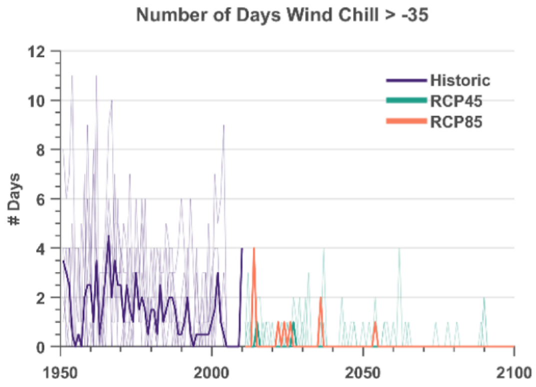


These plots are used when there are a large number of models available for a given index.

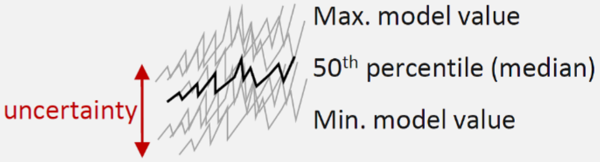


Colors represent various climate scenarios.

(2) Timeseries Plot with Individual Lines



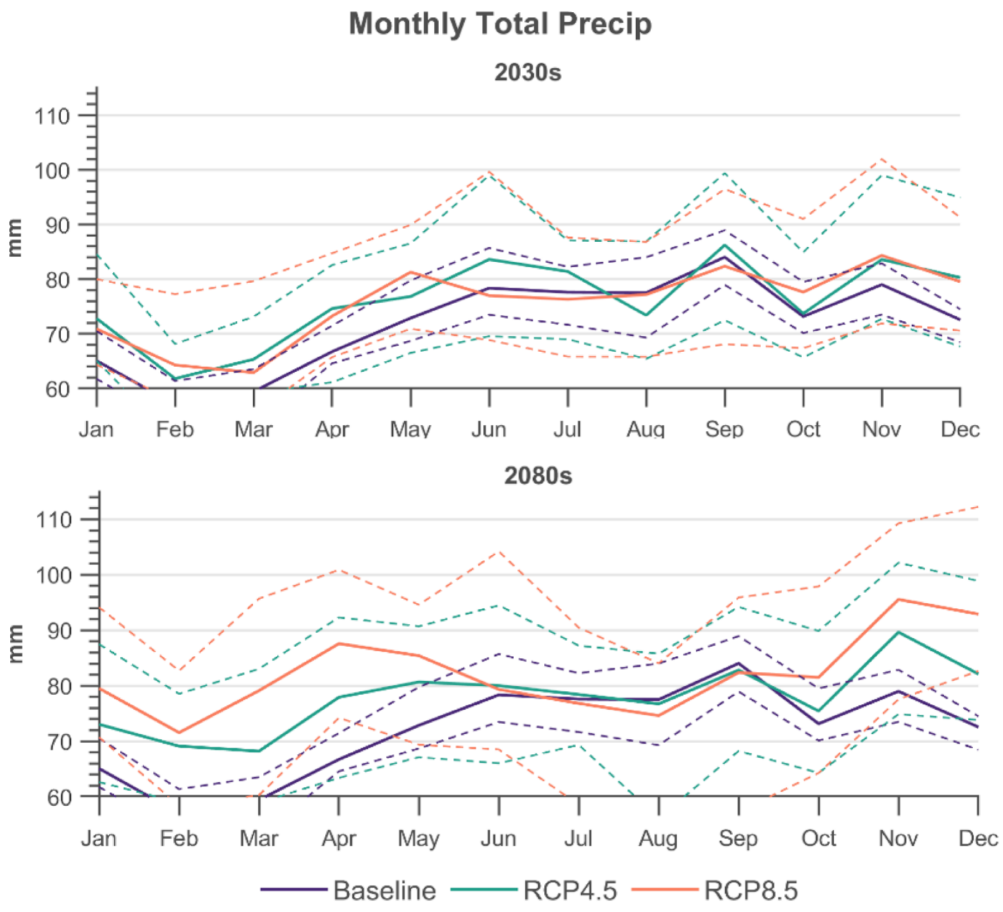
If there are fewer models available for a given index, the 10th and 90th percentiles cannot be calculated. Instead, the timeseries can be shown with individual lines for each model.

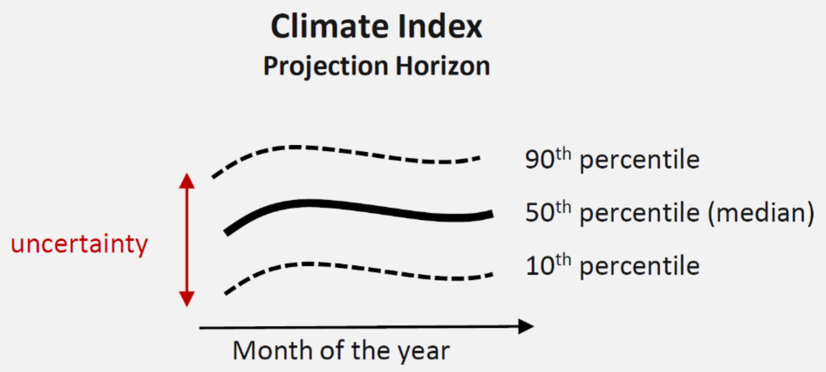


Colors represent various climate scenarios.

Monthly change plots are used to investigate whether climate projections are different for different months of the year.

(3) Monthly Change Plot

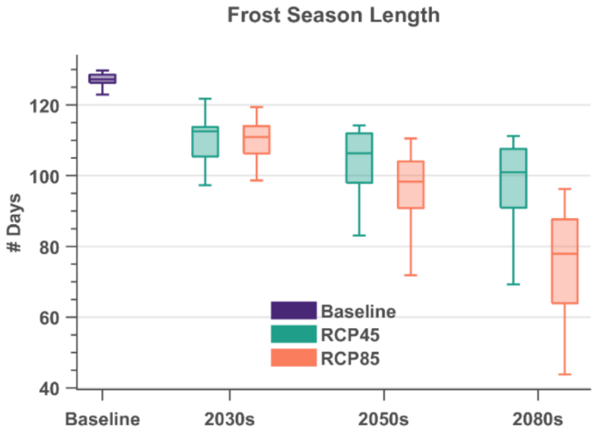




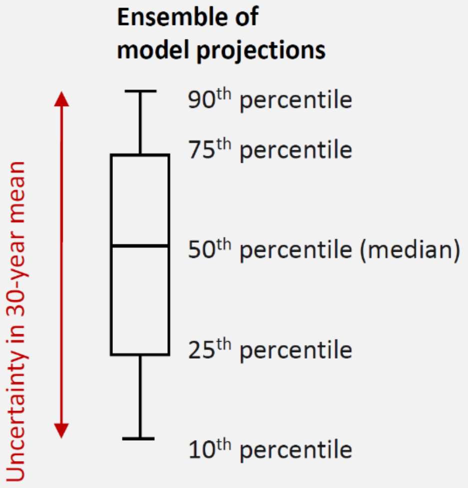
Colors represent various climate scenarios. The baseline is shown on each plot for reference.

Box plots are used to show 30-year medians and the range of results from the modelling ensemble.

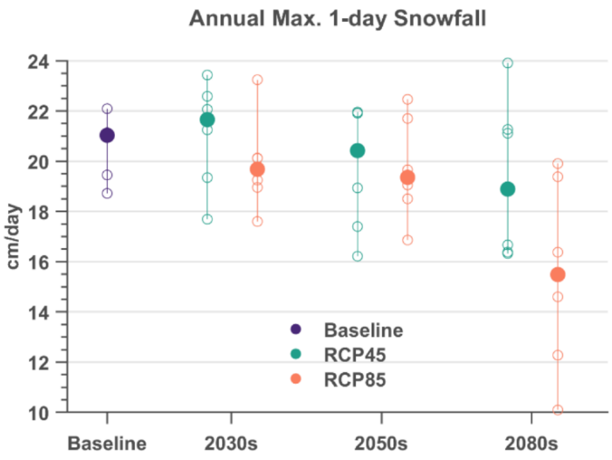
(4) Box Plot with 10th, 50th (median), and 90th Percentiles



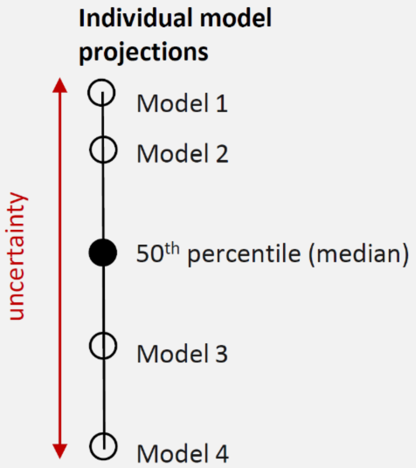
These plots are used when there are a large number of models available for a given index.



(5) Box “Point” Plot with 50th (median) and Individual Models



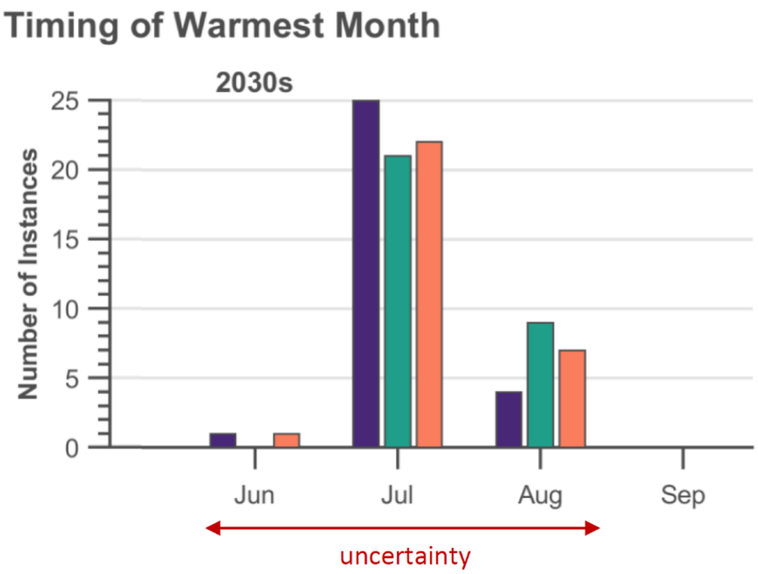
If there are fewer models available for a given index, the 10th and 90th percentiles cannot be calculated. Instead, the projections are shown with a circle for each individual model.



The 10th, 50th, and 90th percentiles of the box/point plots and timeseries plots are not equivalent. For the box/plot plots, 30-year means are calculated first. Therefore, the box/point plots represent a range of values for 30-year means, whereas the timeseries represent a range of values for a given year.

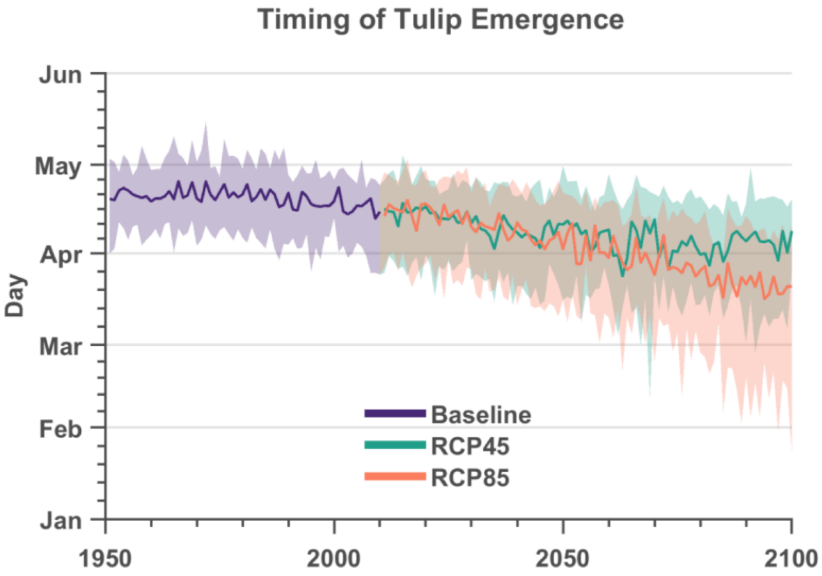
Timing plots are used to show the month or day at which a given index occurs.

(6) Timing Plot (Monthly)



A Timing Plot (Monthly) shows the number of models that selected a given month. The most probable month is the one with the largest bar (largest number of models).

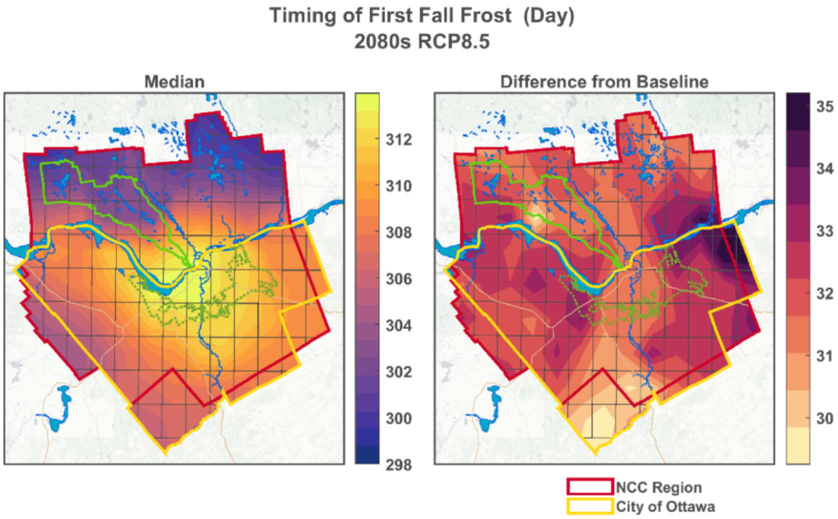
(7) Timing Plot (Daily)



A Timing Plot (Daily) is similar to a timeseries plot, except that the vertical axis shows a time of the year instead of a quantity.

Maps are used to show the spatial variation in projections.

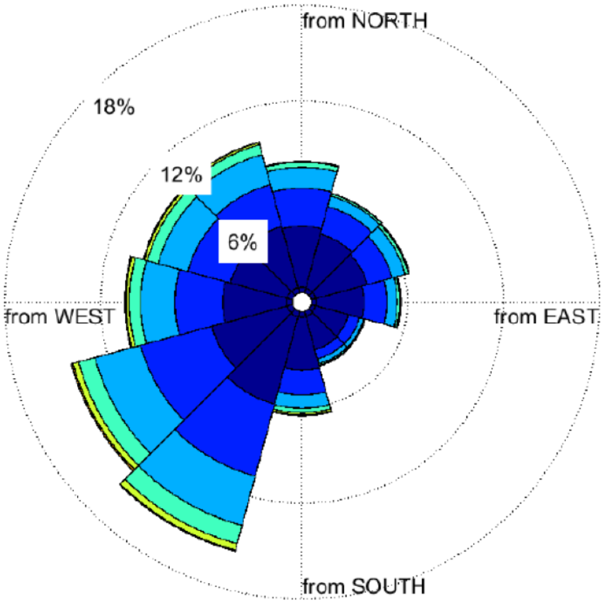
(8) Map



Note that colour scales differ from map to map (e.g., different RCP) in order to emphasize geographic variation.

Wind Roses are used to show a distribution of wind speeds and directions.

(9) Wind Rose



The circle is divided into 12 cardinal directions.

The length of each spoke from the center of the circle represents the frequency that the wind blows in that particular direction (% of time).

Wind speed scale

V [m/s]	[km/hour]
🟫 15 - Inf	> 54
🟥 13 - 15	47 - 54
🟧 11 - 13	40 - 47
🟨 9 - 11	32 - 40
🟩 7 - 9	25 - 32
🟦 5 - 7	18 - 25
🟦 3 - 5	11 – 18
🟦 1 - 3	3.6 - 11
🟦 <1	<3.6

APPENDIX C – Methodology

The purpose of this Appendix is to provide additional background on selected topics from the methodology presented in Chapter 1 of the report.

C.1 – Selection of Climate Indices

C.1.1 – Climate Science Considerations

One goal for the selection of indices was to obtain a full characterization of the future climate system. This requires not only a measure of average trends but also a range of different types of indices in order to represent:

- Minima and maxima;
- Extreme values (e.g., 1 in 100 year 24-hour precipitation intensity);
- Counts of instances below or above a threshold (e.g., number of days where the maximum daily temperature is less than 0°C);
- Timing indices (e.g., the start of the tulip season);
- Duration indices (e.g., the maximum length of wet spells);
- Indices with multiple requirements on a single parameter (e.g., freeze-thaw cycles, with requirements on both daily temperature minimum and daily temperature maximum);
- Combined indices with requirements on two climate parameters (e.g., winter precipitation and high winds).

Standardized climate indices from the literature were considered, in particular, the 27 "Climdex" indices from the Expert Team on Climate Change Detection and Indices (ETCCDI). These indices were conceived to enable comparisons across different regions. Some of these indices are relative thresholds (e.g., the percentage of daily temperatures above the baseline 95th percentile, calculated on a moving window). These relative thresholds facilitate proper statistical characterizations that enable cross-comparisons of changing climates across various regions but are not typically used in impact studies, where absolute thresholds are considered more intuitive (e.g., the percentage of days above 30°C are used instead). Thus, ETCCDI indices were used only where it made sense to do so within the overarching objectives of this study. In several cases, region and impact-specific indices were favoured.

C.1.2 – Impact-Driven Considerations

Impact-specific considerations were determined based on high-level research across a broad range of sectors, as well as through engagement with NCC and City of Ottawa staff.

High-level research was conducted using the following sources of information:

- Research on impact studies in relevant fields (e.g., vector-borne diseases, agriculture, mechanical systems, fires, regional flooding mechanisms) including best practices in relevant climate vulnerability assessments and resiliency planning.
- Environment and Climate Change Canada (ECCC) weather warnings (extreme precipitation, snowfall, cold, heat).
- National Building Code of Canada (2015).

- Emergency Management Ontario 2019 Hazard Identification Report and Methodology Guidelines.
- Global Covenant of Mayors for Climate and Energy.

A working list of parameters and indices that could be used by stakeholders for future risk and vulnerability assessments was developed based on input and discussions with staff from the NCC, the City of Ottawa and the Ville de Gatineau.

Once the preliminary list of parameters and indices was developed, a half-day workshop was held on July 9th, 2019 to gather input from a broader group of stakeholders and refine the list of proposed indices. Over 60 people participated in the workshop, largely staff from the NCC and City of Ottawa, as well as representatives from the Ville de Gatineau, regional Conservation Authorities, and the Canadian Center for Climate Services (CCCS). The workshop included a series of presentations to provide background material on climate change projections and indices. Next, the attendants were separated into five groups based on sectors to identify climate processes and impacts relevant to their sector and identify indices that would be useful to them in future risk and vulnerability assessments.

C.1.3 – Other Considerations

The following were also considered:

- Where possible, indices were selected to enable consistency and comparison with previous and ongoing projects in the region (e.g., projects by Public Services and Procurement Canada, Ville de Gatineau, and HydroOttawa).
- Indices from example projects in other cities were reviewed (e.g., Durham, Waterloo, and Metro Vancouver).

C.2 – Computation of Climate Projections

C.2.1 – Data Sources

After establishing the list of climate indices and projection horizons, the next step was to identify appropriate sources of climate information. There are many sources of climate data and projections available, including global and regional climate models, and bias-corrected as well as raw outputs, each having advantages and disadvantages.

The sections below outline the criteria used to select the sources of climate information, and the list of sources used. Some were downloaded from web portals, some provided by CCCS (e.g., Université du Québec à Montreal, INRS models), some acquired from ECCC (e.g., historical hourly precipitation), and some provided by University of Prince Edward Island Climate Lab (PRECIS).

Some of the projections were obtained and analysed as grids (the GCMs, which were downscaled to 10 km) and others (the RCMs, with spatial resolutions of 25-50 km) were area-averaged as there were only a few grid cells that spanned the project area.

Historical Data

Information on the historical climate in the NCR was obtained from ECCC climate stations and a City of Ottawa report from 2011 ("Characterization of Ottawa's Watersheds"). See Chapter 2 for additional information.

Emission Scenarios for Model Projections

Climate models are driven by different emission scenarios, or "Representative Concentration Pathways" (RCPs). See Chapter 1 for additional information.

Gridded Downscaled Global Climate Models (GCMs)

The primary source of climate projections used was statistically downscaled GCM data with a spatial resolution of 10 km. The GCMs consist of 24 models from the CMIP5 that were downscaled using the Bias Correction/Constructed Analogues with Quantile mapping, version 2, (BCCAQv2) algorithm (Werner and Cannon 2016). The models were corrected with observed gridded daily datasets of minimum temperature, maximum temperature and precipitation (McKenney *et al.* 2011) over a 1951–2010 historical reference period.

The advantages of this data source are the 10 km resolution and 24 models in the ensemble. This is important as:

- Some climate parameters can only be predicted at a higher resolution (for example convective storms which cause intense precipitation). GCMs that are not bias-corrected have grid cells that are typically hundreds of kilometres wide, which is too coarse for resolving some important phenomena. Even the 50 km grid cells of most RCMs remain coarse relative to smaller-scale processes such as convective storms.
- An ensemble of models (in this case, 24) is a method of characterizing uncertainty. There are several major sources of uncertainty in climate modelling, including natural variability, emission scenarios, and inter-model variability. For this reason, the IPCC recommends in their most recent Fifth Assessment Report (AR5) that an ensemble or range of models be considered, because individual models may be less accurate on their own.

A statistically downscaled dataset is constrained to variables for which there are good observational records (temperature and precipitation). Therefore, only indices based on daily or monthly variables for temperature and precipitation were calculated from this data source; indices requiring hourly resolutions or other climate parameters (humidity, snow, wind) were based on RCMs (discussed below).

Gridded Regional Climate Models (RCMs)

RCMs were used to project sub-daily time steps (e.g., hourly, 12 hours) as well as parameters other than temperature and precipitation such as humidity, snow, and wind. Different sources of RCMs were used in order to compare as many models as possible in the small ensemble, including:

- **CORDEX/UQAM**. RCMs were used from the North American Cordex Program. Several simulations with resolutions of 25-50 km are available publicly on the NCAR Climate Data Gateway. In addition, ECCC obtained permission from UQAM to use sub-daily wind and precipitation outputs from the fifth-generation Canadian Regional Climate Model (CRCM5; Hernández-Díaz *et al*. 2019, Šeparović *et al*. 2013).

- **ECCC**. The regional model CanRCM4 is a CORDEX member, but in addition, the ECCC website makes available additional parameters not available on the NCAR web portal. For instance, daily solid precipitation and daily snow depth were obtained for CanRCM4 from the ECCC web portal.
- **INRS/Ouranos**. Permissions were obtained for this project to use indices of solid precipitation and snow depth developed for the ArcticNet project by ETE-INRS in collaboration with Ouranos Consortium on Climate Change (Diaconescu *et al*. 2017, Mailhot *et al*. 2017, Chaumont *et al*. 2017).
- **University of PEI**. Projections from the regional climate model "Providing Regional Climates for Impact Studies" (PRECIS) under moderate (RCP 4.5) and high (RCP 8.5) emission scenarios were obtained from Dr. Wang at the UPEI Climate Lab. These were compared with the other RCMs.

Literature

For the remaining parameters that are not readily available in GCM or RCM outputs (see section labelled "Other Events and Extreme Indices" in the list of indices), information was obtained through limited reviews of both peer-reviewed literature (scientific articles) and grey literature (e.g., government reports). Variables such as the occurrence of lightning or freezing rain cannot be accurately modelled due to limitations of the current process understanding, natural variability, or computation capabilities.

Summary

In summary, the following sources of data were used:

	GCM (CMIP5 BCCAQv2)	RCM (NACORDEX, PRECIS)	Literature
Daily Temperature and Precipitation	x		
Daily Snow and Humidity		x	
Daily & Sub-daily Wind Sub-daily Precipitation		x	
Combined Parameters	x (combinations of temperature and precipitation only)	x	
"Other Parameters"			x

C.2.2 – Bias Correction

Although climate models are the best tools currently available to study future changes in climate parameters, they still have significant biases. Biases vary depending on the model, location, and time, whereas others are systematic across models (e.g., caused by the inability to represent convective processes when the spatial resolution is coarse). Bias correction consists of correcting raw climate model outputs using the differences between model and observations over a reference period (typically the baseline).

The GCM dataset used for this project was already downscaled/bias-corrected using the BCCAQv2 method. However, the RCM projections obtained for this project were not bias-corrected. It has been demonstrated that bias correction can lead to the generation of "artifacts" (anomalies or errors resulting from the modelling or data processing; Maraun 2016). In addition, bias correction of daily data does not necessarily ensure that indices calculated from this data are properly corrected. Nonetheless, it has generally been shown that model projections are improved with most forms of bias correction, including mean-based approaches and distribution-based approaches that perform better (e.g., Maraun 2016). Distribution-based bias correction (quantile-quantile mapping) was therefore conducted for the RCMs. It is noted that multivariate bias correction would have been ideal but was outside the scope of the project due to the level of effort required.

The following sections provide a technical summary of the bias correction methodology used.

Area Averaging

The RCM projections have grid cells of 25 km or 50 km spatial resolution, which means that there were only a few grid cells within the approximately 80 km by 80 km study area. Therefore, a weighted area-average was applied to the grid cells which overlapped with the study area. The bias correction was then applied to this area average. The exception is for extreme hourly precipitation, where the bias correction was applied to a single grid cell, at the location of the Ottawa airport. This was to minimize smoothing to extreme precipitation for these indices. These distinctions are important for the interpretation of the results: the snow, humidity, and wind projections represent averages over the study area that have been downscaled to a point location (e.g., Ottawa Airport).

Quantile-Quantile Mapping

Observations from the Ottawa MacDonald-Cartier Airport were used to conduct empirical non-parametric quantile-quantile mapping to bias-correct all RCM projections except the INRS dataset (see below). Transfer functions were computed for each model, parameter, and month separately. Validation of the method was conducted with a split-sample cross-validation using as many years as possible from the baseline time slice (1981–2010), with Root Mean Square Error (RMSE) and bias to assess the goodness of fit. For precipitation-based indices (including solid precipitation), the validation of the bias correction was done in two steps, by first correcting the frequency of wet days (> 1 mm).

The following is an example of the bias correction validation plot for daily relative humidity, with the training dataset shown in the left frame and the validation in the right frame.

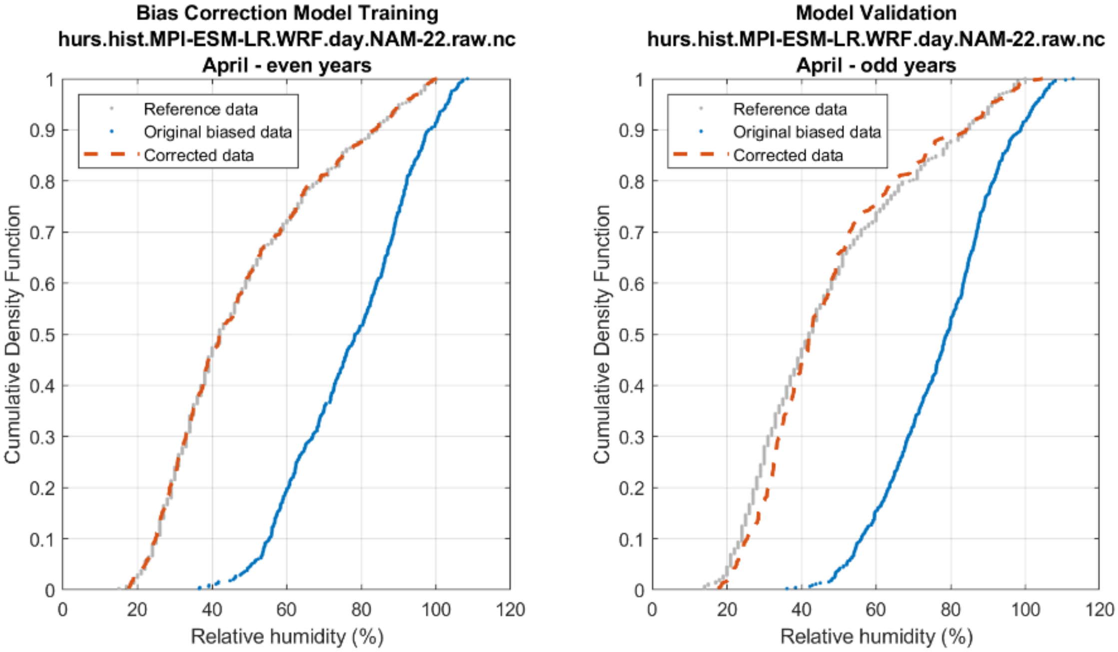


Figure C1: **Example of Bias Correction (Left – Training Dataset) and Validation (Right – Validation Dataset) for Relative Humidity**

Delta Method

While most RCM data was available as a time series of daily or sub-daily projections, the INRS dataset was already calculated into annual and monthly indices, and the raw data was not available. Therefore, for this dataset only, the bias correction was applied after the indices were calculated, on the 30-year averages, using the delta method. The delta method consists of adding the average difference (delta) between historical observations and a model results over the same period to future model projections. Validation of the method was also conducted with a split-sample cross-validation, using RMSE and bias to assess the results of the correction.

Uncertainties and Assumptions of Bias Correction

Bias correction makes a major assumption that the corrections applied in the historical period will still apply in the future. However, it is possible that the statistical distributions of climate parameters may change as climate processes shift.

In addition, the bias correction applied is only a statistical method, and it doesn’t correct the underlying physics of the models.

That said, although not perfect, bias correction does improve the models. We found the distributions to be particularly problematic for snow, for example, but overall the bias correction helped with a general underestimation of snow in the models, which would have been unrealistic if it had been shown without any post-processing.

Nonetheless, the climate projections must be interpreted within the context of uncertainty and the underlying assumptions.

Considerations for Specific Parameters

Snow projections were obtained from multiple sources, either as solid precipitation, snow water equivalent precipitation, or snow cover. The following conversions from snow to water were used:

- Density of falling snow of 100 kg/m^3.
- Density of snow on ground 250 kg/m^3.

These convections were based on Shook and Grey (1994; values from Southern Saskatchewan), Adams (1976; East Central Ontario), and personal communication with Dr. Emilia Diaconescu and Dr. Ross Brown (ECCC, 2019).

Bias corrections for **wind** were applied to each direction separately. Wind projections are challenging to bias-correct and no approach for correcting directions from the literature has shown perfect results.

Bias correction of daily **humidity** was done using a time-series of hourly humidity at the time of hourly maximum temperature. Therefore, the bias correction also served as a transfer function between average daily humidity and daily humidity at the time of maximum temperature. The purpose was to improve the calculation of humidex projections.

C.2.3 – Computation of Indices

Extreme value analyses were conducted on each grid cell separately using Generalized Extreme Value (GEV) for precipitation (fitting with maximum likelihood), and Generalized Pareto Distribution (GPD) for wind.

Humidex was calculated using approximate projections of humidity at the time of hourly maximum temperature (see bias correction method above).

Wind chill was calculated using daily mean wind speeds.

Snow melt was approximated based on projected snowpack (on days when the snow depth decreased from one day to the next).

C.3 – Communicating Findings

Once all of the required indices were determined and the climate projections were obtained, the next step was to calculate the indices based on multiple models and multiple sources and represent them together on the same plots. The purpose is to use a range of index projections (including the 10th and 90th percentiles) to characterize uncertainty. A processing toolbox was developed for this study to accurately derive indices and make various plot types (time-series, box plots, wind roses, spatial distribution maps, etc.).

APPENDIX D – Technical Review of Methods for Extreme Precipitation Projections

Background

In this report, precipitation extremes are defined as having a return period of greater than 1 year. These extremes are particularly challenging to project. Therefore, although other indices are addressed with a single ensemble, for extreme precipitation it is better to compare ensembles from several approaches. There is no uniformly accepted method and approach for projecting future extreme precipitation, and in Canada alone there have been 5-10 different methodologies used (Coulibali *et al*. 2016, Switzman *et al*. 2017, CSA 2019).

Therefore, the purpose of this appendix is to provide:

(1) A technical background on the **strengths and limitations of existing approaches** for estimating future extreme precipitation. The primary methods (including those used in this project) are addressed in the sections below, and additional approaches are summarized in Table D1.

(2) A **summary of findings from multiple methods** is presented. Findings based on the primary methods are compared in Figure D1 and Figure D2, and additional findings are summarized in Table D2.

The purpose of this appendix is not to provide values that can be used directly in design or adaptation projects. A vulnerability/impact assessment and/or risk assessment (Phase 2) is needed to determine which values to use from the range of projections provided (see Chapter 3).

Why are precipitation extremes difficult to project?

Extreme precipitation (in particular sub-daily) can result from processes at very small scales. Convective updraft cores can be only a few hundred metres to a few kilometres across (Westra *et al*. 2014). Since GCMs have grid cells of 100-300 km, they need to use parameterizations to compute average convection over model grid squares. Therefore, these parameterizations are not designed for realistic rainfall (Westra *et al*. 2014).

Larger-scale processes (e.g., jet stream, teleconnections, and temperature gradients) are also important for precipitation extremes (Trenberth *et al*. 2003, O'Gorman *et al*. 2015), in particular in winter and time scales longer than 12 hours (Westra *et al*. 2014), but also for hourly extremes (Barbero *et al*. 2018). However, GCMs still struggle to resolve some of these features (Trenberth *et al*. 2003). See Cheng *et al*. (2011) and Paixao *et al*. (2015) for precipitation processes in the NCR.

Strengths and Limitations of Methods

Mixed Approach with CORDEX[2]

For the present NCR study, hourly RCM projections were bias-corrected using empirical non-parametric quantile mapping (with the occurrence of wet days corrected separately) using data from the Ottawa airport (Maraun *et al*. 2010). A Generalized Extreme Value (GEV) distribution

---

[2] COordinated Regional climate Downscaling Experiment

was applied to the hourly precipitation values using maximum likelihood. This method combines both dynamic (RCM) and statistical downscaling/bias correction (quantile mapping). Results are provided in APPENDIX F – *Plots of Climate Indices*.

Are findings from the RCM method reliable? RCMs generally have a better representation of mesoscale dynamics than GCMs (Westra *et al*. 2014), and cyclones and fronts are reasonably well simulated (O'Gorman *et al*. 2015). Studies have found that characteristics of extreme precipitation (including sub-daily extremes) improve with increased resolution (Westra *et al*. 2014). Yet, parameterizations are still needed if grid cells exceed 10 km (Westra *et al*. 2014). Therefore, there are still issues with reproducing diurnal cycles (Trenberth *et al*. 2003) and spatial characteristics of extremes (Westra *et al*. 2014), which results in the underestimation of extreme precipitation (Goree Bi *et al*. 2017). Furthermore, RCMs are still dependent on GCMs for processes outside their domains (Wilby *et al*. 2014). In conclusion, **shorter-duration (e.g., hourly) extremes obtained from RCM projections should be interpreted with caution.**

Are findings from the quantile mapping method reliable? Notwithstanding some limitations (Ehret *et al*. 2012; Maraun 2013), bias correction is generally found to improve model output (Cannon *et al*. 2015, Chen *et al*. 2013, Maraun and Widmann 2018). Furthermore, quantile mapping has been found to consistently outperform simpler methods for precipitation (Teutschbein and Seibert 2012; Gudmundsson *et al*. 2012, Teng *et al*. 2015). However, quantile mapping struggles with representing extremes and has some other problems like keeping trends (Cannon *et al*. 2015). Bias corrections that operate on individual high-resolution grid boxes separately and independently are prone to misrepresentation (Maraun 2013, Gutmann *et al*. 2014). **Therefore, higher return periods (e.g., 1 in 100 year event) and spatial patterns should be interpreted with caution.** The use of RCMs is widely used nationally and internationally (e.g., Ganguli and Coulibaly 2019, Switzmann *et al*. 2017); however, this should be done with caution, especially for hourly projections, as evident by the high variability of results (Switzmann *et al*. 2017).

Statistical Downscaling with PCIC/CCCS Dataset

The present NCR study used a dataset of 24 GCMs downscaled using BCCAQv2, a hybrid method that combines results from BCCA (Maraun *et al*. 2010) and quantile mapping (QMAP) (Gudmundsson *et al*. 2012). The gridded observation dataset that was used for bias correction is ANUSPLIN[3], produced by Natural Resources Canada, with 10 km x 10 km grid cells. As part of this project, GEV was applied to the daily precipitation values (fitting using maximum likelihood). Results are provided in APPENDIX F – *Plots of Climate Indices*.

BCCAQv2 combines advantages and lessons-learned from multiple different methods. For example, it uses information from larger-scale fields and does not distort coarse-resolution trends (Werner and Cannon 2016, Cannon *et al*. 2015). It performs well with respect to the day-to-day sequencing of precipitation events, distribution characteristics, and spatial correlation (ECCC ClimateData.ca). Nonetheless, it is still a bias correction method, and as mentioned above, **extremes and spatial patterns should be interpreted with caution**. Like other downscaling

---

[3] Australian National University Spline

methods, it makes stationarity assumptions. Unlike the RCMs, the BCCAQv2 relies only on GCMs for processes, which is problematic if GCMs do not represent an important aspect of large-scale circulation.

This dataset was chosen by the ECCC for its new national platform and was provided by ECCC for precipitation indices for this project. It is cautioned that this dataset has not yet been widely tested for precipitation extremes. For example, Desai (2017) found that the PCIC data has a significantly lower standard deviation than that of the historical data. Nonetheless, the dataset has been tested with Climdex "frequent" annual indices (Werner and Cannon 2016, Li *et al*. 2018).

The reliance of bias correction methods on observed data is both a strength and limitation of this method. For instance, analysis can be informed by realistic characteristics of observed data, but this is a constraint if there is poor or missing data (Gooré Bi *et al*. 2017, Maraun and Widmann 2018). The ECCC dataset uses ANUSPLIN for gridded observation data. One study found that ANUSPLIN underestimates precipitation extremes because it is generated based on unadjusted precipitation-gauge stations (Wong *et al*. 2017), while another study found that ANUSPLIN was more successful than another dataset (Werner and Cannon 2016).

Statistical Downscaling with IDF-CC

To calculate daily extremes, the IDF-CC[4] tool from Western University interpolates the BCCAQv2 dataset (above) to a point location (inverse square distance weighting method), and extreme values are estimated using GEV and L-moments (Srivastav *et al*. 2014). For sub-daily durations, a quantile scaling method is used to establish a relationship between the annual maximum daily precipitations of the base period with that of the future period.

This method is becoming widely used because of its simplicity. It has been mapped across Canada (Simonovic *et al*. 2017), and has been compared to other approaches (Schardong *et al*. 2018) and tested with both GCMs and RCMs as input (Schardong and Simonivic 2019). The major drawback of the method is that it assumes that the existing relationship between daily and sub-daily precipitation will remain unchanged in the future, and there is evidence to show that this is incorrect (Trenbeth *et al*. 2003, O'Gorman *et al*. 2015, Westra *et al*. 2014, Cannon and Innocenti 2019). The tool also uses only one value per year, which has been suggested to be more effective than correcting the total rainfall distribution (Li *et al*. 2017). Because this assumption is a significant source of uncertainty, **the tool should be used for future sub-daily precipitation estimates with caution** (Coulibaly *et al*. 2016), as they are likely to be underestimated. In contrast, the PCIC/CCCS dataset, which is also statistically downscaled from GCMs, does not venture into providing sub-daily extremes.

Scaling with Clausius-Clapeyron Equation

As air warms, its capacity to hold water increases, which is expected to intensify rainfall extremes (Trenberth *et al*. 2003). Therefore, studies have developed correlations between precipitation intensity and temperature. The Clausius-Clapeyron (CC) rate of approximately 7% water content

---

[4] Intensity-Duration-Frequency curves with Climate Change

increase per °C warming or double this rate for temperatures between 12°C-22°C, is applied to average daily temperatures (Westra *et al*. 2014).

A number of studies have shown a CC-scaling rate based on observations and convection-permitting models (Westra *et al*. 2014). The scaling rate is supported by robust thermodynamic understanding, and it has recently been adopted in 2019 by the Canadian Standards Association (CSA PLUS 4013:19) and the Australian Rainfall & Runoff Guide and has been argued to be the only defensible approach based on studies by Zhang *et al*. (2017) and Zwiers (2017).

However, there are major factors such as moisture sources, large-scale dynamics and temperature gradients (Westra *et al*. 2014), and changes in precipitation efficiency (O'Gorman *et al*. 2015), which also affect extreme precipitation, but are not accounted for by the scaling rate (Blenkinsop *et al*. 2018, CSA 2019, Pfahl *et al*. 2017). Furthermore, we do not fully understand the scaling rate in the sense that there are alternative hypotheses for the cause of increased scaling at sub-daily durations (e.g., cloud dynamics due to latent heat release, or changes in the rainfall generating mechanisms; Westra *et al*. 2014). These reasons may be why variations in the scaling rates have been observed in Canada and elsewhere (Li *et al*. 2019, Gaur *et al*. 2018, Panthou *et al*. 2014).

As a result, there are divergent opinions on whether this scaling rate should be used (Prein *et al*. 2017, Schardong *et al*. 2018). One challenge is that there is not enough research to know precisely how to apply it. For example, the CSA (2019) is not prescriptive about which temperature to use (e.g., mean annual, seasonal, temperature during heavy rainfall, dew point temperatures). Nonetheless, results based on the scaling rate have been comparable to the IDF-CC tool, although higher for the prairies (which may be moisture limited; Schardong *et al*. 2018).

Other Approaches

The strengths and limitations of other approaches are summarized in Table D1.

Table D1 – Strengths and Limitations of Other Studies.

Method	Projections for NCR	Strength, Limitations, and Comments
Dynamic Downscaling		
Convection Permitting model (12 km) e.g., Wang and Kotamarthi (2015)	**Projections**: RCP 4.5, 8.5; 1995–2004, 2045–2054, 2085–2094; available as box plots with inter-annual variabilities and bar plot. **Method Details:** Driven by CCSM4 with and without bias correction. * also see Kendon *et al*. 2017, Prein *et al*. 2017, Cannon and Innocenti 2019.	**Strengths:** Convection-permitting due to high-resolution. **Limitations:** Limited runs and models. **Comments**: Some have argued convection-permitting models are the best chance we have to do sub-hourly rainfall extremes (Westra *et al*. 2014, O'Gorman 2015). However, limits on simulation length, domain, and # of studies (Westra *et al*. 2014).
OCCDP (25 km) Wang *et al*. (2015)	**Projections:** RCP 4.5, 8.5; 1986–2005, 2020–2039, 2040–2069, 2070–2099; available in online portal. **Method Details**: PRECIS and RegCM driven by 5 HadCM3 boundary conditions; Gumbel.	**Strengths:** Higher resolution projections than GCM. **Limitations:** Not bias-corrected; two regional models and one driving model; 25 km not sufficient for hourly rainfall. **Comparisons:** Found to overestimate historical quantiles (Desai 2017). *also see Wang *et al*. 2014, and Wang and Huang 2014.
Statistical Downscaling		
Waterloo Interpolator Topography, Temperature, Time Desai (2017)	**Projections:** RCP 2.6, 4.5, 8.5; 1960–2010, 2010–2099; available as map of points for Ontario. **Method details:** Combines atmospheric thermodynamics, temporal trends, and interpolated physiographic parameters; temp. inputs from OCCDP and PCIC**.**	**Strengths:** Combination of scaling, trends, and physiographic parameters. **Limitations**: Only two GCMs (CanESM 4.2 and MPIESM); not widely used; need to contact authors for NCR findings off of map. **Comparisons:** Better match of empirical distribution than OCCDP (Desai 2017).
Stochastic Weather Generator (0.125°) Deng *et al*. (2018)	**Projections:** RCP 6.0; 1980–2010, 2041–2070, 2071–2100; available as map of Ontario (Fig. 6) **Method Details:** BCCA; days≥10mm are temporally disaggregated; GEV with Gumbel.	**Strengths**: 12-member ensemble **Limitations**: Only RCP 6.0; for 15 min, return period calculated with indirect method using IDF function; analyses only from May–Nov; not widely used. * also see Hayhoe (2000)
Weather Typing Cheng *et al*. (2011)	**Projections:** A2, B2; 1958–2002, 2001–50, 2026–75; available as a table. **Method Details:** Comparing weather types; Rainfall simulation models; 4 downscaled GCMs; Ottawa meteorological station.	**Strengths**: Makes use of synoptic weather patterns rather than downscaling points in isolation. **Limitations**: Stationarity assumption & GCMs may not reproduce all weather patterns. * also see Gaitan *et al*. (2014)
PSPC (2019)	**Projections:** RCP 4.5 (appendix), RCP 8.5; 2021–2050, 2041–2070, 2071–2100; available as a table. **Method Details**: Used Clausius-Clapeyron equation.	**Strengths**: Based on theoretical understanding. **Limitations**: Selection of reduced scaling rate for daily durations. Unclear in literature which temperature projections should be used to apply scaling.

Other considerations from the literature

It is important to consider this discussion in the context of **other IDF uncertainties**:

- Statistical uncertainty (confidence intervals on extreme value fitting; CSA 2019);
- Use of different distribution functions (Paixao *et al*. 2011, Switzman *et al*. 2017);
- Instrument and data recording/logging practices (Shephard *et al*. 2014);
- Length of records compared to return periods (Shephard *et al*. 2014);
- Changes in rainfall quality control procedures (Coulibaly *et al*. 2016);
- Geographic variability (Switzman *et al*. 2017);
- Uncertainty related to antecedents, and combined events, e.g., rain on snow (Westra *et al*. 2014);
- Influence of low-frequency variability modes in Canada's climate (Vincent *et al*. 2015).

Some of these factors can lead to downward trends when updating historical IDFs (Coulibaly *et al*. 2016). To reduce uncertainty, the following approaches should be considered:

- Making use of multiple sources of information (Paixao *et al*. 2011, 2015; Burn 2014);
- Regional frequency analyses (Cannon 2015, CSA 2019);
- Multivariate statistical downscaling (Cannon *et al*. 2018);
- Nonstationary statistical methods (Shephard 2014, Cheng and Aghakouchak 2014, Gore Bi 2017, Miranda *et al*. 2018).

Summary of Findings

Despite the high natural variability and challenges with projecting precipitation extremes, different methods show an increase in precipitation extremes is projected for all durations (sub-daily, daily, and multi-day rain events).

The PCIC/CCCS projections underestimate the ECCC Intensity Duration Frequency (IDF) value in the historical period for daily events (note that the underestimation is less for multi-day events). This is likely because the projections represent precipitation that is averaged over 10 km. This is important for interpreting the findings; for example, if the percent change in the GCMs is applied to the ECCC IDF value, this assumes that the change in precipitation over a 10 km area is applicable for an IDF curve derived from a point location.

The Cordex RCM underestimates the ECCC IDF value in the historical period for hourly projections and overestimates the ECCC IDF value for longer sub-daily durations (e.g., 6-12 hours). The extremes for longer sub-daily durations also show greater increasing trends than the hourly extremes. This may be due to the challenge of representing small convection events (Westra *et al*. 2014) and could be amplified by the quantile mapping bias correction (Maraun 2010). A higher increase in sub-daily (compared to daily) extremes is supported by physical understanding (e.g., O'Gorman *et al*. 2015).

Location of Extreme Precipitation Projections:

- Figure D1– Projections of the **24-hour precipitation for a 1 in 100 year event**, based on three methods (PCIC/CCCS, IDF-CC, and Clausius-Clapeyron)

- Figure D2 – Projections of the **hourly precipitation for a 1 in 50 year event**, based on three methods (Cordex RCMs, IDF-CC, and Clausius-Clapeyron)
- Table D2 – Projections from **additional studies** not included in Figures D1/D2 (sub-daily, daily, and multi-day rain events).
- Appendices F and G – **Additional durations and return periods** for two methods (PCIC/CCCS and Cordex RCMs).

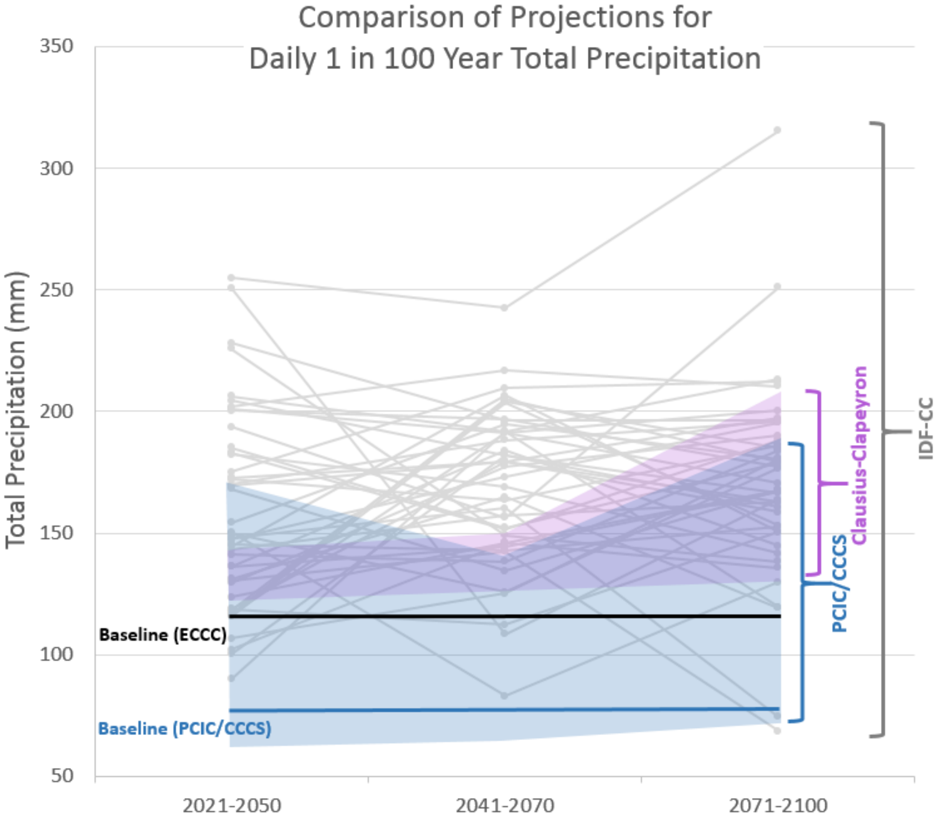


Figure D1: **Comparison of Projections for Extreme Precipitation at Ottawa Airport (1-day total, 1 in 100 year event)**

Interpretation of Figure D1:

- Projections for Daily 1 in 100 year event are provided based on different methods and models. All projections are **averaged over 30 years**.
- Projections from the PCIC/CCCS are provided in blue. Projections using the Clausius-Clapeyron scaling are provided in purple. For both of these, the solid fill depicts the 10th-90th percentiles of the **model ensemble**. Projections from the IDF-CC tool are provided in grey. The lines depict results from **individual models**.
- The PCIC/CCCS estimate for the baseline is shown with the horizontal blue line. This should be similar to the ECCC baseline value (horizontal black line), but instead, it underestimates the ECCC baseline. This suggests that **PCIC/CCCS projections may be an underestimation** of "true" projections (see discussion in the main text).
- The range of results obtained from different models and from different methods characterizes the uncertainty in the climate projections. The values provided in this plot

cannot be used directly in design or adaptation projects. A vulnerability/impact assessment and/or risk assessment (Phase 2) is needed to determine which values to use from the range of projections provided in this figure.

- It is cautioned that projections from **moderate (RCP 4.5) and high (RCP 8.5) emission scenarios are grouped** in this graphic for readability, but it is best practice to consider the range of projections from the two scenarios separately.

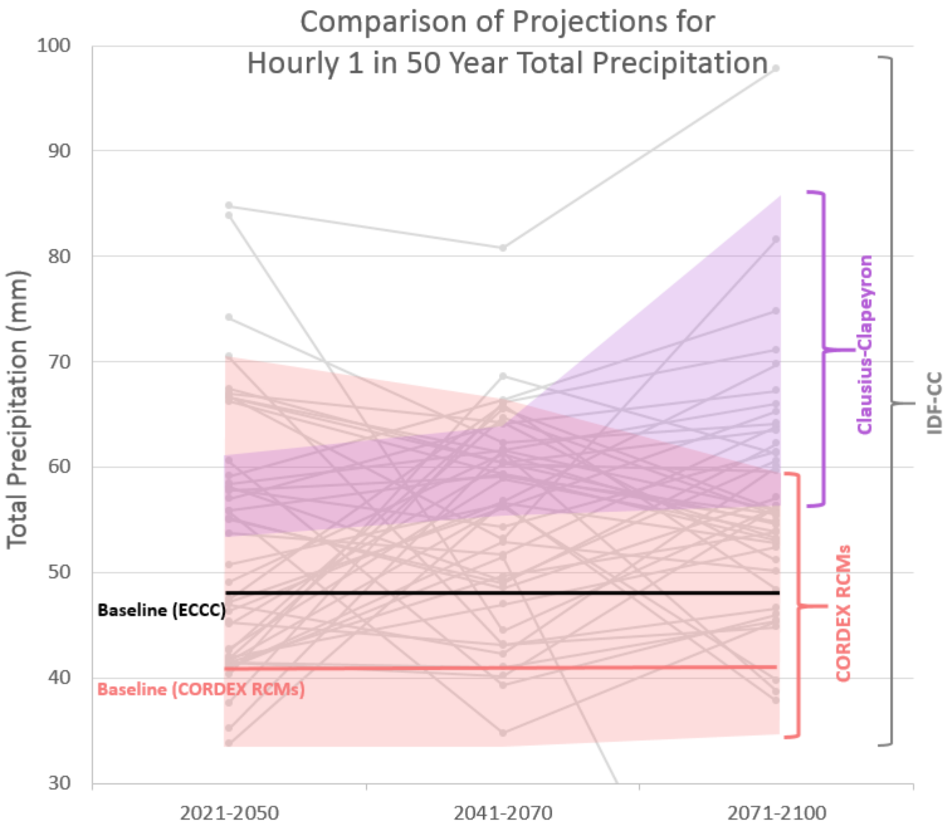


Figure D2: Comparison of Projections for Extreme Precipitation at Ottawa Airport (1-hour total, 50-year return).

Interpretation of Figure D2:

- Projections for Hourly 1 in 50 Year Precipitation are provided based on different methods and models. All projections are **averaged over 30 years**.
- Projections from the Cordex RCMs are provided in orange. Projections using the Clausius-Clapeyron scaling are provided in purple. For both of these, the solid fill depicts the 10th-90th percentiles of the **model ensemble**. Projections from the IDF-CC tool are provided in grey. The lines depict results from **individual models**.
- The Cordex RCMs estimate for the baseline is shown with the horizontal orange line. This should be similar to the ECCC baseline value (horizontal black line), but instead, it underestimates the ECCC baseline. This suggests that **Cordex RCM projections may be an underestimation** of “true” projections (see discussion in the main text).
- The range of results obtained from different models and from different methods characterizes the uncertainty in the climate projections. The values provided in this plot

should **not be used directly in design or adaptation projects without additional analysis**. A vulnerability/impact assessment and/or risk assessment is needed to determine which values to use from the range of projections provided in this figure.

- It is cautioned that projections from **moderate (RCP 4.5) and high (RCP 8.5) emission scenarios are grouped** in this graphic for readability, but it is best practice to consider the range of projections from the two scenarios separately.

Table D2 – Findings from additional studies not included in Figures D1/D2.
Note: these methods are not directly comparable due to different baselines, scenarios, etc., see Table D1)

Method	Multiple Days	Daily	Sub-daily
Dynamic Downscaling			
WRF Wang and Kotamarthi (2015)	**2-day 1 in 5**: incr. in # occurrences/year by 3.5 (2045–2054) and 6.5 (2085–2094) **5-day 1 in 10**: incr. in # occurrences/year by 3 (2045–2054) and 5.5 (2085–2094)	**Daily 55th-99th percentile**: projected to increase (except during the fall), with the greatest increase for 55th-75th. Greater increase found with a higher-resolution model.	
OCCDP Wang *et al.* (2015)		**Daily 1 in 100:** -15-85% (2020–2039), 15-65% (2040–2069), 3-55% (2070–2099)	**Hourly 1 in 50:** 15-93% (2020–2039), 50-65% (2040–2069), 40-80% (2070–2099)
Statistical Downscaling			
Desai (2017)		Frequency will almost double for all return periods, greater increase for 1 in 5/10 year storms.	Frequency will almost double for all return periods, greater increase for 1 in 5/10 year storms.
Deng *et al.* (2018)		**Daily 1 in 50**: increases approx. 10 mm between 2050s and 2080s	**15 min** increases 2-4 mm by 2080s.
Cheng *et al.* (2011)	3-day return incr. 30%–55% (2001–50), 25%–60% (2026–75)		
PSPC (2019)		**Future Probability of Existing Daily 1 in 50:** 4% (2030s), 5% (2050s), 9% (2080s)	**Future Probability of Existing Hourly 1 in 50:** 5% (2030s), 8% (2050s), 15% (2080s)

Bias Correction and Spatial Variation Artifacts

It is cautioned that when bias correction is applied to individual grid boxes separately, this can create spatial patterns that are not real (Maraun 2013). What this means is that maps in APPENDIX F – *Plots of Climate Indices* should be interpreted with caution. **Gradients that are consistent with process-based understanding (e.g., from south to north, or between the urban core and surrounding areas) are more reliable, whereas speckled results may be artifacts of the data analysis.**

The figure below provides an example for the 1 in 100 year 1-day precipitation (with the colour smoothing removed for emphasis): it is not realistic that precipitation extremes would vary this drastically and with no clear pattern (the issue remains when individual models are plotted; this was tested but results are not shown in this project). This phenomenon is particularly challenging with return-period extremes because they are sensitive to a small number of data points. For this reason, only the 1 in 100 year 1-day precipitation plots have been provided in APPENDIX F – *Plots of Climate Indices* for reference, and maps of other return periods and storm durations are not shown.

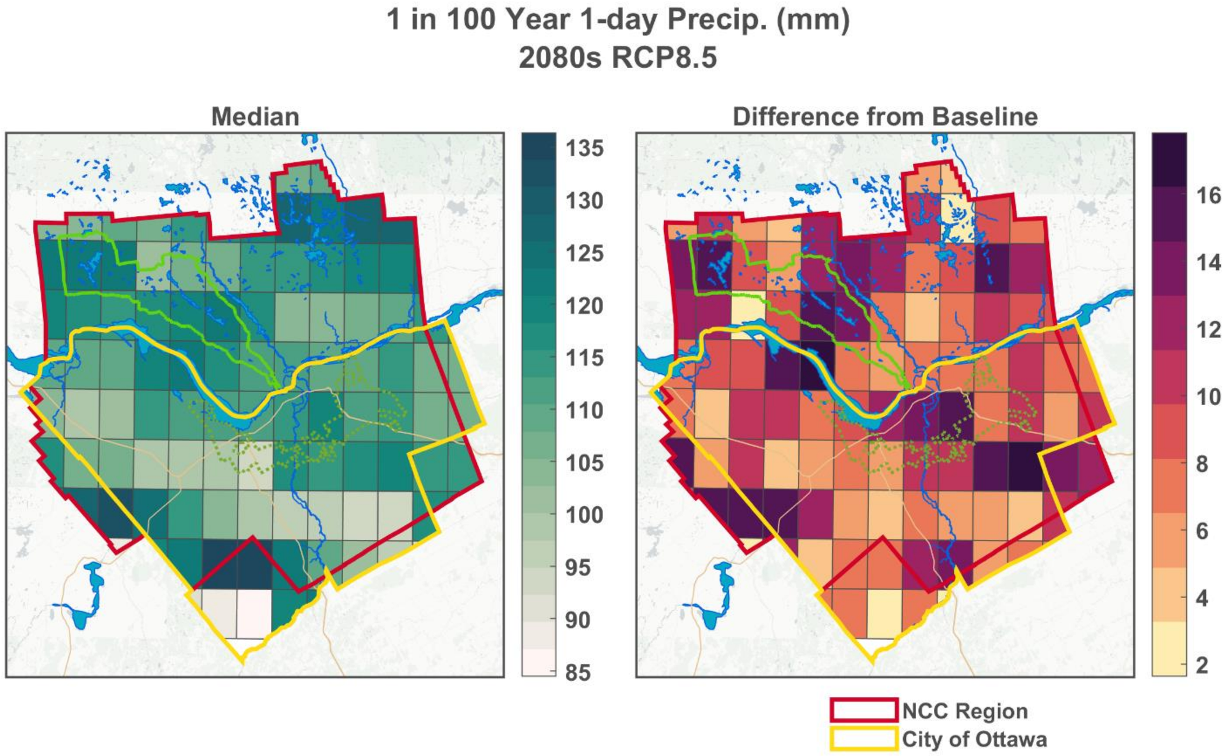


Figure D3: Sample Maps of Extreme Precipitation (1 in 100 year 24-hours)

APPENDIX E – References

Al, Griffith E. T. (2016) "Journal of Geophysical Research : Atmospheres." *Journal of Geophysical Research : Atmospheres*, pp. 4211–32, doi:10.1002/2015JD024358.Received.

Allard, Denis, and Marc Bourotte. *Disaggregating Daily Precipitations into Hourly Values with a Transformed Censored Latent Gaussian Process*. https://informatique-mia.inra.fr/sites/informatique-mia.inra.fr.biosp-d7/files/oldfiles/Allard_Bourotte_SERRA_Revision.pdf. Accessed 25 Apr. 2019.

Gorée Bi, E., Gachon, P., Vrac, M., & Monette, F. (2017). Which downscaled rainfall data for climate change impact studies in urban areas? Review of current approaches and trends. Theoretical and Applied Climatology, 685–699. https://doi.org/10.1007/s00704-015-1656-y

Blenkinsop, S., Fowler, H. J., Barbero, R., Chan, S. C., Guerreiro, S. B., Kendon, E., ... Tye, M. R. (2018). The INTENSE project: using observations and models to understand the past, present and future of sub-daily rainfall extremes. Advances in Science and Research, 15, 117–126. https://doi.org/10.5194/asr-15-117-2018

Bonsal, Barrie R. *et al*. (2011). "Drought Research in Canada: A Review." *Atmosphere - Ocean*, vol. 49, no. 4, pp. 303–19, doi:10.1080/07055900.2011.555103.

Booth, James F., *et al*. (2015) "The Paths of Extratropical Cyclones Associated with Wintertime High-Wind Events in the Northeastern United States." *Journal of Applied Meteorology and Climatology*, vol. 54, no. 9, pp. 1871–85, doi:10.1175/JAMC-D-14-0320.1.

Bornman, Janet F., *et al*. (2019) "Linkages between Stratospheric Ozone, UV Radiation and Climate Change and Their Implications for Terrestrial Ecosystems." *Photochemical and Photobiological Sciences*, vol. 18, no. 3, Royal Society of Chemistry, pp. 681–716, doi:10.1039/c8pp90061b.

Brooks, H. E. (2013) "Severe Thunderstorms and Climate Change." *Atmospheric Research*, vol. 123, Elsevier B.V.,pp. 129–38, doi:10.1016/j.atmosres.2012.04.002.

Brown, Ross D., *et al*. (2019) "Update of Canadian Historical Snow Survey Data and Analysis of Snow Water Equivalent Trends, 1967–2016." *Atmosphere - Ocean*, vol. 57, no. 2, Taylor & Francis, pp. 149–56, doi:10.1080/07055900.2019.1598843.

Canadian Council of Forest Ministers. (2015). *Climate Change and Sustainable Forest Management in Canada: A Guidebook for Assessing Vulnerability and Mainstreaming Adaptation into Decision Making*.

Cannon, A. J., & Innocenti, S. (2019). Projected intensification of sub-daily and daily rainfall extremes in convection-permitting climate model simulations over North America: implications for future intensity–duration–frequency curves. *Natural Hazards and Earth System Sciences*, *19*(2), 421–440. https://doi.org/10.5194/nhess-19-421-2019

Cannon, A. J., Sobie, S. R., & Murdock, T. Q. (2015). Bias correction of GCM precipitation by quantile mapping: How well do methods preserve changes in quantiles and extremes? *Journal of Climate*, *28*(17), 6938–6959. https://doi.org/10.1175/JCLI-D-14-00754.1

Cannon, Alex J. (2018) "Multivariate Quantile Mapping Bias Correction: An N-Dimensional Probability Density Function Transform for Climate Model Simulations of Multiple Variables." *Climate Dynamics*, vol. 50, no. 1–2, Springer Berlin Heidelberg, pp. 31–49, doi:10.1007/s00382-017-3580-6.

Cao, Zuohao, and Huaqing Cai. (2008) "Tornado Frequency and Its Large-Scale Environments Over Ontario, Canada." *The Open Atmospheric Science Journal*, vol. 2, no. 1, pp. 256–60, doi:10.2174/1874282300802010256.

Cao, Zuohao, *et al*. (2011) *Detection of Tornado Frequency Trend Over Ontario, Canada*. no. 1, pp. 27–31.

CBC. (2019). Blasts from the past: Canada's worst snowstorms | CBC News. [online] Available at: https://www.cbc.ca/news/canada/blasts-from-the-past-canada-s-worst-snowstorms-1.1370387 [Accessed 20 Sep. 2019].

CCMA. (2013). *Tools for Climate Change Vulnerability Assessments for Watersheds*.

Centers for Disease Control and Prevention (CDC) (2019). Climate and Health Program. https://www.cdc.gov/climateandhealth/default.htm

Centre for Indigenous Environmental Resources. (2006). *Climate Change Planning Tools for First Nations Guidebook 3*.

Cesana, Gregory, and Trude Storelvmo. (2017). "Improving Climate Projections by Understanding How Cloud Phase Affects Radiation." *Journal of Geophysical Research*, vol. 122, no. 8, 2017, pp. 4594–99, doi:10.1002/2017JD026927.

Changnon, Stanley A. "Urban Modification of Freezing-Rain Events. (2003). " *Journal of Applied Meteorology*, vol. 42, no. 6, pp. 863–70, doi:10.1175/1520-0450(2003)042<0863:umofe>2.0.co;2.

Charron, I. (2016). A Guidebook on Climate Scenarios: Using Climate Information to Guide Adaptation Research and Decisions, 2016 Edition. Ouranos, 94p.

Chaumont D., Mailhot A., Diaconescu E.P., Fournier É., Logan T. (2017). Élaboration du portrait bioclimatique futur du Nunavik – Tome II. [Rapport présenté au Ministère de la forêt, de la faune et des parcs] Lieu d'édition : Ouranos. 215 pages (https://www.ouranos.ca/publication-scientifique/RapportNunavik2018-Tome2-Fr.pdf)

Chen, J., Brissette, F. P., Chaumont, D., & Braun, M. (2013). Performance and uncertainty evaluation of empirical downscaling methods in quantifying the climate change impacts on hydrology over two North American river basins. *Journal of Hydrology*, *479*, 200–214. https://doi.org/10.1016/j.jhydrol.2012.11.062

Chen, Yong-Jhih, *et al*. (2019). "Distinct Patterns of Cloud Changes Associated with Decadal Variability and Their Contribution to Observed Cloud Cover Trends." *Journal of Climate*, pp. 1–62, doi:10.1175/jcli-d-18-0443.1.

Cheng, C. S., *et al*. (2007). "Possible Impacts of Climate Change on Freezing Rain in South-Central Canada Using Downscaled Future Climate Scenarios." *Natural Hazards and Earth System Science*, vol. 7, no. 1, pp. 71–87, doi:10.5194/nhess-7-71-2007.

Cheng, C. S., Li, G., Li, Q., & Auld, H. (2011). A synoptic weather-typing approach to project future daily rainfall and extremes at local scale in Ontario, Canada. *Journal of Climate*, *24*(14), 3667–3685. https://doi.org/10.1175/2011JCLI3764.1

Cheng, Chad Shouquan, *et al*. (2007). "A Synoptic Climatological Approach to Assess Climatic Impact on Air Quality in South-Central Canada. Part I: Historical Analysis." *Water, Air, and Soil Pollution*, vol. 182, no. 1–4, 2007, pp. 131–48, doi:10.1007/s11270-006-9327-3.

Cheng, Chad Shouquan, *et al*. (2012) "Climate Change and Heavy Rainfall-Related Water Damage Insurance Claims and Losses in Ontario, Canada." *Journal of Water Resource and Protection*, vol. 04, no. 02, pp. 49–62, doi:10.4236/jwarp.2012.42007.

Cheng, Chad Shouquan, *et al*. (2012) "Possible Impacts of Climate Change on Extreme Weather Events at Local Scale in South-Central Canada." *Climatic Change*, vol. 112, no. 3–4, pp. 963–79, doi:10.1007/s10584-011-0252-0.

Cheng, Chad Shouquan, *et al*. (2014). "Possible Impacts of Climate Change on Wind Gusts under Downscaled Future Climate Conditions: Updated for Canada." *Journal of Climate*, vol. 27, no. 3, pp. 1255–70, doi:10.1175/JCLI-D-13-00020.1.

Cheng, Chad Shouquan, *et al*. (2011). "Possible Impacts of Climate Change on Wind Gusts under Downscaled Future Climate Conditions over Ontario, Canada." *Journal of Climate*, vol. 25, no. 9, pp. 3390–408, doi:10.1175/JCLI-D-11-00198.1.

Cheng, Vincent Y. S., *et al*. (2016). "Predicting the Climatology of Tornado Occurrences in North America with a Bayesian Hierarchical Modeling Framework." *Journal of Climate*, vol. 29, no. 5, pp. 1899–917, doi:10.1175/JCLI-D-15-0404.1.

City of Ottawa. (2011) "Characterization of Ottawa's Watersheds: An Environmental Foundation Document with Supporting Information Base."

Coleman, Jill S. M., and Robert M. Schwartz. (2017) "An Updated Blizzard Climatology of the Contiguous United States (1959-2014): An Examination of Spatiotemporal Trends." *Journal of Applied Meteorology and Climatology*, vol. 56, no. 1, pp. 173–87, doi:10.1175/JAMC-D-15-0350.1.

Cortinas, John. (2000) "A Climatology of Freezing Rain in the Great Lakes Region of North America." *Monthly Weather Review*, vol. 128, no. 10, pp. 3574–88, doi:10.1175/1520-0493(2001)129<3574:ACOFRI>2.0.CO;2.

Coulibaly, P., Burn, D. H., Switzman, H., Henderson, J., & Fausto, E. (2016). *A Comparison of Future IDF Curves for Southern Ontario Addendum-IDF Statistics, Curves and Equations Currently a consulting hydrologist in Calgary, AB The authors are grateful to Ryan Ness and Fabio Tonto (TRCA) for their contribution in sites selection*. (February). Retrieved from https://climateconnections.ca/app/uploads/2014/01/IDF-Comparison-Report-and-Addendum.pdf

Croce, Pietro, *et al*. (2018) "The Snow Load in Europe and the Climate Change." *Climate Risk Management*, vol. 20, no. March, Elsevier, pp. 138–54, doi:10.1016/j.crm.2018.03.001.

CSA. (2019). *Technical Guide Development, interpretation, and use of intensity-duration-frequency (IDF) information: Guideline for Canadian water resource practitioners*.

Deng, Z., Liu, J., Qiu, X., Zhou, X., Babazadeh, H., & Zhu, H. (2018). Projection of Temperature and Precipitation Related Climatic Design Data Using CMIP5 Multi-Model Ensemble: A case study for Ontario, Canada under RCP 6.0. In *Journal of Buildings and Sustainability* (Vol. 39). Retrieved from www.insightcore.com

Desai, H. (2017). *Relating Extreme Temperature and Precipitation to Improve IDF Curve Estimates for Ontario in Response to Climate Change*. Waterloo.

"Detecting the Impact of Temperature on Transmission of Zika, Dengue, and Chikungunya Using Mechanistic Models." PubMed Central (PMC), 1 Apr. 2017, www.ncbi.nlm.nih.gov/pmc/articles/PMC5423694.

Diaconescu E., Mailhot A., Chaumont D., Brown R. (2017) Développement de scénarios climatiques pour le Canada basés sur les simulations régionales CORDEX, 7e symposium Ouranos, Montréal, Qc., Canada, 15 - 17 novembre 2017. https://www.ouranos.ca/publication-scientifique/Diaconescu_3A.pdf

ECCC. (2019). About Datasets. Retrieved June 13, 2020, from https://climatedata.ca/about/#about-datasets

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., & Liebert, J. (2012). HESS Opinions "should we apply bias correction to global and regional climate model data?" *Hydrology and Earth System Sciences*, *16*(9), 3391–3404. https://doi.org/10.5194/hess-16-3391-2012

Engineers Canada. (n.d.). *Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol*.

Environment and Climate Change Canada. "Air Health Trends." Canada.ca, Government of Canada, 28 Sept. 2018, https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/air-health-trends.html.

Environment and Climate Change Canada. "ARCHIVED - Environment and Climate Change Canada - Weather and Meteorology - Archives - Feature Articles - Hurricane Hazel Storm Information." ARCHIVED - Environment and Climate Change Canada - Weather and Meteorology - Archives - Feature Articles - Hurricane Hazel Storm Information, 23 July 2013, https://www.ec.gc.ca/ouragans-hurricanes/default.asp?lang=En&n=5C4829A9-1.

Environment and Climate Change Canada. "Top Weather Events of the 20th Century." Environment and Climate Change Canada - Weather and Meteorology - Top Weather Events of the 20th Century, 8 Aug. 2017, https://ec.gc.ca/meteo-weather/default.asp?lang=En&n=6A4A3AC5-1.

Fajber, Robert, *et al*. (2014) "At What Time of Day Do Daily Extreme Near-Surface Wind Speeds Occur?" *Journal of Climate*, vol. 27, no. 11, pp. 4226–44, doi:10.1175/JCLI-D-13-00286.1.

Fowler, R. B. S. W. G. L. H. J. (2018). *Temperature‐extreme precipitation scaling: a two‐way causality?*

Fu, Tzung May, and Heng Tian. (2019) "Climate Change Penalty to Ozone Air Quality: Review of Current Understandings and Knowledge Gaps." *Current Pollution Reports*, Current Pollution Reports, pp. 159–71, doi:10.1007/s40726-019-00115-6.

Gaitan, C. F., Hsieh, W. W., & Cannon, A. J. (2014). Comparison of statistically downscaled precipitation in terms of future climate indices and daily variability for southern Ontario and Quebec, Canada. *Climate Dynamics*, *43*(12), 3201–3217. https://doi.org/10.1007/s00382-014-2098-4

Ganguli, P., & Coulibaly, P. (2019). Assessment of future changes in intensity-duration-frequency curves for Southern Ontario using North American (NA)-CORDEX models with nonstationary methods. *Journal of Hydrology: Regional Studies*, *22*. https://doi.org/10.1016/j.ejrh.2018.12.007

Gaur, A., A. Schardong, and S. P. Simonovic. (2018). "Effects of global warming on precipitation extremes: Dependence on storm characteris- tics." Water Resour. Manage. 32 (8): 2639–2648. https://doi.org/10 .1007/s11269-018-1949-x.

Girardin, Martin Philippe, *et al*. (2004) "Trends and Periodicities in the Canadian Drought Code and Their Relationships with Atmospheric Circulation for the Southern Canadian Boreal Forest." *Canadian Journal of Forest Research*, vol. 34, no. 1, pp. 103–19, doi:10.1139/x03-195.

Government of Canada. (2008). *Integrating Climate Change into Invasive Species Risk Assessment/ Risk Management*.

Groisman, Pavel Ya, *et al*. (2016) "Recent Changes in the Frequency of Freezing Precipitation in North America and Northern Eurasia." *Environmental Research Letters*, vol. 11, no. 4, IOP Publishing, 2016, doi:10.1088/1748-9326/11/4/045007.

Gudmundsson, L., Bremnes, J. B., Haugen, J. E., & Engen-Skaugen, T. (2012). Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations – A comparison of methods. *Hydrology and Earth System Sciences*, *16*(9), 3383–3390. https://doi.org/10.5194/hess-16-3383-2012

Gutmann, E., T. Pruitt, M. P. Clark, L. Brekke, J. R. Arnold, D. A. Raff, and R. M. Rasmussen (2014): An intercomparison of statistical downscaling methods used for water resource assessments in the United States. Water Resour. Res., 50, 7167– 7186, doi:10.1002/2014WR015559.

Gutmann, Ethan D., *et al*. (2018) "Changes in Hurricanes from a 13-Yr Convection-Permitting Pseudo- Global Warming Simulation." *Journal of Climate*, vol. 31, no. 9, 2018, pp. 3643–57, doi:10.1175/JCLI-D-17-0391.1.

Hanson, Helena. "3 Ottawa Homes Were Struck By Lightning On Thursday Night And The Pictures Are Terrifying." Narcity, Narcity, https://www.narcity.com/news/ca/on/ottawa/ottawa-lightning-struck-3-different-homes-causing-fires-and-the-pictures-are-shocking.

Hawkins, E., and R. Sutton (2009).The potential to narrow uncertainty in regional climate predictions. Bulletin of the American Meteorological Society, 90, 1095–1107, doi:10.1175/2009BAMS2607.1.

Hayhoe, H. N. (2000). Improvements of stochastic weather data generators for diverse climates. *Climate Research*, *14*(2), 75–87. https://doi.org/10.3354/cr014075

Hernández-Díaz, L., O. Nikiéma, R. Laprise, K. Winger and S. Dandoy (2019) Effect of empirical correction of sea-surface temperatures on the CRCM5-simulated climate and projected climate change over North America. Clim. Dyn. 24 pp https://link.springer.com/content/pdf/10.1007%2Fs00382-018-4596-2.pdf

Holland, Greg, and Cindy L. Bruyère. (2014) "Recent Intense Hurricane Response to Global Climate Change." *Climate Dynamics*, vol. 42, no. 3–4, pp. 617–27, doi:10.1007/s00382-013-1713-0.

Hosseinzadehtalaei, P., Tabari, H., & Willems, P. (2017). Uncertainty assessment for climate change impact on intense precipitation: how many model runs do we need? *International Journal of Climatology*, *37*(April), 1105–1117. https://doi.org/10.1002/joc.5069

Huryn, Steven M., *et al*. (2016) "A Review of Thunderstorm Trends across Southern Ontario, Canada." *Atmosphere - Ocean*, vol. 54, no. 5, Taylor & Francis, pp. 519–28, doi:10.1080/07055900.2016.1211085.

ICLEI Canada. (2017). *Building Adaptive and Resilient Communities Program*.

Institute for Sustainable Infrastructure. (n.d.). *Envision*.

IPCC (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://ar5-syr.ipcc.ch/topic_futurechanges.php

IPCC (2018). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.

Janoski, Tyler P., *et al*. (2018). "Effects of Climate Change on Wind-Driven Heavy-Snowfall Events over Eastern North America." *Journal of Climate*, vol. 31, no. 22, pp. 9037–54, doi:10.1175/JCLI-D-17-0756.1.

Jeong, Dae Il, and Laxmi Sushama. (2018). "Projected Changes to Extreme Wind and Snow Environmental Loads for Buildings and Infrastructure across Canada." *Sustainable Cities and Society*, vol. 36, no. December 2016, Elsevier, pp. 225–36, doi:10.1016/j.scs.2017.10.004.

Jeong, Dae Il, *et al*. (2018) "Projected Changes to Extreme Ice Loads for Overhead Transmission Lines across Canada." *Sustainable Cities and Society*, vol. 39, no. July 2017, pp. 639–49, doi:10.1016/j.scs.2018.03.017.

Kar, Sanjib Kumar, and Yuei An Liou. (2019) "Influence of Land Use and Land Cover Change on the Formation of Local Lightning." *Remote Sensing*, vol. 11, no. 4, doi:10.3390/rs11040407.

Kendon, E. J., Ban, N., Roberts, N. M., Fowler, H. J., Roberts, M. J., Chan, S. C., … Wilkinson, J. M. (2017). Do convection-permitting regional climate models improve projections of future precipitation change? *Bulletin of the American Meteorological Society*, *98*(1), 79–93. https://doi.org/10.1175/BAMS-D-15-0004.1

Klima, Kelly, and M. Granger Morgan. (2015) "Ice Storm Frequencies in a Warmer Climate." *Climatic Change*, vol. 133, no. 2, pp. 209–22, doi:10.1007/s10584-015-1460-9.

Knutson, Thomas R., *et al*. (1998) "Simulated Increase of Hurricane Intensities in a CO2-Warmed Climate." *Science*, vol. 279, no. 5353, pp. 1018–20, doi:10.1126/science.279.5353.1018.

Knutson, Thomas, *et al*. (2019) "Tropical Cyclones and Climate Change Assessment: Part II. Projected Response to Anthropogenic Warming." *Bulletin of the American Meteorological Society*, 2019, p. BAMS-D-18-0194.1, doi:10.1175/BAMS-D-18-0194.1.

Kunkel, Kenneth E., *et al*. (2016). "Trends and Extremes in Northern Hemisphere Snow Characteristics." *Current Climate Change Reports*, vol. 2, no. 2, Current Climate Change Reports, pp. 65–73, doi:10.1007/s40641-016-0036-8.

Lee, Cameron C. (2012) "Utilizing Synoptic Climatological Methods to Assess the Impacts of Climate Change on Future Tornado-Favorable Environments." *Natural Hazards*, vol. 62, no. 2, pp. 325–43, doi:10.1007/s11069-011-9998-y.

Li, C., Zwiers, F., Zhang, X., & Li, G. (2019). How Much Information Is Required to Well Constrain Local Estimates of Future Precipitation Extremes? *Earth's Future*, *7*(1), 11–24. https://doi.org/10.1029/2018EF001001

Li, G., Zhang, X., Cannon, A. J., Murdock, T., Sobie, S., Zwiers, F., … Qian, B. (2018). Indices of Canada's future climate for general and agricultural adaptation applications. *Climatic Change*, *148*(1–2), 249–263. https://doi.org/10.1007/s10584-018-2199-x

Linning, Shannon J. (2015) "Crime Seasonality and the Micro-Spatial Patterns of Property Crime in Vancouver, BC and Ottawa, ON." *Journal of Criminal Justice*, vol. 43, no. 6, Elsevier Ltd, pp. 544–55, doi:10.1016/j.jcrimjus.2015.05.007.

Lisa V. Alexander Xuebin Zhang, Hayley J. Fowler, Claudia Tebaldi, Amanda Lynch, Nigel Tapper, *et al*. (2009) "Climate Extremes: Progress and Future Directions." *International Journal of Climatology*, vol. 29, no. 3, pp. 317–19, doi:10.1002/joc.

Littell, Jeremy S., *et al*. (2016) "A Review of the Relationships between Drought and Forest Fire in the United States." *Global Change Biology*, vol. 22, no. 7, pp. 2353–69, doi:10.1111/gcb.13275.

Lucas, R. M., *et al*. (2019) "Human Health in Relation to Exposure to Solar Ultraviolet Radiation under Changing Stratospheric Ozone and Climate." *Photochemical and Photobiological Sciences*, vol. 18, no. 3, Royal Society of Chemistry, pp. 641–80, doi:10.1039/C8PP90060D.

Lucio-Eceiza, Etor E., *et al*. (2018) "Quality Control of Surface Wind Observations in Northeastern North America. Part I: Data Management Issues." *Journal of Atmospheric and Oceanic Technology*, vol. 35, no. 1, pp. 163–82, doi:10.1175/JTECH-D-16-0204.1.

Mailhot A., Chaumont D., Berteaux D., Brodeur V., Casajus N., Barette C., Brown R., Côté S., Diaconescu E.P., Fournier É., Guay C., Logan T., Ropars P., Tremblay B. (2017): Élaboration du portrait bioclimatique futur du Nunavik – Tome I. [Rapport présenté au Ministère de la forêt, de la faune et des parcs] Lieu d'édition : Ouranos. 214 pages (https://www.ouranos.ca/publication-scientifique/RapportNunavik2018-Tome1-Fr.pdf)

Maraun, D., (2013). Bias correction, quantile mapping, and downscaling: Re- visiting the inflation issue. J. Climate, 26, 2137–2143, doi:10.1175/ JCLI-D-12-00821.1.

Maraun, D., *et al*. (2010: Precipitation downscaling under cli- mate change: Recent developments to bridge the gap between dynamical models and the end user. Rev. Geophys., 48, RG3003, doi:10.1029/2009RG000314.

Maraun, D., and Widmann, M. (2018). *Statistical Downscaling and Bias Correction for Climate Research* (2018 Editi). Cambridge: Combridge University Press.

Maraun, D., Shepherd, T. G., Widmann, M., Zappa, G., Walton, D., Gutiérrez, J. M., … Mearns, L. O. (2017). Towards process-informed bias correction of climate change simulations. *Nature Climate Change*, *7*(11), 764–773. https://doi.org/10.1038/nclimate3418

Matte, Dominic, *et al*. (2019) "Mixed Precipitation Occurrences over Southern Québec, Canada, under Warmer Climate Conditions Using a Regional Climate Model." *Climate Dynamics*, vol. 53, no. 1–2, Springer Berlin Heidelberg, 2019, pp. 1–17, doi:10.1007/s00382-018-4231-2.

McGrath, Pat, and Jean Levac. "Third Ottawa Tornado inside Year a 'Statistical Anomaly:" Environment Canada." Ottawa Citizen, 3 June 2019, https://ottawacitizen.com/news/local-news/third-ottawa-tornado-inside-year-a-statistical-anomaly-environment-canada.

McGrath, Pat, and Jean Levac. "Third Ottawa Tornado inside Year a 'Statistical Anomaly:" Environment Canada." Ottawa Citizen, 3 June 2019, https://ottawacitizen.com/news/local-news/third-ottawa-tornado-inside-year-a-statistical-anomaly-environment-canada.

Megan Gillis. (2016, May 12). Brush, forest fire doused in Gatineau. *Ottawa Citizen*.

Meyer, Judith, *et al*. (2019). "Effects of Univariate and Multivariate Bias Correction on Hydrological Impact Projections in Alpine Catchments." *Hydrology and Earth System Sciences*, vol. 23, no. 3, pp. 1339–54, doi:10.5194/hess-23-1339-2019.

Ministry of Health and Long-Term Care. (2016). Ontario Vulnerability and Adaptation Assessment Guideline. *Climate Change and Health Toolkit*.

Ministry of Natural Resources and Forestry. "Least Bittern: Ontario Recovery Strategy Series." 2016. PDF.

Mortsch, Linda, *et al*. (2015) “Climate and Water Availability Indicators in Canada: Challenges and a Way Forward. Part II – Historic Trends.” *Canadian Water Resources Journal*, vol. 40, no. 2, Taylor & Francis, pp. 146–59, doi:10.1080/07011784.2015.1006024.

Murphy, Colleen, *et al*. (2018). *Climate Change and Its Impacts : Risks and Inequalities*.

Ngonghala, Calistus & Ryan, Sadie & Tesla, Blanka & Demokovsky, Leah & Brindley, Melinda & Mordecai, Erin & Murdock, Courtney & Bonds, Matthew. (2019). Effects of temperature on Zika dynamics and control. 10.1101/855072.

Office of the Fire Marshall and Emergency Management. (2019). Hazard Identification Report 2019. Emergency Management Ontario.

O’Gorman, P. A. (2015). Precipitation Extremes Under Climate Change. *Current Climate Change Reports*, *1*(2), 49–59. https://doi.org/10.1007/s40641-015-0009-3

Pacific Climate Impacts Consortium (PCIC)(2017) *PCIC SCIENCE BRIEF: EVOLUTION OF SNOWMELT AND DROUGHT*. Vol. i, no. October.

Pagowski, Mariusz, *et al*. (2004) “Analysis and Modeling of an Extremely Dense Fog Event in Southern Ontario.” *Journal of Applied Meteorology*, vol. 43, no. 1, pp. 3–16, doi:10.1175/1520-0450(2004)043<0003:AAMOAE>2.0.CO;2.

Paixao, E., Monirul Qader Mirza, M., Shephard, M. W., Auld, H., Klaassen, J., & Smith, G. (2015). An integrated approach for identifying homogeneous regions of extreme rainfall events and estimating IDF curves in Southern Ontario, Canada: Incorporating radar observations. *Journal of Hydrology*, *528*, 734–750. https://doi.org/10.1016/j.jhydrol.2015.06.015

Paixao, Edson, *et al*. (2015) “An Integrated Approach for Identifying Homogeneous Regions of Extreme Rainfall Events and Estimating IDF Curves in Southern Ontario, Canada: Incorporating Radar Observations.” *Journal of Hydrology*, vol. 528, Elsevier B.V., pp. 734–50, doi:10.1016/j.jhydrol.2015.06.015.

Palko K. and D.S. Lemmen (Eds.)(2016). Climate risks and adaptation practices for the Canadian transportation sector 2016 (pp. 139-179). Ottawa, ON: Government of Canada.

Panthou, G., A. Mailhot, E. Laurence, and G. Talbot (2014). Relationship between surface temperature and extreme rainfalls: A multi-timescale and event-based analysis, J. Hydrometeorol., doi:10.1175/JHM-D-14-0020.1. Teng *et al*., 2015 in Velasquez 2019

Pelmorex Weather Networks Inc. “UPDATE: Officials Increase Friday's Tornado Count to SIX.” The Weather Network, https://www.theweathernetwork.com/news/articles/gatineau-ottawa-dunrobin-tornado-storm/112859.

Pfahl, S., O’Gorman, P. A., & Fischer, E. M. (2017). Understanding the regional pattern of projected future changes in extreme precipitation. *Nature Climate Change*, *7*(6), 423–427. https://doi.org/10.1038/nclimate3287

Pielkejr, B. Y. R. A., *et al*. (2005). *Hurricanes and Global Warming*. no. NOVEMBER, pp. 1571–76, doi:10.1175/BAMS-86-II-1571.

Poole, Jill A., *et al*. (2019). “Impact of Weather and Climate Change with Indoor and Outdoor Air Quality in Asthma: A Work Group Report of the AAAAI Environmental Exposure and Respiratory Health Committee.” *Journal of Allergy and Clinical Immunology*, vol. 143, no. 5, Elsevier Inc., pp. 1702–10, doi:10.1016/j.jaci.2019.02.018.

Prein, A. F., Rasmussen, R. M., Ikeda, K., Liu, C., Clark, M. P., & Holland, G. J. (2017). The future intensification of hourly precipitation extremes. *Nature Climate Change*, *7*(1), 48–52. https://doi.org/10.1038/nclimate3168

Province of Ontario and the Ontario Centre for Climate Impacts and Adaptation Resources. (2011). *A Practitioner's Guide to Climate Change Adaptation in Ontario's Ecosystems V1*.

Pryor, S. C., and R. J. Barthelmie. "Hybrid Downscaling of Wind Climates over the Eastern USA." *Environmental Research Letters*, vol. 9, no. 2, (2014), doi:10.1088/1748-9326/9/2/024013.

Pryor, S. C., *et al*. (2012) "Influence of Spatial Resolution on Regional Climate Model Derived Wind Climates." *Journal of Geophysical Research Atmospheres*, vol. 117, no. 3, pp. 1–11, doi:10.1029/2011JD016822.

Public Services and Procurement Canada. (2019). Identification of Climate-Related Hazards for Real Property Assets in the National Capital Area.

Public Health Agency of Canada. "Government of Canada." Climate Change and Infectious Diseases 2019 - Canada.ca, Government of Canada, 25 Oct. 2019, www.canada.ca/en/public-health/services/reports-publications/canada-communicable-disease-report-ccdr/monthly-issue/2019-45/issue-4-april-4-2019/article-1-climate-change-infectious-diseases.html.

Rasmussen, D. J., *et al*. (2011). "Opportunities and Challenges in Assessing Climate Change Impacts on Wind Energy - A Critical Comparison of Wind Speed Projections in California." *Environmental Research Letters*, vol. 6, no. 2, doi:10.1088/1748-9326/6/2/024008.

Rauber, *et al*. "Ice Storms •Caused by an Accumulation of Freezing Rain - Ppt Video Online Download." SlidePlayer, https://slideplayer.com/slide/5977830/.

Sax, Christoph, and Peter Steiner. *Temporal Disaggregation of Time Series*. https://journal.r-project.org/archive/2013-2/sax-steiner.pdf. Accessed 25 Apr. 2019.

Schardong, A., & P. Simonovic, S. (2019). Application of Regional Climate Models for Updating Intensity-duration-frequency Curves under Climate Change. *International Journal of Environment and Climate Change*, *9*(5), 311–330. https://doi.org/10.9734/ijecc/2019/v9i530117

Schardong, A., Gaur, A., & Simonovic, S. P. (2018). Comparison of the theoretical Clausius-Clapeyron Scaling and IDF_CC tool for updating intensity-duration-frequency curves under changing climatic conditions in Canada. *Journal of Hydrologic Engineering*, *23*(9), 1–12. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001686

Šeparović L, Alexandru A, Laprise R, Martynov A, Sushama L, Winger K, Tete K, Valin M (2013) Present climate and climate change over North America as simulated by the fifth-generation Canadian Regional Climate Model (CRCM5). Clim Dyn 41(11-12):3167-3201. doi:10.1007/s00382-013-1737-5

Shaw, T. A., *et al*. (2016). "Storm Track Processes and the Opposing Influences of Climate Change." *Nature Geoscience*, vol. 9, no. 9, pp. 656–64, doi:10.1038/ngeo2783.

Sillmann, Jana, *et al*. (2017). "Understanding, Modeling and Predicting Weather and Climate Extremes: Challenges and Opportunities." *Weather and Climate Extremes*, vol. 18, no. August, Elsevier Ltd, pp. 65–74, doi:10.1016/j.wace.2017.10.003.

Simonovic, S. P., Schardong, A., & Sandink, D. (2017). Mapping Extreme Rainfall Statistics for Canada under Climate Change Using Updated Intensity-Duration-Frequency Curves. *Journal of Water Resources Planning and Management*, *143*(3), 04016078. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000725

Srivastav, R. K., Schardong, A., & Simonovic, S. P. (2014). Equidistance Quantile Matching Method for Updating IDFCurves under Climate Change. *Water Resources Management*, *28*(9), 2539–2562. https://doi.org/10.1007/s11269-014-0626-y

Stocks, Brian J. (2013). "Evaluating Past, Current and Future Forest Fire Load Trends in Canada." *B.J. Stocks Wildfire Investigations Ltd., Sault Ste. Marie, ON. 50 P.*, http://www.ccfm.org/pdf/2 Fire Load Trends.pdf.

Summit Entreprises International Inc. (2010). *Adapting to Climate Change: A Risk-based Guide for Local Governments V1 and V2*.

Switzman, H., Razavi, T., Traore, S., Coulibaly, P., Burn, D. H., Henderson, J., … Ness, R. (2017). Variability of future extreme rainfall statistics: Comparison of multiple IDF projections. *Journal of Hydrologic Engineering*, *22*(10), 1–20. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001561

Tam, Benita Y., *et al*. (2019) "CMIP5 Drought Projections in Canada Based on the Standardized Precipitation Evapotranspiration Index." *Canadian Water Resources Journal*, vol. 44, no. 1, Taylor & Francis, pp. 90–107, doi:10.1080/07011784.2018.1537812.

Teutschbein, C., & Seibert, J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology*, *456–457*, 12–29. https://doi.org/10.1016/j.jhydrol.2012.05.052

Thober, Stephan. *Evaluation and Disaggregation of Climate Model Outputs for European Drought Prediction*. 1984, www.reklim.de.

Tippett, Michael K., *et al*. (2015). "Climate and Hazardous Convective Weather." *Current Climate Change Reports*, vol. 1, no. 2, pp. 60–73, doi:10.1007/s40641-015-0006-6.

Trenberth, K. E., Dai, A., Rasmussen, R. M., & Parsons, D. B. (2003). The changing character of precipitation. *Bulletin of the American Meteorological Society*, Vol. 84, pp. 1205-1217+1161. https://doi.org/10.1175/BAMS-84-9-1205

Trenberth, Kevin E., *et al*. (2018). "Hurricane Harvey Links to Ocean Heat Content and Climate Change Adaptation." *Earth's Future*, vol. 6, no. 5, pp. 730–44, doi:10.1029/2018EF000825.

Trenberth, Kevin E., *et al*. (2007) "Water and Energy Budgets of Hurricanes: Case Studies of Ivan and Katrina." *Journal of Geophysical Research Atmospheres*, vol. 112, no. 23, pp. 1–11, doi:10.1029/2006JD008303.

Van Uytven, E., & Willems, P. (2018). Greenhouse gas scenario sensitivity and uncertainties in precipitation projections for central Belgium. *Journal of Hydrology*, *558*, 9–19. https://doi.org/10.1016/j.jhydrol.2018.01.018

Wang, J., & Kotamarthi, V. R. (2015). High-resolution dynamically downscaled projections of precipitation in the mid and late 21st century over North America. *Earth's Future*, *3*(7), 268–288. https://doi.org/10.1002/2015EF000304

Wang, X., & Huang, G. (2014). Technical Report: Developing Future Projected IDF Curves and a Public Climate Change Data Portal for the Province of Ontario. *Ieesc*, 81. Retrieved from http://www.ontarioccdp.ca/final_tech_report.pdf

Wang, X., Huang, G., & Liu, J. (2014). Projected increases in intensity and frequency of rainfall extremes through a regional climate modeling approach. *AGU PPublications*, *175*(4449), 238. https://doi.org/10.1038/175238c0

Wang, X., Huang, G., Liu, J., Li, Z., & Zhao, S. (2015). Ensemble projections of regional climatic changes over Ontario, Canada. *Journal of Climate*, *28*(18), 7327–7346. https://doi.org/10.1175/JCLI-D-15-0185.1

Webster, P. J., *et al*. (2005) "Atmospheric Science: Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment." *Science*, vol. 309, no. 5742, pp. 1844–46, doi:10.1126/science.1116448.

Wells, G. (1996). “Hazard Identification and Risk Assessment.” *Hzard Identification and Risk Assessment*.

Werner, A. T., & Cannon, A. J. (2016). Hydrologic extremes - An intercomparison of multiple gridded statistical downscaling methods. *Hydrology and Earth System Sciences*, *20*(4), 1483–1508. https://doi.org/10.5194/hess-20-1483-2016

Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., … Roberts, N. M. (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

Wey, Karen M. (2006). *Temporal Disaggregation of Daily Precipitation Data in a Changing Climate*. Waterloo,https://uwspace.uwaterloo.ca/bitstream/handle/10012/2859/kmwey2006.pdf?sequence=1&isAllowed=y.

Wilby, R. L. (2010). Evaluating climate model outputs for hydrological applications. *Hydrological Sciences Journal*, *55*(7), 1090–1093. https://doi.org/10.1080/02626667.2010.513212

Wilby, R. L., Dawson, C. W., Murphy, C., O’Connor, P., & Hawkins, E. (2014). The Statistical DownScaling Model -Decision Centric (SDSM-DC): Conceptual basis and applications. *Climate Research*, *61*(3), 251–268. https://doi.org/10.3354/cr01254

Wild, Martin, *et al*. (2015) “Projections of Long-Term Changes in Solar Radiation Based on CMIP5 Climate Models and Their Influence on Energy Yields of Photovoltaic Systems.” *Solar Energy*, vol. 116, 2015, pp. 12–24, doi:10.1016/j.solener.2015.03.039.

Wong, J. S., Razavi, S., Bonsal, B. R., Wheater, H. S., & Asong, Z. E. (2017). Inter-comparison of daily precipitation products for large-scale hydro-climatic applications over Canada. *Hydrology and Earth System Sciences*, *21*(4), 2163–2185. https://doi.org/10.5194/hess-21-2163-2017

Wotton, B. M., *et al*. (2010) “Forest Fire Occurrence and Climate Change in Canada.” *International Journal of Wildland Fire*, vol. 19, no. 3, pp. 253–71, doi:10.1071/WF09002.

Wu, Jian, *et al*. (2018) “Changes in Terrestrial Near-Surface Wind Speed and Their Possible Causes: An Overview.” *Climate Dynamics*, vol. 51, no. 5–6, Springer Berlin Heidelberg, doi:10.1007/s00382-017-3997-y.

Yair, Yoav. (2018) “Lightning Hazards to Human Societies in a Changing Climate.” *Environmental Research Letters*, vol. 13, no. 12, IOP Publishing, doi:10.1088/1748-9326/aaea86.

Yang, W., *et al*. (2015) “Forest Fire Risk Assessment in Sweden Using Climate Model Data: Bias Correction and Future Changes.” Natural Hazards and Earth System Sciences Discussions, vol. 3, no. 1, pp. 837–90, doi:10.5194/nhessd-3-837-2015.

Yao, Yao, *et al*. (2012) “Climate Change Impacts on Ontario Wind Power Resource.” Environmental Systems Research, vol. 1, no. 1, p. 2, doi:10.1186/2193-2697-1-2.

Zhang, X., *et al*. (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.

Zhang, X., Zwiers, F. W., Li, G., Wan, H., & Cannon, A. J. (2017). Complexity in estimating past and future extreme short-duration rainfall. *Nature Geoscience*, *10*(4), 255–259. https://doi.org/10.1038/ngeo2911

Zhang, Xuebin, *et al*. (2011) “Indices for Monitoring Changes in Extremes Based on Daily Temperature and Precipitation Data.” Wiley Interdisciplinary Reviews: Climate Change, vol. 2, no. 6, pp. 851–70, doi:10.1002/wcc.147.

Zwiers, F.W. (2017). "Challenges in understanding and projecting precipitation extremes, 121-134, climate change & codes implementation." In Proc., Int. Workshop,121–134. Ottawa: National Research Council Canada.

"Climate Change and Extreme Snow in the U.S." National Climatic Data Center, https://www.ncdc.noaa.gov/news/climate-change-and-extreme-snow-us.

"More Evacuation Alerts as Wildfires Tear through Ontario, B.C." APTN News, 24 July 2018, https://aptnnews.ca/2018/07/24/more-evacuation-alerts-as-wildfires-tear-through-ontario-b-c/.

"Ottawa's Record Snow Day: Three Ways of Picturing White Tuesday's Aftermath." The Globe and Mail, 12 Nov. 2017, https://www.theglobeandmail.com/news/national/ottawas-record-snow-day-three-ways-of-picturing-white-tuesdaysaftermath/article28779734/.

"Ottawa's Wild Weather 'the Tip of the Iceberg,' Some Experts Say | CBC News." CBC News, CBC/Radio Canada, 4 June 2019, https://www.cbc.ca/news/canada/ottawa/tornado-climatologist-june-3-1.5159862.

"Preparing for the next Tornado." Ottawa Business Journal, https://obj.ca/article/uottawa-engineering-preparing-next-tornado.

"These Are All the Hurricanes That Hit Canada since 1900 | CBC News." CBCnews, CBC/Radio Canada, 22 Sept. 2017, https://www.cbc.ca/news/canada/montreal/hurricane-history-canada-1.4284076.

"These Are All the Hurricanes That Hit Canada since 1900 | CBC News." CBCnews, CBC/Radio Canada, 22 Sept. 2017, https://www.cbc.ca/news/canada/montreal/hurricane-history-canada-1.4284076.

"Tornado Basics." NOAA National Severe Storms Laboratory, https://www.nssl.noaa.gov/education/svrwx101/tornadoes/