Localized Climate Projections for Waterloo Region

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Prepared for: Cambridge; Kitchener; The City of Waterloo; Region of Waterloo

Cover photos:

- *Top:* The rooftop of the Seagram Lofts provides a bird's eye view of a deadly thunderstorm rolling in over Uptown Waterloo on September 5, 2014. Credit: Jason Thistlethwaite
- *Bottom left:* Hail in Waterloo Region on August 2, 2015. Credit: Jason Thistlethwaite
- *Bottom right:* Flash flooding at Fairview Park Mall in Kitchener on June 28, 2013. Credit: Driveseat Kitchener via CTV News Kitchener

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Executive Summary

Addressing climate change is one of the global challenges of this century. Regions across Canada are experiencing changing climatic conditions such as higher average temperatures, new precipitation patterns, and increased frequency and severity of extreme weather events (e.g. heat waves, intense rainfall, and strong winds)[1]. These changes are having a variety of impacts on ecosystems and everyday life in Canadian communities, including property damage and infrastructure failure during extreme events, shifting growing seasons, a range of economic losses (e.g., construction delays, crop damage, tourism patterns), increased health risks posed by extreme weather, and shifts in the ranges of pests and infectious disease.

Climate adaptation refers to measures taken to reduce the vulnerability of natural and human systems to actual or expected effects of climate change. In addition to efforts to mitigate climate change by reducing greenhouse gas (GHG) emissions, the importance of climate adaptation is rising across Canada. Municipalities are being called upon to respond to vulnerabilities exposed by current changing conditions and recent extreme weather events, as well as to prepare for both risks and opportunities that may arise given longer-term local climate impacts. The City of Windsor and the City of Toronto, for example, have developed climate adaptation plans that were driven largely in response to extreme heat and urban flooding pressures affecting their respective communities. To enable effective adaptation planning and action that builds community resilience, it is imperative for municipal decision-makers to have access to locally-relevant and robust climate projections that examine how temperature and precipitation are expected to change in the future.

The effort to develop localized climate projections for Waterloo Region was initiated in response to the need expressed by municipal staff to gain a greater understanding of climate-related risks that are relevant to our region as a means to inform municipal strategic and collaborative planning. The University of Waterloo's Interdisciplinary Centre on Climate Change (IC3) prepared this report to contribute to ongoing climate collaborations on climate action between the Cities of Cambridge, Kitchener, and Waterloo, and the Region of Waterloo. The purpose of the report is to summarize information on projected climate change for our local region that could aid in advancing a local dialogue on climate adaptation planning and extreme weather resilience.

How are localized climate projections developed?

The process of developing climate projections uses both historical weather data for this region as well as an ensemble of climate models, which provide the best available scientific assessment of how future social and economic conditions will influence the global climate system and climate in this region.

[1] Warren, F.J. and Lemmen, D.S., editors (2014): Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation; Government of Canada, Ottawa, ON, 286p.

For Waterloo Region, projections for a number of climate parameters of interest to municipal stakeholders (e.g. monthly mean temperature, seasonal precipitation) have been provided for three different time periods: the 2020s, 2050s, and 2080s (respectively covering the years of: 2011-2040, 2041–2070, and 2071-2100). The projected changes in climate are relative to historical data from the 1990s (1981-2010) as the baseline (or "observed") period. Across each of these time periods, three different future GHG emissions scenarios are examined:

- A net-zero carbon emission scenario that would be necessary to limit global warming to 2^{o}C;
- An aggressive emission reduction scenario consistent with the emission reduction pledges of countries; and,
- A business-as-usual (BAU) emission trajectory.

Our current trajectory as a global society is in line with the BAU scenario, and recent global efforts to curb GHG emissions have not yet been substantial enough to deviate from this path. The other two scenarios considered here are still plausible; however, substantial international commitment will be required to reduce emissions to the levels on which those scenarios are based.

Which climate conditions are projected to change in Waterloo Region, by how much, and by when?

Temperature:

- Annual mean temperature is projected to increase by about 2-3^{o}C by the 2050s across all emission scenarios.
- Increases in monthly temperatures are projected to be the most marked throughout the winter and into early summer (see Table ES1). For example, under all scenarios the monthly mean temperature in February in 2050s in expected to be 3-5^{o}C warmer than it is today, pushing the average temperature for the month closer to, or slightly above, 0^{o}C.
- Currently, the region experiences around 10 days per year with extreme heat (daily maximum temperature exceeding 30^{o}C). Under a BAU scenario, the number of days with extreme heat is projected to more than triple to 32 days by the 2050s, and then nearly double again to 60 days by the 2080s (see Figure ES1).
- Currently, around 22 days per year are observed with extremely cold temperatures (daily minimum temperature lower than -15^{o}C). A reduction in the number of extremely cold days is projected under all scenarios, with less than half as many extreme cold days occurring in the 2020s as were recorded during the 1990s, and further reductions occurring over the rest of the century (as few as 6 days by the 2080s under a BAU scenario).

Table ES1: Range of projected changes for Waterloo Region by the 2050s compared to the 1990s

	Temperature Change (^{o}C)		Precipitation Change (%)	
Scenario	*Summer*	*Winter*	*Summer*	*Winter*
Net-zero carbon	**+ 1.1 to 2.1**	**+ 1.1 to 2.9**	**6.3 to 21.5%**	**-5.0 to 17.1%**
Aggressive mitigation	**+ 1.6 to 2.6**	**+ 1.8 to 3.7**	**-3.8 to 22.2%**	**6.1 to 20.4%**
Business-as-usual	**+ 2.8 to 3.5**	**+ 2.8 to 4.4**	**5.5 to 25%**	**4.7 to 26.9%**

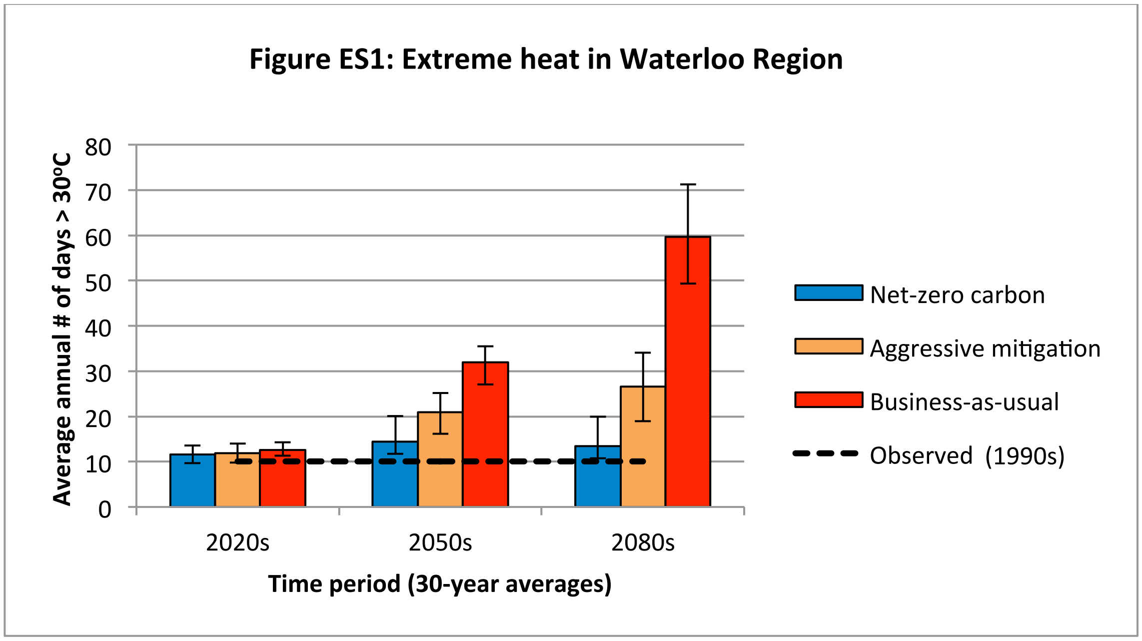

Figure ES1 demonstrates the average annual number of days projected to reach extreme heat conditions, which is defined as days where maximum air temperatures reach or exceed 30^{o}C. These values are shown in comparison to the observed average value (10 days) for the 1990s period. Error bars represent the range of uncertainty for the multi-model ensemble.

Precipitation:

- Total annual precipitation is projected to increase by approximately 4-6% by the 2020s, and by approximately 8-12% in the 2050s and 2080s (see Table ES1).
- Seasonally, the largest precipitation increases are expected in winter, spring, and summer, although the magnitude of change in summer is associated with the largest range of uncertainty due to a lack of consensus between climate models.

- Increased amounts of precipitation are likely to initially result in increases in total annual snow in the 2020s, yet into the 2050s and 2080s, warmer winter temperatures are likely to cause less precipitation to fall in the form of snow, compared to today's climate.
- In Southern Ontario, the months of December, January, and February are expected to experience 40% more freezing rain events by the 2050s, and 45% more freezing rain events by the 2080s.
- Rainfall intensities are projected to increase across all scenarios and time periods, with large-magnitude rainfall events expected to occur more frequently than in the historical record. If the variability of precipitation events does not change, then climate change is projected to slightly decrease the frequency of 6-day dry spells from an average of 14 to 13 events occurring per year by the 2050s.

Wind:

- More wind gust events are expected in Southern Ontario by the end of the century, as both large-scale frontal storms and local convective windstorms are projected to occur more frequently.

What action can be taken at the municipal level to respond to these projected changes?

Successful adaptation to climate change requires a robust range of projections on how the local climate is expected to evolve as well as an understanding of the remaining scientific uncertainties. Projections can be considered the starting point towards developing a shared base of information upon which to develop a plan and specific responses or projects. Having access to future scenarios of what climate is expected to look like in Waterloo Region is one of the foundational steps of an adaptation planning process, along with identifying stakeholders and assessing current climate impacts (both risks and opportunities). Using localized climate projections and other community knowledge as inputs, a full assessment of potential impacts and vulnerability across community assets and services can begin.

Contents

List of Figures

List of Tables

1.0 Introduction

Addressing climate change is one of the global challenges of this century. Regions across Canada are experiencing changing climatic conditions such as higher average temperatures, new precipitation patterns, and increased frequency and severity of extreme weather events (e.g. heat waves, intense rainfall, and strong winds)[2]. These changes are having a variety of impacts on ecosystems and everyday life in Canadian communities, including property damage and infrastructure failure during extreme events, shifting growing seasons, a range of economic losses (e.g., construction delays, crop damage, tourism patterns), increased health risks posed by extreme weather, and shifts in the ranges of pests, invasive species and infectious disease. Regardless of actions that have been taken or are planned in efforts to reduce greenhouse gas (GHG) emissions both locally and worldwide, all scenarios modelled for the future indicate that some degree of climate change will persist over the course of this century. The questions that remain are, which conditions will change in certain regions, by how much; and, how will our communities adapt?

In addition to efforts to mitigate climate change by reducing GHG emissions, the importance of climate adaptation is rising across Canada. Climate adaptation refers to measures taken to reduce the vulnerability of natural and human systems to actual or expected effects of climate change. Municipalities are being called upon to respond to vulnerabilities exposed by current changing conditions and recent extreme weather events, as well as to prepare for both risks and opportunities that may arise given longer-term local climate impacts. The City of Windsor and the City of Toronto, for example, have adopted climate adaptation plans that were driven largely in response to extreme heat and urban flooding pressures felt in their respective communities. To enable effective adaptation planning and action that builds community resilience, it is imperative for municipal decision-makers to have access to locally-relevant and robust climate projections that examine how temperature and precipitation are expected to change in the future.

1.1 Report purpose and context

Climate models allow us to conduct safe, controlled, and reproducible experiments with the Earth's climate system that can be used to make projections about how the global climate will change in the future. The purpose of this report is to summarize information on projected local climate change for Waterloo Region. Having access to localized, or downscaled, climate projections will provide some of the base knowledge and information needed to guide thoughtful adaptation planning and extreme weather resilience in Waterloo Region.

[2] Warren, F.J. and Lemmen, D.S., editors (2014): Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation; Government of Canada, Ottawa, ON, 286p.

In 2013, the Cities of Cambridge, Kitchener and Waterloo, and the Region of Waterloo collectively developed and unanimously endorsed a Climate Action Plan to provide Waterloo Region with a relevant course of action for addressing climate change *mitigation* at a local level. To complement this work, municipal staff have continued to come together to discuss issues and coordinate actions related to climate change *adaptation.*

In October of 2014, the Interdisciplinary Centre on Climate Change (IC3) at the University of Waterloo (UW), in partnership with the Region of Waterloo, convened a forum to advance a dialogue on climate adaptation planning and extreme weather resilience in Waterloo Region. The forum was intended to be a preliminary workshop where staff from the Region and area municipalities could gain a greater understanding of the climate change issues that are relevant to our region as a means to inform municipal strategic and collaborative planning.

The forum illuminated the fact that many local stakeholders are looking for the same information. A priority was identified: "Conduct a comprehensive study on localized climate projections which will help to communicate what the potential changing conditions are and also to better assess risk and plan for medium and long term action." To act on this next step, a localized climate projections study was conducted by a research team at UW in collaboration with four local municipalities: the Cities of Cambridge, Kitchener, and Waterloo, and the Region of Waterloo.

1.2 Study area

This study encompasses the geographical area of Waterloo Region, which is covered by the political jurisdictions of a regional municipality (Region of Waterloo), three urban municipalities (City of Cambridge, City of Kitchener, and City of Waterloo), and four rural townships (Township of North Dumfries, Township of Wellesley, Township of Wilmot, and Township of Woolwich).

As shown in Figure 1.1, Waterloo Region lies centrally in Southern Ontario, approximately 50 kilometres west of Lake Ontario on the western edge of Ontario's greenbelt. The entire region falls within the Grand River watershed, which has headwaters north of Waterloo Region in Dufferin County, and flows southbound through Southwestern Ontario before emptying into Lake Erie.

The climate projections within this report have been localized specifically to this study area, to ensure that the broader implications of global climate change can be understood in terms of local impacts.

Figure 1.1: Location of study area (Waterloo Region, Ontario, Canada)[3]

1.3 What is the difference between weather and climate?

This report presents projections for future climate. One might wonder how the long-term statistics of climate relate to the day-to-day weather we experience. Weather and climate are differentiated by a measure of time. Weather is the conditions of the atmosphere over a short period of time, and climate is the long-term behaviour or trends of the atmosphere. NASA offers a further interpretation of this difference as follows: "Weather can change from minute-to-minute, hour-to-hour, day-to-day, and season-to-season. Climate, however, is the average of weather over time and space. An easy way to remember the difference is that climate is what you expect, like a very hot summer, and weather is what you get, like a hot day with pop-up thunderstorms."[4] Climate is often studied by analyzing average monthly quantities over minimum 30-year periods, which is a standard endorsed by the World Meteorological Organization. This focus on long-term statistics also allows climate scientists to be reasonably confident in projecting changes that are expected decades from now, even as predicting exact weather conditions beyond 1-2 weeks remains challenging.

[3] Map of Waterloo Region. <http://www.remaxsolidgold.biz/Docs/REM028Docs/Submit/explore_map.jpg>
[4] NASA. 2005. What's the difference between weather and climate? <http://www.nasa.gov/mission_pages/noaa-n/climate/climate_weather.html>

2.0 Overview of the modelling process

2.1 Why use climate modelling?

A climate model is a complex series of mathematical algorithms and equations that represent the different components of the climate system[5]. By dividing the earth into thousands of three-dimensional grid boxes, a climate model can track the ways in which energy, water, GHGs, aerosols, and many other components of the atmosphere, ocean, and land interact across the globe. One of the greatest strengths of climate models is that they allow us to conduct safe, controlled, and reproducible experiments with the Earth's climate system that would otherwise be impossible. With these capabilities, models can be used to make projections about how the global climate will change in the future.

There is not a single climate model that is universally relied upon, but rather a variety of independently-developed models are used in combination to produce the best results. Examining data from multiple models minimizes any errors that may exist within a single model, helps to identify which results are most robust, and improves our confidence in the projections that are being made for the future[5].

Consistent with best practices, this study uses the most recent climate data from a full ensemble of the latest generation of climate models (Coupled Model Intercomparison Project version 5 - CMIP5).

2.2 What is statistical downscaling?

While climate models are powerful tools for understanding global and regional change, the vast computing resources required to run a model limit its spatial resolution to grid boxes of around 100km by 100km in size. Bridging the gap between this climate model output and the more fine-resolution data needed to assess local impacts is one of the major challenges facing current climate change studies[6], but a number of different statistical and dynamical downscaling techniques have been developed for precisely this purpose. Dynamical downscaling relies on running regional climate models which are driven at their boundaries by global models; an appealing but computationally expensive approach[7]. An alternative approach is statistical downscaling, which requires analysis of the relationships between variables over time[7]. This is a more accessible and widely used method, and thus it has been used to produce the projections in this report. Creating a downscaled, or "localized", picture of what climate change will look like at the local level is useful for building understanding and informing planning processes.

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[5] Müller, P. (2010). Constructing climate knowledge with computer models. *WIREs Climate Change, 1*, 565-580. doi:10.1002/wcc.60

[6] Fatichi, S., Ivanov, V. Y., & Caporali, E. (2011). Simulation of future climate scenarios with a weather generator. *Advances in Water Resources, 34*, 448-467. doi:10.1016/j.advwatres.2010.12.013

[7] Gaitan, C. F., Hsieh, W. W., Cannon, A. J., & Gachon, P. (2014). Evaluation of Linear and Non-Linear Downscaling Methods in Terms of Daily Variability and Climate Indices: Surface Temperature in Southern Ontario and Quebec, Canada. *Atmosphere-Ocean, 52*(3), 211-221. doi:10.1080/07055900.2013.857639

The results presented within Section 3 of this report have been localized, wherever possible, to the level where changes in temperature, precipitation, and wind are spatially relevant for the Waterloo Region area. When used throughout this report, the term “localized climate projections” refers to global climate projections that have been statistically downscaled.

2.3 Greenhouse gas emission (GHG) scenarios

Compounds such as carbon dioxide, methane, and nitrous oxide are commonly referred to as GHGs. In the atmosphere these gases absorb and emit infrared radiation, which provides a warming effect for the globe. The existence of this “greenhouse effect” has been understood since the 1820s, with the processes and chemistry involved becoming more effectively quantified towards the end of the 19th century. The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 to provide a forum for scientists around the world to advance our understanding of climate change. Since GHGs can persist in the atmosphere for decades or even centuries, predicting how they will accumulate over time is crucial to gaining an understanding of future climate change.

An emissions scenario represents one plausible representation of future GHG emissions, with each scenario being based on different assumptions regarding human activities such as rates of economic growth, technological development, and changes in land use. Since we cannot predict the future of human development, there is no “best” scenario to use – all of them are plausible. In fact, best practice is to consider a full range of scenarios to understand different possible outcomes.

There are three scenarios considered in this report, each of which has a scientific identifier code and has also been assigned a plain-language identifier to help understand what kind of world we would be living in under each of the scenarios. “RCP” is short-form for a “representative concentration pathway”. This term is meant to emphasize that both the eventual concentration of GHGs in the atmosphere and the trajectory taken over time to reach these values are important. The associated numbers quantify the magnitude of the effect that GHG concentrations in each scenario would have on the global energy balance. The scenarios used for this study are described below.

> **RCP 8.5** represents a future where regular economic growth continues without regard for reducing GHG emissions. Our current trajectory as a global society is in line with this scenario, and recent global efforts to curb GHG emissions have not yet been substantial enough to deviate from this path. The other scenarios considered here are still plausible, but substantial international commitment, technological, societal, and economic transformation will be required to reduce emissions to these levels. In this study, RCP 8.5 is referred to as **“business-as-usual”.**
>
> **RCP 4.5** is an optimistic scenario that relies on global emissions increasing slowly and reaching a peak around 2050, before drastically declining towards the end of the century. It is a scenario

that would require major international cooperation to aggressively reduce emissions. In this study, RCP 4.5 is referred to as **"aggressive mitigation".**

The **RCP 2.6** scenario represents a future where there is strong and immediate global commitment to drastically reduce GHG emissions, with emissions peaking in approximately 2020 and declining substantially thereafter until net-zero emission levels are reached by the end of the century. Net-zero refers to a situation where GHG emissions are effectively balanced by natural or artificial sequestration processes that remove these gases from the atmosphere. While it is considered an incredibly optimistic scenario, it is important to include as it is the only scenario that meets the internationally agreed upon target of limiting the increase in global mean temperature to 2^{o}C above pre-industrial levels. This 2^{o}C target is the level beyond which anthropogenic interference with the climate system could become dangerous[8], with substantial negative effects being felt around the globe. The IPCC has suggested that at the current rates of global emissions, a temperature of 2^{o}C is likely to be exceeded by 2040[9]. In this study, RCP 2.6 is referred to as **"net-zero carbon."**

2.4 Summary of methodology

The process used to generate the localized climate projections for Waterloo Region presented in this report followed three overall steps:

1. **Scoping and data collection** - A list of climate parameters of interest to key stakeholders was assembled (e.g. duration and intensity of rainfall events, temperature, wind, etc.). Modelling scenarios, a baseline period and projection periods were also chosen, and local weather data was collected (see Table 2.1). The baseline period of 1981-2010 represents the most recent 30-year period for which complete weather data was available for Waterloo Region. However, some recent climate warming has already been observed in Waterloo region: around 0.3^{o}C since the 1960s. Climate data from these earlier time slices shows that the average annual temperature was 6.7^{o}C in the 1960s, 6.6^{o}C in the 1970s, and 6.7^{o}C in the 1980s. This has increased to 7.0^{o}C in our 1990s baseline period, indicating that some degree of climate change has already occurred. However, a lack of quality, consistent data for Waterloo Region made comparisons with these earlier time periods difficult.
2. **Statistical downscaling -** Downscaled projections for Waterloo Region were completed for as many parameters as possible based on data availability and modelling capacity. The methods used for this study involve utilizing the LARS-WG weather generator to derive a variety of climate statistics using observed weather data for Waterloo Region[10]. Factors of change were then determined by calculating the difference between climate model data for the baseline and

[8] Avoiding Dangerous Climate Change: A Scientific Symposium on Stabilisation of Greenhouse Gases (2005)
[9] Freedman, A. (2013). IPCC Report Contains 'Grave' Carbon Budget Message. *Climate Central.*
[10] Semenov, M. A., & Barrow, E. M. (2002). *A stochastic weather generator for use in climate impact studies.*

future periods, and these change factors were applied to the derived climate statistics to generate a new series of simulated observations for analysis[6,11]). This approach of using a weather generator has been successful in reproducing the statistical characteristics of the observed climate in locations around the world, including Southern Ontario[12,13,14].

3. **Literature review -** To fill any gaps where localized projections could not be produced for Waterloo Region, scientific literature related to downscaled climate projections for Southern Ontario was reviewed. This literature was from locations in proximity and/or characteristically similar to Waterloo Region, and included river basins and weather stations in and around the cities of London, Hamilton, and Toronto.

A full account of the methodology used in this study can be found in Appendix A.

Table 2.1: Components of the modelling process

Scenarios (see Section 2.3)	RCP 8.5 "business-as-usual" RCP 4.5 "aggressive mitigation" RCP 2.6 "net-zero carbon
Baseline Period	1990s (1981-2010)
Projection Periods	2020s (2011-2040) 2050s (2041-2070) 2080s (2071-2100)
Input Data	Environment Canada weather data from the Waterloo Region Airport weather station, supplemented with data from Roseville weather station as needed.
Model Data	Historical and future runs from a 22-member ensemble of CMIP5 climate models. A list of models used can be found in Appendix A.

[11] Wilks, D. S., & Wilby, R. L. (1999). The weather generation game: a review of stochastic weather models. *Progress in Physical Geography, 23*(3), 329-357. doi:10.1177/030913339902300302
[12] Hashmi, M. Z., Shamseldin, A. Y., & Melville, B. W. (2009). Downscaling of future rainfall extreme events: a weather generator based approach. *18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009,*3928-3934.
[13] Irwin, S. E., Sarwar, R., King, L. M., & Simonovic, S. P. (2012). *Assessment of Climatic Vulnerability in the Upper Thames River Basin: Downscaling with LARS-WG.* (No. 081). London, Ontario, Canada: Department of Civil and Environmental Engineering, The University of Western Ontario.
[14] King, L. M., Irwin, S., Sarwar, R., McLeod, A. I., & Simonovic, S. P. (2012). The Effects of Climate Change on Extreme Precipitation Events in the Upper Thames River Basin: A Comparison of Downscaling Approaches. *Canadian Water Resources Journal, 37*(3), 253-274. doi:10.4296/cwrj2011-938

2.5 Understanding uncertainty

Climate projections are powerful tools, but must be used within an understanding of their limitations. The climate system is incredibly complex, and the term *uncertainty* refers to all aspects of climate science and global socio-economic futures that are unknown, such as the parameters and structure of climate models, the future global emissions trajectory, and even our instrumental weather observations. Capturing this range of uncertainty allows us to determine the fraction of future change that is due to our imperfect models, compared to the fraction due to our decision-making (emissions scenarios) and natural fluctuations. Another important contributor to the uncertainty range is the parameter itself. For example, there is more of a consensus amongst climate models about how mean values will change than about how extreme values will change, as projecting the frequency and intensity of rare events is far more difficult to evaluate. In general, projections for temperature are also more consistent between all climate models than projections for precipitation.

For this project, we have used confidence limits that represent the interquartile (25^{th} to 75^{th} percentile) range of our 22-model ensemble for each parameter. Percentiles can be thought of as a ranking of all models, from those projecting the most warming to the least. We are thus looking at the 11 total models that straddle the central value of the ensemble, as this value represents our best guess for the most likely change. Values presented in tables represent the mean value from the entire ensemble of climate models. Values in graphs show the median value, with the error bars representing the 25^{th} and 75^{th} percentiles of the ensemble. In most cases the median and mean are indistinguishable, so only mean values are reported in the text.

Changes are determined to be significant when the range of uncertainty (represented by the 25^{th}-75^{th} percentile error bars) separate from the observational mean. This indicates a parameter has undergone an important change from the conditions of the baseline period, and should be particularly noted as examples of new local climatic conditions that must be addressed.

Comparisons with Previous Assessments and Reports

The projections within this report are a reflection of the methodology used to generate them. Over the course of preparing this report, care has been taken to compare our results with other available climate projections for Southern Ontario and understand any differences that may exist. Generally any inconsistencies noted result from other studies using different ensembles of climate models, emissions scenarios, time periods, and downscaling methodologies. Through these comparisons we have verified that the downscaled projections presented here are broadly consistent with previous assessments and reports, and are within a range of uncertainty consistent with other research. Studies that incorporate the results of fewer models, or older versions of these models, must be interpreted in this light.

As noted above, this project uses output from a 22-member ensemble of state-of-the-art climate models, with the range of uncertainty reported as the middle 50% of these models for each parameter.

The climate models themselves have been substantially updated in the intervening years between CMIP3 and CMIP5, with modeling groups continuously working on improving resolutions, adding additional physical processes, and refining parameterizations.

Developing new emissions scenarios has been another advancement in research on climate change. Older studies will typically make use of the scenarios developed in the Special Report on Emissions Scenarios (SRES) developed by the Intergovernmental Panel on Climate Change[15]. It is thus useful to note brief comparisons between these older scenarios and the RCP scenarios used in this report[16].

- RCP 8.5 is roughly comparable to SRES A1FI. Temperatures in RCP 8.5 rise more slowly than A1FI between 2035 and 2080, and more quickly in other parts of the century.
- RCP 4.5 is comparable to SRES B1. Temperatures in RCP 4.5 rise more quickly than B1 until mid-century, and more slowly afterwards.
- RCP 2.6 has no analogue amongst the SRES scenarios, which did not consider a future scenario with net-zero carbon emissions.

It must be noted that all projections for changes in extreme quantities (such as extreme temperatures, precipitation, and return periods) were calculated using mean quantities only, and assuming no changes in variance would occur in the future. This was necessary due to daily-scale climate model data being unavailable, meaning that no reliable estimate of changes in temperature or precipitation variability could be made. Thus, estimates for temperature and precipitation extremes are necessarily very conservative, and likely represent a lower bound for the expected changes.

[15] Intergovernmental Panel on Climate Change. (2000). IPCC Special Report: Emissions Scenarios.
[16] Rogelj, J., Meinshausen, M., & Knutti, R. (2012). Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change, 2*, 248-253. doi:10.1038/nclimate1385

3.0 Localized climate projections for Waterloo Region

The following section presents a selection of key results from the localized climate projections study completed for Waterloo Region, including:

- Mean temperature (annual mean temperature, monthly mean temperature)
- Extreme temperature thresholds (extreme heat, extreme cold, days below freezing, and freeze-thaw cycles)
- Degree days (heating demand, cooling demand, growing degree days)
- Total precipitation (total annual and seasonal precipitation, days with precipitation, snowfall, freezing rain, wet and dry spells, precipitation return periods)
- Wind gusts

Results are presented by parameter, with each section containing basic information on what each parameter is and how it was calculated, climate projection data in tabular or graphical format, and some explanation or context for these results. Full results from the climate model downscaling exercise can be found in Appendix B.

3.1 Mean temperature

Annual mean temperature

Mean temperature is the average of the maximum and minimum temperatures recorded each day. Averaging all of the daily mean temperatures for one year gives an annual mean temperature for each year, which has then in turn been averaged across each 30-year period. This calculation smooths out the effects of year-to-year variability and provides the clearest signal for climatic trends. While an annual mean temperature value has little practical relevance in itself, it is a common metric for analyzing the overall effects of climate change on temperature and helps to relate global mean warming to the local scale.

For this area, all scenarios result in a similar amount of warming until around mid-century. This is due to warming that has already been committed to as the climate system catches up with all the additional greenhouse gases that have been emitted since the time of the Industrial Revolution. Emissions scenarios diverge to a greater extent after about 2050, as the climate change that occurs after that point is strongly dependent on the decisions made over the next few decades.

Table 3.1: Change in average annual mean temperature from 1990s baseline of 7^{o}C in Waterloo Region (^{o}C)

	2020s	2050s	2080s
Business-as-usual	+1.4	+3.2	+5.2
Aggressive mitigation	+1.2	+2.4	+2.9
Net-zero carbon	+1.2	+1.8	+1.7

Projections indicate that, irrespective of emissions scenario, the annual mean temperature for Waterloo Region is very likely to increase by about 2-3°C by the middle of the century (*Table 3.1*). This equates to increases of 2-3°C in both average maximum and minimum daily temperatures over the course of a year. If extensive mitigation is pursued then this temperature increase largely stabilizes by 2100, while in the business-as-usual scenario, average temperatures are projected to rise further to more than 5°C higher than the 1990s average (Figure 3.1). The projected increases reported here must also be understood in the context of the climate change that has already occurred, as a climatic warming of 0.3°C has been observed at the Waterloo Airport weather station between the 1961-1990 period and our baseline period of 1981-2010.

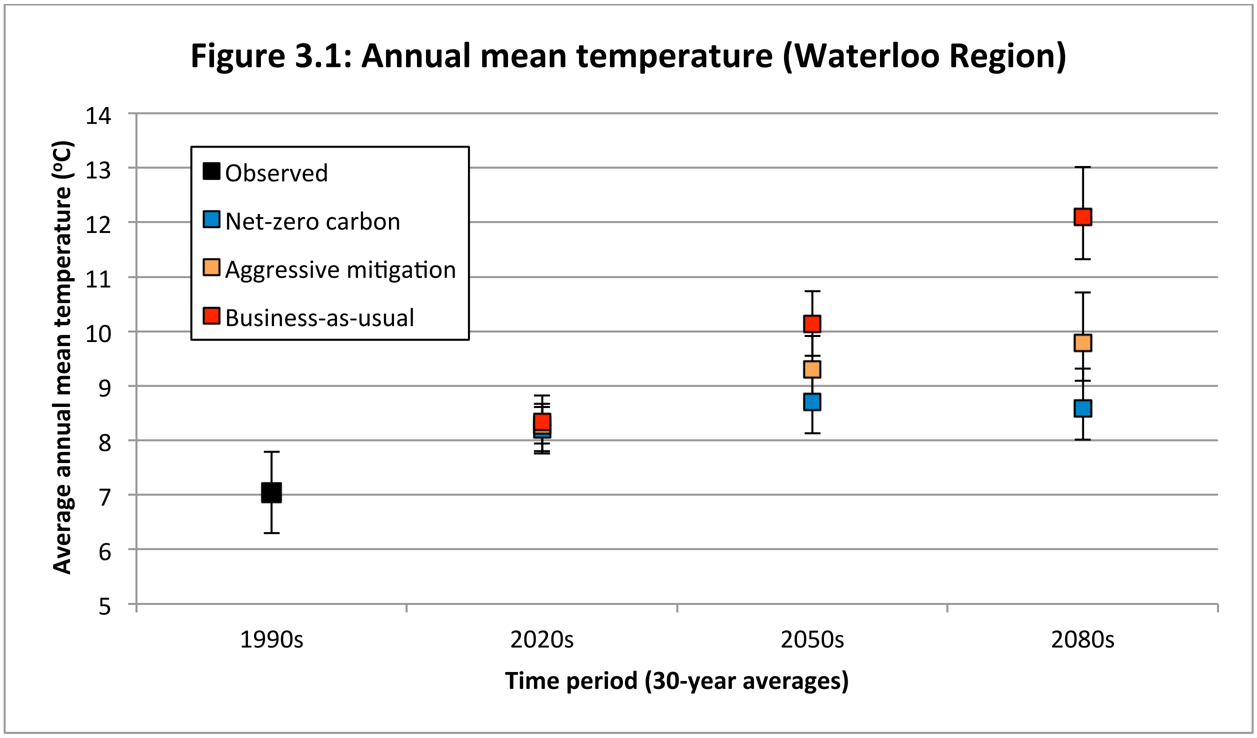


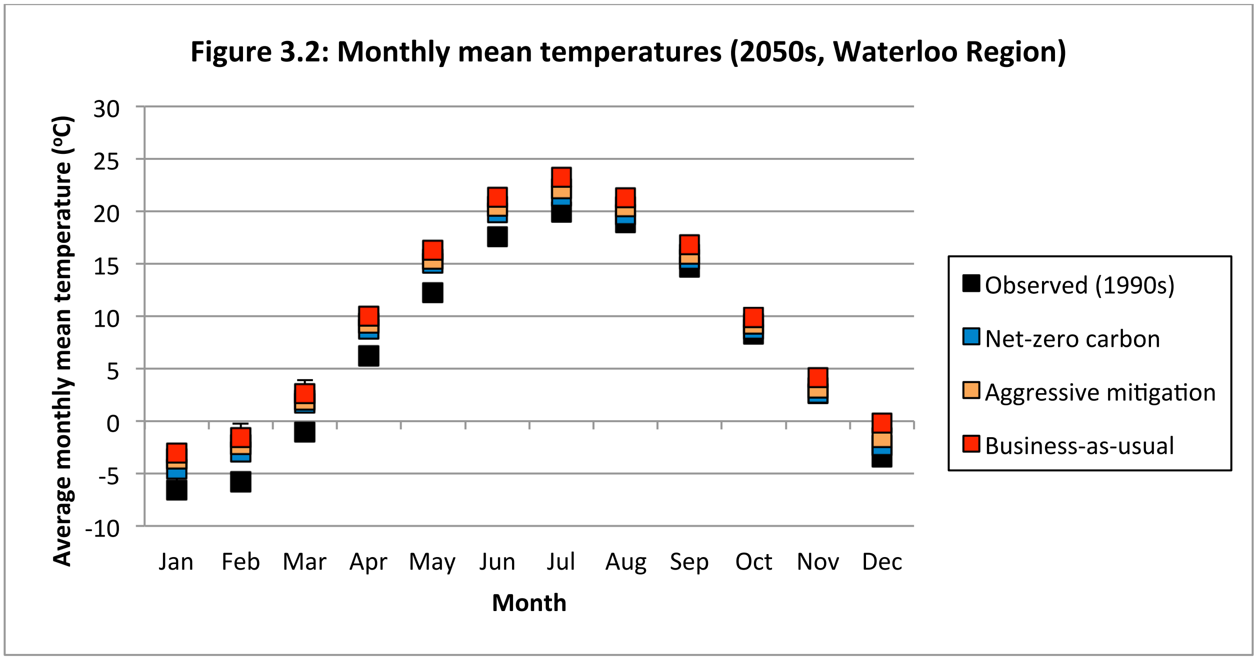
Figure 3.1 shows average annual mean temperature for Waterloo Region for three different emissions scenarios across three time periods. Coloured squares represent the median value, while the error bars are associated with the 25th and 75th percentiles of the CMIP5 ensemble.

Monthly mean temperature

While annual mean temperature statistics are useful to show a general warming trend, looking at monthly mean temperature can provide seasonal information that is more relevant for planning at the local level. Monthly mean temperature data for the 2050s show that across all three scenarios there are significant deviations from the climate of the 1990s as mean monthly temperatures are projected to increase throughout the winter and into early summer (Figure 3.2)[17]. These findings have important

[17] Additional monthly data for the 2020s and 2080s is provided in Appendix B, as well as tabular data for annual, seasonal, and monthly mean, maximum, and minimum temperatures.

practical significance. For example, mean temperatures in the 2050s period in February will then be much closer to 0°C (compared to -6°C in the 1990s period) and mean temperatures in March will be above freezing, which has implications for road maintenance and outdoor winter recreation. Large temperature increases in April and May over the same period (each over +3°C increase) will result in growing seasons beginning earlier in the year. Higher mean temperatures in June, July, and August will likely result in higher water consumption and more electricity demand for air conditioning (see Section 3.3).



In Figure 3.2 (and several other quantities to be explored later on), the error bars for our confidence range are so close together that they are indistinguishable from the median value (and thus not seen on the chart). In general, the smaller the range between the upper and lower confidence limits, the more confident we can be in the projections for that quantity, since the entire range of models is predicting very similar results. As might be expected, the range of uncertainty tends to expand as projections are made further into the future.

3.2 Extreme temperature thresholds

Changes in mean temperatures will alter the distribution of extreme temperatures. Prior studies across the Great Lakes Basin have found that increases in extreme high temperatures and reductions in extreme low temperatures have already been occurring[18,19], and that more frequent warm temperature

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[18] Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M. G., . . . Griffiths, G. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research, 111* doi:10.1029/2005JD006290

extremes and fewer cold temperature extremes are projected[20]. In order to examine how extreme temperature will evolve in Waterloo Region over the remainder of the century, the following four thresholds were decided to be of the most relevance to municipal stakeholders:

- Extreme heat (days with maximum temperatures > 30°C),
- Extreme cold (days with minimum temperatures < -15°C),
- Days below freezing (days with minimum temperatures below 0°C), and
- Freeze-thaw cycles (days with minimum temperature below 0°C and maximum is above 0°C).

Extreme heat

While definitions of extreme heat vary, 30°C provides a suitable threshold to analyze how episodes of extreme heat will be affected by climate change. Above 30°C there is a strong correlation between temperature and excess mortality[21], ambulance calls for heat-related illness[22], and reduced air quality[23].

For Waterloo Region, the frequency of extreme heat is not expected to change significantly during the 2020s or in any time periods in the net-zero carbon scenario (Figure 3.3). For the aggressive mitigation and business-as-usual scenarios, however, substantial increases in extreme heat are seen in the 2050s and 2080s. **Under a business-as-usual scenario, an average of two full months with air temperatures greater than 30°C would be the new expected normal condition, compared to the current annual average of 10 days.** These localized results are consistent with similar studies completed for Southern Ontario which indicate that the number of days each year with temperatures over 30°C could triple by the 2050s and quadruple to quintuple by the 2080s across much of Southern Ontario[24].

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[19] Mohsin, T., & Gough, W. A. (2013). Impact of Climate Change on the Extremes of Observed Daily Temperature Data in the Greater Toronto Area. *The International Journal of Climate Change: Impacts and Responses, 5*(1), 11-33.

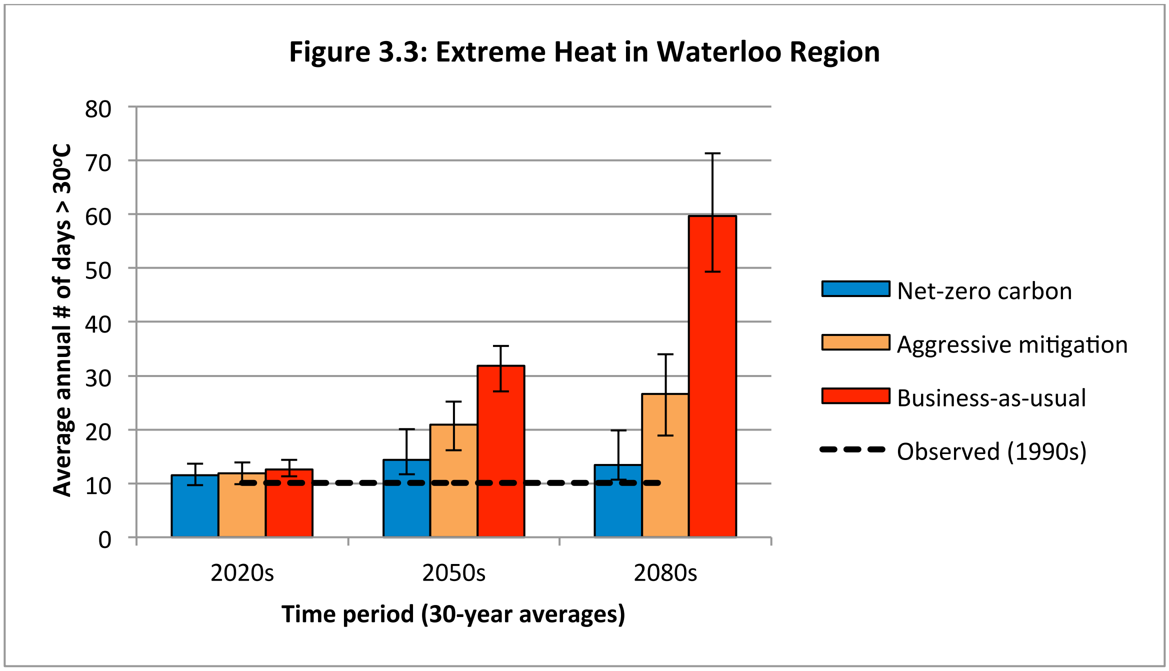
[20] Thibeault, J. M., & Seth, A. (2014). Changing climate extremes in the Northeast United States: observations and projections from CMIP5. *Climatic Change, 127*, 273-287. doi:10.1007/s10584-014-1257-2

[21] City of Windsor. (2012). *Climate Change Adaptation Plan.*

[22] Bassil, K. L., Cole, D. C., Moineddin, R., Lou, W., Craig, A. M., Schwartz, B., & Rea, E. (2011). The relationship between temperature and ambulance response calls for heat-related illness in Toronto, Ontario, 2005. *Journal of Epidemiology & Community Health, 65*, 829-831. doi:10.1136/jech.2009.101485

[23] Cheng, C. S., Campbell, M., Li, Q., Li, G., Auld, H., Day, N., . . . Lin, H. (2008). Differential and combined impacts of extreme temperatures and air pollution on human mortality in south–central Canada. Part II: future estimates. *Air Quality, Atmosphere and Health, 1*, 223-235. doi:10.1007/s11869-009-0026-2

[24] Cheng, C. S., Li, G., Li, Q., & Auld, H. (2008). Statistical downscaling of hourly and daily climate scenarios for various meteorological variables in South-central Canada. *Theoretical and Applied Climatology, 91*, 129-147. doi:10.1007/s00704-007-0302-8

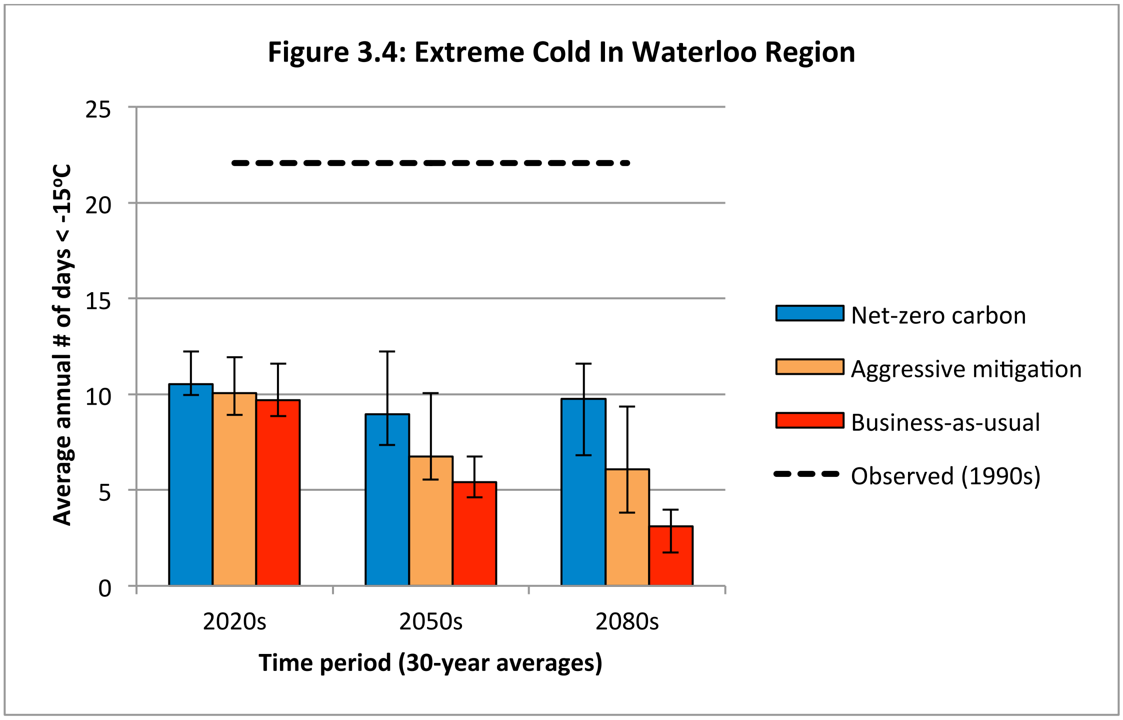


In addition to extreme heat being more frequent, extreme maximum temperatures will also be higher. Comparable data from Hamilton, Ontario, found that a temperature of 32.4°C historically represented a 1-in-50 year maximum temperature, while projections indicate a new 1-in-50 year value may increase by up to 6°C by the 2050s[25]. While we did not have sufficient data to quantitatively project changes in heat waves for Waterloo Region, comparable research shows that the higher number of days with temperatures exceeding the extreme heat threshold will lead to a likely increase in the frequency, duration, and intensity of heat waves[26], and episodes of extremely hot weather may last around 20% longer[27]. With these substantial changes in extreme heat, adaptation will be essential to maintaining a healthy society[24].

Extreme cold

To analyze extreme cold, a threshold of -15°C was chosen as it aligns with other studies examining changes in extreme cold temperatures within Southern Ontario.[28] For any measure of extreme cold, it should also be noted that wind chill factors are a crucial determinant of how cold temperatures are experienced. These values rely on accurate projections of future wind speeds and directions, which were not available for this project, meaning that only air temperatures are analyzed here.

[25] Grillakis, M. G., Koutroulis, A. G., & Tsanis, I. K. (2011). Climate change impact on the hydrology of Spencer Creek watershed in Southern Ontario, Canada. *Journal of Hydrology, 409*, 1-19. doi:j.jhydrol.2011.06.018
[26] Smoyer-Tomic, K. E., Kuhn, R., & Hudson, A. (2003). Heat Wave Hazards: An Overview of Heat Wave Impacts in Canada. *Natural Hazards, 28*, 463-485.
[27] Eum, H., & Simonovic, S. P. (2012). Assessment on variability of extreme climate events for the Upper Thames River basin in Canada. *Hydrological Processes, 26*, 485-499. doi:10.1002/hyp.8145
[28] A lower threshold of -30°C was considered, but because air temperatures below this value are extremely rare (e.g. there were only 3 days below -30°C in the baseline 30-year period) and there is an overall trend of warming, it was decided that -30°C would not be a useful index for tracking changes in extreme cold into the future.



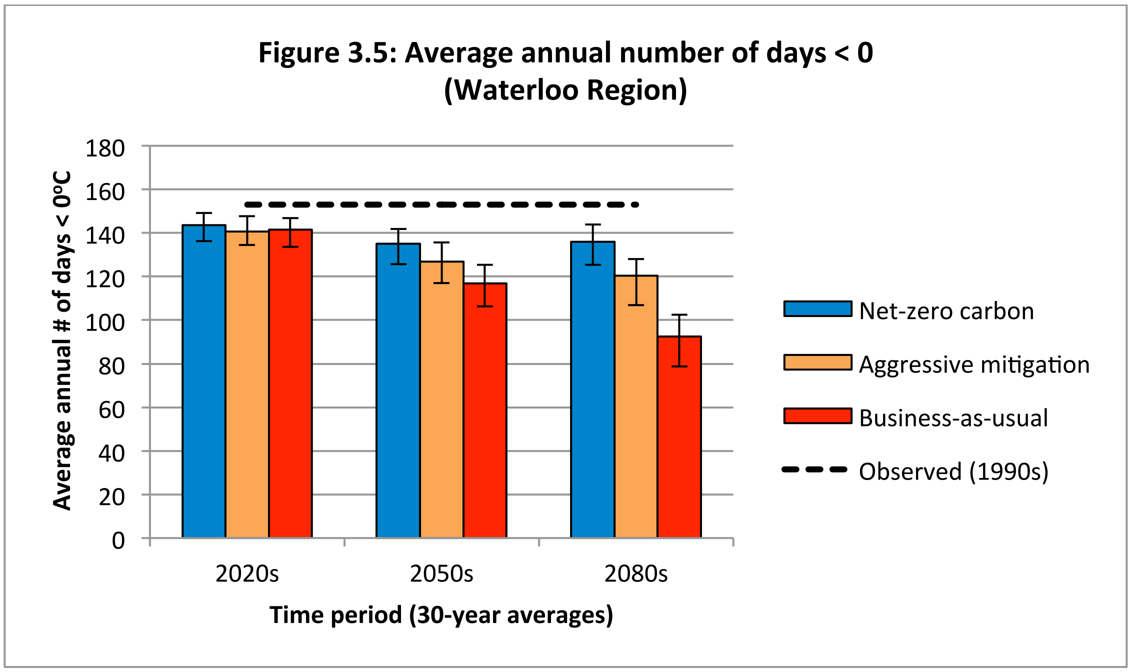
In Waterloo Region, a reduction in the number of days with extremely cold temperatures (<-15 °C) is expected, with less than half as many extreme cold days occurring in the 2020s as were recorded during the 1990s, and further reductions occurring over the rest of the century (Figure 3.4). It should be noted that even over the course of the 30-year baseline period, decreases in the occurrence of extreme cold temperatures have already occurred[29], although these have not been as substantial as the changes projected for the rest of the century.

These results for Waterloo Region are consistent with downscaled results for the City of Toronto, which also projected reductions of up to 70% in temperatures below -15°C[30]. While extreme cold events will become less frequent during the rest of this century, they will not cease entirely as some years will continue to experience few extreme cold events, and other years will experience extreme cold events comparable to current frequencies[28]. Projections for extreme minimum temperatures from Hamilton, Ontario, found that a temperature of -21.8°C historically represented a 1-in-50 year minimum temperature, while a new 1-in-50 year value may be as high as -16.9°C by the 2050s[23]. Occasional extreme cold temperatures may still occur, as evidenced by a record low temperature of -34.1°C being recorded at Waterloo Airport in February of 2015, but these events will likely become significantly more rare in the future.

[29] Allen, S. M. J., Gough, W. A., & Mohsin, T. (2015). Changes in the frequency of extreme temperature records for Toronto, Ontario, Canada. *Theoretical and Applied Climatology, 119*, 481-491. doi:10.1007/s00704-014-1131-1
[30] Gough, W. A., Tam, B. Y., Mohsin, T., & Allen, S. M. J. (2014). Extreme cold weather alerts in Toronto, Ontario, Canada and the impact of a changing climate. *Urban Climate, 8*, 21-29. doi:10.1016/j.uclim.2014.02.006

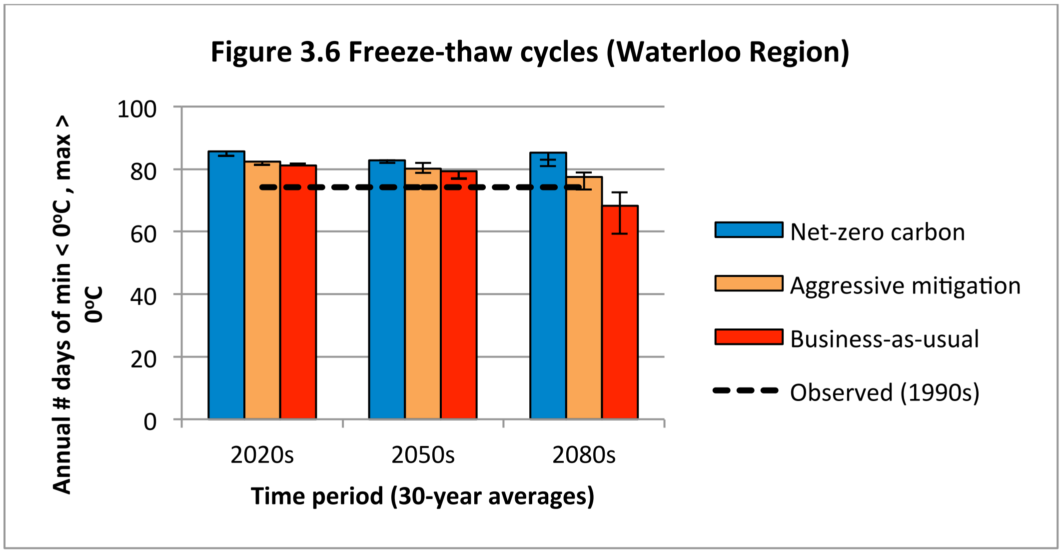
Days below freezing

If temperatures below 0^oC are taken as an analogue for winter-like conditions in Southern Ontario, results of this study indicate that the current 150-day period of sub-zero temperatures will be reduced by an average of approximately two weeks over the next 30 years, and by the end of the century, it may be reduced by a total of 3-9 weeks (Figure 3.5). While these results are for average number of days where the minimum temperature drops below freezing, a very similar trend is projected for number of days with maximum temperatures below 0^oC.



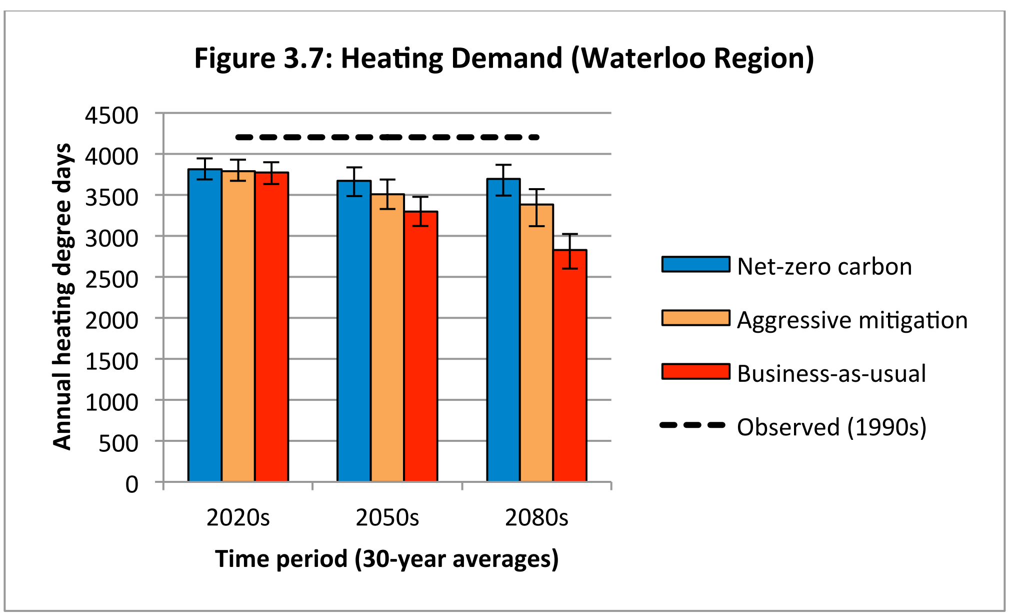
Freeze-thaw cycles

Counts of freeze-thaw cycles are taken as the number of days with minimum temperatures below 0^oC and maximum temperatures above 0^oC, implying that surface water will transition through both frozen and liquid states over the course of the day. Rising temperatures are expected to cause an increase in the number of freeze-thaw cycles experienced in Waterloo Region, particularly over the next 30 years (Figure 3.6). This increase is driven by a greater number of winter days where maximum temperatures exceed 0^oC. If significant warming continues unabated, the number of days with freeze-thaw cycles will begin to decline by the end of the century as fewer days will reach minimum temperatures below 0^oC.

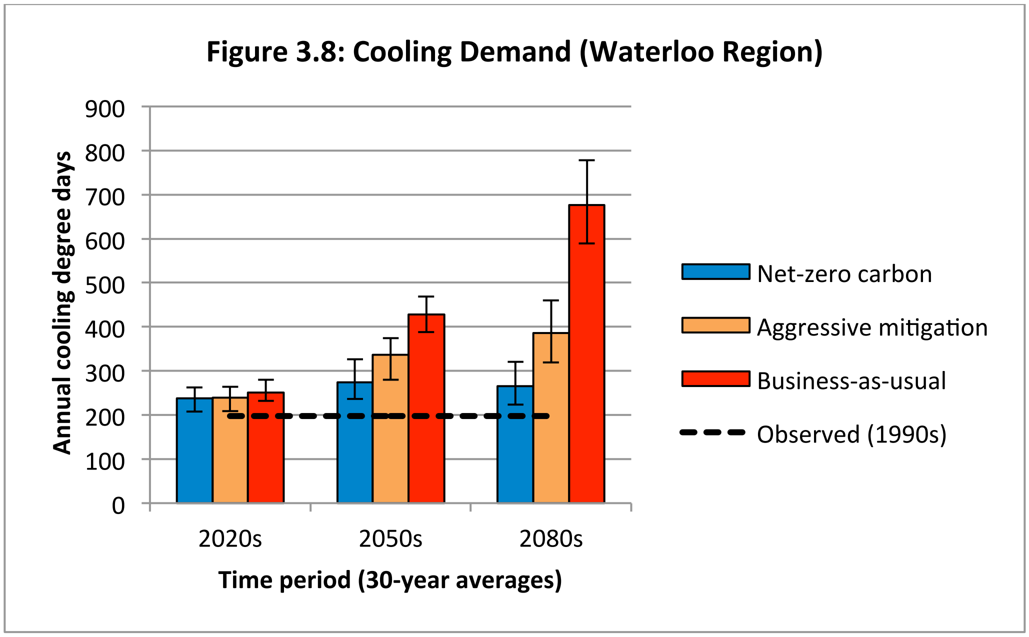


3.3 Degree days

Heating and cooling degree days are measures of the energy use required to maintain comfortable indoor temperatures in buildings. It is a concept based on the idea that at outdoor temperatures below a certain threshold heating is required to raise indoor temperatures, and conversely, above this threshold cooling is needed to lower indoor temperatures. Temperature thresholds can vary for degree day calculations, and should thus always be explicitly stated. For this report the threshold value of 18^{o}C has been used, as it a commonly cited figure for degree day calculations in North America (note that indoor temperatures are generally 1-2^{o}C warmer than outdoor air temperatures, with this threshold thus representing a “comfortable” indoor temperature of approximately 20^{o}C). Degree days are computed by taking the difference between daily mean temperature and the threshold temperature, and have been summed annually.



Rising air temperatures over the rest of the century correspond to moderate reductions in demand for heating (Figure 3.7), along with more substantial increases expected in demand for air conditioning (Figure 3.8), which is due to hot days increasing at a more rapid rate.



Growing degree days (GDD) are a measurement of heat accumulation in plants, which can be used to predict rates of crop development and timing of maturation. Growing degree days are calculated similarly to heating and cooling degree days, but using a lower threshold temperature. Although baseline temperatures for GDD calculations vary depending on the crop of interest, the generic baseline of 5°C used here is largely applicable across Southern Ontario. Modest to moderate increases in the length of the growing season are anticipated. Projected results for growing degree days can be found in Appendix B.

3.4 Precipitation

Total annual and seasonal precipitation

Waterloo Region is expected to become slightly wetter over the rest of the century, with total annual precipitation increasing by approximately 5-12% depending on the time period and scenario. Although the changes reported here are referenced to a baseline period of 1981-2010, earlier weather station data for Waterloo Region was also examined. Average annual precipitation amounts have remained roughly constant at around 915mm since the 1960s, indicating that the projected increases in precipitation due to climate change represent significant departures from the normal conditions of the past half-century.

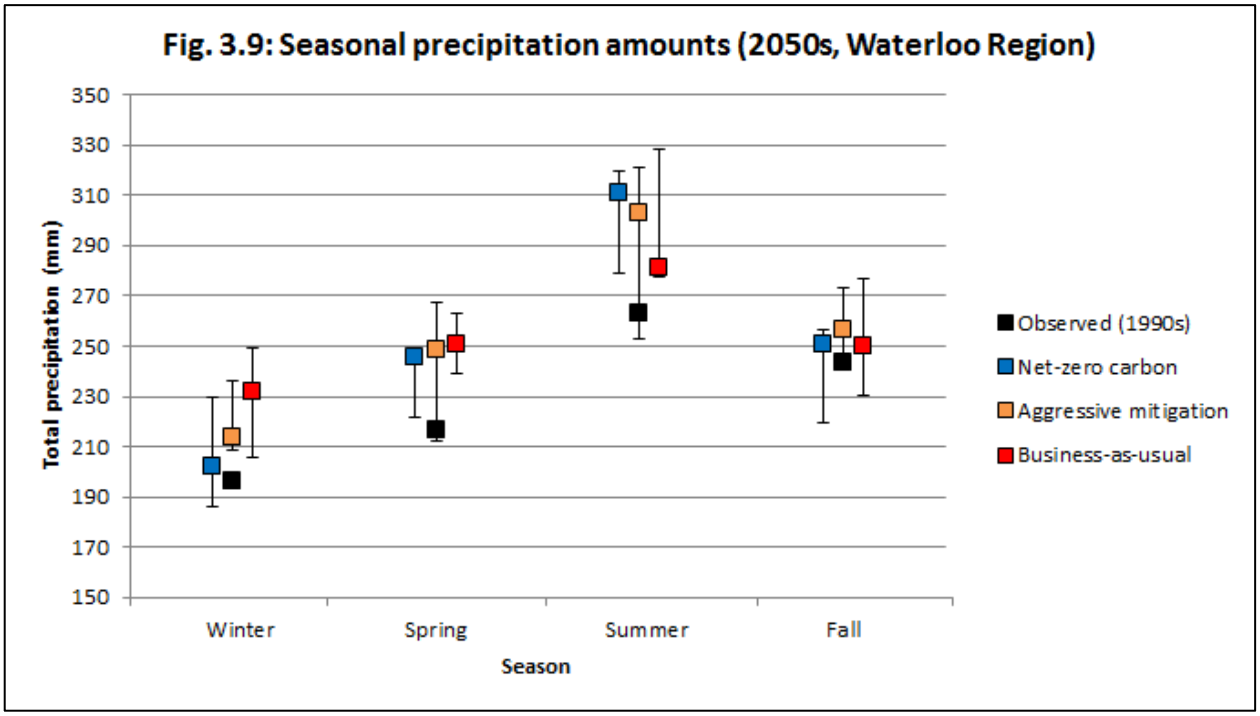
Table 3.2: Percentage change in total annual precipitation from baseline of 918.5mm

	2020s	2050s	2080s
Business-as-usual	+ 3.8%	+ 10.4%	+ 12.0%
Aggressive mitigation	+ 6.2%	+ 8.5%	+ 10.0%
Net-zero carbon	+ 4.3%	+ 11.7%	+ 7.3%

Precipitation projections are subject to larger uncertainty than temperature (as demonstrated by the error bars in Figure 3.9), mainly because precipitation exhibits greater spatial and temporal variation and it is represented in climate models using more varied assumptions. Projections for seasonal precipitation in the 2050s show that increases are expected in many cases, although some of these changes are difficult to definitively interpret. The range of uncertainty for all scenarios and seasons overlap, suggesting that projections of future precipitation are more sensitive to year-to-year climate variability and model uncertainty than they are to the emissions scenario used. In many cases, there is also no robust separation between a scenario and the observations. In particular, summer (June to August) is the season with by far the largest uncertainty range across all scenarios.

The uncertainty in summer precipitation is driven by a lack of consensus amongst climate models as to how the continental-scale processes driving precipitation will evolve at different latitudes. As projected by the CMIP5 multi-model mean, Waterloo Region is located just within the zone of net precipitation increases, which extends roughly from this latitude northwards, while decreases in summer precipitation are expected further to the south. However, there is no consensus among climate models over the direction of summer precipitation change across Southern Ontario – increases and decreases are projected by almost equal numbers of models[31]. Downscaled results for Waterloo Region show that most models within our 25-75% confidence intervals project precipitation increases in summer, although it should be noted that several models (<5) outside this confidence range do project precipitation decreases in summer. Due to this lack of consensus amongst climate models, the results presented here for precipitation parameters should be interpreted cautiously.

[31] Maloney, E. D., Camargo, S. J., Chang, E., Colle, B., Fu, R., Geil, K. L., . . . Zhao, M. (2014). North American Climate in CMIP5 Experiments: Part III: Assessment of Twenty-First-Century Projections. *J. Climate, 27*, 2230-2270. doi: 10.1175/JCLI-D-13-00273.1



Days with precipitation

The annual number of days with precipitation (> 0.1mm) is projected to decrease by 2-5 days, irrespective of scenario. Viewed in isolation, this slight decrease does not represent a significant change below the baseline value of 165 days. However, a reduction in the number of precipitation days, accompanied by an increase in total precipitation, implies an increase in the intensity of precipitation events[25]. In Waterloo Region, the number of days with heavy precipitation (> 10mm) is projected to increase by 2-3 days from the current average of 30 days per year by the 2050s, and the number of days with very heavy precipitation (> 25mm) is expected to increase by 1.5-2 days from the current average of 5 days per year (see Appendix B). Similar results have been shown in several other studies for Southern Ontario, each finding small increases in the number of days with precipitation >10mm and >20mm of approximately 3 days by the 2050s[18,32,33].

Precipitation return periods

One of the major concerns regarding precipitation and climate change is that changes in extreme precipitation will occur more rapidly than changes in mean precipitation[25]. One method for analyzing precipitation extremes is to calculate expected return periods for heavy precipitation events. A return period is an estimate of how frequently a storm of a given magnitude is expected to occur. For example,

[32] 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*, 3667-3685. doi:10.1175/2011JCLI3764.1

[33] Gula, J., & Peltier, W. R. (2011). *Dynamical Downscaling over the Great Lakes Basin of North America using the WRF Regional Climate Model.* Department of Physics, University of Toronto: Report for the Ontario Ministry of the Environment.

a 1-in-20 year storm event occurs on average once every 20 years, or a probability of p=0.05 (a 5% chance of occurring in any given year).

Table 3.3 presents maximum 1-day total precipitation amounts for return periods of 5, 10, 20, 30, 50, and 100 years in Waterloo Region; while return periods for 5-day accumulated totals are included within Appendix B. The differences in return period values across the three scenarios are a reflection of there being overlapping uncertainty ranges in the multi-model consensus for precipitation changes (as evidenced by the error bars in Figure 3.9). In the business-as-usual (RCP 8.5) scenario for example, models are divided on the question of whether precipitation amounts will increase or decrease in the latter half of the century, leading to the multi-model mean reflecting lower quantities for precipitation return periods under a business-as-usual scenario in the 2080s. Overall however, the majority of models project some degree of increase in precipitation by 2050, and the strength of the projected changes is largely independent of emissions scenario.

It should be emphasized that the estimates for precipitation return levels presented in Table 3.3 are necessarily conservative, because only projected changes in the mean, and not in the variance, of daily precipitation are included in this future estimate. Thus, the results likely represent a lower bound for the expected changes. Regardless, the increases in the magnitude of rainfall projected for each return period are consistent across all scenarios and time periods, and make a compelling case for adjusting existing intensity-duration-frequency (IDF) curves to account for future climate change. In addition, these estimates are generally consistent in magnitude with other studies in Southern Ontario (discussed below), which also indicate that precipitation intensity is expected to increase over the rest of the century.

Table 3.3: Return levels for maximum 1-day precipitation amounts (mm)

Return Period	Observed	RCP 2.6			RCP 4.5			RCP 8.5		
	1990s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
2-yr	50.0	59.6	63.1	61.9	58.8	61.2	60.8	58.5	51.6	51.9
5-yr	66.5	79.8	83.6	83.4	80.7	81.1	82.0	78.0	66.9	67.4
10-yr	78.5	94.6	98.4	99.4	98.3	94.9	97.5	92.5	78.1	80.3
25-yr	94.8	114.9	118.7	121.8	124.9	113.3	118.8	112.6	93.4	100.5
50-yr	107.8	131.2	134.9	140.2	148.4	127.5	136.0	129.2	105.7	118.9
100-yr[34]	121.6	148.6	152.2	160.0	175.4	142.3	154.4	147.0	118.8	140.6

[34] Note: The calculation for 100-year return period has been extrapolated from limited data and thus should have a lower degree of confidence assigned to it.

Given their importance for municipal water infrastructure and flood plain management[35], the impact of climate change on precipitation return periods has been studied by numerous groups across Southern Ontario. Increases in the magnitude and frequency of extreme precipitation events have been found in all cases. At sub-daily timescales, the magnitude of rainfall associated with intense 2-hour and 6-hour events is expected to occur approximately twice as frequently, largely due to more frequent and intense convective weather systems[36]. The rainfall intensities corresponding to extreme precipitation events are also expected to increase, with larger percentage changes being found for longer return periods[37]. Thus, the rainfall intensity associated with a 1% chance of occurring each year in the current climate may now have a 3% probability of occurring in a given year in the future[32]. Stated in probabilistic terms, the likelihood of experiencing larger intensity storms will increase substantially.

Return periods can also be calculated for multi-day precipitation events. The return periods for 3-day accumulated rainfall extremes under a business-as-usual scenario are projected to increase by about 20-70% over the present century in Southern Ontario river basins, with the percentage increase rates for longer return periods again being greater than for shorter return periods[29]. In terms of rainfall magnitude, the most extreme multi-day precipitation event simulated for the Upper Thames River Basin was found to be on the order of 250mm by the 2050s,

What does a "1-in-100" year storm mean?

A 1-in-100 year storm does not necessarily mean that this magnitude of storm will only occur once every 100 years, but rather it has a 1% statistical probability of occurring in any given year. Major flooding or storm events can cause significant damages at lower precipitation intensities, depending on the stormwater infrastructure and flood plain management in place. For example, in Ontario during the 2002–2013 period the cities of Hamilton, London, Peterborough, and Toronto all experienced major community flooding events.

The largest storm event used in Ontario regulations is built upon the observations and weather measurements connected to Hurricane Hazel that occurred in October 1954, which was significantly more rare than a 1-in-100 year event. This storm featured 285mm of rain in 48 hours, over 200mm in the first 24 hours alone[1]. Damages resulting from the storm included bridges, roads, structures, 81 people dead, thousands homeless, and with an estimated cost of $100 million ($1 billion today).

[35] Peck, A., Prodanovic, P., & Simonovic, S. P. (2012). Rainfall Intensity Duration Frequency Curves Under Climate Change: City of London, Ontario, Canada. *Canadian Water Resources Journal, 37*(3), 177-189. doi:10.4296/cwrj2011-935

[36] Mailhot, A., Duchesne, S., Caya, D., & Talbot, G. (2007). Assessment of future change in intensity–duration–frequency (IDF) curves for Southern Quebec using the Canadian Regional Climate Model (CRCM). *Journal of Hydrology, 347*, 197-210. doi:10.1016/j.jhydrol.2007.09.019

[37] Wang, X., Huang, G., & Liu, J. (2014). Projected increases in intensity and frequency of rainfall extremes through a regional climate modeling approach. *Journal of Geophysical Research: Atmospheres, 119*, 13,271-13,286. doi:10.1002/2014JD022564

compared to a maximum of 200mm in the observed record[38]. All of these projected increases in thunderstorms are robust across a suite of climate models and emerge in response to relatively moderate global warming, which occurs in all scenarios examined. This suggests that continued increases in greenhouse forcing are likely to increase severe thunderstorm occurrence[39].

These expected changes in extreme precipitation have resulted in recommendations in some cases that Intensity-Duration-Frequency (IDF) curves and flood protection plans should be revised to consider climate change impacts[25]. For example, it has been recommended that IDF curves for the Upper Thames River Basin established using historical data should be increased by 30% to account for future climate change[40], and that all cities in Southern Ontario should consider increasing the current values of IDF curves by around 20%[32].

Analyzing IDF curves for area municipalities was not within the scope of this study; however a separate 2012 study found that "the existing IDF curves for the City of Waterloo and the City of Kitchener are likely somewhat conservative for rainfall durations less than two hours, although the impacts of climate change could result in more severe events in the future."[41]

Snowfall

Total snowfall is computed by assuming that all precipitation falls as snow when daily mean temperatures are below 0^{o}C, and that when temperatures are between 0^{o}C and 2^{o}C, the fraction of snow to rain can be calculated as a linear function of air temperature[42]. These results necessarily assume that 1mm of precipitation measured at the Waterloo weather station is equivalent to the water content of 1cm of snow. In reality the water content of snow does vary between 0.5-1.5mm depending on its density, though on average this assumption holds true.

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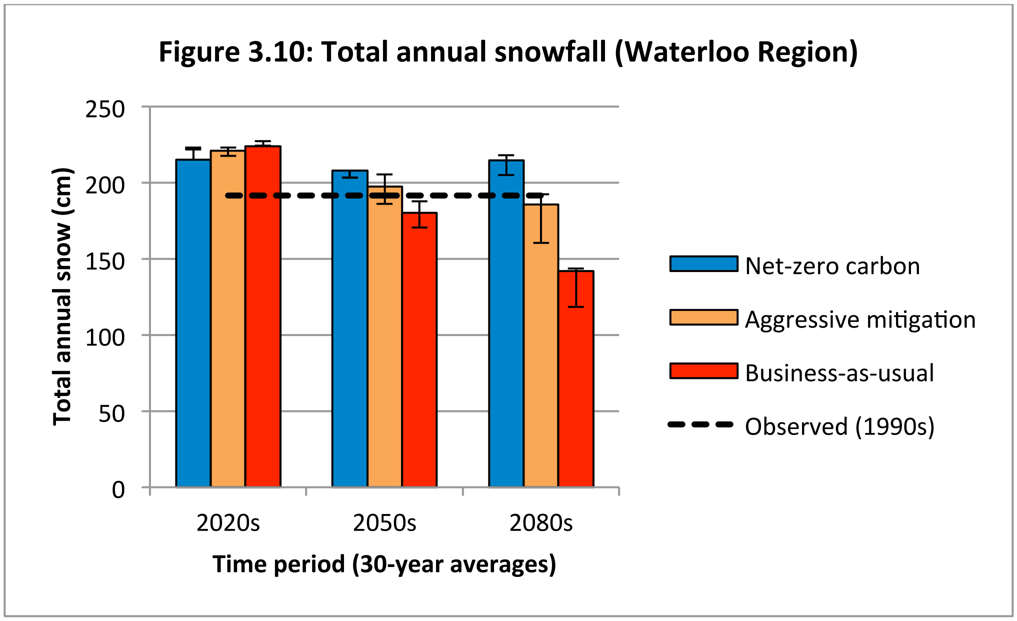
[38] Sharif, M., Burn, D. H., & Hofbauer, K. M. (2013). Generation of Daily and Hourly Weather Variables for use in Climate Change Vulnerability Assessment. *Water Resources Management, 27*, 1533-1550. doi:10.1007/s11269-012-0253-4

[39] Diffenbaugh, N. S., Scherer, M., & Trapp, R. J. (2013). Robust increases in severe thunderstorm environments in response to greenhouse forcing. *PNAS, 110*(41), 16361-16366. doi:10.1073/pnas.1307758110

[40] Das, S., Millington, N., & Simonovic, S. P. (2013). Distribution choice for the assessment of design rainfall for the city of London (Ontario, Canada) under climate change. *Canadian Journal of Civil Engineering, 40*, 121-129. doi:10.1139/cjce-2011-0548

[41] Burn, D. 2012. Update of Intensity-Duration-Frequency (IDF) Curves for the City of Waterloo and the City of Kitchener

[42] Brown, R. D., Brasnett, B., & Robinson, D. (2003). Gridded North American monthly snow depth and snow water equivalent for GCM evaluation. *Atmosphere-Ocean, 41,* 1-14.



Increased amounts of precipitation initially result in increases in total annual snow in the 2020s, yet into the 2050s and 2080s, higher winter temperatures eventually cause a smaller fraction of precipitation to fall as snow. These trends are echoed in the number of days with snowfall (> 0.1cm) and the number of days with very heavy snowfall (> 5cm), both of which are projected to decrease slightly by 2050[30]. Full tabular data for total snow and days with snowfall > 5cm is in Appendix B.

Freezing rain

Under a business-as-usual scenario in Southern Ontario, the months of December, January, and February are expected to experience 40% more freezing rain events by the 2050s and 45% more freezing rain events by the 2080s[43]. This is an effect of rising temperatures, resulting in more precipitation falling as freezing rain that in the past would have fallen as snow. In contrast, freezing rain in the months of November, March, and April will decrease by 10% by the 2050s, and decrease by 15% by the 2080s[39]. This decrease is also driven by temperature increases, since a portion of precipitation that would have fallen as freezing rain during these months is now more likely to fall as liquid rain.

Wet and dry spells

Dry spells are defined as periods of 6 or more consecutive days with no precipitation, and wet spells are defined as periods of 6 or more days with precipitation occurring on each day. In our projections for Waterloo Region, no projected changes were found in the maximum length of wet and dry spells over time, with the longest dry spells lasting 31-34 days and the longest wet spells lasting 8-10 days across all scenarios and time periods. Some similar studies have projected increases of 2-3 days in the maximum length of wet and dry spells within other river basins of Southern Ontario[35], but the methods used in this

[43] Cheng, C. S., Auld, H., Li, G., Klaassen, J., & Li, Q. (2007). Possible impacts of climate change on freezing rain in south-central Canada using downscaled future climate scenarios. *Natural Hazards and Earth System Sciences,7*, 71-87.

study (which assume constant precipitation variance) have suggested that this may not be the case for Waterloo Region.

Projections indicate that the frequency of dry spells is expected to decrease slightly, but not significantly with climate change. The fact that no large changes are expected for dry spells is in itself significant, as it contrasts with the findings for other parts of the world where droughts are expected to become more frequent. The frequency of wet spells will increase moderately, although there is still an average of less than one 6-day wet spell per year (see Appendix B). In Southern Ontario, individual months could experience slight changes in the frequency or length of wet and dry spells[44], but this was not examined further in the Waterloo Region data considering the small overall annual changes.

3.5 Wind

Wind speed is closely tied to temperature and air pressure, and thus the frequency and speed of wind gusts are expected to vary with climate change. More wind gust events are expected in Southern Ontario (in a corridor from Windsor to London to Toronto) by the end of the century, as both large-scale frontal storms and local convective windstorms could occur more frequently[45]. The frequency of hourly wind gusts greater than 40km/h is expected to increase by 10-20%, and the frequency of wind gusts greater than 70km/h will increase by 20-40% compared to the 1994-2007 historical average[41]. More severe wind gust events are generally expected to increase by greater magnitudes, although since these are rare events this is a more uncertain prediction[41]. Avoiding more substantial increases in wind gusts will be tied to limiting global warming, as scenarios with greater warming indicate a larger increase in wind gusts[41].

[44] Rahman, M., Bolisetti, T., & Balachandar, R. (2012). Hydrologic modelling to assess the climate change impacts in a Southern Ontario watershed. *Canadian Journal of Civil Engineering, 39*, 91-103. doi:10.1139/L11-112
[45] Cheng, C. S., Li, G., Li, Q., Auld, H., & Fu, C. (2012). Possible Impacts of Climate Change on Wind Gusts under Downscaled Future Climate Conditions over Ontario, Canada. *Journal of Climate, 25*, 3390-3408. doi:10.1175/JCLI-D-11-00198.1

4.0 Next steps: Local climate impacts and adaptation planning

4.1 Changing conditions and related impacts for Ontario municipalities

While climate change is sometimes thought of as only a long-term phenomenon, Ontario municipalities are already experiencing both negative and positive impacts. Canada-wide, the economic impacts of climate change are estimated to be $5 billion per year by 2020, and between $21 and $43 billion by 2050[46]. Some of the impacts that are related more specifically to the types of projected changes identified for Waterloo Region include:

- Rising winter temperatures with more winter days above freezing will have a range of positive and negative implications in areas such as road maintenance, outdoor winter recreation and reduced heating demand, while higher temperatures in the summer will increase cooling demand.
- Higher and more frequent heat maximums, heat waves, smog episodes and extreme weather will increase the risk of human illness, injury and premature death[20,47]. Data from Windsor, Toronto, Ottawa, and Montreal reveals that heat-related mortality is projected to double by the 2050s and triple by the 2080s[21].
- Higher average temperatures in the spring will shift growing seasons to begin earlier in the year, which could have advantages for crop yields, but pose risk for crop losses due to early frost and/or changes in the freeze-thaw cycles.
- Warming temperatures will allow the range of ‘nuisance’ species, such as insect pests and invasive plants, to reach Eastern Canada causing negative effects to native flora and fauna as well as increased exposure of humans to vector-borne diseases.
- Increased frequency and intensity of storms and extreme precipitation events will expose property and infrastructure, such as buildings, water and wastewater systems, transportation and energy transmission services, to risk of damage and service disruption due to flooding and wind gusts.[48]
- Freezing rain events and ice storms are associated with very high damage costs[39], substantial power outages, and disruptions to transportation networks[49].

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[46] National Roundtable on the Environment and the Economy (NRTEE). (2012). Framing the Future: Embracing the Low-Carbon Economy. Accessed 14 August 2015 from: http://collectionscanada.gc.ca/webarchives2/20130322145416/http://nrtee-trnee.ca/wp-content/uploads/2012/10/framing-the-future-summary-eng.pdf

[47] Lemmen, D.S., Warren, F.J., Lacroix, J. and Bush, E., editors (2008): From Impacts to Adaptation: Canada in a Changing Climate 2007; Government of Canada, Ottawa, ON, 448 p.

[48] ibid

[49] Armenakis, C., & Nirupama, N. (2014). Urban impacts of ice storms: Toronto December 2013. *Natural Hazards, 74*, 1291-1298. doi:10.1007/s11069-014-1211-7

4.2 Climate adaptation planning at the local level

Municipalities are taking action to respond to changing trends and prepare for future impacts. A 2012 survey of municipalities across Canada highlighted that adaptation planning at the local level is emergent, and that larger and mid-size cities seem more likely to have advanced adaptation planning, but some small communities are also engaged[50]. The City of Windsor and the City of Toronto, for example, have adopted climate adaptation plans that were driven largely in response to extreme heat and urban flooding pressures felt in their respective communities. Durham Region is another nearby municipality that is actively developing a Community Climate Adaptation Plan.

How are other Canadian communities addressing adaptation planning?

- 238 Canadian communities are addressing adaptation planning in some form (55% of respondents to a 2012 survey). Of this, 5% have an adaptation plan in place (e.g. Durham, Windsor, Peel, Toronto), and a further 8% have incorporated adaptation into an existing plan.[45]
- Over 30 government entities have completed projects using the PIEVC Engineering Protocol.
- 19 communities are participating in ICLEI's Building Adaptive and Resilient Communities (BARC) program.

As of September 2015, the Federation of Canadian Municipalities encourages action stating on its website, "it is never too soon for municipalities to begin assessing their vulnerability to climate change impacts that are already occurring, and to develop responses that protect their citizens, the local environment and the local economy. Climate change adaptation could save Canadians billions of dollars, and position our economy to provide solutions for a challenge that will soon face communities around the world." There are significant avoided costs to be realized by bolstering the resilience of municipal assets (e.g. community facilities, parks, roads, water and wastewater systems), and increasing our ability to adapt community services to best suit changing climatic conditions (e.g. emergency services, public health, and transit). A "no-regrets" approach is highly encouraged so that adaptive actions improve community resiliency and have other benefits regardless of whether the projected climate changes follow the high or low scenario.

4.3 Using climate projections in ongoing adaptation planning

New emissions scenarios and updated climate models will inevitably be used to create new generations of climate projections, and advanced downscaling techniques may offer new avenues of adapting these projections to local areas. Since the rate of scientific advancement cannot be predicted, users of this report should familiarize themselves with any major changes in models or scenarios that have occurred

[50] Hanna, K., Dale, A., Filion, P., Khan, Z., Ling, C., Rahaman, K. and Seasons, M. (2013): Planning for adaptation in an uncertainty setting: local government action in Canada; Conference paper submitted to AESOP-ACSP Joint Congress, 15-19 July, 2013, Dublin

since the publishing of this report, to ensure that the content presented here still meets municipal needs.

This task may seem daunting to practitioners not familiar with climate science, but many resources exist to streamline the process of delivering climate projections to end users. Understanding the local impacts of climate change is relevant to all Canadians, and to this end numerous services and data portals provide downscaled climate projection data to the general public, many of which can be accessed free-of-charge. Academic institutions and consultants can also provide guidance in locating and utilizing these various resources.

Successful adaptation to climate change requires high-quality climate data. Having access to projections about what the future climate may look like in Waterloo Region is one of the first steps of an adaptation planning process, along with identifying stakeholders and assessing current climate impacts and adaptive actions. This knowledge provides an important platform for a subsequent full assessment of potential impacts and vulnerability across community assets and services along with identification and prioritization of risk management measures.

Appendix A: Waterloo Region Localized Climate Projections Process Manual

The following information details the process that was following to prepare a report on localized climate projections for Waterloo Region. The material provided here should be sufficient to resolve any questions regarding the methodology that was used to create downscaled climate projections, as well as allow this procedure to be replicated in the future. The approach taken for the Waterloo Region project encompassed the following major steps, which will each be described in further detail.

1) Determine project scope
2) Data analysis
   i. Data cataloguing and pre-processing
   ii. Statistical downscaling with LARS-WG
   iii. Data processing
3) Literature review

1) DETERMINE PROJECT SCOPE

Following an agreement with the Cities of Cambridge, Kitchener, Waterloo, and the Region of Waterloo to produce localized climate projections for Waterloo Region, the first necessary task was to confirm the purpose of the proposed project and determine its scope. Two initial meetings between municipal representatives and the University of Waterloo (UW) team were held to address these questions. Since this work was highly tailored to the needs of municipal end-users, offering adequate opportunities for input, feedback, and dialogue was crucial to the project's success in providing relevant and decision-useful information.

Major decisions involved selecting a list of climate parameters to investigate, a set of emissions scenarios to use, and the baseline and future time periods to analyze. Climate parameters were determined through an information gathering process, which involved consulting with municipal departments (e.g. Facilities, Transportation, Water Services, Engineering, and Fire Rescue) by asking questions about how operations are impacted by climate and which climate parameters would be useful to guide future planning. Climate parameters that have been discussed in other climate projection reports were also reviewed to expand upon this list. The final list of the climate parameters analyzed is given in Table B1, which has been sorted into the overall categories of parameters dependent on temperature, precipitation, and wind.

Table B1: Climate Parameters	
Temperature	Mean, maximum, and minimum temperatures (monthly, seasonal, and annual)
	Number of days with temperature: > 30^oC (extreme heat), < 0^oC (frost days), and

	< -15^oC (extreme cold)
	Freeze-thaw frequency (number of days where max temp > 0^oC and min temp < 0^oC)
	Heat waves / cold spells
	Heating, cooling, and growing degree days
Precipitation	Average total precipitation: rain and snow (monthly, seasonal, and annual)
	Average number of precipitation days
	Number of intense precipitation events: > 10mm, > 25mm, and snow > 5cm
	Dry spells / wet spells
	Precipitation return periods (e.g. 1-in-10 year precipitation event)
Wind	Wind gusts

Emissions scenarios and time periods were recommended by the UW team to align with best practices and common conventions. Three emissions scenarios were proposed: the business-as-usual scenario of RCP 8.5, the aggressive mitigation scenario of RCP 4.5, and the net-zero carbon scenario of RCP 2.6. This range of scenarios was important to show the range of potential future conditions, as well as to demonstrate the beneficial effects of extensive greenhouse gas mitigation.

The time periods chosen were all 30 years in length, which is the standard endorsed by the World Meteorological Organization for examining long-term climate trends. The years 1981-2010 were selected as the baseline period, as this represented the most recent 30-year period for which quality data was available for Waterloo Region. The projection periods were chosen to align with Intergovernmental Panel on Climate Change standards, comprising the 2020s, 2050s, and 2080s. The scoping decisions regarding scenarios and time periods are summarized in Table B2.

Table B2: Emissions scenarios and time periods	
Emissions Scenarios	RCP 8.5 “business-as-usual” RCP 4.5 “aggressive mitigation” RCP 2.6 “net-zero carbon
Baseline Period	1990s (1981-2010)
Projection Periods	2020s (2011-2040) 2050s (2041-2070) 2080s (2071-2100)

2) DATA ANALYSIS

i. Data cataloguing and pre-processing

The first step in the data analysis procedure was to obtain the required data files. All necessary data from the Coupled Model Intercomparison Project version 5 (CMIP5) were downloaded through the Earth System Grid Foundation Peer-to-Peer enterprise system, an international and interagency collaboration which acts as a portal for the dissemination of climate model data. Monthly output from a total of 22 climate models was used. To be considered, each model was required to have output available for both variables of surface temperature and precipitation, and projections for each of the three scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) out to the year 2100. The full list of models used is given in Table B3.

Table B3: Full list of climate models[1]

Model	Expanded Name	Center
BCC-CSM1-1	Beijing Climate Center, Climate System Model, version 1.1	Beijing Climate Center, China Meteorological Administration, China
CanESM2	Second Generation Canadian Earth System Model	Canadian Centre for Climate Modeling and Analysis, Canada
CCSM4	Community Climate System Model, version 4	National Center for Atmospheric Research, United States
CESM1-CAM5	Community Earth System Model version 1, including the Community Atmospheric Model version 5	National Center for Atmospheric Research, United States
CNRM-CM5	Centre National de Recherches Meteorologiques Coupled Global Climate Model, version 5.1	National Centre for Meteorological Research, France
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation Mark, version 3.6.0	Commonwealth Scientific and Industrial Research Organization / Queensland Climate Change Centre of Excellence, Australia
FGOALS-g2	Flexible Global Ocean–Atmosphere–Land System Model gridpoint, second spectral version	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences
GFDL-CM3	Geophysical Fluid Dynamics Laboratory Climate Model, version 3	NOAA/Geophysical Fluid Dynamics Laboratory, United States

[1] Eric D. Maloney, Suzana J. Camargo, Edmund Chang, Brian Colle, Rong Fu, Kerrie L. Geil, Qi Hu, Xianan Jiang, Nathaniel Johnson, Kristopher B. Karnauskas, James Kinter, Benjamin Kirtman, Sanjiv Kumar, Baird Langenbrunner, Kelly Lombardo, Lindsey N. Long, Annarita Mariotti, Joyce E. Meyerson, Kingtse C. Mo, J. David Neelin, Zaitao Pan, Richard Seager, Yolande Serra, Anji Seth, Justin Sheffield, Julienne Stroeve, Jeanne Thibeault, Shang-Ping Xie, Chunzai Wang, Bruce Wyman, and Ming Zhao, 2014: North American Climate in CMIP5 Experiments: Part III: Assessment of Twenty-First-Century Projections*. *J. Climate*, **27**, 2230–2270. doi: http://dx.doi.org/10.1175/JCLI-D-13-00273.1

GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component	NOAA/Geophysical Fluid Dynamics Laboratory, United States
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component and with Modular Ocean Model 4 (MOM4) component	NOAA/Geophysical Fluid Dynamics Laboratory, United States
GISS-E2-R	Goddard Institute for Space Studies Model E, coupled with the HYCOM ocean model and coupled with the Russell ocean model	National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies, United States
HadGEM2-ES	Hadley Centre Global Environment Model, version 2–Earth System	Met Office Hadley Centre, United Kingdom
IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, low resolution	L'Institut Pierre-Simon Laplace, France
IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, mid resolution	L'Institut Pierre-Simon Laplace, France
MIROC5	Model for Interdisciplinary Research on Climate, version 5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
MIROC-ESM	Model for Interdisciplinary Research on Climate, Earth System Model	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan
MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan
MPI-ESM-LR	Max Planck Institute Earth System Model, low resolution	Max Planck Institute for Meteorology, Germany
MPI-ESM-MR	Max Planck Institute Earth System Model, mid resolution	Max Planck Institute for Meteorology, Germany
MRI-CGCM3	Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3	Meteorological Research Institute, Japan
NorESM1-M	Norwegian Earth System Model, version 1 (intermediate resolution)	Norwegian Climate Center, Norway

NorESM1-ME	Norwegian Earth System Model, version 1 (intermediate resolution) and with carbon cycle	Norwegian Climate Center, Norway

Once all data had been downloaded and catalogued, a shell script program was written and run within the UNIX command-line shell to pre-process the data. The gridded data for Waterloo Region were extracted from the global dataset by latitude/longitude (approximately 43.5^{o}N, 80.5^{o}W), and the data was segmented into proper time periods. Since historical GCM runs only extended to 2005, the period from 2006-2010 was filled using RCP 4.5 data from each model. Average monthly climatologies were then calculated for each variable, scenario, model, and time period. By comparing the historical and future climatologies for each model, factors of change could be calculated to express the difference between each pair of two cases. Change factors for monthly mean temperatures were calculated as absolute differences, while change factors for monthly mean precipitation were calculated as relative changes.

After all calculations were completed for each model individually, the results were aggregated into an ensemble and percentiles were calculated. The multi-model mean was calculated as an average of all the change fields for each model, while percentiles were calculated individually for each variable, scenario, and time period. The advantage of this method for determining percentiles was that a different aggregation of models could be used in each case, as the 25th to 75th percentile range was determined at each step (e.g. the 25th and 75th percentile range for temperature under RCP 2.6 in the 2020s would not necessarily include the same set of models as for precipitation under RCP 4.5 in the 2080s). Ideally, this approach would highlight the aggregation of models which best represented certain parameters within each scenario at each time period. For completeness, the ensemble maximum and minimum were also analyzed to understand the full spread of all CMIP5 models. Since the maximum and minimum represent the outliers of the CMIP5 ensemble and thus are subject to a lower degree of confidence, these results are not presented within the report and only referred to where necessary to establish greater context for the results being discussed.

In addition to CMIP5 data, observed data from a local weather station was also required for the statistical downscaling process. A full list of all stations within 50km of Waterloo Region was compiled. This was narrowed down to the stations that were situated closest to the study area and had complete temperature and precipitation data available for the baseline period of 1981-2010. The most appropriate location was determined to be the weather station at the Region of Waterloo International Airport, near the town of Breslau in Woolwich Township, Waterloo Region. The station was renamed (from Waterloo Wellington A, to Region of Waterloo Int'l Airport, to Kitchener/Waterloo) and moved slightly in both 2002 and 2010. Daily data for each year of the baseline period was downloaded from Environment Canada's National Climate Archives. The data record for this station was largely complete, with only a very small percentage of missing values. These missing values were infilled using data from Roseville weather station (located in the township of North Dumfries, Waterloo Region) and where necessary, from the weather station in Elora (located within neighbouring Wellington County). A map showing the locations of these weather stations is included below.

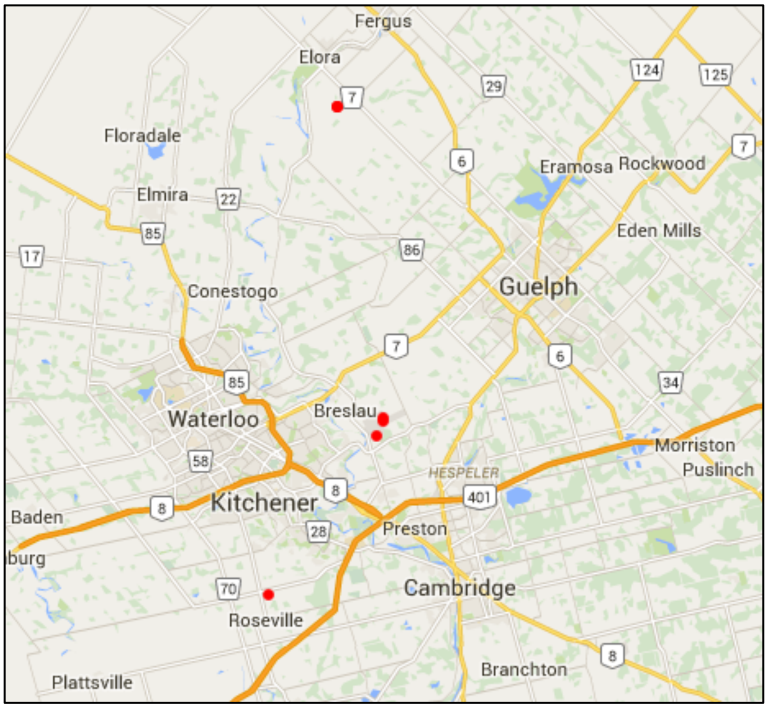


Figure B1: Map of all weather stations from which data was used.

The conclusion of the data cataloguing and pre-processing portion of this project thus resulted in two sets of data: observed data from a weather station representative of Waterloo Region, and monthly change fields for temperature and precipitation calculated using CMIP5 model output. These two datasets were then utilized together in the following step to generate downscaled future weather data.

ii. ***Statistical downscaling with LARS-WG***

The Long Ashton Research Station Weather Generator (LARS-WG) version 5.0 is a statistical downscaling model that can simulate a time series of daily weather at a given site. It is a computationally-inexpensive and robust model that has been used extensively for climate change impact assessments in locations around the globe. To generate future weather data, a time series of historical data is first input into the model, which analyzes the statistical characteristics and probability distributions of observed weather. Scenario files were then created for each scenario, time period, and percentile. These user-generated files specify changes in the characteristics of temperature and precipitation, which are applied to modify the statistical properties of the observed data. For each scenario file run through LARS-WG, a daily time series is produced containing maximum temperature, minimum temperature, and precipitation data for a specified number of years. For this project, 50 years of data for each scenario were produced for analysis.

iii. ***Data processing***

All analysis was completed on the output data from LARS-WG with the aid of the Climate Data Operators (CDO) toolset developed by the Max Planck Institute for Meteorology. A shell script program was created to automate all processing tasks, with commands being written to run calculations and extract data for each climate parameter in Table B1. Necessary information on how each parameter was calculated is included within the appropriate sections of the main report. Full data for every parameter of each scenario, time period, and percentile was compiled in a master spreadsheet, from which the tables and figures throughout the main report and Appendix A were created.

Precipitation return periods were computed using a different method, as yearly maximum precipitation amounts were analyzed using R statistical software with the aid of the "*extRemes*" extreme value analysis package developed by Gilleland and Katz (2011). A generalized extreme value distribution function was fit to the input data, which then allowed return periods to be calculated for specified intervals. Maximum 5-day precipitation totals were calculated using the same method, but the input data were the yearly maximums of a 5-day running sum.

3) LITERATURE REVIEW

A literature review process was undertaken simultaneously with ongoing data analysis. The primary focus of this review was to obtain information for climate parameters where localized climate projections could not be produced. This was the case for parameters such as wind gusts and freezing rain, where inadequate historical data was available for Waterloo Region to assess the occurrences of these events in the observed record, let alone attempt to project future changes in these parameters. In general, these parameters also represent more localized phenomena than what would be captured at the scale of a global climate model. A secondary focus of the literature review was to corroborate the projected changes in extremes that were calculated for Waterloo Region. The relative rarity of extreme precipitation and temperature events makes them more difficult to capture accurately, and thus comparing the results for these quantities between studies using different methodologies helps to improve overall confidence in the changes expected. Incorporating scientific literature in this way helped to establish a more detailed story of how climate change will impact Southern Ontario.

An initial discovery phase of literature databases identified potentially useful sources through searches using varying combinations of key words. Relevant notes for each paper were compiled and organized to create a comprehensive literature review of downscaled projections for changes in climatic extremes. This document was drawn from as needed to flesh out the results of the data analysis portion of the project.

REFERENCES AND ACKNOWLEDGEMENTS

The Interdisciplinary Centre on Climate Change at the University of Waterloo would like to acknowledge the following sources for providing either data or modeling and analysis software.

For the use of CMIP5 data, we acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table B3 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

The National Climate Archives maintained by Environment Canada. http://climate.weather.gc.ca/

The LARS Weather Generator version 5. http://www.rothamsted.ac.uk/mas-models/larswg
Semenov M.A. and Barrow E.M. (1997): Use of a stochastic weather generator in the development of climate change scenarios. Climatic Change 35: 397-414.

The Climate Data Operators (CDO) toolset developed by the Max Planck Institute for Meteorology.
CDO 2015: Climate Data Operators. Available at: http://www.mpimet.mpg.de/cdo

R statistical software.
R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

The extRemes package for R. https://cran.r-project.org/web/packages/extRemes/index.html
Gilleland E and Katz RW (2011). “New software to analyze how extremes change over time.” *Eos*, **92**(2), pp. 13–14.

Appendix B: Waterloo Region Localized Climate Projections
Full Results for All Parameters

Note: Throughout this appendix, the following identifiers are used interchangeably for greenhouse gas scenarios. For more details, refer to Section 2.3 in the main report.

Scientific identifier code	*Plain-language identifier*
RCP 2.6	Net-zero carbon
RCP 4.5	Aggressive mitigation
RCP 8.5	Business-as-usual

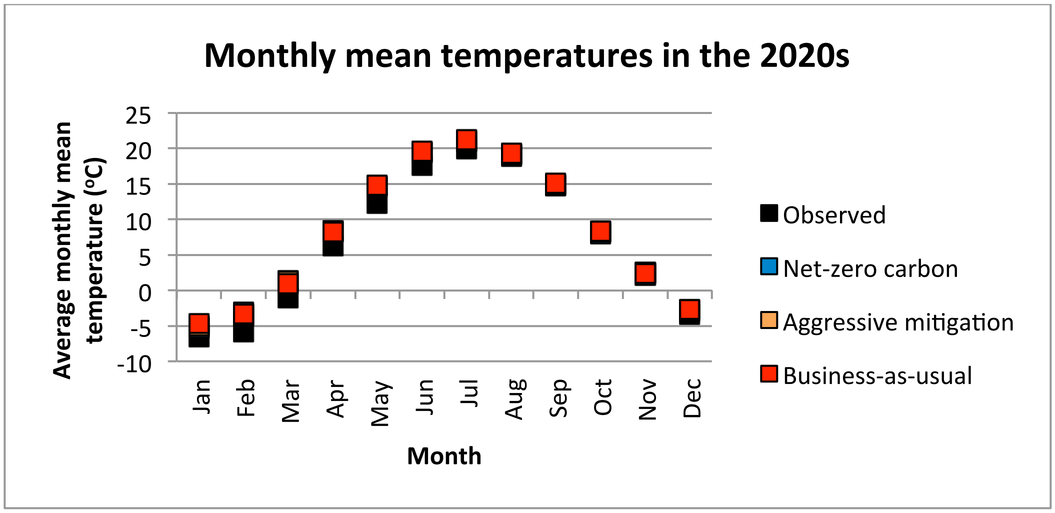
MEAN TEMPERATURE

Table 1a: Change in average annual mean temperature (°C)

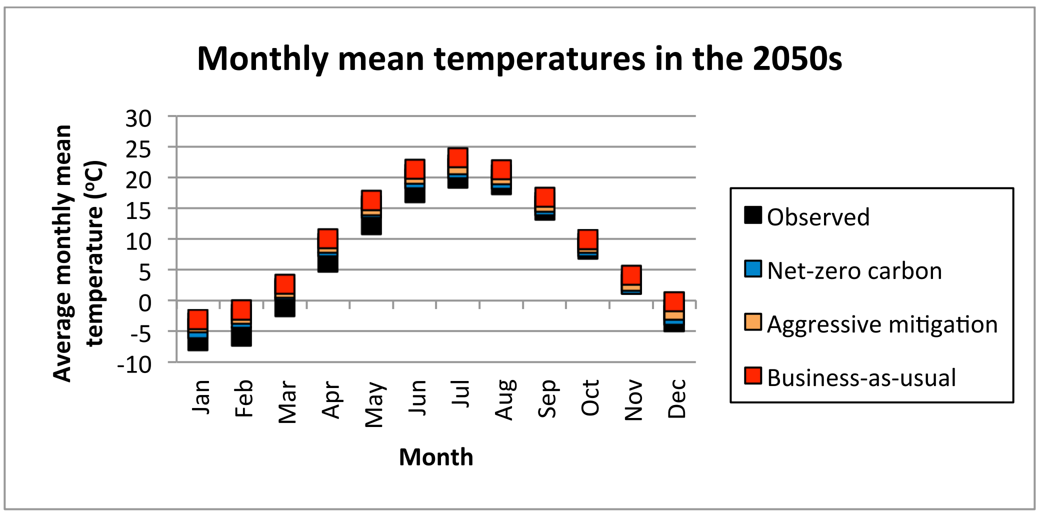
	1990s	2020s	2050s	2080s
RCP 2.6	**7.0**	1.2	1.8	1.7
RCP 4.5		1.2	2.4	2.9
RCP 8.5		1.4	3.2	5.2

Table 1b: Average seasonal mean temperatures (°C)

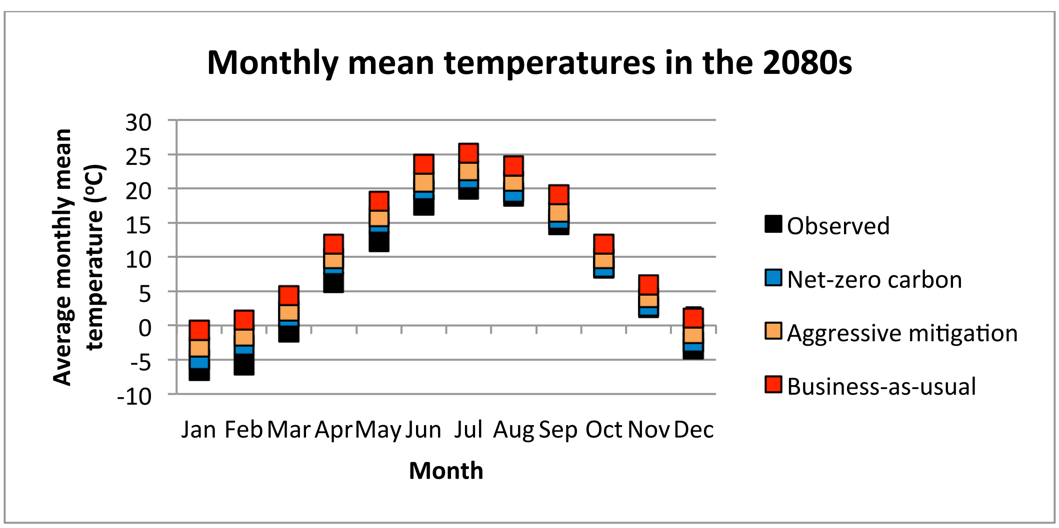
		Winter	Spring	Summer	Fall
1990s	**Observed**	-5.2	5.8	18.8	8.5
2020s	**RCP 2.6**	-3.9	8.0	19.9	8.5
	RCP 4.5	-3.8	8.0	19.9	8.6
	RCP 8.5	-3.6	8.1	20.1	8.8
2050s	**RCP 2.6**	-3.1	8.6	20.4	9.0
	RCP 4.5	-2.4	9.1	21.0	9.7
	RCP 8.5	-1.6	9.9	21.9	10.3
2080s	**RCP 2.6**	-3.2	8.5	20.3	9.1
	RCP 4.5	-1.9	9.7	21.5	10.2
	RCP 8.5	0.5	11.7	24.1	12.4



Monthly mean temperatures in the 2020s
Average monthly mean temperature (ºC)
25
20
15
10
5
0
-5
-10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Observed
Net-zero carbon
Aggressive mitigation
Business-as-usual



Monthly mean temperatures in the 2050s
Average monthly mean temperature (ºC)
30
25
20
15
10
5
0
-5
-10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Observed
Net-zero carbon
Aggressive mitigation
Business-as-usual



Monthly mean temperatures in the 2080s
Average monthly mean temperature (ºC)
30
25
20
15
10
5
0
-5
-10
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month
Observed
Net-zero carbon
Aggressive mitigation
Business-as-usual

MAXIMUM TEMPERATURE

The highest temperature reached on each day is recorded as its maximum temperature. In the tables below, maximum temperatures are averaged annually, seasonally, and monthly.

Table 2a: Average annual maximum temperatures (^oC)

	1990s	2020s	2050s	2080s
RCP 2.6	12.2	13.4	14.0	13.9
RCP 4.5		13.5	14.6	15.2
RCP 8.5		13.6	15.5	17.5

Table 2b: Average seasonal maximum temperatures (^oC)

		Winter	Spring	Summer	Fall
1990s	Observed	-1.3	11.3	25.0	13.7
2020s	RCP 2.6	0.1	13.6	26.1	13.6
	RCP 4.5	0.9	14.2	26.6	14.1
	RCP 8.5	0.8	14.1	26.5	14.1
2050s	RCP 2.6	0.2	13.6	26.1	13.7
	RCP 4.5	1.6	14.7	27.2	14.7
	RCP 8.5	2.2	15.2	27.8	15.2
2080s	RCP 2.6	0.4	13.7	26.3	13.8
	RCP 4.5	2.5	15.6	28.1	15.3
	RCP 8.5	4.6	17.3	30.2	17.4

MINIMUM TEMPERATURE

Minimum temperatures represent the lowest temperature recorded on each day. Projected increases in minimum temperatures are similar in magnitude to the expected increase in maximum temperatures.

Table 3a: Average annual minimum temperatures (^oC)

	1990s	2020s	2050s	2080s
RCP 2.6	1.9	3.0	3.6	3.5
RCP 4.5		3.0	4.2	4.7
RCP 8.5		3.2	5.0	7.0

Table 3b: Average seasonal minimum temperatures (^oC)

		Winter	Spring	Summer	Fall
1990s	Observed	-9.2	0.3	12.7	3.4
2020s	RCP 2.6	-8.0	2.4	13.7	3.5
	RCP 4.5	-7.9	2.4	13.6	3.6
	RCP 8.5	-7.6	2.5	13.9	3.8
2050s	RCP 2.6	-7.1	3.1	14.3	4.0
	RCP 4.5	-6.4	3.5	14.7	4.7
	RCP 8.5	-5.7	4.2	15.7	5.3
2080s	RCP 2.6	-7.3	2.9	14.1	4.0
	RCP 4.5	-5.9	4.2	15.3	5.1
	RCP 8.5	-3.5	6.0	17.9	7.4

TEMPERATURE THRESHOLDS

Table 4a: Average annual number of days with maximum temperatures > 30^oC

	1990s	2020s	2050s	2080s
RCP 2.6	10.1	12.0	15.2	14.5
RCP 4.5		11.7	20.6	28.2
RCP 8.5		12.7	30.9	59.3

Table 4b: Average annual number of days with minimum temperatures < -15^oC

	1990s	2020s	2050s	2080s
RCP 2.6	22.1	10.8	8.4	9.0
RCP 4.5		10.3	7.0	5.8
RCP 8.5		9.9	5.8	2.8

Table 4c: Average annual number of days with minimum temperatures < 0^oC

	1990s	2020s	2050s	2080s
RCP 2.6	153.0	141.4	133.1	133.4
RCP 4.5		141.1	125.1	117.4
RCP 8.5		138.8	114.5	90.1

Table 4d: Average annual number of days with freeze-thaw cycles

	1990s	2020s	2050s	2080s
RCP 2.6	74.1	83.3	82.3	82.0
RCP 4.5		83.0	80.1	78.1
RCP 8.5		82.6	76.7	66.6

DEGREE DAYS

Table 5a: Average annual heating degree days (% change)

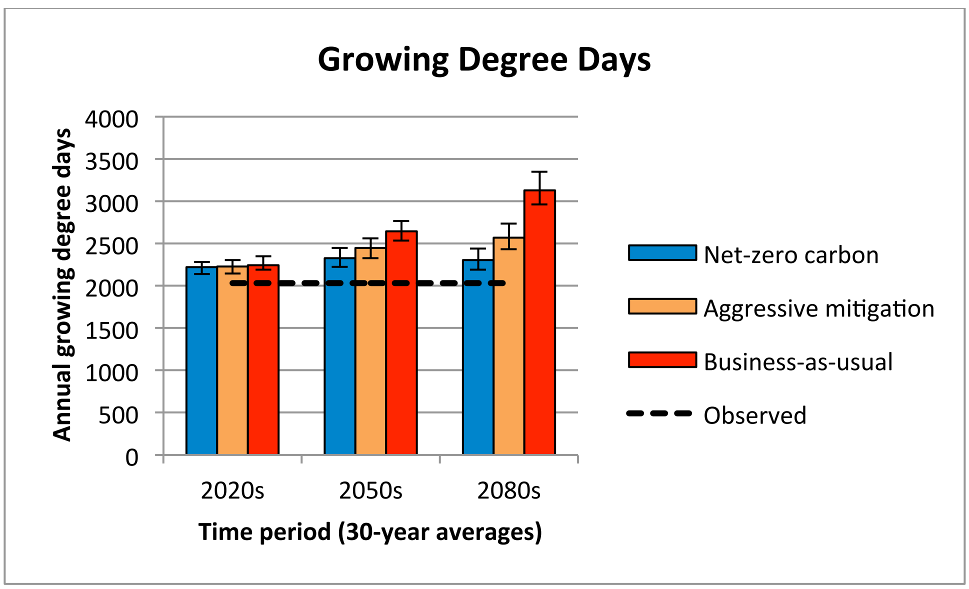
	1990s	2020s	2050s	2080s
RCP 2.6	4199.6	-9.2%	-13.5%	-13.0%
RCP 4.5		-9.6%	-17.3%	-20.8%
RCP 8.5		-10.6%	-22.1%	-33.7%

Table 5b: Average annual cooling degree days (% change)

	1990s	2020s	2050s	2080s
RCP 2.6	197.7	19.1%	42.7%	36.5%
RCP 4.5		18.3%	67.4%	96.6%
RCP 8.5		26.4%	116.3%	242.6%

Table 5c: Average annual growing degree days (% change)

	1990s	2020s	2050s	2080s
RCP 2.6	2031.6	9.3%	15.5%	14.4%
RCP 4.5		9.4%	21.3%	27.8%
RCP 8.5		11.4%	30.8%	55.5%



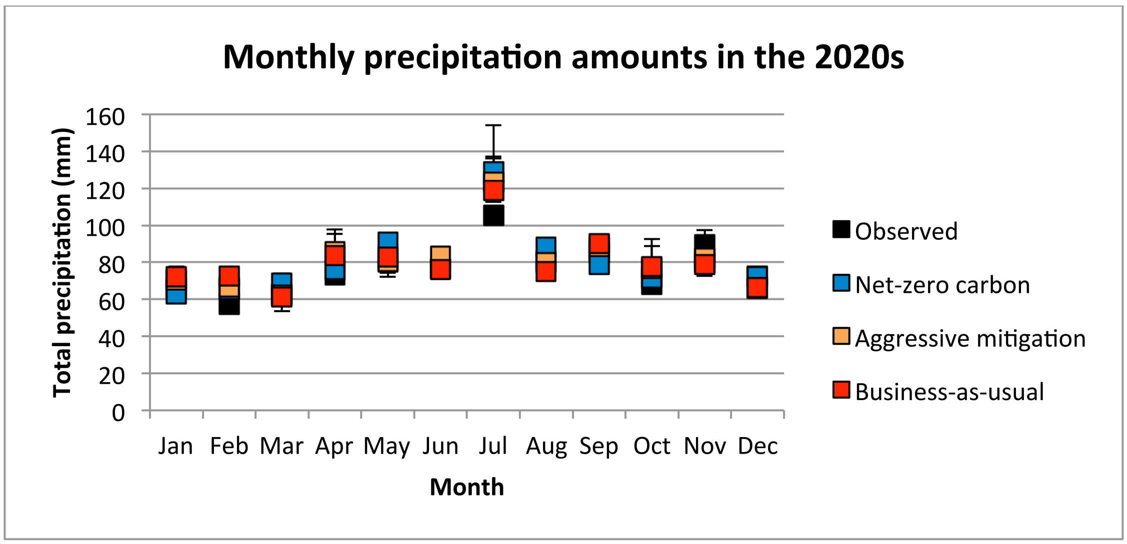
PRECIPITATION AMOUNTS

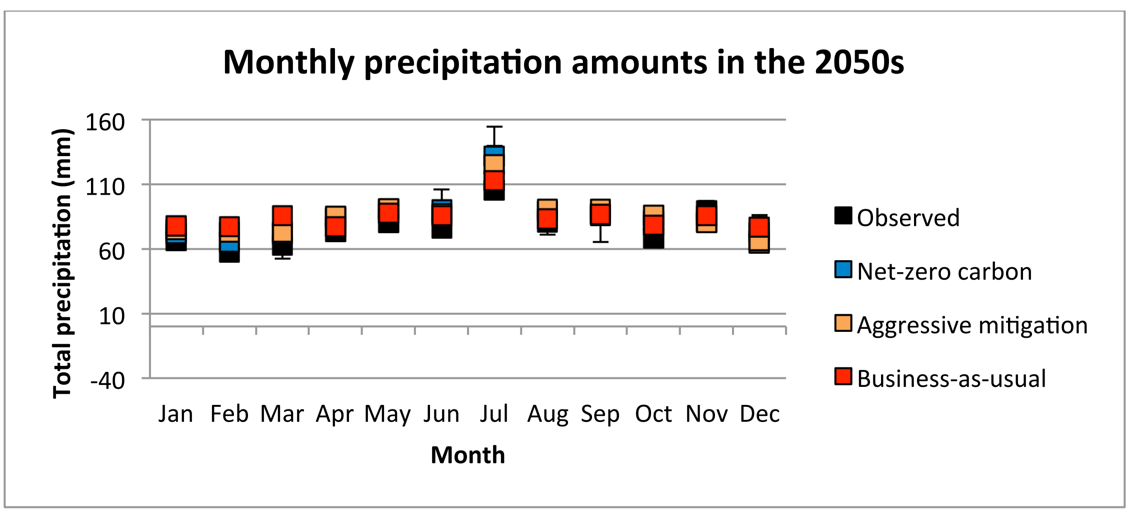
Table 6a: Average total annual precipitation (% change from 1990s baseline)

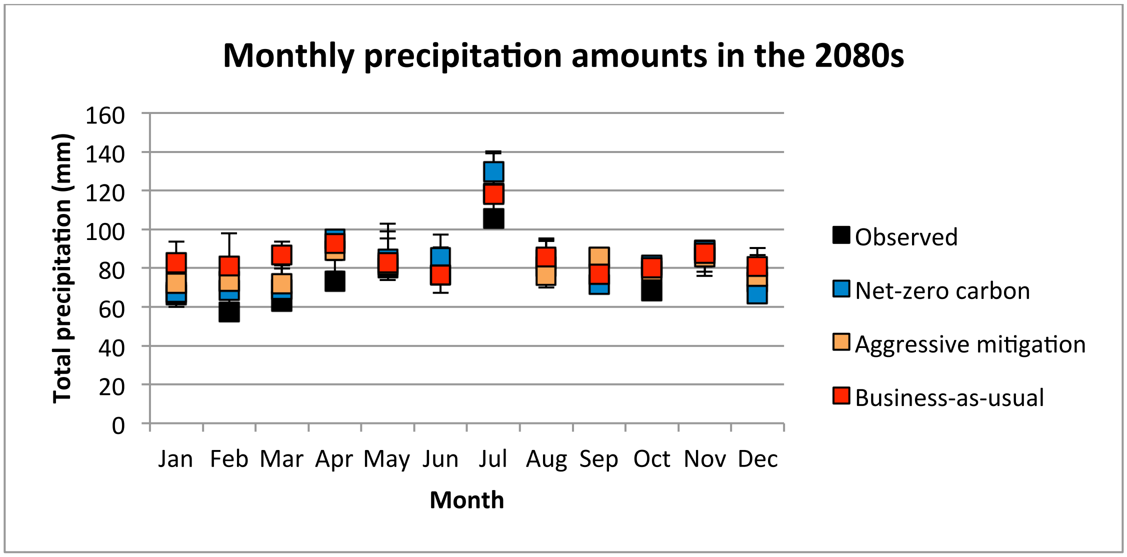
	1990s	2020s	2050s	2080s
RCP 2.6	918.5mm	4.3%	11.7%	7.3%
RCP 4.5		6.2%	8.5%	10.0%
RCP 8.5		3.8%	10.4%	12.0%

Table 6b: Average total seasonal precipitation (% change from 1990s baseline)

		Winter	Spring	Summer	Fall
1990s	Observed (mm)	**196.4**	**216.3**	**262.7**	**243.1**
2020s	RCP 2.6	6.2%	8.2%	3.3%	0.2%
	RCP 4.5	5.3%	9.9%	8.1%	1.7%
	RCP 8.5	7.5%	9.1%	-0.2%	0.7%
2050s	RCP 2.6	6.5%	16.7%	18.0%	4.7%
	RCP 4.5	9.8%	15.0%	3.3%	7.5%
	RCP 8.5	14.4%	11.5%	14.1%	2.1%
2080s	RCP 2.6	7.3%	13.3%	7.5%	1.7%
	RCP 4.5	13.8%	17.6%	9.5%	0.7%
	RCP 8.5	23.1%	25.5%	2.0%	1.9%







PRECIPITATION THRESHOLDS

Table 7a: Average annual number of days with precipitation:

	1990s	2020s	2050s	2080s
RCP 2.6	165.3	162.7	165.0	162.8
RCP 4.5		162.6	161.4	163.6
RCP 8.5		162.1	162.8	159.7

Table 7b: Average annual number of days with precipitation > 10mm:

	1990s	2020s	2050s	2080s
RCP 2.6	30.1	29.8	32.7	30.9
RCP 4.5		30.7	31.6	32.3
RCP 8.5		30.0	32.9	33.1

Table 7c: Average annual number of days with precipitation > 25mm:

	1990s	2020s	2050s	2080s
RCP 2.6	5.0	6.2	6.8	6.5
RCP 4.5		6.3	6.5	6.4
RCP 8.5		6.2	6.5	7.0

SNOW

Table 8a: Average annual total snowfall (cm)

	1990s	2020s	2050s	2080s
RCP 2.6	191.4	222.7	204.9	209.9
RCP 4.5		224.2	188.4	180.8
RCP 8.5		222.1	173.0	123.2

Table 8b: Average annual number of days with snowfall > 5cm

	1990s	2020s	2050s	2080s
RCP 2.6	11.5	13.9	13.0	12.8
RCP 4.5		14.1	11.5	11.0
RCP 8.5		13.7	10.3	7.2

WET & DRY SPELLS

Table 9a: Average annual number of dry spells

	1990s	2020s	2050s	2080s
RCP 2.6	14.0	13.1	13.1	12.9
RCP 4.5		13.2	13.2	13.2
RCP 8.5		13.2	13.2	13.3

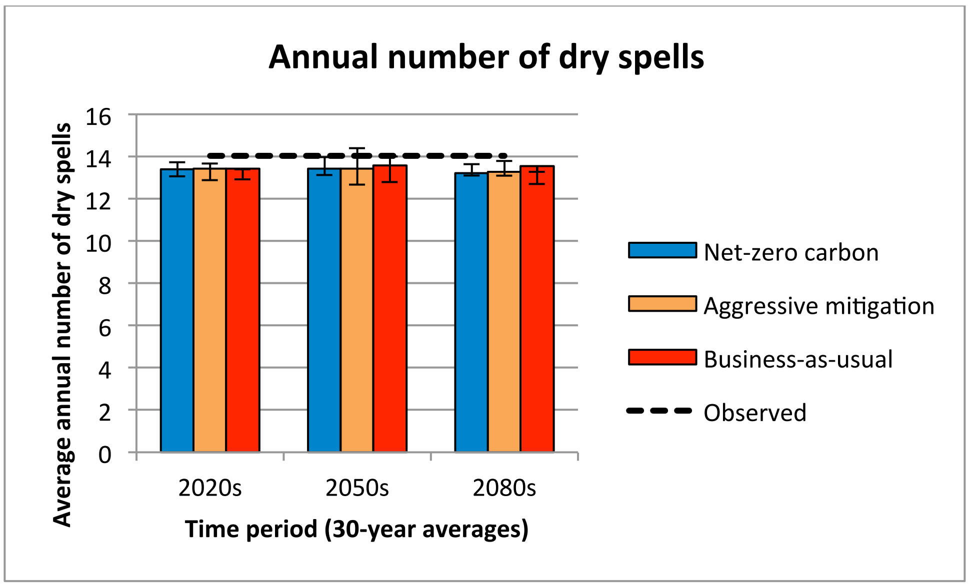
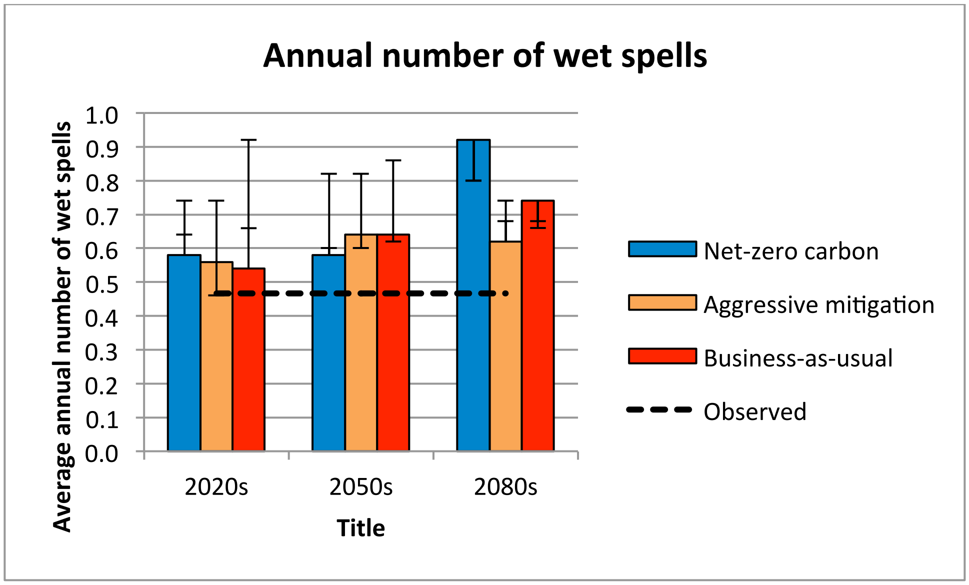


Table 9b: Average annual number of wet spells

	1990s	2020s	2050s	2080s
RCP 2.6	0.47	0.58	0.78	0.64
RCP 4.5		0.50	0.72	0.72
RCP 8.5		0.64	0.76	0.74



RETURN PERIODS

Table 10a: Return periods for maximum 1-day total precipitation amounts (mm)

Return Period	Observed 1990s	RCP 2.6			RCP 4.5			RCP 8.5		
		2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
2-yr	50.0	59.6	63.1	61.9	58.8	61.2	60.8	58.5	51.6	51.9
5-yr	66.5	79.8	83.6	83.4	80.7	81.1	82.0	78.0	66.9	67.4
10-yr	78.5	94.6	98.4	99.4	98.3	94.9	97.5	92.5	78.1	80.3
25-yr	94.8	114.9	118.7	121.8	124.9	113.3	118.8	112.6	93.4	100.5
50-yr	107.8	131.2	134.9	140.2	148.4	127.5	136.0	129.2	105.7	118.9
100-yr	121.6	148.6	152.2	160.0	175.4	142.3	154.4	147.0	118.8	140.6

Table 10b: Return periods for maximum 5-day total precipitation amounts (mm)

Return Period	Observed 1990s	RCP 2.6			RCP 4.5			RCP 8.5		
		2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
2-yr	71.9	85.1	92.2	89.5	87.5	90.0	90.2	85.9	79.6	83.8
5-yr	92.0	113.1	120.6	120.1	117.1	118.5	119.4	112.9	102.2	106.7
10-yr	105.7	132.0	140.7	141.5	137.1	138.3	140.8	131.2	122.1	121.9
25-yr	123.5	156.3	167.7	170.2	162.6	164.4	170.3	154.9	154.7	141.0
50-yr	137.1	174.6	188.9	192.6	181.9	184.6	194.2	172.8	185.7	155.1
100-yr	150.8	193.0	211.0	215.9	201.2	205.4	219.7	191.0	223.8	169.0