Climate Projections for Niagara Region

Prepared by: Toronto and Region Conservation Authority

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Executive Summary

Climate projections for the Great Lakes Basin anticipate a rise in temperatures between 1.5 to 7 °C and a 20% increase in annual precipitation by the 2080s (McDermid et al., 2015). Great Lakes ice cover has been declining rapidly since the 1970s and is expected to continue to decrease with future warming (Di Liberto, 2018). Recent projections developed by Environment and Climate Change Canada (ECCC) also indicate the potential for more frequent and severe extreme high and extreme low water levels (Seglenieks & Temgoua, 2021). These changes can have a cascading impact on the land-water fluxes that lead to changes in precipitation patterns, flooding, erosion of shorelines, and alteration of aquatic and terrestrial habitats (Mortsch, 1998). While these projections are summaries for the entire Great Lakes Basin, individual regions may experience differences due to their location and physiography.

With this context, Niagara Region identified the need to develop regional climate projections using the updated method provided by Toronto and Region Conservation Authority (TRCA) and Ontario Climate Consortium (OCC) to support the implementation of climate adaptation initiatives across the region. Using the standardized approach presented in the guidance document, TRCA has retrieved, bias-corrected and analyzed region-specific climate data for Niagara Region to support policy development in the new Regional Official Plan (Niagara Official Plan), as well as other policies and programs.

Data sets of four climate variables were downloaded from the North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX) portal at the daily time scale: average, maximum and minimum near-surface air temperature, and total precipitation. For each of the four climate variables, outputs from multiple climate models were downloaded for the baseline (1971-2000), short-term (2021-2050) and long-term periods (2051-2080). Data for future periods were downloaded for two different socio-economic scenarios of greenhouse gas (GHG) emissions: RCP 8.5 and RCP 4.5. RCP 8.5 is a high emissions pathway that projects continued increases to GHG concentration beyond the end of the century. The RCP 4.5 scenario projects emissions to decline by mid-century and stabilize radiative forcings at 4.5 W m^{-2} (approximately 650 ppm CO_2) by 2100 without exceedance. To reach this target, the RCP 4.5 scenario assumes climate policies limiting emissions by introducing global greenhouse gas emissions prices that would drive shifts in the energy system (e.g., introduction of technologies that emit lower emissions, use alternative energy, or capture carbon). Forest lands are also assumed to increase from current extents to play a role in carbon sequestration (Thomson et al., 2011).

Observed climate data recorded at climate station gauges within and around the Niagara Region were retrieved from Environment and Climate Change Canada data portal for the baseline period of 1971-2000 to compare and correct the inherent bias in modelled data. The delta difference method was used for bias-correction, where the difference in means between modelled and observed data for the baseline period (1971-2000) is used to correct the model outputs of the two future periods. This method assumes that the model bias remains constant from the baseline through the future climate periods.

Bias-corrected data for the four climate variables were analyzed to produce 52 climate parameters for Niagara Region. Table 1 summarizes a few of the baseline and future climate trends the Region can expect to see under the RCP 8.5 scenario. A complete list of climate parameters and results under the high emissions scenario can be found in Table 6.

TABLE 1. SELECTED CLIMATE PARAMETERS CALCULATED FOR NIAGARA REGION USING THE RCP 8.5 (HIGH-EMISSIONS) SCENARIO FOR SHORT- AND LONG-TERM PERIODS COMPARED TO BASELINE VALUES.

Climate Parameter	Baseline (1971-2000)	Short Term (2021-2050)	Long Term (2051-2080)	Climate Trend
Mean Annual Temperature (˚C)	8.7	10.7	12.3	↑
Annual Average Number of Days above 35˚C	0.3	2.1	7.1	↑
Annual Average Number of Days above 25˚C	53.5	77.7	95.8	↑
Tropical Nights	9.4	24.5	46.2	↑
Annual Average Number of Days below -15˚C	12.3	6.5	1.0	↓
Total Average Annual Precipitation (mm)	1080.6	1135.0	1192.0	↑
Annual Average Maximum Amount of Precipitation Falling in 1 Day (mm)	70.7	72.7	78.1	↑
Annual Average Maximum Amount of Precipitation Falling in 3 Days (mm)	112.4	109.3	119.5	↑
Annual Average Simple Daily Intensity Index (SDII) (mm/day)	5.2	5.4	5.7	↑
Average Growing Season Length for Climate Period	186	194	201	↑

The results presented in Table 1 and summaries following for the two future climate periods are based on climate model outputs for the RCP 8.5 scenario, assuming one of the highest no-climate-policy baseline emissions scenarios published in literature. The summary values for each climate period are ensemble averages taken from outputs of 16 models for the 30- year span. The baseline period values are also extracted from bias-corrected model outputs instead of observed climate normals since most of the climate parameters require analysis of continuous climate time series that aren't readily available for 30-yr periods.

Niagara Region's Climate in the Short Term (2021-2050)

Daily mean, maximum and minimum **air temperatures** across Niagara Region are expected to rise on average by 2℃ in the short term over the 30 years. Seasonally, winter and fall daily mean temperatures are expected to increase the most, on average by 2.4 and 2.2℃ respectively, followed by summer and spring (2 and 1.6 ℃ respectively) (Table 6). The spring season has the least projected increase in daily maximum and minimum temperatures (1.5 and 1.7 ℃), while the remaining seasons show an approximate increase of 2℃. The minimum temperatures in winter season of the baseline period average around -7.1℃, but as the climate warms, this is expected to increase to -5 ℃ in the coming decades. The number of days below 0˚C is projected to decrease from 125.1 days/year during the baseline to 105.7 days/year in the short-term. The warming of temperatures will increasingly cause winter precipitation to occur as rainfall instead of snow. Rainfall during winter months when soils are less pervious to infiltration (due to freezing temperatures) will result in more runoff and flooding conditions within the Region's water systems. Furthermore, milder winters may have implications for winter recreational activities and tourism.

Maximum air temperatures are projected to rise. This result implies that heat, and the vast impacts associated with it, are expected to be prevalent as we move into the future. Health-related conditions associated with extremely hot days and ecosystem-related impacts such as heat stress and warming of waters could also be expected to become more common. During the baseline period, Niagara region has an average annual of 10.4 days with daily maximum temperature exceeding 30℃. This is expected to more than double to about 23.9 days in the short term. Days with maximum daily temperatures exceeding 25℃ show the same trend. Niagara averages approximately 53.5 days during the baseline period, and this is expected to increase by an additional 24.2 days in the short-term. The number of days with daily minimum temperatures exceeding 20℃ (Tropical Nights) is projected to increase from 9.4 days in the baseline period to 46.2 days in the long-term future. The demand for cooling on these additional days/nights can be expected to strain the Region's energy systems. On the other hand, **extreme cold** conditions are expected to decline. The number of days where air temperatures are below -20 and -15℃ are projected to decrease from about 4.2 and 12.3 days during the baseline period to around 2.2 and 6.5 days per year in the short-term, respectively.

Total precipitation is also projected to increase across all four seasons resulting in a 5% increase in the annual total within the short term. The average annual total precipitation for the baseline period is higher than in most surrounding regions with an average annual of 1080.6 mm, which is projected to increase to 1135 mm on average in the short term. Greatest increase in seasonal precipitation is projected for the winter (22mm increase) and spring (15 mm increase) seasons, with lesser changes in the summer (8.4 mm increase) and fall (3.2 mm increase).

In terms of annual **extreme precipitation**, the 1-day maximum precipitation is projected to increase on average by approximately 2 mm, while the maximum 3-day precipitation is projected to decrease by 3.1 mm. However, the average annual Simple Daily Intensity Index (SDII), the mean precipitation on wet days, is increasing by 3.8%, with fall and winter seasons having the greatest increase (5.7 and 4.7%, respectively). Furthermore, the annual number of days with precipitation that exceeds 25 mm is also increasing from 4.8 to 5.8 days in the short term. While increases in precipitation volume and intensity seem minimal in the short term (approximately 5% or less), it is important to note that these differences are evaluated using the mean values. There is high variability in model outputs for precipitation which the mean statistic alone may not be able to represent adequacy. For example, the 1-day maximum precipitation can be interpreted to decrease by 10.6 mm or increase by 23.5 mm when considering the 10^{th} and 90^{th} percentile values (Table 6) but shows an increase of only 2mm when considering the mean values. Municipalities may need to consider the range of values and devise a methodology of adaptation to mitigate risk of under- or over- preparedness.

In the short term, the number of days with a **freeze-thaw** cycle are projected to decrease from 76.6 days to 67.4. This trend aligns with other temperature parameters indicating milder temperatures during the colder seasons during which these cycles would occur.

Trends related to **dry conditions** are consistent between baseline and the short-term periods. Both total annual dry days and maximum total consecutive dry days remain unchanged between the two climate periods, supporting the notion that any increases in rainfall volume for the future periods is likely due to an increase in intensity on days with rainfall.

Finally, the length of **growing season** is increasing on average (increase by 8 days) due to earlier growing season start days and later end dates. The temperature time-series of some models showed the occurrence of cold snaps following the onset of the growing season such that the daily minimum temperature drops below the 5 ℃ threshold after being sustained above it for 5 consecutive days. Inversely, there were also instances of warmer temperatures returning post the growing season end day that is marked by 5 consecutive days of daily minimum temperatures below 5 ℃. As a result, further to the identified average trends, the growing season length will be impacted by the hardiness of the crops to withstand temperature fluctuations between days. Considering cumulative measures of heat availability for plant growth, there is high model agreement that growing degree days will increase, aligning with the projection of a warming regional climate. However, pests will also thrive given a more suitable climate for completing their lifecycle stages.

Niagara Region's Climate in the Long Term (2051-2080)

Projections for the long-term climate period generally follow the same trends as the short-term period, a warmer and wetter climate in comparison to both the baseline and short-term periods. However, projections further into the future (i.e., the long-term period) should be interpreted as having greater uncertainty. This is because policies, conditions and decisions made locally and globally may influence the climate condition trajectories. Assuming the RCP 8.5 scenario without further mitigation interventions, the following describes notable changes to climate from the baseline to the long-term climate period for the Niagara region, with the complete parameter list available in Table 6 of this report.

Between 2051-2080, the RCP 8.5 trajectory projects Niagara region to warm by 3.6℃, leading to an average **annual air temperature** of 12.3℃ in comparison to the baseline average of 8.7℃. Seasonally, the lowest increase is projected for the spring (+3.2 ℃) while projections for winter (+3.7℃), summer (+3.8℃), and fall (+3.8℃) are consistently higher. Furthermore, even the lowest 10^{th} percentile values from all 16 models for seasonal temperature projections are higher than the baseline mean values, indicating a strong trend of warming climate for this RCP scenario.

The annual average of daily **maximum and minimum temperatures** are projected to continue warming through the long-term period, by an average of 3.5 and 3.9 ℃ respectively. Seasonally, the daily maximum and minimum temperatures are increasing the most for winter (+4 ℃, +4.8 ℃) and fall (+3.8 ℃ , +3.9 ℃). As a result, the average number of days with minimum temperatures below -15℃ decreases by 92% (12.3 in baseline to 1 day) and the average number of days with maximum temperatures above 30℃ increases by 279% (10.4 in baseline to 39.4 days). Furthermore, the number of days with minimum temperatures below 0℃ decrease on average by a third (125.1 in baseline to 83.8 days). As winter precipitation is expected to continue increasing through the long-term period, with fewer days of minimum temperature below freezing, winter precipitation will frequently occur as rainfall instead of snow.

On average, **precipitation volume** is projected to increase slightly through the long-term period. The average annual precipitation volume increases by 10% (totaling 1192 mm), the majority of which falls in the winter (+43 mm) and spring (+42.4 mm). **Extreme precipitation** parameters indicate that 1-day maximum and 3-day maximum precipitation are projected to increase by 7% and 9% at the end of century, respectively compared to baseline conditions. Since the average count of dry days remains the same as the baseline, increases in precipitation intensity can be expected on wet days to account for the increased precipitation volume. Average annual precipitation intensity is projected to be 5.7 mm/day, with the highest projected increases during the two seasons with the highest precipitation volume, the spring (6.3 mm/day) and summer (6.1 mm/day).

Agriculture parameters remain favorable for crop growth but may also support existing and new pests. Due to a warming climate, the growing season continues to lengthen (186 days in baseline to 201 days) with earlier start date (April 29) and a later end date (Nov 16). Growing degree days increase by 29% with fewer days of freeze-thaw and ice potential. Increased precipitation and lower number of consecutive dry days would seem to also support crop growth. However, intense heat and precipitation events could potentially harm crops in addition to threats posed by pests supported by warmer and wetter climates.

Climate Trend Differences Between Niagara’s Northern and Southern Regions

Difference in climate can be observed within the Niagara region. Anecdotally, regions north and south of Niagara Escarpment have been observed to have noticeably different climates, likely due to orographic and elevation differences. Areas north of the escarpment are generally at a lower elevation and likely affected more by the land-water energy transfers with Lake Ontario while areas south of the escarpment are at a higher elevation draining towards Lake Erie. The resolution of climate data used for this report (25 km x 25 km) is too coarse to discretize North and South regions based on the escarpment ridgeline provided by the Region. At most, the region can be split by assigning certain grid cells as northern and southern parts of the region. The escarpment runs horizontally across the region and passes through both the arbitrarily selected northern and southern regions.

The mean values of the four datasets (daily precipitation, average temperature, maximum temperature and minimum temperature) were summarized at each grid cell using the ensemble mean of all 16 models for each climate period. Generally, the North/ Northwestern areas of the region had warmer temperatures from the baseline through the short- and long-term periods (Figure 11; Figure 12). The maximum daily temperature follows the same trend as the daily average temperature (Figure 13; Figure 14) but the minimum daily temperatures are projected to be highest in the southern region by the long-term period (Figure 16,Figure 17). While precipitation is projected to increase region wide, sub-regionally, average daily precipitation increases from the Northwest to Southeast regions for all climate periods. Additional climate parameters derived from the four datasets are summarized by North and South subregions in Table A1 and A2.

Next Steps

The ensemble climate modeling outputs presented in this report will be a useful tool for the Niagara Region's planning initiatives. It will serve as the foundational dataset and driver for setting climate change adaptation goals. Below is a list of next steps and recommendations that Niagara may wish to consider advancing their climate change mitigation and adaptation practices.

- Work with climate and subject matter experts to integrate the climate projections into various projects (e.g., hydrogeological modeling, water quality modeling, hydrological modeling, forecasting threats to public health etc.) to better understand how climate change may impact these systems.

- Consider conducting additional studies for select climate parameters (e.g., drought, snow, etc.) that would need to be validated through additional data. For example, a comprehensive analysis on drought would require additional data on solar radiation to estimate potential evapotranspiration (OCC, 2016).

- Work with climate and subject matter experts to continually update the climate projections as new climate information becomes available to ensure that climate adaptation initiatives are based on the best available science. There are more suitable methods to bias correct precipitation data (e.g., quantile mapping) that may produce model outputs that are higher in agreement. Updates to plans (e.g., climate change plans) should be reviewed every 5 years in order to keep pace with the rapidly evolving science and changing policy environment.

- Build staff capacity through education and training on the use and application of the climate modeling. This will allow staff to have a better understanding of the limitations or caveats associated with the climate data.

- Consider developing an online web application that would provide the Region and its municipalities with an easy-to-use interface for data handling. The web application would be used to present the climate projections while also providing a space to access the data easily.

- Conduct climate change vulnerability and risk assessments (e.g., ecosystem impact analyses, neighborhood-scale vulnerability assessments, etc.) to better understand the climatic, biophysical, and human factors that contribute to the effects of climate change on various systems (e.g., natural systems, infrastructure, etc.). This will also allow the Region to undertake quantitative vulnerability analyses to identify and map highly vulnerable areas in the region.

- Consider updating policies, design standards and guidelines to account for projected changes in climate.

- Continue understanding and addressing the impacts of climate change by bolstering high resolution and long-term monitoring programs to support better adaptive management and planning.

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Acronyms

AR6	IPCC's Sixth Assessment Report
CMIP5	Fifth Coupled Model Intercomparison Project
CHU	Corn Heat Units
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRCM5-OUR	Canadian Regional Climate Model 5 (OURANOS) (RCM)
CRCM5-UQAM	Canadian Regional Climate Model 5 (Université du Québec a Montréal) (RCM)
ECCC	Environment and Climate Change Canada
GCM	Global Climate Model
GDD	Growing Degree Days

GHG	Greenhouse Gases
HIRHAM5	Based on a subset of HIRLAM (High Resolution Limited Area Model) RCM and the ECHAM (European Centre developed at Hamburg)
IDF	Intensity Duration Frequency
IPCC	Intergovernmental Panel on Climate Change
LSRCA	Lake Simcoe Region Conservation Authority
NARCCAP	National American Regional Climate Change Assessment Program
NetCDF	Network Common Data Form
OCC	Ontario Climate Consortium
RCA4	Rossby Centre Regional Atmospheric Model 4
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RegCM4	Regional Climate Model 4
SCCCAP	St. Catharines Corporate Climate Change Action Plan
SDII	Simple Daily Intensity Index
SST	Sea Surface Temperature
TRCA	Toronto and Region Conservation Authority
WRF	Weather Research and Forecasting Model (RCM)

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1.0 Introduction

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) states that it is unequivocal that human influence has warmed the atmosphere, ocean, and land, which has led to increased average global temperatures, more frequent and intense heat and heavy precipitation events, rising sea levels, and more compound extreme events (IPCC, 2021). Furthermore, the scale and impact of change observed across the global climate system are considered unprecedented over many centuries to thousands of years (IPCC, 2021). As demonstrated in *Canada in a Changing Climate Report* (2019), Canada's annual average temperature over land has warmed by 1.7°C since 1948, which is a faster warming rate than the rest of the world. Changes in climate will continue to significantly affect all communities across Canada, with regional and local differences.

Climate projections for the Great Lakes Basin anticipate a rise in temperatures between 1.5 and 7 °C by the 2080s, with an increased winter precipitation (160mm) and decreased summer precipitation (60 mm less) (McDermid et al., 2015). Great Lakes ice cover has been declining rapidly since the 1970s and is expected to continue to decrease with future warming (Di Liberto, 2018). Recent projections developed by Environment and Climate Change Canada (ECCC) also indicate the potential for more frequent and severe extreme high and low water levels (Seglenieks and Temgoua, 2021). These changes can have a cascading impact on the land-water fluxes that lead to changes in precipitation patterns, flooding, erosion of shorelines, and alteration of aquatic and terrestrial habitats (Mortsch, 1988).

In recent years, confidence around future climate modeling projections has significantly increased. Since the IPCC released their second assessment report in 1995, the number of Global Circulation Models (GCMs) has grown to over 40 different models (Auld et al., 2016). GCMs have increasingly included more components of the Earth's systems and their coupled interactions (e.g., ocean, atmosphere and land interactions) so their resolution has also improved over time. Regional Climate Models (RCMs) have also increased their spatial resolution significantly (IPCC, 2014). This increase in the number of climate models has provided the opportunity for practitioners to analyze climate projections through an ensemble of models, reducing the overall uncertainty associated with climate projections.

In Ontario, the state of climate modeling has improved significantly in the past few decades. Most climatological studies in the Great Lakes Basin now use RCMs which offer high resolution, dynamically downscaled GCM output under a more regional climate context. This increased resolution allows for a more accurate representation of climatological variables across hydrological features, which are typically represented as land surfaces in GCMs. However, despite these improvements, a consistent approach to undertaking climate modeling in Ontario does not currently exist. Many municipalities in Ontario have undertaken their own climate modeling studies, but a lot of uncertainty exists around which climate models to use, how many models to use, and how to conduct the modeling itself. By enhancing the way in which we examine current conditions and projected future climates, and applying a consistent approach across the region, this study will help equip decision-makers and resource managers with the necessary background to inform the implementation of adaptation strategies and help residents prepare for the impacts of climate change.

There is growing demand for Ontario's municipalities to address climate change at the local scale. Provincial policies require municipalities to consider climate change impacts as part of policies and plans such as Official Plans and Asset Management Plans. To enhance the way in which we examine projected future climates and apply a consistent approach across the region, Toronto and Region Conservation Authority (TRCA) and Ontario Climate Consortium (OCC) partnered with the Region of Durham to update the Durham Region's climate projections and provide an updated methodology for deriving the climate projections based on the latest climate science and information. Using an ensemble of Regional Climate Models (RCMs), this project provided a new set of climate projections for the Durham Region, its eight local municipalities and five conservation authorities, along with a guidance document referred to as the *Guide to Conducting a Climate Change Analysis at the Local Scale: Lessons Learned from Durham Region (2020).* The guidance document provides a step-by-step methodology for deriving regional climate projections that can be replicated in municipalities across Ontario, including Niagara Region, to establish a consistent and practical approach to accessing, analyzing, and deriving climate data for use by municipalities, conservation authorities, and other stakeholders.

While climate projections are available for the entire Great Lakes Basin, there will likely be significant differences between regions. With this context, Niagara Region identified the need to develop regional climate projections using the updated method provided by TRCA and OCC to support the implementation of climate adaptation initiatives across the region. Using the standardized approach presented in the guidance document, TRCA has retrieved, bias-corrected and analyzed region-specific climate data for Niagara Region to support policy development in the new Regional Official Plan (Niagara Official Plan), as well as other policies and programs.

1.1 Objectives

The purpose of this project is to replicate the methods used in the *Guide to Conducting a Climate Change Analysis at the Local Scale: Lessons Learned from Durham Region* (2020) report to improve consistency around climate modelling and provide updated climate projections for Niagara Region. The specific objectives of this project are to:

- Retrieve an ensemble of regionally downscaled climate (temperature and precipitation) projections for the Niagara region for the short (2021-2050) and long term (2051-2080) climate periods;
- Correct for model bias using baseline station data within the study region; and
- Derive relevant climate parameters from the bias-corrected datasets.

This report presents an overview of the methods used and summarizes both the climate projections and derived parameters by climate periods at regional and sub-regional spatial scales using tabular and graphical results.

2.0 Study Area: Niagara Region

The Regional Municipality of Niagara ("Niagara Region") includes the area commonly referred to as the "Niagara Peninsula." While this is not a true peninsula, much of the region lies in a narrow stretch of land between Lake Ontario and Lake Erie (Figure 1). The Region contains 12 municipalities, 15 watershed planning areas, and an approximate population of 500 000 (Niagara Region, 2016).

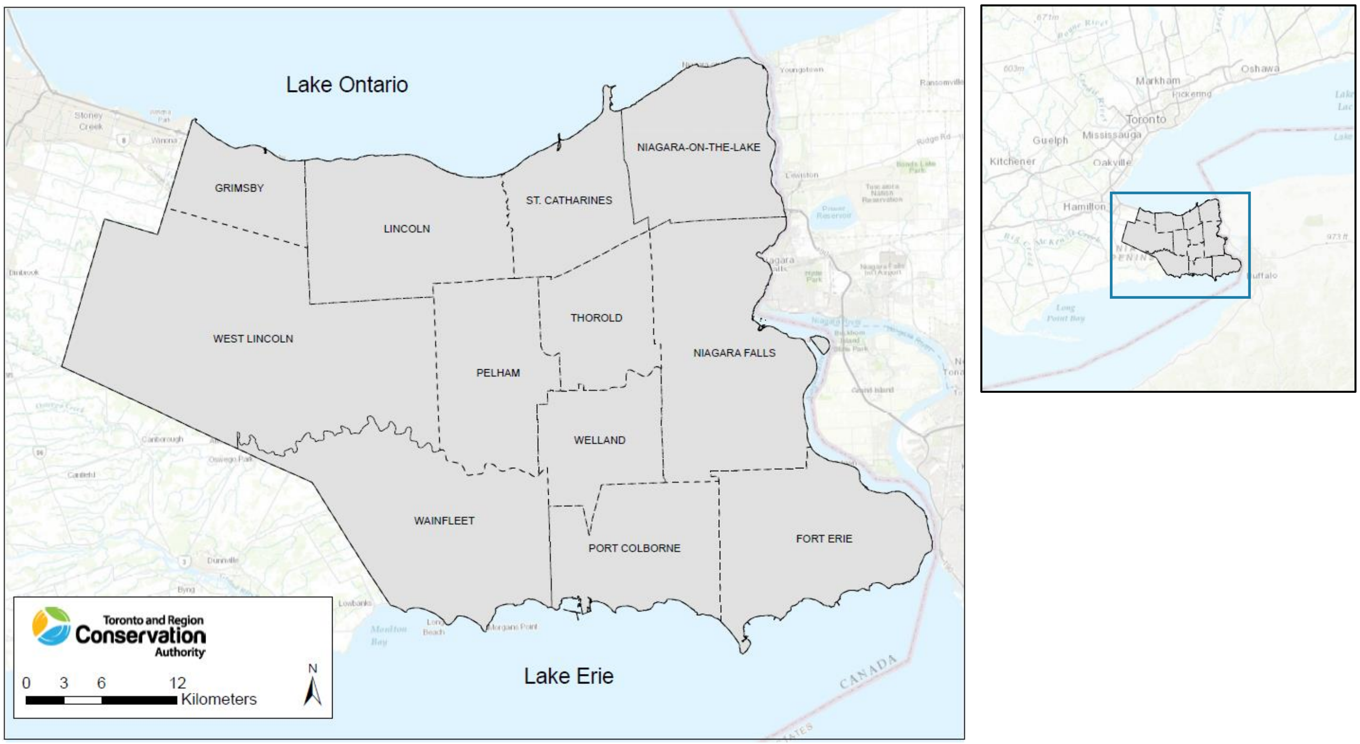

FIGURE 1. LOCATION OF THE REGIONAL MUNICIPALITY OF NIAGARA IN SOUTHERN ONTARIO.

The Niagara Escarpment is a dominant physical feature that runs East-West in the northern part of the region, measuring roughly 100 m high (Niagara Region, 2014). The less prominent Onondaga Escarpment runs East to West parallel to Lake Erie in the southern region. However, the highest point in Niagara Region is on the centrally located Fonthill Kame Moraine (Figure 2).

The location of the region between lakes and the topography creates a climate that is unique to the rest of the province. Temperatures rarely fall below -18^{o}C with more frost-free days and generally lighter snowfall than the rest of the province. The climate along with well-draining sandy-silty soils found on the moraine and Lake Ontario/ Iroquois plains make it very suitable for growing fruits such as peaches, cherries, and grapes. However, most of the other agriculture crops are grown in the central part of the region where there is moderate to poor draining soils. The agriculture industry is an essential component of the region's economy, supporting roughly 1,827 farms of various sizes and types that farm general crops, fruits, vegetables, poultry, livestock, and greenhouse products (Niagara Region, 2014).

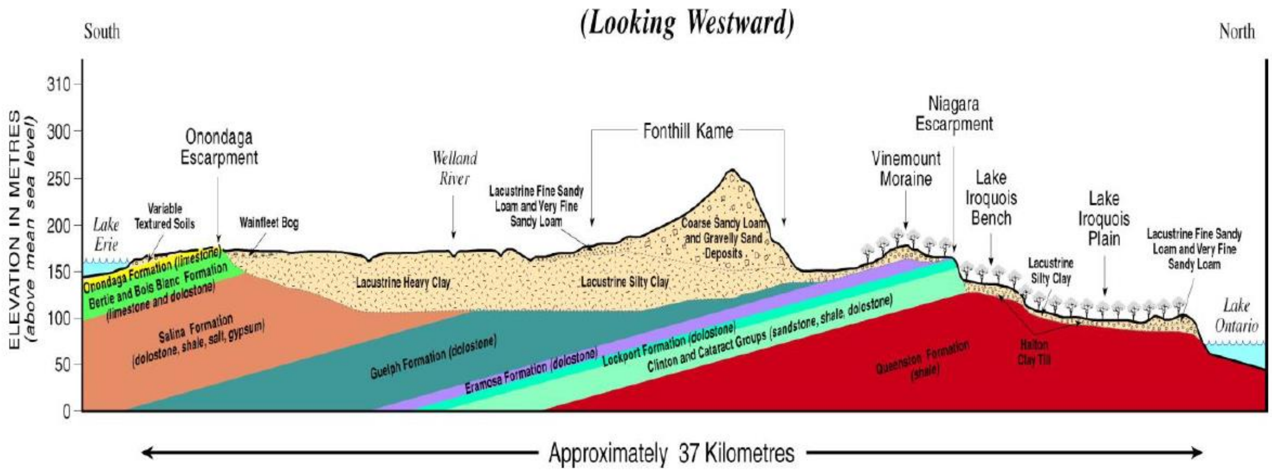

FIGURE 2. A SCHEMATIC CROSS-SECTION OF THE TOPOGRAPHY WITH THE SURFICIAL AND BEDROCK GEOLOGY OF THE NIAGARA REGION (SOURCE: SHAW, 2007)

3.0 Background on Climate Models and Future Climate data

The following section provides a summary of the common approaches to climate modelling, as well as key terminologies used throughout this report. This section discusses the differences between Global Climate Models and Regional Climate Models, various downscaling methods, ensemble approaches, and the different climate change scenarios used in climate modelling. A more detailed discussion is available in Appendix F.

Global Climate Models (GCM) are mathematical equations written in computer code and solved by high-performance computers (supercomputers) representing the interactions of parameters within the global climate system. Different models representing mass and energy exchange between land, water, and the atmosphere are coupled to form climate models. Each of these processes are modelled in each defined grid cell (Figure 3). However, their limited native resolution cannot model critical regional and local climate aspects (e.g., locally occurring intensive precipitation).

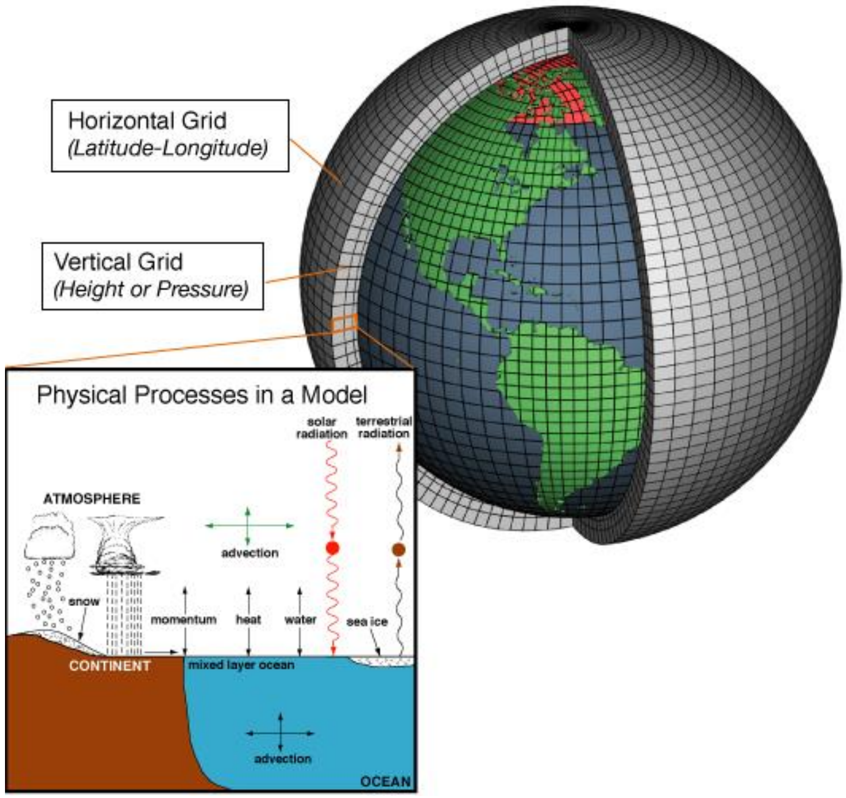

FIGURE 3. SCHEMATIC OF GLOBAL CLIMATE MODEL PROCESSES EVALUATED AT EACH GRID CELL.

Regional Climate Models (RCMs) compliment global climate models. Their higher resolution (25-50 km grid cells) allows the inclusion of landscape features like mountain ranges, lakes, and other surface features that can impact local/regional precipitation, temperature, and winds within the model (Wilby & Wigley, 1997). As a result, RCMs are more acceptable for supporting climate impact studies, policy, and adaptation planning at the regional scale (Rummukainen, 2010). The outputs of GCM are coupled with finer scale RCM models to produce climate outputs at finer resolution (25 x 25 km). This coupling is referred to as **dynamical downscaling** since there is a continuous dynamic relationship between the GCM and RCM.

Empirical/Statistical downscaling is computationally more efficient than dynamic downscaling. This approach derives quantitative relationships between global circulation processes and local climate. A mathematical or statistical relationship is created by comparing locally observed (measured) climate variables (e.g., precipitation and temperature) to larger-scale atmospheric variables for the same baseline period, which can be derived from GCMs (Pielke & Wilby, 2012). This relationship is then used to derive the future local climate parameters from GCM projections. While statistical downscaling can produce site-specific climate projections down to the scale of the climate station (finer resolution than an RCM), they work on the critical assumption that the relationship between observed data in the baseline period and GCM outputs will remain the same for future climate periods (Trzaska & Schnarr, 2014). Table 2 summarizes the advantages and disadvantages of statistical and dynamical downscaling.

TABLE 2. KEY ADVANTAGES AND DISADVANTAGES OF DOWNSCALING TECHNIQUES (ADAPTED FROM HOSTETLER ET AL., 2011 AND DELANEY ET AL., 2020).

<table>
<tr><th>Statistical Downscaling</th><th>Dynamical Downscaling</th></tr>
<tr><td colspan="2">Advantages</td></tr>
<tr><td>• Fast and computationally inexpensive (relatively)
• High resolution (e.g., 4 km or less)
• Multiple GCMs for ensembles and different emissions scenarios</td><td>• More accurate simulation of high-resolution representative concentration pathway (RCP) scenarios and climate compared to statistical downscaling
• Large, internally consistent set of atmospheric and surface variables
• Avoids stationary assumption (i.e., uses trends into the future that differ from the baseline rates of change, and incorporates feedback cycles)</td></tr>
<tr><td colspan="2">Disadvantages</td></tr>
<tr><td>• Limited ability to account for finer scale topography (reducing ability to account for features such as precipitation induced by mountain ranges, or evaporation over lakes)
• May not conserve mass and heat
• Uses stationary assumption (uses baseline rates of change to model the future), and mostly only models for precipitation and temperature</td><td>• Time consuming. For example, requires more time to incorporate local influences (e.g., bias correcting (see section 4.3)).
• Many RCMs and GCMs still lack the Great Lakes representation so it is important to carefully select the RCMs being used
• Limited number of GCMs used
• Greater number of uncertainties as the number of climate models increase</td></tr>
</table>

No one model can project the range of future climate that we could plausibly observe. While most models are similar in the systems they model, the way they are parameterized will differ considering the assumptions made regarding future scenarios or how the systems are represented. One solution is to consider the projections of many models and take a statistical distribution of the results to gauge the range of possible outcomes (Charron, 2016). This approach is referred to as the **ensemble or multi-model method**, which essentially reduces the bias from any one model (Figure 4). This study uses the North American-CORDEX ensemble of models, which couples multiple GCM models with multiple RCM models.

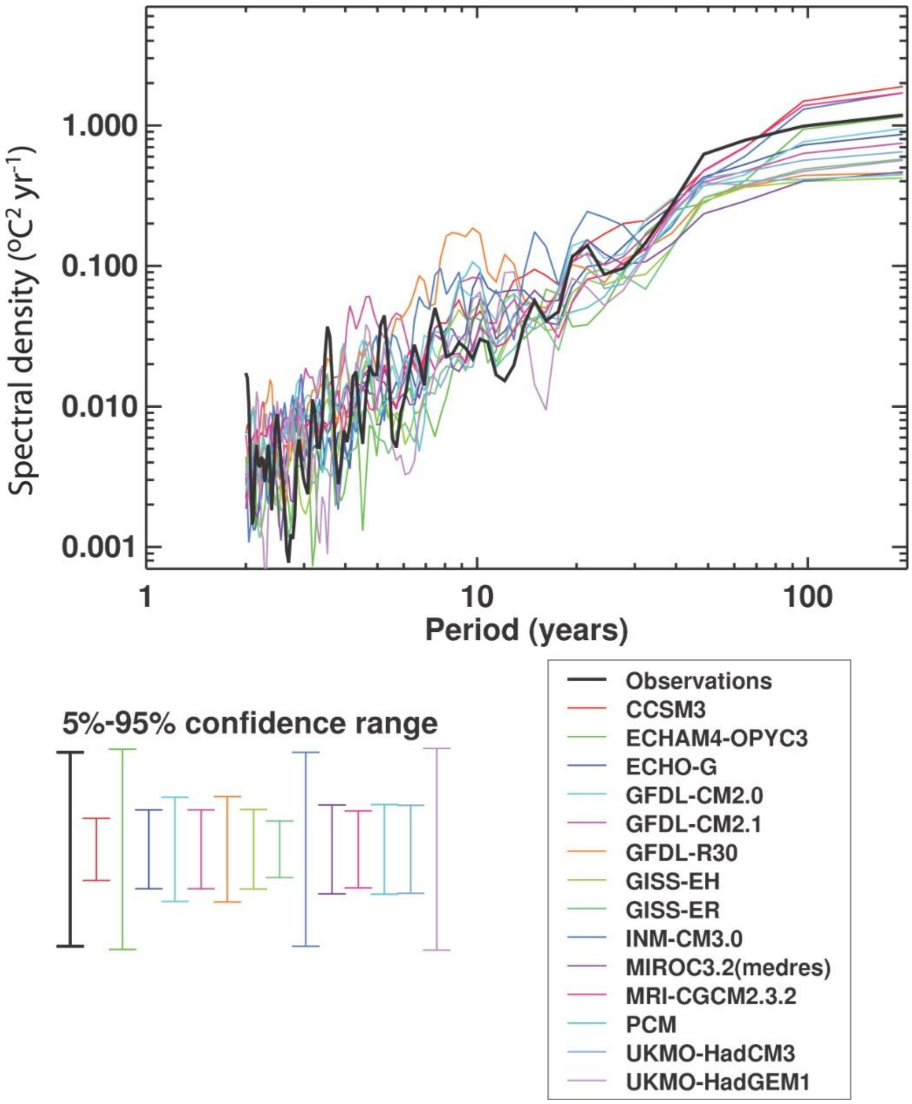

FIGURE 4. OBSERVED ANNUAL GLOBAL MEAN TEMPERATURE COMPARED TO OUTPUTS FROM AN ENSEMBLE OF MODELS THAT ARE CONSIDERING NATURAL AND ANTHROPOGENIC FORCINGS FOR THE 20TH CENTURY (SOURCE: HEGERL ET AL., 2007)

3.1 Climate Change Scenarios

When projecting climate for future periods, there is uncertainty around the state of socio-economic factors that can impact the climate, including changes to land use and emissions of greenhouse gases (GHG) and air pollutants (Vuuren et al., 2011). Representative Concentration Pathways (RCPs) are a series of plausible pathways or targets that represent the relationships among human behavior, emissions, GHG concentrations, and temperature change. The use of standardized RCPs provide consistency in parameterizing socio-economic factors into climate modeling, allowing comparisons between climate projections. RCP scenarios consider the impacts of policies that may reduce GHG emissions significantly (e.g., RCP 2.6), as well as the impact of the continued heavy reliance on fossil fuels (e.g., RCP 8.5). Figure 5 demonstrates the four RCP scenario projections through time for three different GHGs including, carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O).

Consolidated spatial data sets were created extending to 2100 that expressed socio-economic "pathways" to varying levels of GHG concentrations in 2100, that would result in the range of radiative forcings expressed in the literature (2.6 to 8.5 W/m2). The trajectories of emissions to future periods were also harmonized with baseline trends, such that each RCP scenario covers the period between 1850-2100, and extensions have been produced for periods up to 2300. In Table 3. , the approximate CO2 concentrations are provided for each RCP scenario, that can be compared with today's (21 December 2021) concentration of 416.87 ppm ("Daily CO2," n.d.) This study uses RCP scenarios 4.5 and 8.5 as we consider them to be the upper and lower limits of climate change trajectories among the available model scenarios.

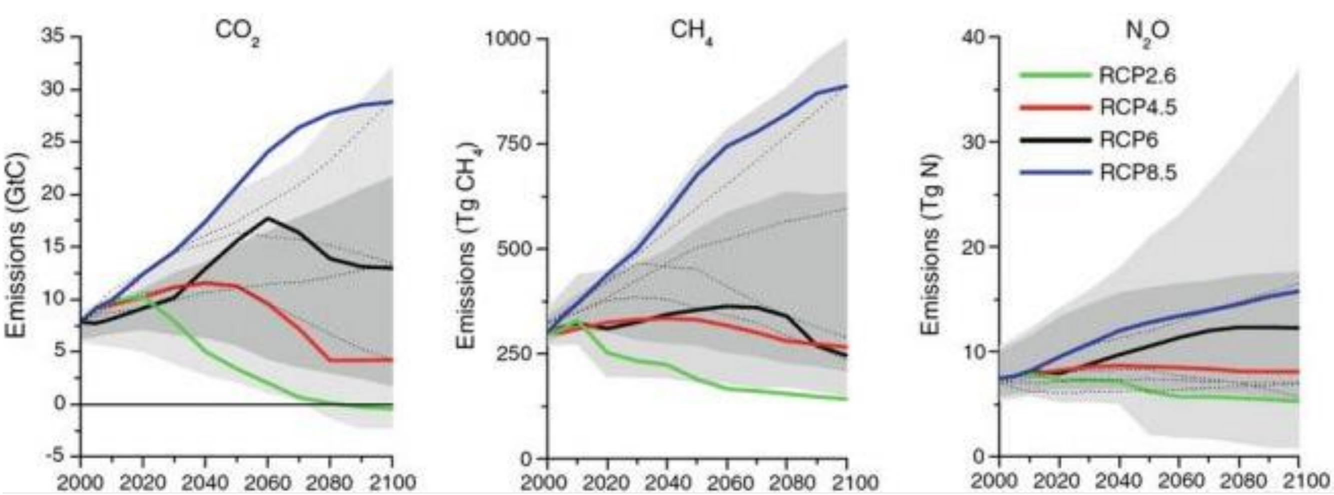

FIGURE 5: GRAPHS DEMONSTRATING ANNUAL EMISSIONS FOR THE FOUR REPRESENTATIVE CONCENTRATION PATHWAYS (RCPS) THROUGH TIME FOR CARBON DIOXIDE (CO_2) METHANE (CH_4), AND NITROUS OXIDE (N_2O) (VAN VUUREN ET AL., 2011)

TABLE 3. THE FOUR REPRESENTATIVE EMISSIONS PATHWAYS AND ASSOCIATED CO_2 CONCENTRATIONS IN 2100 (ADAPTED FROM: VAN VUUREN ET AL., 2011)

Scenario	Description	CO^2 concentration (ppm) in 2100
RCP 8.5	The highest emission scenario, where rising radiative forcing pathway leading to 8.5 Wm^{-2} in 2100 and continues to rise for some amount of time (IPCC, 2014). GHG concentrations are up to seven times higher than preindustrial levels.	1370
RCP 6	The second highest emission scenario, where stabilization without overshoot pathway to 6 Wm^{-2} and stabilization after 2100 (IPCC, 2014).	850
RCP 4.5	The second lowest emission scenario, where stabilization without overshoot pathway to 4.5 Wm^{-2} and stabilization after 2100 (IPCC, 2014).	650
RCP 2.6	The lowest emission scenario, where peak radiative forcing is 3 Wm^{-2} and declines before 2100 (IPCC, 2014). This scenario would require all the main GHG emitting countries, including developing countries, to participate in climate change mitigation initiatives and policies.	490

4.0 Methodology

The following section provides a high-level overview of the methodology used to retrieve, bias-correct, and analyze regional dynamically downscaled climate projections for the Niagara Region. This study adopted the approach provided by the *Guide to Conducting a Climate Change Analysis at the Local Scale: Lessons Learned from Durham Region* that was written to guide Ontario municipalities, Conservation Authorities, and broader community to develop local climate projections (Delaney et al., 2020). Appendix D provides a detailed, step-by-step description of the methods used in this study; Figure 6 illustrates the key components.

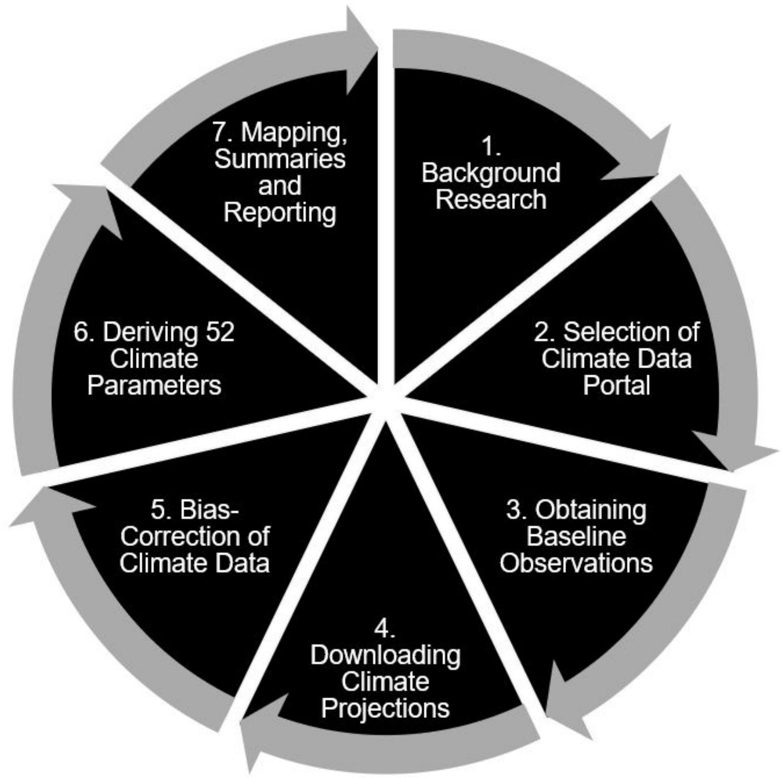

Figure 6. Methodology for conducting regional climate change analysis

Delaney et al. (2020), reviewed and selected climate data portals based on suitability for Ontario municipalities using the following selection criteria:

- The data had the ability to capture the influence of the Great Lakes (e.g., through the incorporation of a lake model into these models, or by spatially accounting for the lakes themselves in the models and treating them as water), since Lake Ontario and Lake Erie would have an influence on Niagara Region's weather and climate patterns
- The data was used in other peer-reviewed climatological publications in the Great Lakes Basin and in Ontario;
- The data was derived through dynamical downscaling, to capture the influence of the Great Lakes;
- The data was driven by multiple models and model runs (i.e., takes an ensemble approach) to ensure more robust results were generated;
- The data had a spatial resolution of 25 km by 25 km or finer;
- The data included projections for both climate change scenarios RCP 4.5 and 8.5, and was available up until 2100; and

The four climate change portals that were identified to examine in further detail included:

- York University's Laboratory of Mathematical Parallel Systems (LAMPS) Climate Change Portal;
- University of Toronto's Peltier Climate Change Ensemble Data;
- University of Wisconsin's Notaro Climate Change Ensemble Data Portal; and
- The second phase of the North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX) Portal.

Ultimately, the NA-CORDEX portal was selected to use as part of this analysis based on its ability to meet the majority of selection criteria identified. The portal was developed by the World Climate Research Programme (WCRP) and provides RCM outputs on baseline data and future RCP climate scenarios running from 1950 to 2005 and 2006 to 2100, respectively (Lucas-Picher, Laprise, and Winger, 2017). Daily mean, maximum, and minimum temperatures as well as total precipitation were downloaded for this project, averaged over 30-year climate normal periods at a maximum spatial resolution of 0.22° (or 25 km by 25 km).

All climate models on the NA-CORDEX data portal are dynamically downscaled. While debate exists around the realism of the RCP 8.5 from a socio-economic perspective (Smith, 2019), it should be noted that the portal has fewer models available for the RCP 4.5 climate scenario (3 compared to 16 models for RCP 8.5), which is used less frequently in climate analysis. Furthermore, among the available models, RCP 8.5 is viewed as the "high-emissions scenario" that aligns with some of the highest projected CO_2 emissions published in literature. As a result, this scenario is used most frequently in climate analysis as a conservative estimation since it is more difficult to anticipate global climate action, resulting in lower emission scenarios. This report focuses on the RCP 8.5 climate scenario results and includes the summary tables for the RCP 4.5 climate scenario in Appendix C. It should be noted that RCP 8.5 and RCP 4.5 should not be directly compared as the RCP 4.5 scenario has fewer models, and therefore, its ensemble means would have higher uncertainty.

The RCMs available in the NA-CORDEX portal account for the Great Lakes differently. Given the Region's location, the representation of the Great Lakes can have a significant impact on the regional climate projections. Table 4 identifies the seven RCMs used and how they account for or simulate the Great Lakes. Four of the seven RCMs have a one-dimensional lake model included, two use nearby sea surface temperatures (SSTs), and one uses the GCM's coarser representation.

TABLE 4. THE SEVEN RCMS FROM NA-CORDEX AND HOW THEY REPRESENT THE GREAT LAKES

RCM	Incorporation of Great Lakes into RCM
CanRCM4	Incorporated through derived GCM
CRCM5 (OURANOS)	Uses the one-dimensional Freshwater Lake (FLake) model
CRCM5 (UQUAM)	Uses the one-dimensional Freshwater Lake (FLake) model
HIRHAM5	No lake model; however, it interpolates lapse-rate corrected for SSTs for lakes > 0.5 gridbox
RCA4	Uses the one-dimensional Freshwater Lake (FLake) model
RegCM4	Uses the one-dimensional Hostetler Lake model
WRF	Uses nearby ocean SSTs as lake surface temperatures

All data were collected and downloaded as NetCDF files (otherwise known as Network Common Data Form files), which are files able to store large datasets and many layers of data into a single package that is easily downloadable. Figure 7 illustrates the spatial scale at which data were obtained. Each point illustrated below represents about 90 years of climate data and are spaced by 25km x 25km.

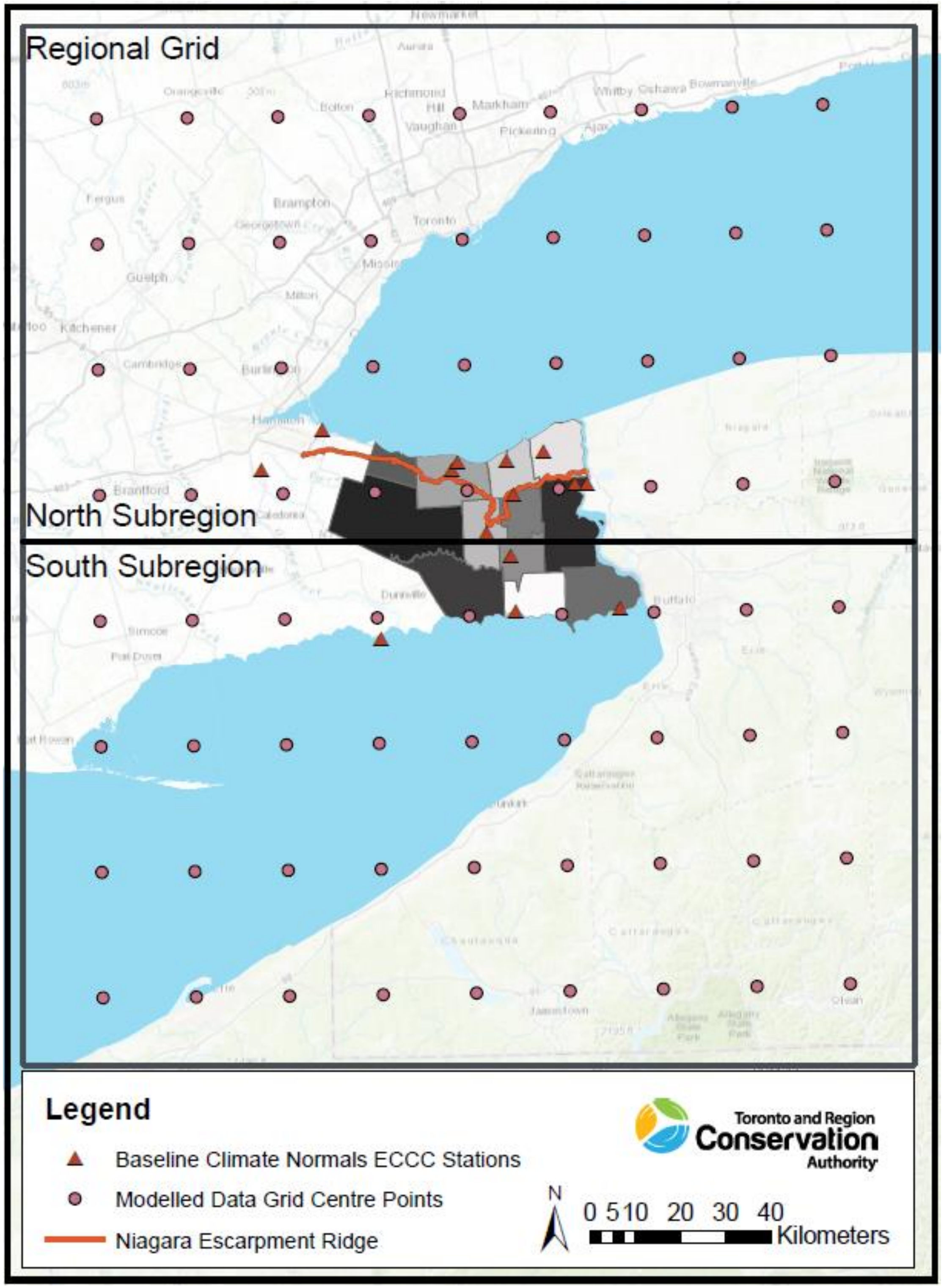

FIGURE 7. OVERVIEW MAP SHOWING THE GRID CELL (25 X 25 KM) CENTER POINTS OF MODELLED DATA USED FOR REGIONAL AND SUBREGIONAL ANALYSIS AND CLIMATE STATIONS WITH OBSERVED CLIMATE NORMAL DATA USED FOR BASELINE BIAS CORRECTION.

Four datasets were downloaded from each regionally downscaled model available for the region, including daily precipitation, maximum temperature, minimum temperature, and average temperature. The different models may either overestimate or underestimate the values for these datasets based on their biases, which occur based on how they represent physical features or climate processes (e.g., topography, vegetation, water bodies, etc.). The delta difference method is used in this study to correct for these model biases. The observed dataset averages (climate n24ormal from Environment and Climate Change Canada) is compared to the ensemble model averages for the same 30-year baseline period (1971-2000). The difference between these ("delta difference") is added to the projected daily values of each model for the entire time series (including two future climate periods), assuming that the delta difference remains the same for the baseline and future periods. In essence, the bias correction aligns the model ensemble average to the observed data average for the baseline period and minimizes the model bias on projected climate for future periods (Figure 8).

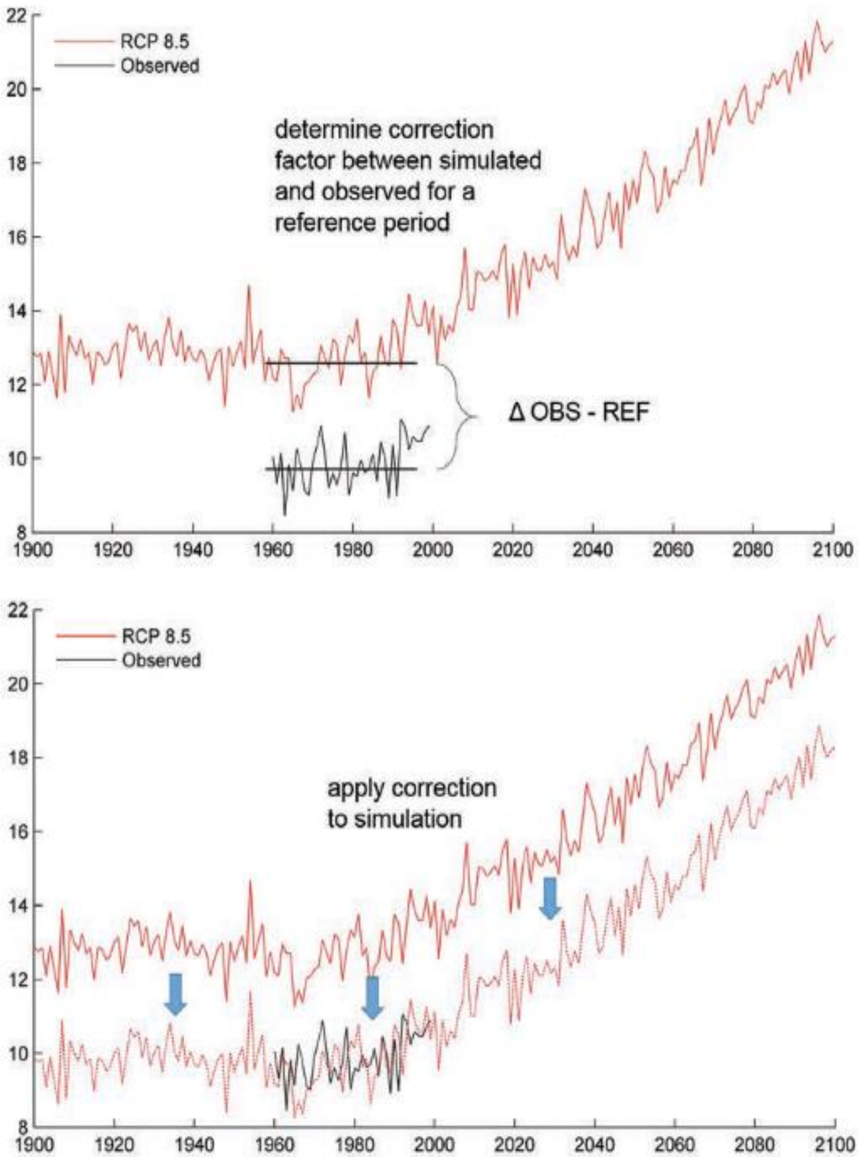

FIGURE 8. THE DELTA DIFFERENCE BIAS-CORRECTION METHOD IN WHICH THE DIFFERENCE BETWEEN THE ENSEMBLE MODEL AVERAGE AND OBSERVED DATA AVERAGE IS CALCULATED FOR THE BASELINE PERIOD (A) AND THE DIFFERENCE IS THEN APPLIED TO THE ENTIRE MODELED DATASET (B) (SOURCE: OURANOS).

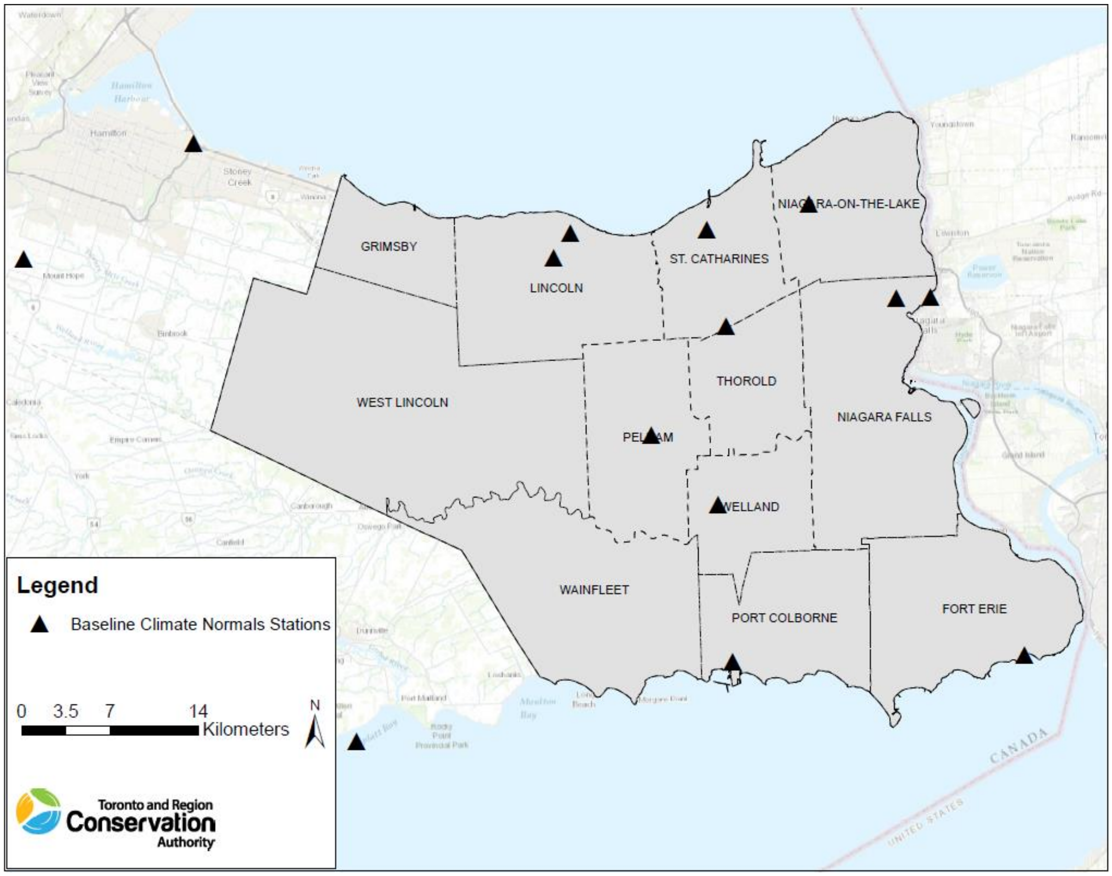

FIGURE 9. THE CLIMATE STATIONS USED FOR BIAS-CORRECTING THE BASELINE MODELED DATA.

Observed data were collected from twelve Environment and Climate Change Canada's (ECCC) climate stations for the baseline period of 1971-2000. This period was selected based on historical modelled data availability. Eleven of the twelve stations used are within the municipal boundary. One station just west of the regional boundary is also included as the other stations inadequately represented that region. The climate stations are listed in Table 5 and mapped in Figure 9.

TABLE 5. LIST OF CLIMATE STATIONS USED TO RETRIEVE OBSERVED DATA CLIMATE NORMALS FOR THE BASELINE PERIOD (1971-2000).

Station #	Station Name	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
1	Fort Erie	42.883	-78.967
2	Niagara Falls NPCSH	43.133	-79.050
3	Niagara Falls	43.133	-79.083
4	St. Catharines A	43.200	-79.167
5	Port Colborne	42.883	-79.250
6	St. Catharines Power Glen	43.117	-79.250
7	Welland	42.993	-79.261
8	Port Dalhousie	43.183	-79.267
9	Ridgeville	43.042	-79.325
10	Vineland Station	43.183	-79.400
11	Vineland Rittenhouse	43.167	-79.417
12	Hamilton A	43.172	-79.934

Bias correction was undertaken separately for regional and sub-regional analysis using different model grid cells and observed station data as shown in Figure 7. Bias correction for regional analysis includes all grid cells and climate stations shown in Figure 7. The values calculated for the climate parameters are averaged over the region extended beyond Niagara. In contrast, sub-regional analysis uses a smaller extent and splits Niagara into northern and southern regions. Climate stations located within the northern and southern boundaries are used to bias correct model grid cell data within the northern and southern boundaries, respectively.

Following bias correction, climate datasets (daily precipitation, mean temperature, maximum temperature, and minimum temperature) were analyzed to derive the climate parameters selected in collaboration with Niagara Region (Appendix B). A climate parameter is a means to identify how much a given climate condition (e.g., air temperature) has changed or will change in the future (Harris et al., 2016). For example, the number of frost days, summer days, tropical nights, and growing season length can be indicators of changes in air temperature. While some climate parameters are derived directly (e.g., mean temperature), others require proxies. For example, Growing Degree Days (GDD) can be used to analyze the survivability of specific crops and pests. Since several climate parameters could not be derived from the observed normal data available from ECCC, the bias-corrected modelled values were used to derive climate parameters for the baseline period instead.

4.1 Change Direction Agreement and Change Signal

To assess the robustness of the projections for the long-term period, the agreement in change direction between models and the strength of the change signal in comparison to the baseline values are assessed and reported in Table 6. The change direction agreement methodology is adapted from Tebaldi et al. (2011). For each climate parameter, we determine whether the mean values from each model projects an increase or decrease from the baseline value. The change direction agreement is recorded as “high” if more than 90% of models showed the same change (i.e., positive or negative), “medium” if 70% to 90% of models are in agreement and “low” if less than 70% models agreed on the change direction.

Change signal, as described by the IPCC (AR5), is intended to compare magnitude of model variability to the magnitude of difference between the baseline and future climate periods (long-term for this study). This is to ensure that the difference calculated between two climate periods are a result of climate change and not because of the variability between models. To determine the change signal of a climate parameter, the standard deviation of the different model means was calculated. The change magnitude for the parameter is calculated as the absolute difference between baseline and long-term ensemble mean. The change signal is identified as “high” if the change magnitude exceeded 2 standard deviations of the model means, as “medium” if it is between 1 - 2 standard deviations, and as “low” if it was less than 1 standard deviation.

5.0 Results: Climate trends in Niagara Region

This section provides the results of the climate analysis for the Niagara Region. Table 6 provides a summary of model ensemble means and the 10th and 90th percentile for each climate parameter for all climate periods for the RCP 8.5 climate scenario (refer to Appendix C for the RCP 4.5 summary table). The subsections describe the trends and patterns for all climate parameter categories under the RCP 8.5 scenario for both the short-term (2021-2050) and long-term (2051-2080) future periods. The maps provided in sub-sections 5.2 and 5.3 illustrate the spatial and temporal variability between climate periods of average annual values for the four bias-corrected climate datasets (precipitation, maximum temperature, minimum temperature, and mean temperature). The maps include Niagara region and surrounding areas to demonstrate the variability in climate trends at a broader scale. In Appendix E, we compare the projections analyzed by TRCA for the entire Niagara region to those published in the City of St. Catharines Corporate Climate Change Action Plan (“SCCCAP”) that were developed through the Niagara Adapts partnership.

TABLE 6. SUMMARY OF ALL CLIMATE PARAMETERS FOR EACH CLIMATE PERIOD ANALYZED FOR THE RCP 8.5 CLIMATE SCENARIO

Climate Parameters	Definition	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Change Direction Agreement+ Change Signal	Trend
			10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile		
Mean Temperature										
Mean Annual Temperature	Average annual air temperature over a climate period.	**8.7**	8.9	**10.7**	13.0	10.7	**12.3**	15.3	High+High	↑
Mean Winter Temperature	Average winter (D-J-F) air temperature over a climate period.	**-2.8**	-3.5	**-0.4**	1.9	-1.8	**0.9**	3.7	High+Medium	↑
Mean Spring Temperature	Average spring (M-A-M) air temperature over a climate period.	**6.6**	6.4	**8.2**	10.4	7.7	**9.8**	12.2	High+Medium	↑
Mean Summer Temperature	Average summer (J-J-A) air temperature over a climate period.	**20.0**	20.2	**22.0**	24.2	21.3	**23.8**	26.4	High+Medium	↑
Mean Fall Temperature	Average fall (S-O-N) air temperature over a climate period.	**10.5**	10.9	**12.7**	15.4	12.7	**14.3**	17.5	High+Medium	↑
Maximum Temperature										
Annual Mean Maximum Daily Air Temperature	Average maximum annual air temperature over a climate period.	**12.9**	12.7	**14.9**	17.4	14.4	**16.4**	19.4	High+Medium	↑
Winter Mean Maximum Daily Air Temperature	Average maximum winter (D-J-F) air temperature over a climate period.	**0.7**	0.8	**3.3**	5.2	2.5	**4.7**	6.9	High+High	↑
Spring Mean Maximum Daily Air Temperature	Average spring (M-A-M) air temperature over a climate period.	**11.2**	10.8	**12.7**	15.0	12.0	**14.1**	16.8	High+Medium	↑

Climate Parameters	Definition	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Change Direction Agreement+ Change Signal	Trend
			10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile		
Summer Mean Maximum Daily Air Temperature	Average maximum summer (J-J-A) air temperature over a climate period.	**24.9**	24.5	**26.7**	29.4	25.3	**28.4**	31.7	Medium+ Medium	↑
Fall Mean Maximum Daily Air Temperature	Average maximum fall (S-O-N) air temperature over a climate period.	**14.4**	14.7	**16.6**	19.6	16.5	**18.2**	21.8	High+Medium	↑
Minimum Temperature										
Annual Mean Minimum Daily Air Temperature	Average minimum annual air temperature over a climate period.	**4.28**	4.2	**6.2**	8.5	6.5	**8.2**	10.7	High+High	↑
Winter Mean Minimum Daily Air Temperature	Average minimum winter (D-J-F) air temperature over a climate period.	**-7.09**	-8.4	**-5.0**	-1.6	-5.3	**-2.3**	0.3	High+High	↑
Spring Mean Minimum Daily Air Temperature	Average minimum (M-A-M) air temperature over a climate period.	**2.02**	2.3	**3.7**	5.7	3.1	**5.4**	7.8	High+Medium	↑
Summer Mean Minimum Daily Air Temperature	Average minimum summer (J-J-A) air temperature over a climate period.	**15.23**	15.3	**17.1**	19.2	16.7	**18.6**	21.3	High+Medium	↑
Fall Mean Minimum Daily Air Temperature	Average minimum fall (S-O-N) air temperature over a climate period.	**6.67**	7.0	**8.7**	11.3	8.6	**10.6**	13.6	High+Medium	↑
Extreme Heat (days per year)										

Climate Parameters	Definition	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Change Direction Agreement+ Change Signal	Trend
			10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile		
Days Above 35˚C	Total number of days of the year with maximum temperatures above 35˚C.	**0.3**	0.0	**2.1**	5.1	0.0	**7.1**	19.5	Medium+Low	↑
Days Above 30˚C	Total number of days of the year with maximum temperatures above 30˚C	**10.4**	4.7	**23.9**	50.8	6.3	**39.4**	83.5	Medium+ Medium	↑
Days Above 25˚C	Total number of days of the year with maximum temperatures above 25˚C.	**53.5**	51.5	**77.7**	112.91	60.1	**95.8**	136.6	Medium+ Medium	↑
Tropical Nights	Total number of days of the year with minimum temperatures above 20˚C.	**9.4**	6.4	**24.5**	51.7	17.1	**46.2**	82.5	High+Medium	↑
Extreme Cold (days per year)										
Days Below -20˚C	Total number of days of the year with minimum temperatures below -20˚C.	**4.2**	0.0	**2.2**	2.5	0.0	**0.1**	0.3	High+High	↓
Days Below -15˚C	Total number of days of the year with minimum temperatures below -15˚C.	**12.3**	0.4	**6.5**	12.5	0.0	**1.0**	2.9	High+High	↓
Days Below -10˚C	Total number of days of the year with minimum temperatures below -10˚C.	**32.4**	4.1	**20.3**	39.3	1.3	**7.6**	16.9	High+High	↓
Days Below -5˚C	Total number of days of the year with minimum temperatures below -5˚C.	**68.0**	24.3	**50.7**	76.2	11.2	**30.7**	50.8	High+High	↓
Days Below 0˚C (Freezing Days)	Total number of days of the year with minimum temperatures below 0˚C.	**125.1**	76.6	**105.7**	132.1	51.9	**83.8**	112.6	High+Medium	↓

Climate Parameters	Definition	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Change Direction Agreement+ Change Signal	Trend
			10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile		
Total Precipitation (mm per climate period)										
Total Average Annual Precipitation (mm)	Total amount of precipitation throughout the year falling on wet days (where precipitation is greater than 0.2 mm).	**1080.6**	1086.0	**1135.0**	1209.1	1131.2	**1192.0**	1286.8	High+Medium	↑
Total Average Winter Precipitation (mm)	Total amount of precipitation throughout the winter (D-J-F) falling on wet days (where precipitation is greater than 0.2 mm).	**231.0**	214.7	**253.0**	288.1	237.4	**274.6**	316.4	Medium+ Medium	↑
Total Average Spring Precipitation (mm)	Total amount of precipitation throughout the spring (M-AM) falling on wet days (where precipitation is greater than 0.2 mm).	**281.1**	256.0	**296.2**	324.2	293.3	**323.4**	347.7	High+Medium	↑
Total Average Summer Precipitation (mm)	Total amount of precipitation throughout the summer (J-JA) falling on wet days (where precipitation is greater than 0.2 mm).	**296.6**	246.8	**305.0**	340.8	224.0	**315.9**	365.3	Low+Low	↑
Total Average Fall Precipitation (mm)	Total amount of precipitation throughout the fall (S-O-N) falling on wet days (where precipitation is greater than 0.2 mm)	**271.2**	244.5	**280.8**	317.5	242.0	**277.0**	320.5	Low+Low	↑
Extreme precipitation										
Max Precipitation in 1 day (mm)	Annual 1-day maximum precipitation accumulation.	**70.7**	60.1	**72.7**	94.2	62.6	**78.1**	97.4	Low+Low	↑

Climate Parameters	Definition	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Change Direction Agreement+ Change Signal	Trend
			10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile		
Max Precipitation in 3 day (mm)	Annual 3-day maximum precipitation accumulation.	**112.4**	95.2	**109.3**	124.6	94.8	**119.5**	137.6	Low+Low	↑
Extreme Precipitation Days (days/year)	The annual average amount of days where precipitation exceeds 25 mm.	**4.8**	4.5	**5.8**	6.9	6.2	**7.1**	8.1	High+High	↑
Annual Simple Daily Intensity Index (SDII) (mm/day)	The average amount of precipitation which occurs per wet day (more than 0.2 mm/day) on average in a year.	**5.2**	4.9	**5.4**	5.8	5.3	**5.7**	6.1	Medium+ Medium	↑
Winter SDII (mm/day)	The average amount of precipitation which occurs per wet day (more than 0.2 mm/day) on average in a year.	**4.2**	3.7	**4.4**	4.8	4.0	**4.7**	5.2	Medium+ Medium	↑
Spring SDII (mm/day)	The average amount of precipitation which occurs per wet day (more than 0.2 mm/day) on average in a year.	**5.6**	5.2	**5.8**	6.4	5.7	**6.3**	6.8	High+Medium	↑
Summer SDII (mm/day)	The average amount of precipitation which occurs per wet day (more than 0.2 mm/day) on average in a year.	**5.8**	5.1	**5.9**	6.7	4.8	**6.1**	7.1	Medium+Low	↑
Fall SDII (mm/day)	The average amount of precipitation which occurs per wet day (more than 0.2 mm/day) on average in a year.	**5.3**	5.2	**5.6**	6.1	5.2	**5.8**	6.3	Medium+ Medium	↑

Climate Parameters	Definition	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Change Direction Agreement+ Change Signal	Trend
			10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile		
95th Percentile Precipitation (mm)	The percent of the total annual precipitation when precipitation is greater or equal to the 95th percentile.	**18.7**	18.3	**20.0**	21.3	19.9	**21.4**	22.7	High+High	↑
99th Percentile Precipitation (mm)	The percent of the total annual precipitation when precipitation is greater or equal to the 99th percentile.	**31.2**	31.4	**33.5**	35.8	34.5	**35.8**	37.5	High+High	↑
Dry Days (days per year)										
Total Annual Dry Days	Total annual number of days where precipitation was less than 0.2 mm.	**155.3**	144.7	**154.5**	166.0	148.7	**155.7**	164.0	Low+Low	↑
Maximum Total Consecutive Dry Days	The number of consecutive days where annual total number of days where precipitation was less than 0.2 mm.	**21.3**	13.5	**19.0**	24.5	14.0	**18.1**	23.0	Low+Low	↓
Growing Season										
Growing Season Start Date (day of year)	The first day after 5 days of consecutive minimum temperatures above 5˚C was reached.	**07-May**	13-Apr	**30-Apr**	12-May	19-Apr	**29-Apr**	14-May	Low+Low	↑

Climate Parameters	Definition	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Change Direction Agreement+ Change Signal	Trend
			10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile		
Growing Season End Date (day of year)	The first day after 5 days of consecutive minimum temperatures below 5˚C was reached.	**30-Oct**	29-Oct	**10-Nov**	23-Nov	07-Nov	**16-Nov**	27-Nov	Medium+Low	↑
Growing Season Length (days/year)	Annual number of days after having 5 consecutive days above 5˚C and before having five consecutive days below 5˚C.	**186**	173	**194**	213	182	**201**	222	Medium+High	↑
Agricultural Variables										
Growing Degree Days per year	Growing Degree Days (GDD) provide an index of the amount of heat available for the growth and maturation of the plants and insects. Different base temperatures (0, 4, 5, 10, 15 °C) are used to capture results for organisms that demand different amount of heat.	**3584.1**	3468.6	**4104.0**	4853.2	4072.6	**4641.7**	5500.5	High+Medium	↑
Canola Growing Degree Days per year		**2537.2**	2517.4	**3077.7**	3742.2	2920.2	**3452.3**	4195.6	High+Medium	↑
Forage Crops Growing Degree Days per year		**2306.8**	2287.5	**2769.4**	3356.6	2666.5	**3186.2**	3899.8	High+Medium	↑
Corn and Bean Growing Degree Days per year		**1321.9**	1302.2	**1747.0**	2249.4	1558.7	**2028.2**	2607.0	High+Medium	↑
Growing Degree Days-Days at Risk of Presence of Pests		**594.2**	603.4	**911.9**	1287.9	734.0	**1128.2**	1582.0	High+Medium	↑
Freeze-Thaw Cycles and Ice Potential										

Climate Parameters	Definition	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Change Direction Agreement+ Change Signal	Trend
			10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile		
Freeze-Thaw Cycles (events/year)	Number of freeze thaw cycles, where the minimum temperature is equal to or below -1°C and the maximum temperature is above 0°C.	**76.6**	54.0	**67.4**	79.0	37.8	**55.8**	70.8	High+Medium	↓
Ice Potential (days/year)	Number of days where minimum temperature is greater than -2˚C and maximum temperature is under 2˚C.	**19.0**	8.3	**16.1**	20.6	4.1	**11.7**	16.1	High+Medium	↓
					Public Health					
P. vivax Climate Threshold (1)	Number of 30 consecutive days where daily minimum temperature is equal or greater than 18°C and daily maximum temperature is equal or less than 33°C.	**0.0**	0.0	**0.6**	0.0	0.0	**2.57**	8.6	Low+Low	↑
P. vivax Climate Threshold (2)	Number of 20 consecutive days where daily minimum temperature is equal or greater than 20°C and daily maximum temperature is equal or less than 33°C.	**0.0**	0.0	**0.0**	0.0	0.0	**1.2**	4.1	Low+Low	↑
P. falciparum Climate Threshold	Number of 30 consecutive days where daily minimum temperature is equal or greater than 20°C and daily maximum temperature is equal or less than 33°C.	**0.0**	0.0	**0.0**	0.0	0.0	**0.0**	0.0	Null	–

Climate Parameters	Definition	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Change Direction Agreement+ Change Signal	Trend
			10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile		
Tick Climate Threshold	Number of days with daily average temperature above 0°C.	**286.9**	278.7	**306.5**	333.7	292.0	**320.9**	346.0	High+Medium	↑

5.1 Temperature and Extreme Heat and Cold

5.2.1 Average Annual Daily Mean Temperatures

Daily mean temperatures within Niagara Region are expected to increase over time across every climate period for the RCP 8.5 climate scenario (Figure 10). Overall, the region will likely experience an average annual temperature increase of 1.5-3°C from the baseline to short-term climate period and 3-4.5 °C from the baseline to long-term climate period. The most significant impact will be observed in areas in the northwest portion of the region, where average annual temperatures are expected to be the highest in all three climate periods (Figure 11).

Figure 12 demonstrates a comparative analysis of the mean daily temperature between regional and sub-regional areas of Niagara. As noted earlier, the northern region will see a slightly warmer temperature than the southern areas.

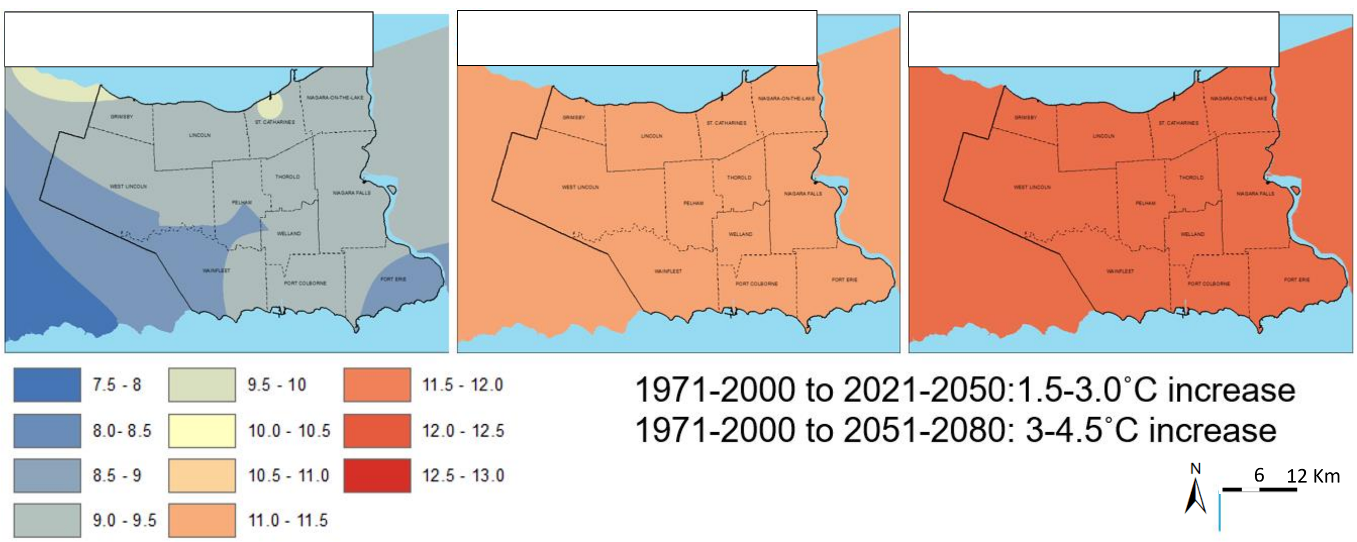

FIGURE 10: AVERAGE ANNUAL DAILY MEAN TEMPERATURE (°C) FOR A) 1971-2000, B)2021-2050, AND C) 2051-2080 FOR RCP 8.5 SCENARIO WITH A SHARED CONTINUOUS TEMPERATURE SCALE ACROSS CLIMATE PERIODS.

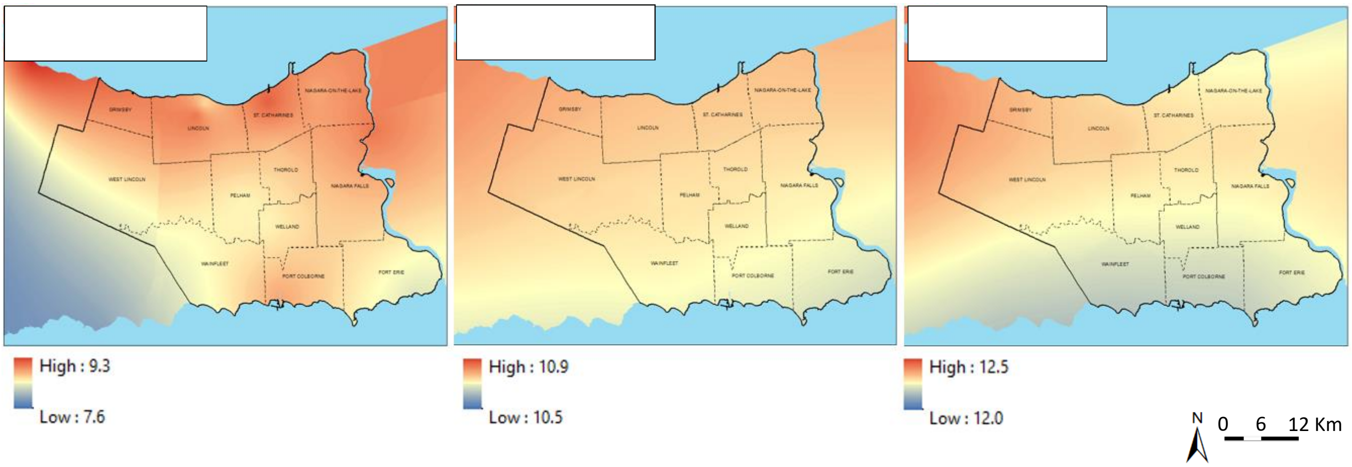

FIGURE 11: AVERAGE ANNUAL DAILY MEAN TEMPERATURE (°C) FOR A) 1971-2000, B) 2021-2020, AND C) 2051-2080 FOR THE RCP 8.5 SCENARIO WITH INDIVIDUAL TEMPERATURE SCALES FOR EACH TIME PERIOD.

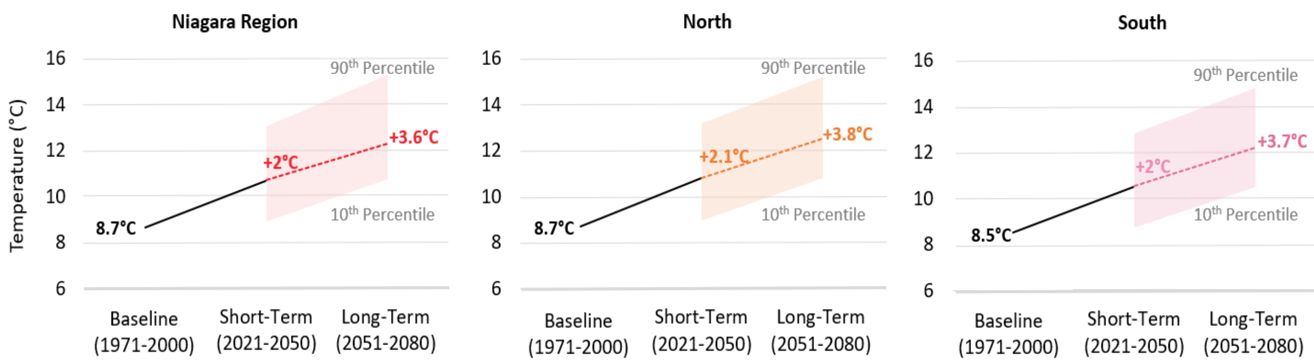

FIGURE 12. COMPARISON OF AVERAGE ANNUAL DAILY MEAN TEMPERATURE BETWEEN REGIONAL AND SUB-REGIONAL ANALYSIS.

5.2.2 Average Annual Daily Maximum Temperatures

Daily maximum temperatures under the RCP 8.5 scenario are projected to increase throughout Niagara, 1-3.5°C and 2.5-5 °C for the short- and long-term climate periods, respectively (Figure 13). The north-central and north-western parts of the region are expected to see more hot extremes than the rest. Annually, these parts of the region are projected to experience an average daily max temperature of up to 15.5 and 17 °C for the short- and long-term periods, respectively, compared to 13.5 °C in the baseline period. (Please refer to Appendix A for a more detailed spatial analysis for the northern and southern parts of the region).

Increasing winter temperatures will result in more variable weather, including the timing and amount of precipitation and an increasing shift from snowfall to rainfall during the winter months. This may cause increased flooding in local water systems. During the summer, increased temperatures will result in more extreme heat days where temperatures are above 30°C. This may intensify heat-related health impacts (e.g., heat stroke, dehydration, etc.), particularly for vulnerable groups such as children, seniors, and those with pre-existing conditions.

High temperatures will also impact resident and migratory wildlife species and may reduce habitat suitability and connectivity. For example, cold water species such as Brook Trout can experience stress even under a small change in maximum annual summer temperatures (LSRCA, 2020). Changes in temperature regimes are also expected to increase northward migration and the spread of invasive species (Tu et al., 2017).

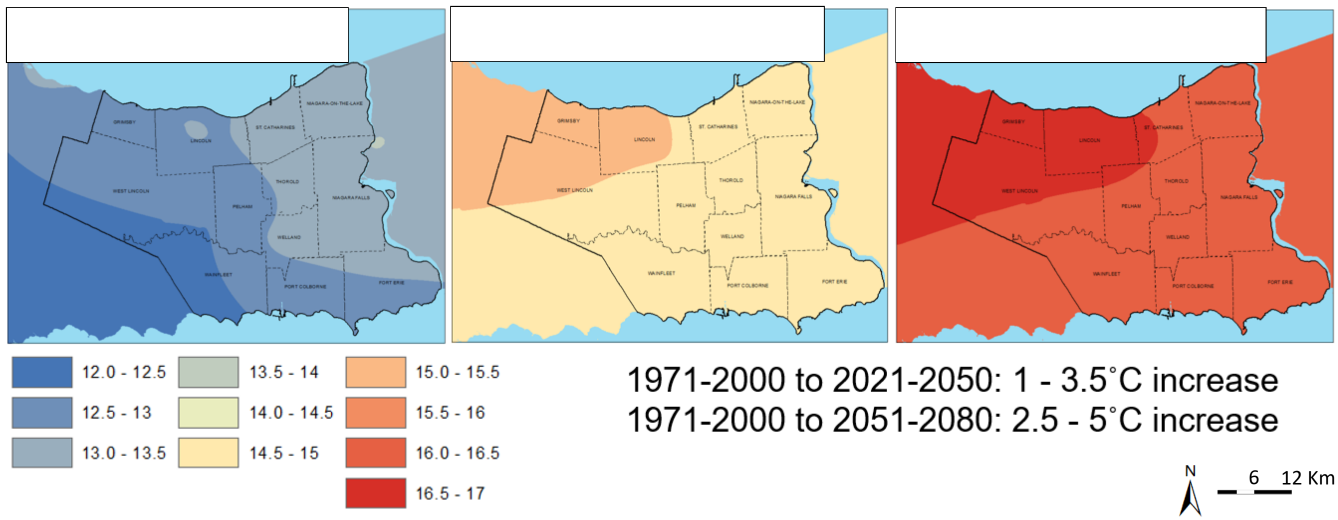

Figure 13. Average maximum annual temperature for A) 1971-2000, B)2021-2050, and C) 2051-2080 for RCP 8.5.

Figure 14 compares the trajectory of mean daily maximum temperature change through the climate periods when analyzed regionally and sub-regionally. The northern region will see the highest increase in daily mean maximum temperature. The southern part of the region has a slightly lower average daily maximum temperature in all climate periods including the baseline period.

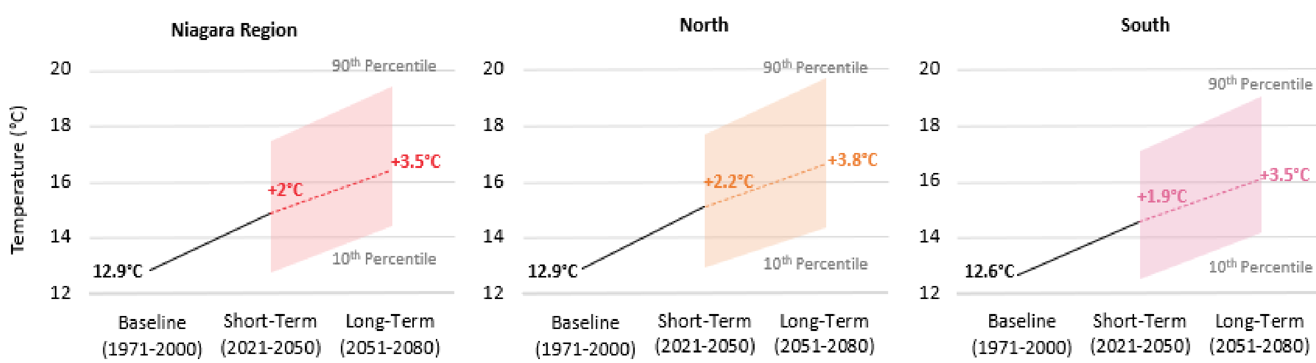

Figure 14: Comparison of mean maximum daily temperature between regional and sub-regional analysis.

5.2.3 Average Annual Daily Minimum Temperatures

Daily minimum temperatures are also projected to increase from the baseline climate period for the RCP 8.5 climate scenario (Figure 15). Annual average minimum daily temperatures will increase from the baseline period by 1-3°C during 2021-2050 and by 3-4.5°C during the 2051-2080 climate periods. The south-eastern portion of the region has the lowest average annual minimum temperature during the baseline period (Figure 16). However, from 2021-2050, the southern and north-eastern portions of the region are projected to have the lowest minimum temperatures. By 2051-2080 the north-central region is projected to have the lowest minimum temperatures. These observations are based on Figure 16 that spatially interpolates the mean values from each grid cell. A slightly different trend occurs when we numerically summarize it by northern and southern regions (Figure 17), where the northern region remains to have the warmest minimum temperatures. While the differences are minimal, the method of summarizing values may have an impact on the magnitude of trends.

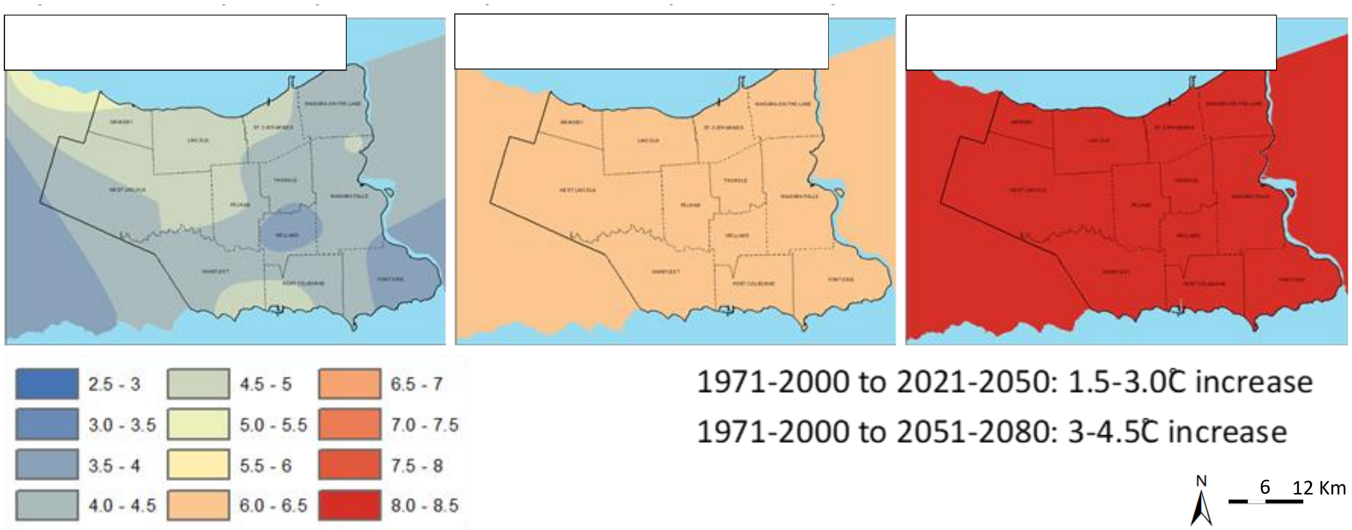

FIGURE 15. AVERAGE ANNUAL MINIMUM TEMPERATURE FOR A) 1971-2000, B) 2021-2050, AND C) 2051-2080 FOR THE RCP 8.5 CLIMATE SCENARIO WITH SHARED CONTINUOUS TEMPERATURE SCALE ACROSS CLIMATE PERIODS.

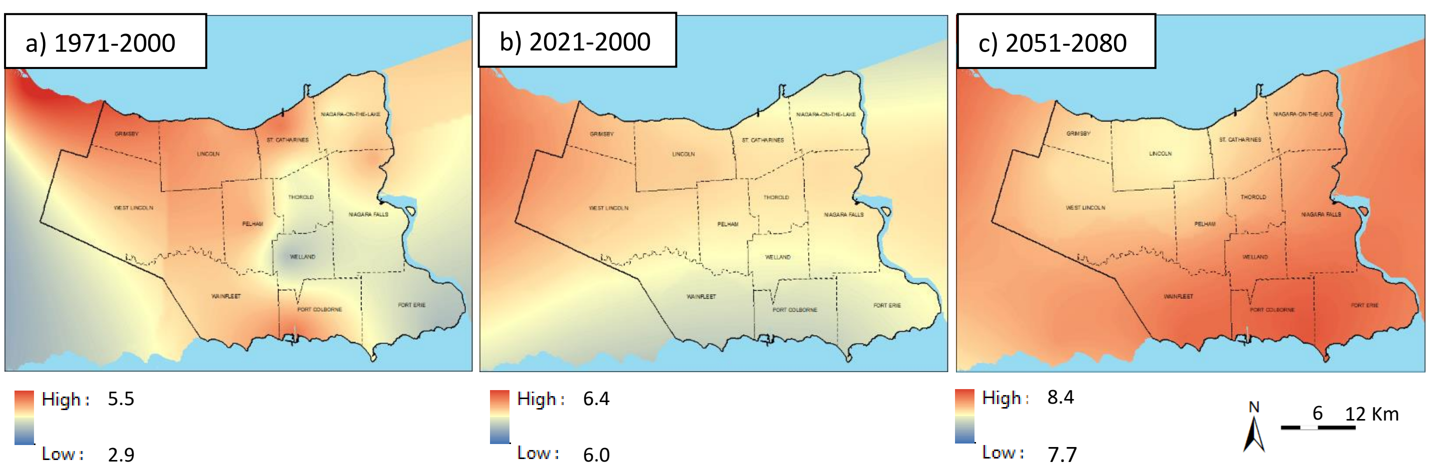

FIGURE 16. AVERAGE ANNUAL MINIMUM TEMPERATURE FOR A) 1971-2000, B) 2021-2050, AND C) 2051-2080 FOR THE RCP 8.5 CLIMATE SCENARIO WITH INDIVIDUAL TEMPERATURE SCALE FOR EACH PERIOD.

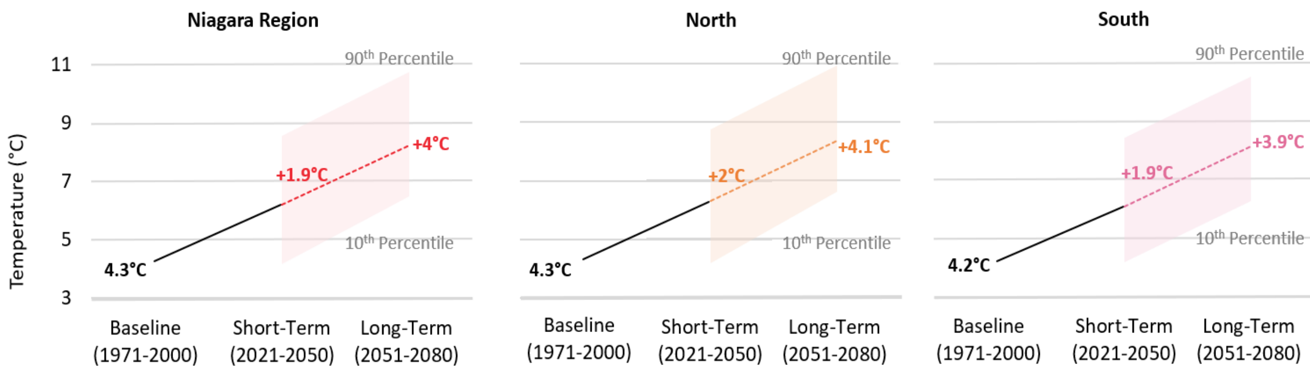

FIGURE 17: COMPARISON OF MEAN MINIMUM DAILY TEMPERATURE BETWEEN REGIONAL AND SUB-REGIONAL ANALYSIS.

5.2 Precipitation and Extreme Precipitation

5.2.1 Average Annual Daily Precipitation

The average daily precipitation is projected to increase over the next two climate periods (2020-2051 and 2051-2080) relative to the baseline for the RCP 8.5 scenario (Figure 18). An increase between 0.1 – 0.9 mm and 0.2 – 1 mm is expected for the short and long-term future periods, respectively. The spatial distribution of precipitation values remains consistent throughout the climate periods with the north-western region having the lowest daily average precipitation and increasing towards the south-eastern regions.

Daily precipitation will vary considerably between sub-regional areas (Figure 19). The southern part of the region has a higher annual precipitation than northern areas across all climate periods. However, considering the change from the baseline to a long-term future climate period, the northern part of the region will see a higher increase (12%) in precipitation than the southern region (11%).

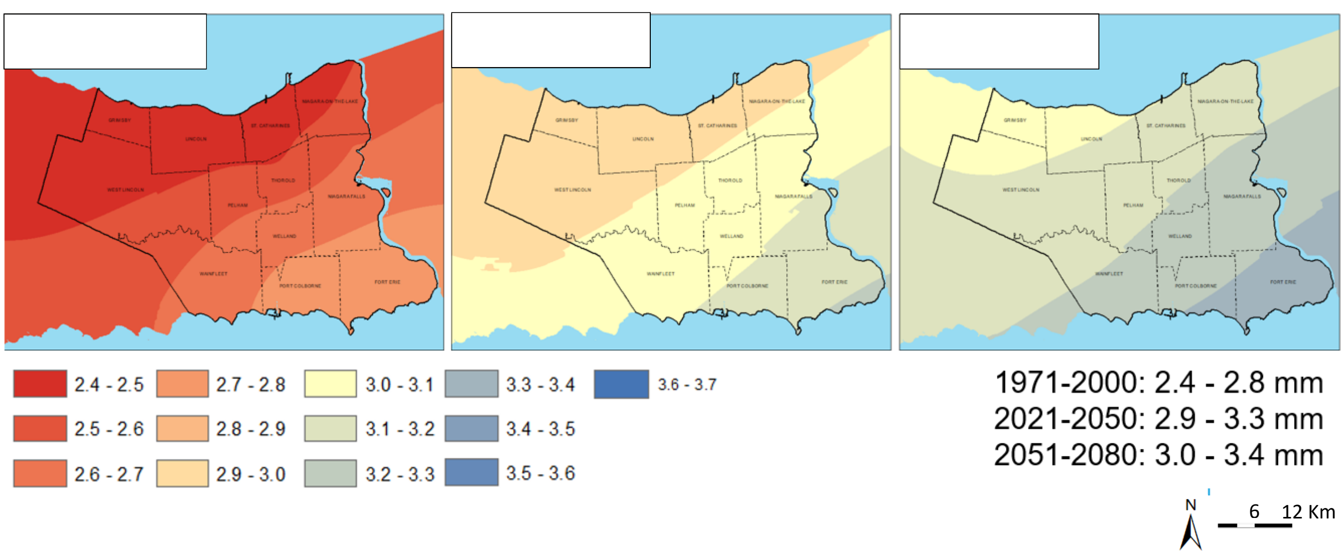

Figure 18: Average annual daily precipitation (mm) for A) 1971-2000, B) 2021-2050, and C) 2051-2080 for RCP 8.5

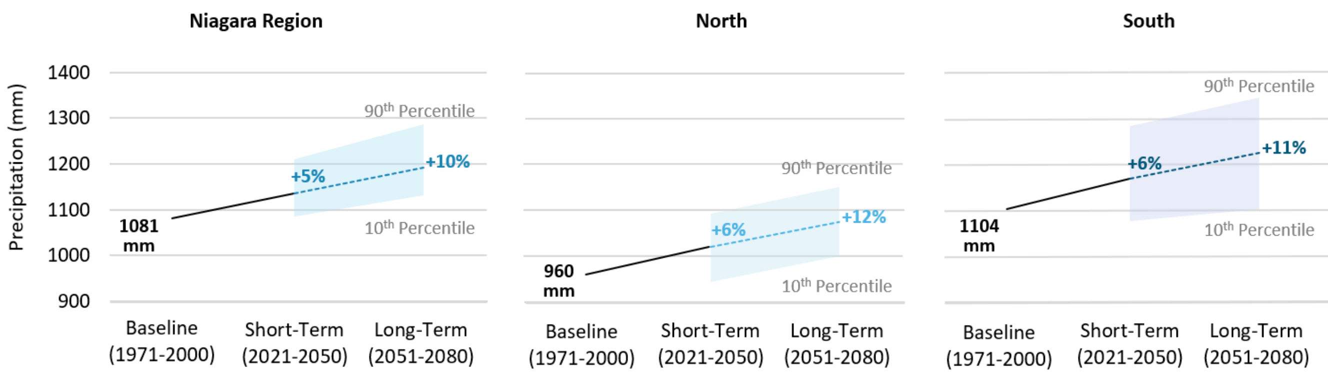

FIGURE 19: COMPARISON OF AVERAGE ANNUAL DAILY PRECIPITATION BETWEEN REGIONAL AND SUB-REGIONAL ANALYSIS.

5.2.2 Extreme Precipitation

Figure 20 illustrates the likelihood that Niagara Region can expect to see a slight increase in extreme precipitation by the end of the century. The maximum precipitation falling in one day is expected to increase by about 10% in the long-term period. The maximum amount of precipitation falling over three consecutive days is expected to increase by 6% from the baseline to the long-term period. No significant difference is observed in either the 1-day or 3-day maximum rainfall between the baseline and short-term periods. It is important to note that the analysis undertaken for 1-day and 3-day maximum rainfall is constrained by only looking at daily precipitation that may not be compatible with the interday temporal distribution of precipitation patterns. For example, a 24-hour maximum rainfall period analysis may not compare closely with a calendar day maximum rainfall analysis.

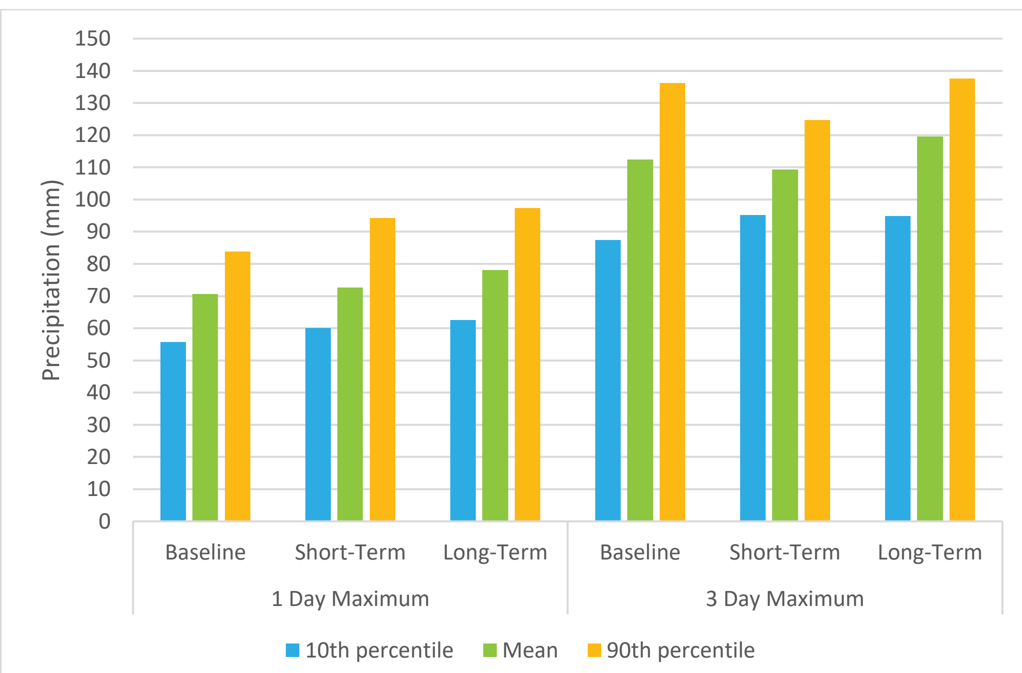

FIGURE 20: ANNUAL MAXIMUM AMOUNT OF PRECIPITATION FALLING IN ONE AND THREE DAYS FOR EACH CLIMATE PERIOD FOR RCP 8.5

The frequency of extreme precipitation days (i.e., daily precipitation > 25mm) is projected to increase by 21% and 47% in the short and long-term periods, respectively, relative to the baseline (Figure 21). While the baseline period recorded an average of 4.8 extreme precipitation days/year, the short- and long-term periods are projecting an average of 5.8 and 7 days/year, respectively. These extreme precipitation events occurring within a single day pose threats to Niagara Region's infrastructure (e.g., flooding of roads and buildings) and its residents (e.g., through the negative impact on water quality, flooding of basements, etc.).

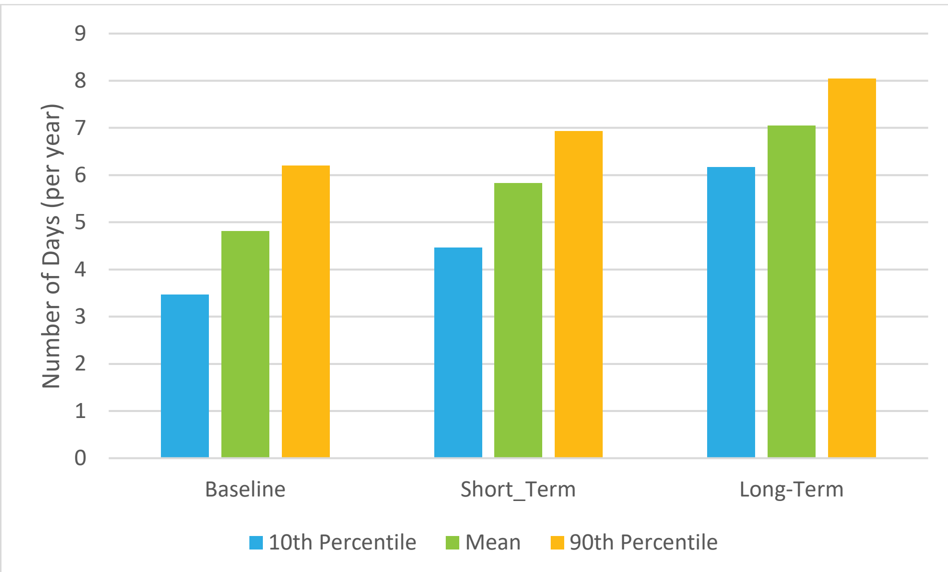

FIGURE 21: ANNUAL EXTREME PRECIPITATION DAYS (DAYS WHERE PRECIPITATION IS GREATER THAN 25 MM IN ONE DAY) FOR EACH CLIMATE PERIOD FOR RCP 8.5.

Furthermore, the projections indicate that Niagara Region will likely experience more precipitation per wet day (days with precipitation >0.2mm) in all seasons (Figure 22). By the long-term climate period, the greatest increase is anticipated in the winter (14%) and spring (12%) months, followed by the fall (10%) and summer (5%) months. Wetter and warmer winter projections can result in more rainfall than snow during the winter, resulting in "flashy" runoff responses given the potentially frozen ground. This type of wet weather flow can result in urban flooding, riverbank erosion, and infrastructure damage.

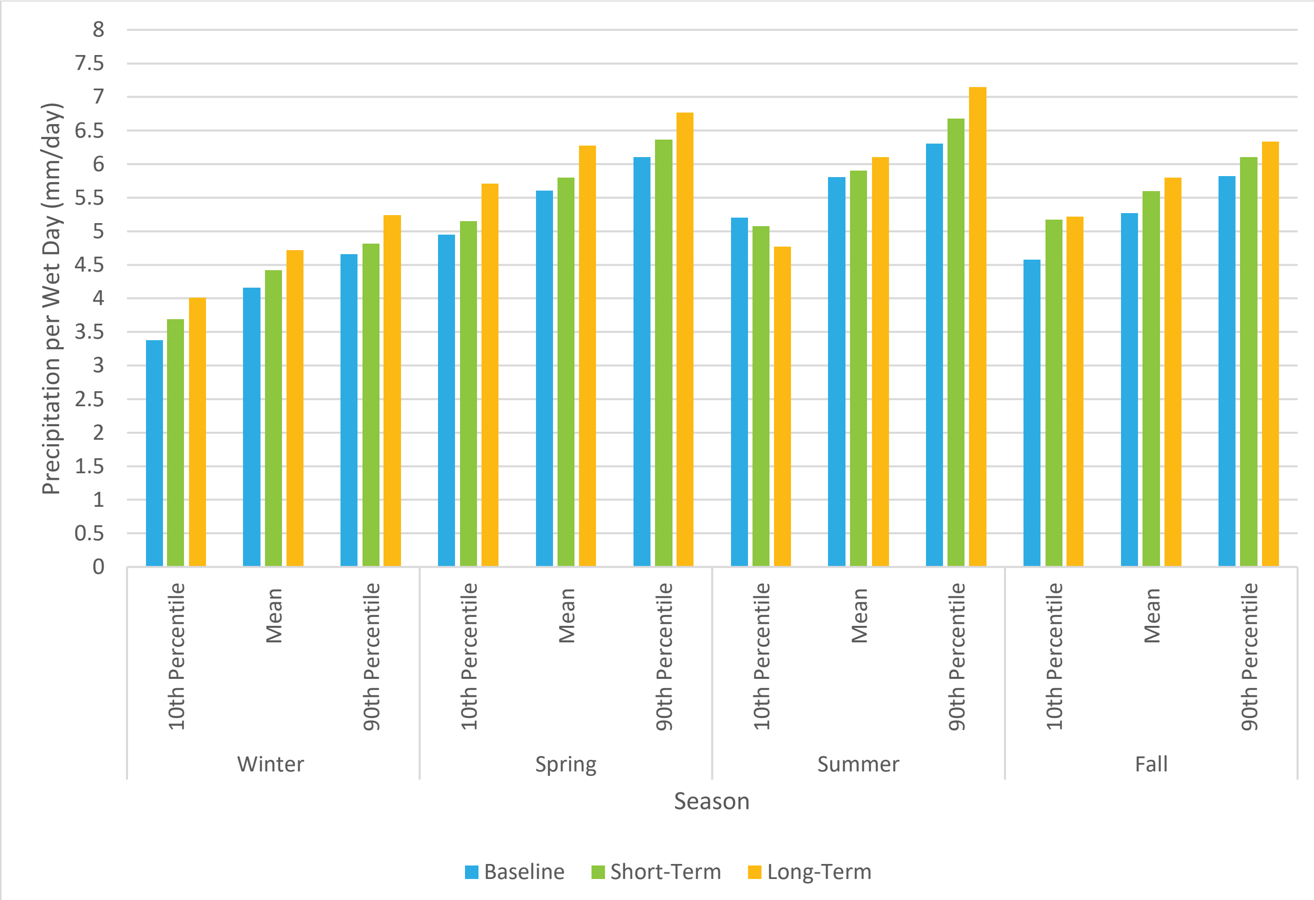

FIGURE 22: THE AVERAGE WINTER, SPRING, SUMMER, AND FALL SIMPLE DAILY INTENSITY INDEXES (SDII) (TOTAL AMOUNT OF PRECIPITATION IN MILLIMETERS PER WET DAY) FOR RCP 8.5.

5.2.3 Dry Conditions

The number of total annual dry days are constant from the baseline through to the long-term climate period, approximately 155 days of 0 to 0.2mm of precipitation per year on average. However, the maximum number of consecutive dry days is expected to decrease slightly over time, from an annual average of 21 consecutive days in the observed baseline record to 19 and 18 days for the short- and long-term climate periods, respectively. Even though the average annual precipitation has increased from the baseline (1,080 mm) to the long-term climate period (1,192 mm), so has the amount of precipitation occurring on wet days (annual simple daily intensity index value), allowing the number of dry days to remain constant throughout the time periods (Table 6).

5.2.4 Growing Season

The results from the growing season analysis indicate that the total increase from 1971-2000 to 2051-2080 in the growing season in Niagara Region will be approximately 15 days under the RCP 8.5 climate scenario. The growing season will likely begin in the last week of April (~April 29th) by the end of the century and will likely end in mid-November (~November 16th), compared to the baseline average start date of May 7th and end date of October 30th. An earlier start date and later end date may increase the risk of plant mortality or crop failure due to cold snaps.

5.2.5 Growing Degree Days

The amount of Growing Degree Days (GDD) is expected to increase over time for each crop (i.e., canola, forage crop, corn, and bean) and pest analyzed under the RCP 8.5 climate scenario (**Error! Reference source not found.**). GDDs above 0°C are expected to increase by 30%, GDDs for canola and forage crops are expected to increase by 36% and 38% respectively, and GDDs for corn and bean are expected to increase by 53% by the long-term future climate period (2051-2080) compared to the baseline period (1971-2000).

With the temperature rise, Niagara Region can expect to have more ideal days for growing corn, canola, forage crops, and beans. However, with an increase in temperature comes the risk of more pests. The number of GDDs for pest occurrence in the region is expected to increase two-fold by the long-term (2051-2080) climate period compared to the baseline period (1971-2000).

While these figures demonstrate opportunities for the agricultural sector in Niagara, it is important to realize that crops have different temperature and precipitation thresholds beyond which they will not be able to survive under certain climate conditions. It is also important to recognize that with the increased potential for cold snap periods, coupled with earlier and longer growing seasons, there is a greater risk of plant mortality or crop failure. For example, in some areas in the Great Lakes Basin in 2012, the mild winter and spring was followed by a frost in April that destroyed many fruit trees in the area (Delaney et al., 2020).

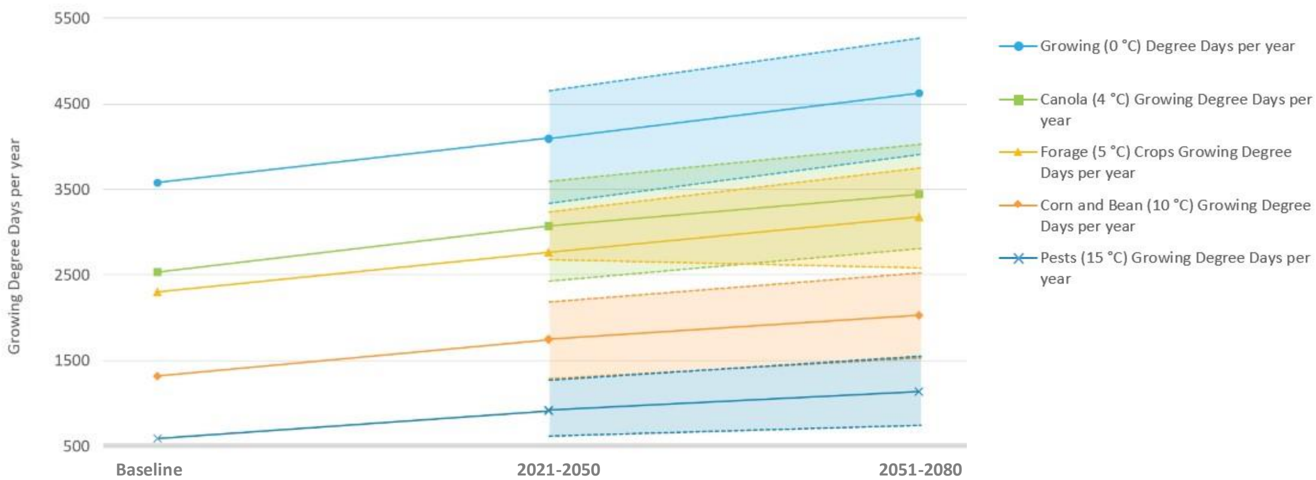

FIGURE 23. PROJECTED NUMBER OF GROWING DEGREE DAYS FOR VARIOUS THRESHOLDS UNDER THE RCP 8.5 SCENARIO. SOLID LINES SHOW THE ENSEMBLE MEAN VALUES WHILE THE SHADED AREA SHOW THE 10TH AND 90TH PERCENTILE RANGE.

5.3 Ice and Freeze-Thaw Cycles

With increased temperatures, it is expected that there will be fewer freeze-thaw cycles and less occurrence of ice. The freeze-thaw cycle in the region is expected to decline by 27% during the long-term climate period compared to the baseline period. The number of freeze-thaw cycles is also expected to gradually decrease (12%) from the baseline period to the short-term climate period. As temperatures will continue to rise, these cycles are expected to decline rapidly (17%) in the short to long-term future under the RCP 8.5 climate scenario (Figure **23**). It should be noted that freeze-thaw cycles are based purely on air temperature and do not take soil temperature into account. Ice potential is likely to see over 35% drop from baseline until the long-term climate period, with a slow decline (15%) by the short-term and a sharp decline (27%) by the long-term future (Figure 25)

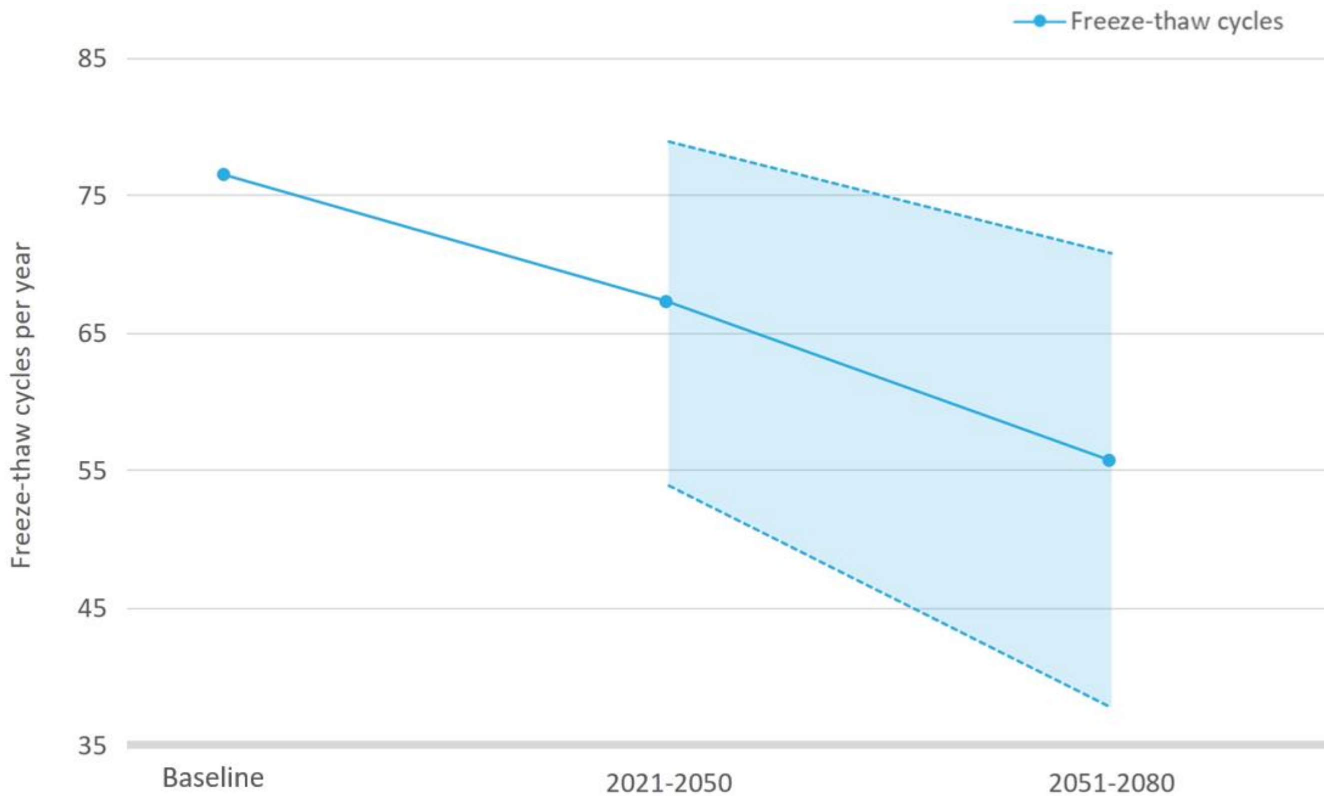

FIGURE 24: PROJECTED NUMBER OF FREEZE-THAW CYCLES PER YEAR FOR EACH CLIMATE PERIOD IN THE RCP 8.5 CLIMATE SCENARIO. DOTTED LINES DEMONSTRATE THE 10TH AND 90TH PERCENTILES, SHADING BETWEEN THE DOTTED LINES REPRESENT THE RANGE IN CLIMATE MODEL RESULTS, AND SOLID LINES DEMONSTRATE THE ENSEMBLE MEANS.

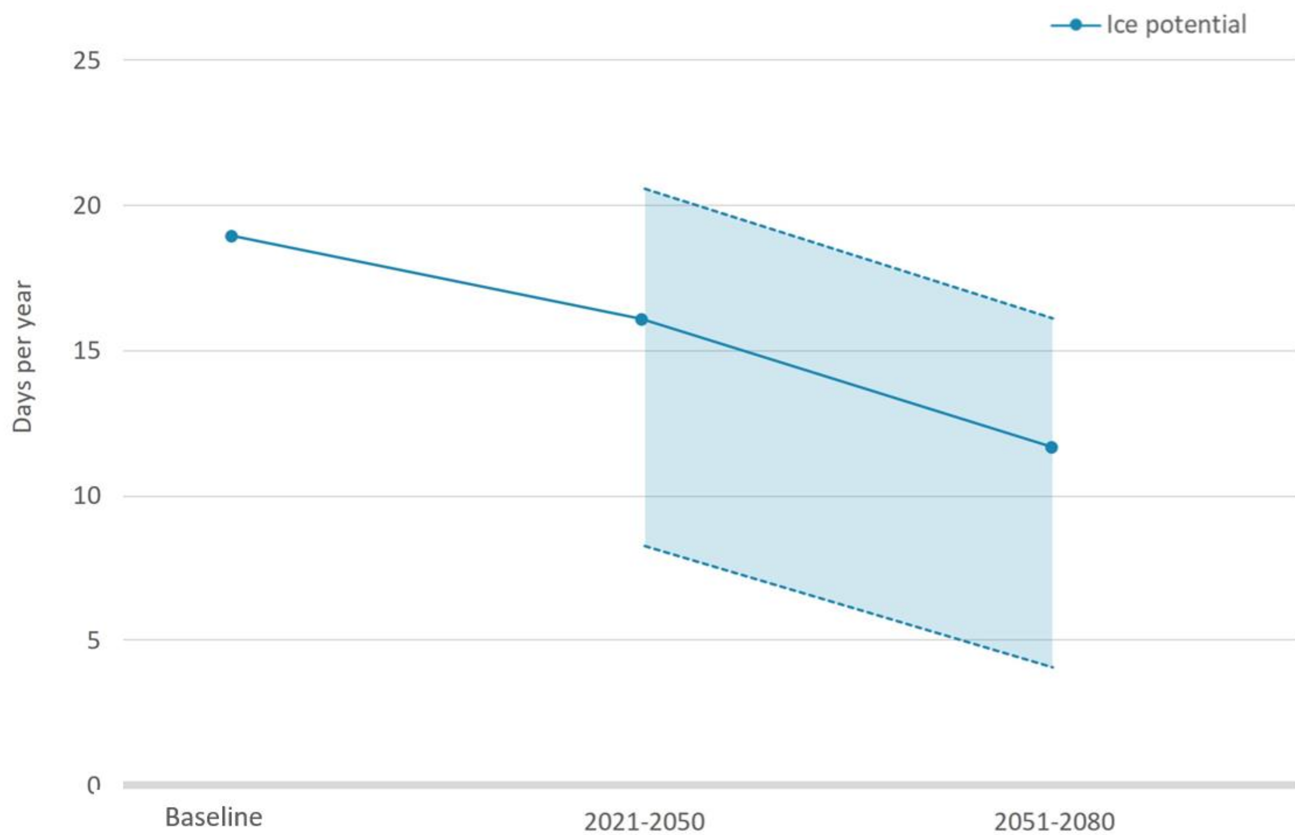

FIGURE 25: PROJECTED NUMBER OF ICE POTENTIAL DAYS PER YEAR FOR EACH CLIMATE PERIOD IN THE RCP 8.5 CLIMATE SCENARIO. DOTTED LINES DEMONSTRATE THE 10TH AND 90TH PERCENTILES, SHADING BETWEEN THE DOTTED LINES REPRESENT THE RANGE IN CLIMATE MODEL RESULTS, AND SOLID LINES DEMONSTRATE THE ENSEMBLE MEANS.

5.4 Comparison to the City of St. Catharines Corporate Climate Change Action Plan

In 2021, the City of St. Catharines released its Corporate Climate Change Action Plan (SCCCAP) as part of Niagara Adapts, an initiative of Brock University in partnership with seven local municipalities in Niagara Region. To inform development of the SCCCAP, climate data specific to the City of St. Catharines was obtained from Climate Atlas of Canada and Climatedata.ca, which are part of a national suite of climate data portals. The summary of baseline and future climate data presented in Appendix B of the SCCCAP was used to inform a rapid comparison with the climate projections developed by TRCA. The purpose of this comparison is to highlight similarities and differences between the approaches used to generate downscaled climate projections and how the regional and local municipal projections compare. This section provides a brief overview of the comparison; for further details, please see Appendix E.

Given that TRCA and the SCCCAP used different baseline periods and future periods, the climate data did not enable a straightforward comparison. TRCA's baseline period covers 1971-2000, while the SCCCAP uses 1976-2005. Moreover, TRCA's future periods cover 2021-2050 and 2051-2080, while the SCCCAP uses the years 2050 and 2100. Given these differences, a high-level comparison of the baseline climate data and climate projections to 2050 was undertaken, using 20 comparable climate variables between TRCA and the SCCCAP.

Table 7Table provides a summary of the climate variables found to be similar or different between TRCA's climate projections and those presented in the SCCCAP based on the baseline climate data and mid-century projections, respectively. Baseline climate data were compared based on percentage difference. Meanwhile, mid-century projections were compared based on whether the SCCCAP ensemble mean falls within TRCA's projected 10th and 90th percentile values. While there was alignment among most of the mid-century projections (12 out of 20 variables, or 60%), most of the baseline climate data was not aligned (60%). The differences in baseline climate data may be a result of the use of different climate stations.

Despite the differences in approach used to develop the climate projections, most of the mid-century projections for Niagara Region and the City of St. Catharines remain similar.

TABLE 7. SUMMARY OF THE SIMILARITIES AND DIFFERENCES BETWEEN 20 CLIMATE VARIABLES USED IN THE NIAGARA CLIMATE MODELING PROJECT AND THE SCCCAP BASED ON BASELINE CLIMATE DATA AND CLIMATE PROJECTIONS TO 2050

Baseline Climate Data TRCA (1971-2000) and the SCCCAP (1976-2005)		**Climate Projections to 2050** TRCA (2021-2050) and the SCCCAP (2050)	
Similar	**Different**	**Similar**	**Different**
(Percentage difference is ≤10%)	(Percentage difference is >10%)	(SCCCAP ensemble mean falls within TRCA's projected 10th and 90th percentile values)	(SCCCAP ensemble mean falls outside of TRCA's projected 10th and 90th percentile values)
• Mean annual air temperature • Mean spring temperature • Mean summer temperature • Mean fall temperature • Mean annual maximum daily air temperature • Growing degree days 0˚C • Growing degree days 5˚C • Growing degree days, 10˚C	• Mean winter temperature • Mean annual minimum daily air temperature • Days over 30˚C • Tropical nights (over 20˚C) • Days below -15˚C • Mean annual total precipitation • Mean winter total precipitation • Mean spring total precipitation • Mean summer total precipitation • Mean fall total precipitation • Maximum 1-day total precipitation • Freeze-thaw cycles	• Mean annual air temperature • Mean winter temperature • Mean spring temperature • Mean summer temperature • Mean fall temperature • Mean annual maximum daily air temperature • Mean annual minimum daily air temperature • Days above 30˚C • Days below -15˚C • Tropical nights (over 20˚C) • Growing degree days 0˚C • Growing degree days 5˚C • Growing degree days, 10˚C	• Mean annual total precipitation • Mean winter total precipitation • Mean spring total precipitation • Mean summer total precipitation • Mean fall total precipitation • Maximum 1-day total precipitation • Freeze-thaw cycles

6.0 Conclusions and Next Steps

This report is intended to provide Niagara Region with climate trend summaries for observed and projected climate data. The study follows the guidance outlined in Delaney et al. (2020), ensuring that the methods employed for retrieving downscaled regional climate projections, model bias- correction, and climate parameter analysis are consistent with other recent climate studies undertaken for Durham Region (Delaney et al. 2020) and Ganaraska Region Conservation Authority (Dokoska et al. 2020).

While downscaled climate information is vital in informing the development and implementation of adaptation strategies, it is important to recognize the uncertainty in climate modeling outcomes. Examples of uncertainty introduced into climate projections include: inter-annual differences not accurately projected by models, projecting far into the future, uncertainties in GCM transferred to RCM, assumptions made about future emissions scenarios and future available technologies.

This climate analysis uses an ensemble of models downloaded from the NA-CORDEX and bias corrects it using observed climate normals for the baseline period (1971-2000) from 12 ECCC climate stations located within and just outside the region. This ensemble is composed of 16 GCM+RCM model runs, which incorporates the feedback from the Great Lakes into its projections.

The analysis demonstrates that the Niagara Region will likely experience a wetter and warmer climate, longer growing season, and increased number of growing degree days by the end of the century. While some of these climatic changes may seem favorable for agriculture, they are also suitable for increased pests, which may outweigh the benefits to agriculture under climate change.

Niagara Region is also expected to experience more extreme precipitation and temperature events. This may impose threats to the health of communities, natural systems, infrastructure, agriculture, economy, and services within the region.

The ensemble climate modeling will be a useful tool for the Niagara Region's planning initiatives. It will serve as the foundational dataset and driver for many climate change adaptation initiatives. Below is a list of next steps and recommendations that Niagara may wish to consider as part of future projects to advance climate change initiatives.

- Work with climate and subject matter experts to integrate the climate projections into various projects (e.g., hydrogeological modeling, water quality modeling, hydrological modeling, etc.) to better understand how climate change may impact these systems.
- Consider conducting additional studies for select climate parameters (e.g., drought, snow, etc.) that would need to be validated through additional data. For example, a comprehensive analysis on drought would require additional data on solar radiation to estimate potential evapotranspiration (OCC, 2016).
- Work with climate and subject matter experts to continually update the climate projections as new climate information becomes available to ensure that climate adaptation initiatives are based on the best available science. Updates to plans (e.g., climate change plans) should be reviewed every 5 years in order to keep pace with the rapidly evolving science and changing policy environment.

- Build staff capacity through education and training on the use and application of the climate modeling. This will allow staff to have a better understanding of the limitations or caveats associated with the climate data.
- Consider developing an online web application that would provide the Region and its municipalities with an easy-to-use interface for data handling. The web application would be a great tool for presenting the climate projections while also providing a space to easily access the data.
- Conduct climate change vulnerability and risk assessments (e.g., ecosystem impact analyses, neighborhood-scale vulnerability assessments, etc.) to better understand the climatic, biophysical, and human factors that contribute to the effects of climate change on various systems (e.g., natural systems, infrastructure, etc.). This will also allow the Region to undertake quantitative vulnerability analyses to identify and map highly vulnerable areas in the region.
- Consider updating policies, design standards and guidelines to account for projected changes in climate.
- Continue understanding and addressing the impacts of climate change by bolstering high resolution and long-term monitoring programs to support better adaptive management and planning.

7.0 Glossary

Climate: Climate is defined as an area's long-term weather patterns. The simplest way to describe climate is to look at average conditions (e.g., temperature, precipitation, etc.) over time. Other useful elements for describing climate include the type and the timing of precipitation, amount of sunshine, average wind speeds and directions, number of days above freezing, and/or weather extremes (IPCC 2012a, IPCC 2012b).

Climate Change: Refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the statistical properties (e.g., mean and/or the variability) in weather and atmospheric conditions that persists for an extended period, typically decades or longer (IPCC 2007, IPCC 2012a)

Climate Change Scenario: “A climate change scenario is a description of a possible future climate based on assumptions of how the earth’s climate operates, future world population levels, economic activity and greenhouse gas emissions” (NRCan, 2018). There are four main climate scenarios that are referenced in the IPCC reports called, Representative Concentration Pathways (RCPs): RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5.

Climate Condition(s): A representation or measurement of a climate driver (e.g., total daily precipitation, minimum daily temperature, 1-day maximum precipitation). In this assessment, climate variables refer to those that have been modeled using a suite of Global Climate Models (GCMs) that are then used to infer trends in changing climate.

Climate Normal: “Refer to arithmetic calculations based on observed climate values for a given location over a specified time period and are used to describe the climatic characteristics of that location. Real-time values, such as daily temperature, are compared to the ‘climate normal’ to determine how unusual or how great the departure from ‘average’ they are” (Environment and Climate Change Canada, 2018). A 30-year period is typically used to smooth out extremes, and ensure that particularly wet, dry, hot or cold years do not dominate the climate conditions overall (which may occur if only a subset of years are used as a normal period). Typically, the middle decade is used to name the climate normal, such as 2041-2070 referred to as the 2050s, 1981-2010 referred to as the 1990s (or baseline period).

Climate Projection: The term "projection" is used in two ways in climate change literature. In its general usage, a projection can be regarded as any description of the future and the pathway leading to it (e.g., WMO 2007). However, a more specific interpretation has been attached to the term "climate projection" by the IPCC when referring to model-derived estimates of future climate (IPCC 2012a, IPCC 2012b).

(Climate Change) Impacts: Consequences of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts:

a) **Potential impacts:** All impacts that may occur given a projected change in climate, without considering adaptation." (IPCC, 2014). This is the product of climate exposure and sensitivity.
b) **Residual impacts:** The impacts of climate change that would occur after adaptation" (IPCC, 2014).

Degree Days: Degree-days for a given day represent the number of Celsius degrees that the mean temperature is above or below a given base temperature. For example, heating degree-days are the number of degrees below 18 °C. If the daily mean temperature is equal to or greater than 18 °C, then the number will be zero. Values above or below the base of 18°C are used primarily to estimate the heating and cooling requirements of buildings. Values above 5°C are frequently called growing degree-days and are used in agriculture as an index of crop growth.

Downscaling: The process of generating climate information from a Global Climate Model (GCM) with coarse spatial resolution to a finer spatial resolution. There are two types of downscaling, statistical and dynamical downscaling. Dynamical downscaling also adds value by incorporating additional physics of the Earth's atmosphere (e.g., wind).

Dynamical Downscaling: A downscaling approach which involves running a very high-resolution model once over the area of interest, driven by global climate model boundary conditions. These boundary conditions provide Regional Climate Models with information about conditions in neighbouring cells (e.g., to calculate rainfall, you need to understand how much moisture is entering the region) (Hannah, 2011). In the simplest of terms one can either have 'many model runs at a coarse resolution' or 'few model runs at high resolution'. These high-resolution models are called 'Regional Climate Models' (RCMs).

Global Climate Model (GCM): GCMs provide projected changes in climate over the entire Earth's surface (Charron, 2014). GCMs use mathematical equations to show how energy and matter interact among the ocean, land and atmosphere (NOAA, n.d.). These climate models divide the surface into 3-D grid cells where the results in each cell are passed to neighbouring cells to show how the exchange of energy and matter has changed over time (ibid). GCMs typically have a large spatial resolution (e.g., typically 200 km by 200 km). Therefore, the smaller the grid cell, the more detailed the information will be.

Intensity-Duration-Frequency (IDF) Curve: "IDF curves describe the relationship between rainfall intensity, rainfall duration, and return period. [They] are commonly used in the design of hydrologic, hydraulic, and water resource systems, and are obtained through frequency analysis of rainfall observations" (Colorado State University, n.d.).

Radiative Forcing: The change in the net, downward minus upward, radiative energy (expressed in Watts per square metre) at the tropopause (the boundary in the Earth's atmosphere between the troposphere and the stratosphere) due to a change in an external driver of climate (e.g., a change in concentration of carbon dioxide or the output energy coming from the sun) (Charron, 2016).

Raster: A raster graphics (also referred to a bitmap image) is a dot matrix data structure that represents a generally rectangular grid of pixels (points of color). Example of raster images include satellite images, aerial photographs, digital elevation models, etc.

Regional Climate Model (RCM): A dynamically downscaled model, derived and reanalyzed from a Global Climate Model (GCM) that produces climate projections on a much finer scale (Charron, 2016). Compared to GCMs, RCMs have a much smaller resolution (e.g., 25km x 25km).

Representative Concentration Pathways (RCPs): There are four RCPs that represent future total radiative forcing, a cumulative measure of human emissions of GHGs from all sources expressed in Watts per square meter pathway and level by 2100 (IPCC, 2014). Each RCP represents a different combination of economic, technological, demographic, policy, and institutional futures.

a) **RCP 2.6:** The lowest emission scenario, where peak radiative forcing is ~3W/m2 and declines before 2100 (IPCC, 2014). This scenario would require all the main GHG emitting countries, including developing countries, to participate in climate change mitigation initiatives and policies.
b) **RCP 4.5:** The second lowest emission scenario, where stabilization without overshoot pathway to 4.5 W/m2 and stabilization after 2100 (IPCC, 2014).
c) **RCP 6.0:** The second highest emission scenario, where stabilization without overshoot pathway to 6 W/m2 and stabilization after 2100 (IPCC, 2014).
d) **RCP 8.5:** The highest emission scenario, where rising radiative forcing pathway leading to 8.5 W/m2 in 2100 (IPCC, 2014). GHG emissions are up to seven times higher than preindustrial levels.

Seasonality: A characteristic of a time series in which the data experiences regular and predictable changes which recur every calendar year. Any predictable change or pattern in a time series that recurs or repeats over a one-year period can be said to be seasonal (e.g., summer, fall, winter, and spring).

Statistical downscaling: An approach that relies on historical observed relationships among climate parameters of various scales and develops mathematical equations to predict future conditions. Statistical downscaling uses observations to develop these relationships between the large-scale conditions and local-scale conditions and then applies these observed relationships to simulated large-scale patterns. Notably, there is uncertainty as to whether these relationships will hold under evolving conditions (e.g., feedback loops, tipping points) associated with climate change (e.g., changing lake temperatures and ice cover, changing soil moisture, changing snowpack).

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Appendix A: Climate Summary Tables for Northern and Southern Part of the Niagara Escarpment within Niagara Region under the RCP 8.5 Scenario

Please note that these summary tables have been bias-corrected to the individual regions.

TABLE A1: CLIMATE TRENDS FOR THE NORTHERN PART OF THE NIAGARA ESCARPMENT UNDER THE RCP 8.5 SCENARIO

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Mean Temperature								
Mean Annual Temperature	**8.7**	9.0	**10.8**	13.2	10.8	**12.5**	15.2	↑
Mean Winter Temperature	**-3.0**	-3.5	**-0.5**	1.9	-1.6	**0.9**	3.8	↑
Mean Spring Temperature	**6.6**	6.1	**8.2**	10.4	7.8	**9.9**	12.3	↑
Mean Summer Temperature	**20.3**	20.1	**22.2**	24.6	21.5	**24.1**	26.8	↑
Mean Fall Temperature	**10.7**	11.2	**12.9**	15.7	12.8	**14.6**	17.7	↑
Maximum Temperature								
Annual Mean Maximum Daily Air Temperature	**12.9**	12.9	**15.1**	17.6	14.3	**16.6**	19.7	↑
Winter Mean Maximum Daily Air Temperature	**0.9**	0.8	**3.2**	5.3	2.5	**4.7**	6.9	↑
Spring Mean Maximum Daily Air Temperature	**11.0**	10.8	**12.8**	15.3	12.1	**14.2**	17.0	↑
Summer Mean Maximum Daily Air Temperature	**24.9**	25.0	**27.2**	30.1	25.4	**28.9**	32.5	↑

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Fall Mean Maximum Daily Air Temperature	**14.5**	15.0	**16.9**	19.9	16.5	**18.5**	22.1	↑
Minimum Temperature								
Annual Mean Minimum Daily Air Temperature	**4.3**	4.2	**6.3**	8.7	6.6	**8.4**	10.9	↑
Winter Mean Minimum Daily Air Temperature	**-7.3**	-8.2	**-5.1**	-1.6	-5.0	**-2.3**	0.4	↑
Spring Mean Minimum Daily Air Temperature	**2.0**	2.3	**3.8**	5.8	3.2	**5.5**	7.9	↑
Summer Mean Minimum Daily Air Temperature	**15.4**	15.3	**17.3**	19.6	17.1	**19.2**	21.6	↑
Fall Mean Minimum Daily Air Temperature	**6.9**	7.3	**8.9**	11.6	8.9	**10.8**	13.8	↑
Extreme Heat (days per year)								
Days Above 35˚C	**0.7**	0.2	**3.8**	9.2	0.0	**10.4**	27.2	↑
Days Above 30˚C	**11.9**	8.9	**28.3**	58.4	6.4	**44.4**	90.8	↑
Days Above 25˚C	**52.7**	57.5	**82.0**	117.1	60.5	**99.2**	139.5	↑
Tropical Nights	**10.9**	7.8	**27.8**	56.6	19.7	**49.3**	85.9	↑
Extreme Cold (days per year)								
Days Below -20˚C	**4.8**	0.0	**2.6**	2.6	0.0	**0.1**	0.2	↓
Days Below -15˚C	**13.7**	0.6	**7.5**	12.1	0.1	**1.2**	2.8	↓
Days Below -10˚C	**34.3**	4.9	**21.6**	38.2	1.6	**8.0**	16.1	↓
Days Below -5˚C	**68.8**	24.9	**51.4**	74.6	12.2	30.8	47.8	↓

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Days Below 0˚C (Freezing Days)	**123.7**	75.3	**103.5**	132.2	51.2	81.9	106.4	↓
Total Precipitation (mm per climate period)								
Total Average Annual Precipitation (mm)	**959.6**	943.2	**1020.0**	1093.3	1000.2	**1075.2**	1151.1	↑
Total Average Winter Precipitation (mm)	**200.6**	179.9	**220.0**	246.9	199.1	**238.9**	273.5	↑
Total Average Spring Precipitation (mm)	**254.6**	227.8	**271.5**	302.9	265.3	**297.6**	329.1	↑
Total Average Summer Precipitation (mm)	**269.9**	230.9	**278.8**	323.0	210.7	**289.4**	333.4	↑
Total Average Fall Precipitation (mm)	**233.9**	222.3	**248.6**	274.4	215.8	**247.9**	278.3	↑
Extreme precipitation								
Max Precipitation in 1 day (mm)	**77.7**	75.5	**86.5**	106.1	72.2	**94.0**	125.8	↑
Max Precipitation in 3 days (mm)	**123.1**	99.5	**122.0**	140.6	99.0	**126.7**	155.1	↑
Extreme Precipitation Days (days/year)	**5.2**	4.8	**6.3**	7.3	6.5	**7.5**	8.6	↑
Annual Simple Daily Intensity Index (SDII) (mm/day)	**5.4**	5.1	**5.8**	6.1	5.5	**6.1**	6.5	↑
Winter SDII (mm/day)	**4.4**	3.9	**4.8**	5.5	4.3	**5.2**	5.8	↑
Spring SDII (mm/day)	**6.0**	5.6	**6.3**	6.9	6.2	**6.8**	7.5	↑
Summer SDII (mm/day)	**5.9**	5.2	**6.1**	6.8	5.0	**6.3**	7.4	↑

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Fall SDII (mm/day)	**5.3**	5.4	**5.9**	6.3	5.5	**6.2**	6.7	↑
Dry Days (days per year)								
Total Annual Dry Days	**186.3**	177.2	**187.6**	196.7	181.6	**188.8**	195.6	↑
Maximum Total Consecutive Dry Days	**23.3**	18.0	**21.3**	24.5	17.0	**21.3**	24.5	↓
Agricultural Variables								
Growing Degree Days (Base 0°C)	**3623.012**	3594.9	**4160.9**	4909.8	4093.3	**4698.8**	5576.2	↑
Canola Growing Degree Days (Base 4°C)	**2575.108**	2543.9	**3032.5**	3679.7	2938.3	**3504.2**	4262.2	↑
Forage Crops Growing Degree Days (Base 5°C)	**2344.603**	2314.0	**2782.9**	3405.8	2684.4	**3237.2**	3965.0	↑
Corn and Bean Growing Degree Days (Base 10°C)	**1356.953**	1325.6	**1705.1**	2207.6	1569.1	**2075.4**	2666.8	↑
Growing Degree Days-Days at Risk of Presence of Pests (Base 15°C)	**622.596**	579.7	**884.0**	1262.8	755.5	**1170.5**	1638.3	↑
Growing Season								
Growing Season Start Date (day of year)	**2021-05-04**	2021-04-13	**2021-04-28**	2021-05-10	2021-04-11	**2021-04-25**	2021-05-07	↑
Growing Season End Date (day of year)	**2021-10-31**	2021-10-29	**2021-11-10**	2021-11-24	2021-11-09	**2021-11-20**	2021-12-01	↑
Growing Season Length (days/year)	**179.6**	178.6	**195.8**	216.2	189.8	**208.4**	225.4	↑

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Freeze Thaw Cycles and Ice Potential								
Freeze-Thaw Cycles (days/year)	**70.5**	54.2	**66.9**	79.0	37.4	**60.1**	82.5	↓
Ice Potential (days/year)	**14.7**	2.5	**9.9**	15.8	0.8	**5.3**	10.5	↓

TABLE A2: CLIMATE TRENDS FOR THE SOUTHERN PART OF THE NIAGARA ESCARPMENT UNDER THE RCP 8.5 SCENARIO

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile	
Mean Temperature								
Mean Annual Temperature	**8.5**	8.7	**10.5**	12.8	10.5	**12.2**	14.8	↑
Mean Winter Temperature	**-2.7**	-3.7	**-0.5**	1.9	-2.0	**0.9**	3.7	↑
Mean Spring Temperature	**6.5**	6.2	**8.1**	10.3	7.5	**9.7**	12.0	↑
Mean Summer Temperature	**19.7**	19.9	**21.6**	23.8	21.0	**23.5**	26.1	↑
Mean Fall Temperature	**10.3**	10.6	**12.4**	15.2	12.3	**14.1**	17.3	↑
Maximum Temperature								
Annual Mean Maximum Daily Air Temperature	**12.6**	12.5	**14.6**	17.1	14.2	**16.1**	19.0	↑
Winter Mean Maximum Daily Air Temperature	**1.2**	0.7	**3.2**	5.3	2.4	**4.5**	6.8	↑
Spring Mean Maximum Daily Air Temperature	**10.9**	10.5	**12.4**	14.7	11.6	**14.0**	16.7	↑
Summer Mean Maximum Daily Air Temperature	**24.1**	24.1	**26.2**	28.5	24.9	**27.8**	31.0	↑
Fall Mean Maximum Daily Air Temperature	**14.0**	14.3	**16.2**	19.3	16.1	**17.7**	21.2	↑
Minimum Temperature								
Annual Mean Minimum Daily Air Temperature	**4.2**	4.2	**6.1**	8.4	6.3	**8.1**	10.5	↑
Winter Mean Minimum Daily Air Temperature	**-6.9**	-8.8	**-5.0**	-1.6	-5.5	**-2.3**	0.3	↑
Spring Mean Minimum Daily Air Temperature	**2.0**	1.8	**3.7**	5.7	3.2	**5.5**	7.7	↑

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Summer Mean Minimum Daily Air Temperature	**15.0**	15.1	**16.9**	19.0	16.5	**18.8**	21.2	↑
Fall Mean Minimum Daily Air Temperature	**6.4**	6.6	**8.5**	11.1	8.3	**10.4**	13.3	↑
Extreme Heat (days per year)								
Days Above 35˚C	**0.1**	0.0	**0.9**	2.2	0.0	**5.4**	14.2	↑
Days Above 30˚C	**6.4**	3.1	**18.8**	41.4	4.0	**34.4**	74.0	↑
Days Above 25˚C	**44.5**	46.3	**71.4**	106.7	56.0	**90.4**	133.0	↑
Tropical Nights	**8.1**	5.4	**22.9**	49.0	18.5	**43.6**	77.9	↑
Extreme Cold (days per year)								
Days Below -20˚C	**3.8**	0.0	**2.1**	2.7	0.0	**0.1**	0.3	↓
Days Below -15˚C	**11.4**	0.3	**6.5**	14.1	0.0	**1.2**	3.0	↓
Days Below -10˚C	**31.0**	3.5	**19.8**	40.9	1.1	**7.7**	17.7	↓
Days Below -5˚C	**67.4**	22.7	**50.7**	79.9	10.9	**30.7**	51.7	↓
Days Below 0˚C (Freezing Days)	**126.8**	79.9	**107.9**	133.6	54.7	**85.3**	114.7	↓
Total Precipitation (mm per climate period)								
Total Average Annual Precipitation (mm)	**1103.8**	1075.8	**1168.4**	1284.6	1102.0	**1226.4**	1346.7	↑
Total Average Winter Precipitation (mm)	**237.1**	221.5	**261.8**	302.4	244.3	**285.9**	332.6	↑
Total Average Spring Precipitation (mm)	**282.5**	260.0	**299.9**	331.6	297.4	**328.0**	354.8	↑
Total Average Summer Precipitation (mm)	**301.6**	246.3	**312.6**	349.6	222.2	**324.0**	381.4	↑

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile	
Total Average Fall Precipitation (mm)	**282.2**	242.3	**293.0**	340.8	248.6	**287.3**	341.4	↑
Extreme Precipitation								
Max Precipitation in 1 day (mm)	**80.3**	77.1	**87.5**	100.9	74.7	**93.4**	117.4	↑
Max Precipitation in 3 days (mm)	**114.2**	102.9	**119.5**	142.5	113.2	**132.6**	153.2	↑
Extreme Precipitation Days (days/year)	**5.3**	5.5	**6.7**	8.0	6.5	**8.0**	9.4	↑
Annual Simple Daily Intensity Index (SDII) (mm/day)	**5.7**	5.5	**6.1**	6.5	5.8	**6.4**	6.8	↑
Winter SDII (mm/day)	**4.5**	4.2	**4.8**	5.2	4.6	**5.1**	5.8	↑
Spring SDII (mm/day)	**6.0**	5.7	**6.3**	6.9	6.2	**6.8**	7.4	↑
Summer SDII (mm/day)	**6.6**	5.9	**6.9**	8.0	5.9	**7.2**	8.4	↑
Fall SDII (mm/day)	**5.8**	5.7	**6.4**	6.9	5.9	**6.6**	7.1	↑
Dry Days (days per year)								
Total Annual Dry Days	**170.8**	162.5	**171.8**	184.6	164.4	**173.0**	183.7	↑
Maximum Total Consecutive Dry Days	**22.1**	16.5	**20.8**	25.0	16.5	**20.1**	23.0	↓
Agricultural Variables								
Growing Degree Days (Base 0°C)	**3531.5**	3519.0	**4058.7**	4778.2	4036.4	**4577.8**	5427.4	↑
Canola Growing Degree Days (Base 4°C)	**2490.3**	2479.5	**2942.1**	3565.7	2885.8	**3396.0**	4117.4	↑
Forage Crops Growing Degree Days (Base 5°C)	**2260.8**	2250.4	**2694.4**	3294.4	2627.4	**3131.5**	3821.0	↑
Corn and Bean Growing Degree Days (Base 10°C)	**1280.5**	1266.1	**1624.5**	2102.1	1524.9	**1979.2**	2534.8	↑

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile	
Growing Degree Days-Days at Risk of Presence of Pests (Base 15°C)	**561.4**	566.9	**815.3**	1167.2	704.7	**1086.0**	1518.2	↑
Growing Season								
Growing Season Start Date (day of year)	**2021-05-06**	2021-04-13	**2021-04-30**	2021-05-12	2021-04-12	**2021-04-28**	2021-05-14	↑
Growing Season End Date (day of year)	**2021-10-27**	2021-10-26	**2021-11-07**	2021-11-20	2021-11-08	**2021-11-17**	2021-11-27	↑
Growing Season Length (days/year)	**174.0**	172.4	**191.7**	209.4	182.3	**202.4**	222.4	↑
Freeze Thaw Cycles and Ice Potential								
Freeze-Thaw Cycles (days/year)	**73.8**	52.2	**67.0**	82.4	37.4	**58.0**	78.4	↓
Ice Potential (days/year)	**22.4**	10.4	**17.9**	26.5	1.8	**11.9**	18.4	↓

Appendix B: List of Climate Parameters

TABLE B1. LIST OF CLIMATE PARAMETERS, DEFINITIONS AND RATIONALE FOR INCLUSION IN THIS STUDY

Climate Parameter	Definition	Rationale for Including in Study
Temperature Parameters		
Mean Air Temperature (°C)	The mean temperature in degrees Celsius (°C) is defined as the average of the maximum and minimum temperature at a location for a specified time interval	The temperature range we expect within a season or year is a very important aspect of climate. Changes in average and extreme temperatures can dramatically affect our everyday lives as well as a wide range of planning and policy decisions. The average highest temperature is an environmental indicator with many applications in agriculture, engineering, health, energy management, recreation, and more **Please note:** Maximum and minimum temperatures can be provided both annually and seasonally
Mean Maximum Air Temperature (°C)	The average of the maximum temperature in degrees Celsius (°C) observed at the location for that month	
Mean Minimum Air Temperature (°C)	The average of the minimum temperature in degrees Celsius (°C) observed at the location for that month	
Maximum Temperature (°C)	The highest temperature in degrees Celsius (°C) observed at a location for a specified time interval	
Minimum Temperature (°C)	The lowest temperature in degrees Celsius (°C) observed at a location for a specified time interval	
Extreme Maximum Air Temperature (°C)	The highest daily maximum temperature in degrees Celsius reached at a specific location for that month	
Extreme Minimum Air Temperature (°C)	The lowest daily minimum temperature in degrees Celsius reached at a specific location for that month	
Extreme Heat Parameters		
D y Abov 3 ˚C	The sum of days in a given period of time when the temperature rises to at least 35˚C	High temperatures determine if plants and animals can thrive, they limit or enable outdoor activities, define how we design our buildings and vehicles, and shape our transportation and energy use. It is useful to know how high summer temperatures are likely to become in the future, to make sure that our cooling and air-conditioning systems can reliably deal with these extremes. When temperatures are very hot, people - especially the elderly - are much more likely to suffer from heat exhaustion and heat stroke. Many outdoor activities become dangerous or impossible. In general, Canadians are not used to extremely hot summers, and further warming will bring new and unusual risks as well as a very different experience of
D y Abov 3 ˚C	The sum of days in a given period of time when the temperature rises to at least 30˚C	
D y Abov ˚C	The sum of days in a given period of time when the temperature rises to at least 25˚C	
Tropical Nights	A tropical night occurs when the lowest temperature of the day does not go below 20˚C	

Climate Parameter	Definition	Rationale for Including in Study
		the summer season. High, persistent temperatures increase the risk of drought, which can severely impact food production and increases the risk of wildfire. High temperatures can also lead to more thunderstorms, which means increased risks of flash flooding, lightning, hail and perhaps even tornadoes.
Extreme Cold Parameters		
Days Below - ˚C	The sum of days in a given period of time when the temperature drops to at least -20˚C	Cold weather is an important aspect of life in Canada, and many places in Canada are well adapted to very cold winters. It is especially important to know how our winters will change in the future, because cold temperatures affect our health and safety, determine what plants and animals can live in the area, limit or enable outdoor activities, define how we design our buildings and vehicles, and shape our transportation and energy use
Days Below - ˚C	The sum of days in a given period of time when the temperature drops to at least -10˚C	
Days Below - ˚C	The sum of days in a given period of time when the temperature drops to at least -5˚C	
D y ow ˚C (Frost D ys)	The sum of days in a given period of time when the coldest temperature of the day is lower than 0˚C. Under these conditions, frost might form at ground level or on cold surfaces	The number of frost days is an indicator of the length and severity of the winter season. A location with a large number of frost days is also likely to have a short growing season, since frost is harmful to many plants
Precipitation Parameters		
Total Annual Precipitation (mm/year)	The sum of the total rainfall and the water equivalent of the total snowfall in millimeters (mm), observed at the location during a specified time interval[1]. Winter is defined as DJF, spring as MAM, summer as JJA, and fall as SON.	Precipitation patterns are critical for many important issues, including water availability, crop production, electricity generation, wildfire suppression, snow accumulation, seasonal and flash-flooding, and short- and long-term drought risk
Total Winter Precipitation (mm/season)		
Total Spring Precipitation (mm/season)		
Total Summer Precipitation (mm/season)		
Total Fall Precipitation (mm/season)		
Extreme Precipitation Parameters		
Maximum Precipitation in one day (mm)	The maximum amount of precipitation (mm) in one day over a given period of time	Precipitation patterns are critical for many important issues, including water availability, crop production, electricity generation, wildfire suppression, snow accumulation, seasonal and flash-flooding, and short- and long-term drought risk

Climate Parameter	Definition	Rationale for Including in Study
Extreme Precipitation Days (days with more than 25 mm)	The sum of days in a given period of time when at least a total of 25 mm of rain or frozen precipitation falls. Frozen precipitation is measured according to its liquid equivalent: 10 cm of snow is usually about 10 mm of precipitation	Heavy rainfall events can create many challenges. In cities and towns, heavy rainfalls can overwhelm storm drains and cause flash flooding. They can also cause problems in rural areas by drowning crops, eroding topsoil, and damaging roads. Heavy snowfall events can disrupt ground transportation, and very heavy snowfall events can cause damage to buildings if their roofs become overburdened.
Annual Simple Daily Intensity Index (SDII) (mm/day)	Average intensity (mm/day) over a given period of time, calculated as total wet day precipitation divided by the total number of wet days	
Winter SDII (mm/day)		
Spring SDII (mm/day)		
Summer SDII (mm/day)		
Fall SDII (mm/day)		
95th Percentile Precipitation (mm)	The percent of the total precipitation when precipitation is greater or equal to the 95th percentile.	
99th Percentile Precipitation (mm)	The percent of the total precipitation when precipitation is greater or equal to the 99th percentile.	See description above
Drought Parameters		
Total Annual Dry Days	Total annual number of days where precipitation was less than 0.2 mm.	Total annual dry days and the maximum consecutive dry days are useful indicators for predicting drought in the future. This is useful for municipalities who have a large agricultural sector, such as Niagara Region.
Maximum Total Consecutive Dry Days	The number of consecutive days where annual total number of days where precipitation was less than 0.2 mm.	
Agricultural Parameters		
Growing Degree Days (Base 0°C)	Growing Degree Days (GDD) provide an index of the amount of heat available for the growth and maturation of plants and insects. Different base temperatures (0, 4, 5, 10, 15°C) are used to capture results for organisms that demand different amounts of heat.	GDDs accumulate whenever the daily mean temperature is above a specified threshold temperature. Generally, 5°C GDDs are used for assessing the growth of canola and forage crops; 10°C GDDs are more appropriate for assessing the growth of corn and beans; and 15°C GDDs are used to assess the growth and development of insects and pests.
Growing Degree Days (Base 4°C)		
Growing Degree Days (Base 5°C)		
Growing Degree Days (Base 10°C)		
Growing Degree Days (Base 15°C)		
Growing Season Length (also referred to as Frost Free Days)	Number of frost-free days is calculated based on the last occurrence of frost in spring and the first occurrence of frost in autumn.	The average length of the growing season (and its year-to-year variability) is an important consideration when selecting or predicting what plants might grow well in a region. A longer frost-free season means plants and crops have a longer window to grow and mature. This is an especially important parameter for agriculture, because the variability in the number of frost-free days is crucial for many agricultural activities such as planting and harvesting.

Climate Parameter		
Growing Season Start Date	The first day after 5 consecutive minimum temperatures above 5°C.	Changes in the length and timing of the frost-free season affect plant and animal life, but also our social, psychological, and physical experience of the changing seasons. The growth of most plants and crops is limited by the temperature of the air and soil. Since crops and plants need time to mature, the later in the fall they experience freezing temperatures, the more likely it is that they will be able to mature to their full potential. The time available for growth, maturity and productivity of these plants is determined by the Growing Season Start and End date, which together determine the length of the frost-free season.
Growing Season End Date	The first day after 5 days of consecutive minimum temperatures below 5˚C.	
Ice Parameters		
Freeze-Thaw Cycles	A simple count of days when the air temperature fluctuates between freezing and non-freezing temperatures. Under these conditions, it is likely that some water at the surface was both liquid and ice at some point during the 24-hour period.	Freeze-thaw cycles can have major impacts on infrastructure. Water expands when it freezes, so the freezing, melting and re-freezing of water can over time cause significant damage to roadways, sidewalks, and other outdoor structures. Potholes that form during the spring, or during mid-winter melts, are good examples of the damage caused by this process.
Ice Potential	Number of days where minimum temperature is greater than -2˚C and maximum temperature is under 2˚C.	Number of days in which air temperature does not rise above freezing is a good indicator of the length and severity of the winter season. It is especially important to know how our winters will change in the future, because cold temperatures affect our health and safety, determine what plants and animals can live in the area, limit or enable outdoor activities, define how we design our buildings and vehicles, and shape our transportation and energy use.
Public Health Parameters		
P. vivax Climate Threshold (1)	Number of 30 consecutive days where daily minimum temperature is equal or greater than 18°C and daily maximum temperature is equal or less than 33°C	Requested by Niagara's Public Health & Emergency Services Department, these threshold based analysis identify the suitability of the projected climate for blacklegged ticks that carry Lyme disease, and the potential for the
P. vivax Climate Threshold (2)	Number of 20 consecutive days where daily minimum temperature is equal	

Climate Parameter	Definition	Rationale for Including in Study
	or greater than 20°C and daily maximum temperature is equal or less than 33°C.	
	Number of 30 consecutive days where daily minimum temperature is equal or greater than 20°C and daily maximum temperature is equal or less than 33°C	

Appendix C: Climate Change in Niagara Region Based on the RCP 4.5 (Low Emissions) Scenario

As the RCP 4.5 climate change scenario is used less frequently by planners and practitioners in comparison to RCP 8.5 scenario, fewer models were available online (e.g., the NA-CORDEX portal had 3 model runs for the RCP 4.5 scenario, while RCP 8.5 had 16 model runs). The variability between models or a lack of differences will lead to more bias in the outputs and, therefore should not be directly compared with results from the RCP 8.5 scenario.

TABLE C1: A SUMMARY OF THE IMPORTANT CLIMATE PARAMETERS FOR EACH CLIMATE PERIOD FOR THE NIAGARA REGION UNDER THE RCP 4.5 CLIMATE SCENARIO

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	Ensemble Mean	90th Percentile	10th Percentile	Ensemble Mean	90th Percentile	
Mean Temperature								
Mean Annual Temperature	**8.7**	9.5	**11.5**	13.1	6.3	**10.7**	14.0	↑
Mean Winter Temperature	**-2.8**	-1.3	**0.7**	2.3	2.8	**3.3**	4.0	↑
Mean Spring Temperature	**6.6**	6.4	**8.7**	10.4	5.5	**9.0**	11.5	↑
Mean Summer Temperature	**20.0**	20.5	**22.3**	24.0	8.4	**17.9**	25.1	↑
Mean Fall Temperature	**10.5**	12.2	**14.1**	15.6	7.2	**12.5**	16.5	↑
Maximum Temperature								
Annual Mean Maximum Daily Air Temperature	**12.9**	13.6	**15.8**	17.4	18.2	**18.3**	18.3	↑
Winter Mean Maximum Daily Air Temperature	**0.7**	2.1	**4.1**	5.7	5.8	**5.9**	6.1	↑
Spring Mean Maximum Daily Air Temperature	**11.2**	10.7	**13.2**	15.1	16.0	**16.3**	16.5	↑
Summer Mean Maximum Daily Air Temperature	**24.9**	25.3	**27.4**	28.9	30.1	**30.1**	30.2	↑

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Fall Mean Maximum Daily Air Temperature	**14.4**	16.1	**18.2**	19.7	20.5	**20.5**	20.6	↑
Minimum Temperature								
Annual Mean Minimum Daily Air Temperature	**4.3**	5.2	**7.2**	8.9	6.0	**10.7**	15.6	↑
Winter Mean Minimum Daily Air Temperature	**-7.1**	-5.2	**-2.9**	-1.3	-4.2	**-0.4**	3.5	↑
Spring Mean Minimum Daily Air Temperature	**2.0**	1.9	**4.2**	6.0	2.3	**7.9**	13.7	↑
Summer Mean Minimum Daily Air Temperature	**15.2**	15.6	**17.3**	19.0	16.6	**21.7**	27.2	↑
Fall Mean Minimum Daily Air Temperature	**6.7**	8.4	**10.2**	11.7	9.0	**13.3**	17.9	↑
Extreme Heat (days per year)								
Days Above 35˚C	**0.3**	0.6	**3.2**	5.9	8.4	**10.5**	11.9	↑
Days Above 30˚C	**10.4**	11.6	**31.4**	47.3	58.4	**62.2**	65.0	↑
Days Above 25˚C	**53.5**	60.5	**90.5**	111.9	120.4	**121.6**	122.5	↑
Tropical Nights	**9.4**	11.2	**28.4**	46.0	23.1	**79.1**	138.3	↑
Extreme Cold (days per year)								
Days Below -20˚C	**4.2**	0.0	**0.1**	0.3	0.0	**0.0**	0.0	↓
Days Below -15˚C	**12.3**	0.0	**1.8**	4.1	0.0	**1.0**	2.3	↓
Days Below -10˚C	**32.4**	2.8	**10.2**	20.5	0.2	**6.9**	15.9	↓
Days Below -5˚C	**68.0**	18.0	**34.9**	57.6	3.2	**25.5**	52.1	↓

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Days Below 0˚C (Freezing Days)	**125.1**	72.0	**90.7**	116.3	20.2	**65.9**	112.3	↓
Total Precipitation (mm per climate period)								
Total Average Annual Precipitation (mm)	**1080.6**	911.2	**1018.7**	1107.8	902.0	**1012.3**	1094.7	↓
Total Average Winter Precipitation (mm)	**231.0**	225.8	**252.5**	283.1	230.6	**252.1**	277.8	↑
Total Average Spring Precipitation (mm)	**281.1**	248.4	**268.1**	290.3	238.6	**260.6**	287.2	↓
Total Average Summer Precipitation (mm)	**296.6**	212.2	**239.3**	264.1	204.7	**238.0**	274.4	↓
Total Average Fall Precipitation (mm)	**271.2**	204.7	**258.8**	303.1	201.9	**261.6**	312.3	↓
Extreme precipitation								
Max Precipitation in 1 day (mm)	**70.7**	60.4	**61.9**	63.7	67.0	**75.5**	82.7	↑
Max Precipitation in 3 day (mm)	**112.4**	82.2	**92.5**	105.6	88.7	**97.7**	104.7	↓
Extreme Precipitation Days (days/year)	**4.8**	4.5	**5.2**	5.8	5.2	**5.6**	6.1	↑
Annual Simple Daily Intensity Index (SDII) (mm/day)	**5.2**	4.8	**5.2**	5.5	4.8	**5.2**	5.5	–
Winter SDII (mm/day)	**4.2**	4.2	**4.6**	5.0	4.2	**4.6**	4.9	↑

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Spring SDII (mm/day)	**5.6**	5.2	**5.6**	6.0	4.9	**5.4**	5.9	–
Summer SDII (mm/day)	**5.8**	4.4	**5.2**	6.0	4.4	**5.3**	6.2	↓
Fall SDII (mm/day)	**5.3**	4.9	**5.4**	5.8	5.2	**5.7**	6.1	↑
Dry Days (days per year)								
Total Annual Dry Days	**155.3**	163.2	**168.6**	175.6	163.1	**170.5**	179.3	↑
Maximum Total Consecutive Dry Days	**21.3**	15.2	**16.3**	17.6	15.4	**19.3**	24.2	↓
Agricultural Variables								
Growing Degree Days per year	**3584.1**	3754.7	**4368.1**	4863.6	2295.3	**3944.2**	5168.6	↑
Canola Growing Degree Days per year	**2537.2**	2673.4	**3192.8**	3617.7	1348.4	**2803.7**	3890.6	↑
Forage Crops Growing Degree Days per year	**2306.8**	2435.0	**2932.0**	3339.8	1211.6	**2579.9**	3604.3	↑
Corn and Bean Growing Degree Days (days/year)	**1321.9**	1420.5	**1807.6**	2131.2	713.4	**1640.9**	2346.6	↑
Days at Risk of Presence of Pests (days/year)	**594.2**	670.6	**952.6**	1193.3	394.9	**937.0**	1360.7	↑
Growing Season								
Growing Season Start Date (day of year)	**07-May**	2021-04-20	**2021-04-30**	2021-05-12	2021-03-13	**2021-04-12**	2021-05-12	↑
Growing Season End Date (day of year)	**30-Oct**	2021-11-11	**2021-11-21**	2021-11-28	2021-11-17	**2021-11-30**	2021-12-11	↑

Climate Parameters	Baseline Values (1971-2000)	Short-Term (2021-2050)			Long-Term (2051-2080)			Trend
		10th Percentile	**Ensemble Mean**	90th Percentile	10th Percentile	**Ensemble Mean**	90th Percentile	
Growing Season Length (days/year)	**186**	194.8	**205.3**	218.8	189.0	**231.3**	273.00	↑
Freeze-Thaw Cycles and Ice Potential								
Freeze-Thaw Cycles (days/year)	**76.6**	48.4	**58.5**	70.6	10.2	**41.8**	71.3	↓
Ice Potential (days/year)	**19.0**	5.2	**11.6**	19.8	1.6	**9.3**	18.5	↓

Appendix D: Step-by-Step Methodology

Step:1 Data Downloading:

The users will need to select the appropriate dataset to gather daily data for the specific climate period for any geographic area of their interest. Figure D1 shows how to select the appropriate variables and experiment (emission scenario), the data frequency (daily in this case), a grid of the interest, and the version of bias-correction. Here the Raw version was selected and then bias-corrected later based on the station data of the Niagara Region. The drivers and models represent the Global and Regional Climate Models respectively. Once the users hit the search button, the portal will generate 16 files (models) with the option subset files. The subset option will take the users to the horizontal subset option which is demonstrated in Figure D1.

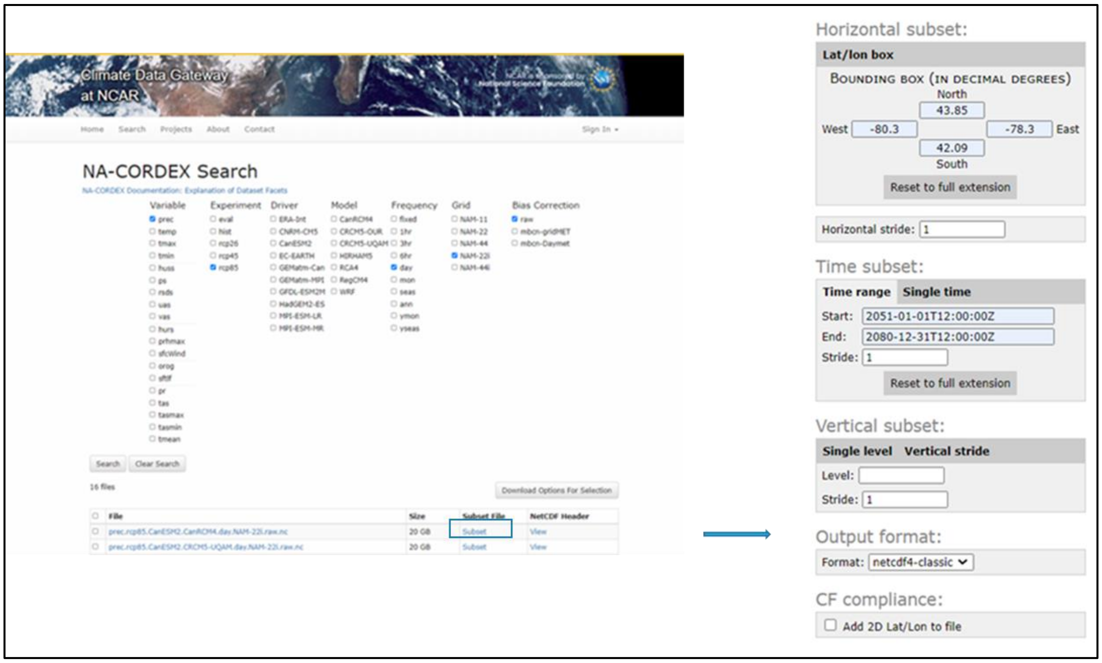


FIGURE D1. A SCREENSHOT OF THE CHECKED BOXES OF THE NA-CORDEX (CLIMATE DATA GATEWAY) PORTAL TO OBTAIN DAILY PRECIPITATION DATA FOR ALL MODEL RUNS FOR THE RCP 8.5 CLIMATE CHANGE SCENARIO.

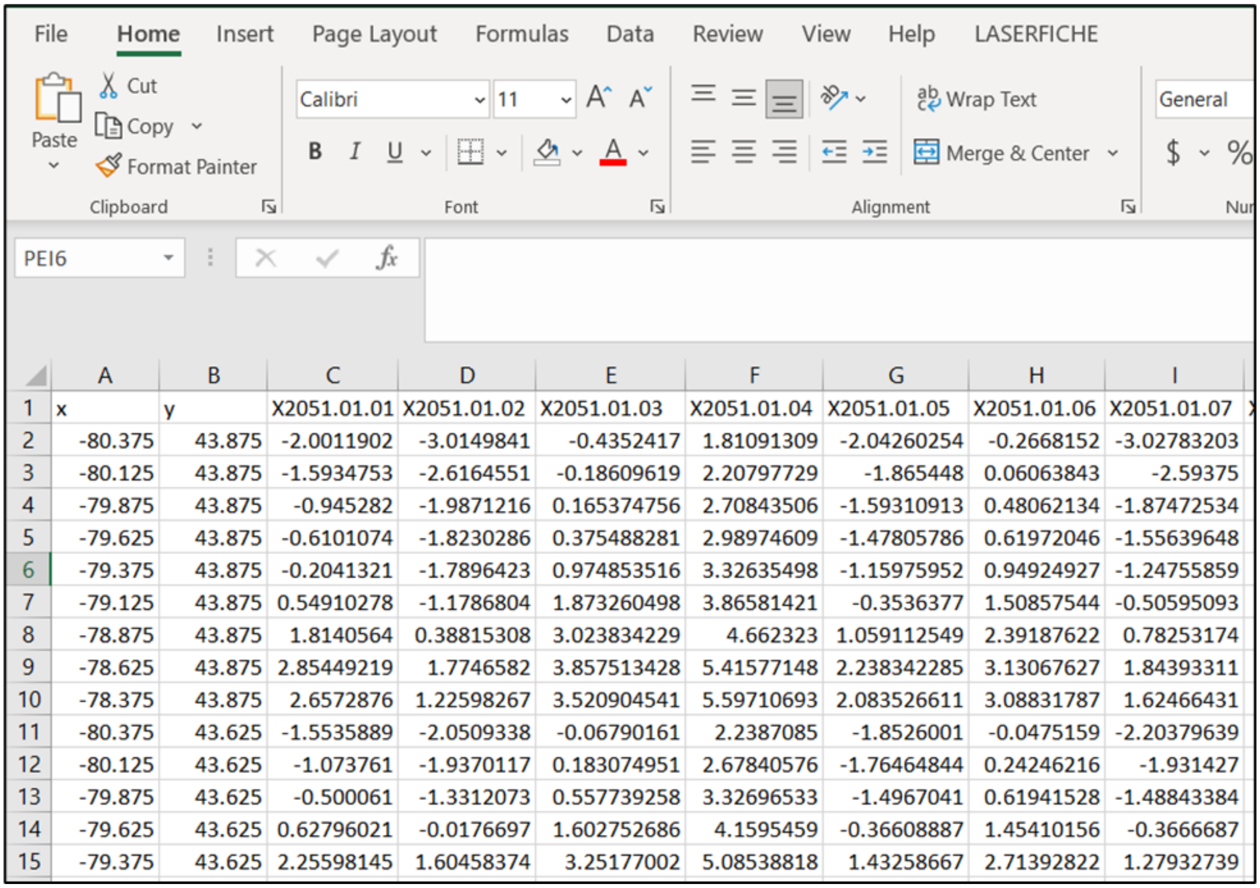
Figure D1 also demonstrates how to get the geospatial data (based on geo-coordinates of the user interest) using the bounding box. The website will ask for specific latitudes and longitudes of the desired subset area (in this case, the project team used the geo-coordinates that apply to the study area). It is to be noted that the selected area is much larger than the desired area to ensure a more robust result. This selection of data was used for each climate period (1971-2000, 2021-2050, and 2051-2080).

The NA-CORDEX portal provides climate data in NetCDF (Network Common Data Format) files, which can store large datasets and many layers of data into one easily downloadable file. The files are interfaced, array-based dataframes used to make large amounts of data available to use in various platforms (e.g., C, Fortran, C++, Java, ArcMap, etc.). Without having specialized software, NetCDF packages can be difficult to interpret. To create accessible data from NetCDF files and have climate variables for each grid cell within and across the area of study, the vector based NetCDF files (e.g., points) were transformed into raster data (e.g., grid cells) using the statistical programming software R. The NetCDF files (with a .nc file extension) were transformed into raster (i.e., images with pixels) by using the raster library in R to organize the data into a date, climate variable, and its corresponding latitude and longitude coordinates. A sample of the code used to transform the file is shown in Figure D2.

```
#Loading the raster package into R:
library(raster)
nc.brick <- brick(file.choose())

#Reading the NetCDF files as raster files (creating grid cell data)
nc.brick
dim(nc.brick)

#Showing the dimensions of your dataframe (e.g., grid number,
latitude and longitude, date)
n = dim(nc.brick)[3]
nc.df <- as.data.frame(nc.brick[[1:n]], xy=T)

#Obtaining the netcdf dataframe to its full dimensions
write.csv(nc.df, file.choose())

#Once the CSV is written, save the dataframe as a comma separated
value to read in Microsoft Excel spreadsheets
```

FIGURE D2: THE INSTRUCTIONS ON HOW TO CONVERT NETCDF DATA INTO A CSV FILE. SOURCE: DELANEY ET AL., 2020.

Once the files are converted into CSV files, the output looks similar to Figure D3. Longitude data is found under the "x" column, and latitudes are under the "y" column. The following columns are titled by their dates. For example, "X2051.01.01" represents January 1st of 2051. Each CSV file represents a specific climate parameter and a climate model run (out of the 16 model runs in the NA-CORDEX ensemble) and has daily data for each grid cell.



	A	B	C	D	E	F	G	H	I
1	x	y	X2051.01.01	X2051.01.02	X2051.01.03	X2051.01.04	X2051.01.05	X2051.01.06	X2051.01.07
2	-80.375	43.875	-2.0011902	-3.0149841	-0.4352417	1.81091309	-2.04260254	-0.2668152	-3.02783203
3	-80.125	43.875	-1.5934753	-2.6164551	-0.18609619	2.20797729	-1.865448	0.06063843	-2.59375
4	-79.875	43.875	-0.945282	-1.9871216	0.165374756	2.70843506	-1.59310913	0.48062134	-1.87472534
5	-79.625	43.875	-0.6101074	-1.8230286	0.375488281	2.98974609	-1.47805786	0.61972046	-1.55639648
6	-79.375	43.875	-0.2041321	-1.7896423	0.974853516	3.32635498	-1.15975952	0.94924927	-1.24755859
7	-79.125	43.875	0.54910278	-1.1786804	1.873260498	3.86581421	-0.3536377	1.50857544	-0.50595093
8	-78.875	43.875	1.8140564	0.38815308	3.023834229	4.662323	1.059112549	2.39187622	0.78253174
9	-78.625	43.875	2.85449219	1.7746582	3.857513428	5.41577148	2.238342285	3.13067627	1.84393311
10	-78.375	43.875	2.6572876	1.22598267	3.520904541	5.59710693	2.083526611	3.08831787	1.62466431
11	-80.375	43.625	-1.5535889	-2.0509338	-0.06790161	2.2387085	-1.8526001	-0.0475159	-2.20379639
12	-80.125	43.625	-1.073761	-1.9370117	0.183074951	2.67840576	-1.76464844	0.24246216	-1.931427
13	-79.875	43.625	-0.500061	-1.3312073	0.557739258	3.32696533	-1.4967041	0.61941528	-1.48843384
14	-79.625	43.625	0.62796021	-0.0176697	1.602752686	4.1595459	-0.36608887	1.45410156	-0.3666687
15	-79.375	43.625	2.25598145	1.60458374	3.25177002	5.08538818	1.43258667	2.71392822	1.27932739

Figure D3: A screenshot of raw daily temperature data outputs of the NA-CORDEX data

Step 2: Bias Correction

To analyze baseline climate data, a reference period, 1971-2000, was established to identify climate trends. This reference period and data were selected and downloaded from Environment and Climate Change Canada's (ECCC) climate normal website. Climate normal are generally used for two purposes, the first involves benchmarking current observations to allow for comparison (WMO, 2011), while the second allows for users to develop predictions for the climate impacts that are expected within the jurisdiction. To reduce the effects of short-term variability created by weather conditions, a general best practice in climate modeling is to use a 30-year reference period (WMO, 2011). The general practice of getting baseline climate information is to obtain observed data from weather stations (Charron, 2016). For this report, a total of 12 representative climate stations were used to examine baseline climate data within Niagara Region and its surrounding vicinity. A list of climate stations can be found in Table 5 and the locations are provided in the map as shown in Figure 9.

To create relevant reference baseline climate data for mean, maximum, and minimum temperature (degrees Celsius) and annual precipitation (millimeters per day), all stations were averaged together to provide single representative coverage of observation values for the entire Niagara Region. Based on best practice, it was agreed upon that taking the average of these climate stations would eliminate any biases or skewed data for variables like topography, surrounding vegetation, human error, and other geographic characteristics (Delaney et al., 2020). Taking the average values of these stations set a baseline period for the Niagara Region which is robust. Therefore, the annual average of daily air temperature, daily mean maximum, and minimum temperatures, mean annual precipitation was calculated from the weather stations within Niagara Region.

Once the climate averages for each climate parameter were calculated from ECCC's climate normal, the projected baseline data (i.e., the climate models' projected baseline conditions) from the NA-CORDEX model ensemble were compared against the observed averages over Niagara Region for the 30 years of 1971- 2000. The subtracted differences between the projected baseline values and the actual observed values were then calculated. By knowing this difference, the same difference can be added/subtracted onto future projections to ensure that the projections are as accurate as possible and represent the local features that may not have been captured in the models themselves. In other words, the future climate change projections from the NA-CORDEX portal were bias-corrected for Niagara Region. Below is an example of how future climate change projections being bias corrected from observed temperature (TOBS):

Averaged Observed Temperature in Durham Region	**Modeled Historical Temperature**	**Difference between modeled and observed values:**
$T_{OBS} = 5.5^{\circ}C$	$T_{RCM\ for\ Baseline} = 8.5^{\circ}C$	$\Delta T = T_{OBS} - T_{RCM\ for\ Baseline}$ $\Delta T = -3.0^{\circ}C$

Modeled Future Temperature Data for the RCP 8.5 Scenario for 2041-2070	**Bias-Corrected Value for the Modeled Future Temperature value**
$T_{RCM\ RCP\ 8.5} = 15.5^{\circ}C$	$T_{BIAS} = T_{RCM\ RCP\ 8.5} + \Delta T$ $T_{BIAS} = (15.5\ ^{\circ}C) + (-3^{\circ}C)$ $T_{BIAS} = 12.5^{\circ}C$

FIGURE D4: THE INSTRUCTIONS OF HOW TO CONDUCT A BIAS-CORRECTION. SOURCE: DELANEY ET AL., 2020.

This was applied to all parameters (mean, maximum, and minimum temperature and mean precipitation) for all grid points of NA-CORDEX modeled data, for all model runs, for all future climate periods (1971-2000, 2021-2050, 2051-2080) under each climate scenario (RCP 4.5 and RCP 8.5). After bias correction, each data set was transposed, and the mean of all grid cells were taken to calculate the region-wide average for each parameter.

Bias correction was undertaken separately for regional and sub-regional analysis using different model grid cells and observed station data as shown in Figure 7. Bias correction for regional analysis includes all grid cells and climate stations shown in Figure 7. The values calculated for the climate parameters are averaged over the region extended beyond Niagara. In contrast, sub-regional analysis uses a smaller extent and splits Niagara into northern and southern regions. Climate stations located within the northern and southern boundaries are used to bias correct model grid cell data within the northern and southern boundaries, respectively.

Step 3: Choosing Climate Parameters

The study aims to provide valuable climate data within Niagara Region under future climate change and a step-by-step methodology that can be replicated by other municipalities within Niagara Region or beyond. Therefore, it is very important that any climate parameters provided for this study are clearly defined (A full list of climate parameters and the definition of the parameters is provided in Table 1. At the most basic level, climate parameters include measures of precipitation and temperature, including total annual precipitation and the annual mean, maximum and minimum temperature. However, it is also important to determine sub-annual indices of climate, ones that capture seasonal changes and extremes of precipitation and temperature, which are not captured by annual measurements. Other parameters of interest, such as Growing Degree Days (GDD), known as agricultural variables where the minimum temperature values act as thresholds (for example canola has a minimum threshold of 4°C).

Step 4: Analysis

Once all the NA-CORDEX data was bias corrected to Niagara Region, additional climate parameters were calculated from the basic climate parameters (e.g., daily mean, maximum, and minimum air temperatures, and total precipitation). As noted earlier, data from each model, for every basic climate parameter, was transposed, mean of all grid cells were taken, and then converted to time series data with two variables (one is a date and another one is the relevant parameter, for example, daily air temperature, for 30 years period). The date column was further formatted to calculate region-wide annual and seasonal values (Figure D5). When time-series data is ready for every basic parameter across all climate periods and all climate scenarios, the additional parameters were calculated using the Excel basic functions such as SUM, COUNTIF, AVERAGE, AVERAGEIF, MAX, MIN, FREQUENCY.

	A	B	C	D
1	Date	Date formatted	Month	Temperature
2	2051.01.01	=DATE(LEFT(A2, 4), MID(A2, 6, 2), RIGHT(A2, 2))		
3	2051.01.02	DATE(**year**, month, day)		2.700551152
4	2051.01.03	2051-01-03	Jan	1.496831907
5	2051.01.04	2051-01-04	Jan	4.457571043
6	2051.01.05	2051-01-05	Jan	2.13666896
7	2051.01.06	2051-01-06	Jan	4.30624285
8	2051.01.07	2051-01-07	Jan	1.23024857
9	2051.01.08	2051-01-08	Jan	3.021223929
10	2051.01.09	2051-01-09	Jan	7.05869019
11	2051.01.10	2051-01-10	Jan	5.092165854
12	2051.01.11	2051-01-11	Jan	-1.89776207
13	2051.01.12	2051-01-12	Jan	2.451944364
14	2051.01.13	2051-01-13	Jan	2.205725153
15	2051.01.14	2051-01-14	Jan	-0.05244593
16	2051.01.15	2051-01-15	Jan	0.464778701
17	2051.01.16	2051-01-16	Jan	-1.07644376
18	2051.01.17	2051-01-17	Jan	-0.75675433
19	2051.01.18	2051-01-18	Jan	0.951900284
20	2051.01.19	2051-01-19	Jan	6.517528335
21	2051.01.20	2051-01-20	Jan	4.19378176
22	2051.01.21	2051-01-21	Jan	-0.51640933
23	2051.01.22	2051-01-22	Jan	5.780487286
24	2051.01.23	2051-01-23	Jan	3.796248343
25	2051.01.24	2051-01-24	Jan	3.28250187
26	2051.01.25	2051-01-25	Jan	6.068739798
27	2051.01.26	2051-01-26	Jan	6.762836258

Biascorrected | Transpose | **Analysis**

FIGURE D5: A SCREENSHOT OF TIME SERIES DATA

Since the NA-CORDEX data already included mean, maximum, and minimum temperatures, calculating the annual and seasonal averages for future climate periods was quite straightforward. It mostly uses Excel AVERAGE function to find the region-wide annual average and AVERAGEIF function to calculate the seasonal averages.

Extreme heat and cold parameters were also calculated quite simply, as these parameters are threshold-based climate parameters (e.g., days above 30˚C, days below -20˚C). For each climate model, the project team calculated the number of days where maximum temperatures were above 35˚C, 30˚C, 25˚C, and where the minimum temperature was higher than 20˚C for tropical nights. Similarly, for cold temperatures, the minimum daily temperatures were used to calculate the number of days below -20˚C, - 15˚C, -10˚C, -5 ˚C, and 0 ˚C. The project team used the “Count If” function statements in Excel to query the number of days that exceeded each of these thresholds. For example, to calculate for days above 30˚C, the following was typed into Microsoft Excel:

= COUNTIF (range, “>30”)

Annual amounts of precipitation were calculated by taking the average amount of daily precipitation for 30 years and then dividing them by 30 for the annual average.

= SUM (range)/30

Similarly, the seasonal amounts of precipitation were calculated by taking the average amount of daily precipitation for the respective months that represent each season. For example:

• Winter represents December, January, and February (D-J-F),

• Spring represents March, April, and May (M-A-M),

• Summer includes June, July, and august (J-J-A), and

• Fall includes September, October, and November (S-O-N).

To calculate extreme precipitation in Niagara Region, the project team calculated the maximum amount of precipitation falling in one and three days, the amount of "extreme precipitation days", where daily values of precipitation exceeded 25 mm, the annual and seasonal simple daily intensity index (SDII), and the 95th and 99th percentiles of precipitation.

To calculate the maximum amount of precipitation falling in one day, the project team used the "MAX" function in Microsoft Excel. Therefore, for 30 years of data for each climate period, the maximum amount of precipitation was recorded. Here is the sample of the Excel formula:

=Max(range)

To calculate the maximum precipitation falling in three days, a rolling sum was applied in Excel. Therefore, for every three days of the year, a value was produced to provide a total amount of precipitation.

To calculate the extreme precipitation days, the project team conducted a similar process to how the temperature threshold-based parameters were calculated. Therefore, the "Count If" function in Microsoft Excel was used to count the number of days where precipitation exceeded 25 mm for the entire climate period, which *is for 30 years. The result is then divided by 30 to get the annual extreme precipitation days.*

= COUNTIF (range, ">25")/30

The annual and seasonal simple daily intensity index (SDII) is a measurement of how much precipitation occurs in one day. The raw NA-CORDEX data provides SDII for each day of the year; therefore, this calculation was quite simple. Annual averages of SDII were calculated for each climate period and model. Seasonal averages were also calculated based on the months defined earlier (e.g., D-J-F, M-A-M, J-J-A, and S-O-N).

The 95th and 99th percentiles of precipitation are defined as the amount of annual precipitation for events (e.g., any day that had more than 0.2 mm) in the top 5% and 1% of precipitation events during a period compared to the baseline, respectively. Therefore the 95th and 99th percentiles represent the fraction of all precipitation events in millimeters above the 95th and 99th percentiles in the baseline period of 1971-2000. As an example, the total amount of precipitation for the baseline period was 952.4 mm, and the top daily 5% of events (i.e., the 95th percentile) produced about 36.11 mm of the total amount of precipitation. To calculate this, there is a function in Excel, "Percentil.Exc" that was used. Therefore, the following formula was used:

=PERCENTILE.EXC(A1:AX, k)

where "X" is the last row in the column and "A" is where you have entered data, and "k" is the desired percentile value. It should be noted that the percentile value must be between zero and one, therefore, to find the 95th percentile, someone would use "0.95" as k value.

To examine the drought and agricultural conditions in Niagara Region, the total annual number of dry days, the annual maximum total amount of consecutive dry days, the growing season start and end dates, the growing season lengths, as well as growing degree days (GDDs) for four different variables were calculated. Dry days are defined as days where daily precipitation values are less than 0.2 mm. To calculate the number of dry days for 30 years (one climate period) the project team used the “Count If” function in Excel to count the number of days where precipitation was less than 0.2 mm. The result is then divided by 30 to get the annual average.

= COUNTIF (range, "<0.2")/30

Growing Degree Days (GDDs) are defined as the number of days where a certain crop can grow. For this study, GDDs were calculated for days above 0˚C, 4 ˚C (where canola can grow), 5˚C (where forage crops can grow), 10˚C (where corn and beans can grow), and 15˚C (where there is a risk of pests). The following equation represents how GDDs are calculated (base temperatures were replaced with the temperature thresholds for the specific types of crops listed earlier):

= [(max daily temp + min daily temp)/2] – base temp

Freeze-thaw cycles are defined as the number of days where the daily minimum temperature is equal to or below -1˚C and the maximum temperature is above 0˚C. Therefore, the project team used the “IF” function in Excel, to note a “1” when maximum temperature above or below -1˚C and used another “IF” statement to determine the minimum temperatures above 0. When there were two “1s” for both criteria, an equation was created to note a “FREEZE” cycle. Then the sum of the number of “FREEZE”s was taken to determine the total number of freeze-thaw cycles. This was calculated for 30 years, and then the annual average was calculated by dividing the result by 30.

A very similar calculation was taken to determine the number of ice potential days. This number of ice potential days (e.g., days where we can expect to see rain freezing to ice on the ground) is defined by the number of days where the minimum temperature is greater than -2˚C and maximum temperature is under 2˚C.

When the calculation for each parameter was completed for each model, a summary table was created by populating 16 model values in Excel file for each parameter. Figure D6 is an example of the summary table for precipitation for the climate period 2051-80. To obtain an ensemble average, the project team took the average of all models for each climate parameter for each climate period.

Year51-80	CanESM2.	CanESM2.	CanESM2.	CNRM-CN	GEMatm-(	GEMatm-I	GFDL-ESM	GFDL-ESM	GFDL-ESM	HadGEM2	HadGEM2	MPI-ESM-	MPI-ESM-	MPI-ESM-	MPI-ESM-	MPI-ESM-
Max Precipitation in 1 day (mm)	84.70224	71.80891	58.90466	85.2227	82.59466	72.21466	72.66035	68.53777	69.33747	76.12403	60.97583	101.1599	64.26872	93.59733	65.95682	121.172
Max Precipitation in 3 day (mm)	136.5091	90.42465	88.79235	103.4302	133.9467	134.2719	100.0846	109.2627	123.3015	162.4665	138.6588	129.048	114.7092	112.9586	99.26345	134.4688
Extreme Precipitation Days (days/year)	5.5	6.933333	6.866667	6.166667	8.466667	6.966667	7.6	6.466667	6.166667	6.766667	9.566667	7.633333	7.466667	6.266667	6.433333	7.566667
Annual Simple Daily Intensity Index (SDII)	4.779452	5.560382	5.552812	5.369455	6.163052	5.937065	5.882353	5.51952	5.150125	5.674309	6.728651	6.016731	5.943488	5.532636	5.392065	5.950602
Winter SDII (mm/day)	4.5627	5.188987	5.30484	3.969447	5.098812	5.290155	4.753488	5.030769	4.04447	4.927121	4.996155	4.329821	4.810529	4.664495	3.884796	4.593744
Spring SDII (mm/day)	5.864032	6.646338	6.515689	5.68432	7.213617	6.447328	5.896775	5.729468	5.493895	5.99175	6.505024	6.669544	6.868748	6.240955	6.035501	6.559268
Summer SDII (mm/day)	3.913109	4.654537	4.882289	6.342428	6.184113	5.935991	6.929889	5.736939	6.055221	5.829715	8.053492	7.369833	6.494669	5.996569	6.394891	6.827456
Fall SDII (mm/day)	4.825187	5.790057	5.493774	5.778685	6.372006	6.208122	6.300379	5.590129	5.238581	6.028683	6.434525	6.138788	5.850001	5.192252	5.340843	6.138579
Total Annual dry days	173.8333	162.1	160.7333	147.4	155.2	155.9667	161.4333	160.2333	129.6	150.0333	165.9	153.3333	153.3	160.1333	151.1667	150.6
Maximum Total Consecutive Dry Days	23	17	23	17	14	20	15	19	14	24	19	14	16	18	14	23
Total Annual Prec	913.6719	1128.202	1137.726	1173.457	1296.246	1242.628	1197.451	1134.102	1212.34	1191.227	1341.469	1275.146	1259.821	1134.928	1153.003	1277.396
Winter total avg	244.7128	307.188	320.0587	248.752	312.7271	322.6995	285.2093	261.9354	282.8432	275.2618	203.0104	269.1705	295.2061	245.8189	230.1094	289.4059
Spring total avg	293.2016	334.3108	330.3454	271.7105	368.1349	325.3752	293.4629	312.065	334.9445	331.5435	311.8075	333.6995	352.5957	342.8365	313.0413	325.121
Summer total avg	199.9598	221.7111	226.3755	323.2524	286.3244	279.3873	306.0701	276.5205	349.3862	316.7478	565.6236	359.4022	315.4244	298.4293	371.1169	357.9863
Fall total avg	175.7976	264.9916	257.4749	326.1105	325.8219	315.1657	312.7088	279.6928	245.1656	267.6735	261.0272	312.8736	296.595	247.8435	238.7357	304.8828

FIGURE D6: SUMMARY TABLE FOR PRECIPITATION (2051-80)

A similar process was undertaken to calculate the 10th and 90th percentiles for all the model runs for each parameter, using the PERCENTILE function in Excel. To calculate the percentiles, Excel asks the user to input (array, k). Therefore, to calculate the 10th and 90th percentile for each parameter, the respective 16 models were selected as an array, 0.1 (10th percentile) and 0.9 (90th percentile) was put as k values. For additional details please consult Delaney et al., (2020).

Appendix E: Rapid Comparison with the Climate Projections in the City of St. Catharines Corporate Climate Change Adaptation Plan

This section presents a rapid comparison between the climate projections developed by TRCA and those found in the City of St. Catharines Corporate Climate Change Adaptation Plan ("SCCCAP"; 2021). The climate projections used in the SCCCAP were retrieved from the Climate Atlas of Canada and Climatedata.ca and are detailed in Appendix B of the SCCCAP. Table E1 provides an overview of the data sources and approaches used to generate downscaled climate projections for Niagara Region and the city of St. Catharines for the Climate Modeling Project and SCCCAP, respectively.

Both baseline periods used by TRCA and the SCCCAP cover a 30-year climate normal period, although TRCA's baseline period starts in 1971 while the SCCCAP starts in 1976. The key difference found in the future periods selected is that TRCA applies a 30-year climate normal period for future projections while the SCCCAP appears to only cover two years in the future (i.e., 2050 and 2100). TRCA has also developed climate projections under RCP 4.5 and 8.5 while SCCCAP focuses only on RCP 8.5. Since there is rough alignment between the mid-century projections, the late century projections are not included in this comparison (see Table E1). Hence, only the baseline values and mid-century projections under the RCP 8.5 scenario are compared.

Another key difference is in the type of downscaling method used. TRCA's climate projections use available dynamically downscaled climate data from NA-CORDEX (the North American component of the Coordinated Regional Downscaling Experiment), which has a resolution of approximately 25 km by 25 km. Meanwhile, data from Climate Atlas of Canada and Climatedata.ca have been statistically downscaled from Global Climate Models (GCMs) and have finer resolutions of approximately 10 km by 10 km and 10 km by 6 km, respectively.

TABLE E1. OVERVIEW OF THE DATA SOURCES AND APPROACHES USED TO DERIVE THE CLIMATE PROJECTIONS DEVELOPED BY TRCA AND THOSE FOUND IN THE CITY OF ST. CATHARINES CORPORATE CLIMATE CHANGE ADAPTATION PLAN (SCCCAP)

	TRCA	SCCCAP
Data Source(s)	NA-CORDEX (the North American component of the Coordinated al Downscaling Experiment)	Climatedata.ca*
Baseline Period	1971-2000	1976-2005
Future Periods	2021-2050 and 2051-2080	2050 (1 year) and 2100 (1 year)
Baseline Data	Station data from ECCC	Station data from ECCC's National Climate Data Archive
Climate Stations	1. Fort Erie 2. Niagara Falls NPCSH 3. Niagara Falls 4. Port Colborne 5. Port Dalhousie 6. Ridgeville 7. St. Catharines A 8. St. Catharines Power Glen 9. Vineland Rittenhouse 10. Vineland Station 11. Welland 12. Hamilton A	It is unclear which stations or how many contributed to St. Catharines projections

	TRCA	SCCCAP
GCMs or RCMs?	Ensemble of RCMs	Ensemble of GCMs from CMIP5 (the Coupled Model Intercomparison Project)
Number of Climate Models	16 climate models	24 climate models
Climate Scenarios	RCP 4.5 and 8.5	RCP 8.5
Bias Correction Method	Delta approach where delta = difference between observed and modelled baseline values; one delta is produced for each model for all climate variables	Statistical downscaling (Bias Correction with Constructed Analogues and Quantile mapping, Version 2; BCCAQv2)
Output Scale	~25 km x 25 km	~10 km x 6 km
Consideration for the influence of the Great Lakes	Part of the model selection criteria so all models include some representation of the Great Lakes	n/a

*Climatedata.ca data was obtained for average seasonal temperature, and average seasonal precipitation, dry days, freeze-thaw cycles, frost days, date of last spring frost, and date of first fall frost.

Given the differences in the two approaches, a high-level comparison was conducted to determine similarities and differences between the projections for comparable climate variables. A total of 20 climate variables were included for comparison, including temperature, precipitation, agricultural variables, and freeze-thaw cycles. Table E2 presents a comparison of the baseline climate data used in the Niagara Region Climate Modeling Project and SCCCAP. While the baseline periods used by TRCA and the SCCCAP are slightly different, there is still significant overlap between the 30-year periods, hence the two sets of baseline climate data can be expected to be similar. Percentage differences were calculated for each of the climate variables (based on values rounded to the nearest whole number to align with the SCCCAP). When percentage differences are less than or equal to 10 percent, the baseline climate data is considered similar.

TABLE E2. COMPARING BASELINE VALUES USED BY TRCA (1971-2000) AND THE CITY OF ST. CATHARINES CORPORATE CLIMATE CHANGE ADAPTATION PLAN (1976-2005)

Variable	TRCA (1971-2000)	SCCAP (1976-2005)	Percentage difference (based on rounded numbers)	Comparison Description ("Similar" = ≤10% difference)
Temperature				
Mean Annual Air Temperature	8.7 → 9	9	0%	Similar
Mean Winter Temperature	-2.8 → -3	-2	40%	Different; SCCAP is greater
Mean Spring Temperature	6.6 → 7	7	0%	Similar
Mean Summer Temperature	20.0 → 20	21	5%	Similar
Mean Fall Temperature	10.5 → 11	11	0%	Similar
Mean Annual Maximum Daily Air Temperature	12.9 → 13	14	7%	Similar; SCCAP is a bit greater
Mean Annual Minimum Daily Air Temperature	4.3 → 4	5	22%	Different; SCCAP is greater
Days over 30˚C	10.4 → 10	13	26%	Different; SCCAP is greater
Tropical Nights (over 20˚C)	9.4 → 9	12	25%	Different; SCCAP is greater
Days below -15˚C	12.3 → 12	6	67%	Different; TRCA is greater
Precipitation				
Mean Annual Total Precipitation	1080.6 → 1081	855	23%	Different; TRCA is greater
Mean Winter Total Precipitation	231.0 → 231	189	20%	Different; TRCA is greater

Variable	TRCA (1971-2000)	SCCAP (1976-2005)	Percentage difference (based on rounded numbers)	Comparison Description (“Similar” = ≤10% difference)
Mean Spring Total Precipitation	281.1 → 281	211	28%	Different; TRCA is greater
Mean Summer Total Precipitation	296.6 → 297	208	35%	Different; TRCA is greater
Mean Fall Total Precipitation	271.2 → 271	216	23%	Different; TRCA is greater
Maximum 1-day Total Precipitation	70.7 → 71	38	61%	Different; TRCA is greater
Other				
Growing degree days 0˚C	3584.1 → 3584	3742	4%	Similar; SCCAP is slightly greater
Growing degree days 5˚C (Forage GDDs)	2306.8 → 2307	2456	6%	Similar; SCCAP is slightly greater
Growing degree days 10˚C (Corn and Bean GDDs)	1321.9 → 1322	1439	8%	Similar; SCCAP is slightly greater
Freeze-thaw cycles	76.6 → 77	57	30%	Different; TRCA is greater

Based on this analysis, 8 variables (40%) were found to be similar while 12 variables (60%) were found to be different. Under the temperature category, baseline mean annual air temperature and most of the mean seasonal temperatures are similar except for mean winter temperature. Differences were also found in the mean annual minimum daily air temperature, the extreme heat variables (days over 30˚C and tropical nights), and the extreme cold variable (days below -15˚C). Notably, SCCCAP’s baseline average for tropical nights was significantly less than TRCA’s baseline value.

Under the precipitation category, all values were found to be different, ranging from a 20% difference (for mean total winter precipitation) to 61% difference (for maximum 1-day total precipitation). Finally, for the other climate variables, the agricultural variables related to growing degree days were found to be similar while the baseline average for freeze-thaw cycles was found to be different.

Table E3 presents a comparison of the climate projections to 2050 as developed by TRCA and in the SCCCAP. Given the different approaches used to develop the projections and the different time periods used (i.e. 2021-2050 versus 2050), it can be expected that the future projections can vary. As such, instead of percentage difference, similarity was determined based on whether the SCCCAP’s 2050 average falls within TRCA’s projected 10th and 90th percentile values.

TABLE E3. COMPARING CLIMATE PROJECTIONS TO 2050 DEVELOPED BY TRCA (2021-2050) AND THOSE FOUND IN THE CITY OF ST. CATHARINES CORPORATE CLIMATE CHANGE ADAPTATION PLAN (2050)

Variable	TRCA (2021-2050)			SCCAP (2050)	Comparison Description (“S m ar” = wh th r TRCA percentiles capture the SCCAP mean)
	10th Percentile	Mean	90th Percentile	Mean	
Temperature					
Mean Annual Air Temperature	8.9	10.7	13.0	9	Similar; closer to TRCA 10th percentile
Mean Winter Temperature	-3.5	-0.4	1.9	0	Similar; between TRCA 10th percentile and mean
Mean Spring Temperature	6.4	8.2	10.4	9	Similar; between TRCA mean and 90th percentile

Variable	TRCA (2021-2050)			SCCAP (2050)	Comparison Description (“S m ar” = wh th r TRCA percentiles capture the SCCAP mean)
	10th Percentile	Mean	90th Percentile	Mean	
Mean Summer Temperature	20.2	22.0	24.2	23	Similar; between TRCA mean and 90th percentile
Mean Fall Temperature	10.9	12.7	15.4	14	Similar; between TRCA mean and 90th percentile
Mean Annual Maximum Daily Air Temperature	12.7	14.9	17.4	17	Similar; closer to TRCA 90th percentile
Mean Annual Minimum Daily Air Temperature	4.2	6.2	8.5	8	Similar; closer to TRCA 90th percentile
Days over 30˚C	4.7	23.9	50.8	50	Similar; closer to TRCA 90th percentile
Tropical Nights (over 20˚C)	9.4	24.5	46.2	20	Similar; closer to TRCA 10th percentile
Days below -15˚C	0.4	6.5	12.5	0	Similar; closer to TRCA 10th percentile
Precipitation					
Mean Annual Total Precipitation	1086.0	1135.0	1209.1	1018	Different; less than TRCA 10th percentile
Mean Winter Total Precipitation	214.7	253.0	288.1	208	Different; less than TRCA 10th percentile
Mean Spring Total Precipitation	256.0	296.2	324.2	233	Different; less than TRCA 10th percentile
Mean Summer Total Precipitation	246.8	305.0	340.8	210	Different; less than TRCA 10th percentile
Mean Fall Total Precipitation	244.5	280.8	317.5	223	Different; less than TRCA 10th percentile
Maximum 1-day Total Precipitation	60.1	72.7	94.2	39	Different; less than TRCA 10th percentile
Other					
Growing degree days 0˚C	3468.6	4104.0	4853.2	4585	Similar; between TRCA mean and 90th percentile
Growing degree days 5˚C (Forage GDDs)	2769.4	2769.4	3356.6	3174	Similar; between TRCA mean and 90th percentile
Growing degree days 10˚C (Corn and Bean GDDs)	1302.2	1747.0	2249.4	2051	Similar; between TRCA mean and 90th percentile
Freeze-thaw cycles	54.0	67.4	79.0	46.5	Different; less than TRCA 10th percentile

Based on this analysis, mid-century projections for 12 variables (60%) were found to be similar while 8 variables (40%) were found to be different. Under the temperature category, mid-century projections for all temperature-related variables were found to be similar except for tropical nights. As noted above, this difference was also observed in the baseline climate data used by TRCA and the SCCCAP. Among the similar temperature projections, most of the SCCCAP's projections either fall between the mean and 90th percentile or lie closer to the 90th percentile, suggesting that the SCCCAP's temperature projections tend to align more with the higher end of the spectrum.

Under the precipitation category, all mid-century projections were found to be different and all the SCCCAP's projections fall below TRCA's projected 10th percentile values. This difference was also observed in the baseline precipitation data used by TRCA and the SCCCAP and the baseline precipitation data used by TRCA was greater than the SCCCAP. Another potential contributing factor to this difference is the uncertainty in projecting future precipitation.

For the other climate variables, the mid-century projections for the agricultural variables were found to be similar and fall between TRCA's projected mean and 90th percentile. Meanwhile, the baseline average for freeze-thaw cycles was found to be different and below TRCA's projected 10th percentile.

Overall, despite the differences in approaches used to develop the climate projections, most of the projections to 2050 were still similar. Differences were observed in the baseline values. Given a lack of details available regarding the climate station data used by Climate Atlas of Canada and Climatedata.ca to generate the baseline for the city of St. Catharines, the baseline data used by TRCA and the SCCCAP could not be compared. Differences in the baseline climate data could be a result of using different climate stations for the analysis.

Appendix F: Background on Climate Models and Future Climate data

The following section provides a summary of the common approaches to climate modeling, as well as key terminologies used throughout this report. This section discusses the differences between Global Climate Models and Regional Climate Models, various downscaling methods, ensemble approaches, and the different climate change scenarios used in climate modeling.

Appendix F1. Global Climate Models (GCMs) and Regional Climate Models (RCMs)

Climate models are mathematical equations written in computer code and solved by high-performance computers (supercomputers) representing the interactions of parameters within the global climate system. Different models representing mass and energy exchange between land, water, and the atmosphere are coupled to form climate models.

Global Climate Models (GCM) can represent the underlying physics of climate-related processes to provide sub-continental patterns of climate parameters (e.g., temperature and precipitation) with reasonable accuracy for resolutions greater than 100 km grid cells (Rummukainen, 2010). For example, even cloud cover at the scale of the GCM grid box can be defined by the relationship drawn from observed cloud profiles for given temperatures and humidity values. Randall et al., (2007) concluded that by the 4th Assessment Report of the IPCC, coupled Global Climate Models provide reliable climate projections at continental scales. Their confidence is based on the fact that climate models are founded on well-established and proven physical laws (e.g., conservation of mass, energy, and momentum) and equations. Secondly, models have simulated crucial aspects of current and baseline climate (Randall et al., 2007). Many multi-model intercomparisons have taken place in the past decade, proving the increasing skill level of models in representing the large-scale distribution of atmospheric temperature, precipitation, radiation, wind, oceanic temperatures, currents, and sea ice cover (Randall et al., 2007). Each of these processes are modeled in each defined grid cell (Figure 7). However, their limited native resolution cannot model critical regional and local climate aspects (e.g., locally occurring intensive precipitation).

Regional Climate Models (RCMs) compliment global climate models. Their higher resolution (25-50 km grid cells) allows the inclusion of landscape features like mountain ranges, lakes, and other surface features that can impact local/regional precipitation, temperature, and winds within the model (Wilby & Wigley, 1997). As a result, RCMs are more acceptable for supporting climate impact studies, policy, and adaptation planning at the regional scale (Rummukainen, 2010). RCMs use outputs of nearby GCM grid cells to set their “boundary conditions,” which are typically temperature, moisture, seas surface temperature, sea ice, and circulation(winds)(Rummukainen, 2010). Since different GCMs would provide varying boundary conditions altering the final RCM projections, it is now standard practice (termed the “ensemble approach”) to combine multiple GCM outputs with multiple RCM models to build confidence in the range of projections. The nesting structure (GCM-RCM) is needed to model the global impact on regional climate.

Despite its limitations, RCMs still have the potential to improve. There are still some climate processes that RCMs cannot resolve at their current resolution such as the evolution of cloud droplets into rain or snowfall, the interaction of aerosols with clouds, and others (Mülmenstädt & Wilcox, 2021; Rummukainen, 2010); some of these processes are approximated by parameterization. Furthermore, an RCM developed for a region is limited in its application to other areas. For example, an RCM developed for a tropical region may not be suitable for polar regions. This study uses RCMs explicitly developed for North American regions from the NA-CORDEX portal. On the horizon, the coupling of RCMs and regional climate system models show that there is promise for further advancements in accounting for regional biogeophysical and chemical components (e.g., vegetation, carbon cycle, atmospheric chemistry, etc.,).

Appendix F2. Downscaling Methods

A primary necessity of climate analysis is to see the climate’s impact on the physical environments affecting human systems. GCMs model climate-related land, water, and atmospheric processes at the planetary scale. They provide reasonable accuracies at the global to continental scales (several degrees of latitude and longitude) (Hewitson & Crane, 1996). When considering context-sensitive societal concerns, regional (100 km or less) impacts need to be analyzed, but the accuracy of GCMs decrease at the finer resolutions. Downscaling refers to methods that derive local to regional scale (10-100 km) climate information from coarser (>100 km) atmospheric data or global climate model outputs (Wilby & Fowler, 2011). Currently, there are two categories of approaches to meet the needs of higher spatial and temporal resolution of climate models for regional impact analysis:

1) ***empirical*** techniques (e.g. regression models) that calculate outputs based on derived relationships between observed data of finer resolution and coarser modeled data; and

2) process-based techniques that solve the physical ***dynamics*** of the system at finer resolutions based on boundary conditions set by coarser global climate models (Hewitson & Crane, 1996).

Empirical/Statistical downscaling is computationally more efficient than dynamic downscaling. This approach derives quantitative relationships between global circulation processes and local climate. A mathematical or statistical relationship is created by comparing locally observed (measured) climate variables (e.g., precipitation and temperature) to larger-scale atmospheric variables for the same baseline period, which can be derived from GCMs (Pielke & Wilby, 2012). This relationship is then used to derive the future local climate parameters from GCM projections. Alternative statistical methods include weather generators that downscale GCM outputs temporally to daily weather forecasts and Artificial Neural Networks that create non-linear relationships between GCM predictor variables and locally observed data. While statistical downscaling can produce site-specific climate projections down to the scale of the climate station (finer resolution than an RCM), they work on the critical assumption that the relationship between observed data in the baseline period and GCM outputs will remain the same for future climate periods (Trzaska & Schnarr, 2014).

Dynamical downscaling uses a nested model approach. A regional climate model is run with a finer horizontal grid resolution of surface features such as surface terrain using time-varying boundary conditions from a coarser scale GCM (Pielke & Wilby, 2012). The physics and calculations of RCM differ from GCM as the modeled processes exist at different scales. RCMs have the ability to model smaller scale atmospheric phenomena so they can better predict extreme precipitation and the impact of surface features on local climate (e.g., orography, water bodies) (Wilby & Wigley, 1997). RCMs use different physics and are more computationally intensive, but improvements in computing power have made these products largely available. The accuracy of RCMs is also dependent on the performance and skill level of the GCM. The RCMs used in this project uses the boundary conditions set by GCMs archived as part of CMIP5 (Coupled Model Intercomparison Project 5) from 2013. These GCM models were used to derive the results discussed in the IPCC's 5th Assessment Report.

Appendix F3. Using an Ensemble Approach

No one model can project the range of future climate that we could plausibly observe. While most models are similar in the systems they model, the way they are parameterized will differ considering the assumptions made regarding future scenarios or how the systems are represented. One solution is to consider the projections of many models and take a statistical distribution of the results to gauge the range of possible outcomes (Charron, 2016). This approach is referred to as the ensemble or multi-model method, which essentially reduces the bias from any one model (Figure 4).

There are multiple ways to take an ensemble approach for RCM outputs. One or multiple GCMs can be coupled with a single or multiple RCMs. Running a single model with multiple representative concentration pathway (RCP) scenarios (e.g., RCP 4.5, 8.5) would also be considered an ensemble of runs (See section 3.4 for RCP scenarios). Various ensemble model collections are available, including CMIP5, CORDEX (Coordinated Regional Climate Downscaling Experiment), NARCCAP (North American Regional Climate Change Assessment Program), among others. **This study uses the North American-CORDEX ensemble of models, which couples multiple GCM models with multiple RCM models.**

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