DURHAM REGION’S FUTURE CLIMATE (2040-2049)

Volume 1 - Overview

Prepared for:

The Regional Municipality of Durham

Prepared by:

SENES Consultants
121 Granton Drive, Unit 12
Richmond Hill, Ontario
L4B 3N4

December 2013

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Acknowledgement

Chapters 1 through 4 of this report are simply an editing of the methodology parts of the City of Toronto's report entitled "Toronto's Future Weather and Climate Driver Study". The authors and the Regional Municipality of Durham thank the City of Toronto for their permission to use their data to create a Durham specific assessment of the impact of climate on the Regional Municipality of Durham in period 2040-2049.

The Durham specific data has been developed from the city of Toronto's database at locations of particular interest to the Regional Municipality of Durham. A copy of all Durham-specific data has been provided to the City of Toronto along with a copy of this report.

Executive Summary

The **main deliverable** from this project is an understanding of what the Regional Municipality of Durham currently experiences in terms of climate and what it will experience in the future in terms of climate and extreme weather. This study has developed the data and information to assess the climate and extreme weather to which the Regional Municipality of Durham must adapt in the near future. The report is based on data generated for a comprehensive study done for the City of Toronto which covered a broad area including the Region of Durham.

How do we figure out what the future weather will be? An international body called the Intergovernmental Panel on Climate Change (IPCC) developed projections of future greenhouse gas (GhG) emissions as early as 1990. However, what will actually happen is the product of very complex dynamic systems, determined by demographic development, socio-economic development and technological change. How emissions will actually evolve is highly uncertain. In order to try to come to grips with how our world will change, various scenarios were developed by the IPCC to provide alternative ideas on how the future might unfold. These scenarios are essential as inputs to climate models. The outputs from the climate models help examine future impacts, adaptation and mitigation activities. The IPCC (2000) report identifies the A1B scenario as a credible, conservative, middle of the road future scenario that generates the highest impact on global warming for the 2040-2049 period. This scenario was selected for this study

What is a climate model? It is really the only way to understand the changes to the climate over long timescales. It simulates the many processes that occur in the atmosphere and oceans using complex mathematical equations. The equations used are derived from a wide range of observations and established physical laws, such as gravity, fluid motion, and the conservation of energy, momentum and mass. These models have been used over the last 40 years to make *projections* of future climate using assumptions about increases in greenhouse gas levels in the atmosphere. The models divide the world into 'boxes', and simulate an average value for the weather within each box (e.g., temperature, wind, humidity, etc.). For this study the British Meteorological Office Hadley Centre climate model, HadCM3, was used. The scale of the boxes in the HadCM3 model is about 300 km. This scale is much larger than that of some of the key processes that drive Durham's weather, such as convection and cloud formation. This means that many climate processes have to be approximated at this scale. It would take too much computer time to run a climate model with sufficient resolution (~1-2 km) to represent directly some of the key small-scale processes. The approximations, and our incomplete understanding of the climate system, are a major source of uncertainty in climate projections.

Why do we have confidence in climate models? Climate models are based on well-established physical laws; moreover, the science underpinning these laws and the way they are represented in models is continually improving. They are able to simulate the main features of the current climate and its variability such as the seasonal cycles of temperature and rainfall in different regions of the Earth, the formation and decay of the monsoons, the seasonal shift of the major rain belts and storm tracks, the average daily temperature cycle, the variations in outgoing radiation at high elevations in the atmosphere as measured by satellites and the large-scale features observed in the ocean circulation. But, most importantly, they have been used to simulate climate for the period 1860 – 2000, which includes the period when greenhouse gas emissions and concentrations rose from pre-industrial levels to those of the present day.

The **steps involved in preparing the data**, from which the information for this report is extracted, were as follows:

1. Simulated global climate with Hadley Climate Model (300x300 km output grid and 6-hour time step);
2. Simulated regional climate with the Hadley PRECIS model (a state-of-the-science Regional Climate Model) using Step 1 data (50x50 km output grid and 30-minute time step);
3. Simulated weather drivers over southern Ontario with FReSH (a state-of-the-science Weather Forecast Modelling System) using Step 2 data (4x4 km output grid and 20-second time step, aggregated up to 1-hour averages);
4. Simulated weather details over the GTA with FReSH using Step 3 data (1x1 km output grid and 20-second time step, aggregated up to 1-hour averages);
5. Prepared 10-year climatologies for specific output locations around the GTA using the Step 4 data as follows:
    i. 2000-2009 driven by observed upper air fields (to assess how well the FReSH Weather Modelling System works); and
    ii. 2040-2049 driven by the PRECIS RCM (to assess the future period);

How do we know that the results are correct? Two specific tests were undertaken as follows:

1. Simulated period 2000-2009
    - using measured broad upper air meteorological fields;
    - compared predicted versus observed data at specific locations; and
    - calculated the error in the weather model output; and

2. Simulated the Year 2000
    - using upper air fields were simulated by the Regional Climate Model;
    - compared predicted versus observed data at specific locations; and
    - calculated the extra error introduced by using climate model.

While all model have errors, the errors from the work reported here are at the low end of the expected range for this type of modelling. The data presented in this report illustrate that the approach used for this project gives results that are better than the best sensitivity commonly identified for Regional Climate Model analyses.

The following summarizes the projected Durham Region climate for the future period (2040-2049) using the **Whitby** location for illustrative purposes:

Less snow and more rain in winter

About 16% more precipitation (snow and rainfall) overall

- the **one** day maximum rainfall will increase by almost 50%
- the one day maximum snow will drop about 40%
- the number of days of rain greater than 25 mm will increase by 100%
- there will be an 80% reduction in the number of days with snow more than 5 cm
- January will have 146% more rain and 61% less snow
- February will have 217% more rain and 75% less snow

Rainstorm events will be more extreme

- there will be a 15% increase in the potential for violent storms
- there will be a 53% increase in the potential for tornadoes
- July will have 74% more rain
- August will have 79% more rain

Average annual temperatures increase of 4.0^{o}C

- average winter temperatures increase by 5.8^{o}C
- average summer temperatures increase by 2.6^{o}C
- extreme daily minimum temperature "becomes less cold " by 12^{o}C
- extreme daily maximum temperature "becomes warmer " by 7.1^{o}C

Average wind speed about the same

- maximum hourly winds reduced
- maximum wind gusts reduced about 13%

"Comfort" remains similar

- humidity and temperature taken together as the Humidex remains similar (within 8% of present on average) for most of the year but shows increases in November (up 30%) and in May through to September (up 15%) and pushes past the “dangerous” level (45) on several summer days
- Wind Chill is reduced by about 50% on average but is reduced 25-45% during the winter months

The following summarizes the predicted Region of Durham climate for 2040-2049, where we can expect, on **average across Durham Region**, to see:

1. fewer snow events, and reduced snow clearing requirements
    - extreme daily minimum temperature "becomes less cold " by 13.1°C;
    - 52 fewer days with temperatures below zero;
    - 29 fewer days with temperatures below -10ºC;
2. much more summer storm precipitation during July and August and increased likelihoods of culvert and sewer capacity exceedances and basement flooding;
    - no change in the total amount of precipitation falling in a year;
    - 33 fewer days with snow;
    - 31 more days with rain;
3. higher temperatures, more frequent summer heat waves and increased heat alert response requirements as follows:
    - average annual temperatures increase of 4.1°C in the future (2040-2049);
    - extreme daily maximum temperature "becomes warmer " by 7.6°C;
    - 56 more days with temperatures above zero; and
    - 14 more days with temperatures above 30ºC.

1.0 What are We Trying to Do and Why are We Trying to Do It?

1.1 Introduction

Local governments and businesses need good information about future climate and weather extremes so that they can be prepared to adapt to any changes that will occur. Of key interest are extreme weather events and their spatial and temporal resolution, such as micro-bursts, intense local rainfall events resulting in flooding and strong local pressure gradients and wind events that might occur within Durham Region.

The main deliverable from this project is an understanding of what the Region of Durham will experience in the period 2040-2049. This study is to develop the data, information and simple and applicable tools to inform climate and extreme weather risk analyses by local governments and businesses.

1.2 Which Climate Stations are Used?

The original broad study area is shown in Figure 1 (outlined in red). It also shows the Climate Stations (numbers) used in the analysis. Table 1 gives the names and locations of the Climate Stations used for the current climate analyses.

1.3 Detailed Output Points

In this document (Volume 1) the Toronto Pearson International Airport (Pearson Airport) is used for validation purposes and Whitby was selected by the client as the proxy location to be used to illustrate the results for Durham Region, while all other points selected for presentation are tabularized in Volume 2 of the report.

Figure 2 presents a map of the locations selected by the Regional Municipality of Durham for the presentation of detailed results.

Figure 1: Study Area Climate Stations Used

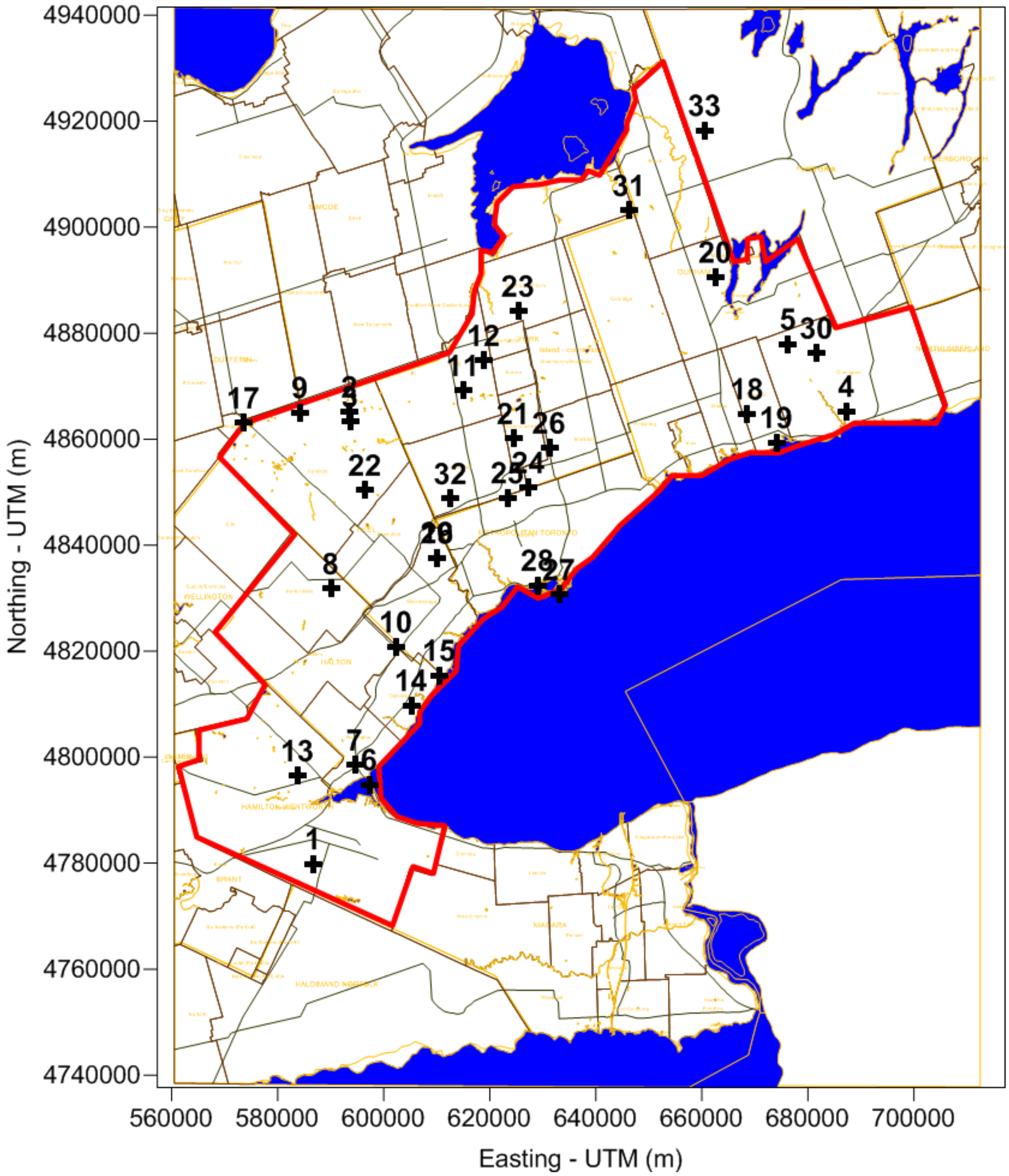


Table 1: Environment Canada Stations Used for Current Climate Summaries

Stn. No	Environment Canada Station Name	Longitude (^{0})	Latitude (^{0})
1	HAMILTON A	79.93333	43.16667
2	ALBION	79.83333	43.93333
3	ALBION FIELD CENTRE	79.83333	43.91667
4	BOWMANVILLE MOSTERT	78.66667	43.91667
5	BURKETON MCLAUGHLIN	78.80000	44.03333
6	BURLINGTON PIERS (AUT)	79.80000	43.30000
7	BURLINGTON TS	79.83333	43.33333
8	GEORGETOWN WWTP	79.88333	43.63333
9	GLEN HAFFY MONO MILLS	79.95000	43.93333
10	HORNBY TRAFALGAR TS	79.73333	43.53333
11	KING RADAR	79.56667	43.96667
12	KING SMOKE TREE	79.51667	44.01667
13	MILLGROVE	79.96667	43.31667
14	OAKVILLE GERARD	79.70000	43.43333
15	OAKVILLE SOUTHEAST WPCP	79.63333	43.48333
16	ONTARIO WEATHER CENTRE	79.63333	43.68333
17	ORANGEVILLE MOE	80.08333	43.91667
18	OSHAWA A	78.90000	43.91667
19	OSHAWA WPCP	78.83333	43.86667
20	PORT PERRY NONQUON	78.96667	44.15000
21	RICHMOND HILL	79.45000	43.88333
22	SANDHILL	79.80000	43.80000
23	SHARON	79.43333	44.10000
24	THORNHILL GRANDVIEW	79.41667	43.80000
25	TORONTO MSC HEADQUARTERS	79.46667	43.78333
26	TORONTO BUTTONVILLE A	79.36667	43.86667
27	TORONTO HEADLAND (AUT)	79.35000	43.61667
28	TORONTO ISLAND A	79.40000	43.63333
29	TORONTO LESTER B. PEARSON INTERNATIONAL AIRPORT	79.63333	43.68333
30	TYRONE	78.73333	44.01667
31	UDORA	79.16667	44.26667
32	WOODBRIDGE	79.60000	43.78333
33	WOODVILLE	78.98333	44.40000

AUT = Automatic Station

Figure 2: Locations Selected for Results Presentation within Durham

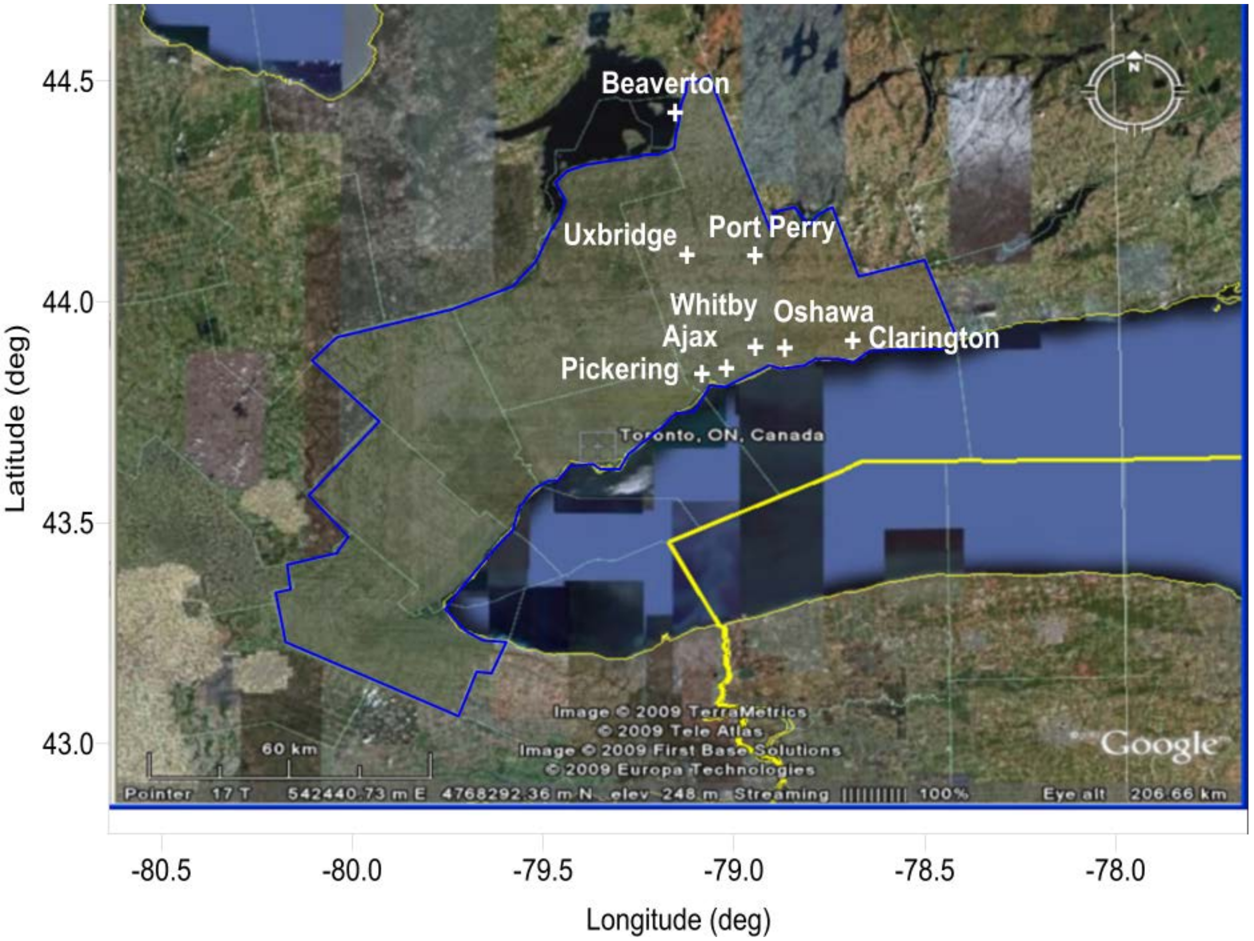


Table 2 lists the 8 Durham locations selected along with the Volume 2 table location numbers where detailed results can be found. The table also gives the model output grid location used. It should be noted that Pearson Airport was also used for quality assurance purposes.

Table 2: List of Sub-Table Number and Model Grid Points for Volume 2

Sub-Table Number	Station Name	Grid Point Number Used
1	Ajax	13414
2	Whitby	14165
3	Oshawa	14171
4	Clarington	14483
5	Uxbridge	17570
6	Port Perry	17584
7	Beaverton	22908
8	Pickering	13110

1.4 Why are we doing it?

The Regional Municipality's climate is characterized by four seasons, albeit of perceptually variable length. Summers are warm to hot, and winters are usually cool to cold. As a result of the rapid passage of weather systems (i.e., high and low air pressure cells), day-to-day weather is variable in each season but the parameters such as precipitation and temperature are relatively uniform within longer periods, such as month-to-month. Since it is located in close proximity to Lake Ontario, the Regional Municipality of Durham experiences moderated and less extreme temperatures in both winter and summer. Other factors such as the height and shape of the land (i.e., topography) as well as the use of the land (open farm land versus houses and buildings) also affect Durham's climate, which means that there will be a North to South variation across the region.

The purpose of this document is to discuss the factors which influence the weather and climate of the Regional Municipality of Durham. First, a background on what drives the weather is provided. Subsequently the document describes, in general, factors which influence climate and explains how these factors help to shape the climate of Durham. On the subject of climate change, this document also examines how some of the anticipated changes to the planet (specifically the planet's integrated system components of the atmosphere, the hydrosphere, the lithosphere and the biosphere) may affect the weather and climate of Durham in the future.

SENES Consultants has predicted, to the degree possible, the likely changes in future weather system patterns that will be experienced in and around Durham and prepared new "normals" and new patterns of extreme events by magnitude and frequency and their probability of occurrence. The main focus of the study was to identify intense events that occur within a limited geographical area and over short time frames (that is, spatially and temporally intense events). This information is to be used by the Durham as it prepares for potential changes in the severity and frequency of extreme storm events and the associated damages and costs of resultant flooding and washouts. A secondary focus was to look at regional events like heat waves and cold snaps that are ameliorated by the Great Lakes.

1.5 How Did We Approach the Study?

First a set of detailed state-of-the-science weather model statistics, based on the period 2000-2009, formed the baseline 1x1 km gridded, hourly summary of current climate for the whole GTA. This period was also used for model validation against the current observational data. This data combined with long term observed weather will be used to explore the magnitudes, frequency and probability of occurrence of present extreme weather events.

The second step was to use the output from a Regional Climate Model (RCM) for a 10-year period in the future (2040-2049) driven by a maximum impact scenario that represents a balance of consumption and pollution release across all energy sources (any source that uses fossil fuel). The output was used as input to the same state-of-the-science weather model to develop an hour-by-hour simulation of the future on the same 1x1 km grid for the GTA. This 10-year data set was examined for major storms, extreme weather and the other climate parameters. The resulting averages and statistics form the future climate summary for the Durham Region which was used to explore future weather and climate as well as what would be the magnitudes, frequency and probability of occurrence of future extreme events and significant weather.

1.6 Why Did We Take This Approach?

Computer models are often regarded as a little suspect by the general public, and computer based climate models are no exception to this. Someone puts lots of data in to one side of a black box, presses a button and answers seem to magically appear out the other side. To the general public, what goes on in the black box is mostly unknown, and what little is explained - is unclear. Doubt and suspicion can follow.

Scientists who create and manipulate the equations and feed the data into the black box "know" that the equations "mimic", to the extent possible, the complexity of all the atmospheric processes that collectively create the climate. They know that the integrated equations contain all the science; they know that the equations contain all that is known about why we get the climate that we get.

A commonality between the general public and climate scientists is that both recognize that mistakes can be made and that common sense and more rigorous safety checks are a necessary requirement for any acceptance of the output from any such a climate black box.

The obvious safety checks to be undertaken are: do the answers make sense, or can they be explained. Rather than simply accepting the answers scientists and the public must ask – "do they make sense"?

In essence, rather than saying "these are the answers so trust them", it is essential that the changes, or pattern variations, can be explained both individually and collectively in a logical and coherent manner. A logical argument that goes along with the computer model output (or the numbers from the black box) and that specifically explains the numbers derived is essential: a) to gain greater public acceptance, and, b) to provide a safety check that the derived numbers do fit the science, and that no human errors have crept into the preparation of the model or the provision of the input data. This is like a cook with a new recipe who is using strange ingredients and that leads to something unexpected – was it the recipe, the ingredients or the cook?

In the context of present and future climate and weather extremes, the logical argument, or story, tries to embrace the following questions:

- what do we get now?
- what will we get in future?
- how big will the future change be?

The last question is really addressed by running the computer model(s). It is very hard for human minds to grapple with complex changes among hundreds of variables all at the same time, but a computer is designed to do just this. Even so, the scale, direction and nature of any and all change have still to make sense and be clearly seen as good, acceptable science – or to encourage new scientific research be undertaken to evaluate and determine if the theory and the output is valid. If the theory is wrong, the theory has to be changed and the results have to be rejected.

In this study we have shown that the theory (as applied through the combination of a climate and a weather model) is able to predict the weather that we have already seen and that gives us confidence that our projection of the future is equally valid.

2.0 The Big Picture

2.1 North America

The distinct continental climate of North America is characterised by cold winters and warm summers. The temperatures in these two seasons are mitigated by the presence of the Great Lakes, which act as a heat store and a humidity source. This means that the winters in the vicinity of the lakes tend to be milder than in other provinces and the summers are less extreme than their eastern location on this large continent would otherwise dictate, but summers still see significant heat waves that are often associated with poor air quality.

Very intense convective events occur in the spring and autumn seasons, which are sometimes associated with outbreaks of tornadoes. Tropical cyclones which have made landfall occasionally make their way up to the Great Lakes region generating a very severe accumulation of precipitation. Extreme events in the province are either floods resulting from melting snow during the spring, or intense precipitation which can be a torrential summer downpour as in the case of three events which occurred in the southern part of the Mackenzie River basin between 1993 and 2001 (Brimelow and Reuter, 2005) or freezing rain as was the case for the 1998 ice storm which, until the Calgary floods of 2013 and the very recent ice storm across the GTA, represented the most devastating extreme weather event in Canadian history. Between the 5th and 10th of January 1998, freezing rain fell over Ontario, Quebec and New Brunswick forming ice whose thickness was between 7 and 11 cm. Trees, utility poles and transmission towers collapsed causing massive power outages which lasted up to a month (Munroe, 2005).

Between 1955 and 2005, the annual mean temperature across North America has increased, with the greatest warming across Alaska and northern Canada (Field et al., 2007). As with many other regions, average night-time temperatures have risen by a larger amount than average daytime temperatures. Spring and autumn have experienced a greater warming than summer and winter. Snowmelt is occurring 1 to 4 weeks earlier across the mountainous areas of the country, and ice break-up across North America has advanced by 0.2 to 12.9 days over the last 100 years (Magnuson et al., 2000).

Across much of North America, precipitation (e.g. rain, hail, snow) has increased during the 20th century, particularly in northern Canada and Alaska. In southern Canada annual precipitation has increased by between 5% and 35% since 1900 (Zhang et al., 2000). Such an upward trend has not been detected in the Canadian Prairies and the eastern Arctic where a decrease in precipitation about of 1 to 2% per decade was observed as drought conditions prevail (Trenberth et al., 2007). The number of days with precipitation (rain and snow) has increased significantly in the south and central sub-regions. Across Canada, snowfall has decreased in recent years, leading to significant changes in the timing and volume of spring runoff and decreasing summer river flows, with an impact on water supply (Schindler &

Donahue, 2006). In recent years, water levels in the Great Lakes have dropped, and with climate change and increased demand for water elsewhere, this trend is likely to continue.

2.2 Ontario

Over the last 50 years Canadian annual temperatures have increased by 1.3°C (Environment Canada, 2006). During the same time period, annual average temperatures across Ontario have increased between 0 and 1.4°C, with larger increases observed in the spring (Chiotti and Lavender, 2008). Eight out of the ten warmest years on record in the region of the Great Lakes have occurred since 1990. Over the same period the number of warm days and warm nights (defined as temperatures above the 90th percentile of observed daily maximum and minimum temperatures respectively for the period 1961-1990) have steadily increased all over the province. The northern part of Ontario has seen a larger increase than other regions. This trend is opposite to what was observed for the number of cold days especially in central and western Ontario (Vincent and Mekis, 2006).

The split between snow and rainfall precipitation has changed with rain becoming more predominant than it was before in southern Ontario (Bruce et al., 2000). Precipitation in some parts of the province has become more variable, with a positive trend in the frequency of the most intense storms (Mekis and Hogg, 1999). A decline in snowfall was observed in most parts of southern Ontario while the north has experienced an increase in snowfall (Zhang et al., 2001).

2.3 The GTA's Current Climate

2.3.1 Introduction

The climate trends presented here are based on the stations presented in Figure 1 and Table 1.

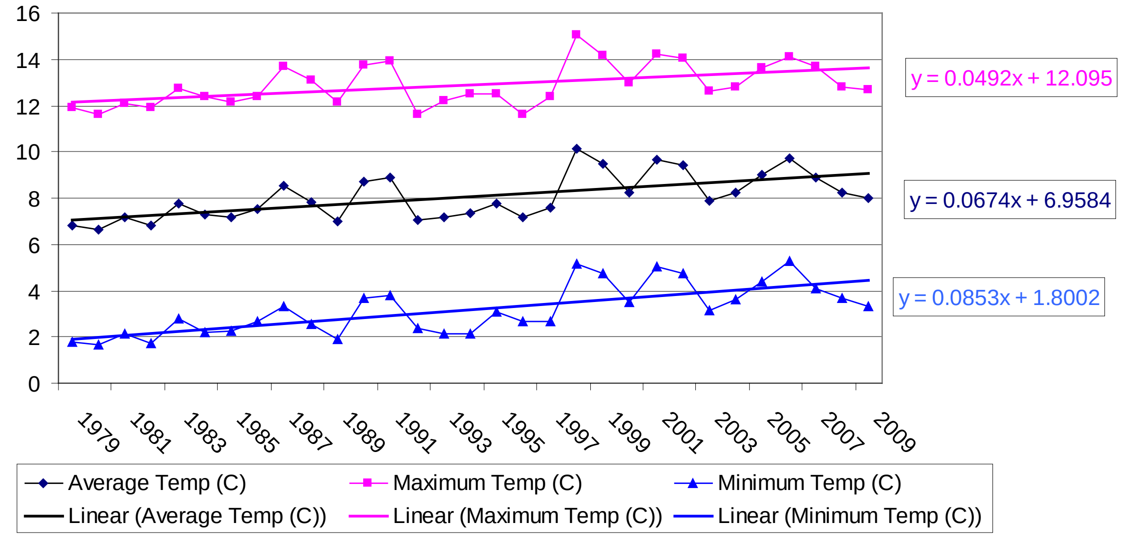
The climatology over the period 1979-2009 for the Greater Toronto Area was developed using all available records from the Environment Canada monitoring stations.

These data were augmented in this study by an hour-by-hour simulation of the period 2000-2009 so that statistics, return periods and other data could be quantified in more detail for the GTA.

2.3.2 Average, Minimum and Maximum Temperature Trends

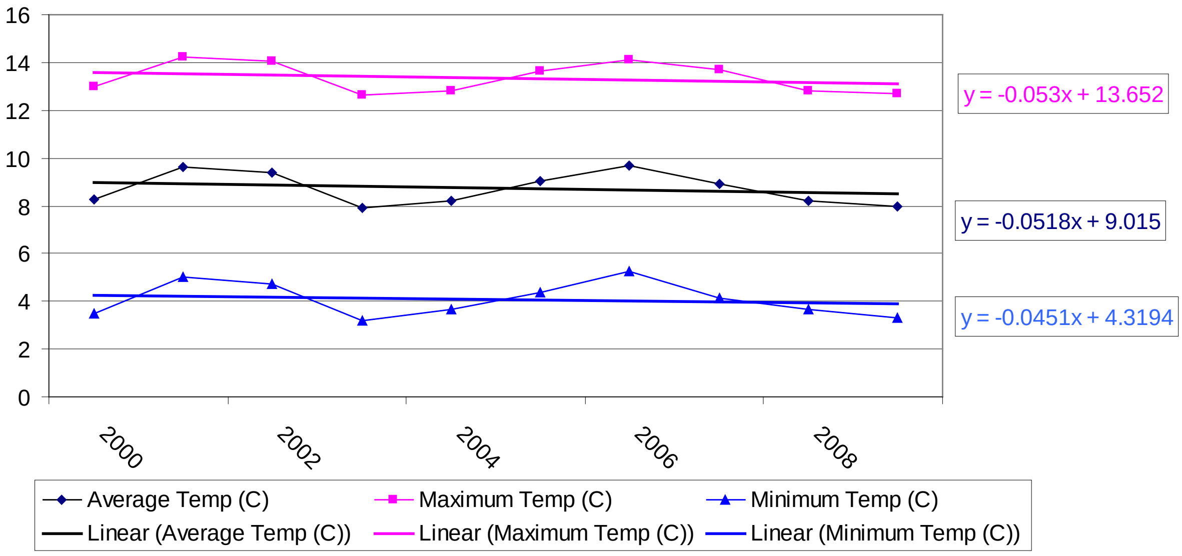
While the analysis was completed for all stations listed in Table 1, an example of the Pearson Airport was selected, as the proxy location for the original study, to show the form of the results. The Pearson Airport location was also used for model validation as it has the most complete record. The most recent 30-year climate trend was assessed (1979-2009) and compared to the study reference period (2000-2009). Figure 3 and Figure 4 present the annual average temperature data well as a linear trend line.

Figure 3: Average Temperature (ºC) at Pearson Airport (1979-2009)



The figure shows that, if the average positive temperature change continues for the next thirty years to 2040, the average temperature will increase by 2.02^{0}C. It also shows that the climate has been warming over the period of record. This matches well with the broad area projections made by the Global and Regional Climate Models (see OURANOS: *Better understanding the horizontal distribution and trends of major climate change indicators through combined downscaling using the Canadian Regional Climate Model (CRCM) at 45km resolution*; the report is available at http://www.ouranos.ca/Ontario/Results_html/index.htm).

Figure 4: Average Temperature (ºC) at Pearson Airport (2000-2009)



The most recent 10-year period (2000-2009) shows that there is a slightly negative temperature trend at the Pearson Airport for this period for the average, average minimum and average maximum temperatures. This is not a demonstration, of a negative climate change trend, but rather an indication that there is variability in the climate and that any conclusions about local or global climate change need to be considered carefully using a longer period of record than 10-years.

2.3.3 Extreme Temperatures

The extreme maximum and minimum temperature trends over 30 and the last 10 years are presented in Figure 5 and Figure 6, respectively. In Figure 5 the extreme maximum temperature shows a slightly positive trend over 30-years while the extreme minimum has a stronger trend over the same period. This indicates that the maximum temperatures are becoming slightly less severe and the minimum temperatures are becoming much less severe.

Figure 5: Extreme Temperature (ºC) – Pearson Airport (1979-2009)

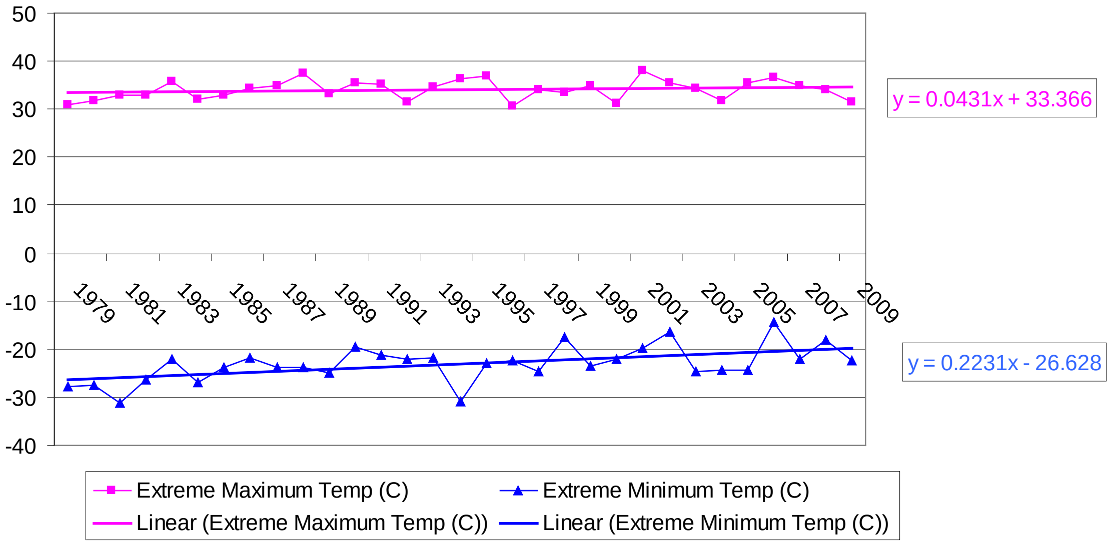


Figure 6 shows that, over the most recent 10-years, there is a negative trend in the extreme maximum temperature while the extreme minimum has remained virtually flat. This is another indication of the variability in our climate.

2.3.4 Rainfall, Snowfall and Total Precipitation

Trends in precipitation are presented here, for the thirty year and the ten year period. Figure 7 and Figure 8 represent the trends in precipitation for these two periods, respectively.

Figure 6: Extreme Temperature (ºC) - Pearson Airport (2000-2009)

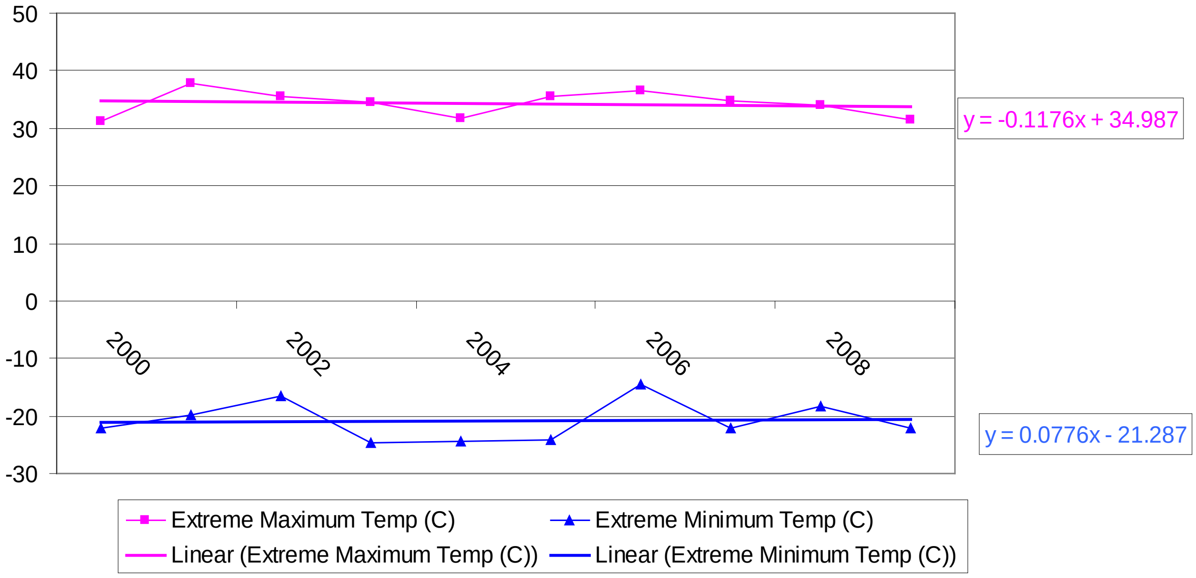
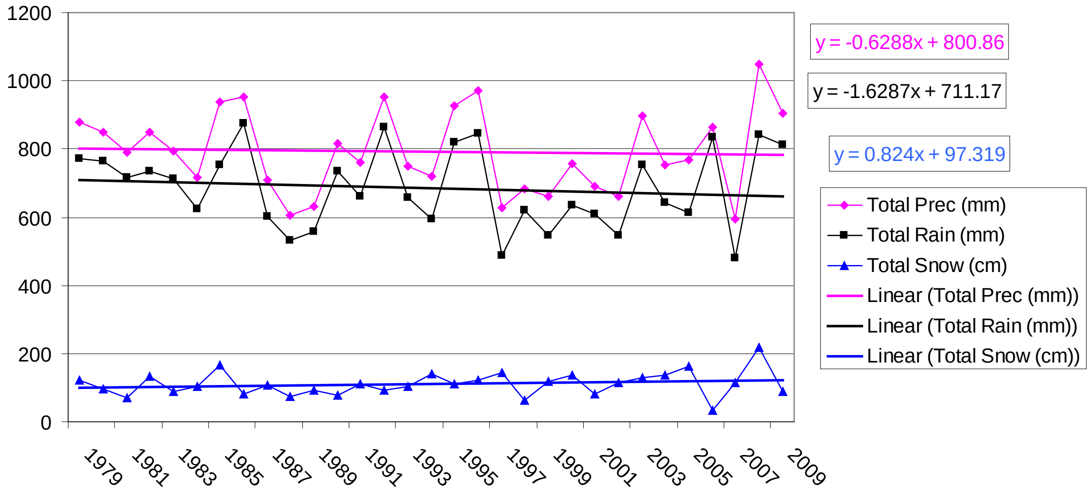
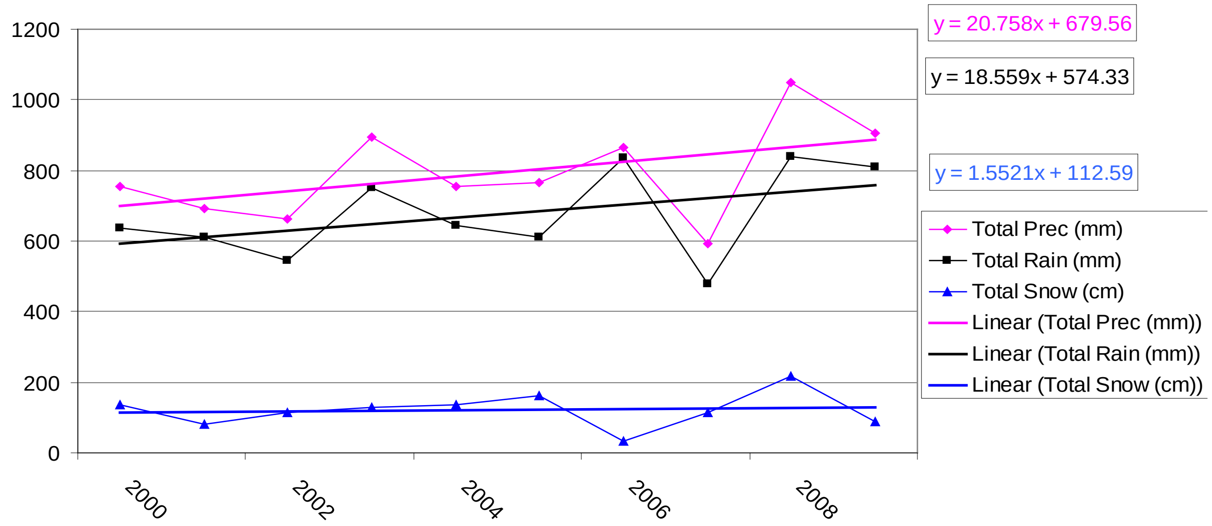


Figure 7: Precipitation at Pearson Airport (1979-2009)



Based on the 30-year period of data (Figure 7), there is a decreasing trend of rainfall and total precipitation, while snowfall is increasing, while the most recent 10-year period (Figure 8) has different trends, with all three parameters indicating an increase.

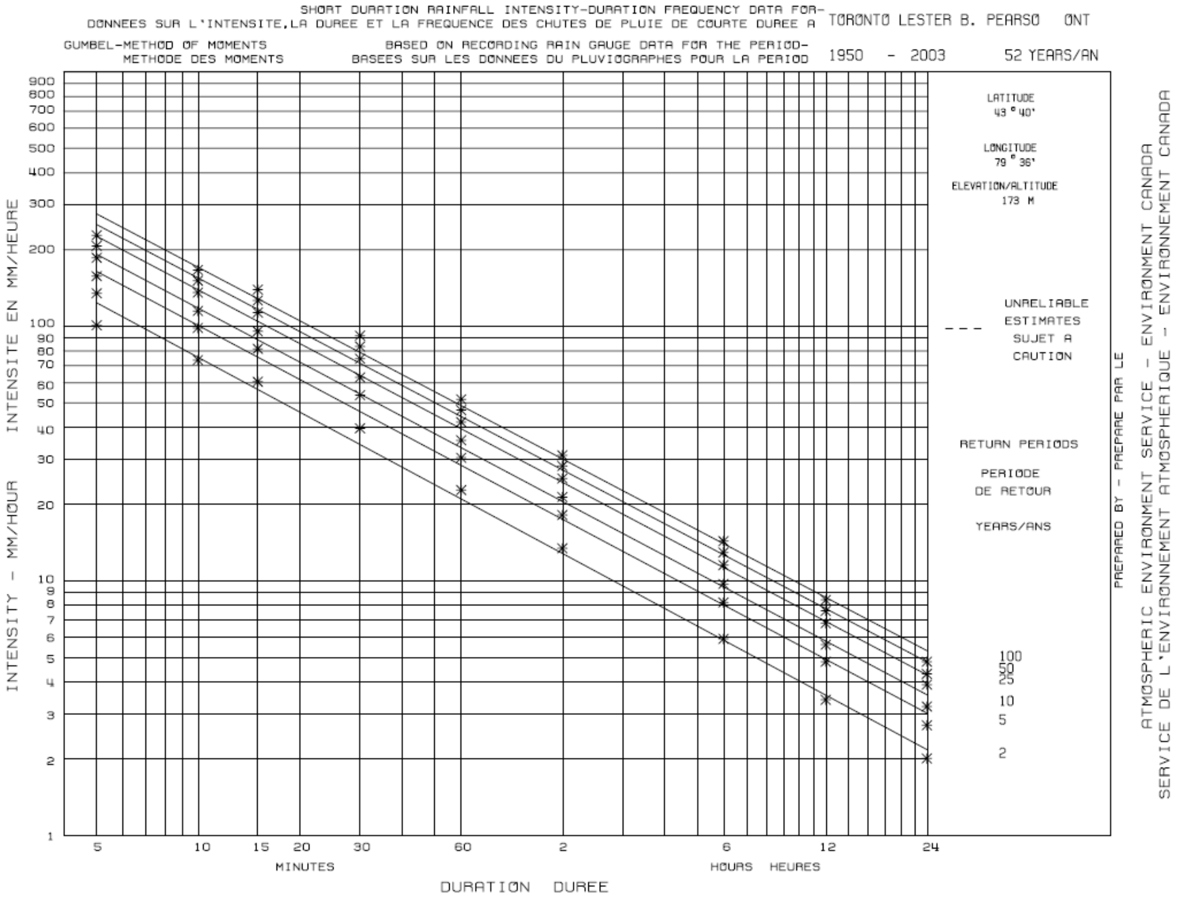
Figure 8: Precipitation at Pearson Airport (2000-2009)



2.3.5 Storm Intensity, Duration and Frequency of Occurrence

The intensity, duration and frequency of precipitation events are commonly typified by an Intensity Duration Frequency (IDF) graph as shown in Figure 9 on which similar storms with similar intensity and duration characteristics have consistently identifiable frequencies or return periods. Six return periods (between 2 and 100 years) for storms observed at Pearson Airport are shown for the period 1950-2003 in Figure 9. This IDF graph will be used as the base reference for comparisons with the predicted return periods of the first future period to be modelled as part of this study.

Figure 9: Intensity Duration Frequency Graph - Pearson Airport (1950-2003)

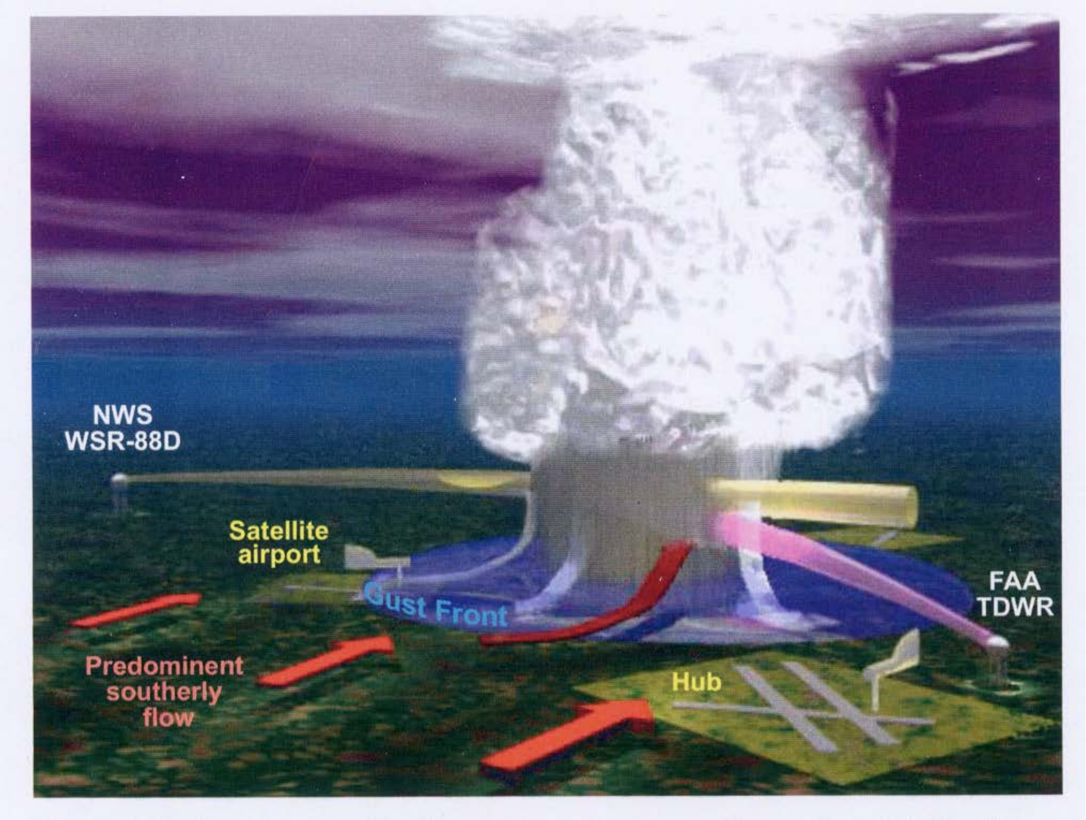


2.3.6 Gust Winds

Around thunderstorm clouds there are strong vertical movements as well as downdrafts. Those downdrafts create local fronts which generate gusting winds. Such frontal systems are quite difficult to detect. This phenomenon is thought to be the most likely cause of the majority of observed damage and increased precipitation. An outflow boundary, or gust front, is a storm-scale boundary separating the thunderstorm cooled air (outflow) from the surrounding air. Outflow boundaries create low-level wind shear which can be hazardous to aircraft. If a thunderstorm runs into an outflow boundary, the low-level wind shear can cause rotation at the base of the storm, at times causing tornado activity.

Figure 10 illustrates the dynamic core around a strong thunderstorm cloud with an indication of gust fronts. The major factor that is causing damage is the wind shear that can be seen in the figure. Storm movement can be in one direction and frontal movement can be in another direction.

Figure 10: Cool Outflow from Thunderstorms Produces a Gust Front



The long term tendency of gust winds is presented in Figure 11 (30-year period) and Figure 12 (10 year period). It should be noted that no tornadoes came through the GTA over this period of record so that the gust record presented is only associated with thunderstorms.

Figure 11: Gust Wind (km/hour) Trend for the 1979-2009 Period

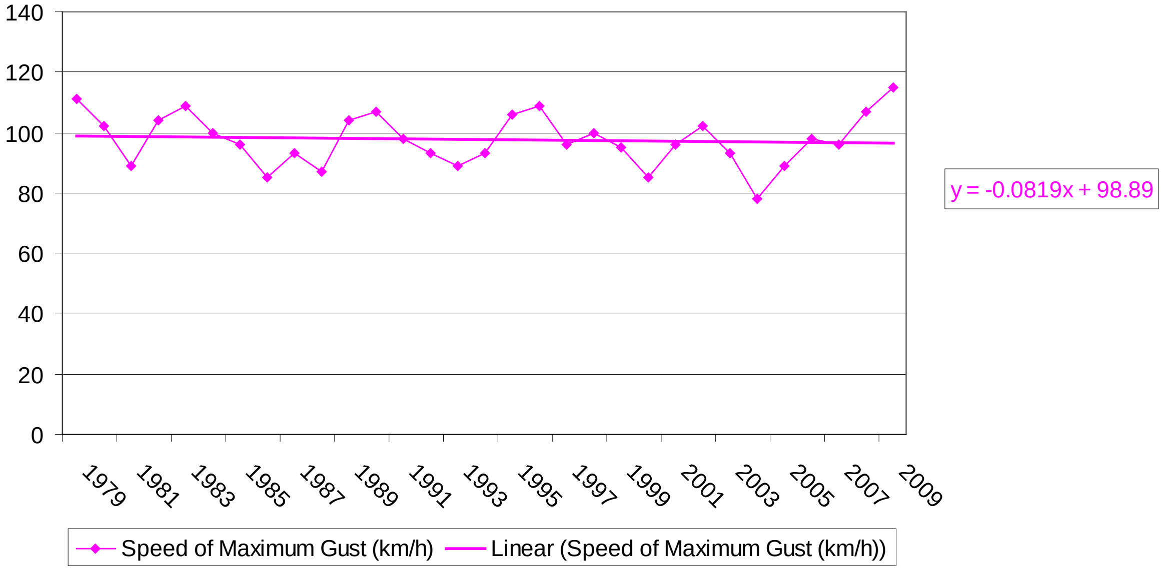
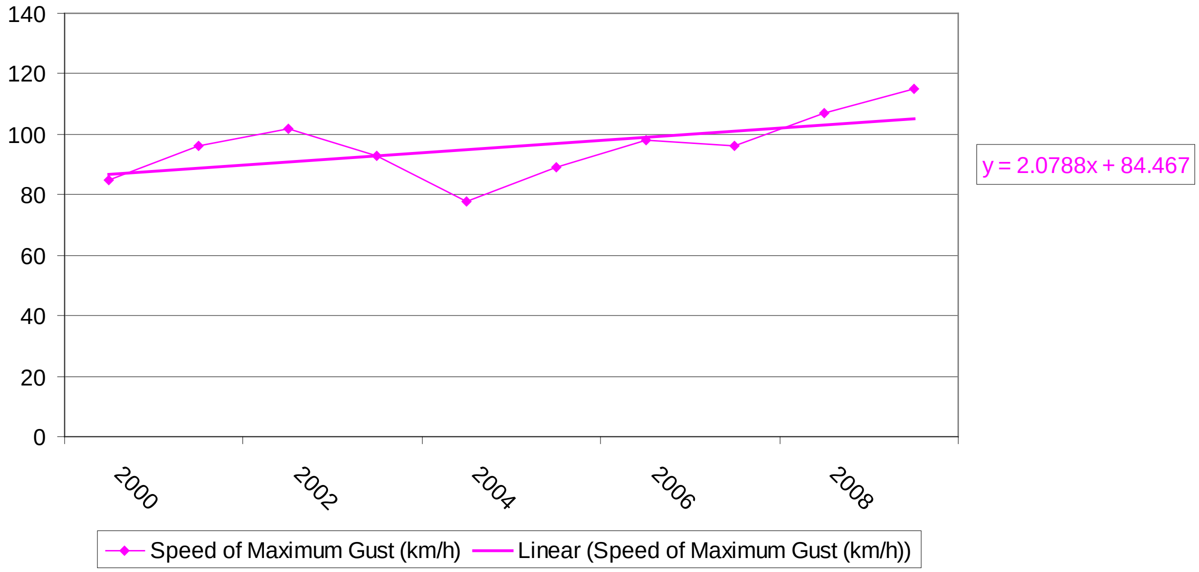


Figure 12: Gust Wind (km/hour) Trend for the 2000-2009 Period



The figures show, based on the thirty year period (Figure 11) that the gust trend is slightly negative (gust wind will decrease in the future), while the most recent 10 years (Figure 12) indicates that gust strength will increase. These differences give some indication of the variability of the climate observations for the 30-year period approach compared with the 10-year period approach that was adopted here.

3.0 Why is the Future Expected to be Different?

3.1 Introduction

According to the most recent synthesis report released by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007b), 11 of the 12 years in the period 1995-2006 have experienced the warmest average global temperatures on record. This historical global temperature record dates from around 1850. In Toronto, 2005 was, for example, one of the warmest years on record with 37 days exceeding 30^oC (Clean Air Partnership, 2006).

Climate change is now evident from observations showing increased global air and ocean temperatures, disappearing snow and sea ice, as well as a rise in sea level (IPCC, 2007b).

3.2 Climate Outlook for the 21st Century

Communities across the north of the North American continent are projected to experience far fewer extreme cold periods over the winter months owing to the significant warming predicted for the area. Ice storms, typically associated with slow or stalled low pressure systems, such as that which hit Ontario and Quebec in 1998, could increase in frequency if the associated storm tracks shift northwards with climate change (Yin, 2005; Roberts & Stewart, 2008). Warmer winter temperatures could result in more freezing rain events, although current investigations in future climates do not show significant changes in the number of such events.

The rest of the region is projected to experience increased temperatures and longer duration heat waves, particularly in the cities where the temperatures will be exacerbated by the 'urban heat island effect' (Christensen et al., 2007). In most Canadian cities, as well as cities around the world, the night-time temperatures recorded in the urban environment are usually significantly warmer than the surrounding countryside, and this is true for the cities of Canada.

Annual mean precipitation is expected to increase over Canada by a maximum in some specific areas of 20% (although there is significant uncertainty in this maximum value) with winter precipitation possibly exceeding 130% of present day values (Christensen et al., 2007). However, there is currently only poor agreement, among the results obtained from various standard climate models (covering large geographic areas), on the projected summer precipitation changes to be expected over much of Canada. Snowfall and snow cover have been decreasing across the continent during the 20th century, a trend which is expected to continue despite increased precipitation, owing to the high likelihood of increasing annual mean temperatures and the even more pronounced (as over Durham) mean minimum annual temperatures. Studies show that precipitation is likely to increase in intensity as well as quantity throughout the 21st century across much of North America, particularly in the Canadian Rockies (Leung et al., 2004).

Increasing demand for water to supply rising populations and demands for crop irrigation, means that any decline in freshwater supply could have significant impacts on water stress in Canada. The projected rise in winter precipitation may help to alleviate some water supply issues, although projections suggest that much of this increased precipitation could be in the form of extreme rainfall events, leading to flooding, difficulties in retaining the water for future supplies and a decline in water quality from increased erosion (Christensen et al., 2007).

Groundwater sources and other reservoirs are expected to be influenced by climate change. With increasing temperatures, demand for irrigation will rise and groundwater sources will be depleted. Recharge of aquifers may not be as great, due to increased evaporation as a result of rising temperatures. Reservoirs and rivers may suffer from oxygen depletion and toxicity more frequently as temperatures increase. Water quality problems may become more common as sediment and chemical loads increase due to erosion during intense rainfall and higher temperatures (Christensen et al., 2007).

3.3 Northern Latitude Storm Tracks

Low pressure systems play a dominant role in a region's climate since they influence important factors such as cloud cover and precipitation. Therefore, any changes to the position of a storm track will consequently have an impact on a region's climate.

There is observational evidence to suggest that the frequency of mid-latitude storms is decreasing as storm tracks shift poleward and that storms are becoming more intense. Climate models also predict that this trend will continue into the future - meaning that Durham is likely to experience fewer, but more intense storms in the future. This suggests that more extreme rainfall events and more extreme snowfall events could occur in Durham in a future climate.

A possible explanation for the shift in Northern Hemisphere storm tracks is the Arctic Oscillation (AO). Storm tracks and temperature are known to be affected by the AO and it has been suggested that the AO will remain in its positive phase in all foreseeable future climates. As a result, storm frequency will decrease but the severity of each will increase in Durham as the track shifts poleward as temperatures become warmer.

3.4 Loss of Arctic Sea Ice

Recent observations show that there has been a decline in Arctic sea ice over the last few decades (WWF, 2005; Singarayer *et al.*, 2006). There are several Arctic climate feedback mechanisms that play a critical role in regional as well as the global climate system and there is evidence emerging which shows that melting sea ice is accelerating global warming (WWF, 2005). This section provides a discussion of the main Arctic climate feedback mechanisms and what the implications of each feedback are with regards to climate. Where possible, the impacts on Durham's climate have been examined, however, there remains much uncertainty about what the implications of melting Arctic sea ice are, so the impacts cannot always be concretely stated.

3.4.1 The Ice-Albedo Feedback Mechanism

One of the most significant climate feedback mechanisms in the Arctic is the ice-albedo feedback. Albedo is simply a measure of how reflective a surface is. A surface with a high albedo, like ice, reflects large amounts of solar radiation back into space and as a result, the surface temperature is lower. When sea ice melts, the once reflective surface is replaced by liquid water which is capable of absorbing a large amount of solar energy. As a result, temperatures begin to rise at a much quicker rate which further erodes existing ice and prevents new sea ice from forming.

At northern and mid-latitudes, including Canada and Durham, it is anticipated that the warming trend will be amplified as a result of the ice-albedo feedback mechanism (Singarayer *et al.*, 2006). In fact, there is now observational evidence which suggests that temperatures are increasing faster at northern locations within Canada due to the melting of sea ice (IPCC, 2007b). Therefore, in a future climate, locations such as Durham may experience a greater increase in temperature than subtropical locations due to the amplifying effect of melting sea ice in the Arctic.

Overall, it is expected that melting Arctic sea ice will amplify warming in northern latitudes as a result of the ice-albedo feedback and that mid-latitude locations such as Durham will observe a greater increase in temperature than more southern locations in the subtropics. Feedback mechanisms such as the marine- and sediment-carbon feedback impacts on future climate are less certain. It is expected, however, that increasing sea surface temperatures in the Arctic and the subsequent release of ocean-sediment bound methane gas will also amplify warming in northern latitudes.

3.5 What Emissions of CO_2 Drive the Future?

The Intergovernmental Panel on Climate Change (IPCC) developed future greenhouse gas (GhG) emissions projections as early as 1990. These projected emissions are the product of very complex dynamic systems, determined by demographic development, socio-economic development and technological change. How emissions will actually evolve in the future is highly uncertain. The various scenarios developed by the IPCC give alternative ideas on how the future might unfold. They are useful as inputs to climate modelling the results of which help examine future impacts, adaptation and mitigation activities.

Four different storylines were developed to describe the world in 2100. Each storyline assumes a distinctly different future. The A1 storyline and scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A1 scenario family develops into three groups – fossil intensive (A1FI), non-fossil energy sources (A1T) and balanced across all sources (A1B).

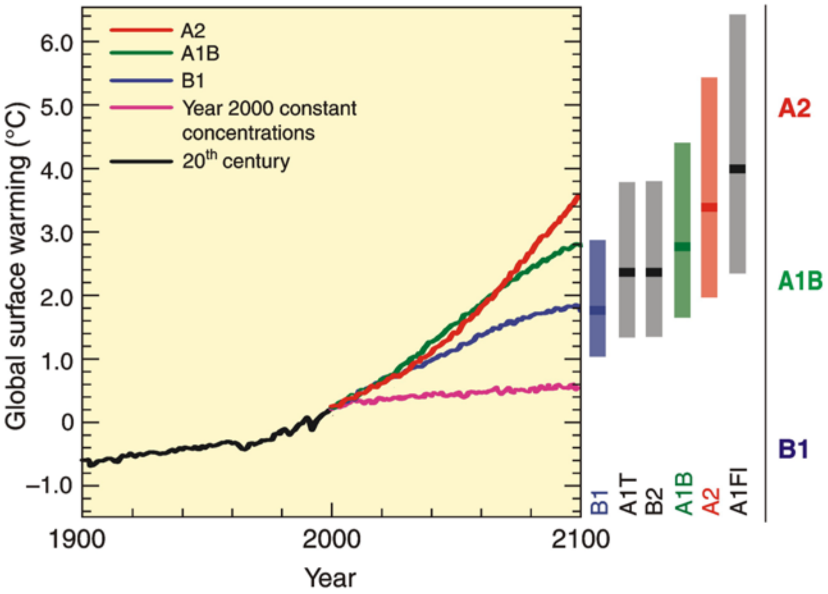
The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Economic development is primarily regionally oriented and per capita economic growth and technological change is more fragmented and slower than in the other storylines.

The B1 storyline and scenario is similar to the A1 scenario but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

The B2 storyline and scenario describes a world with an emphasis on local solutions to economic, social and environmental sustainability. It has a continuously increasing global population but at a rate lower than A2.

The IPCC (2000) report identifies the A1B scenario as the scenario that gives the highest impact of CO_2 for the 2040-2049 period as can be seen graphically in Figure 13. This scenario was selected for this study.

Figure 13: Impact of Various Climate Change Scenarios



3.6 Climate Oscillations

Simply put, climate oscillations are recurring anomalies in large-scale atmospheric pressure patterns observed over a given region of the globe. Sometimes, the changes in atmospheric pressure are coupled with changes in sea surface temperature in the same area. Together, these changes affect climate not only in the regions in which the oscillations occur, but all over the globe. Since their impacts can be felt in faraway places, climate oscillations are sometimes referred to as “teleconnections”.

The most commonly known climate oscillation is the El Niño Southern Oscillation (ENSO) where changes in sea surface temperature and mean sea level pressure are observed in the tropical Pacific Ocean. Other oscillations which can affect North America's climate include the Arctic Oscillation/North Atlantic Oscillation (AO/NAO) and the Pacific Decadal Oscillation (PDO). Each oscillation and its effect on the Canadian climate, where known, are discussed below.

3.6.1 El Niño Southern Oscillation

The most well-known (and understood) climate oscillation is the El Niño Southern Oscillation (ENSO) which occurs about every 2 to 7 years. As described by Environment Canada (2010), under normal climatic conditions in the tropical Pacific Ocean, trade winds blow from east to west between South America and Australia/Indonesia allowing cool water to upwell along the west coast of South America. During an ENSO event, sea level pressure over the western Pacific and Australia tends to be a little higher than normal and the easterly trade winds are weakened. Subsequently, warmer waters move toward the west coast of South America bringing more precipitation and storms with it. The added heat to the eastern Pacific also affects the westerly flow in the mid-latitudes by forming a wave train of alternating high and low pressure that curves eastward in the northern hemisphere due to the Coriolis Effect. As a result, an anomalous high pressure feature develops over Canada, and a corresponding low pressure anomaly occurs in the Gulf of Alaska. These changes, shown in Figure 14, to the pressure pattern inherently alter the course of the jet stream (especially the winter jet), shifting it further south into the United States (Cook-Anderson, 2008) and significantly affecting Canada's temperature and precipitation patterns while the phenomenon remains.

Figure 15a to Figure 15d from Environment Canada (2010abc) show the effect of ENSO on winter and springtime temperatures and precipitation departures from normal in Canada. The figure is a plot of the impact of the El Niño effect with the seasonal warming trend removed. As can be seen in the figures, the largest temperature anomalies occur over central Canada during the winter with a 0.5 to 1 degree temperature increase in Southern Ontario. Most of Canada experiences above normal temperatures in the spring as well. During the winter, below normal precipitation occurs in the Great Lakes Region since the jet stream is mostly kept to the south of Canada resulting in fewer winter storms (see Figure 14). There is little to no effect of ENSO on precipitation during the spring in Southern Ontario.

The North Atlantic Oscillation (NAO) is sometimes used as a separate term to describe the AO; however, some controversy still remains about how the AO and the NAO are related, if at all. The NAO, which has been recognized for some time, is the alternating pattern between an intensified subtropical high (Bermuda High) and an intensified polar low (Icelandic Low). This oscillation mostly affects the eastern United States and Europe (NOAA, 2009b).

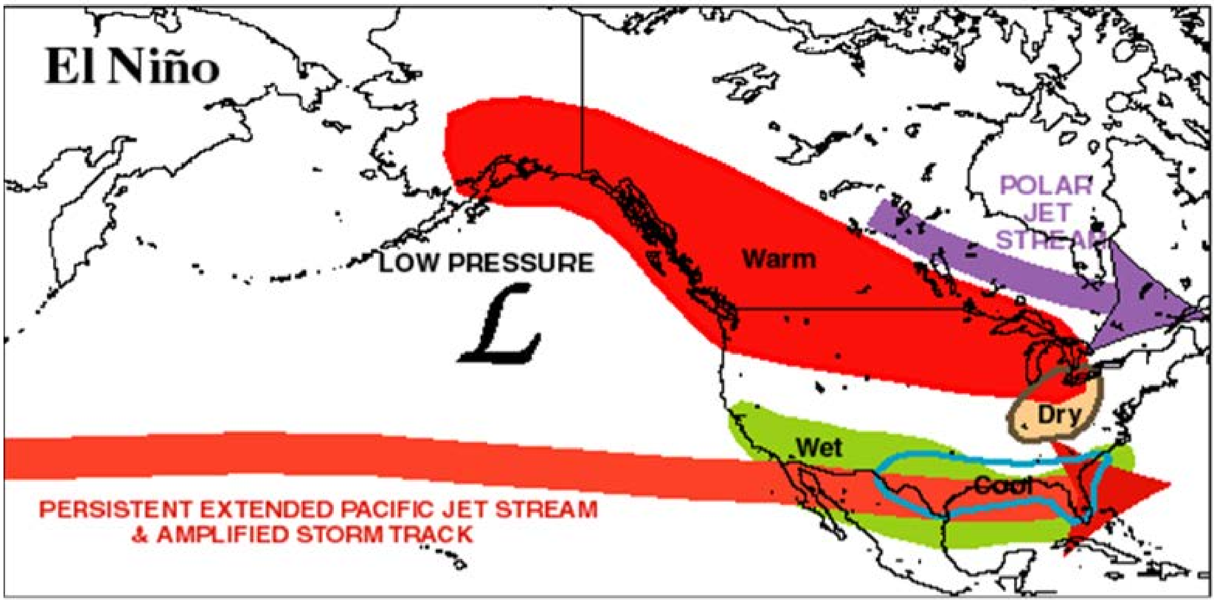
La Niña is the counterpart to El Niño. It occurs when the trade winds are strengthened resulting in more cold water upwelling on the west coast of South America. An anomalous low pressure feature develops over Canada and most of the country experiences colder, wetter winters.

3.6.2 Arctic Oscillation/North Atlantic Oscillation

The Arctic Oscillation (AO) is a fluctuation in sea level pressure over the northern latitudes. The AO is said to be in its positive phase when anomalously low pressure occurs over the mid- to high latitudes. In its negative phase, the pressure pattern is reversed. When the AO index[1] is positive, upper-level winds are stronger and keep cold air in place around the poles making areas to the east of the Rockies warmer than normal (NSIDC, No Date). Storms are steered further north during this phase bringing wetter weather to northern locations such as Alaska and Scandinavia. In contrast, during the negative phase of the AO upper level winds are weaker (NSIDC, No Date) and as a result, cold Arctic air can plunge into North America and storm tracks are maintained over the mid-latitudes (NOAA, 2009b).

The North Atlantic Oscillation (NAO) is sometimes used as a separate term to describe the AO; however, some controversy still remains about how the AO and the NAO are related, if at all. The NAO, which has been recognized for some time, is the alternating pattern between an intensified subtropical high (Bermuda High) and an intensified polar low (Icelandic Low). This oscillation mostly affects the eastern United States and Europe (NOAA, 2009b).

Figure 14: January-March Weather Anomalies and Circulation Pattern



Source: Cook-Anderson (NASA), 2008

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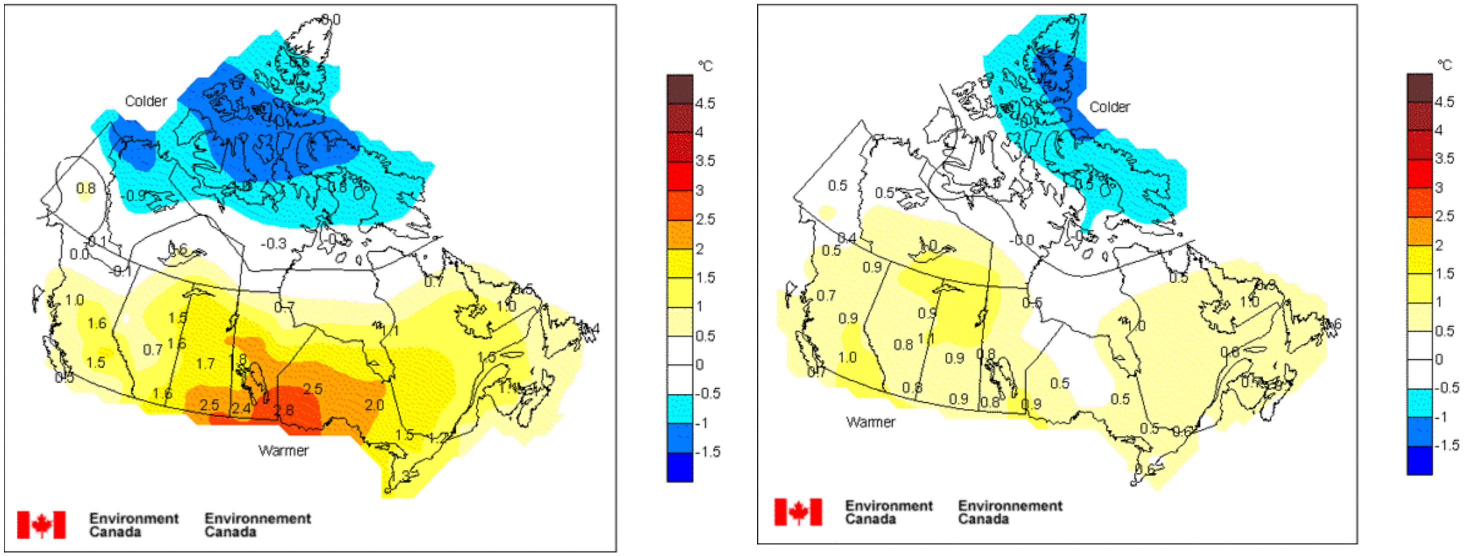
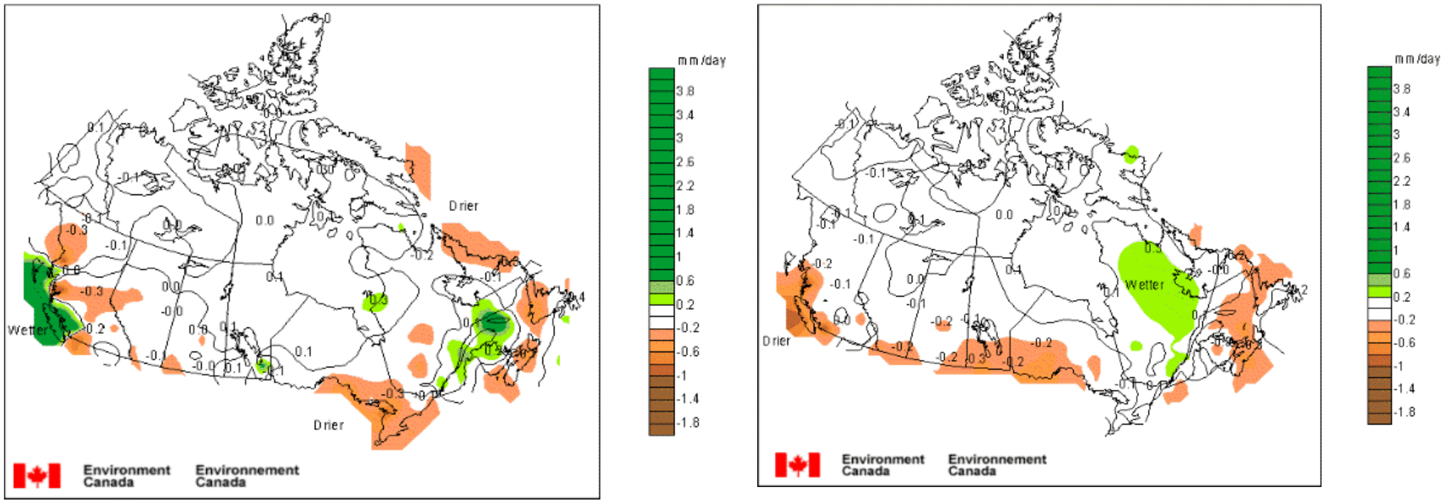
[1] Climate indices are used to characterize the phase of a climate oscillation. For example, a positive AO index would indicate that the AO is in its positive phase (i.e., anomalously low pressure); the magnitude of the AO index quantifies how much the mean sea level pressure deviates from the norm.

Figure 15: Temperature and Precipitation Departure from Normal



A: Dec-Jan-Feb Temperature (Source: EC, 2010b)

B: Mar-Apr-May Temperature (Source: EC, 2010b)



C: Dec-Jan-Feb Precipitation (Source: EC, 2010c)

D: Mar-Apr-May Temperature (Source: EC, 2010c)

3.6.3 Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) is a 20-30 year cycle in sea surface temperature and sea level pressure in the northern Pacific Ocean. This oscillation was first identified in the late 1990's when oscillations in salmon production in the northwest Pacific Ocean were identified by a fisheries scientist (Mantua *et al.*, 1997). The PDO warm (positive) phase is characterized by cooler sea surface temperatures in the central North Pacific Ocean and warm sea surface temperatures along the west coast of North America. Sea level pressure is anomalously low in the North Pacific and high over western North America and the sub-tropical Pacific during the positive PDO phase (Mantua, No Date).

Since this oscillation is not yet well understood, its effects on climate remain unclear; however, many consider this oscillation to be a long-lived ENSO like event and for it to have similar impacts on North America's climate. Recent studies actually show that ENSO events are dependent on the PDO and that they must be in-phase for a strong ENSO event to occur (Mantua, 1997).

4.0 How Do We Project the Future Climate?

4.1 Approaches to Modelling the Future

4.1.1 What is a climate model?

The only way to understand the changes to the climate over long timescales is to use a computer model which simulates the many processes that occur in the atmosphere and oceans; such a model is referred to as a climate model. These models solve complex mathematical equations which define the behaviour of the atmosphere and oceans. The equations used have been derived from a wide range of observations and established physical laws, such as gravity, fluid motion, and the conservation of energy, momentum, and mass. These models have been used over the last 40 years to make projections of future climate using assumptions about increases in greenhouse gas concentrations in the atmosphere. It is more correct to refer to future climates as "projections", not predictions, because it is not possible to know what future emissions of greenhouse gases will be.

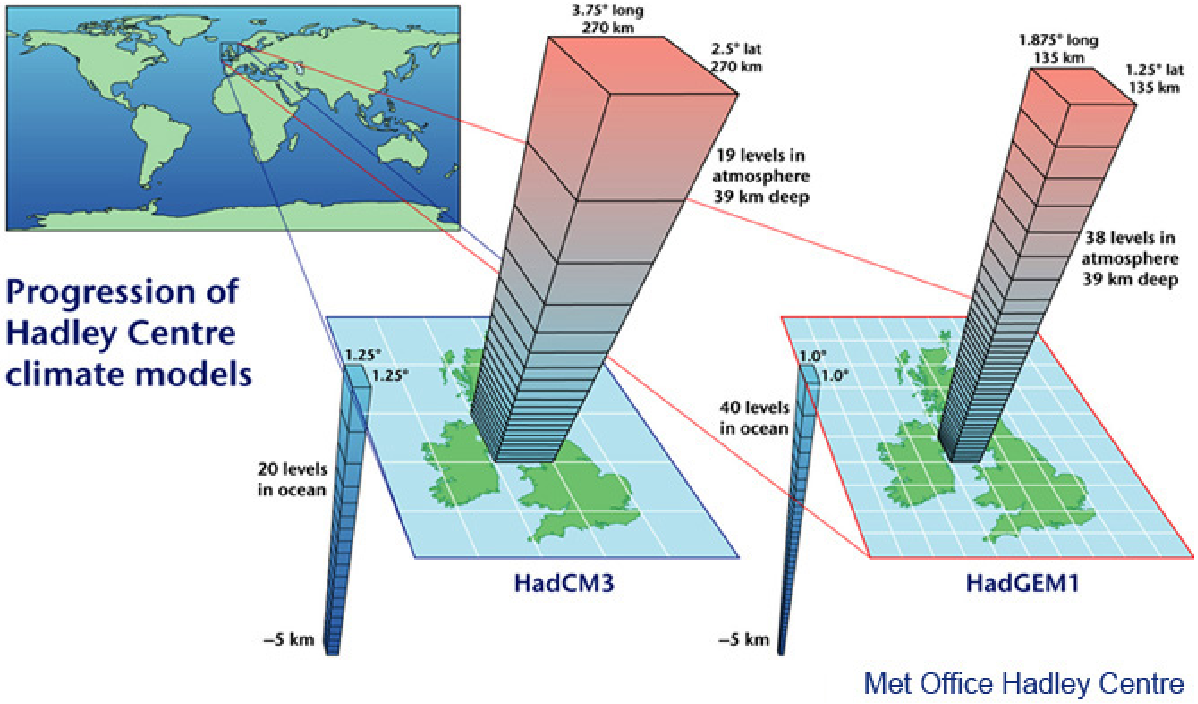
One common question asked is how reliable are climate models, and can we be confident in their projections of future climate? There are three reasons for placing confidence in projections of future climate from these models. The first reason is because climate models are based on well-established physical laws. The science underpinning these laws, and the way they are represented in models is continually improving.

A second reason for placing confidence in climate model projections is because they are able to simulate the main features of the current climate and its variability, such as the seasonal cycles of temperature and rainfall in different regions of the Earth, the formation and decay of the monsoons, the seasonal shift of the major rain belts and storm tracks, the average daily temperature cycle, and the variations in outgoing radiation at high elevations in the atmosphere as measured by satellites. Similarly, many of the large-scale features observed in the ocean circulation have been reproduced by climate models.

Climate models have also been used to simulate past climates. They have been used to simulate climate for the period 1860 – 2000, which includes the period when greenhouse gas emissions and concentrations rose from preindustrial levels to those of the present day. A third reason for placing confidence in climate model projections is because they can reproduce observed changes in the climate over this period.

Climate models are not perfect, and our understanding of the earth's climate and all the interactions is incomplete. Most climate models divide the world into "boxes", and the model simulates an average value for the meteorological variables within each box (such as temperature, wind, humidity, and many others). An illustration of the boxes used by two Hadley Centre climate models, HadCM3 and HadGEM1, is shown in Figure 16. The scale of these boxes (~300 km for HadCM3, and ~150 km for HadGEM1) is much larger than that of some of the key processes, such as convection and cloud formation. Consequently, many climate processes have to be approximated. It would take too much computer time, or is simply beyond the capacity of current supercomputers, to run a climate model with sufficient resolution (~1-2 km) to represent directly some of the key small-scale processes that affect climate over the time periods of interest (e.g., 1860-2000 and 2000-2100). These approximations, together with our incomplete understanding of the climate system, are a major source of uncertainty in climate projections.

Figure 16: Progression of the Hadley Centre Climate Models



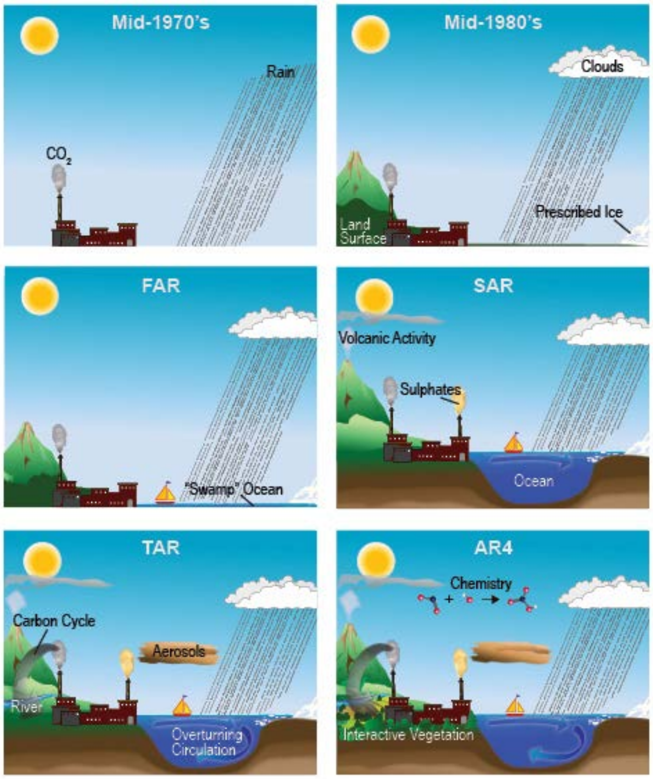
Met Office Hadley Centre

4.1.2. Evolution of Climate Models

Climate models have been, and continue to be, improved. Our knowledge of the real world continues to expand, and the speed and power of computers has increased dramatically, allowing more detail to be included in climate models at smaller spatial scales. The evolution of climate models between the 1970s and 2000s is illustrated in Figure 17. Back in the 1970s, climate models were very simple. Rain was modelled but clouds were not. Concentrations of carbon dioxide (CO_2) were included and the radiation (heating) that determines the effect of CO_2 on temperature was also simulated. Now, state-of-the-art climate models include fully interactive clouds, oceans, land surfaces and aerosols. Some models also include representations of atmospheric chemistry and the carbon cycle. Our knowledge of the real world has improved, which in turn allows us to improve the models.

Early climate models did not represent clouds, although rainfall was simulated. By the mid-1980s, clouds were included in the models together with a crude representation of the land surface. The remaining four panels show the components of a typical climate model used in each of the IPCC Assessment Reports: First (FAR, 1991), Second (SAR, 1995); Third (TAR, 2001) and Fourth (AR4, 2007). When the FAR was published, oceans were represented for the first time. In 1995 (SAR), ocean circulation was better represented, and sulphate aerosol particles were also included. By 2001 (TAR), the carbon cycle, where CO_2 is exchanged between vegetation, soils and the atmosphere, was represented for the first time along with a larger number of aerosol particles (e.g., dust, black carbon from combustion). Modelling of the ocean circulation had also improved. In 2007 (AR4), many models had interactive vegetation, so that the potential changes in forest, grasslands and other types in response to change could be modelled. Atmospheric chemistry, describing reactions of methane, ozone (which are important greenhouse gases), and other trace gases was also included in some models. The resolution of the climate models (both horizontally and vertically) has also increased during the last 20 years.

Figure 17: Evolution of climate models between the 1970s and 2000s



This figure © IPCC 2007

The climate system is highly complex, with many potential interactions and feedbacks. Over the years, more of this complexity has been included in models. Clouds affect the heating and cooling of the atmosphere. For example, on a cloudy day, less radiation (heating) from the sun reaches the Earth's surface and temperatures are lower than when the skies are clear. On the other hand, on a cloudy night the heat generated during the day is trapped and the temperature near the surface remains relatively warm. However, it is not just the amount of cloud that is important, but also the detailed properties of the cloud. Thin cirrus clouds at high altitudes let sunlight through and trap infra-red radiation, causing the surface climate to warm. Low level clouds reflect incoming sunlight and trap little infra-red radiation. Their dominant effect is to cool the surface.

The oceans take much longer to warm up than the land. They also distribute heat around the world. For example, the Gulf Stream in the North Atlantic Ocean brings warm water from the tropical Atlantic up to northern Europe, and has a strong effect on the temperatures that the UK experiences. The land surface influences how much radiation is absorbed at the surface. An area that is covered in trees will be dark and will heat up more by absorbing more radiation. Areas likes Canada's north, covered in ice will reflect more radiation and absorb less heat.

Aerosols are atmospheric particles, such as sulphate and black carbon that are produced naturally from volcanoes and forest fires, as well as by humans from burning fossil fuels for transport, power generation and other industrial activities. They generally have a cooling effect on climate, by reflecting incoming sunlight (the so-called "global dimming" effect) and by changing the properties of clouds (by making them longer lived and more reflective). The presence of man-made aerosols is reducing global warming in the short term. The chemistry of the atmosphere and the carbon cycle determine how much methane and carbon dioxide remains in the atmosphere. Currently, the biosphere (plants, soils and phytoplankton) absorbs half of the carbon dioxide that humans produce. The latest climate model projections suggest that this will not continue indefinitely and that some parts of the biosphere (in particular soils) could start to release carbon if temperatures increase too much.

Increases in computing power are also a key part of the improvement in climate models. Very often climate modelling capability has been limited by the power of computers available. In the 1970s, as well as including only limited science, the models included very little detail and could only be run for very short periods. A typical model from this era divided the world into boxes 600 km across and used just five vertical levels to represent all the vertical structure in the atmosphere. These models were used to predict changes on timescales of months, up to a year. They were mainly used to understand climate processes rather than to predict the future. The latest Hadley

Centre models, HadGEM2 and HadGEM3 (which are typical of current state-of-the-art models), use 135 km boxes with 38 levels in the vertical, and includes all of the complexity of the climate system outlined above. Other versions of the HadGEM3 model have even higher resolutions (boxes as small as 60 km), up to 85 vertical levels and include a representation of the stratosphere.

The massive increases in computer power since the 1970s have been used in several ways for climate modelling. The climate models have higher resolution which is used to give more regional detail. In fact, the changes in climate modelling between the 1970s and the present day as outlined in Figure 17 required 256 times more computer power. Representations of all the key processes identified as important for climate change are included in various versions of the climate models. Much longer projections are run, typically reproducing the last 150 years and predicting the next 300 years. Many more experiments are run with different versions of the models so that the level of certainty in the projections of future climate can be quantified (Murphy et al., 2004; Collins et al., 2006).

4.1.3. How are Climate Projections Made?

We cannot know the future for certain. In order to perform a simulation of future climate, plausible scenarios are required. Many climate projections use scenarios developed by the IPCC, which are described in the Special Report on Emission Scenarios (IPCC, 2000); these scenarios are often called the 'SRES scenarios'. These scenarios are the driving force behind all future assessments of climate change.

Future greenhouse gas (GhG) emissions are the product of very complex interactions between demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. Scenarios are projections of how the future might unfold and are an appropriate tool with which to analyse how different driving forces may influence future GhG emissions. They assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation.

The SRES scenarios do not include implementation of the United Nations Framework Convention on Climate Change (UNFCCC) or the emissions targets of the Kyoto Protocol. However, GhG emissions are directly affected by non-climate change policies designed for a wide range of other purposes. Government policies can influence the GhG emission drivers such as demographic change, social and economic development, technological change, resource use, and pollution management. This influence is broadly reflected in the storylines and resultant scenarios. No probabilities have been placed on any of the scenarios, so they are considered equally likely to represent possible future emissions.

Climate models generally need greenhouse gas concentrations, not greenhouse gas emissions. Concentrations of greenhouse gases are obtained from Integrated Assessment Models (IAMs). These models simulate the interactions between demographic development, socio-economic development, and technological change, and calculate greenhouse gas concentrations from the emissions. These concentrations are then used by climate models to project how the climate could change under that scenario.

Uncertainty in climate projections originates from three main sources; an incomplete understanding of the Earth's climate system and the way it is represented in climate models, natural variability, and the future emissions of greenhouse gases. Despite the uncertainties, all models project that the Earth will warm in the next century, with a consistent geographical pattern.

4.2 The Approach Used for this Project and Why

4.2.1 The Climate Models HadCM3 and PRECIS

For the work presented in this report, climate data from a version of the HadCM3 global climate model (Gordon et al., 2000) was used to drive the regional climate model, PRECIS. PRECIS has a very similar structure to HadCM3. It uses the same mathematical equations which describe the atmosphere as HadCM3, and has the same vertical structure. The biggest difference is that the horizontal resolution of PRECIS is 25 km or 50 km, whereas that of HadCM3 is about 300 km.

The HadCM3 model has been very well characterised. Collins et al. (2001) examined the internal climate variability of a 1000 year long integration of HadCM3 where concentrations of greenhouse gases, solar forcing and other external factors were held at constant levels. The climate simulated by HadCM3 was stable throughout the simulation, and did not drift (e.g., there is no trend in global mean temperatures). The modelled representation of known modes of the climate, such as the El Niño-southern oscillation (ENSO), and the North Atlantic Oscillation (NAO) was similar to observed patterns. The spatial patterns of surface temperature variability are similar to observations, with greater variability over land, especially northern hemisphere continents, than over the oceans. Given that the structure of PRECIS is very similar to HadCM3, we can be confident that it too will simulate regional climate well.

It is important to remember that no climate model is perfect. Our understanding of the climate system is incomplete. There may be local topographical or other effects on climate in locations (e.g., the city of Toronto) which have not been captured by the regional climate model. Many important processes which can affect rainfall, such as the flow of air upwards and over hills, convection and cloud formation, take place at spatial scales smaller than the model resolution. These processes cannot be modelled explicitly, and so they must be estimated using relationships with variables such as wind, temperature and humidity calculated at the scale of the model (here, 50 km). These relationships are called parameterisations. By their nature, parameterisations are approximations of the actual process they represent, and the equations they contain will use parameters whose values are uncertain. Previous work has shown significant improvements in the representation of, for example, extreme rainfall using very high resolution (1.5 km) climate models, which have a better representation of the diurnal cycle of rainfall and of internal cloud dynamics. However, such models are computationally very expensive to run.

PRECIS does not calculate the depth or cover of snow. The only data available from the model are the mass of snow per model grid box. The formulae developed by Roesch et al. (2001) were used to calculate the snow covered fraction of each grid box and the depth of snow from the snow mass. These formulae were derived using observed snow masses, depths and coverage. The snow mass produced by the model has units of kg m^{-2}. If the snow were melted, the water produced would have a depth in mm equal to the snow mass, since 1 kg (H_2O) m^{-2} has a volume of 1 litre, which would have a depth of 1 mm if spread over an area of 1 m^2. The first stage is to calculate the snow density ρ_s (in kg m^{-3}) from the snow mass, S_m, as shown below:

$$\rho_s = 188.82 + 0.419 \times S_m$$

ρ_s is limited to a maximum value of 450 kg m^{-3}. The snow depth d_s (in m) is then simply calculated by dividing the mass by the density,

$$d_s = S_m / \rho_s$$

The snow cover fraction f_s is found from S_m using the equation below:

$$f_s = 0.95 \times \tanh (0.1 \times S_m)$$

Over the last few years, the North American Regional Climate Change Assessment Program (NARCCAP) has been set up. NARCCAP is an international program that will serve the climate scenario needs of both the United States and Canada. One of the aims is to systematically investigate the uncertainties in regional scale projections of future climate. NARCCAP will produce high resolution climate change scenarios using multiple regional climate models (RCMs) driven by meteorological data from multiple global climate models. This project has not yet finished, and the model results are still being analysed.

4.2.2 Overview of Approach Used

The best resolution available for future weather from Global Climate Models (GCMs) is about 150x150 km. The output of these GCMs can be used as input to more detailed

Regional Climate Models (RCMs). The PRECIS RCM was used to provide the boundary conditions for future GTA weather for this project. The RCM minimum scale available is about 25x25 km. At this scale a lot of local factors (the escarpment and the Oak Ridges moraine) have started to influence the resulting weather so there is some inherent error involved.

Since the purpose of this study was to examine the local influences, something more than an RCM was required. SENES decided to use a state-of-the-science weather forecast model (WRF-NMM within the FReSH Forecasting System) driven by the 6-hourly 50x50 km PRECIS RCM output. This allowed all of the local influences (on the scale of about 1x1 km) to be included in the simulation and the outputs would then show the differences across the GTA.

Figure 18 is a simplified diagram of how future weather or future climate was projected for this project.

SENES started with the climate normals[3] covering the period 2000 through 2009 as the base period for this study. SENES then analyzed this period of 10 years on an hourly basis using a state-of-the-science weather model (WRF-NMM) which SENES runs internally as part of its FReSH Forecasting System. This model simulation used a 1x1 km grid over the GTA and was driven by the 6-hourly analysis fields (global fields with a spatial resolution of about 40x40 km created from the global observations taken every 6 hours at an approximate spacing of 300x300 km) archived by the National Centre for Environmental Prediction (NCEP). The 10-year model output data set from FReSH was then examined for major storms, extreme weather and climatological parameters as follows:

- average temperature;
- average minimum temperature;
- average maximum temperature;
- extreme minimum temperature;
- extreme maximum temperature;
- degree days;
- gust wind;
- rainfall;
- snowfall;
- total precipitation and
- return periods for rainfall.

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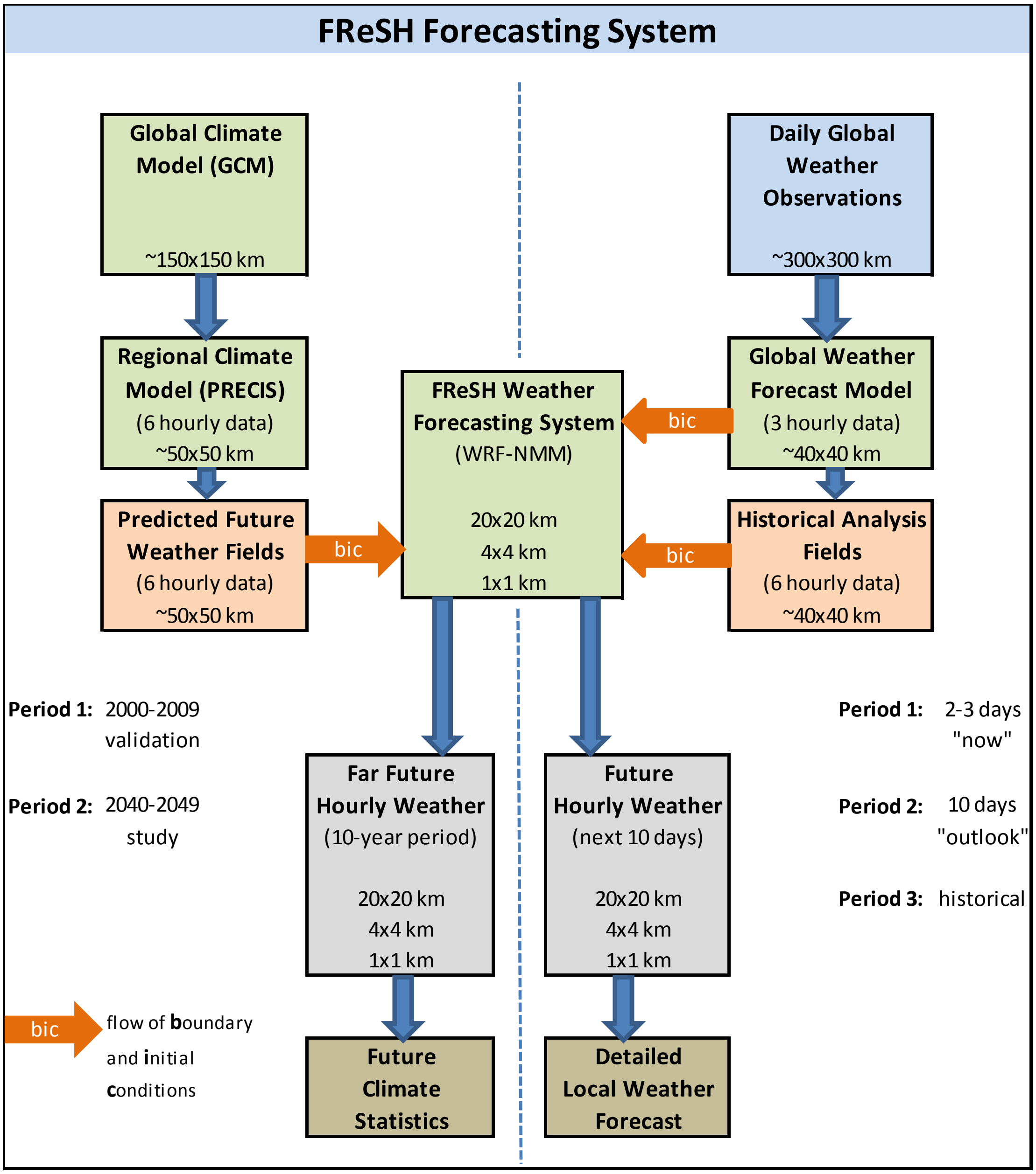
[3] Climate Normals are the data created to summarize or describe the average and the extremes of climatic conditions of a particular location. At the completion of each decade Environment Canada updates its climate normals for as many locations and climatic characteristics as possible. The latest climate normals provided by Environment Canada are based on stations with at least 15 years of data from 1971-2000.

Figure 18: Schematic of How Future Weather and Climate is Determined



This set of statistics formed the baseline summary of current climate for the Greater Toronto Area.

The second step was to use the 50x50 km output from the Regional Climate Model (RCM) called PRECIS that represents a 10-year period in the future (2040-2049) driven by the IPCC maximum impact scenario A1B. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in the mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A1B scenario used here represents a balanced consumption and pollution release across all energy sources. The six hourly values output by the PRECIS Regional Climate Model were used as input boundary conditions for the FReSH System to develop an hour-by-hour simulation of the future on a 1x1 km grid for the GTA. This 10-year data set was examined for major storms, extreme weather and the other climate parameters listed above. This data base is comprised of 346 days, the limit of the regional input data available for each year. For estimating the frequency of occurrence each modelled month was corrected for the difference in the number of modelled vs. actual days.

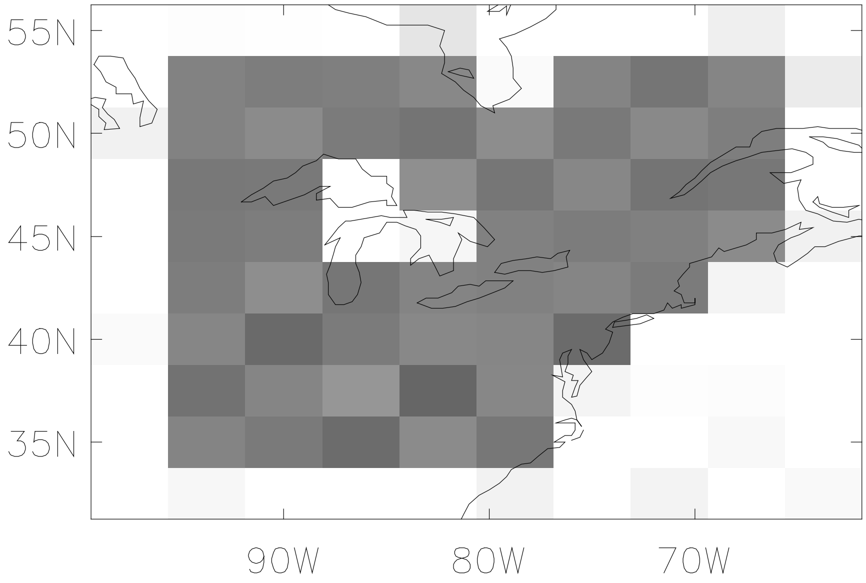
The third step was to compare the outputs from the present and the future climate simulations in order to provide insight what Durham's future weather and climate will be.

4.3 Introduction to the Climate Model Used

4.3.1 Introduction

Not all climate models show the same thing. As a result often average results over a number of models are used. Our partner, The UK Met Office Hadley Centre, has produced a collection (ensemble) of perturbed physics global climate model simulations in order to assess the levels of certainty in the climate projections (Collins et al., 2006). The ensemble consists of 1 standard climate model and 16 versions where uncertain parameters within the atmospheric component have been changed (perturbed) slightly from their normal values. The global climate model used, HadCM3, has a horizontal resolution of 3.75º longitude and 2.5º latitude, and 19 vertical levels, extending from the surface to 10 hPa. It has components that represent the integrated exchanges of energy and matter within the atmosphere and the oceans which are fully coupled. The ability of the each member of this ensemble to reproduce the climate over the area around the Great Lakes for the period 1961-1990 has been assessed (see shaded area in Figure 19) and used to assess the performance of the various ensemble members in the global model. The ensemble member which most closely reproduces the observed climate of the Great Lakes region was selected to drive the regional climate model, PRECIS. However, the projected future change in climate from this ensemble member may not necessarily reflect the actual future situation; it is just one illustrative projection. Datasets, describing four key meteorological variables, were created from the ensemble members, which could be compared with observations of the same four variables; these datasets are termed 'climatologies'. A similar set of model simulations has also been run where uncertain parameters within the ocean component of the model were perturbed, but the change in the climate projections was much smaller than when the atmospheric component was perturbed.

Figure 19: Great Lakes Region Used to Assess the Perturbed Physics Ensemble



The shaded area represents land (shaded) and water (unshaded) as seen by the Global Climate Model.

4.3.2 Generation of Climatologies

Climatologies for surface pressure, temperature, precipitation and height of the 500 hPa pressure surface were generated from gridded observations which are readily available for the entire globe. The climatologies consist of 30 years of monthly mean values (except precipitation, which are monthly totals) for the period 1961-1990. This period is commonly used as a 'climatologically normal period' for assessing model performance. The observations are available on different horizontal resolutions to the climate model, and so were interpolated to the same horizontal resolution as the global climate model.

4.3.3 Comparisons of Climate Model Ensemble with Observations

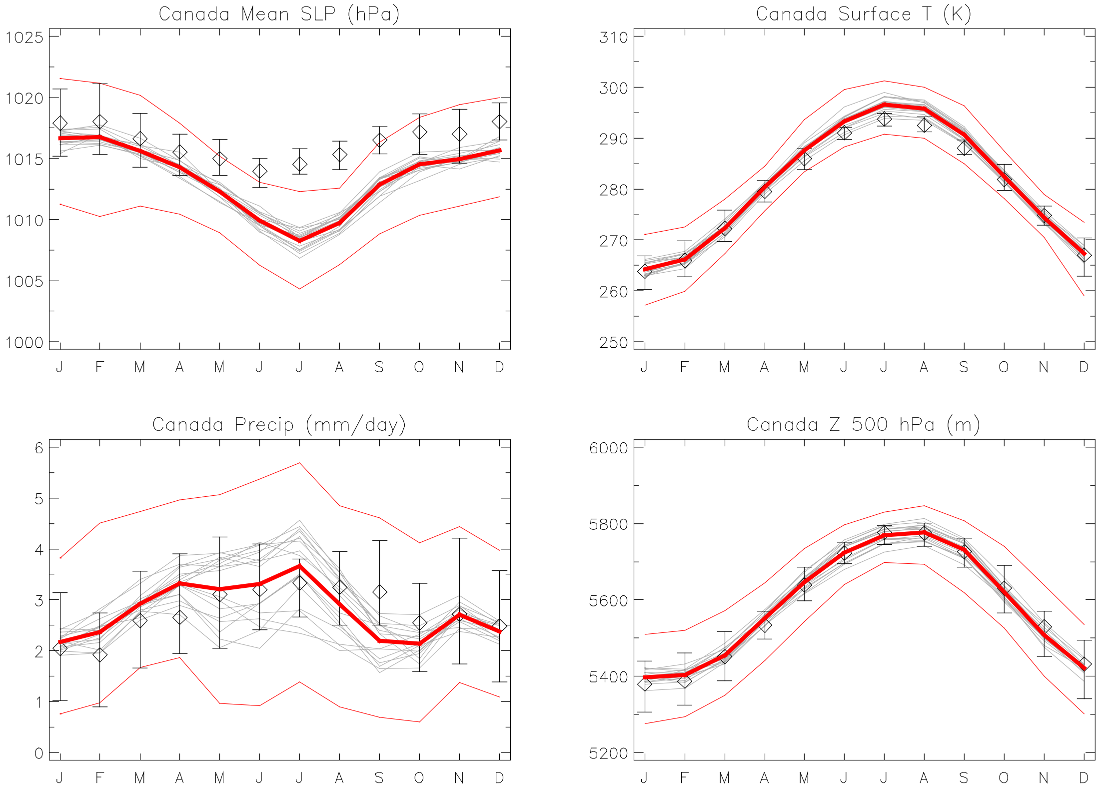
Observations and model data for the shaded region shown in Figure 19 were extracted and used in the assessment of the global climate model, as this area was simulated in more detail using the regional climate model, PRECIS. A comparison of the entire perturbed physics ensemble with the four sets of observations is shown in Figure 20.

The data shown in Figure 20 are monthly mean modelled parameters at 500 mb over the Great Lakes Region averaged over the period 1961-1990. The ensemble reproduces the observed temperatures and heights at 500 hPa very well, although there is some spread in the precipitation in this region. There is a small bias in the modelled surface pressures as a result of the way each ensemble member was initialised, but this will not have a significant impact on the results.

The climate model ensemble members were then ranked using the temperature and precipitation data. For each ensemble member, the modelled temperature and precipitation amounts were plotted separately as a function of the observed data, and a straight line fitted through the points. The correlation coefficients of the fitted straight lines were then used to rank the ensemble members. For temperature, all correlation coefficients were greater than 0.995, whereas there was a considerably greater range for precipitation. The highest correlation coefficient for precipitation was 0.83, and this ensemble member (known as Quantifying Uncertainty in Modelling Predictions [QUMP] 15) was selected to drive the regional climate model.

In Figure 20, the observations are marked as diamonds, and the error bars show the 5th–95th percentile range (which is equivalent to 2 standard deviations). Each perturbed physics ensemble member is shown as a grey line and the ensemble mean by the thick red line. The thin red lines indicate the 5th–95th percentile range of the entire perturbed physics ensemble.

Figure 20: Comparison of Modelled vs. Observed Parameters (1961-1990)



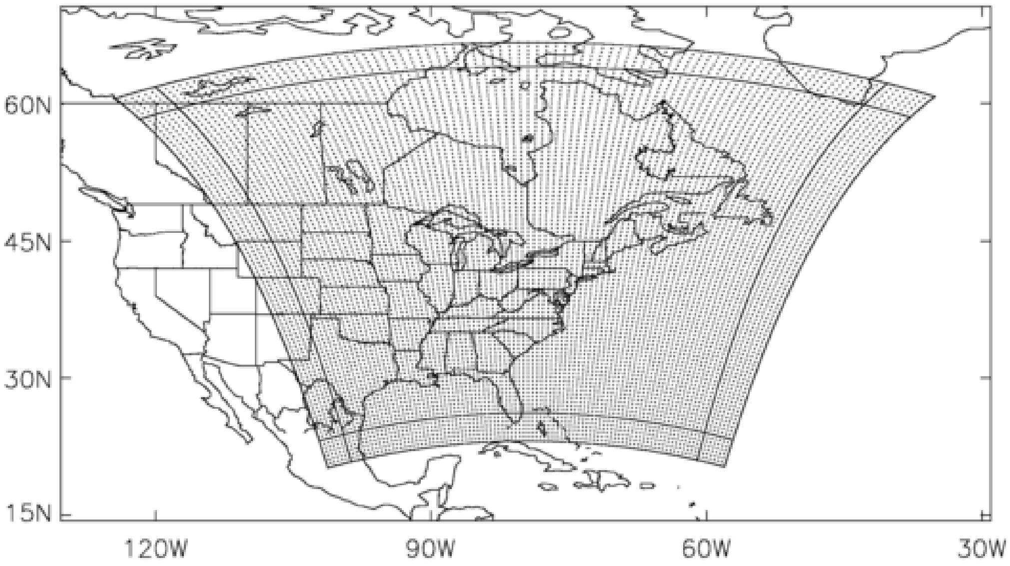
4.3.4 Global and Regional Models

The resolution of the global climate model, HadCM3, is approximately 300 km over the Great Lakes region. Consequently, the global model cannot provide climate projections of key variables (such as temperature and precipitation) on small spatial scales needed for impacts assessment. In order to provide detail on smaller spatial scales, a regional climate model is required.

The regional climate model used for this work was PRECIS. A similar (but not identical) version of this model was used as part of the process to generate the UKCP09 climate projections for the UK government (Murphy et al., 2009). PRECIS itself has been distributed to many countries where it has been used to produce high resolution climate change information. PRECIS is based on the global climate model HadCM3. It uses many of the same representations of meteorological processes and has the same vertical structure as HadCM3. It has a horizontal resolution of approximately 50x50 km over the Great Lakes Region. A map of the domain used by PRECIS is shown in Figure 21. The inner region of Figure 21 is the area from which the model results are extracted. The climate of the outer border is a blend of the regional model climate and the driving global model data, and are not analysed further.

Regional climate models only simulate climate over small regions, and so boundary conditions of key meteorological variables (such as wind speed and direction, humidity, and temperature) are needed at the edges of the regional model domain. The boundary conditions were supplied from the global climate model simulation selected above, at 6 hourly intervals. These boundary conditions are interpolated in time and space by PRECIS to provide the required data at every model time step (30 minutes). The climates simulated by the global model and PRECIS over the Great Lakes region will be essentially the same. PRECIS adds detail to the selected region, but is dependent on the GCM providing the boundary conditions to initiate and maintain the modelled simulation. There are still large uncertainties in the regional patterns of climate change from GCMs.

Figure 21: **Map Showing the Regional Climate Model (PRECIS) Domain**



4.3.5 Comparison of Climate Model Output with Observations

It is important to compare calculated values, as obtained from climate models through simulations of meteorological variables, with observed values of those variables. When a climate simulation is undertaken using known greenhouse emissions, the modelled climate will, on average, be close to the observed climate, but it is highly unlikely the climate from a single year in the model will perfectly match the observations in the same year. One reason for this is the initial conditions used by the model. Before a simulation can be made, values of meteorological variables (for example, temperature, winds, clouds) at all locations within the model must be specified. These conditions are usually taken from an existing simulation, but over the selected time period of the climate simulation, the influence of the initial conditions is very small. However, if the same climate scenario was used, but the model was initialised with slightly different initial conditions, the climate generated in individual years would not match the original run, owing to internal variability of the model. However, over many simulations the average climate for the selected time period, or the longer term average climate, would be the same.

4.4 Introduction to the Weather Model Used

4.4.1 The FReSH System

The SENES FReSH Forecasting System is a state-of-the-science weather modelling system developed by SENES in-house to predict/simulate 3-dimensional meteorological conditions over a study area, from the surface up to a height of 20 km. The FReSH system is comprised of four different components, which are:

- the pre-processor;
- the weather model;
- the post-processor; and
- the graphics package.

These are described in more detail in the following sections.

4.4.1.1 Pre-Processor

The pre-processor collects and formats initial and boundary conditions from the National Center for Environmental Prediction (NCEP) analyses on a 12 km horizontal resolution grid. These analyses incorporate all available weather observations over North America (surface upper air, radar etc.). The FReSH pre-processor creates model boundary conditions every 6 hours. It also interpolates directly from the native grid (Lambert Conformal rotated projection) into the model's grid system thus avoiding an additional module for interpolation through a Lat/Long grid.

The pre-processor uses time-dependent surface fields that vary in horizontal resolution from 12 km to 40 km. The resolution of these data is modified to match the selected output resolution of the FReSH model (in this case 1x1 km). The surface data used by the model (obtained from NCEP) are as follows:

- soil temperature (4 levels);
- soil wetness (4 levels);
- water-surface temperature;
- snow and ice cover; and
- snow depth.

The system also uses the following time-independent surface fields (created once for the selected area of model integration):

- soil type (resolution 4x4 km); Source: United Nations Food and Agriculture Organization (FAO) soil data set;
- vegetation type (resolution 1x1 km); Source: United States Geological Survey (USGS);
- monthly vegetation fraction (which is modified during the model run), NCEP climatology; and
- seasonal albedo (which is modified by actual surface characteristics); Source: NCEP climatology.

The pre-processor uses global GTOPO-30 USGS terrain data on 1x1 km resolution, and creates a topographic data set for the FReSH model integration area. The terrain data (heights measured in metres) used in this analysis is illustrated on Figure 22 which also shows the computational grid used.

Figure 22: Terrain Data Used for the FReSH Small Modelling Domain (1x1 km)

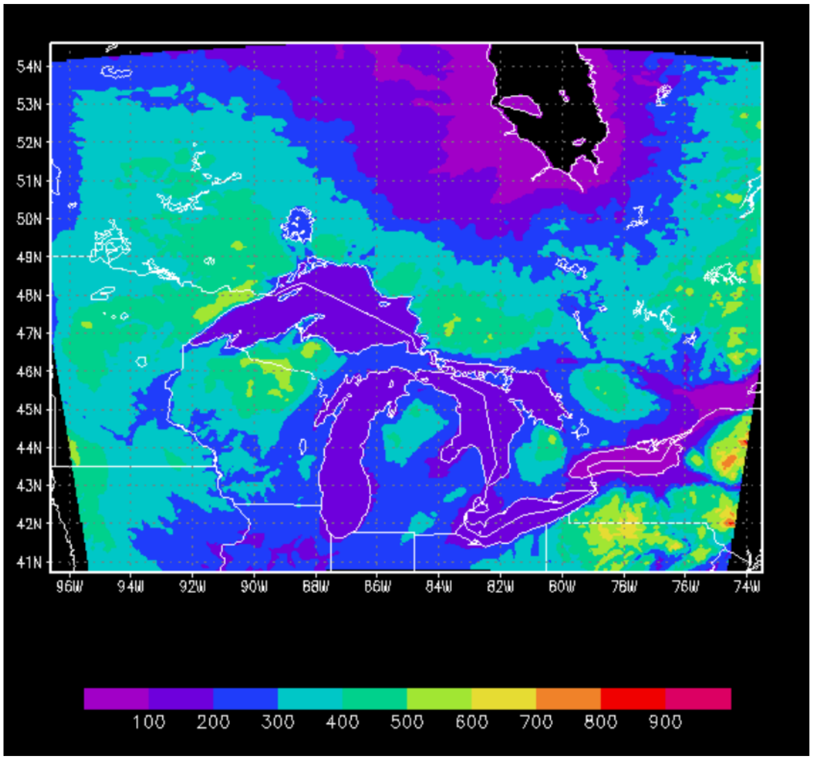
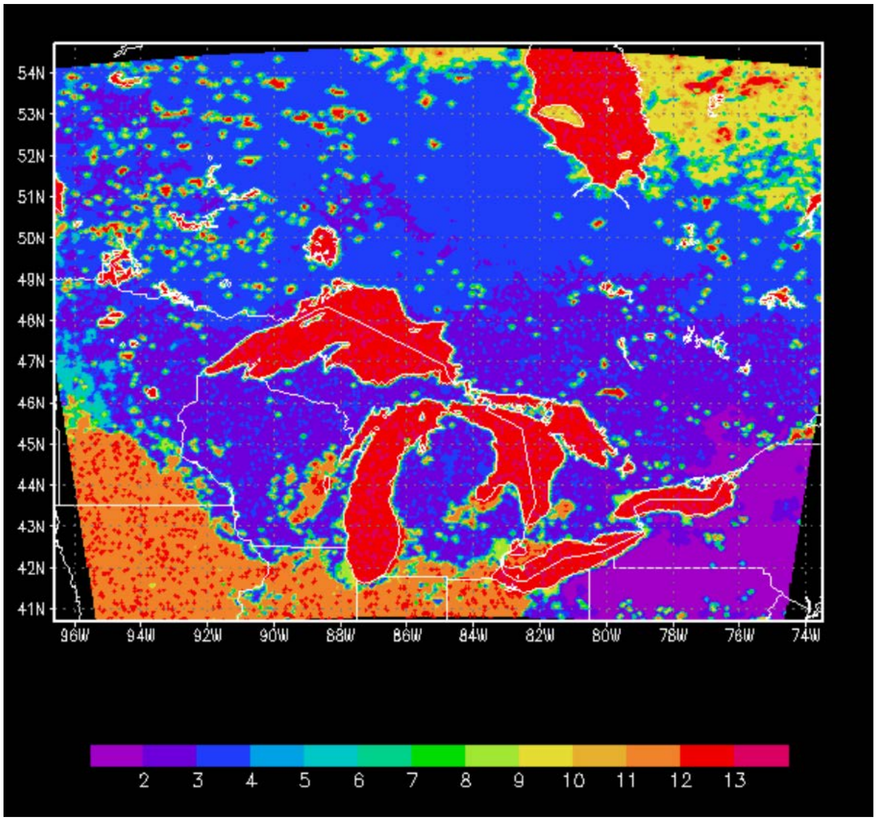


Figure 23 shows the vegetation data used as an input to FReSH system, based on GTOPO-30 global USGS land use data.

Figure 23: Vegetation Data Used in the FReSH Small Modelling Domain (1x1 km)



Vegetation Scale:

C1: Broadleaf-Evergreen Trees (Tropical Forest)
C2: Broadleaf-Deciduous Trees
C3: Broadleaf and Needleleaf Trees (Mixed Forest)
C4: Needleleaf-Evergreen Trees
C5: Needleleaf-Deciduous Trees (Larch)
C6: Broadleaf Trees with Groundcover (Savannah)
C7: Groundcover Only (Perennial)
C8: Broadleaf Shrubs with Perennial Groundcover
C9: Broadleaf Shrubs with Bare Soil
C10: Dwarf Trees and Shrubs with Groundcover (Tundra)
C11: Bare Soil
C12: Cultivations (The Same Parameters as For Type 7)
C13: Glacial (The Same Parameters as For Type 11)
Red Colour – Represents Water

4.4.1.2 The Weather Forecast Model

The main component of FReSH system is the WRF-NMM[4] Weather Forecast Model. The NMM model is state-of-the-science numerical limited area model. The main features of the model dynamics are:

- it is a fully compressible, non-hydrostatic model with an hydrostatic option;
- the terrain following hybrid pressure sigma vertical coordinate is used;
- second order energy and enstrophy conserving (Janjic, Z. I., 1984);
- the grid staggering is the Arakawa E-grid;
- the same time step is used for all terms;
- time stepping: horizontally propagating fast-waves: forward-backward scheme;
- vertically propagating sound waves: Implicit scheme;
- advection (time): horizontal: the Adams-Bashforth scheme; and
- vertical: the Crank-Nicholson scheme.

The physics package is based on:

- explicit Microphysics: Ferrier (Ferrier, B. S., *et al,* 2002);
- cumulus parameterizations: Betts-Miller-Janjic, Kain-Fritsch with shallow convection (Kain, J. S., and J. M. Fritsch, 1993);
- free atmosphere turbulence above surface layer: Mellor-Yamada-Janjic (Janjic, Z. I., 1996a);
- planetary boundary layer: Mellor-Yamada-Janjic (Janjic, Z. I., 1996b);
- surface layer: Similarity theory scheme with viscous sub layers over both solid surfaces and water points (Janjic, 1996b);
- radiation: longwave radiation: GFDL Scheme (Fels-Schwarzkopf);
- shortwave radiation: GFDL-scheme (Lacis-Hansen) (Schwarzkopf, M. D., and S. B. Fels, 1991); and
- gravity wave drag: none.

Two different grids were used for the local simulations – a 4x4km grid (Figure 24) over a larger area to ensure that the inflow to the GTA was correct and a 1x1km grid (Figure 25) over the GTA to allow local details to be properly incorporated. Both figures also show the variation in terrain height across the modelling areas.

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[4] NMM – Non-hydrostatic Mesoscale Model. NMM has been operational since June, 2006 in the National Centre for Environmental Prediction (NCEP) Washington. (Janjic, Z. I., 2003a)

Figure 24: 4x4 Kilometre Gridded Area Used for Upwind FReSH Modelling

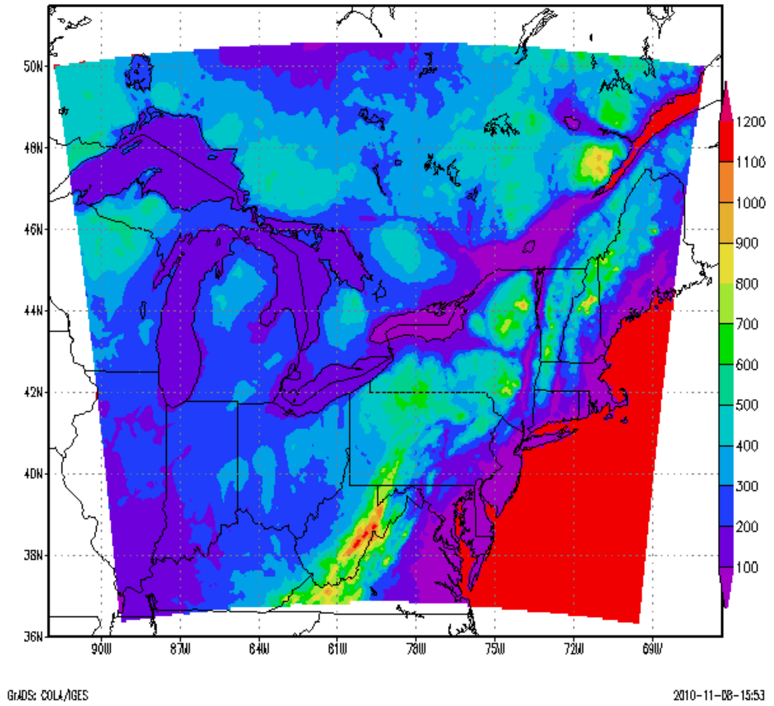
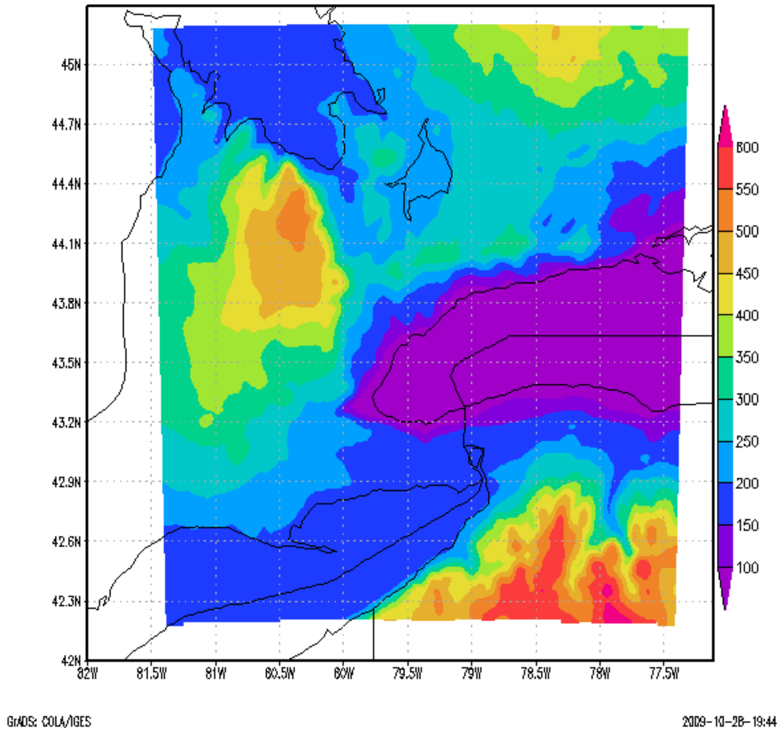


Figure 25: 1x1 Kilometre Gridded Area Used for Detailed GTA FReSH Modelling



4.4.1.3 Post Processor

The post processor has several functions: to interpolate the model outputs from the model levels to the standard-pressure levels, to interpolate horizontally meteorological data produced by model from the model grid to the latitude-longitude or other specific grid and to prepare model results for a specific application. The NMM model outputs are in standard World Meteorological (WMO) GRIB format and can be tailored to suit different application needs.

4.4.1.4 Graphics Package

A graphical output module has also been incorporated into the FReSH system. This permits the resulting data to be plotted and viewed. The Grid Analysis and Display System (GrADS) is used for visualization of hourly model outputs.

The FReSH system was set-up over the study area to match the regional modelling domain to capture part of USA, Great Lakes and the extended GTA area on 4x4 km (Figure 24) resolution and was nested down to 1x1 km (Figure 25) to refine and resolve thunderstorms as well for coupling with the CALMET model over GTA. The computational domain had 123,201 points at 39 vertical layers and grid size of approximately 4x4 km. Typical run time for this application over Ontario was ~2 minutes per hour of simulation on a dedicated Dual Core Pentium *Linux* machine.

In general, NMM is able to match the observed wind speeds, wind directions and precipitation data and has been extensively tested in different locations around the world. This gives confidence that the FReSH results can be used for further refined analyses.

4.4.2 How is FReSH Driven?

Table 3 outlines how a typical weather forecast model is run and how it was used for this project. It was run in two ways: (1) to simulate current conditions and (2) to simulate future conditions. For current conditions, the 6-hourly, 32x32 km gridded analysis fields for the period 2000-2009 were input as boundary and starting conditions from which the FReSH System produced 4x4 km hourly simulations over a broad area of southern Ontario. The FReSH System was then run again using the 4x4 km, 3-dimensional fields as input to produce a detailed hour-by-hour simulation over 10 years on a 1x1 km grid over the GTA and at some specifically selected output locations of interest across the GTA. For future conditions, the 6-hourly climate projections on a 50x50 km grid from the PRECIS Model were used as the boundary and starting conditions for the FReSH simulation which produced an hour-by-hour simulation on a 4x4 km grid over a broad area of southern Ontario. The FReSH System was then run again using the 4x4 km, 3-dimensional hourly fields as input to produce a detailed hour-by-hour future simulation over 10 years on a 1x1 km grid over the GTA.

Table 3: How Weather Models are Used

<table>
<tr><th colspan="8">Current Weather Forecasting System</th></tr>
<tr><th>Approach</th><th>Observations</th><th>Data Assimilation</th><th>Model</th><th>Produces</th><th>Model</th><th>Produces</th><th>City Forecasts</th></tr>
<tr><td>TYPICAL WEATHER FORECAST</td><td>world-wide every 12 hours on a spacing of ~350km</td><td>4-dimensional balancing of forces to produce global analysis fields every 12 hours</td><td>global forecast</td><td>fields every 3-hours out to 150 hours, then every 12 hours out to 384 hours, on a 40x40grid</td><td>WRF-NMM or other regional forecast</td><td>every 3-hours on a 15x15km grid over North America</td><td>Washington State uses MM5 down to 4x4 km with outputs every 3 hours, interpolates to 1-hour forecasts</td></tr>
<tr><td>SENES "NOW" WEATHER</td><td></td><td></td><td></td><td>↳</td><td>FReSH NMM</td><td>every hour on a 4x4 km grid over area of interest</td><td>use CALMET to give 200x200m outputs every hour (or less)</td></tr>
<tr><td>SENES HISTORICAL WEATHER</td><td></td><td></td><td></td><td>use 365 days of 6-hourly analysis fields out to 24-hours</td><td>FReSH NMM</td><td>every hour on a 4x4 km grid over area of interest</td><td>use CALMET to give 200x200m outputs every hour (or less)</td></tr>
<tr><th colspan="8">Climate Weather Forecasting System</th></tr>
<tr><td>SENES CLIMATE CHANGE</td><td></td><td></td><td>PRECIS or other Regional Climate Model</td><td>6-hourly fields for one year based on a climate scenario on a 50x50 km grid</td><td>FReSH NMM</td><td>every hour on a 4x4 km grid over area of interest</td><td>nest down to 1x1 km or use CALMET to give 200x200m outputs every hour (or less)</td></tr>
</table>

The key attributes of the FReSH Forecasting System compared to other weather forecast models are given in Table 4.

Table 4: Key Weather Model Attributes of the FReSH System

Key Parameter	Other Models	FReSH System
Horizontal Resolution in km	40x40 internationally 12x12 in North America	4x4 for best dynamics 1x1 in local areas
Best Tested Horizontal Resolution	12x12 km	0.1x0.1 km
Time Step Resolution	3 hours	20 seconds aggregated up to 1 hour
Best Time Step Resolution	Interpolated to 1 hour	20 seconds

4.5 How Good is the 10-Year Simulation Compared to the Observed Data?

This section has two parts – (1) a comparison of the detailed weather model's hour-by-hour predictions vs. the observed data over the 10-year period 2000-2009 and (2) an assessment for the year 2000 of how much error is introduced by driving FReSH with the outputs of the Regional Climate Model PRECIS.

4.5.1 How Well Does the Local Weather Model Work?

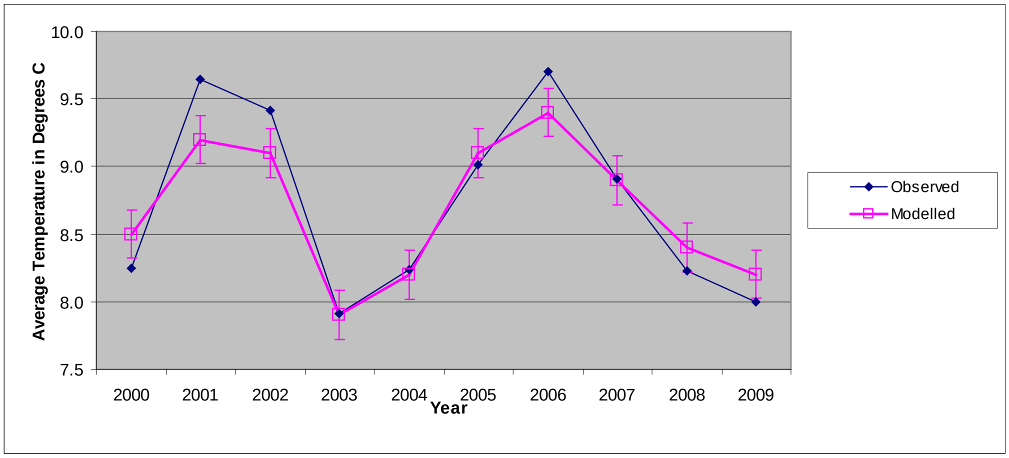
This section will present the weather model's capability to reproduce real observations. It confirms that the modelling approach is capable of correctly simulating the weather and climate over the GTA (including Durham). The comparison shows that weather parameters can be correctly projected when weather model parameters are driven by the observed global fields.

4.5.1.1 Temperature

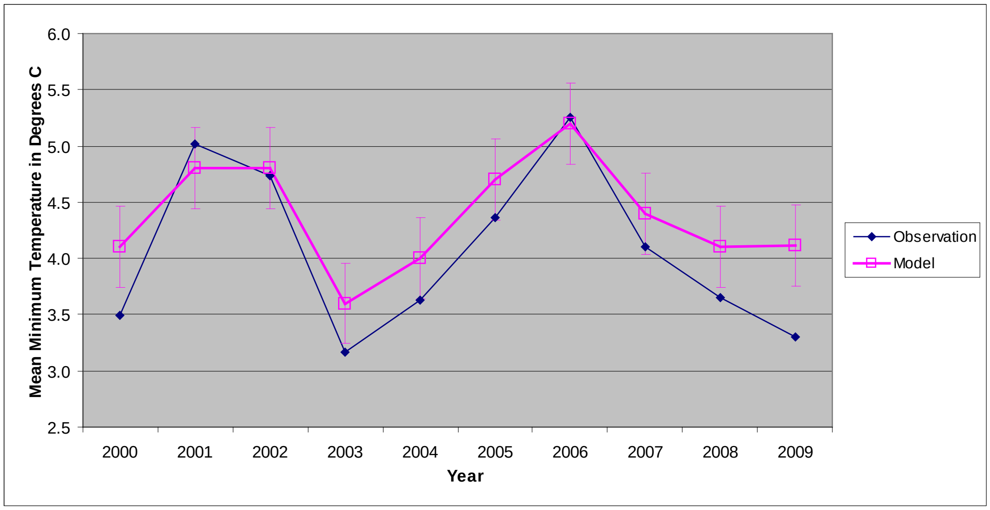
Figure 26 presents average, mean minimum and mean maximum temperatures for Pearson Airport vs. FReSH modelling simulations based on the analysis data. The figure also presents the mean absolute error (difference between modelled and observed values) for the model results.

Figure 26: Model vs. Observations – Pearson Airport

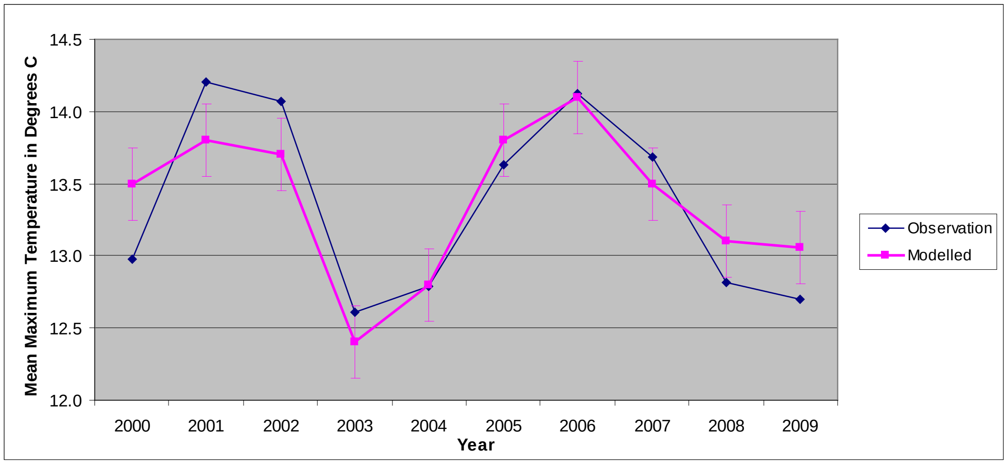
a) Average Temperature



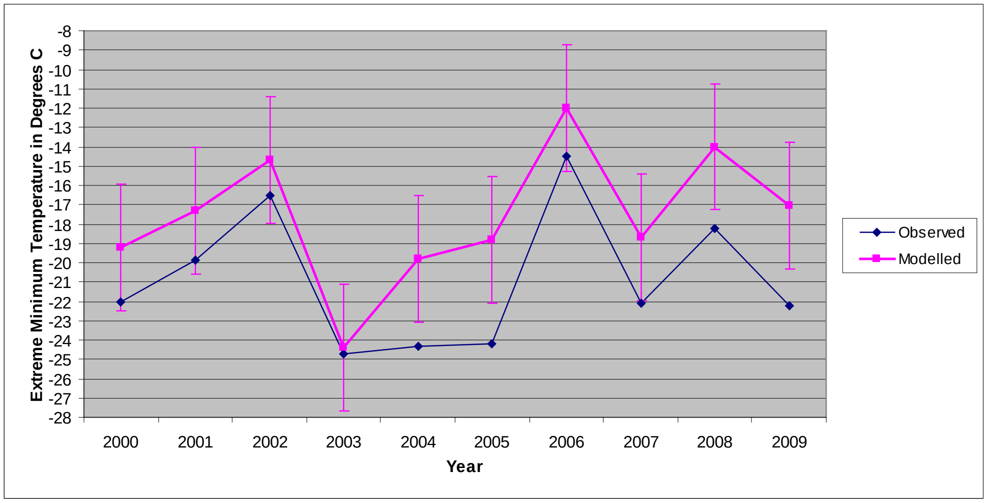
b) Mean Minimum Temperature



c) Mean Maximum Temperature



d) Extreme Minimum Temperature



e) Extreme Maximum Temperature

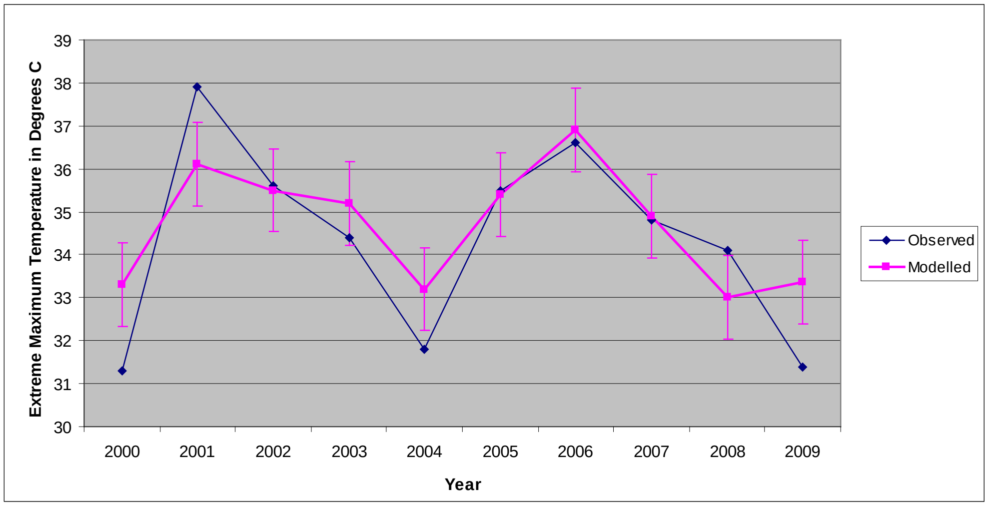


Figure 26a through Figure 26e demonstrate that the model reproduces the average, minimum and maximum temperatures quite well, as well as the extreme maximum, while the extreme minimum temperatures are under-estimated by about 19% on average over the 10 year period.

4.5.1.2 Precipitation

A meteorological numerical model is a simplified abstraction of the real atmosphere, which is valid for a certain space and time scale. The model is a set of equations and the corresponding numerical solvers. Within the model, a scale dependent discretization of the atmosphere in space and time is necessary. The temporal and spatial resolution of a mesoscale model is better than that in a macroscale model but coarser than in a microscale model. For this study, the microscale horizontal resolution was 1000 m.

Generally, in today's numerical schemes the precipitation parameterization performs very well when the horizontal resolution is between about 4 and 10 km. If the horizontal resolution is smaller than this (in our case 1 km) then the precipitation parameterization will simulate more successfully the "tornado type precipitation" and extreme precipitation events. This was demonstrated here for the case of the re-simulation of the July 11, 2009 storm that hit Oshawa's Lakeview Park. However, using this fine scale, the average precipitation rates are over-estimated. Based on a comparison for the 2000-2009 simulated period against observed data, the over-estimation calculated was a factor of 2. The climatological data presented in this study have been corrected by this factor of 2 for the current and future cases. Even without this correction, the relative change from the current conditions to the future state will be correct.

This is a modelling numerical problem which remains unresolved in the present state-of-the-science mesoscale models.

The results for total precipitation are presented in Figure 27. Figure 28 presents total rainfall in comparison with observed data and Figure 29 shows total snowfall (mm) compared with measurements. The figure also presents the mean absolute error (difference between modelled and observed values) for the model results.

Figure 27: Total PRECIPITATION – Model vs. Observations – Pearson Airport

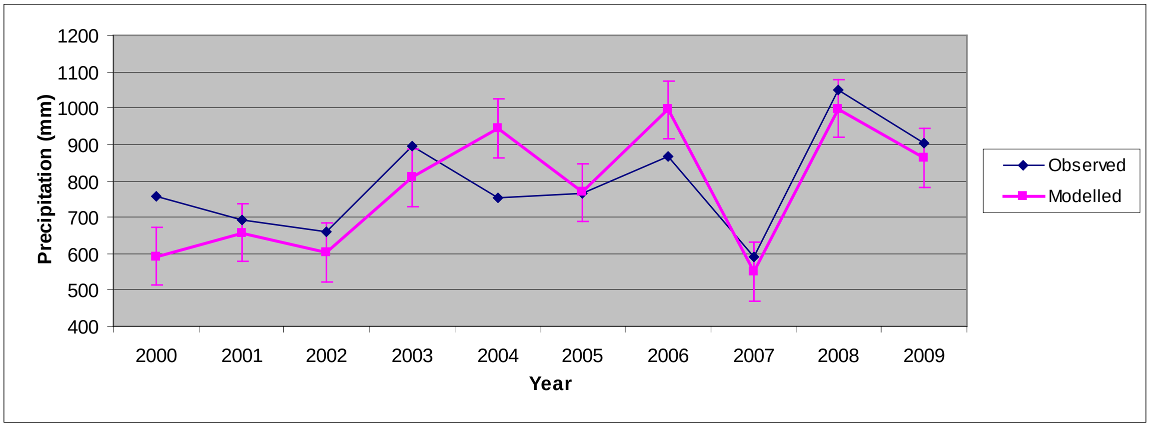


Figure 28: Total RAINFALL – Model vs. Observations – Pearson Airport

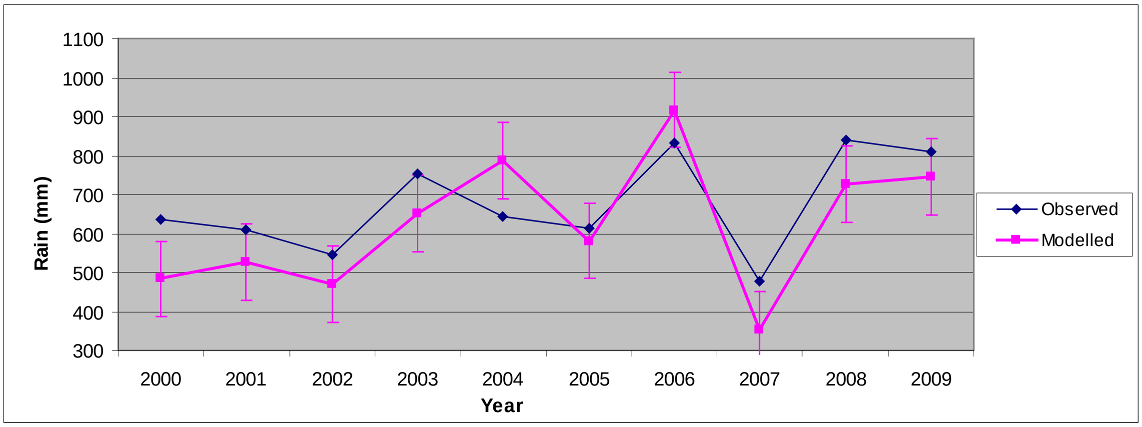
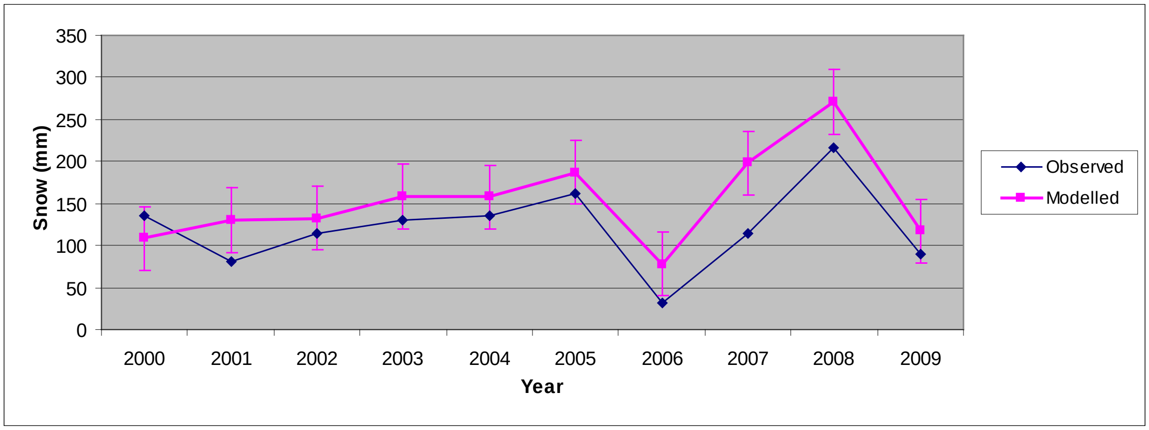


Figure 29: Total SNOWFALL - Model vs. Observations – Pearson Airport



The model predicts total precipitation well and slightly under-predicts rain and over-predicts snowfall.

4.5.1.3 Wind

The results for average wind speed are presented in Figure 30. Figure 31 presents maximum wind speed compared to observed data and the model predicts well average wind speed since the best weather models predict wind speed within about 1 m/s (~4 km/hour) and this study shows it to be within 2 km/hour of the observed value. Maximum wind speed is under-estimated but the gust wind speed is simulated reasonably well, when one considers the complexity of gust winds. In conclusion, the model validation shows good agreement with the current observations. It gives SENES a lot of confidence that the relative change between current simulated results and future simulated results is a reflection of the impact of climate change with no particular bias.

Figure 32 shows predicted gust winds in comparison with measurements. The figure also presents the mean absolute error (difference between modelled and observed values) for the model results.

Figure 30: Average Wind Speed – Model vs. Observations – Pearson Airport

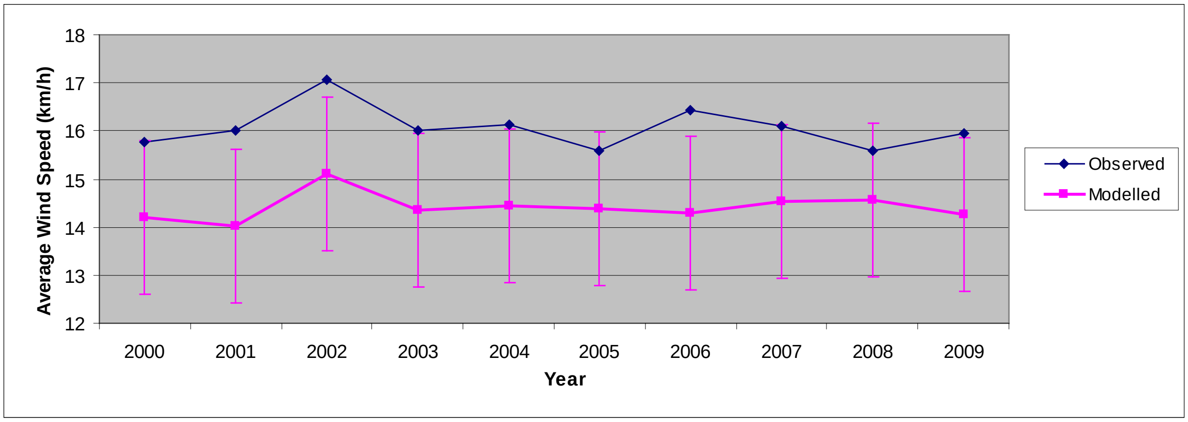
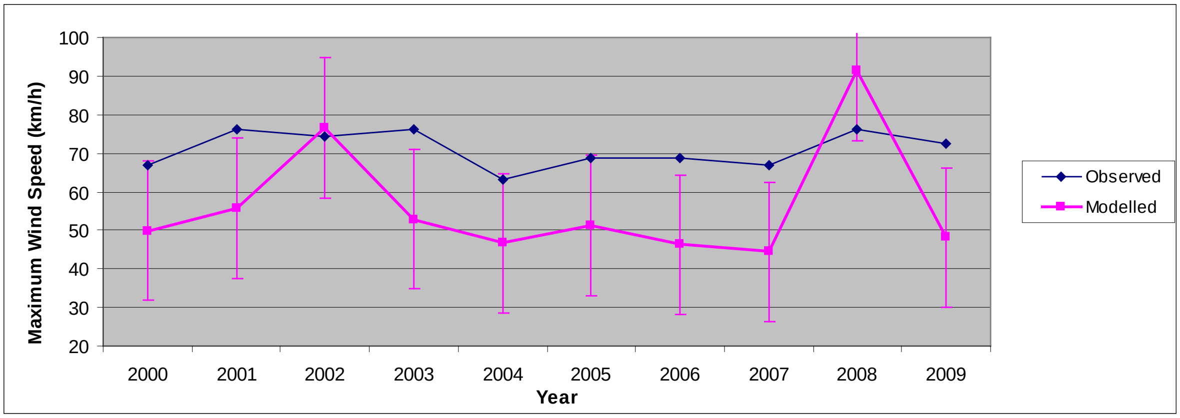
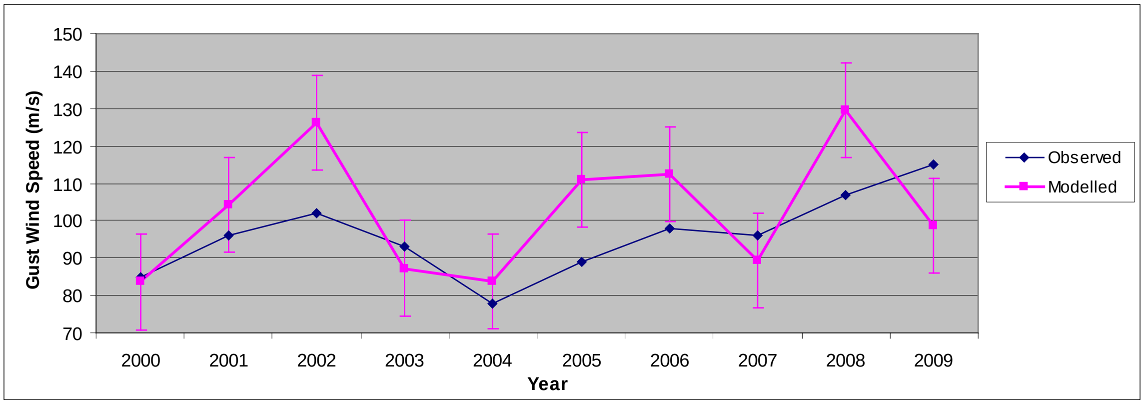


Figure 31: Maximum Wind Speed – Model vs. Observations – Pearson Airport



In conclusion, the model validation shows good agreement with the current observations. It gives SENES a lot of confidence that the relative change between current simulated results and future simulated results is a reflection of the impact of climate change with no particular bias.

Figure 32: Gust Wind Speed – Model vs. Observations – Pearson Airport



4.5.1.4 Specific Historical Event

11 July 2009 – Oshawa Lakeview Park

An extreme weather event, on 11 July 2009, resulted in the loss of 200 trees from municipal parks and streets and damage to 300 more. The dead trees represented about 0.1% of the total tree canopy. Environment Canada described it as an "F-0 microburst," with large hail, wind speeds in excess of 110 km/h and 11 mm of rain.

As part of this study, SENES Consultants re-analyzed that particular storm. Figure 33 and Figure 34 present the results of a 1x1 kilometre grid simulation of part of that day.

Figure 33 shows the total accumulated precipitation over the day for the area centred on the Oshawa Lakeview Park for 11 July 2009. At the Oshawa Airport observing station, Environment Canada measured 11mm of rain which was matched exactly by the model simulation.

Figure 34 shows the Storm Relative Helicity (SRH) for a 40-minute period on the afternoon of 11 July 2009. SRH is an estimate of the rotational potential that can be realized by a storm moving through an area. If the SRH value is in the range 150-300, supercells can form with weak tornadoes. An SRH in the range 300-450 indicates strong tornado potential. The data shows values increasing over the Lakeview Park area until 1410 when the SRH goes above 300 and stays at that level for 30 minutes.

After that period, the SRH values again decrease. This matches the observed weather on that day. A more in-depth description of the SRH is given in Section 5.81.

Figure 35 presents the modelled maximum wind gust over the study area at 1450 on 11 July 2009. The model does show maximum gusts during this 10-minute period of 50-60 km/hour near Lakeview Park and gusts above 90 km/hour north of Peterborough.

Figure 33: Simulated Total Accumulated Precipitation (mm) – 11 July 2009

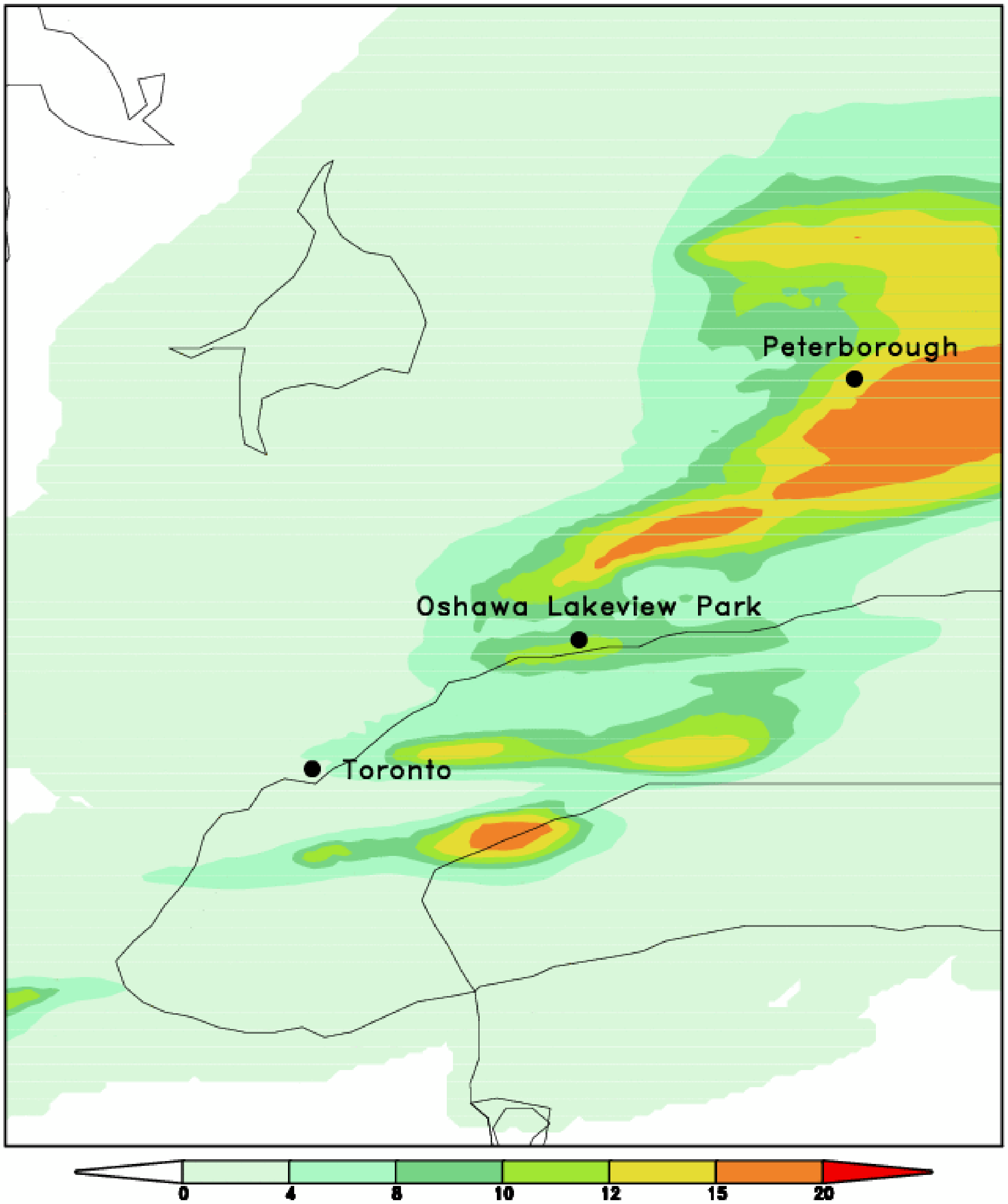


Figure 34: Storm Relative Helicity – 11 July 2009

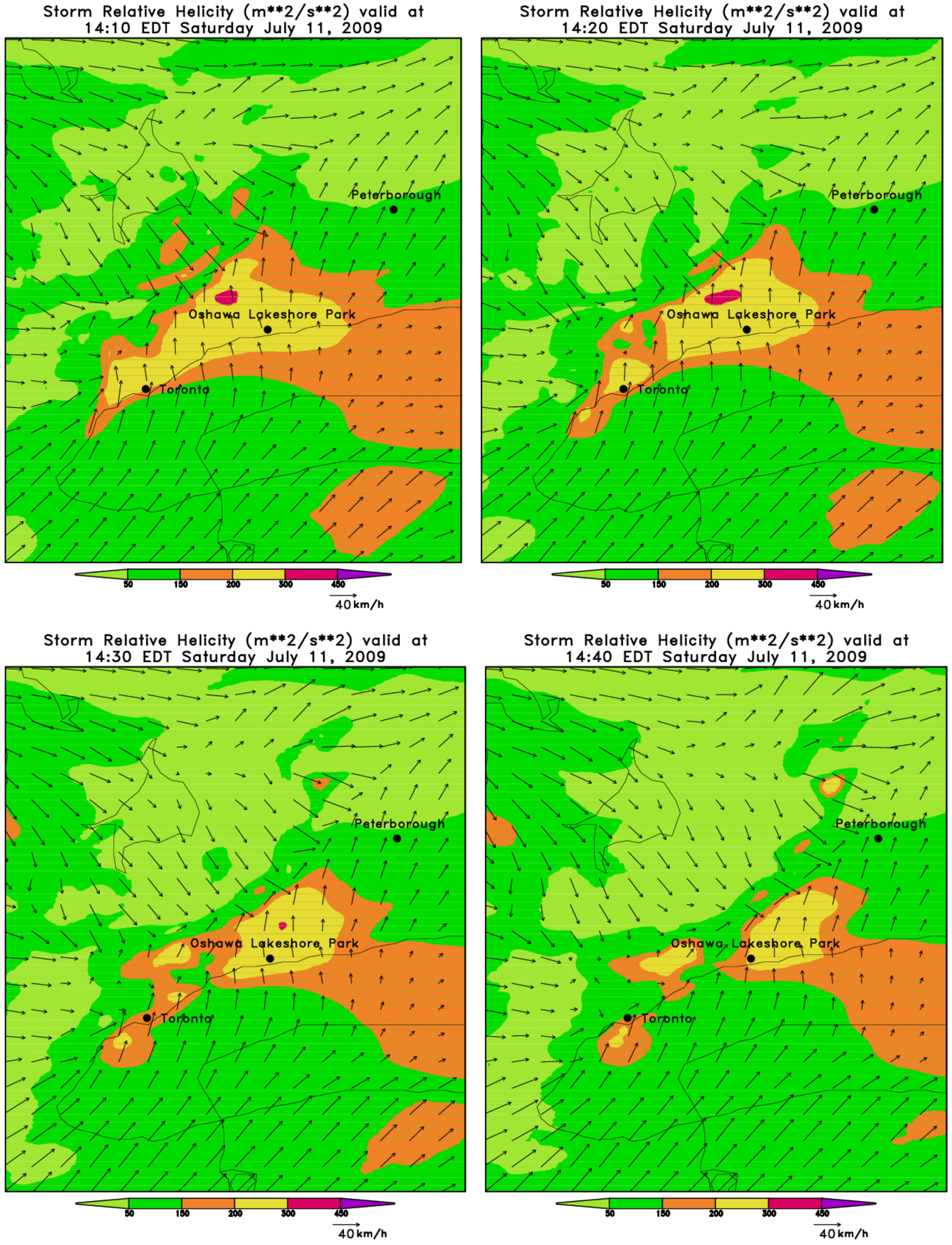
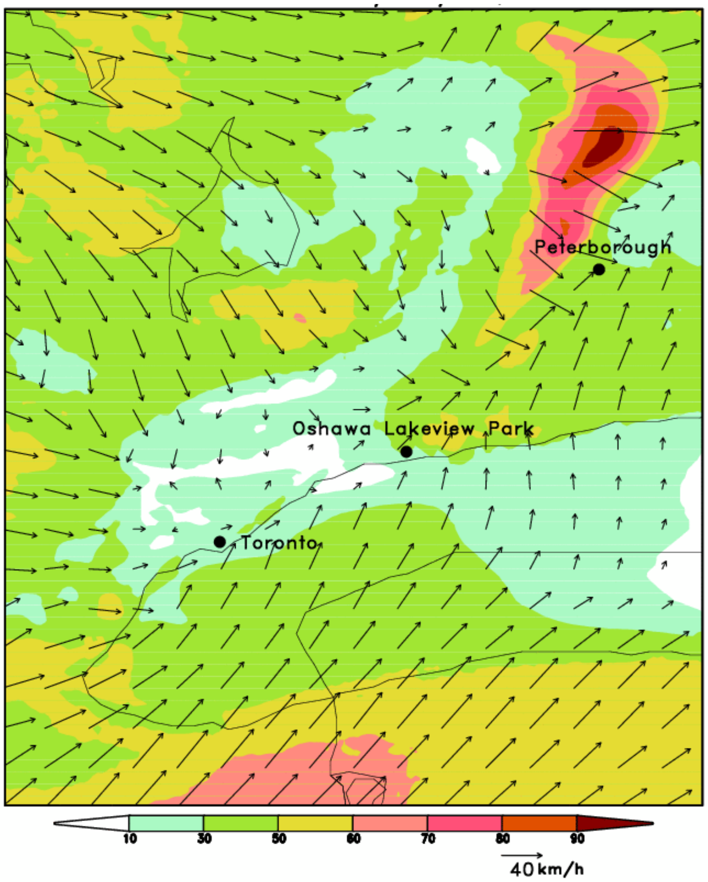


Figure 35: Map of Wind Gusts at 1450 on 11 July 2009



The three figures show that it is possible to forecast the temporal and spatial characteristics of super-cell storms using a state-of the-science weather model (WRF-NMM) running with fine spatial (1x1 kilometre) and temporal (10-minute average) grids. It is also important to point out that that this storm moved through very rapidly so that local details within the traditional reporting time of 1-hour were not seen.

4.5.2 How Well Does the PRECIS-FReSH Combination Work?

In this section the combination of using the Hadley PRECIS Regional Climate Model (RCM) as input to the FReSH Weather Model is tested for accuracy by comparing the average calculated monthly values from the simulation against the observed monthly data for the Year 2000. Three parameters were used for this comparison: temperature, rain and wind.

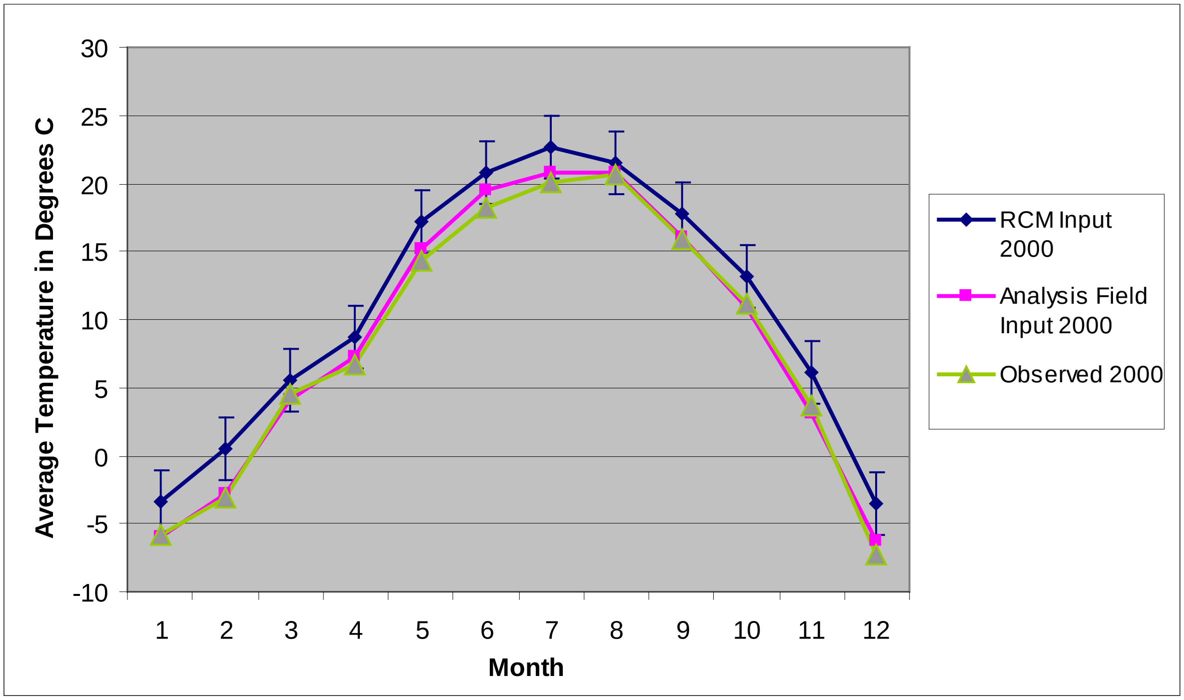
It should be noted that, since FReSH is driven by the output from the PRECIS Regional Climate Model (RCM), hour-by-hour comparisons with observational data are not expected to match, but the descriptive statistics of that hour-by-hour output for the period simulated is expected to provide the long term average climate (over 10-years) – albeit within the caveats expressed for the regional climate modelling approach.

4.5.2.1 Temperature

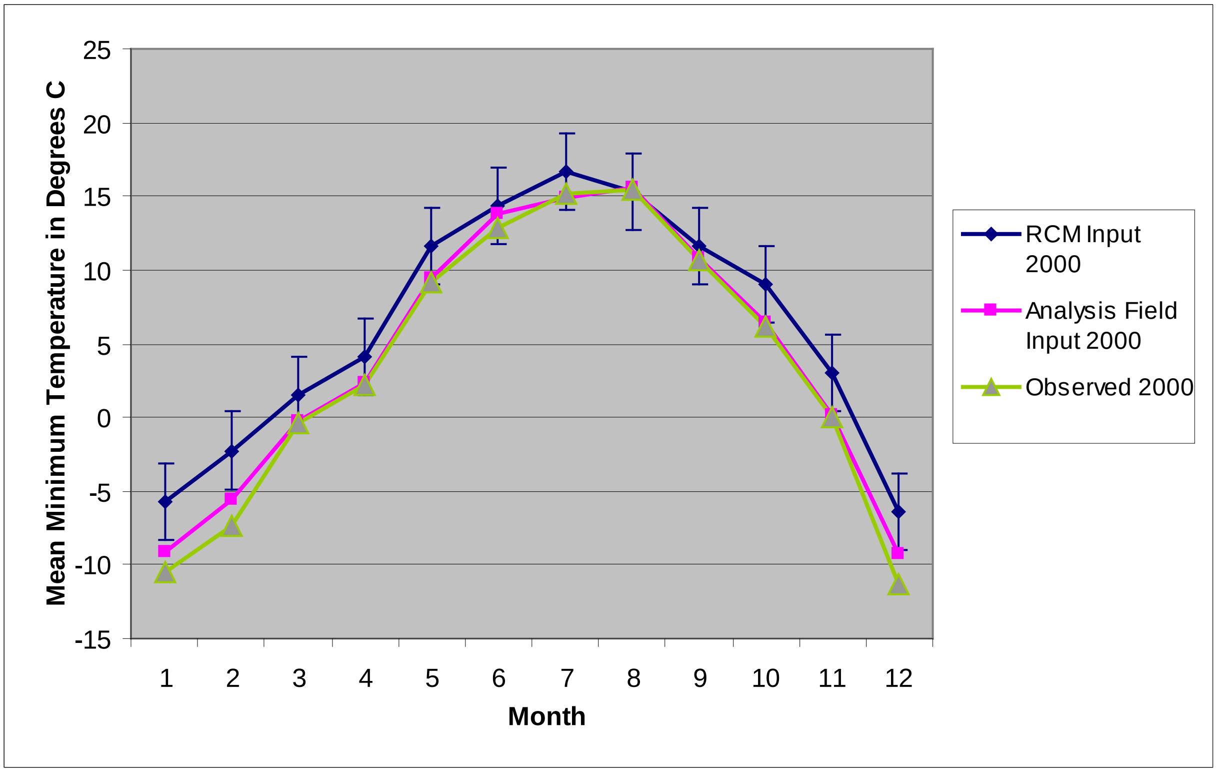
Figure 36 presents the average, mean minimum and mean maximum temperatures for the year 2000 for the Pearson Airport vs. FReSH modelling simulation driven by (1) the analysis fields (Analysis Field Input) and (2) the regional climate model (RCM Input). This comparison shows the capability of the combined model to reproduce the current period (the real observations at a particular point) as well as the uncertainty in using an RCM output to do the same thing. The figure also presents the mean absolute error (difference between modelled and observed values) for the model results.

Figure 36: Pearson Airport - Observed vs. Modelled Temperatures - 2000

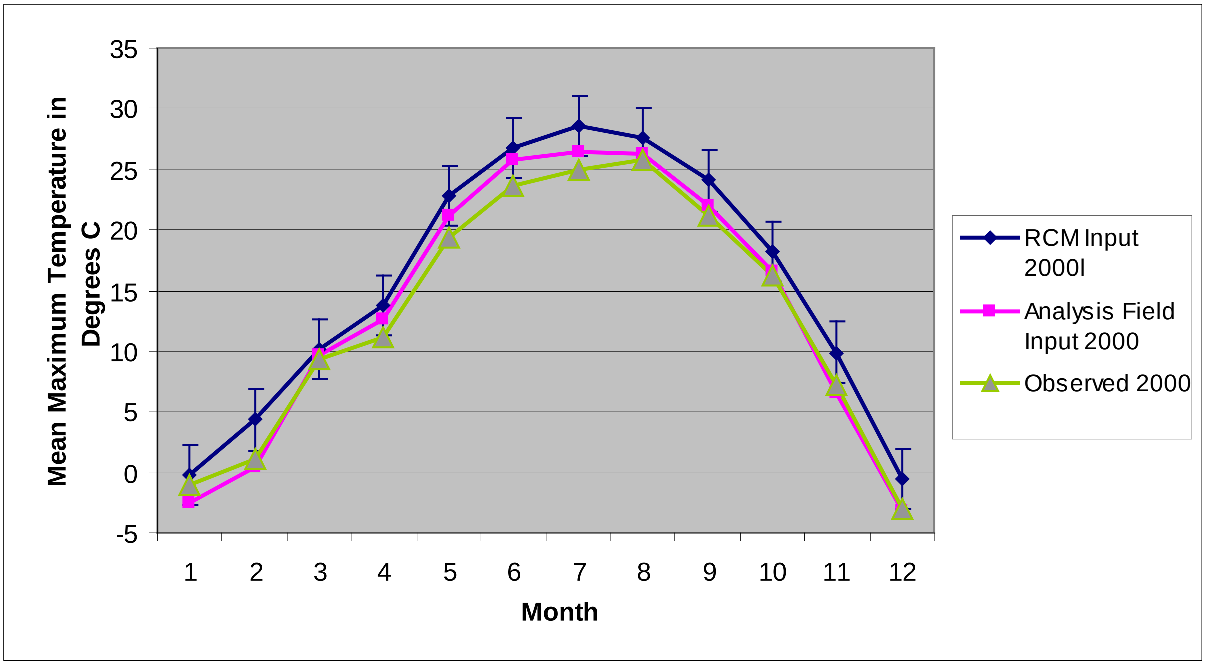
a) Average Temperature



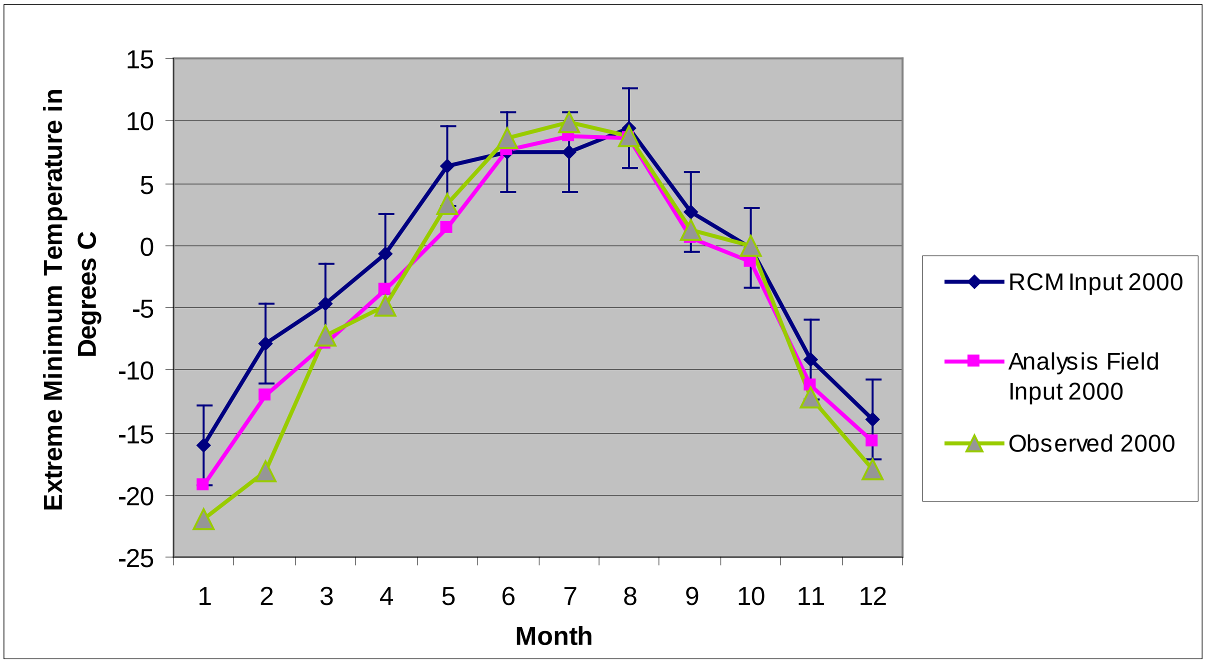
b) Mean Minimum Temperature



c) Mean Maximum Temperature



d) Extreme Minimum Temperature



e) Extreme Maximum Temperature

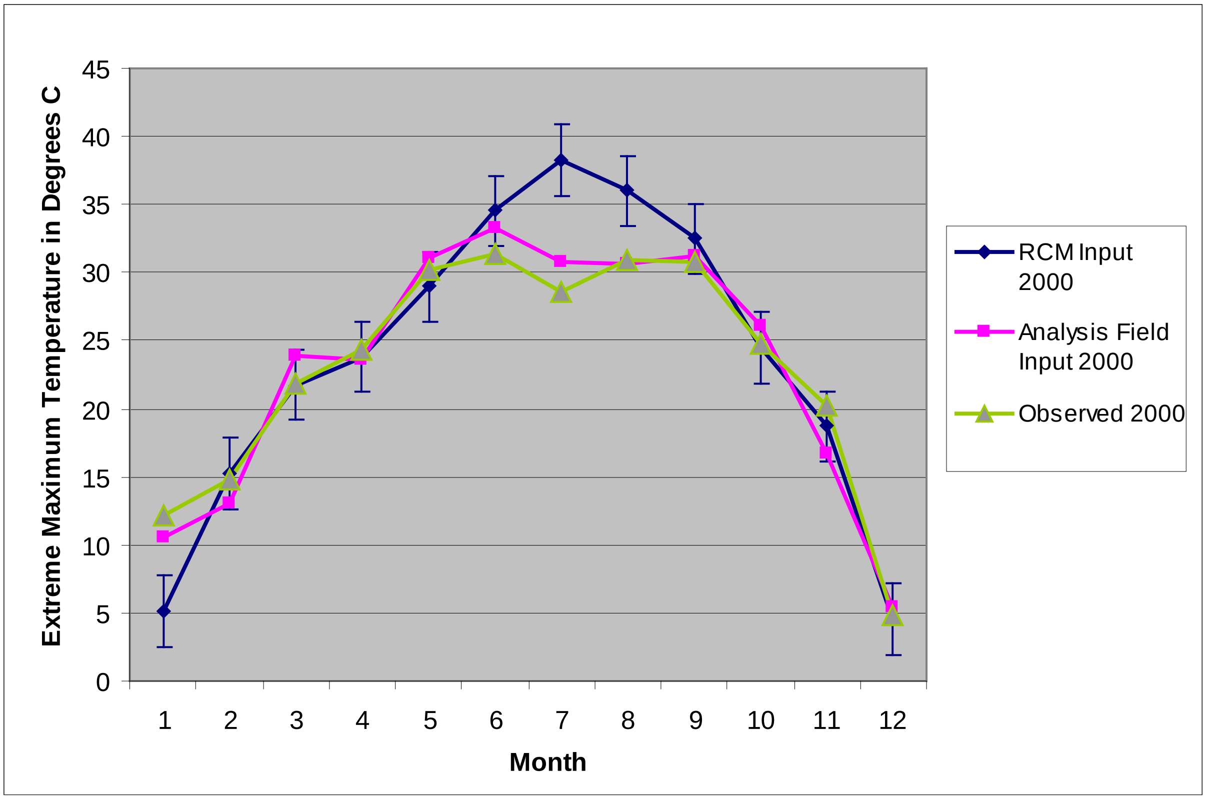


Figure 36a through Figure 36e demonstrate that the model driven by the analysis fields can reproduce the average, mean minimum, mean maximum and extreme maximum temperatures quite well, while the extreme minimum temperatures are under-estimated by about 13% for year 2000. Figure 36e does show the weakness of using a climate simulation to drive a particular year and season in that the summer period for 2000 was not accurately captured by the climate model (see discussion of uncertainties in climate models).

When FReSH is initialized with the output of the Regional Climate Model, the average temperature is overestimated by 2.3°C, the mean maximum by 2.4°C and the mean minimum by about 2.6°C while above zero (and underestimated below zero). The extreme maximum temperature is over-estimated by 6.9°C, while the extreme minimum is under-estimated by ~ 5.9°C.

All these uncertainties are well within the range of the uncertainty of the Global and Regional Climate Models.

4.5.2.2 Precipitation

The results for total precipitation for 2000 are presented in Table 5. This table summarizes the rain, the snow and total precipitation for year 2000. Variability on a monthly basis is larger.

Table 5: Pearson Airport - Observed vs. Modelled Precipitation – Year 2000

Parameter	*Model Driven by*		*Observed*
	Analysis Fields	**RCM Fields**	
Rainfall (mm)	483.3	485.4	635.2
Snowfall (cm)	108.5	71.0	135.7
Precipitation (mm)	591.9	556.4	755.7
Extreme Daily Rainfall (mm)	47.6	61.4	59.4
Extreme Daily Snowfall (cm)	16.3	7.5	12.4
Extreme Daily Precipitation (mm)	47.6	61.4	59.4

As can be seen in Table 5, using both types of inputs, rainfall in this year is under-estimated by ~ 30%. Snowfall is under-estimated by ~25% based on using the analysis data, while based on using the RCM the under-estimation is ~ 91%. Total precipitation is under-estimated by ~27% based on the analysis data and by about 35% based on the regional model initialization. Extreme daily rainfall is better predicted by using the RCM input (within ~3%) while snowfall is better predicted using the analysis data (within

~31%). For the purpose of estimating the uncertainty of the future extreme snowfall, Table 5 shows that the model underestimates the observed value by almost 40% for the Year 2000. It should be noted, however, that the 10-year comparison between observed and modelled (Figure 27) did show that the precipitation for the Year 2000 was significantly under-estimated, perhaps due to an unusually large number of convective storms during that year.

4.5.2.3 Wind

The results for average wind speed are presented in Figure 37. Figure 38 presents maximum wind speed in comparison with observed data and Figure 39 shows predicted gust in comparison with measurements. The figure also presents the mean absolute error (difference between modelled and observed values) for the model results.

Figure 37: Pearson Airport - Observed vs. Modelled Average Wind Speed - 2000

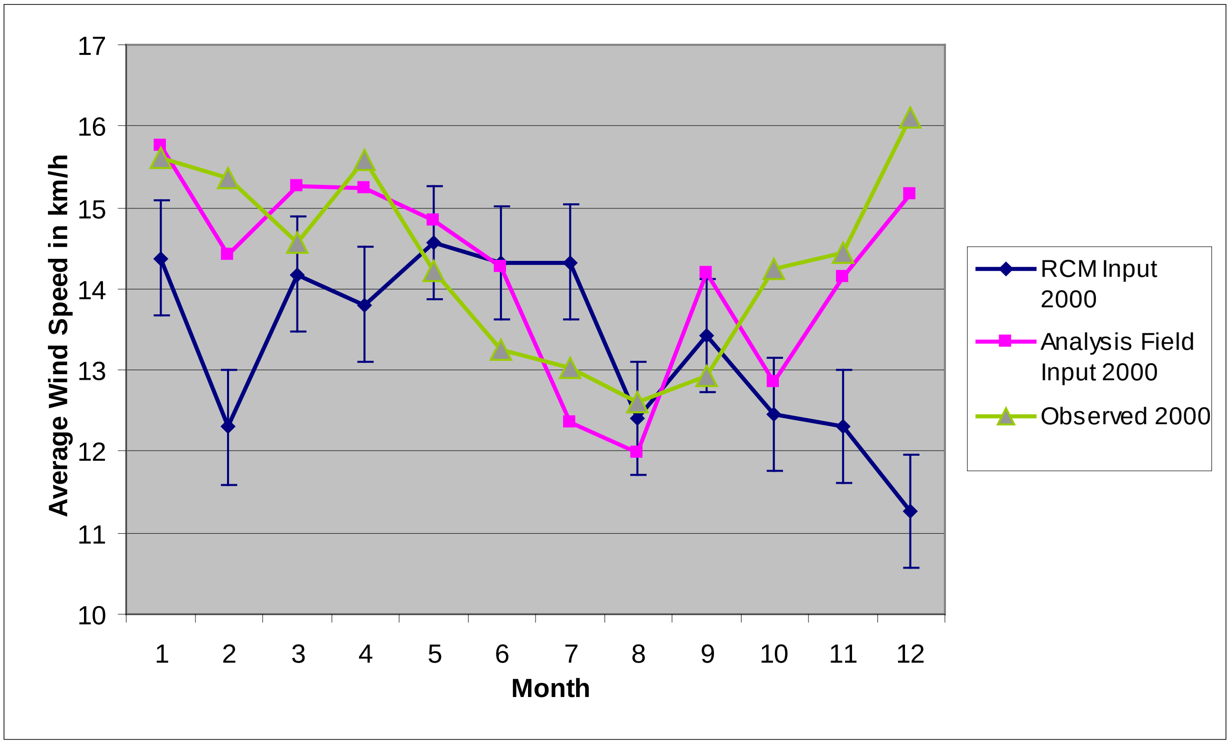


Figure 38: Pearson Airport - Observed vs. Modelled Maximum Wind Speed - 2000

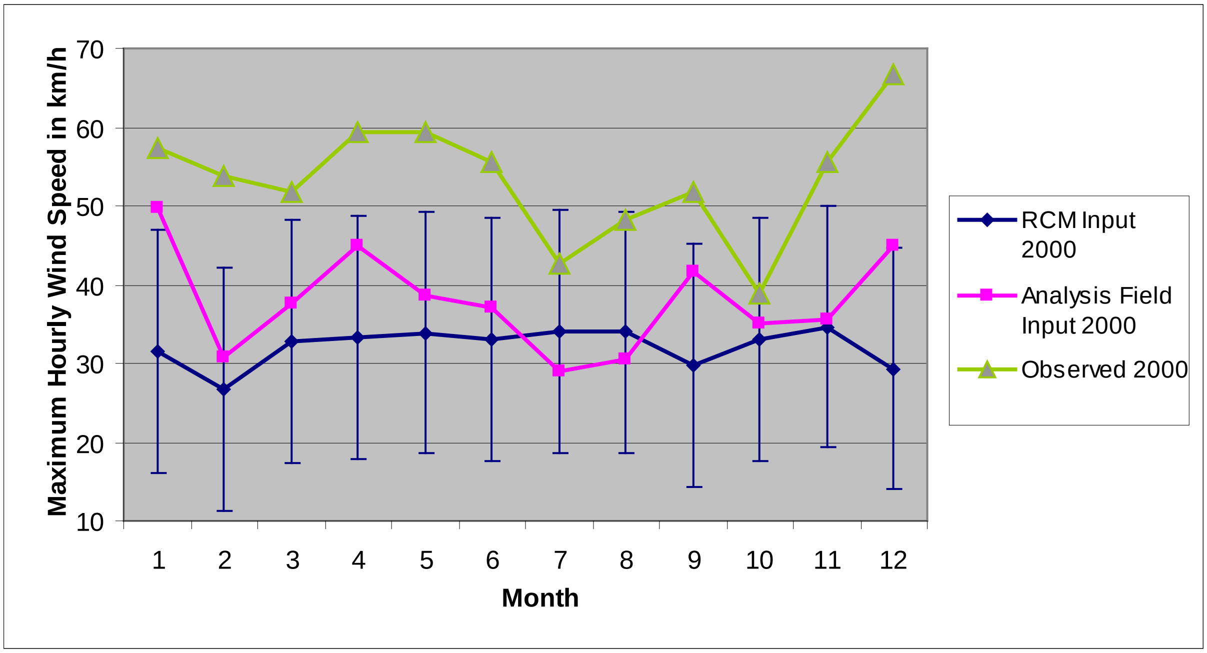
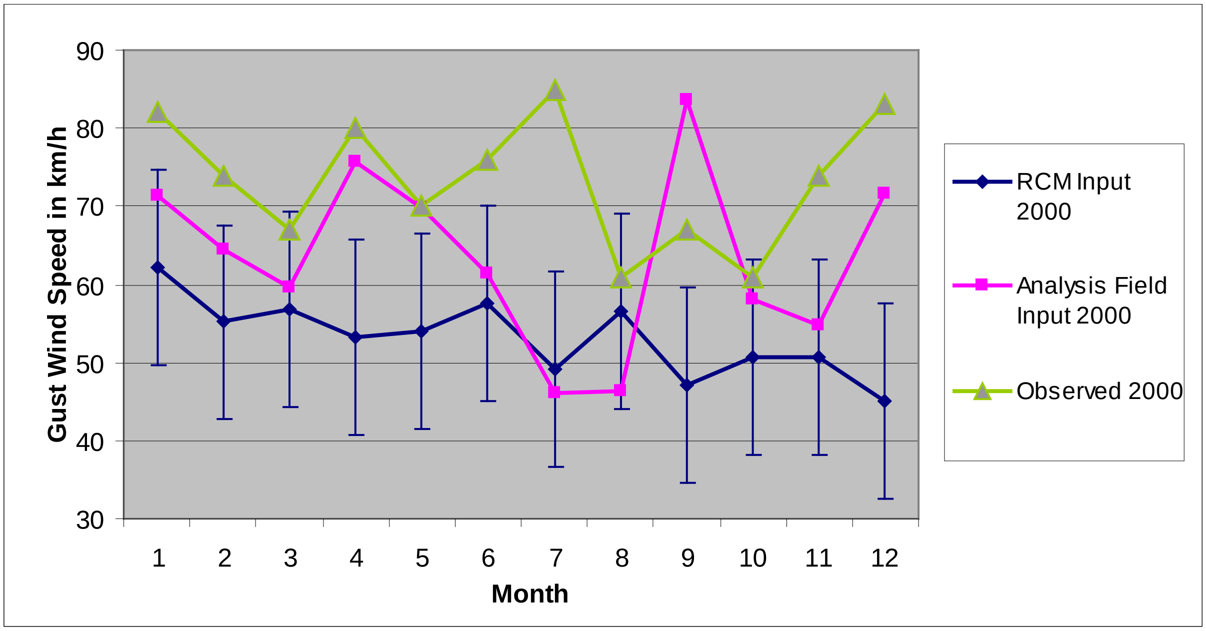


Figure 39: Pearson Airport – Observed vs. Modelled Gust Wind – 2000



The model predicts the average wind speed quite well. The maximum wind speed is underestimated equally based on using the analysis or the RCM inputs. The gust speed is simulated reasonably well by using the analysis data and is underestimated when using the Regional Climate Model input.

4.6 Summary

The approach used in this study is capable of producing detailed weather data on a very fine scale. The testing shows that driving a local weather model with the outputs from a Regional Climate Model simulation of the future state of the climate can produce a very good representation of the current weather with precision and accuracy that can be quantified as presented in Table 6. This means that using the same approach to infer future detailed local weather statistics will likely have the same precision and accuracy.

Table 6: Bias Statistics for NMM vs. Observation –Pearson Airport - 2000

Measure of Bias	WS km/hour	WD degrees	TEMP °C
Good Performance	< ±7.2	< ±45	
Fair Performance	< ±14.4	< ±-90	
Poor Performance	> ±21.6	> ±90	
Pearson Airport	**0.7**	**-2.2**	**-0.2**

(Observation – Model)

The data presented in this chapter illustrate that the approach used for this project gives results that are better than the lowest sensitivity commonly identified for Regional Climate Model analyses of 2.4 to 5.4°C.

5.0 What is the Future Climate Expected to Be in Durham?

This chapter presents some illustrative results for one station, Whitby, extracted from the hour-by-hour simulations of the future period (2040-2049). A comparison is made with the current climate statistics (2000-2009) for the same location.

5.1 Future Period

5.1.1 Temperature

An example of the results from the NMM simulation for 2000-2009 is presented in Table 7 for Whitby.

An example of the results from the NMM simulation for 2040-2049 is presented in Table 8 for Whitby.

Table 9 presents the differences between the future period and the present period.

Table 7: Whitby Data - Temperature Summary for 2000-2009

Temperature:	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Daily Average (°C)	-4.9	-4.6	-0.5	6.6	12.3	18.1	20.5	20.5	16.8	9.8	4.4	-2.1	**8.1**
Standard Deviation of Daily Average (°C)	4.6	3.8	4.5	4.2	3.3	3.1	2.2	2.5	3.3	4.1	3.7	3.8	**3.6**
Daily Maximum (°C)	-1.9	-1.2	3.5	11.4	17.2	22.8	24.9	24.8	21.1	13.9	7.7	0.7	**12.1**
Standard Deviation of Daily Maximum (°C)	4.4	3.9	4.9	4.9	3.9	3.4	2.4	2.7	3.3	4.4	4.0	3.6	**3.8**
Daily Minimum (°C)	-7.6	-7.6	-3.9	2.3	7.4	13.4	16.0	16.1	12.6	6.3	1.5	-4.5	**4.3**
Standard Deviation of Daily Minimum (°C)	4.9	4.1	4.6	3.9	3.6	3.6	2.9	3.0	3.9	4.4	3.7	4.0	**3.9**
Extreme Maximum (°C)	12.3	20.7	19.8	25.7	29.7	31.2	32.6	32.4	29.9	30.2	17.7	13.6	**32.6**
Extreme Minimum (°C)	-21.3	-21.2	-25.0	-9.8	-1.8	3.5	6.4	7.8	-0.8	-2.2	-12.4	-22.3	**-25.0**

Table 8: Whitby Data - Temperature Summary for 2040-2049

Temperature:	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Daily Average (°C)	1.1	2.1	4.9	9.6	15.7	20.2	23.1	23.6	20.1	14.4	8.0	2.6	**12.1**
Standard Deviation of Daily Average (°C)	3.1	3.3	2.9	3.5	2.8	2.5	1.9	2.1	3.5	3.9	3.3	3.1	**3.0**
Daily Maximum (°C)	4.0	5.2	8.9	14.2	20.8	25.5	28.0	28.3	24.5	18.7	11.6	5.7	**16.3**
Standard Deviation of Daily Maximum (°C)	3.0	3.5	3.4	4.2	3.5	3.3	2.3	2.5	3.6	4.0	3.1	3.0	**3.3**
Daily Minimum (°C)	-1.2	-0.4	1.5	5.3	10.8	15.2	18.7	19.6	16.1	10.6	5.0	0.1	**8.4**
Standard Deviation of Daily Minimum (°C)	3.4	3.5	3.0	3.7	3.0	2.5	2.1	2.3	3.9	4.4	3.8	3.3	**3.2**
Extreme Maximum (°C)	13.3	15.2	18.0	28.3	38.0	39.7	39.3	38.6	33.3	31.5	20.6	13.7	**39.7**
Extreme Minimum (°C)	-11.8	-9.6	-7.3	-4.8	3.2	4.4	12.1	11.1	3.5	-0.6	-5.5	-13.1	**-13.1**

Table 9: Whitby – Temperature Difference 2040-2049 to Present

Difference	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Daily Average Temperature in Degrees C	5.9	6.7	5.3	3.0	3.4	2.1	2.6	3.1	3.3	4.5	3.6	4.7	**4.0**
Daily Max Temperature in Degrees C	5.9	6.5	5.4	2.8	3.5	2.7	3.2	3.5	3.4	4.8	3.9	5.1	**4.2**
Daily Min Temperature in Degrees C	6.4	7.1	5.3	3.0	3.4	1.8	2.7	3.5	3.5	4.2	3.5	4.6	**4.1**
Extreme Max Temperature in Degrees C	1.0	-5.6	-1.8	2.7	8.3	8.5	6.7	6.2	3.4	1.3	3.0	0.1	**7.1**
Extreme Min Temperature in Degrees C	9.5	11.6	17.7	5.0	5.0	0.8	5.7	3.3	4.3	1.5	6.9	9.2	**12.0**

Figure 40 shows the temperature differences between the current and future period, over the entire GTA.

Comparing Table 7 with Table 8 indicates that the future period is predicted to be about 4.0 degrees warmer on average at Whitby (i.e. 12.1°C – 8.1°C = 4.0°C) and that the extreme maximum and minimum temperatures could be 7.1 and 12.0 degrees warmer than today, respectively. A more detailed look at the monthly average differences, between the current and future period for the Whitby location, is presented in Chapter 6.

Table 10 and Table 11 present the number of days of temperatures experienced within certain ranges.

Table 10: Whitby Data - Temperature Day Summary - 2000-2009

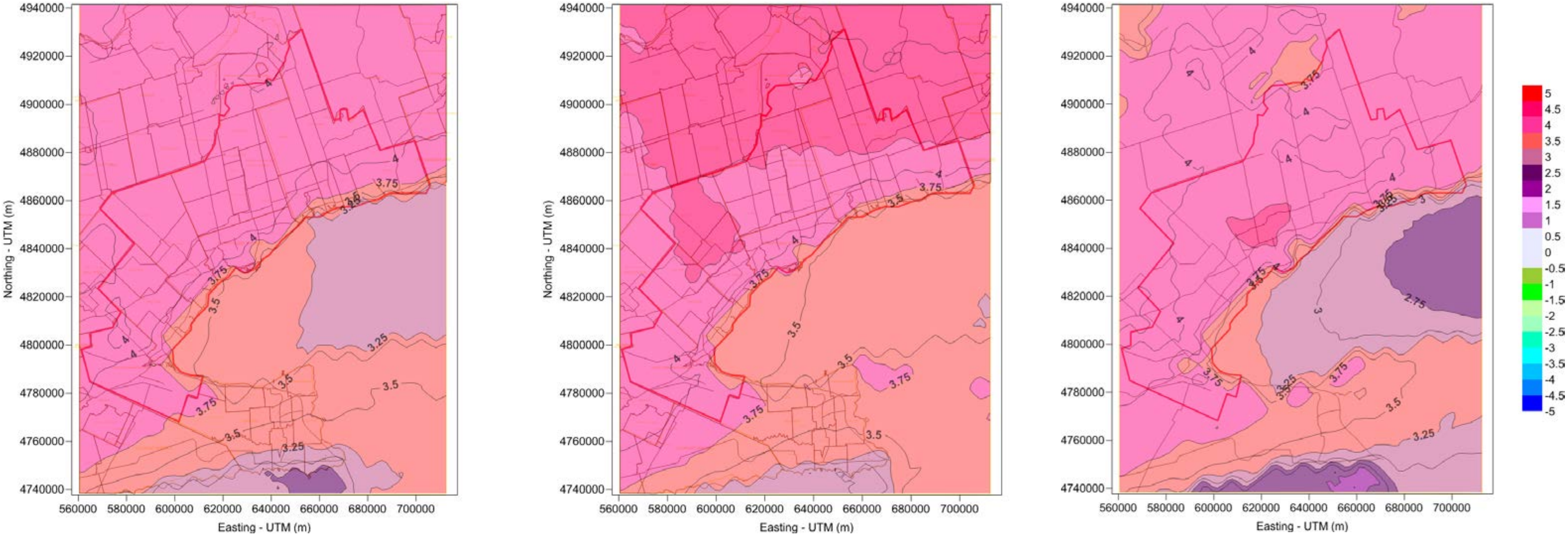
Max Temp (deg C)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
<= 0 C	19	17	8	0	0	0	0	0	0	0	1	13	**59**
> 0 C	12	11	23	30	31	30	31	31	30	31	29	18	**306**
> 10 C	1	0	4	18	30	30	31	31	30	24	9	1	**209**
> 20 C	0	0	0	1	6	23	30	29	19	4	0	0	**114**
> 30 C	0	0	0	0	0	0	1	1	0	0	0	0	**2**
> 35 C	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Min Temp (deg C)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
> 0 C	3	1	7	21	30	30	31	31	30	28	19	5	**236**
<= 2 C	30	28	27	15	3	0	0	0	0	7	17	30	**156**
<= 0 C	28	27	25	9	1	0	0	0	0	3	11	26	**129**
< -2 C	25	25	19	4	0	0	0	0	0	0	5	21	**99**
< -10 C	11	10	3	0	0	0	0	0	0	0	0	4	**27**
< -20 C	1	0	0	0	0	0	0	0	0	0	0	0	**1**
< -30 C	0	0	0	0	0	0	0	0	0	0	0	0	**0**

Table 11: Whitby Data - Temperature Day Summary - 2040-2049

Max Temp (deg C)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
<= 0 C	4	3	0	0	0	0	0	0	0	0	0	2	**9**
> 0 C	27	26	31	30	31	30	31	31	30	31	30	29	**337**
> 10 C	1	4	13	25	31	30	31	31	30	31	20	4	**238**
> 20 C	0	0	0	3	18	28	31	31	25	12	0	0	**141**
> 30 C	0	0	0	0	0	3	6	7	2	0	0	0	**17**
> 35 C	0	0	0	0	0	0	1	1	0	0	0	0	**2**
Min Temp (deg C)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
> 0 C	10	12	18	26	31	30	31	31	30	31	26	14	**291**
<= 2 C	25	22	19	8	0	0	0	0	0	1	8	22	**104**
<= 0 C	21	17	13	4	0	0	0	0	0	0	4	17	**75**
< -2 C	14	10	4	1	0	0	0	0	0	0	1	8	**38**
< -10 C	0	0	0	0	0	0	0	0	0	0	0	0	**1**
< -20 C	0	0	0	0	0	0	0	0	0	0	0	0	**0**
< -30 C	0	0	0	0	0	0	0	0	0	0	0	0	**0**

Examining these tables we see that in the current period, the number of days per year above 20 ^{0}C is 114 days and in the future period this is increased to 141 days, an increase of about 27 days. The number of days per year above 0 ^{0}C is increased by approximately 10%. The number of days per year below -10 ^{0}C is reduced from 27 days, to 1. These tables can give valuable results for future building code design parameters.

Figure 40: Mean Daily Temperature Differences 2040-2049



Mean Daily Temperature Difference (^oC)

Mean Daily Minimum Temperature Difference (^oC)

Mean Daily Maximum Temperature Difference (^oC)

5.1.2 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 temperature is equal to or greater than 18, 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.

Table 12 and Table 13 present a summary of degree days for the periods 2000-2009 and 2040-2049, respectively.

Table 12: Whitby Data - Degree Day Summary for 2000-2009

Temperature	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Above 24 C	0	0	0	0	0	1	3	3	1	0	0	0	**8**
Above 22 C	0	0	0	0	1	5	14	15	3	0	0	0	**37**
Above 18 C	0	0	0	0	4	42	84	86	25	2	0	0	**242**
Above 15 C	0	0	0	1	15	103	170	170	75	10	0	0	**543**
Above 10 C	0	0	0	17	88	242	325	324	204	53	4	0	**1258**
Above 5 C	2	0	9	79	226	392	480	479	353	157	39	3	**2219**
Above 0C	15	8	53	202	381	542	635	634	503	305	140	26	**3444**
Below0 C	165	139	67	4	0	0	0	0	0	0	9	91	**475**
Below5 C	306	273	179	31	0	0	0	0	0	7	58	222	**1076**
Below10 C	459	414	325	119	17	0	0	0	2	58	173	375	**1941**
Below15 C	614	555	479	253	99	11	0	0	22	170	319	530	**3052**
Below18 C	706	640	572	342	181	40	7	10	62	255	409	623	**3847**

Table 13: Whitby Data - Degree Day Summary for 2040-2049

Temperature	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Above 24 C	0	0	0	0	1	4	17	23	4	0	0	0	**49**
Above 22 C	0	0	0	0	2	12	49	61	19	0	0	0	**143**
Above 18 C	0	0	0	0	13	75	159	173	87	12	0	0	**520**
Above 15 C	0	0	0	3	48	157	252	266	159	44	0	0	**929**
Above 10 C	0	1	2	42	178	305	407	421	302	145	21	1	**1825**
Above 5 C	8	16	44	146	332	455	562	576	452	291	104	18	**3004**
Above 0C	61	81	155	287	487	605	717	731	602	446	241	95	**4508**
Below0 C	28	22	4	0	0	0	0	0	0	0	1	15	**70**
Below5 C	130	99	48	9	0	0	0	0	0	0	14	93	**393**
Below10 C	277	225	161	55	1	0	0	0	0	9	81	231	**1040**
Below15 C	432	366	314	166	27	2	0	0	7	63	210	385	**1971**
Below18 C	525	450	407	253	84	10	0	0	25	124	300	478	**2657**

Comparing the two tables it is easy to see that there is a substantial change in the number of temperature degree-days in the future. For example, in the current period there are typically 8 degree days above 24 ^{0}C every year and in the future period this is increased to 49, an increase of over 6 times. The category of above 0 ^{0}C increases by approximately 31%. And the degree days below 18 ^{0}C are reduced by approximately 31%, while the category of below 0 ^{0}C is reduced by approximately 85%.

5.1.3 Humidex

Humidex is an index to indicate how hot or humid the weather feels to the average person. It is derived by combining temperature and humidity values into one number to reflect the perceived temperature. For example, a humidex of 40 means that the sensation of heat when the temperature is 30 degrees and the air is humid feels more or less the same as when the temperature is 40 degrees and the air is dry.

The future temperature increase is also causing a change in the humidex. Table 14 and Table 15 present the average humidex summary for the periods 2000-2009 and 2040-2049, respectively.

The tables show that, in the current period, extreme humidex is 47; while in the future period the extreme humidex is 51. The category of above 30 is increased by approximately 66% on average. For the category >=45, there is an increase from 0 to 5 on the average value of humidex.

Table 14: Whitby Data - Humidex Summary for 2000-2009

Humidex	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Extreme Humidex	14	20	21	32	40	42	45	47	39	39	20	15	**47**
Days with Humidex > =30	0	0	0	0	2	12	19	20	5	1	0	0	**59**
Days with Humidex > =35	0	0	0	0	0	4	8	8	1	0	0	0	**21**
Days with Humidex >= 40	0	0	0	0	0	0	2	1	0	0	0	0	**3**
Days with Humidex >= 45	0	0	0	0	0	0	0	0	0	0	0	0	**0**

Table 15: Whitby Data - Humidex Summary for 2040-2049

Humidex	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Extreme Humidex	15	17	21	34	45	49	50	51	44	37	26	16	**51**
Days with Humidex > =30	0	0	0	0	4	17	29	28	17	3	0	0	**98**
Days with Humidex > =35	0	0	0	0	0	9	21	21	9	0	0	0	**60**
Days with Humidex >= 40	0	0	0	0	0	3	7	9	1	0	0	0	**19**
Days with Humidex >= 45	0	0	0	0	0	1	1	2	0	0	0	0	**5**

5.1.4 Precipitation

Precipitation change between the current and future periods is presented in summary tables, as well as on the grid points. Parameters analyzed were rainfall, snowfall, total precipitation and freezing rain.

5.1.4.1 Rainfall, Snowfall and Total Precipitation

Table 16 and Table 17 present, for Pearson Airport, the precipitation summaries for the 2000-2009 and the 2040-2049 periods, respectively. Table 18 presents the precipitation differences at Whitby between the 2040s and the present period.

Table 16: Whitby Data – Precipitation Summary for 2000-2009

Precipitation (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rainfall (mm)	19	17	32	69	81	90	98	63	68	66	71	43	**717**
Snowfall (cm)	37	41	25	6	0	0	0	0	0	0	7	35	**152**
Precipitation (mm)	55	58	57	75	81	90	98	63	68	66	79	78	**869**
Std of Precipitation	3	4	4	5	5	7	7	6	6	4	6	5	**5**
Extreme Daily Rainfall (mm)	24	26	35	35	35	73	65	60	75	33	79	31	**79**
Extreme Daily Snowfall (cm)	17	25	18	14	0	0	0	0	0	0	14	28	**28**
Extreme Daily Precipitation (mm)	24	26	35	35	35	73	65	60	75	33	79	32	**79**

Table 17: Whitby Data - Precipitation Summary for 2040-2049

Precipitation (mm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Rainfall (mm)	46	53	53	63	76	119	170	113	99	42	82	49	**965**
Snowfall (cm)	14	10	4	1	0	0	0	0	0	0	0	9	**39**
Precipitation (mm)	61	63	57	64	76	119	170	113	99	42	82	58	**1004**
Std of Precipitation	4	4	4	5	6	9	12	10	9	4	7	4	**7**
Extreme Daily Rainfall (mm)	32	34	49	42	64	76	76	117	82	29	58	46	**117**
Extreme Daily Snowfall (cm)	11	17	6	4	0	0	0	0	0	0	0	8	**17**
Extreme Daily Precipitation (mm)	32	34	49	42	64	76	76	117	82	29	58	46	**117**

Table 18: Whitby - Precipitation Differences between the 2040s and the Present

Difference	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Rainfall (mm)	27.4	36.0	20.4	-6.1	-5.0	29.0	72.3	49.8	30.8	-23.5	10.7	5.2	**247.1**
Snowfall (cm)	-22.3	-31.0	-21.2	-4.8	0.0	0.0	0.0	0.0	0.0	0.0	-7.3	-26.0	**-112.6**
Precipitation (mm)	5.1	5.0	-0.8	-11.0	-5.0	29.0	72.3	49.8	30.8	-23.5	3.4	-20.8	**134.6**
Extreme Daily Precipitation (mm)	8.6	8.2	14.2	7.6	28.9	3.0	11.4	57.2	6.5	-3.4	-20.6	14.0	**37.9**
Extreme Daily Rainfall (mm)	8.6	8.2	14.2	7.6	28.9	3.0	11.4	57.2	6.5	-3.4	-20.6	14.8	**37.9**
Extreme Daily Snowfall (cm)	-5.8	-8.4	-11.9	-10.3	0.0	0.0	0.0	0.0	0.0	0.0	-14.0	-20.3	**-11.4**

Based on the predicted current and future scenario (2040-2049) for Whitby, total rainfall will increase by 34%, snowfall is predicted to be reduced by 74% and total precipitation is predicted to be increased by 15%. Details, of the spatial distribution of the rainfall, snowfall and total precipitation across the GTA for the current period and future period, are presented in Figure 59 (Appendix A).

Figure 41 presents the differences in rainfall, snowfall and total precipitation between the two periods.

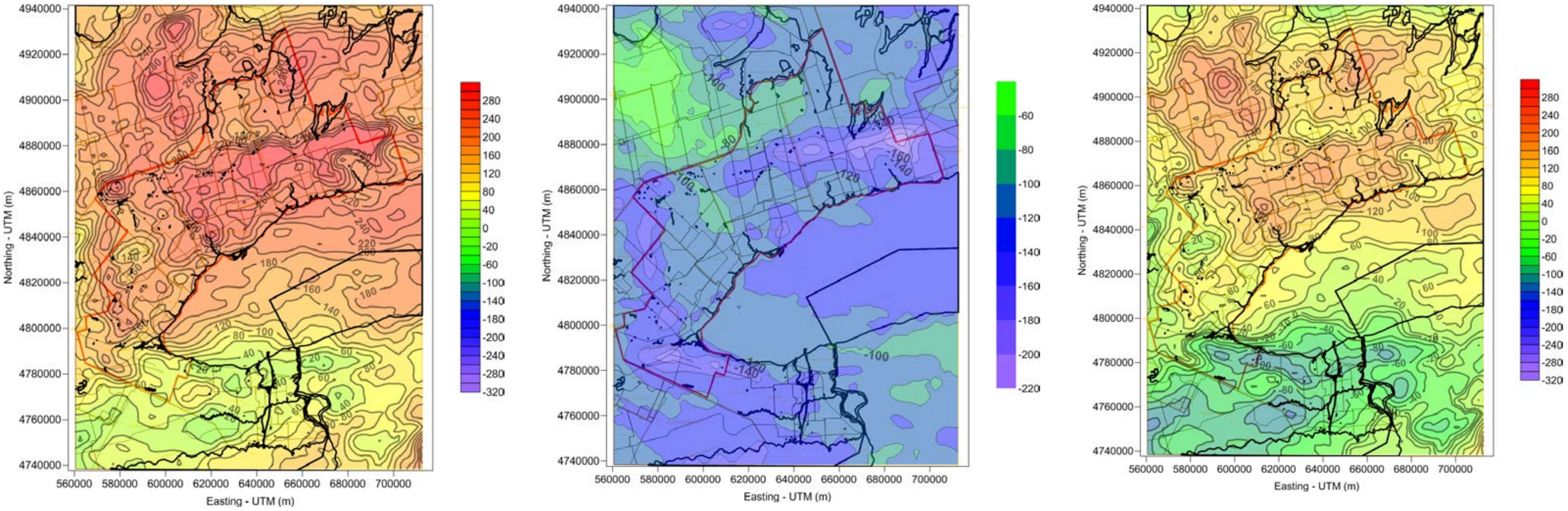
Figure 41 shows an enhanced precipitation in Durham (downwind of the GTA) to the east and northeast. This is simply a reflection of the orographic and/or lake effects, and the prevailing storm tracks.

5.1.5 Number of Precipitation, Snowfall and Rainfall Days

The numbers of days for rainfall, snowfall and precipitation are presented in Table 19 and Table 20 for current (2000-2009) and future (2040-2049) scenario respectively.

It is interesting that, while the number of days with precipitation remains the same, the number of days with larger amounts is increasing. This means that there will be more intense storms in the future (a smaller number of events with a higher amount of precipitation). This conclusion is confirmed by examining the total precipitation data (see part of the table), where there is one day with greater than 50mm of precipitation in the current case but 2 days for the future case. Also the table shows a significant reduction in the number of snowstorm days but an increase in the number of days with rainfall. These results match the work of Angel and Isard (1998), Levinson and Bromirski (2007) and McCabe et al. (2001) who identified an increase in the number of intense storms. They did not, however, identify that the occurrence of individual storms would decrease.

Figure 41: Rainfall, Snowfall and Total Precipitations Differences 2040s to Present



Rainfall Difference (mm)

Snowfall Difference (cm)

Total Precipitation Difference (mm)

Table 19: Whitby Data – Number of Days Summary for 2000-2009

Total Precipitation (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
>= 0.2 mm	16	15	13	12	11	11	11	9	9	12	13	16	**147**
>= 5 mm	3	4	4	5	5	4	4	3	4	4	4	5	**49**
>= 10 mm	2	1	2	3	3	3	3	2	2	2	2	3	**27**
>= 25 mm	0	0	0	0	1	1	1	1	0	0	0	1	**6**
>= 50 mm	0	0	0	0	0	0	0	0	0	0	0	0	**1**
>= 100 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
>= 150 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
>= 200 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
>= 250 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Snowfall (cm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
>= 0.2 mm	13	13	8	2	0	0	0	0	0	0	2	11	**49**
>= 5 mm	2	3	1	0	0	0	0	0	0	0	0	2	**9**
>= 10 mm	1	1	1	0	0	0	0	0	0	0	0	1	**4**
>= 25 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Rainfall (mm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
>= 0.2 mm	4	3	7	11	11	11	11	9	9	12	11	7	**106**
>= 5 mm	1	1	2	4	5	4	4	3	4	4	4	3	**41**
>= 10 mm	1	0	1	3	3	3	3	2	2	2	2	1	**23**
>= 25 mm	0	0	0	0	1	1	1	1	0	0	0	0	**5**

Table 20: Whitby Data – Number of Days Summary for 2040-2049

Total Precipitation (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
>= 0.2 mm	16	13	11	12	10	12	14	12	11	10	13	15	**147**
>= 5 mm	5	4	4	4	4	5	7	6	5	3	5	4	**55**
>= 10 mm	1	2	1	2	2	4	6	4	3	1	2	1	**31**
>= 25 mm	0	0	0	0	1	2	3	1	1	0	1	0	**10**
>= 50 mm	0	0	0	0	0	1	1	0	0	0	0	0	**2**
>= 100 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
>= 150 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
>= 200 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
>= 250 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Snowfall (cm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
>= 0.2 mm	7	5	2	0	0	0	0	0	0	0	0	5	**19**
>= 5 mm	1	0	0	0	0	0	0	0	0	0	0	1	**2**
>= 10 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
>= 25 mm	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Rainfall (mm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
>= 0.2 mm	11	10	10	12	10	12	14	12	11	10	13	13	**136**
>= 5 mm	3	4	4	4	4	5	7	6	5	3	5	3	**52**
>= 10 mm	1	2	1	2	2	4	6	4	3	1	2	1	**30**
>= 25 mm	0	0	0	0	1	2	3	1	1	0	1	0	**10**

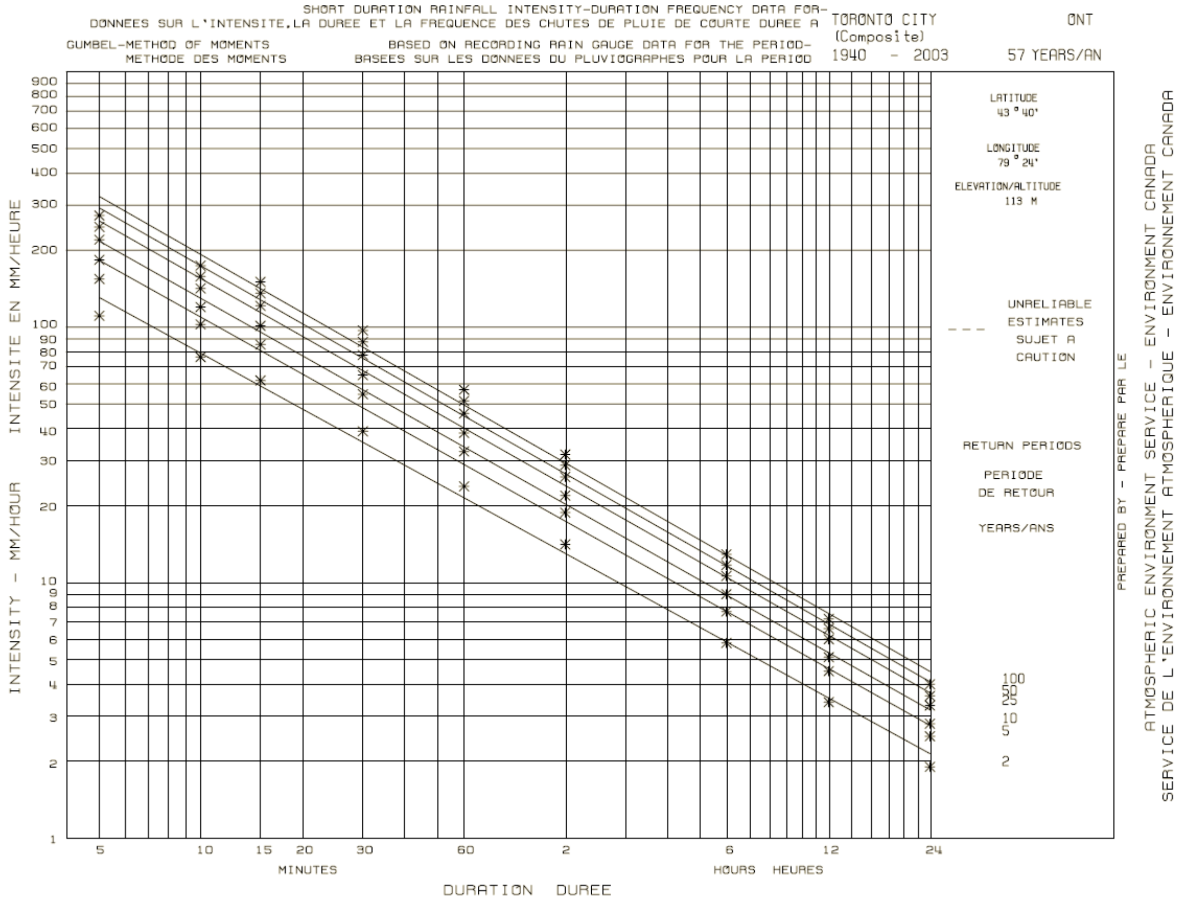
5.1.6 Return Periods

Return periods were only calculated only for Pearson Airport as part of the original study but the database allows such a calculation to be made for any of the 8 Durham Region locations. The current IDF curve for Pearson Airport is presented in Figure 42.

This figure is a reference point for the calculated return periods based for the current period (2000-2009) and for the future period (2040-2049).

Meteorological data projections have been derived using FReSH for the current period and the future period. The maximum rainfall events during these periods are of interest. Maximum annual precipitation events lasting over 1-hour, 2-hour, 6-hour, 12-hour and 24-hour periods were extracted from the current and future period computer modelled meteorological output. These values have been summarized and used to determine the 2-year, 5-year, 10-year, 25-year, 50-year and 100-year return periods for maximum annual precipitation events in 1-hour, 2-hour, 6-hour, 12-hour and 24-hour periods.

Figure 42: IDF Curves for Pearson Airport



This section also provides the annual maximums and the estimated return periods for extreme rainfall events for each year of the current and future time periods modelled. The future period consistently exhibits higher means, standard deviations and maximums for the annual maximums and higher overall maximums than the current period.

The projected maximum events were summarized from rolling summations made over 1-hour, 2-hour, 6-hour, 12-hour and 24-hour periods. There was a potential for bias in the maximum rainfall events for the future condition as these were based on computer model output from PRECIS, which simulates future months with fewer hours per year (specifically February had only 27 days and the rest of the months had 29 days each per month). The output from the Regional Climate Model (PRECIS) limits the number of days that the FReSH model can simulate. Consequently, the maximum annual rainfall event, if calculated on 365 days rather than 346 days might have been higher than the maximum shown here.

Table 21 shows the annual maximum values for varying durations of precipitation. A visual review of these maximums indicates that the future maximum events tend to be higher than the current events.

Table 21: Annual Maximum Precipitation Events (mm) at Pearson Airport

Year	1-hour	2-hour	6-hour	12-hour	24-hour
Current (2000-2009)					
2000	15.9	23.8	45.8	47.3	47.5
2001	9.7	15.4	18.8	30.2	39.7
2002	10.5	16.1	21.8	35.1	35.1
2003	11.8	15.4	25.3	34.4	40.2
2004	13.2	24.9	47.9	50.8	56.7
2005	12.8	19.4	31.1	45.8	51.8
2006	15.1	26.8	44.9	44.9	57.6
2007	5.9	10.8	16.7	21.9	35.4
2008	25.2	26.3	48.2	49.9	53.5
2009	15.6	28.3	44.7	58.2	65.9
Future (2040-2049)					
2040	44.0	72.4	164.9	165.7	181.3
2041	13.2	23.0	43.1	50.4	88.2
2042	18.0	30.8	50.8	55.1	97.4
2043	46.2	53.4	67.5	67.5	67.6
2044	23.4	46.8	49.8	60.3	62.4
2045	17.2	33.1	58.2	65.4	70.6
2046	19.9	39.2	51.6	73.4	104.3
2047	20.9	37.1	43.7	44.3	44.4
2048	21.3	32.6	41.5	62.0	71.1
2049	14.8	23.6	49.7	70.9	71.3

5.1.6.1 Summary Statistics

Table 22 provides a statistical summary of the annual maximum precipitation data shown in Table 21 that is predicted to occur at the Pearson Airport station. The future projections reveal higher means and higher standard deviations compared to the current projections. The maximums, over the 10-year periods, are higher for the future compared to current projections.

Table 22: Summary Annual Maximum Precipitation (mm) at Pearson Airport

Statistic	1-hour	2-hour	6-hour	12-hour	24-hour
Current (2000-2009)					
Mean	13.6	20.7	34.5	41.9	48.3
Standard Deviation	5.1	6.1	13	11.1	10.5
Max	25.2	28.3	48.2	58.2	65.9
Future (2040-2049)					
Mean	23.9	39.2	62.1	71.5	85.9
Standard Deviation	11.6	15	36.9	34.3	37.8
Max	46.2	72.4	164.9	165.7	181.3

5.1.6.2 Estimated Return Periods

The 2-year, 5-year, 10-year, 25-year, 50-year and 100-year return periods for maximum precipitation have been calculated using the method described in Environment Canada's *Rainfall intensity-duration frequency values for Canadian Locations* (Hogg et al, 1985). Environment Canada used the mathematical "method of moments" and assumed a Gumbel distribution for maximum rainfall events. The mean and standard deviation of the annual extremes was multiplied by a scaling factor based on the Gumbel distribution to estimate the return periods for maximum rainfall. It is noted in the Environment Canada document that the annual rainfall maximums are typically calculated for the period of April through October for most locations in Canada. For this assessment shown here, we have used meteorological predictions for the entire year. Based on an analysis of all the future data predicted (including the temperature data), it is considered most probable that the maximum precipitation rate will occur as rainfall rather than snowfall.

The return periods for the various duration rainfall events are shown in Table 23. There has been substantial extrapolation in estimating 100 year return periods from 10 years of data and, hence, the longer return periods have additional uncertainty. As might be expected, there is reasonable agreement between the shorter return periods and the summary statistics of Table 22 (e.g. the 10-year return period would be expected to be similar to the maximum from the 10 years of data).

If different methods and distribution assumptions were employed, slightly different results would probably be seen for the estimated return periods.

Table 23: Return Periods - Maximum Precipitation (mm) at Pearson Airport

Return Period	1-hour	2-hour	6-hour	12-hour	24-hour
Current (2000-2009)					
2-year	12.7	19.7	32.4	40.0	46.6
5-year	17.2	25.1	43.9	49.8	55.9
10-year	20.2	28.6	51.5	56.3	62.0
25-year	24.0	33.1	61.2	64.5	69.7
50-year	26.8	36.4	68.3	70.5	75.5
100-year	29.6	39.7	75.4	76.6	81.2
Future (2040-2049)					
2-year	22.0	36.7	56.0	65.9	79.7
5-year	32.2	50.0	88.6	96.2	113.0
10-year	39.0	58.8	110.3	116.3	135.2
25-year	47.6	69.8	137.6	141.6	163.1
50-year	53.9	78.1	157.8	160.5	183.8
100-year	60.3	86.2	178	179.2	204.4

A comparison of results for the values derived from the current 10-year period (2000-2009) and the best available IDF values as derived from the longer climatological period (1950-2003) are presented in. Based on this comparison it can be concluded that the 6-hour, 12-hour and 24-hour durations for return period of 2, 5, 10 years are in reasonable agreement, while the other values are under-estimated.

The key observation is that the future scenario (2040-2049) exhibits a consistent doubling of the current return period values. This also shows the advantage of examining 10-year periods of time rather than an all-encompassing 52-year period. This is potentially very important for infrastructure design purposes.

So, considering the comparison in Table 24, the return periods for 25, 50 and 100-year should also be increased for design calculations (roughly by about 40%). For example, the 24-hour value (204.4mm) estimated in Table 23 for a return period of 100 years should be increased to a value 285.6 mm. This is quite critical in design, and demonstrates that future local climate and its effects should be considered carefully.

Table 24: Return Period Comparison for Pearson Airport

Return Period	1-hour	2-hour	6-hour	12-hour	24-hour	Number of Years
Current (2000-2009)						
2-year	12.7	19.7	32.4	40.0	46.6	10
5-year	17.2	25.1	43.9	49.8	55.9	10
10-year	20.2	28.6	51.5	56.3	62.0	10
25-year	24.0	33.1	61.2	64.5	69.7	10
50-year	26.8	36.4	68.3	70.5	75.5	10
100-year	29.6	39.7	75.4	76.6	81.2	10
IDF (1950-2003)						
2-year	22.7	26.8	35.6	41.3	47.0	52
5-year	30.4	36.3	49.0	57.2	65.2	52
10-year	35.6	42.5	57.9	67.8	77.3	52
25-year	42.0	50.5	69.2	81.1	92.5	52
50-year	46.8	56.3	77.5	90.9	103.8	52
100-year	51.6	62.2	85.8	100.8	115.1	52

5.1.7 Wind Events

The "wind" is a simplification of a complex integrated set of variables, including wind speed, wind direction, wind gustiness and turbulence that are typically described separately. The predicted wind results are quite complex and are presented in several different forms. Wind speeds are presented in tabular and contour plot form. Using this standard approach, a general picture of the winds and wind changes can be seen effectively.

5.1.7.1 Average Winds, Maximum Winds and Gust Winds

Summarised data of wind speed by number of days of occurrence are presented (by month and year) in Table 25 and Table 26 for the periods 2000-2009 and 2040-2049, respectively. It should be noted that the future results have been corrected. The Region Climate Models use months of 29 days except for February which uses 27 days. In order to provide comparable statistics for number of days in any given year the results from the model were extrapolated to 30 or 31 days per month and to 28 days for February.

Table 25: Whitby – Wind Summary for 2000-2009

Wind	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Speed (km/h)	17	17	17	17	15	13	13	13	14	16	16	18	**16**
Maximum Hourly Speed	54	54	56	53	47	41	46	46	50	56	60	62	**62**
Maximum Gust Speed	79	98	94	85	81	66	69	65	85	89	87	119	**119**
Days with Winds >= 52 km/h	0	0	0	0	0	0	0	0	0	0	0	1	**2**
Days with Winds >= 63 km/h	0	0	0	0	0	0	0	0	0	0	0	0	**0**

Table 26: Whitby – Wind Summary for 2040-2049

Wind	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Speed (km/h)	15	16	16	16	14	12	11	11	13	14	16	14	**14**
Maximum Hourly Speed	43	54	44	40	41	50	38	45	37	42	45	42	**54**
Maximum Gust Speed	66	74	74	63	66	74	58	66	58	70	74	72	**74**
Days with Winds >= 52 km/h	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.1**
Days with Winds >= 63 km/h	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**

Comparing these two tables shows that average wind speed, maximum wind speed and gust speed are all reduced in the future. The average wind speed is reduced by ~ 11%, while maximum wind speeds are reduced by ~ 13% and the gust speeds by ~ 38%. This finding can be explained by the fact that, with increased temperature, the differences between the air masses will decrease and the driving force for wind speed will decrease.

Figure 60 (Appendix A) presents the average wind speed in the form of a contour plot.

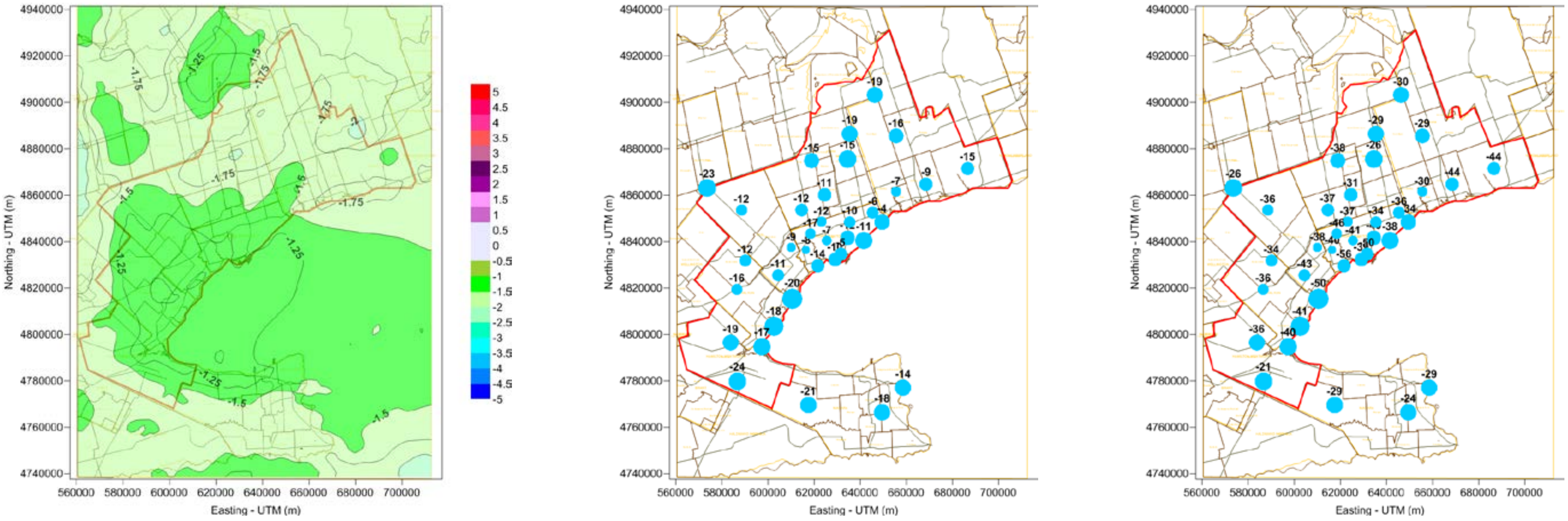
Figure 61 (Appendix A) shows maximum wind speed over the GTA, as a discrete variable, because for grid points the contour plots are difficult to read. The maximum wind speed and gust are function of surface roughness; the spatial variability is quite large. Figure 62 (Appendix A) shows the gust wind speed over the GTA.

Figure 43 shows the spatial distribution of the differences between the 2000-2009 period and the 2040-2049 period for average, maximum and gust wind speeds.

The figures show that there are large differences between the future and current periods for maximum and gust wind speeds along the Lake Ontario shoreline. The figures indicate smaller differences in average wind speed than for gust and the maximum wind speeds.

This means that the warming is pushing the cold/and warm air mass contact zones further north and the pressure gradient is changing at the latitude of the GTA.

Figure 43: Wind Speed Differences between the 2000-2009 and 2040-2049 Periods



Average Wind Speed Difference (km/h)

Maximum Wind Speed (km/h)

Wind Gust Difference (km/h)

5.1.7.2 Wind Speed

Wind direction is not expected to change very much in the future so no documentation is provided. Wind speed is expected to change and the diagrams below present various wind speed categories for the Whitby location for the current and future period. Figure 44 presents changes in average wind speed categories and Figure 45 the difference in the maximum gust wind speed categories.

Figure 44: Whitby Average Wind Speed by Category (in km/hour)

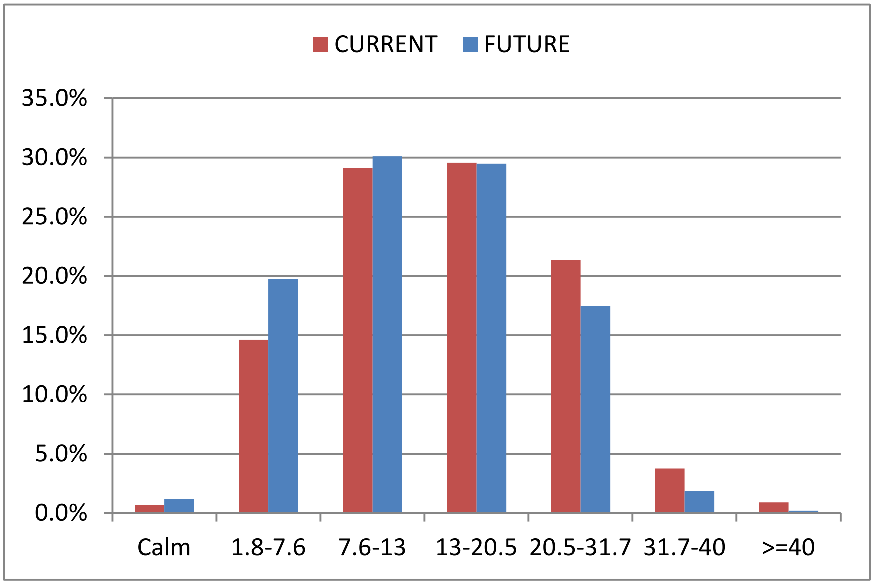
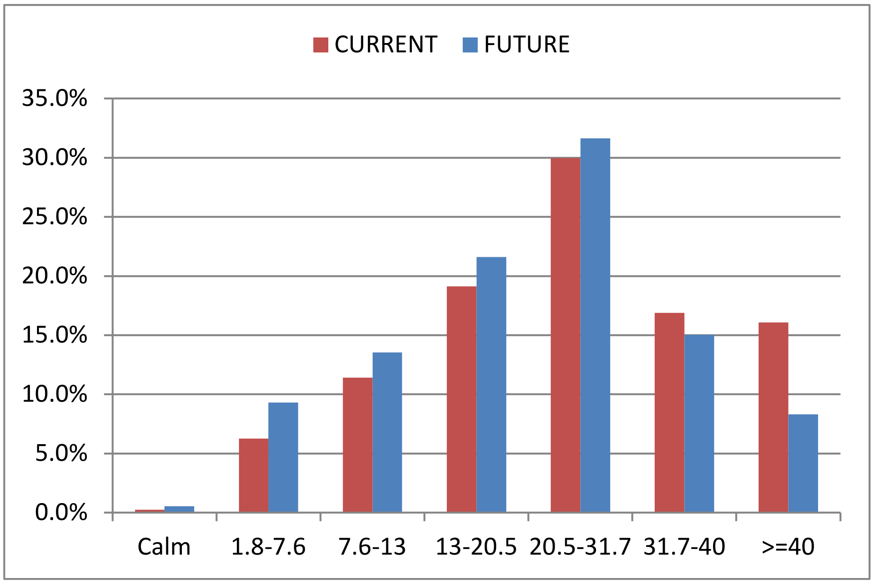


Figure 45: Whitby Maximum Gust Speed by Category (in km/hour)



The data shows an increasing frequency of wind speeds below 20.5 km/hour in the future along with a decreased frequency of higher wind speeds. The gust winds show the same type of behaviour with increasing frequency of gust winds up to 31.7 km/hour and a decreasing frequency beyond that speed category. The percentage of calms (periods of time with no discernible wind) increases by about 0.5% in the future.

5.1.7.3 Wind Chill

Summarised data of wind chill events are presented in Table 27 and Table 28 for the 2000-2009 and 2040-2049 periods, respectively. The occurrence of wind chill is reduced in the future period, because of the general increase in temperature in the future. The tables show, for example, that wind chill events with temperatures below -20°C are no longer expected to occur; indeed the total number of days with wind chill less than -20 is predicted to reduce from 15 to zero.

Table 27: Whitby – Wind Chill Summary for 2000-2009

Windchill	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Extreme Windchill	-32	-31	-37	-18	-6	-1	0	0	-6	-8	-18	-25	**-37**
Days with Windchill < -20	6.1	5.5	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	**15.1**
Days with Windchill < -30	0.5	0.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**1.2**
Days with Windchill <- 40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Days with Windchill <- 45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**

Table 28: Whitby – Wind Chill Number of Days Summary for 2040-2049

Windchill	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Extreme Windchill	-18	-17	-15	-10	0	0	0	0	-1	-5	-11	-19	**-19**
Days with Windchill < -20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Days with Windchill < -30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Days with Windchill <- 40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Days with Windchill <- 45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**

5.1.8 Storms

To put the difficulty of predicting the occurrence of storms in the future into perspective, it should be recognized that predicting storms in the present is considered to be "nearly impossible" as borne out by Marsh et al. (2007) who stated "*Severe convective weather events (thunderstorms, hail, tornadoes, etc.) are relatively rare atmospheric phenomena due to their very small temporal and spatial scales. Consequently, assessing climatologies of actual severe convective weather events is difficult. Inconsistencies in reporting criteria and improvements in the technology used to observe severe weather make the problem of developing reliable long-term climatologies of severe weather events nearly impossible*".

For this study, storms have been categorized through the Storm Relative Helicity (SRH), the Convective Available Potential Energy (CAPE) and the Energy Helicity Index (EHI) indices as well as by wind gust and blowing snow.

5.1.8.1 Storm Relative Helicity

Storm relative helicity (SRH) estimates the rotational potential that can be realized by a storm moving through an environment with vertical wind shear. An environment with vertical wind shear has vorticity about a horizontal axis; the greater the vertical wind shear, the greater the horizontal vorticity. A storm moving in such an environment will tilt this horizontal vorticity into the vertical through the upward motion in the storm's updraft, creating vertical vorticity or midlevel rotation. If strong enough, this can detected on radar as the familiar mesocyclone signature on radar that is associated with supercell storms. The purpose of using SRH is to get a measure of how much rotational potential is available through the vertical wind shear at lower levels that can be tilted into the vertical by a storm moving through the environment. Typically, one considers the layer from the surface to 3 km above ground level (AGL) when calculating SRH.

The index is derived for the following equation:

$$SRH=\int (V_h-C)*\nabla * V_h * dz \qquad \text{(0-3 km layer)}$$

where C is the cloud motion to the ground; and
V_h is the vector of horizontal wind.

The SRH scale used is given in the following table:

Description	**SRH Value**
Supercells with weak tornadoes	**150 - 300**
Supercell development with strong tornadoes	**300 – 450**
Violent tornadoes	**>450**

5.1.8.2 Convective Available Potential Energy

CAPE (Convective Available Potential Energy) is a measure of region where the theoretical parcel temperature is warmer than the actual temperature at each pressure level in the lower atmosphere (troposphere). The theoretical parcel temperature is the change in temperature with height that a parcel would take if raised from the lower Planetary Boundary Layer (PBL).

The larger the region (the positive area), the higher the CAPE. The units of CAPE are Joules per kilogram (energy per unit mass).

The operational significance of CAPE is presented in the following table:

CAPE	
1 - 1,500	Positive
1,500 - 2,500	Large
2,500+	Extreme

High CAPE means that storms will develop very quickly vertically. The updraft speed depends on the CAPE environment.

As CAPE increases (especially above 2,500 J/kg), the potential to produce hail increases. Large hail requires very large CAPE values. An intense updraft often produces an intense downdraft since an intense updraft will condense out a large amount of moisture. Expect isolated regions of very heavy rain when storms form in a large or extreme CAPE environment.

5.1.8.3 The Energy Helicity Index

The Energy Helicity Index (EHI) is a combination of two indices. By itself, it is the best index available for storm and tornado prediction since it combines both CAPE and Helicity. The CAPE is the amount of pure instability present in a parcel of air that rises from the lower PBL. Helicity is the product of low level shearing (known as streamwise vorticity) and storm inflow directly into the streamwise vorticity. The Helicity is storm relative which means the Helicity is calculated from the storm's frame of reference.

EHI determined from the following equation:

$$EHI = (CAPE * SRH) / 160{,}000$$

The EHI has no units. This value is calculated as follows:

If CAPE = 4,385 J/kg and SRH = 220 m^2/s^2, then EHI = (4,385 * 220) / 160,000 = 6

The operational significance of the EHI is given in the table below:

EHI	
> 1	Supercell potential
1 to 5	Up to F2, F3 tornadoes possible
5+	Up to F4, F5 tornadoes possible

For the Regional Municipality of Durham, hourly present weather data were used for the period of 2000-2009, as the basis for comparison with future situations. The following criteria were calculated: SRH > 300; CAPE > 1000; EHI > 0.5 and Wind Gust > 40 km/h.

If any of these criteria is fulfilled then the day is categorized as a storm day. Additional analyses for storms were taken from a report that SENES completed for Hydro One (SENES, 2007) that examined power line interruptions.

For the winter storms, in November, December, January, February or March, one of the main criteria was blowing snow (which is only correct if snow is on the ground). Because the SRH and CAPE indices are more predictive tools, applying all of the conditions at the same time, the number of storm days will be over-estimated. Based on 2000-2009 period, it was concluded that the estimated number of storms using these three methods as described will not miss anything significant.

SENES used the average of the three different approaches to estimate the number of storms. The number of storms was estimated using three indices (CAPE, SRH and EHI) because each used different metrics to determine number of storms. The SENES assessment was that the average of the three metrics best represented the number of storms that occurred by comparing the estimated number against the observed number of storms over the period 2000-2009.

Table 29 summarizes the number of storms based on a detailed observational analysis for the current period, for Pearson Airport. Table 30 summarizes the current period (2000-2009) and the future based on the adjusted derived criteria.

Table 31 and Table 32 show the SRH indexes for the current and first future periods for the Whitby location. Table 33 and Table 34 show the CAPE indexes for current and future (2040-2049) periods for Whitby.

Table 29: Pearson Airport – Observed Number of Storms by Year

Year	Total	Summer	Winter
2000	32	25	7
2001	18	11	7
2002	26	20	6
2003	30	21	9
2004	35	16	19
2005	31	15	16
2006	29	16	13
2007	20	15	5
2008	26	18	8
2009	33	18	15
Average	**28**	**18**	**11**

Table 30: Pearson Airport - Derived Number of Storms by Year

Current Period (2000-2009)

Year	Total	Summer	Winter
2000	28	16	12
2001	26	16	10
2002	39	23	16
2003	30	16	14
2004	32	16	15
2005	28	16	11
2006	32	18	14
2007	32	16	16
2008	30	16	14
2009	26	15	11
Average	**30**	**17**	**14**

Future Period (2040-2049)

Year	Total	Summer	Winter
2000	15	10	5
2001	23	15	7
2002	22	14	8
2003	21	18	4
2004	27	19	8
2005	32	26	5
2006	21	15	6
2007	24	19	5
2008	27	21	6
2009	21	17	4
Average	**23**	**17**	**6**

Based on the average of the derived criteria results for Pearson Airport, it appears that the future period (2040-2049) will have a reduced total number of storm days with approximately 23% fewer storm days than the current period, with an even larger reduction of approximately 57% in the number of winter storms. This is also confirmed by SRH index, for the category >300, the number of storm days in the period 2040-2049 is reduced by ~56%.

Table 31: Whitby - Number SRH Days for 2000-2009

SRH	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Days with SRH 150-300	14.6	12.5	9.9	11.0	12.4	10.1	9.2	11.3	12.3	13.0	12.8	14.0	**143.1**
Days with SRH 300-450	5.3	3.9	5.0	4.9	3.7	2.6	1.8	1.3	2.5	4.9	5.4	6.0	**47.3**
Days with SRH >450	4.2	5.4	6.4	5.9	2.9	1.5	0.6	0.6	1.4	3.1	4.4	4.7	**41.1**

Table 32: Whitby – Number of SRH Days for 2040-2049

SRH	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Days with SRH 150-300	10.5	11.6	10.9	11.4	11.2	9.7	9.2	7.9	7.8	10.6	11.7	8.8	**121.2**
Days with SRH 300-450	3.2	3.4	2.0	2.0	1.4	1.8	2.4	1.7	1.4	1.4	2.1	2.2	**24.9**
Days with SRH >450	0.4	1.3	1.3	1.8	0.7	1.3	0.5	1.2	0.2	0.6	0.9	0.5	**10.8**

Table 33: Whitby - Number of CAPE Days for 2000-2009

CAPE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Days with CAPE 0	1.8	2.5	5.9	8.6	6.1	2.7	0.6	2.1	5.5	6.6	5.3	2.4	**50.1**
Days with CAPE 0-1000	30.9	28.3	31.0	29.7	29.0	21.6	17.3	19.5	28.1	30.5	30.0	31.0	**326.9**
Days with CAPE 1000-2500	0.0	0.0	0.0	0.3	1.7	7.3	12.1	10.1	1.9	0.5	0.0	0.0	**33.9**
Days with CAPE 2500-3500	0.0	0.0	0.0	0.0	0.2	1.1	1.0	1.1	0.0	0.0	0.0	0.0	**3.4**
Days with CAPE >3500	0.0	0.0	0.0	0.0	0.1	0.0	0.6	0.3	0.0	0.0	0.0	0.0	**1.0**

Table 34: Whitby – Number of CAPE Days for 2040-2049

CAPE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Days with CAPE 0	3.5	4.1	6.1	5.8	6.1	3.5	0.9	0.7	2.5	5.9	5.9	2.0	**47.0**
Days with CAPE 0-1000	31.0	28.3	31.0	29.9	30.5	24.0	17.4	14.9	24.1	30.6	30.0	31.0	**322.6**
Days with CAPE 1000-2500	0.0	0.0	0.0	0.1	0.5	5.2	12.1	12.6	5.6	0.4	0.0	0.0	**36.5**
Days with CAPE 2500-3500	0.0	0.0	0.0	0.0	0.0	0.8	1.4	2.7	0.2	0.0	0.0	0.0	**5.1**
Days with CAPE >3500	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.9	0.1	0.0	0.0	0.0	**1.1**

The CAPE index based results are presented in Table 34 and show that the number of days for CAPE > 1000 goes up slightly, from 33.9 to 36.5 (an increase of about 8%).

This is also in the agreement with the precipitation days >50mm (see Table 20 above) which doubles in the future. The data confirms that the total number of storms is going down, but the potential for severe future summer storms is going up.

Table 35 shows the EHI indices year-by-year for Whitby and also shows that the potential for future severe storms is going up and that, on average, they will get stronger.

The spatial distributions of the average indexes SHR (vortices potential), CAPE (convective energy potential) and EHI (composite of these two) are presented in Appendix A in Figure 63, Figure 64 and Figure 65. The percent differences between the current and future periods are presented in
Figure 46.

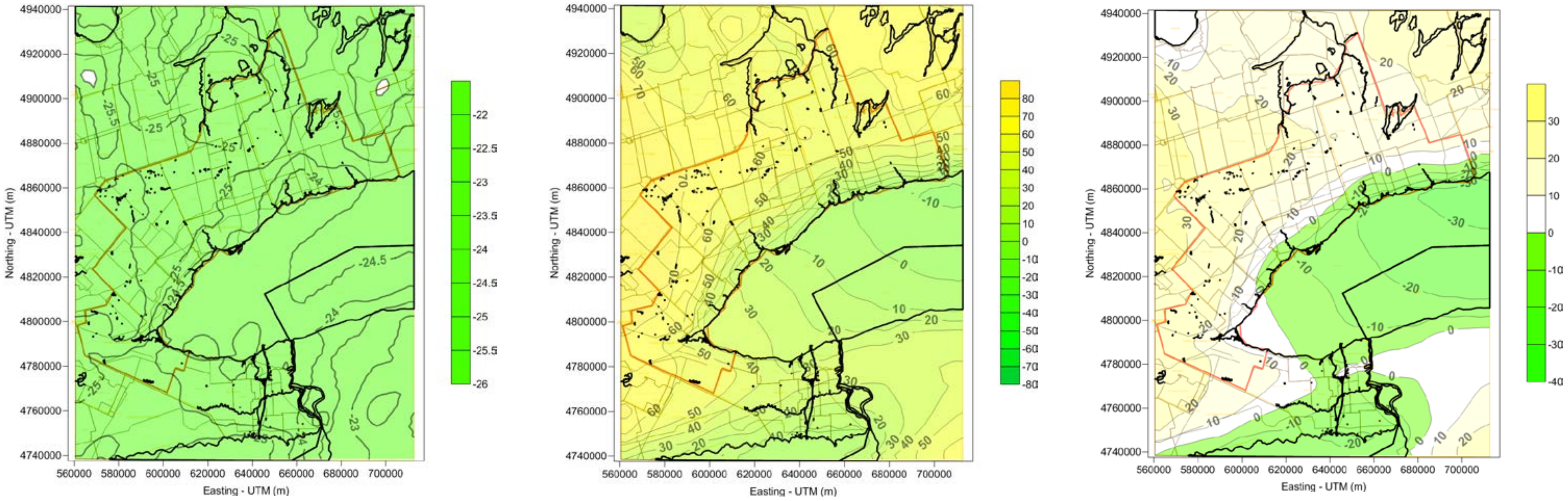
Table 35: Summary of Extreme Whitby Indexes (Current and Future Scenario)

Year	SRH	CAPE	EHI	Year	SRH	CAPE	EHI
2000	1478	2834	2.3	**2040**	721	2279	2.1
2001	1144	2399	1.5	**2041**	829	3480	5.8
2002	1389	4842	4.2	**2042**	799	2620	1.9
2003	1079	2836	3.6	**2043**	701	3886	4.2
2004	1295	2954	2.5	**2044**	865	3286	4.3
2005	1043	3611	2.8	**2045**	827	4246	4.0
2006	1394	3886	4.9	**2046**	719	2889	1.9
2007	1192	3742	4.3	**2047**	791	3805	3.0
2008	1211	3445	3.4	**2048**	630	3229	6.7
2009	1455	2617	2.3	**2049**	882	3758	6.3
Maximum	1478	4842	**4.9**		882	4246	**6.7**
Average	1268	3317	**3.2**		776	3348	**4.0**

Based on Figure 63 though Figure 65 (Appendix A), SENES has demonstrated that the index related to the wind (SRH) is decreasing, while CAPE (energy) is increasing over the land and decreasing over the water. The increase over the land can be as high as 70%. The EHI index shows an increase of 20% over land and decrease of about 20-30% over the lake. The over land increase reflects increasing temperatures over land in the future with decreasing wind speeds.

A comparison to the other results is presented in Appendix A of Volume 2 which also shows the average CAPE values derived from (P. T. Marsh, 2007). The values derived in this study compare well with Marsh's data.

Figure 46: Spatial Distribution of SRH, CAPE and EHI Differences



Mean SRH Difference (%)

Mean CAPE Difference (%)

Mean EHI Difference (%)

6.0 What Does It All Mean for Durham?

6.1 Certainty in Future Climate Change and Its Direction

Observations of the Earth's climate (from the instrumental record) show that it has warmed by an average value of 0.76ºC since preindustrial times, and Arctic temperatures have increased at nearly twice the global average rate. Water vapour levels have risen since the 1980s (and possibly earlier), and are broadly consistent with the observed rises in air temperatures. Glaciers have retreated and melted, and snow cover has fallen in many areas. Since 1900, sea levels have risen by an average of 1.8 mm/year. A comparison of current temperatures with those derived from proxy data (such as tree rings and corals) shows that average temperatures in the Northern Hemisphere between 1950 and 2000 were almost certainly higher than any other 50 year period since 1500, and are likely the highest over the last 1,300 years. These observed rises in temperature have occurred since the beginning of the industrial revolution, when fossil fuels were burned in large quantities.

Climate model simulations of observed temperatures in the continents between 1900 and 2000 have been made using natural climate forcings only (solar output changes and volcanic eruptions) and then repeated including forcing due to anthropogenic emissions of greenhouse gases. The two sets of simulations diverge after about 1960, and only the simulations which include anthropogenic emissions reproduce the observed temperature changes. The simulations which only consider natural climate forcings are too cool, and project a climate for 2000 similar to that of 1900. For this reason, we can be confident that anthropogenic emissions are responsible for the recent observed global warming.

The IPCC 4th Assessment Report only considered the SRES scenarios of future greenhouse gas emissions. An extra simulation, where greenhouse gas levels were held at 2000 levels showed that global temperatures continued to rise by about 0.35ºC throughout the 21st century. More recently, an aggressive mitigation scenario has been developed which assumes continuous reductions in greenhouse gas emissions from about 2015 (Lowe et al., 2009; Moss et al., 2010). Even under this scenario, global temperatures are projected to increase by 2ºC compared to preindustrial levels by 2100.

Carbon dioxide and other greenhouse gases have long lifetimes in the atmosphere, which means, even if CO_2 and other gases were stabilised, climate change will continue for 100s if not 1,000s of years. This is known as committed climate change. The climate system does not respond instantly to additional levels of greenhouse gases, owing to the thermal inertia of the oceans. This inertia means that the full impact of emissions will not be realised until many years later, even if the levels of greenhouse gases are stabilised. Models have been used to study committed climate change resulting from past greenhouse emissions. The results show that climate change continues for more than 1000 years, and even on these timescales temperatures and sea levels do not return to preindustrial levels. The uptake of CO_2 by the oceans and creation of calcium carbonate sediments takes place over 30,000 – 35,000 years.

CO_2 emissions would need to be reduced by 50% to stabilise CO_2 levels in the atmosphere, but this would only last for about a decade owing to a decline in land and ocean removal rates. Other greenhouse gases have different lifetimes. Nitrous Oxide (N_2O) would require a reduction of over 50% of its emissions to stabilise its concentrations at present day levels, whereas for methane (CH_4), a 30% or greater reduction in its emissions would stabilise its concentrations at levels significantly below those at present.

In summary, climate change will continue into the future, because of the thermal inertia of the oceans, even if very large cuts in greenhouse gas emissions are made in the very near future. Climate simulations using a recent aggressive mitigation scenario, which uses plausible and significant reductions of greenhouse gas emissions, show that global temperatures continue to rise to 2100. No plausible future scenarios of greenhouse gas emissions produce a cooling of the earth. These results mean we can be confident that the Earth's climate will continue to warm throughout the 21st century. What we can control is by how much the climate warms. The Copenhagen Accord agreed in December 2009 has the stated aim of limiting global warming to 2.0°C above preindustrial temperatures. This target may be technically possible to achieve but will require substantial cuts in global greenhouse gas emissions in the very near future (Meinshausen et al., 2009). However, current national emissions-reduction pledges appear to be insufficient to keep global warming below 2.0°C (Rogelj et al., 2010).

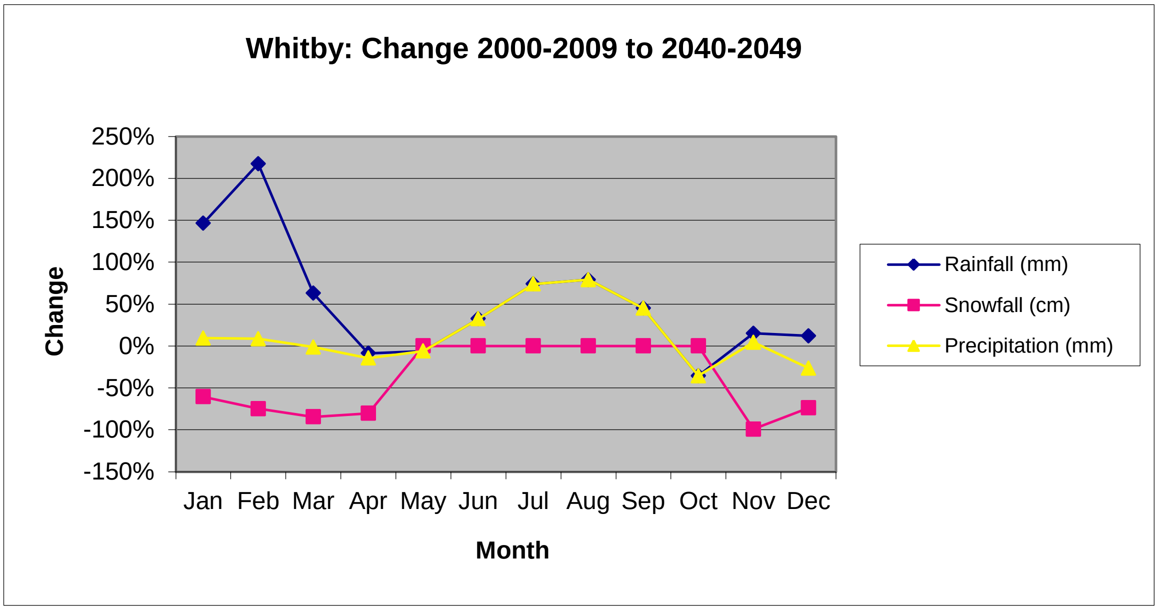
6.2 Overview

Locally we can expect larger changes as a result of the local weather drivers. In this study, the 10-year climatology of current period (2000-2009) was compared with the future 10-year climatology – 2040-2049. Hourly data was produced for 8 surface locations for the 10-year period and the data from the Whitby location was analyzed in some detail to show the magnitude of the expected climate warming impact across the Regional Municipality of Durham.

6.3 Future Period

Using Whitby as the proxy location for Durham Region, the future period (2040-2049) is predicted to have almost the same amount of precipitation on a month-by-month basis except in June, July, August and September when there will be about 29, 72, 50 and 31mm more, respectively (see Figure 47). It also shows that October and December will have less precipitation by 36 and 26%, respectively. This figure also shows decreasing snowfall but increasing rainfall in the future winter months.

Figure 47: Whitby – Change in Monthly Precipitation Amounts



Comparing predictions between current and the future period also shows (see Figure 48) that fewer days with precipitation are anticipated, except June through September where there will be 2-3 additional days of rain in each month. It is also expected that the number of snow days will be reduced by up to 8 days in the worst month (February) and overall by 30 days a year.

Figure 49 shows that the number of days with heavy snow (25cm) is predicted to be reduced and with heavy rain (>50mm) to be increased.

But the results also show that extreme events will be more severe in the future. Figure 50 and Figure 51 present a monthly comparison of the extreme daily precipitation amounts and the extreme daily snowfall amounts, respectively. Figure 50 shows a large increase in the August extreme event. Figure 51, on the other hand, shows a significant decrease in the occurrence of extreme snow events during all months that typically have such snowfall events in the current period.

Figure 48: Whitby - Monthly Difference in the Number of Precipitation Days

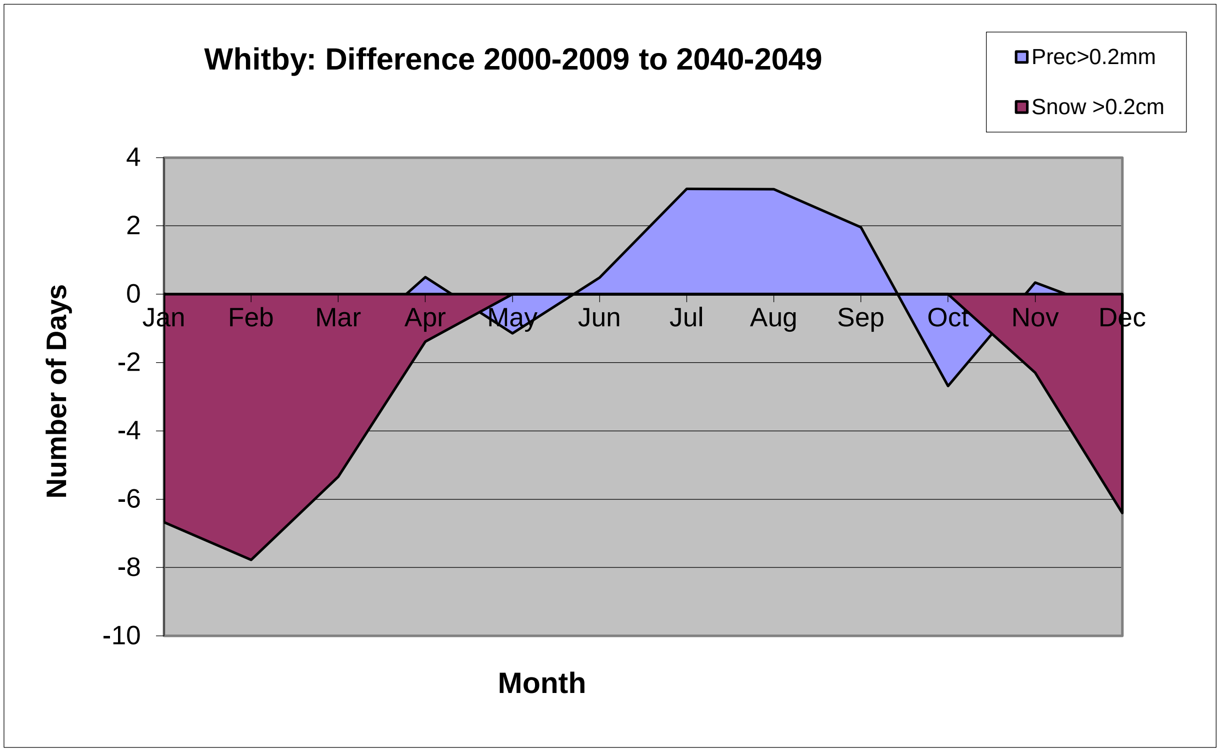


Figure 49: Whitby - Difference in the Number of Heavy Precipitation Days

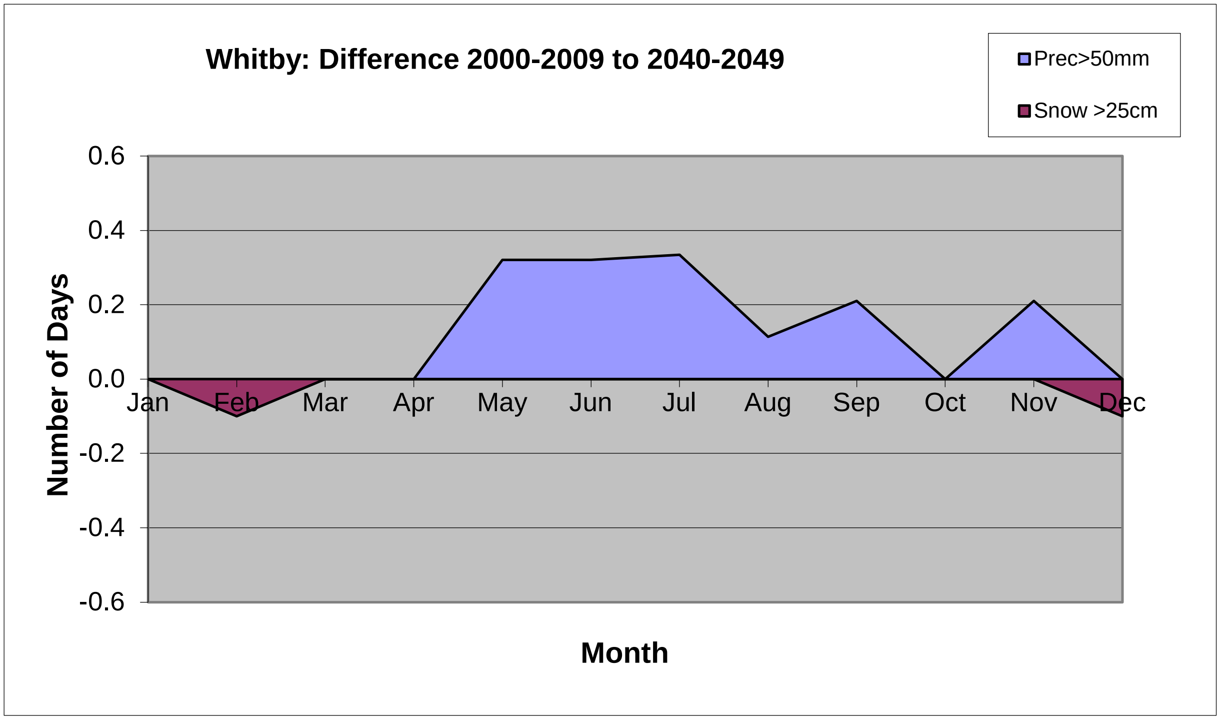


Figure 50: Whitby - Month-by-Month Extreme Daily Precipitation

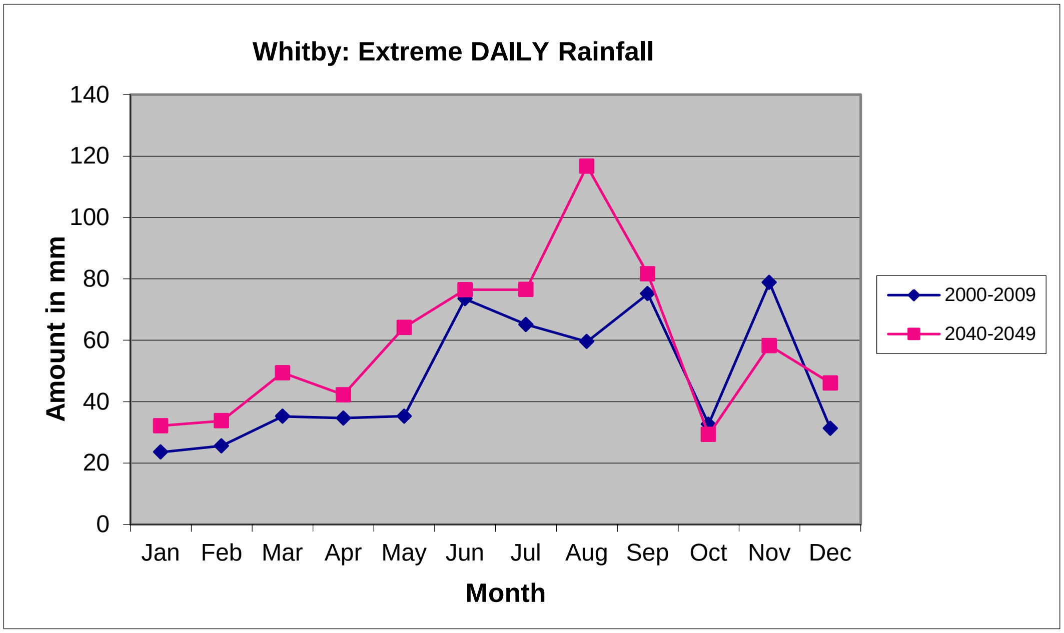
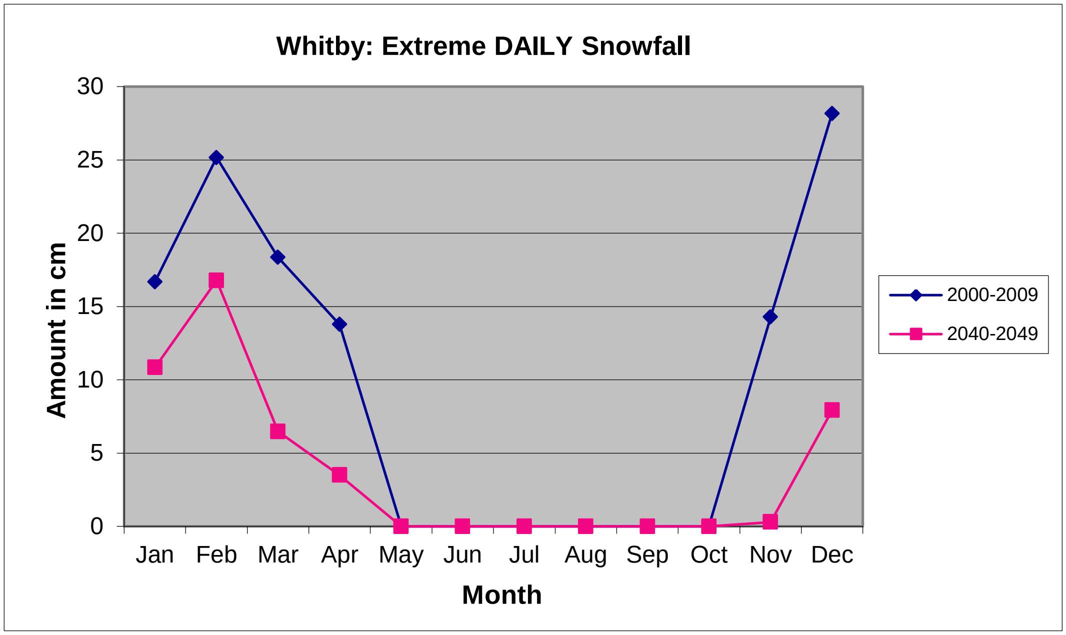


Figure 51: Whitby - Month-by-Month Extreme Daily Snowfall



While there are variations in the changes of climate predicted among the different areas of the Regional Municipality of Durham, analysis of the model results indicates future temperature increases and a generally warmer future than is experienced today. Basing conclusions only on analyses of results respecting Whitby reveals that the future average temperature will be 4.0 degrees C warmer. The predicted future month-by-month temperature differences are presented in Figure 52, and show a range from a high of 7 to a low of 2 degrees higher than today. If we look at extremes, Figure 53 shows the differences in extreme maximum and extreme minimum temperature between 2000-2009 and 2040-2049 at Whitby. The figure shows an expected reduction in extreme minimum temperature of almost 12 degrees C on average but an expected increase in extreme maximum temperature of about 7 degrees C on average.

Figure 52: Whitby - Month-by-Month Temperature Differences

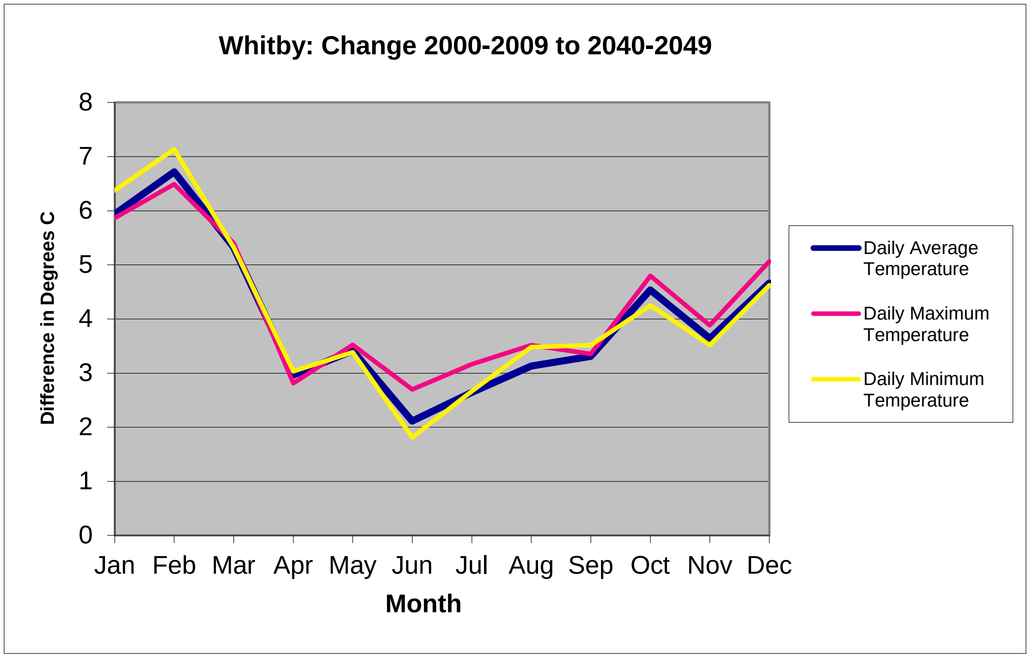


Figure 53: Whitby - Monthly Differences in Temperature Extremes

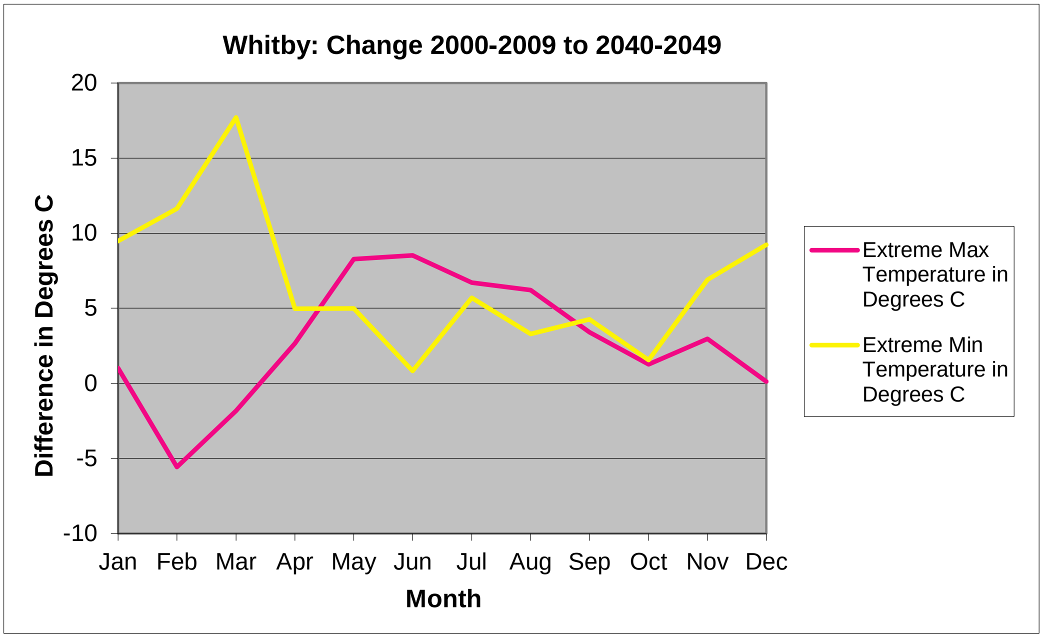
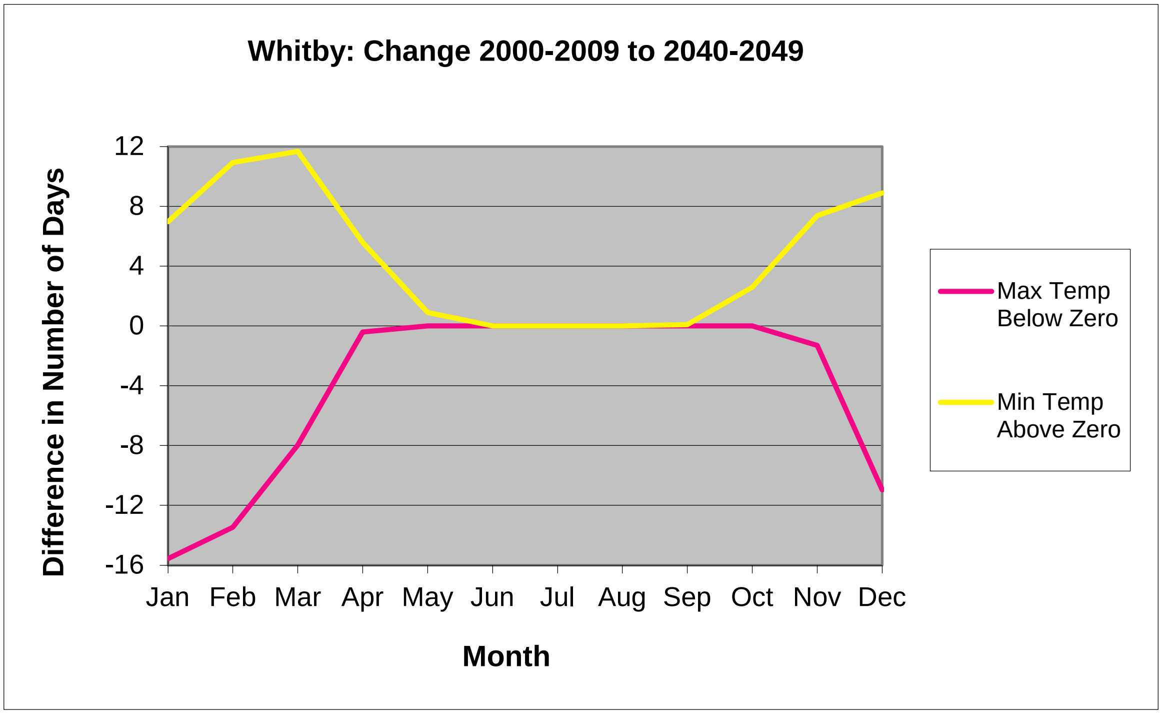


Figure 54 plots the differences in the number of days above and below zero. The figure shows virtually no change in the summer but a significant change in the spring, fall and winter seasons. The figure shows a significant reduction in the number of days the maximum temperature will be below zero and a significant increase in the number of days that the minimum temperature will be above the freezing point.

Figure 54: Whitby - Differences in Number of days Above and Below Zero



Concerning wind differences, Figure 55 shows that the future will have about the same average wind speed but that the maximum hourly and maximum gust wind speeds will be significantly reduced especially in the shoulder and winter seasons.

Figure 56 presents the changes in extreme humidex by month. The figure shows increases in every month, except February and October, with an average increase of 8% and a maximum increase in November of 31%.

Figure 57 presents the predicted change in extreme wind chill between now and the future (2040-2049). It shows on average about a 49% reduction in wind chill varying from a high of 100% in June to a low of 25% in December.

Figure 55: Whitby - Monthly Differences in Winds

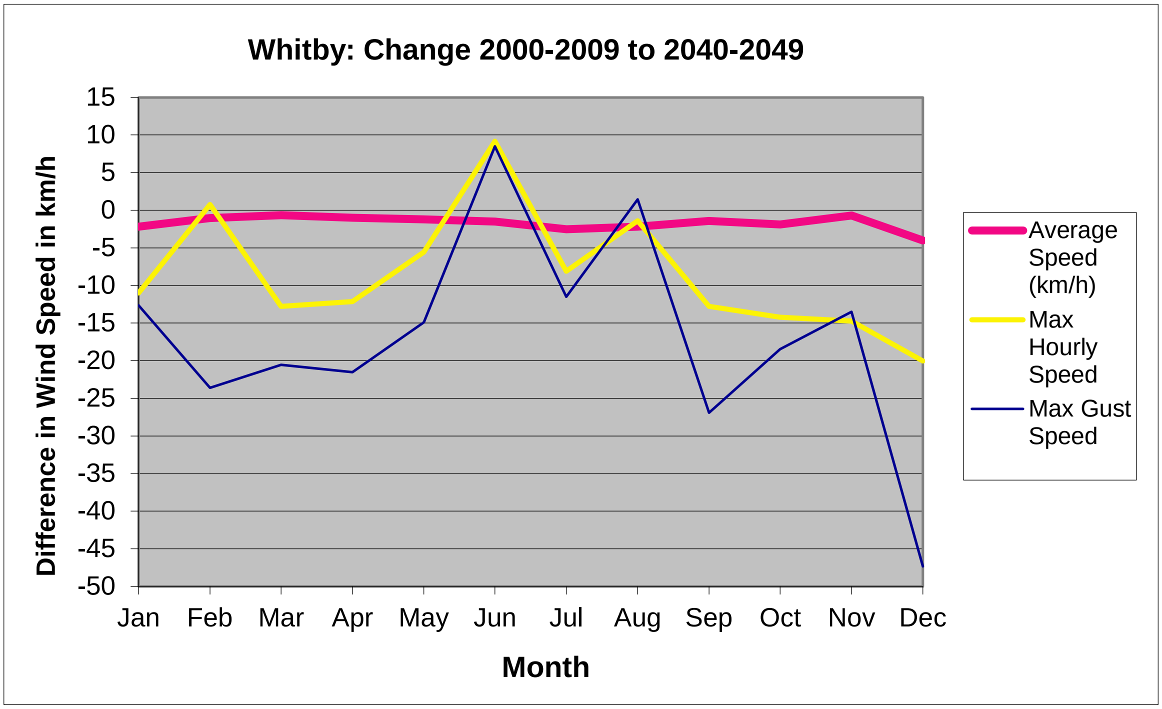


Figure 56: Whitby - Monthly Changes in Extreme Humidex

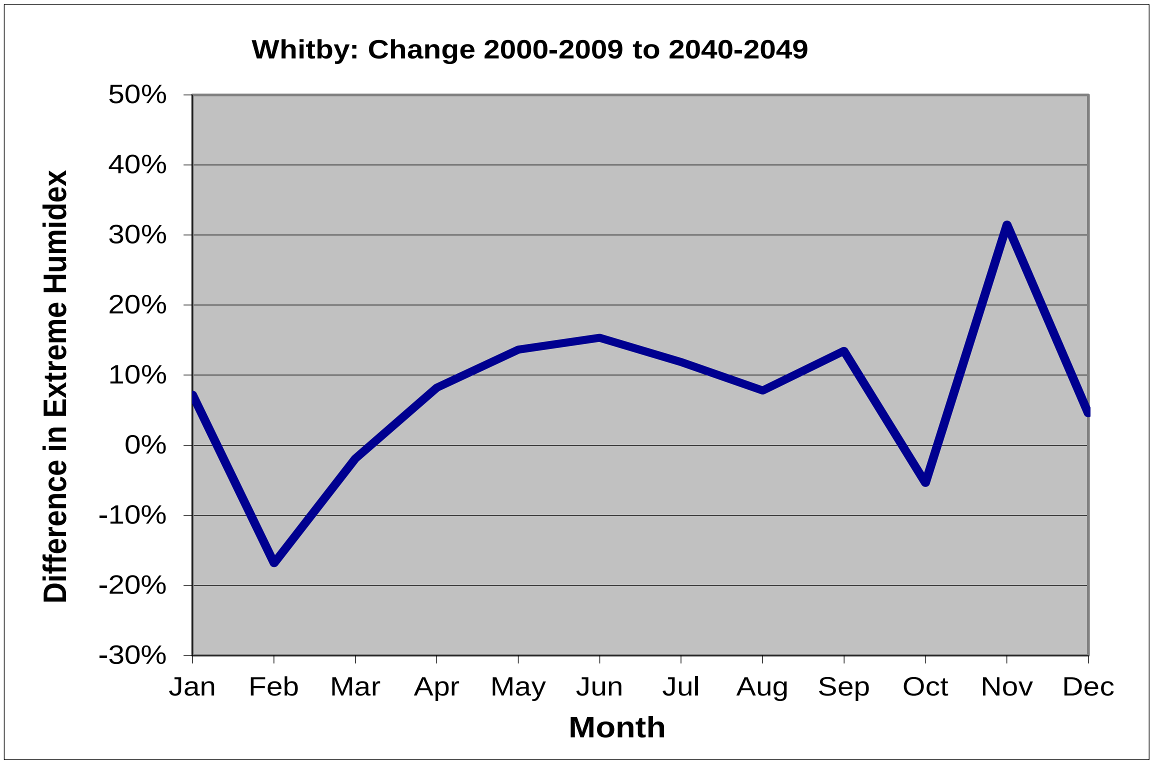
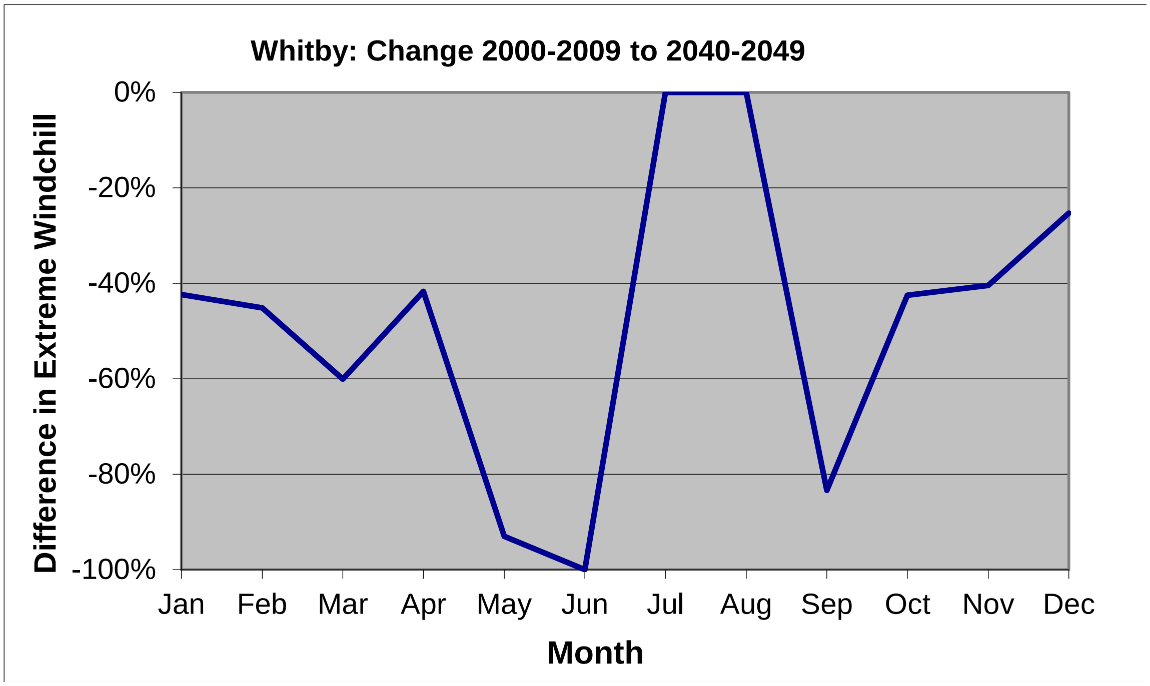


Figure 57: Whitby - Monthly Changes in Extreme Wind Chill



6.5 Combinations of Parameters

The Regional Municipality of Durham was also interested in some combinations of extreme parameters as they might affect local infrastructure. These combinations of parameters are presented here.

Heavy Rain

Definition

This is defined as number of events with total precipitation greater than 50 millimetres over a 6-hour time period while the temperature is above 1 degree C.

Validation

With this parameter there are no instances of this event occurring at Pearson Airport within the period 2000-2009 so it was not possible to validate the model prediction of this type of event.

Discussion

Table 36 presents the current and future occurrences of this type of event for both the current (2000-2009) and future (2040-2049) period.

Main Finding

Table 36 shows an increased number of days with heavy rain events across Durham ranging from 0 to 8 days/year. The largest increase is predicted to occur in Port Perry.

Table 36: Occurrences of Heavy Rain across Durham

Current 2000-2009

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	4	5	3	1	2	0	4	3	0
2001	0	0	0	3	4	0	4	0	0
2002	0	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0	0
2004	3	7	11	11	0	0	0	0	0
2005	4	0	0	5	4	0	4	4	0
2006	2	0	0	0	0	3	0	3	0
2007	0	0	0	0	0	4	0	0	0
2008	0	0	1	0	0	2	8	0	0
2009	0	0	4	0	3	0	2	3	0
10-year Period	13	12	19	20	13	9	22	13	0

Future 2040-2049

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	0	0	0	0	8	9	0	0	8
2041	0	0	7	0	0	9	0	5	0
2042	0	7	5	12	2	13	0	0	1
2043	19	20	21	19	7	9	5	23	8
2044	1	3	0	5	12	12	5	5	4
2045	5	5	5	8	9	11	0	5	4
2046	0	0	4	14	9	8	6	0	6
2047	9	7	6	4	5	8	0	8	0
2048	0	0	0	3	2	5	3	0	0
2049	0	7	5	4	2	6	4	0	0
10-year Period	34	49	53	69	56	90	23	46	31

Difference (Future - Current)

Number of Events

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	21	37	34	49	43	81	1	33	31
per year	2.1	3.7	3.4	4.9	4.3	8.1	0.1	3.3	3.1

High Intensity Short Duration Rainfall

Definition

This is defined as more than 50 millimetres of precipitation occurring in 1 hour while the temperature was above 1 degree C.

Validation

With this parameter there are no instances of this event occurring at Pearson Airport within the period 2000-2009 so it was not possible to validate the model prediction of this type of event.

Discussion

Table 37 presents the occurrences of this type of event for both the current (2000-2009) and future (2040-2049) period.

Table 37: High Intensity Short Term Rainfall across Durham

Current 2000-2009

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	0
10-year Period	0	0	0	0	0	0	0	0	0

Future 2040-2049

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	0	0	0	0	0	0	0	0	0
2041	0	0	0	0	0	0	0	0	0
2042	0	0	0	0	0	0	0	0	0
2043	1	0	0	0	0	0	0	1	0
2044	0	0	0	0	0	0	0	0	0
2045	0	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0	0
2047	0	1	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	0
10-year Period	1	1	0	0	0	0	0	1	0

Difference (Future - Current)

Number of Events

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	1	1	0	0	0	0	0	1	0
per year	0.1	0.1	0	0	0	0	0	0.1	0

Main Finding

Table 37 shows no occurrences of this type of event during the current (2000-2009) period and only three events projected across Durham (at Pickering, Ajax and Whitby) over the future (2040-2049) period.

Accumulated Storm Surface Runoff

Definition

This is defined as the hourly average and maximum hourly runoff in litres within a month. This is a direct output from the model.

Validation

With this parameter there is no simple way to validate the simulated results. This is because run-off depends on how porous the ground is and how much water is already in the ground. Porosity depends on surface type which varies across Durham from zero on paved surfaces to fairly high with sandy soils. The model sees a fixed average surface type for each square kilometre which does not reflect the actual situation.

Discussion

Table 38 and Table 39 present the average and maximum monthly surface runoff in litres, respectively, as well as the difference between the current and future (2040-2049) periods across the stations in Durham.

Main Finding

Table 38 shows either the same or a slightly reduced average hourly runoff in the future but Table 39 shows a generally larger maximum hourly runoff (ranging from about 0.5 to 2.5 litres per hour) in any year which is consistent with increased severity of future storms.

Table 38: Modelled Hourly Average Surface Runoff in Litres

Current 2000-2009

Average L/hr

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02
2001	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.02
2002	0.02	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.01
2003	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02
2004	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.02	0.03
2005	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.02
2006	0.01	0.01	0.01	0.01	0.03	0.03	0.03	0.01	0.02
2007	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01
2008	0.02	0.02	0.02	0.02	0.03	0.04	0.02	0.02	0.03
2009	0.02	0.02	0.02	0.02	0.02	0.04	0.04	0.02	0.02
10-year Period	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Future 2040-2049

Average L/hr

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.00	0.02
2041	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2042	0.02	0.02	0.02	0.03	0.02	0.03	0.01	0.01	0.02
2043	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.04	0.03
2044	0.02	0.03	0.02	0.02	0.03	0.04	0.02	0.03	0.03
2045	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02
2046	0.02	0.02	0.02	0.03	0.04	0.03	0.03	0.02	0.03
2047	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.03
2048	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02
2049	0.01	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.02
10-year Period	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Difference (Future - Current)

Average L/hr

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	-0.003	0.000	0.000	0.000	0.001	0.001	-0.004	-0.001	0.002
per year	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 39: Modelled Hourly Maximum Surface Runoff in Litres

Current 2000-2009

Max L/hr

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	11.77	14.84	10.06	10.13	10.44	5.90	9.60	9.48	5.62
2001	4.74	4.90	4.31	9.62	8.98	8.58	13.30	3.69	4.36
2002	7.13	6.48	5.15	8.45	3.71	10.60	10.38	8.60	7.37
2003	5.86	9.09	7.56	8.12	6.77	3.43	5.55	5.59	4.98
2004	4.74	16.93	18.22	11.53	6.25	6.86	6.06	4.70	7.45
2005	15.37	9.60	13.43	13.10	10.99	5.52	13.10	15.99	6.69
2006	8.20	7.39	5.09	3.91	5.01	8.66	9.98	7.55	12.75
2007	7.53	6.14	5.62	10.08	3.72	11.22	3.66	7.17	2.21
2008	6.44	6.77	11.61	9.64	9.94	10.64	14.14	6.76	22.60
2009	17.09	9.86	10.90	7.86	7.28	12.20	12.61	12.34	7.68
10-year Period	17.09	16.93	18.22	13.10	10.99	12.20	14.14	15.99	22.60

Future 2040-2049

Max L/hr

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	10.70	5.43	5.56	4.17	8.40	11.84	7.00	2.99	27.42
2041	12.92	8.31	14.21	5.44	9.33	15.47	11.65	19.44	5.80
2042	7.12	11.52	8.88	35.50	11.86	17.78	8.62	3.75	10.76
2043	32.07	21.08	20.35	19.08	12.83	15.73	10.31	40.72	32.05
2044	8.88	16.72	10.98	11.27	22.05	31.23	15.06	26.20	21.80
2045	9.35	11.39	11.31	9.78	27.36	24.23	7.60	15.31	11.21
2046	8.24	7.64	11.02	26.23	17.09	18.49	22.27	8.85	12.73
2047	19.85	38.87	21.91	7.98	16.78	14.09	8.50	11.20	15.04
2048	6.90	6.37	5.25	7.14	5.30	8.97	10.90	9.44	10.84
2049	5.36	7.92	9.50	12.33	10.54	15.40	21.87	4.67	7.43
10-year Period	32.07	38.87	21.91	35.50	27.36	31.23	22.27	40.72	32.05

Difference (Future - Current)

Max L/hr

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	14.99	21.94	3.69	22.40	16.38	19.03	8.13	24.73	9.45
per year	1.50	2.19	0.37	2.24	1.64	1.90	0.81	2.47	0.95

Freezing Rain More Than 3 Hours

Definition

This is defined as the number of calendar days with freezing precipitation lasting more than 3 hours. This parameter was modelled as precipitation lasting 4 hours or more on a day within the temperature range >0.5 and less than or equal to 1 degree C.

Validation

Table 40 presents the numbers of observed and modelled hours for this parameter for Pearson Airport for the period 2000-2009. The data show that the model simulates the number of days with freezing rain very well. The comparison between observations and model predictions for the current period is excellent considering that modelling any kind of precipitation is one of the hardest things to get right. The study showed that the model estimated extreme daily rainfall is too high by 2 mm at the same time that the modelled daily minimum temperature predicts high.

Table 40: Freezing Rain More Than 3 Hours Validation at Pearson Airport

Observed Days with Freezing Rain or Freezing Drizzle 3h+ at Pearson Airport

Year	Day Counts
2000	2
2001	2
2002	3
2003	4
2004	3
2005	2
2006	1
2007	5
2008	1
2009	1
Total	**24**

Model - Days with Freezing Rain 3h+ at Pearson Airport

Year	Day Counts
2000	2
2001	6
2002	2
2003	0
2004	1
2005	3
2006	3
2007	1
2008	4
2009	1
Total	**23**

Discussion

While precipitation, in all forms, is the most difficult parameter to model Table 41 was created by using the same model for both the current and future cases so that the differences should be valid. Table 41 shows a decrease in the number of days with more than 3 hours of freezing rain in the period 2040-2049 at the majority of locations across Durham.

Main Finding

This difference is projected to range from 0 to 2 days per year less with 3 hours or more of freezing rain for Durham.

Table 41: Modelled Freezing Rain Lasting 3 Hours or More

Current 2000-2009

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	0	0	0	1	2	1	2	0	2
2001	1	0	1	1	2	3	1	2	6
2002	2	2	4	3	0	2	2	2	2
2003	2	1	2	3	2	1	0	2	0
2004	3	4	3	5	3	4	1	3	1
2005	3	2	3	3	3	2	3	3	3
2006	2	2	2	1	5	5	6	2	3
2007	1	0	0	0	2	2	2	1	1
2008	6	7	8	7	2	2	2	7	4
2009	3	1	1	2	3	4	1	1	1
10-year Period	23	19	24	26	24	26	20	23	23

Future 2040-2049

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	5	4	4	1	5	2	5	3	3
2041	2	1	1	1	0	1	2	1	2
2042	2	3	1	1	2	2	0	2	2
2043	2	0	0	1	1	2	2	1	0
2044	1	0	0	0	2	2	3	1	1
2045	2	3	3	2	2	2	2	2	2
2046	0	3	2	1	6	3	2	2	3
2047	0	1	1	1	1	2	3	0	1
2048	0	1	1	1	0	0	3	1	1
2049	1	2	1	1	1	1	2	2	3
10-year Period	15	18	14	10	20	17	24	15	18

Difference (Future - Current)

Number of Calendar Days

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	-8	-1	-10	-16	-4	-9	4	-8	-5
per year	-0.8	-0.1	-1	-1.6	-0.4	-0.9	0.4	-0.8	-0.5

Freezing Rain More Than 1 Hour

Definition

This parameter is defined as the number of days with freezing precipitation lasting more than 1 hour. This parameter was modelled as precipitation lasting more than 1 hour on a day within the temperature range >0.5 and less than or equal to 1 degree C.

Validation

Table 42 presents the number of observed and modelled days and hours which meet the criteria for Pearson Airport for the period 2000-2009. The table shows that the model overestimates the number of days with freezing rain. The comparison between observations and model predictions for the current period is not very good. One must consider that modelling any kind of precipitation is one of the hardest things to get right. The model estimated extreme daily rainfall is too high by 2 mm at the same time that the modelled daily minimum temperature predicts high. Both of these factors contribute to this poor result.

Table 42: Freezing Rain More than 1 Hour Validation

Observed - Days with Freezing Rain or Freezing Drizzle at Pearson Airport

Year	Day Count
2000	4
2001	8
2002	6
2003	7
2004	6
2005	5
2006	3
2007	7
2008	1
2009	3
Total	**50**

Modelled - Freezing Rain Days at Pearson Airport

Year	Day Count
2000	4
2001	10
2002	9
2003	2
2004	7
2005	9
2006	7
2007	6
2008	13
2009	7
Total	**74**

Discussion

While precipitation, in all forms, is the most difficult parameter to model Table 43 was created by using the same model for both the current and future cases so that the differences should be valid.

Table 43: Modelled Freezing Rain Lasting More than1 Hour

Current 2000-2009

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	1	2	2	2	6	8	9	1	4
2001	8	4	5	7	5	10	8	4	10
2002	16	10	14	16	9	9	6	10	9
2003	7	6	7	6	6	3	3	9	2
2004	9	7	10	12	9	8	8	9	7
2005	5	8	7	7	4	8	4	5	9
2006	4	4	6	5	12	11	14	6	7
2007	3	6	5	5	7	8	8	5	6
2008	13	15	14	19	9	7	14	15	13
2009	7	5	4	6	5	11	7	10	7
10-year Period	73	67	74	85	72	83	81	74	74

Future 2040-2049

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	9	11	7	7	10	10	13	7	7
2041	5	2	3	4	2	3	8	5	5
2042	6	5	5	4	10	5	5	4	4
2043	3	4	5	7	1	3	6	3	2
2044	3	1	0	2	9	5	7	2	2
2045	6	8	4	3	6	10	9	7	5
2046	3	7	8	7	10	6	14	4	7
2047	0	1	1	1	5	3	6	0	2
2048	7	2	3	3	1	7	10	4	3
2049	3	4	4	3	4	6	5	4	5
10-year Period	45	45	40	41	58	58	83	40	42

Difference (Future - Current)

Number of Calendar Days

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	-28	-22	-34	-44	-14	-25	2	-34	-32
per year	-2.8	-2.2	-3.4	-4.4	-1.4	-2.5	0.2	-3.4	-3.2

Main Finding

The data in Table 43 show that the 2040-2049 period will have less occurrences of freezing rain lasting an hour or more (ranging from 1.4 - 4.4 days less), but there is one location in Durham (Beaverton) that shows a small increase of 0.2 days/year.

Ice Storms

Definition

Five different definitions of ice storm were examined in this work. They were as follows:

1. a 24-hour period with freezing rain of 25.4 millimetres or more;
2. a 24-hour period with freezing rain of 50.8 millimetres or more;
3. a 72-hour period with freezing rain of 12.5 millimetres or more;
4. a 72-hour period with freezing rain of 25.4 millimetres or more; and
5. a 72-hour period with freezing rain of 50.8 millimetres or more.

Validation

There are no data available to validate freezing rain by amount.

Main Finding

No matter how they were defined, the data shows that "ice storm days" are not very frequent at the present time and will totally disappear in Durham by 2040-2049. In fact of all the definitions examined, Definitions #1 and 4 showed one ice storm each in the current period at Port Perry. Table 44 presents the data for Definition #3. It shows that in the current period (2000-2009) there were from 0 to 5 storms across Durham. In the future (2040-2049) there are projected to be no more than one (1) similar storm over ten years.

Freezing Rain and High Winds

Definition

Two different definitions of ice storm were examined in this work. They were as follows:

1. a 72-hour period with freezing rain of 12.5 millimetres or more with a wind gust of 90 km/hour or more; and
2. a 72-hour period with freezing rain of 19 millimetres or more with a wind gust of 100 km/hour or more.

Validation

No validation was possible for either of these definitions as no storms matching the criteria were observed at Pearson Airport in the current (2000-2009) period.

Main Finding

The data examined shows no future (2040-2049) period cases matching the criteria used.

Table 44: Number of Storm Events (72 hours freezing rain greater than 12.5 mm)

Current 2000-2009

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	0	0	0	0	0	1	0	0	0
2001	0	0	0	0	0	1	0	0	0
2002	0	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	1	0
2005	0	0	1	1	0	0	0	1	0
2006	0	0	0	0	1	2	0	0	0
2007	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	1	0	0	0
10-year Period	0	0	1	1	1	5	0	2	0

Future 2040-2049

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	1	0	0	0	1	1	1	0	0
2041	0	0	0	0	0	0	0	0	0
2042	0	0	0	0	0	0	0	0	0
2043	0	0	0	0	0	0	0	0	0
2044	0	0	0	0	0	0	0	0	0
2045	0	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0	0
2047	0	0	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	1
10-year Period	1	0	0	0	1	1	1	0	1

Difference (Future - Current)

Number of Events

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	1	0	-1	-1	0	-4	1	-2	1
per year	0.1	0	-0.1	-0.1	0	-0.4	0.1	-0.2	0.1

Days with Lightning

Definition

This is defined as the number of days with a high potential for lightning strikes. It was characterized by looking at the vertical development of clouds because the model does not simulate lightning occurrence. From a research approach, it was found that if the modelled cloud depth was greater than approximately 11 kilometres, this corresponded well with observed lightning on a daily basis. The modelled parameter used was hourly cloud depth greater than or equal to 11300 metres.

Validation

Table 45 compares observed thunderstorms against the model extracted lightning potential (cloud depth greater than 11.3 km). It shows a very close correlation but the model tends to overestimate the potential for lightning occurrence slightly.

Table 45: Days with Lightning

Observed - Thunderstorms at Pearson Airport

Year	Day Count
2000	21
2001	17
2002	19
2003	21
2004	17
2005	17
2006	20
2007	19
2008	30
2009	22
Total	**203**

Modelled - Potential for Lightning days at Pearson Airport

Year	Day Count
2000	12
2001	19
2002	35
2003	17
2004	24
2005	23
2006	25
2007	14
2008	27
2009	20
Total	**216**

Discussion

Table 46 shows an increased frequency for lightning potential by 2040-2049 which is consistent with more violent summer storms in the future. There is some variability across Durham ranging from a low of 5.5 increased days per year in Uxbridge to a high of 15.8 days/year in Ajax and Pickering.

Main Finding

The projected increase in days with high lightning potential is 11 days per year on average across Durham by the 2040s which represents about a 50% increase.

Table 46: Modelled Days with High Potential for Lightning

Current 2000-2009

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	15	19	18	21	19	17	13	15	18
2001	24	27	28	27	26	25	22	28	27
2002	41	40	36	38	29	28	27	42	42
2003	20	22	23	20	19	19	18	21	20
2004	34	36	35	34	32	28	20	36	36
2005	24	30	27	26	26	25	27	24	25
2006	24	26	25	26	25	28	20	27	34
2007	23	22	20	20	23	20	19	25	19
2008	39	40	39	37	36	33	36	40	36
2009	27	24	23	20	26	25	18	28	30
10-year Period	271	286	274	269	261	248	220	286	287

Future 2040-2049

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	30	29	27	23	25	17	22	29	25
2041	47	42	49	44	30	32	30	47	40
2042	50	48	47	44	41	34	36	50	46
2043	38	36	35	32	26	27	28	41	37
2044	60	62	63	64	44	46	37	64	48
2045	38	42	37	40	28	27	24	38	36
2046	53	52	55	55	42	47	47	56	53
2047	42	45	47	42	39	39	24	47	44
2048	46	44	44	40	27	31	26	47	35
2049	25	24	25	27	14	19	20	25	20
10-year Period	429	424	429	411	316	319	294	444	384

Difference (Future - Current)

Number of Calendar Days

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	158	138	155	142	55	71	74	158	97
per year	15.8	13.8	15.5	14.2	5.5	7.1	7.4	15.8	9.7

Heat Wave Temperature

Definition

Heat waves were looked at in a number of different ways as follows:

1. the number of calendar days with a maximum temperature of 30ºC or more;
2. the number of calendar days with a maximum temperature of 40ºC or more;
3. the number of events with maximum temperature of 30ºC or more for at least 2 consecutive days; and
4. the number of events with maximum temperature of 40ºC or more for at least 2 consecutive days.

Validation

Table 47 compares observed occurrences of calendar days with maximum temperatures of 30ºC or more against the model extracted number of days with a maximum daily temperature of 30ºC or more. It shows a very close correlation with the model tending to overestimate the number of days slightly.

Table 47: Number of Days with Tmax Greater than 30ºC

Observed - Days >=30C at Pearson Airport

Year	Day Count
2000	6
2001	24
2002	40
2003	15
2004	3
2005	41
2006	20
2007	27
2008	10
2009	3
Total	**189**

Modelled - Days >=30C at Pearson Airport

Year	Day Count
2000	10
2001	21
2002	33
2003	14
2004	5
2005	39
2006	26
2007	30
2008	17
2009	10
Total	**205**

Discussion

Table 48, Table 49, Table 50 and Table 51, respectively, show the results of the four different heat wave definitions examined.

Table 48 show an increase in the number of days/year with maximum temperatures of 30ºC or more ranging from 4 to 21 across Durham.

Table 49 shows that there will be from 0 to 4 days in 10 years with maximum daily temperatures of 40ºC or more.

Table 50 show an increase in the events/year with maximum temperatures of 30ºC or more ranging lasting two days or more increases from near zero to as many as 8 per year across Durham.

Table 51 shows that there will be one event at Uxbridge over the 10-year future period with a maximum daily temperature of 40ºC or more and lasting for two or more days.

Table 48 Heat Wave (days with T_{max} >30ºC)

Current 2000-2009

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	0	0	0	0	1	1	0	2	10
2001	2	2	2	2	6	5	5	5	21
2002	4	8	3	2	14	12	8	7	33
2003	0	1	0	0	1	2	2	2	14
2004	1	1	0	0	0	0	0	1	5
2005	2	5	4	4	13	11	10	11	39
2006	1	2	2	2	10	9	9	3	26
2007	2	5	2	1	7	6	6	4	30
2008	0	1	0	0	2	0	1	2	17
2009	0	0	0	0	1	1	0	0	10
10-year Period	12	25	13	11	55	47	41	37	205

Future 2040-2049

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	2	9	4	5	16	17	17	9	58
2041	4	9	6	4	12	12	15	9	42
2042	4	7	4	2	12	11	7	7	45
2043	10	23	15	14	36	36	36	20	69
2044	0	13	6	4	25	25	27	9	75
2045	11	24	17	12	36	38	33	20	67
2046	0	5	0	0	18	13	14	3	64
2047	5	31	19	14	42	40	39	19	71
2048	9	27	22	16	36	35	35	20	65
2049	11	30	20	16	33	31	28	22	71
10-year Period	56	178	113	87	266	258	251	138	627

Difference (Future - Current)

Number of Calendar Days

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	44	153	100	76	211	211	210	101	422
per year	4.4	15.3	10	7.6	21.1	21.1	21	10.1	42.2

Table 49: Heat Wave (days with T_{max} >40°C)

Current 2000-2009

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	0
10-year Period	0	0	0	0	0	0	0	0	0

Future 2040-2049

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	0	0	0	0	0	0	0	0	0
2041	0	0	0	0	0	0	0	0	0
2042	0	0	0	0	0	0	0	0	0
2043	1	0	0	0	1	1	0	2	7
2044	0	0	0	0	0	0	0	0	1
2045	0	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0	0
2047	0	0	0	0	3	2	0	0	5
2048	0	0	0	0	0	0	0	1	1
2049	0	0	0	0	0	0	0	0	2
10-year Period	1	0	0	0	4	3	0	3	16

Difference (Future - Current)

Number of Calendar Days

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	1	0	0	0	4	3	0	3	16
per year	0.1	0	0	0	0.4	0.3	0	0.3	1.6

Table 50: Heat Wave (events with T_{max} >30ºC for more than 2 consecutive days)

Current 2000-2009

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	7
2002	0	0	0	0	0	0	0	0	4
2003	0	0	0	0	0	0	0	0	3
2004	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	1	1	0	0	12
2006	0	0	0	0	0	0	0	0	5
2007	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	2
2009	0	0	0	0	0	0	0	0	1
10-year Period	0	0	0	0	1	1	0	0	34

Future 2040-2049

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	0	0	0	0	1	2	1	0	28
2041	0	1	0	0	4	4	7	1	20
2042	0	0	0	0	0	0	0	0	19
2043	1	6	2	3	13	13	11	2	35
2044	0	4	0	0	7	7	7	0	38
2045	2	4	5	2	7	7	7	3	31
2046	0	0	0	0	1	0	0	0	38
2047	0	9	5	5	21	20	13	1	46
2048	2	6	4	1	14	13	7	3	39
2049	1	7	2	1	13	13	12	0	48
10-year Period	6	37	18	12	81	79	65	10	342

Difference (Future - Current)

Number of Events

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	6	37	18	12	80	78	65	10	308
per year	0.6	3.7	1.8	1.2	8	7.8	6.5	1	30.8

Table 51: Heat Wave (events with T_{max} >40ºC for more than 2 consecutive days)

Current 2000-2009

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	0
10-year Period	0	0	0	0	0	0	0	0	0

Future 2040-2049

Number of Events

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	0	0	0	0	0	0	0	0	0
2041	0	0	0	0	0	0	0	0	0
2042	0	0	0	0	0	0	0	0	0
2043	0	0	0	0	0	0	0	0	3
2044	0	0	0	0	0	0	0	0	0
2045	0	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0	0
2047	0	0	0	0	1	0	0	0	3
2048	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	0
10-year Period	0	0	0	0	1	0	0	0	6

Difference (Future - Current)

Number of Events

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	0	0	0	0	1	0	0	0	6
per year	0	0	0	0	0.1	0	0	0	0.6

Main Finding

There will be an increasing number of heat waves in Durham’s future.

Extreme Humidex

Definition

This parameter is defined as the number of calendar days that have a humidex value of greater than or equal to 40. Humidex is short for "humidity index" and is an index number used by Canadian meteorologists to describe how hot the weather feels to the average person. It is a combination of the effect of heat and humidity. The humidex is a unit-less number based on the dew point, but it is equivalent to dry temperature in degrees Celsius. For example, if the temperature is 30°C, and the calculated humidex is 40, then it indicates the humid heat feels approximately like a dry temperature of 40°C.

According to the Meteorological Service of Canada, a humidex of at least 30 causes "some discomfort", at least 40 causes "great discomfort" and above 45 is "dangerous". When the humidex hits 54, heat stroke is imminent.

Validation

With this parameter there is no validation data available.

Discussion

Table 52 presents the current (2000-2009) and future (2040-2049) data for humidex values of 40 or greater across Durham. It shows that the number of events is projected to increase by from 5 to 20 events per year by the 2040s.

Main Finding

Table 52 shows a significant increase in the number of days with "great discomfort" humidex (values greater than or equal to 40). On average across Durham, the number of days with humidex of 40 or more will increase by about 14 per year by 2040-2049.

Table 52: Number of Calendar Days with a Humidex of 40 or More

Current 2000-2009

Number of Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	0	0	0	0	0	0	0	0	0
2001	1	2	2	2	3	4	4	4	7
2002	2	10	10	7	8	9	7	10	16
2003	0	0	0	0	1	2	2	2	4
2004	0	1	1	0	0	0	0	1	3
2005	1	12	8	7	7	8	14	11	24
2006	2	6	5	3	8	8	9	6	13
2007	1	4	3	1	2	3	4	4	11
2008	0	1	0	0	2	2	3	1	8
2009	0	1	0	0	1	1	0	1	5
10-year Period	7	37	29	20	32	37	43	40	91

Future 2040-2049

Number of Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	2	7	7	5	11	9	14	7	26
2041	6	15	11	8	15	14	14	12	25
2042	4	9	8	3	15	17	14	11	23
2043	9	19	17	16	26	28	25	20	44
2044	3	16	12	9	23	25	28	12	39
2045	11	31	22	19	33	36	32	22	48
2046	1	7	4	1	17	16	19	3	37
2047	5	30	25	21	31	32	30	24	43
2048	8	25	22	20	31	31	32	24	46
2049	11	25	24	19	26	28	25	23	38
10-year Period	60	184	152	121	228	236	233	158	369

Difference (Future - Current)

Number of Days

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	53	147	123	101	196	199	190	118	278
per year	5.3	14.7	12.3	10.1	19.6	19.9	19	11.8	27.8

Tornado Precursors

Definition

The Energy Helicity Index (EHI) is a combination of two indices. By itself, it is the best index available for storm and tornado prediction since it combines both CAPE and Helicity. The CAPE is the amount of pure instability present in a parcel of air and Helicity is the product of low level shear and inflow directly into the storm.

The operational significance of the EHI is given in the table below:

EHI	
> 1	Supercell potential
1 to 5	Up to F2, F3 tornadoes possible
5+	Up to F4, F5 tornadoes possible

For the purposes of this analysis, conditions across Durham that had an EHI greater than one (1) were examined to look at the current (2000-2009) and future (2040-2049) supercell potential. Also examined was the number of cases of EHI in various ranges.

Validation

With this parameter there is no possibility for validation as EHI values are not calculated or archived.

Discussion

Table 53 shows that in the future there will be 2 to 8 additional days per year that have the potential to create supercells across Durham. This represents a 7 to 38% increase or 23% on average across Durham.

Table 54 presents various levels of EHI analyzed for the Whitby location. It shows increases over all categories of storms. It shows a 15% increase overall in the potential for supercell formation. But within that increase we see a 58% increase in the potential for F2 and F3 types of tornadoes and the potential for three (3) F4 or F5 type tornadoes over the future 10-year period (where there was no potential in the current period).

Table 55 shows the distribution by month for the future storm potential. It shows that August is the most likely month for the very violent storms to occur with July a close second.

Table 53: Number of Calendar Days with EHI Greater than 1

Current 2000-2009

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2000	6	13	8	5	20	18	22	12	20
2001	8	9	6	6	15	13	11	12	16
2002	28	31	30	28	37	38	36	36	45
2003	11	15	11	8	12	15	12	11	14
2004	5	9	7	6	21	22	15	9	21
2005	17	20	20	20	26	24	27	18	26
2006	14	17	14	14	20	18	23	16	24
2007	8	14	13	9	22	23	19	19	26
2008	10	12	11	8	20	24	18	16	23
2009	5	10	8	5	12	12	10	7	10
10-year Period	112	150	128	109	205	207	193	156	225

Future 2040-2049

Number of Calendar Days

Year	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
2040	3	3	3	3	14	11	12	4	13
2041	10	11	11	7	19	15	15	12	19
2042	3	4	5	1	21	23	18	8	20
2043	15	21	19	18	26	27	25	19	33
2044	11	17	15	11	32	30	28	15	37
2045	32	39	34	28	55	54	52	35	50
2046	5	5	7	4	21	23	21	6	22
2047	17	21	20	18	26	24	19	20	30
2048	19	25	22	20	36	39	34	28	33
2049	20	26	22	19	32	29	27	20	34
10-year Period	135	172	158	129	282	275	251	167	291

Difference (Future - Current)

Number of Calendar Days

PERIOD	Ajax 13414	Whitby 14165	Oshawa 14171	Clarington 14483	Uxbridge 17570	Port Perry 17584	Beaverton 22908	Pickering 13110	Pearson Airport 10385
10-years	23	22	30	20	77	68	58	11	66
per year	2.3	2.2	3	2	7.7	6.8	5.8	1.1	6.6

Table 54: Various Levels of EHI at the Whitby Location

Current 2000-2009

Number of Calendar Days

Year	Days with EHI				
	>=1	>=2	>=3	>=4	>=5
2000	13	1	0	0	0
2001	9	0	0	0	0
2002	31	7	3	1	0
2003	15	4	1	0	0
2004	9	1	0	0	0
2005	20	7	0	0	0
2006	17	8	3	1	0
2007	14	3	1	1	0
2008	12	4	1	0	0
2009	10	2	0	0	0
10-year Total	150	37	9	3	0

Future 2040-2049

Number of Calendar Days

Year	Days with EHI				
	>=1	>=2	>=3	>=4	>=5
2040	3	1	0	0	0
2041	11	5	2	1	1
2042	4	0	0	0	0
2043	21	5	3	1	0
2044	17	6	3	1	0
2045	39	12	3	0	0
2046	5	0	0	0	0
2047	21	9	1	0	0
2048	25	9	2	1	1
2049	26	7	2	1	1
10-year Total	172	54	16	5	3

Difference (Future - Current)

Number of Calendar Days

PERIOD	Days with EHI				
	>=1	>=2	>=3	>=4	>=5
10-years	22	17	7	2	3
per year	2.2	1.7	0.7	0.2	0.3

Table 55: Month of Occurrence for Various Future EHI Levels at Whitby

Month	Days with EHI				
	>=1	>=2	>=3	>=4	>=5
March	0	0	0	0	0
April	0	0	0	0	0
May	0	0	0	0	0
June	24	5	0	0	0
July	54	17	7	2	1
August	71	30	7	3	2
September	22	2	2	0	0
October	1	0	0	0	0
November	0	0	0	0	0
10-year Total	172	54	16	5	3

Main Finding

The future promises to have not only storms with more precipitation but also many more violent storms.

6.6 Final Findings

The significance of the findings that are apparent from this study relate to the underlying purpose of the study and the methods by which results were sought and obtained.

The Original Study

In the original study, the City of Toronto very specifically sought future climate information that could not be reliably provided by GCMs and RCMs as these did not include "weather-vital" features such as the Great Lakes or other "weather-significant" local topographic features such as the Oak Ridges Moraine and the Niagara Escarpment. Toronto had neither the resources available to address 30-year normal climate depictions, nor the resources to undertake "ensembles".

What the City wanted to obtain was data and information concerning the future extremes-of-weather rather than the future means-of-climate.

The City wanted to use local weather modeling at a much finer resolution, i.e. using 1x1 km finer gridded data, to include the influences of local features rather than 50x50 km coarser gridded data, "driven" by GCM/RCM model output. Effectively, time appropriate climate model output was used as the input to a state-of-the-science weather model to depict the present 2000-2009 (as an accuracy and validation check) and the future 2040-2049.

The City needed to know the scale and significance of climate and weather changes, of both means and extremes. Extremes are more significant for public operations and service provision regarding such basics as flood appropriate sewer and culvert pipe sizing, heat wave appropriate load-bearing resistance of road surface materials, and heat appropriate public services for the elderly and disadvantaged.

Just as climate models around the world have different "regional" characteristics (e.g. Canadian RCMs are honed to address snow and ice coverage), they are also "run" with different IPPC scenarios relating to different assumptions of global population growth and fossil fuel use (and carbon dioxide releases). These scenarios range from those that portray slower growth rates and peaking points of population growth and carbon based fuel consumption, to those that portray a much more rapid rate of growth and earlier peaking points.

The City, as part of the original study, looked at 10-year climate periods rather than 30-year periods and looked at the potential consequences of scenario A1b for 2040-2049 which allowed the examination of extremes during this future period. The A1b scenario is considered as the "most likely" scenario given current data and trends.

The Current Study

The following findings are based on an analysis of the data produced by the combined climate-weather model runs. The focus in this report has been to look at the data representing Whitby rather than predicted data from across the GTA.

6.6.1 Projected Climate Changes

Table 56 presents a summary of the changes that can be expected in Whitby by 2040-2049.

Table 56: Summary for Whitby

Weather Type	Parameter	2000-2009	2040-2049
Extreme Precipitation	Maximum in One Day (in mm)	79	117
	Number of Days/Year with more than 25 mm	6	10
	Annual Total Precipitation (in mm)	869	1004
Extreme Rain	Maximum in One Day (in mm)	79	117
	Number of Days/Year with more than 25 mm	5	10
Extreme Snowfall	Maximum in One Day (in cm)	28	17
	Number of Days/Year with more than 5 cm	9	2
Extreme Heat	Average Maximum Daily (in °C)	25	28
	Extreme Maximum (in °C)	33	40
	Number of Days/Year with more than 30 °C	2	17
Extreme Cold	Average Minimum Daily (in °C)	-8	-1
	Extreme Minimum (in °C)	-25	-13
	Number of Days/Year with less than -10 °C	27.0	1.0
	Number of Days/Year with minimum less than 0 °C (frost days)	129	75
Wind Chill	Extreme Daily (in °C)	-37	-19
	Number of Days/Year with less than -20 °C	15	0
Degree Days	Number of Degree Days/Year Greater than 24 °C (air conditioning required)	8	49
	Number of Degree Days/Year Greater than 0 °C	3444	4508
	Number of Degree Days/Year Less than 0 °C (extra heating required)	475	70
Extreme Wind	Maximum Hourly Speed in km/hour	62	54
	Maximum Gust Speed in km/hour	119	74
	Number of Days/Year with Wind Speed Greater than 52 km/hour	2.0	0.1
	Number of Days/Year with Wind Speed Greater than 63 km/hour	0.0	0.0
Humidex	Maximum (in °C)	47	51
	Average Number of Days/Year greater than 40 °C	3	19
Potential for Violent Storms	Number of Days/Year with EHI Greater than 1	150	172
	Number of Days/Year with EHI Between 2 and 5	49	75
	Number of Days/Year with EHI = 5 or More	0	3

6.6.1.1 Future Period: 2040-2049 Compared to 2000-2009

The following summarizes the projected climate for the proxy Whitby site for the future period:

- **Less snow and more rain in winter**
- **About 16% more precipitation (snow and rainfall) overall**
  - the one day maximum will increase by almost 50%
  - the one day maximum snow will drop about 40%
  - the number of days of rain greater than 25 mm will increase by 100%
  - there will be an 80% reduction in the number of days with snow more than 5 cm
- **Extreme rainstorm events will be more extreme**
  - there will be a 15% increase in the potential for violent storms
  - there will be a 53% increase in the potential for tornadoes
- **Average annual temperatures increase of 4.0^{o}C**
  - average winter temperatures increase by 5.8^{o}C
  - average summer temperatures increase by 2.6^{o}C
  - extreme daily minimum temperature "becomes less cold " by 12^{o}C
  - extreme daily maximum temperature "becomes warmer " by 7.1^{o}C
- **Average wind speed about the same**
  - maximum hourly winds reduced
  - maximum wind gusts reduced about 13%
- **"Comfort" remains similar**
  - humidity and temperature taken together as the Humidex remains similar (within 8% of present on average) for most of the year but shows increases in November (up 30%) and in May through to September (up 15%) and pushes past the "dangerous" level (45) on several summer days
  - Wind Chill is reduced by about 50% on average but is reduced 25-45% during the winter months

6.6.1.2 Across the Regional Municipality of Durham

The following summarizes the projected climate on average across Durham Region, where we can expect to see:

- fewer snow events, and reduced snow clearing requirements
  - extreme daily minimum temperature "becomes less cold " by 13.1^{o}C;
  - 52 fewer days with temperatures below zero;
  - 29 fewer days with temperatures below -10ºC;

- much more summer storm precipitation during July (57% on average) and August (94% on average) and increased likelihoods of culvert and sewer capacity exceedances and basement flooding;
    - no change in the total amount of precipitation falling in a year;
    - 33 fewer days without snow;
    - 31 more days with rain;
- higher temperatures, more frequent summer heat waves and increased heat alert response requirements as follows:
    - average annual temperatures increase of 4.1°C in the future (2040-2049);
    - extreme daily maximum temperature "becomes warmer " by 7.6°C;
    - 56 more days with temperatures above zero;
    - 14 more days with temperatures above 30°C;

References

Brimelow, J.C. and G.W. Reuter, 2005. *Transport of Atmospheric Moisture during Three Extreme Rainfall Events over the Mackenzie River Basin*. J. Hydrometeorol., 6, no.4, 423-440.

Bruce, J., I. Burton, H. Martin, B. Mills and L. Mortsch, 2000. *Vulnerability and adaptation to climate change.* Report submitted to Natural Resources Canada, Climate Change Impacts and Adaptation Program, 144 p.

Chiotti, Q. and B. Lavender, 2008. *Ontario; in From Impacts to Adaptation Canada in a Changing Climate 2007*, edited by D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON, p. 227-274.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007. *Regional Climate Predictions. Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H. L. Miller, Eds., Cambridge University Press, Cambridge, UK, 847-940.

Clean Air Partnership (CAP), 2006. *A Scan of Climate Change Impacts on Toronto.* http://www.cleanairpartnership.org/pdf/climate_change_scan.pdf

Collins M., S.F.B. Tett, and C. Cooper, 2001. *The internal variability of HadCM3, a version of the Hadley Centre coupled model without flux adjustments*. Clim. Dyn., 17, no.1, 61-81.

Collins, M., B.B.B. Booth, G.R. Harris, J.M. Murphy, D.M.H. Sexton, and M.J. Webb, 2006. *Towards quantifying uncertainty in transient climate change*. Clim. Dyn, 27, no.2/3, 127-147.

Cook-Anderson, G., 2008. *El Niño at Play as Source of More Intense Regional U.S. Wintertime Storms.* NASA's Goddard Space Flight Center, January News. http://www.nasa.gov/topics/earth/features/elnino_winter.html

Environment Canada, 2006. *Temperature and precipitation in historical perspective: annual 2006*. Environment Canada, Climate Trends and Variations Bulletin, <http://www.msc-smc. ec.gc.ca/ccrm/bulletin/annual06/national_e.cfm>, [accessed Feb 19, 2010].

Environment Canada, 2010a. *El Niño.* Climate Change Monitoring and Analysis. http://www.ec.gc.ca/adsc-cmda/default.asp?lang=En&n=208ED67A-1

Environment Canada, 2010b. *El Niño – Mean Temperatures.* Climate Change Monitoring and Analysis. http://www.ec.gc.ca/adsc-cmda/default.asp?lang=En&n=1E16C028-1

Environment Canada, 2010c. *El Niño – Mean Precipitation.* Climate Change Monitoring and Analysis. http://www.ec.gc.ca/adsc-cmda/default.asp?lang=En&n=6D84577E-1

Ferrier, B. S., Y. Lin, T. Black, E. Rogers, and G. DiMego, 2002. *Implementation of a New Grid-scale Cloud and Precipitation Scheme in the NCEP Eta Model*. Preprints, 15th Conference on Numerical Weather Prediction, San Antonio, TX, Amer. Meteor. Soc., 280-283.

Field, C.B., L.D. Mortsch, M. Brklacich, D.L. Forbes, P. Kovacs, J.A. Patz, S.W. Running and M.J. Scott, 2007. *North America. Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. Van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 617-652.

Gordon C, C. Cooper, C.A. Senior, H. Banks, J.M. Gregory, T.C. Johns, J.F.B. Mitchell, R.A. Wood, 2000. *The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments*. Climate Dynamics, 16, 147-168.

Hogg, W.D. and D.A. Carr, 1985. *Rainfall Frequency Atlas for Canada*. Canadian Climate Centre Publication, ISBN 0-660-52992-0, Minister of Supply and Services Canada, 89pp.

Intergovernmental Panel on Climate Change (IPCC), 2000. *Special Report on Emissions Scenarios*. Nakićenović N. and Swart R. (Eds.), Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC), 2007a. *Climate Change 2007: The Physical Science Basis, Annex I: Glossary.* Working Groups I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/annex1sglossary-a-d.html

Intergovernmental Panel on Climate Change (IPCC), 2007b. *Fourth Assessment Report (AR4): Synthesis Report.* Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm

Intergovernmental Panel on Climate Change (IPCC), 2007c. *Climate Change 2007: The Physical Science Basis, Chapter 3.* Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter3.pdf

Intergovernmental Panel on Climate Change (IPCC), 2007d. *Climate Change 2007: The Physical Science Basis, Chapter 11.* Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter11.pdf

Intergovernmental Panel on Climate Change (IPCC), 2007e. *Climate Change 2007: The Physical Science Basis, Chapter 10.* Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter10.pdf

Janjic, Z. I., 1984: *Non-linear advection schemes and energy cascade on semi-staggered grids*. *Monthly Weather Review*, Vol. **112**, 1234-1245.

Janjic, Z. I., 1996a: *The surface layer in the NCEP Eta Model*. Eleventh Conference on Numerical Weather Prediction, Norfolk, VA, 19-23 August 1996; American Meteorological Society, Boston, MA, 354-355.

Janjic, Z. I., 1996b: *The Mellor-Yamada Level 2.5 turbulence closure scheme in the NCEP Eta Model*. Research Activities in Atmospheric and Oceanic Modelling, WMO, Geneva, CAS/JSC WGNE, 4.14-4.15.

Janjic, Z. I., 2003a. *A Non-hydrostatic Model Based on a New Approach*. Meteorology and Atmospheric Physics, 82, 271-285.

Kain, J. S. and J. M. Fritsch, 1993. *Convective Parameterization for Mesoscale models: The Kain-Fritcsh Scheme, the Representation of Cumulus Convection in Numerical Models,* K. A. Emanuel and D.J. Raymond, Eds., Amer. Meteor. Soc., 246 pp.

Leung, L.R., Y. Qian, X. Bian, W.M. Washington, J. Han and J.O. Roads, 2004. *Mid-century ensemble regional climate change scenarios for the western United States*. Clim. Change, 62, 75-113.

Levinson, D.H. and P.D. Bromirski, 2007. *Extra-Tropical Cyclones in a Warming Climate: Observational Evidence of Trends in Frequencies and Intensities in the North Pacific, North Atlantic, and Great Lakes Regions.* 10th International Workshop on Wave Hindcasting and Forecasting & Coastal Hazard Symposium. November 11-16.

Lowe J.A., C.D. Hewitt, D.P. van Vuuren, T.C. Johns, E. Stehfest, J.F. Royer and P.J. van der Linden, 2009. *New study for climate modeling, analyses, and scenarios*. EOS Trans AGU 90: 181-182.

Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T. Arai, R.A. Assel, R.G. Barry, V. Card, E. Kuusisto, N.C. Granin, T.D. Prowse, K.M. Stewart and V.S. Vuglinski, 2000. *Historical trends in lake and river ice cover in the Northern Hemisphere*. Science, 289, 1743-1746.

Mantua, N., S.R. Hare, Y. Zhang, J.M. Wallace and R.C. Francis, 1997. *A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production.* Bulletin of the American Meteorological Society, **78:** 1069-1079.

Marsh, P.T., D.J. Karoly and H. E. Brooks, 2007*. Assessment of the Severe Weather Environment in North America Simulated by a Global Climate Model.* 19th Conference on Climate Variability and Change San Antonio, TX, January.

McCabe, G.J., M.P. Clark and M.C. Serreze, M.C., 2001. *Trends in Northern Hemisphere Surface Cyclone Frequency and Intensity.* American Meteorological Society Journal of Climate, **14**: 2763-2768.

Meinshausen, M., N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame and M.R. Allen, 2009. *Greenhouse-gas emission targets for limiting global warming to 2 °C.* Nature, 458, 1158-1162, doi:10.1038/nature08017.

Mekis É. and W.D. Hogg, 1999. *Rehabilitation and analysis of Canadian daily precipitation time series*. Atmosphere-Ocean, v. 37, no. 1, p. 53–85.

Moss R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakićenović, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant and T.J. Wilbanks, 2010. *The next generation of scenarios for climate change research and assessment*. Nature, 463, 747-756, doi:10.1038/nature08823.

Munroe, S., 2005. *Canadian ice storm in 1999.* Canada Online, (http://canadaonline.about.com/cs/weather/p/icestorm.htm).

Murphy, J.M., D.M.H. Sexton, D.N. Barnett, G.S. Jones, M.J. Webb, M. Collins and D.A. Stainforth, 2004. *Quantification of modelling uncertainties in a large ensemble of climate change simulations.* Nature, 430, 768-772.

Murphy, J.M., D.M.H. Sexton, G.J. Jenkins, B.B.B. Booth, C.C. Brown, R.T. Clark, M. Collins, G.R. Harris, E.J. Kendon, R.A. Betts, S.J. Brown, K.A. Humphrey, M.P. McCarthy, R.E. McDonald, A. Stephens. C. Wallace, R. Warren, R. Wilby and R.A. Wood, 2009. *UK Climate Projections Science Report: Climate Change Projections*. Met Office Hadley Centre, Exeter, UK.

NASA Jet Propulsion Laboratory (NASA), 2008. *The Spherical Shape of the Earth: Climatic Zones.* California Institute of Technology. http://sealevel.jpl.nasa.gov/overview/climate-climatic.html

National Oceanic and Atmospheric Administration (NOAA), 2009b. *National Weather Service Glossary: Arctic Oscillation.* http://www.nws.noaa.gov/glossary/

National Snow and Ice Data Center (NSIDC). *The Arctic Oscillation.* Arctic Climate and Meteorology Education Center. http://nsidc.org/arcticmet/patterns/arctic_oscillation.html

Roberts, E. and R.E. Stewart, 2008. *On the occurrence of freezing rain and ice pellets over the eastern Canadian Arctic.* Atmos. Res., 89, no.1-2, 93-109.

Roesch, A., M. Wild, H. Gilgen and A. Ohmura, 2001. *A new snow cover parameterization for the ECHMA4 GCM*. Clim, Dyn., 17, 933-946.

Rogelj, J., J. Nabel, C. Chen, W. Hare, K. Markmann, M. Meinshausen, M. Schaeffer, K. Macey and N. Höhne, 2010. *Copenhagen Accord pledges are paltry*. Nature 464, 1126-1128, doi:10.1038/4641126a.

Schindler, D.W. and W.F. Donahue, 2006. *An impending water crisis in Canada's western prairie provinces*. Proc. Nat. Acad. Sci., 107, doi/10.1073/pnas.0601568103.

Schwarzkopf, M. D. and S. B. Fels, 1991. *The Simplified Exchange Method Revisited: An Accurate, Rapid Method for Computations of Infrared Cooling Rates and Fluxes.* J. Geophys. Res., 96, 9075-9096.

SENES, 2007. *Weather Analysis and Weather Impacts*. Report Number 34528 for Hydro One Networks Inc., December.

Singarayer, J.S., J.L. Bamber and P.J. Valdes, 2006. *Twenty-First-Century Climate Impacts from a Declining Arctic Sea Ice Cover.* American Meteorological Society.

Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden and P. Zhai, 2007. *Observations: Surface and Atmospheric Climate Change, in: Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H. L. Miller, Eds., Cambridge University Press, Cambridge, UK, 235-336.

Vincent, L.A. and E. Mekis, 2006. *Changes in daily and extreme temperature and precipitation indices for Canada over the 20th century.* Atmosphere-Ocean, v. 44, no. 2, p.177–193.

Wallace, J.M. and P.V. Hobbs, 2006. *Atmospheric Science: an Introductory Survey, 2nd Edition*. Elsevier Inc., U.S.A.

Wilby, R., 2003: *Past and projected trends in London's urban heat island*. Weather, 58, 251-260.

World Wildlife Fund (WWF), 2005. *Arctic Climate Feedbacks: Global Implications.* http://www.worldwildlife.org/what/wherewework/arctic/arctic-climate-feedbacks.html

Yin, J., 2005. *A Consistent Poleward Shift of the Storm Tracks in Simulations of 21st Century Climate.* Geophysical Research Letters, 32, L18701.

Zhang, X., W.D. Hogg and E. Mekis, 2001. *Spatial and temporal characteristics of heavy precipitation events over Canada.* Journal of Climate, 14, no. 9, p.1923–1936.

Zhang, X., L.A. Vincent, W.D. Hogg and A. Nitsoo, 2000. *Temperature and precipitation trends in Canada during the 20th century.* Atmosphere-Ocean, 38, no. 3, p. 395–429.

Appendix A – Detailed Maps

Future Period 2040-2049

Figure 58 presents the GTA temperature results based on the gridded output from the NMM model for the current and future period (2040-2049). It should be noted that a consistent temperature scale was used for all diagrams so that visually warmer temperatures are darker shades of red and colder temperatures are darker shades of blue.

Details of the GTA spatial distribution of the rainfall, snowfall and total precipitation for the current and future periods are presented in Figure 59.

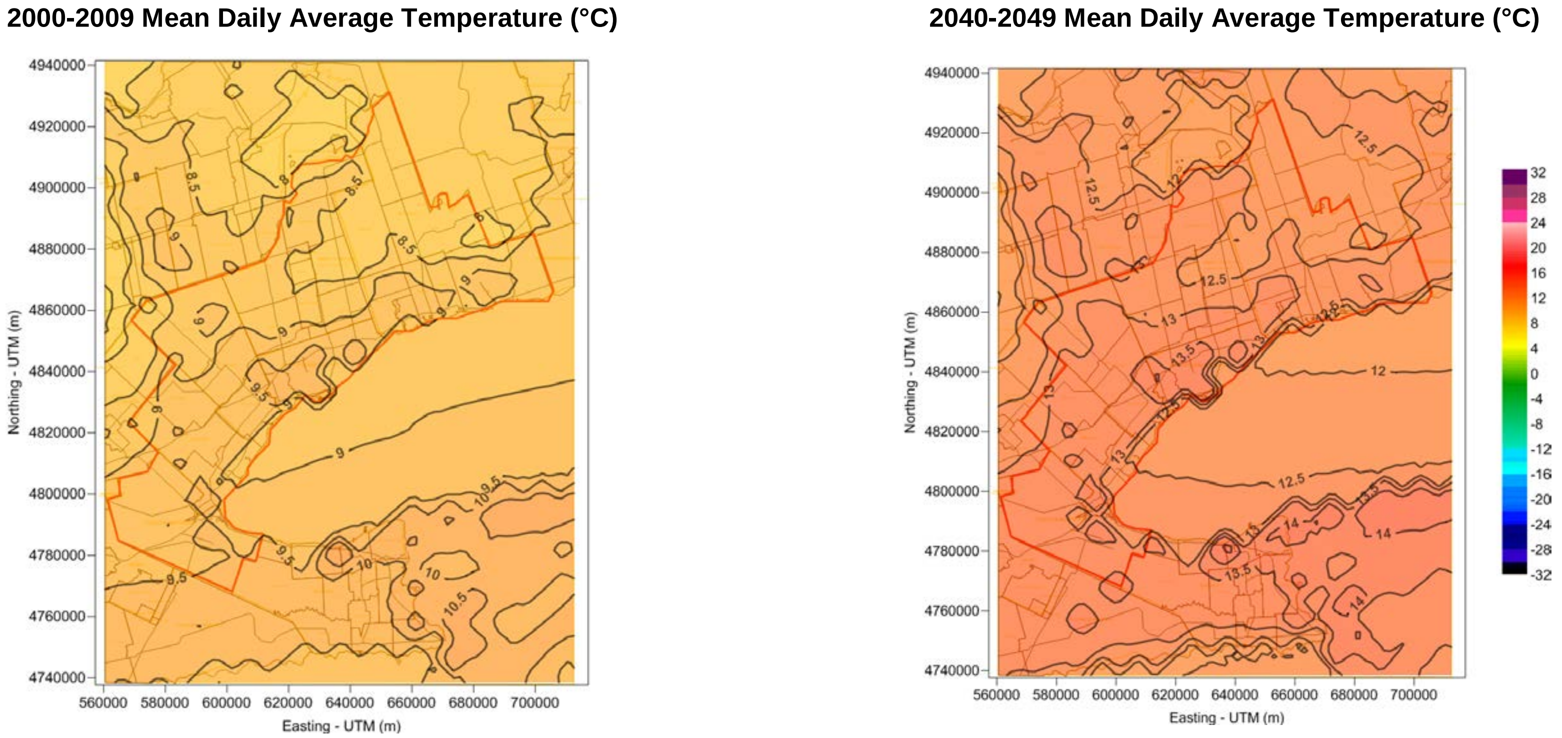
Figure 60 presents the average wind speed in the form of a contour plot.

Figure 61 shows maximum wind speed over the GTA, as a discrete variable, because for grid points the contour plots are difficult to read.

Figure 62 shows the gust wind speed over the GTA.

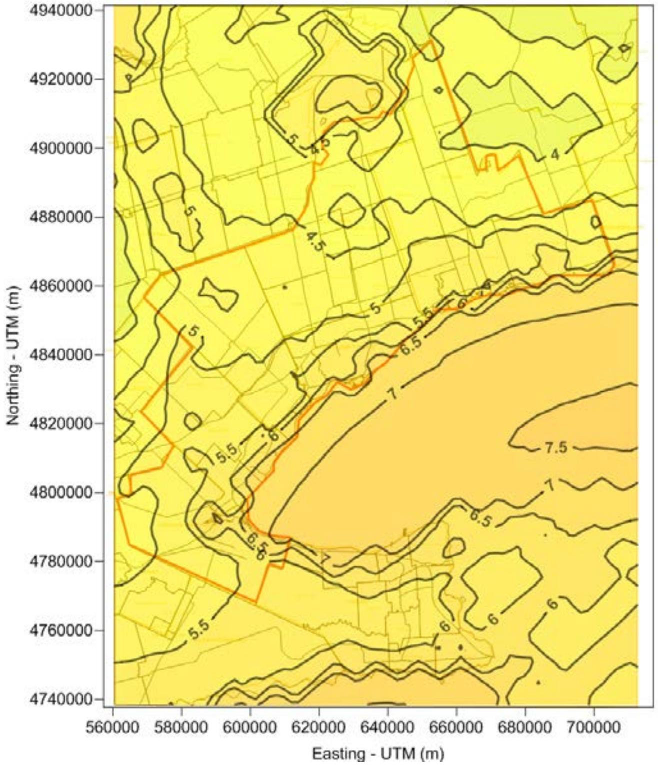
Based on Figure 63 though Figure 65, SENES has demonstrated that the index related to the wind (SRH) is decreasing, while CAPE (energy) is increasing over the land and decreasing over the water.

Figure 58: Mean Daily Average, Minimum and Maximum Temperature for the GTA

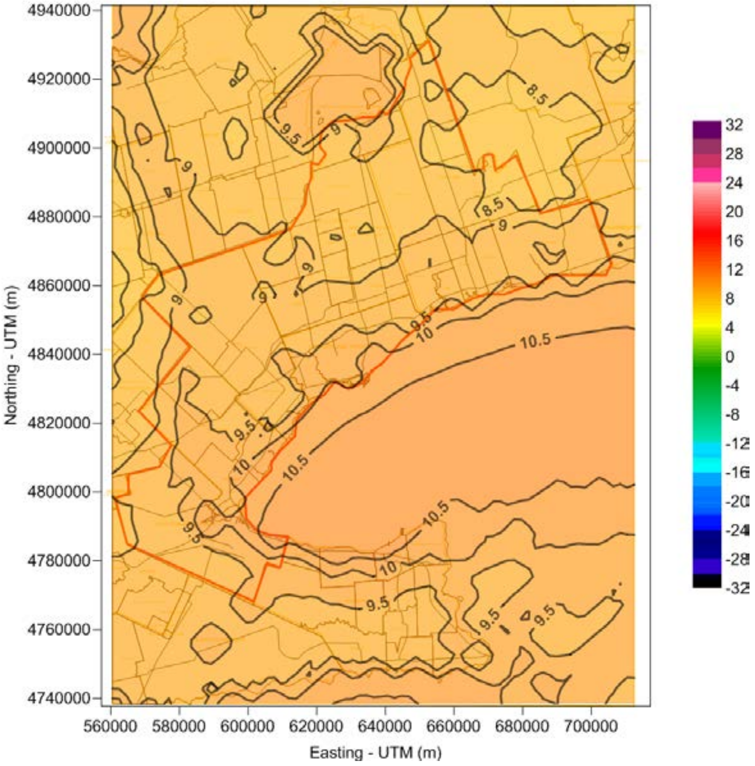


2000-2009 Mean Daily Average Temperature (°C)

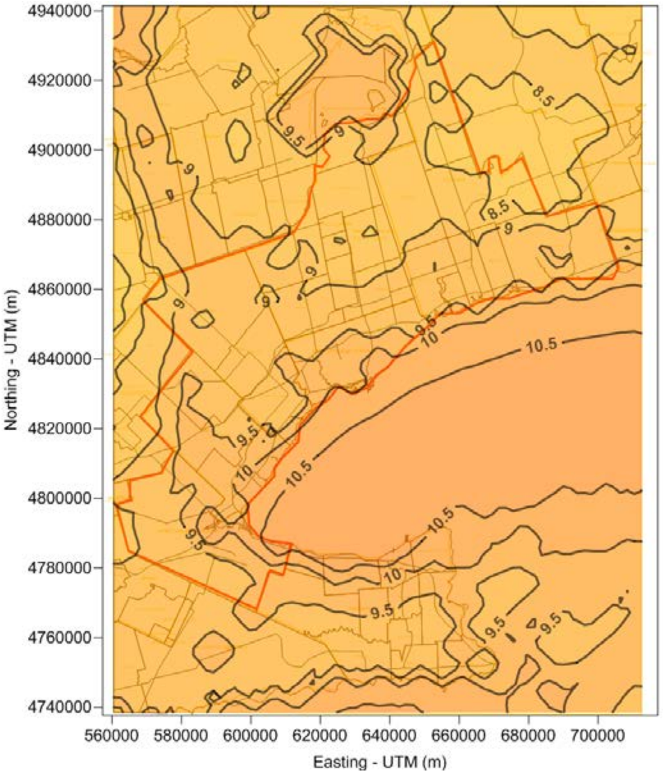
2040-2049 Mean Daily Average Temperature (°C)



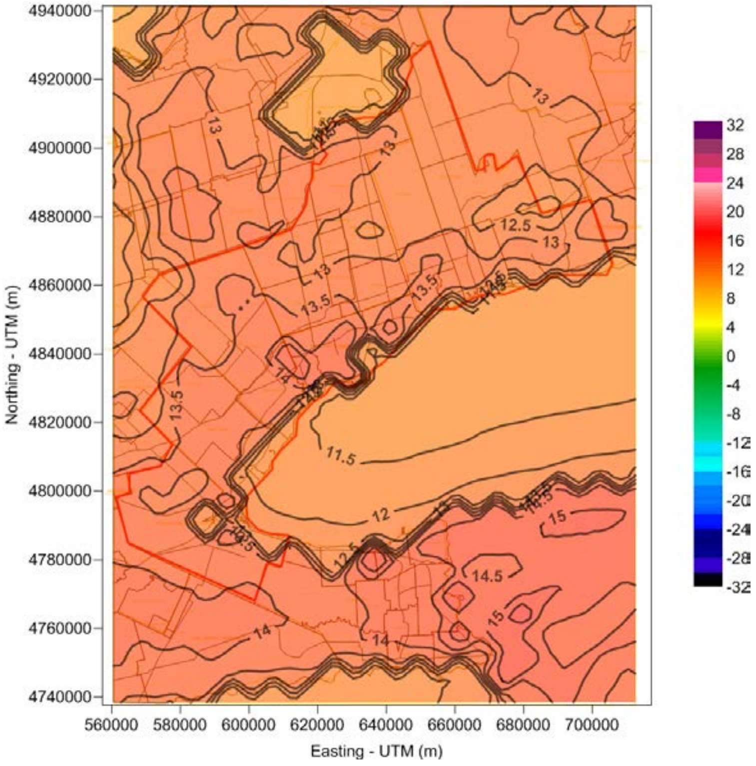
2000-2009 Mean Daily Minimum Temperature (°C)



2040-2049 Mean Daily Minimum Temperature (°C)

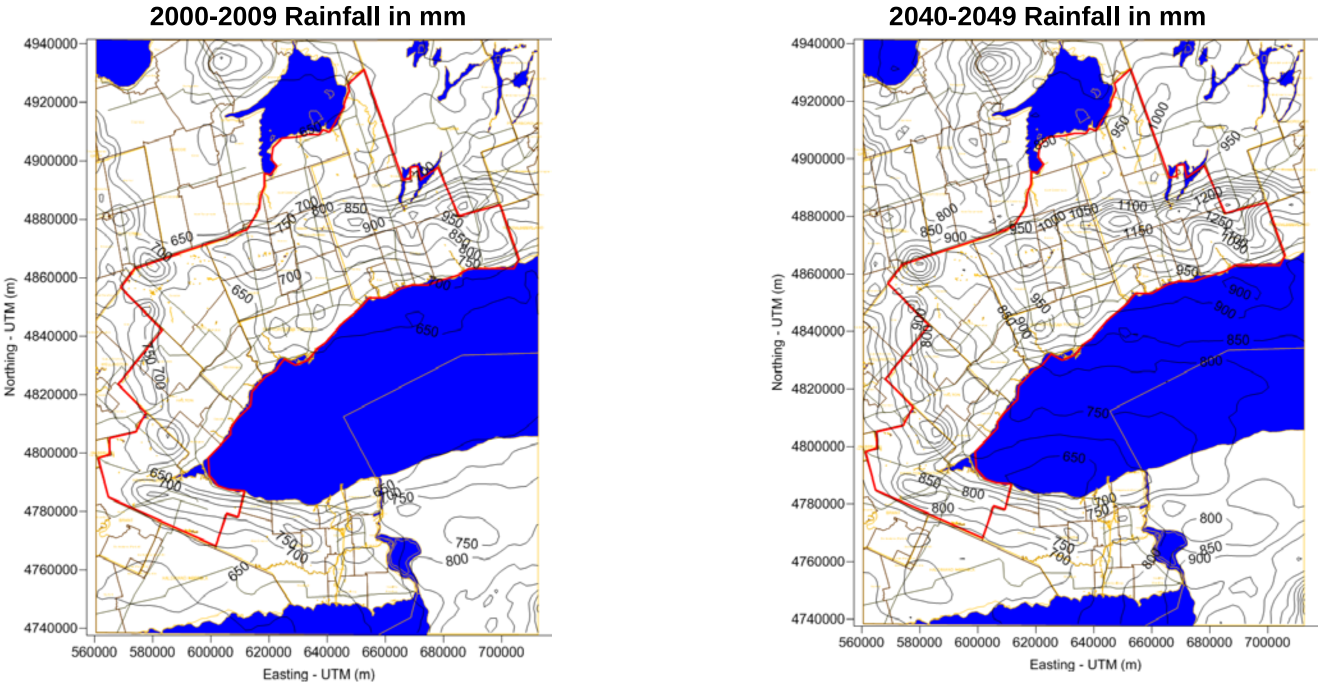


2000-2009 Mean Daily Maximum Temperature (°C)



2040-2049 Mean Daily Maximum Temperature (°C)

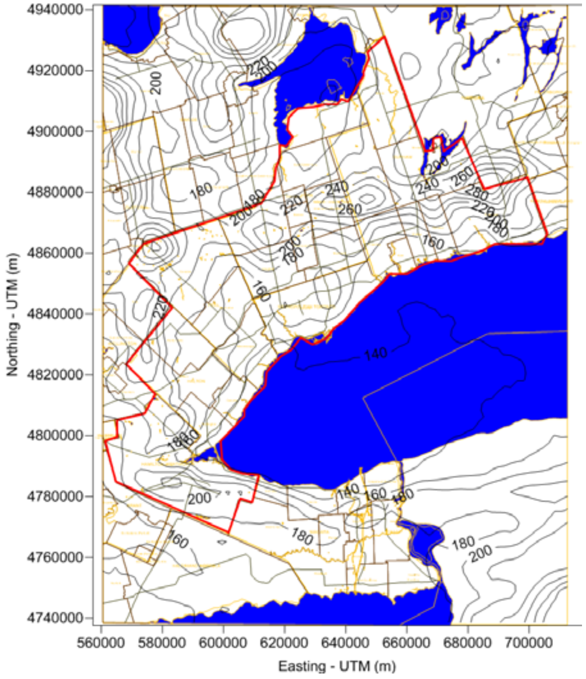
Figure 59: Rainfall, Snowfall and Total Precipitation over the GTA



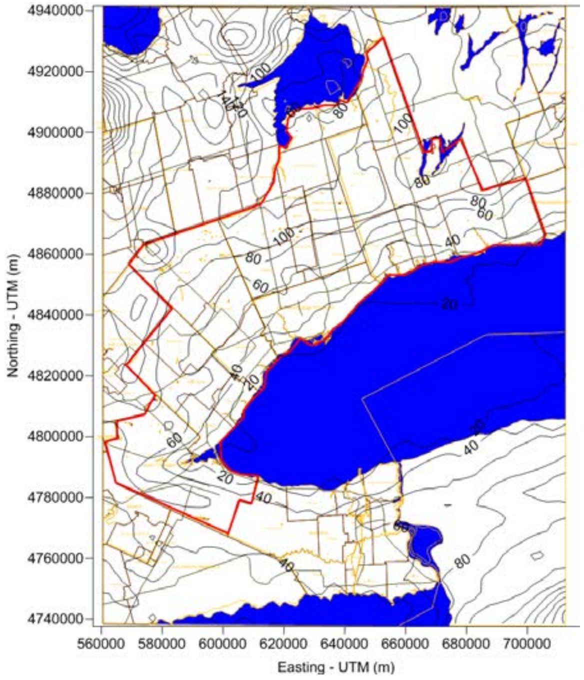
2000-2009 Rainfall in mm

2040-2049 Rainfall in mm

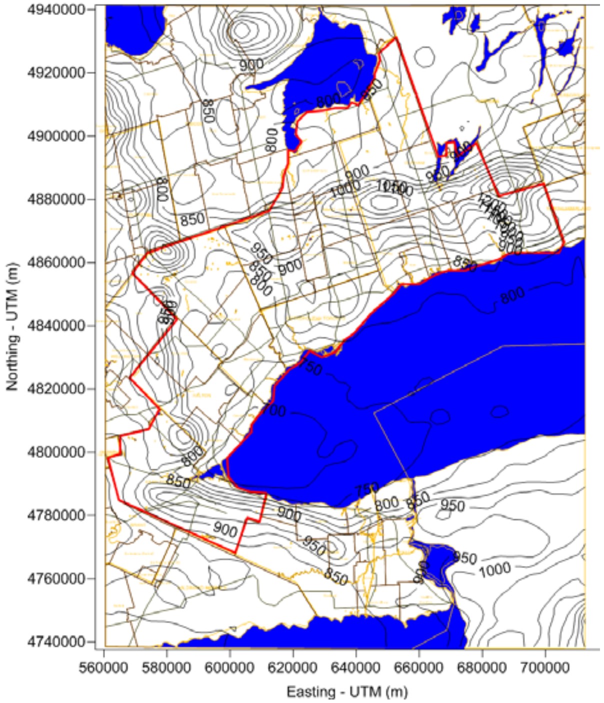
It is very clear in the left panel above that there is enhanced rainfall along the windward slopes and crest of the Niagara Escarpment with a rain shadow on the lee (East) side of the Escarpment. This panel provides much more specificity for the location of the rain shadow than the Atlas of Canada.



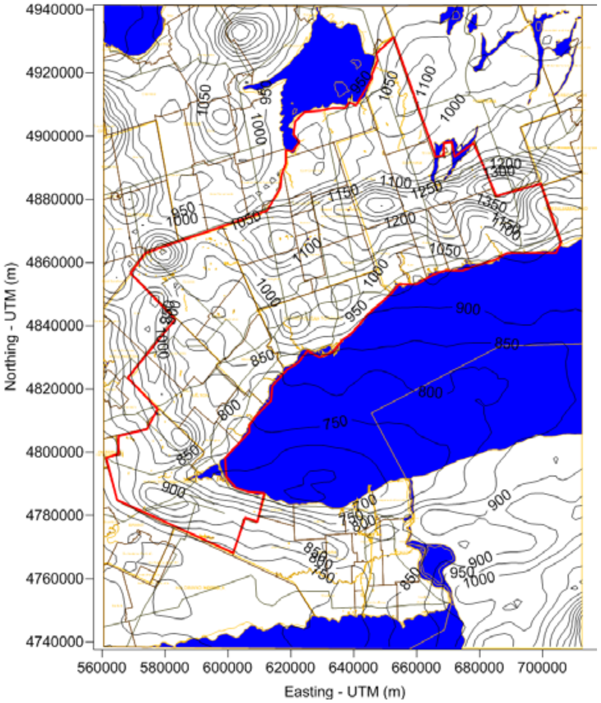
2000-2009 Snowfall in cm



2040-2049 Snowfall in cm



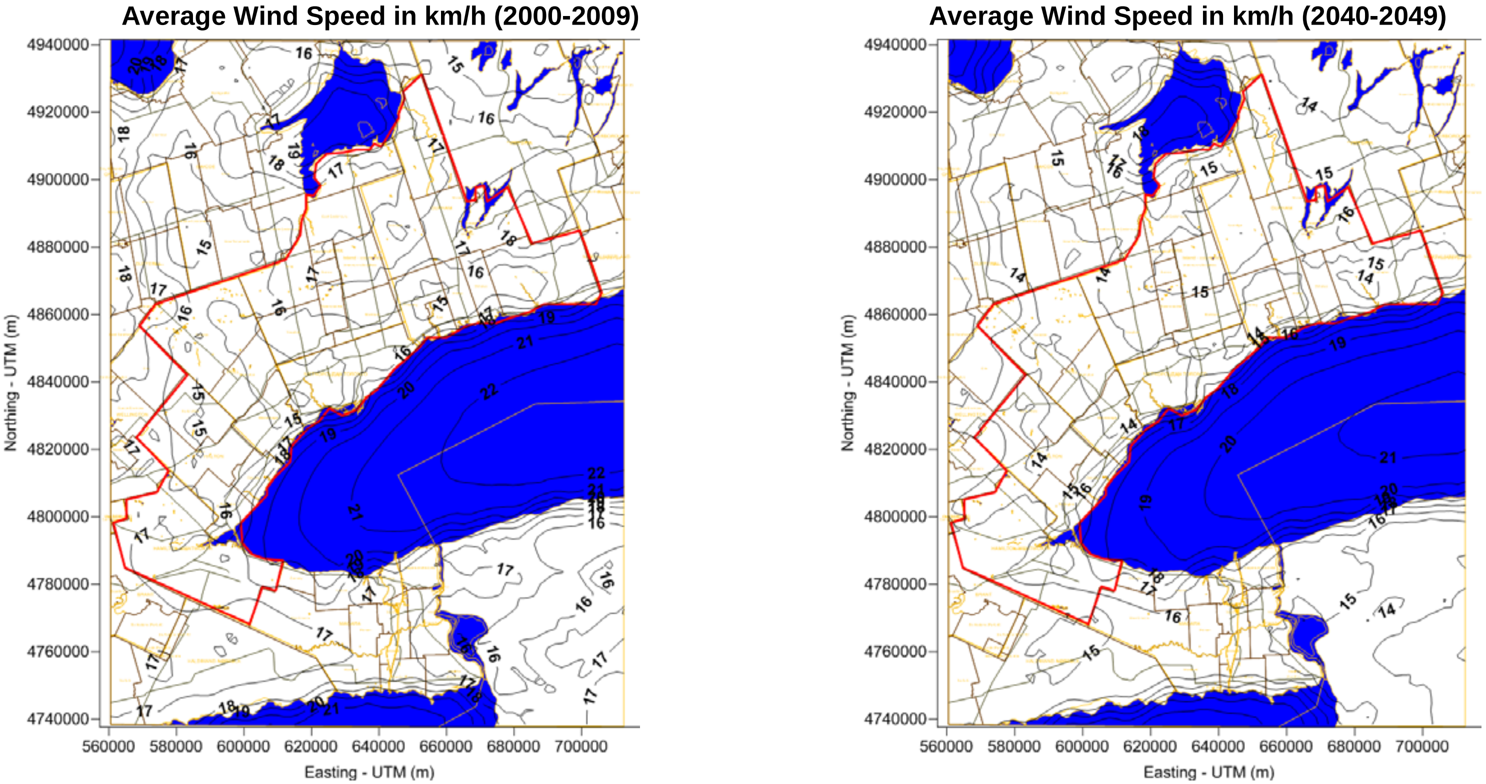
2000-2009 Total Precipitation in mm



2040-2049 Total Precipitation in mm

Examination of these total precipitation figures shows higher values downwind of lakes and the city.

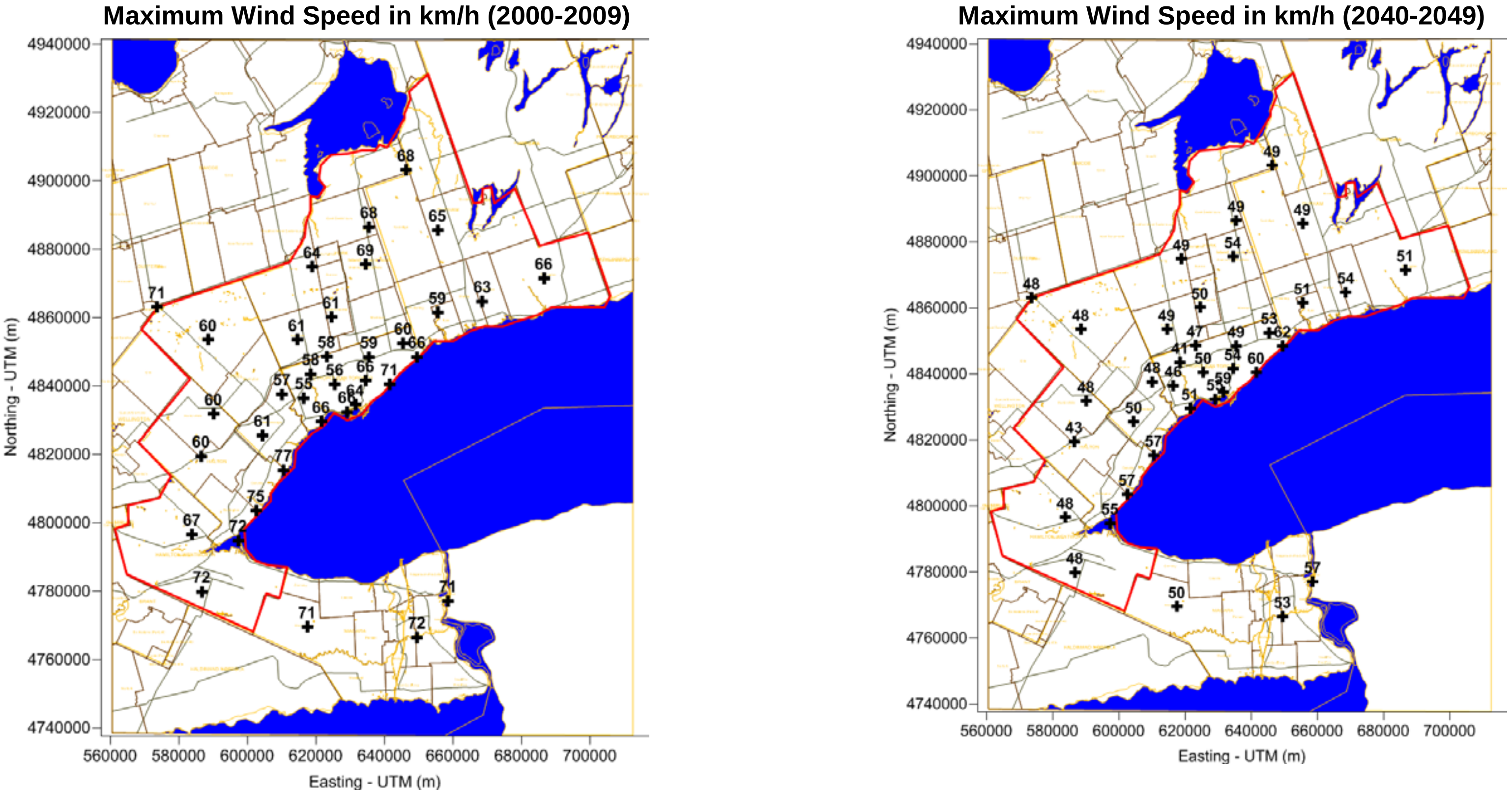
Figure 60: Average Wind Speed over the GTA



Average Wind Speed in km/h (2000-2009)

Average Wind Speed in km/h (2040-2049)

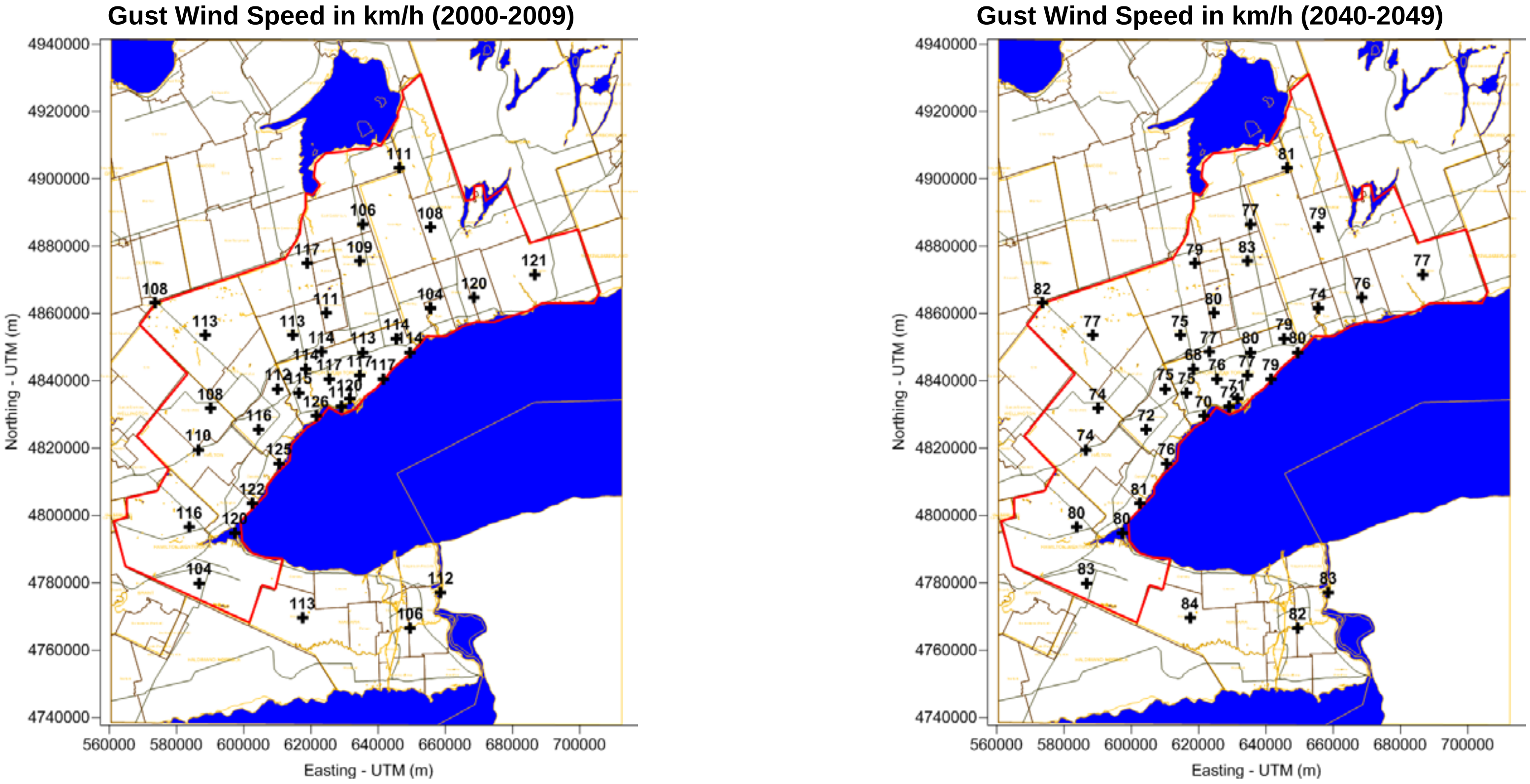
Figure 61: Maximum Wind Speed over the GTA



Maximum Wind Speed in km/h (2000-2009)

Maximum Wind Speed in km/h (2040-2049)

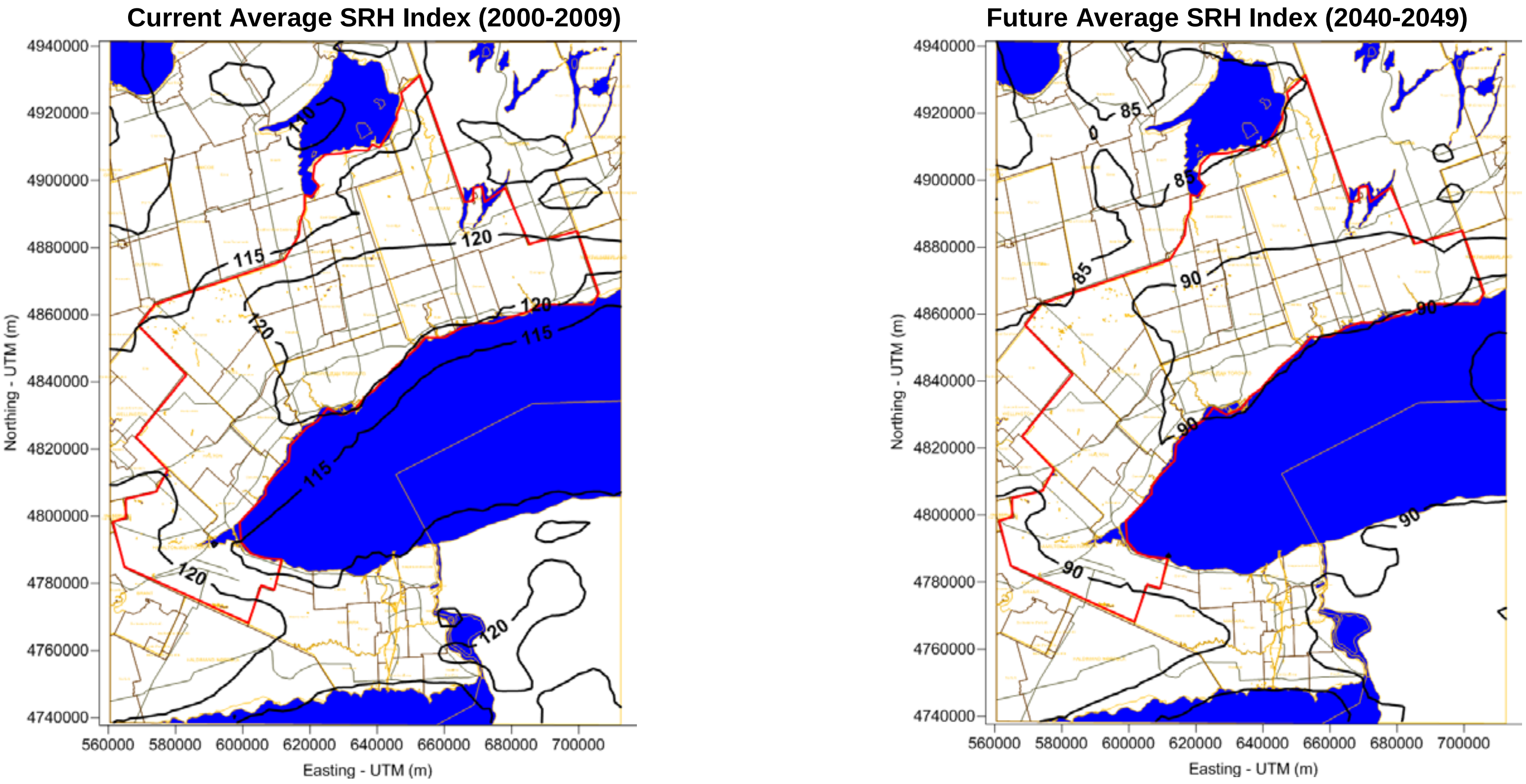
Figure 62: Gust Wind Speed over the GTA



Gust Wind Speed in km/h (2000-2009)

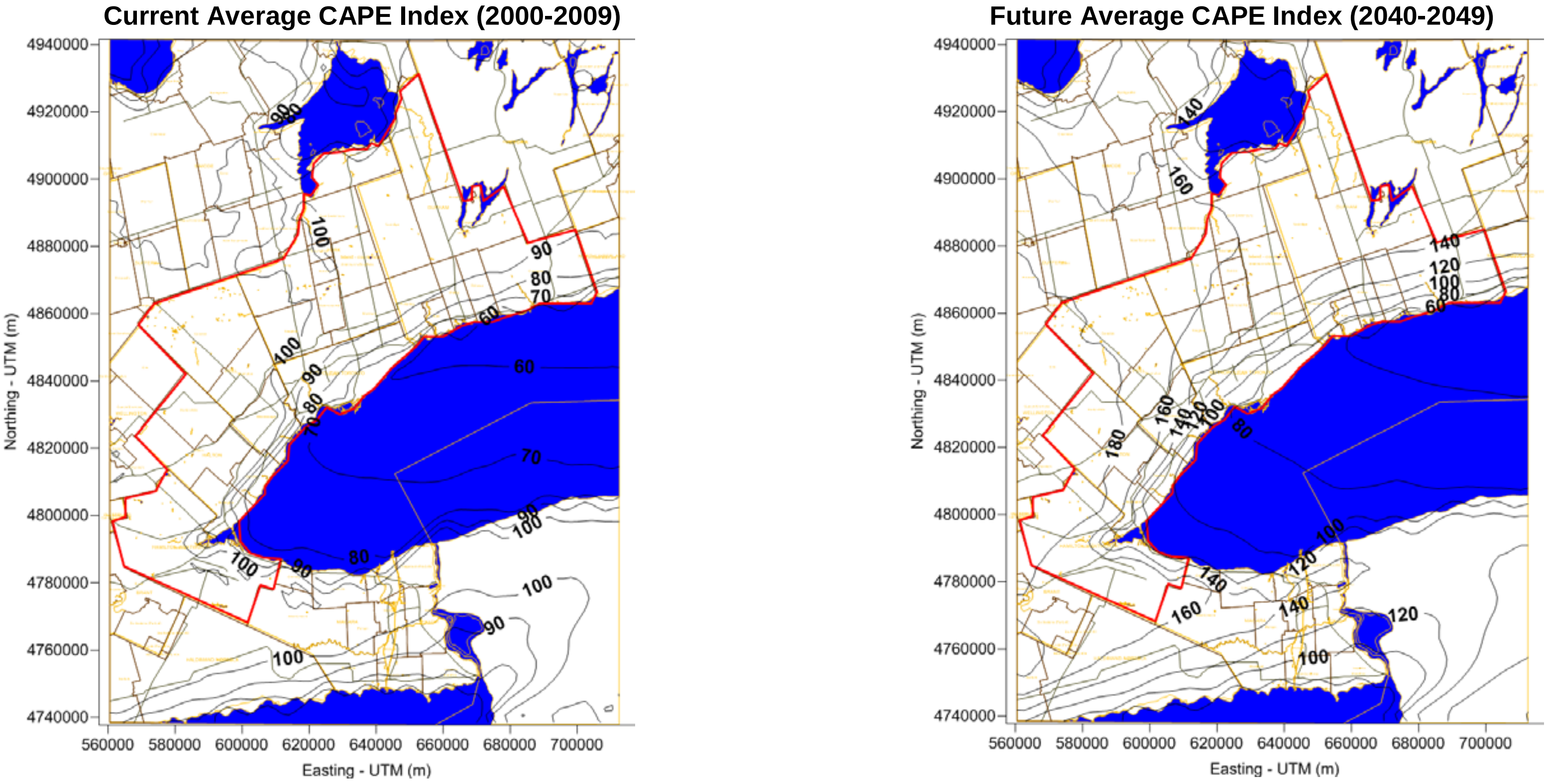
Gust Wind Speed in km/h (2040-2049)

Figure 63: Spatial Distribution of SRH for Current and Future Period


Current Average SRH Index (2000-2009)

Future Average SRH Index (2040-2049)

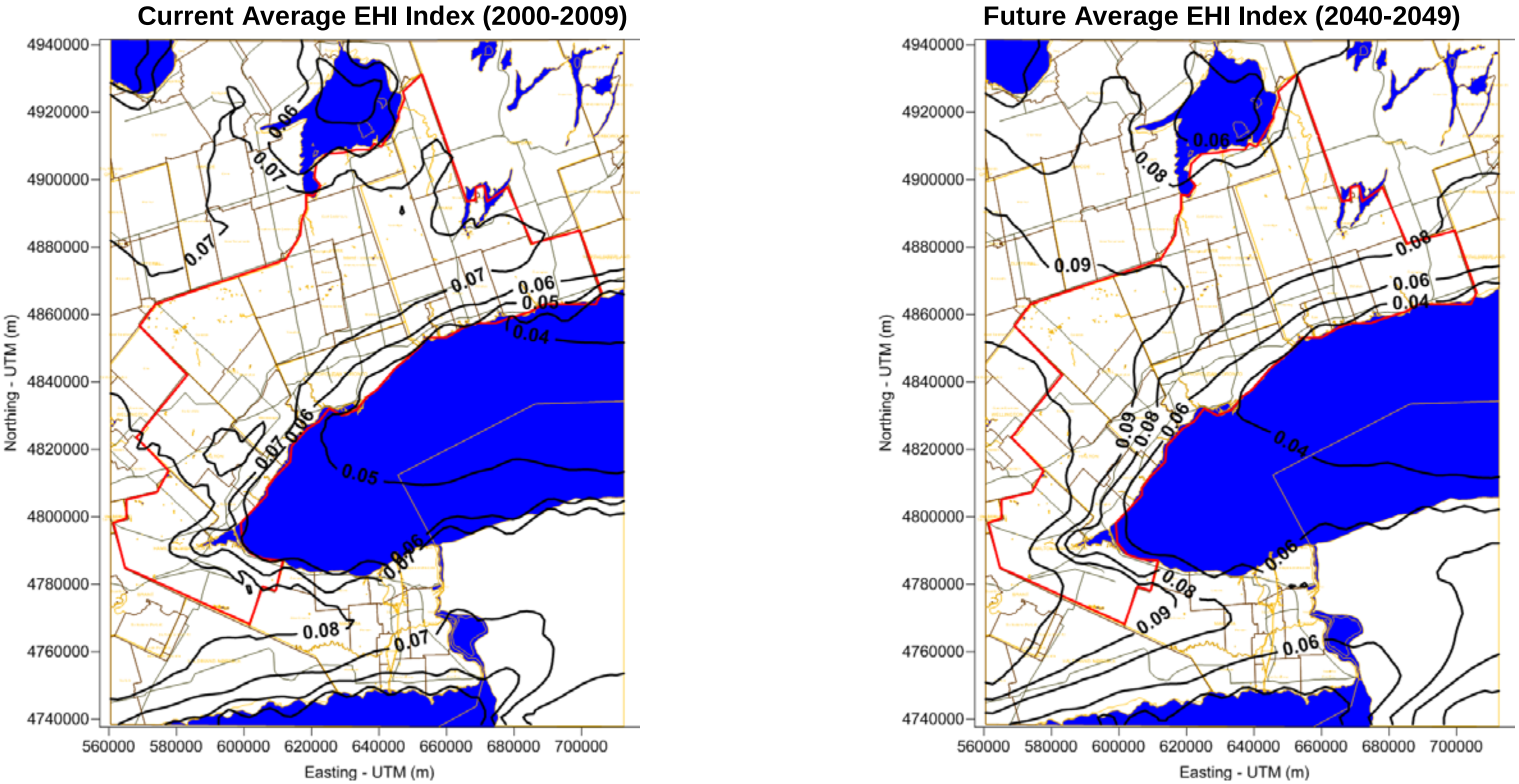
Figure 64: Spatial Distribution of CAPE for Current and Future Period



Current Average CAPE Index (2000-2009)

Future Average CAPE Index (2040-2049)

Figure 65: Spatial Distribution of EHI for Current and Future Period



Current Average EHI Index (2000-2009)

Future Average EHI Index (2040-2049)