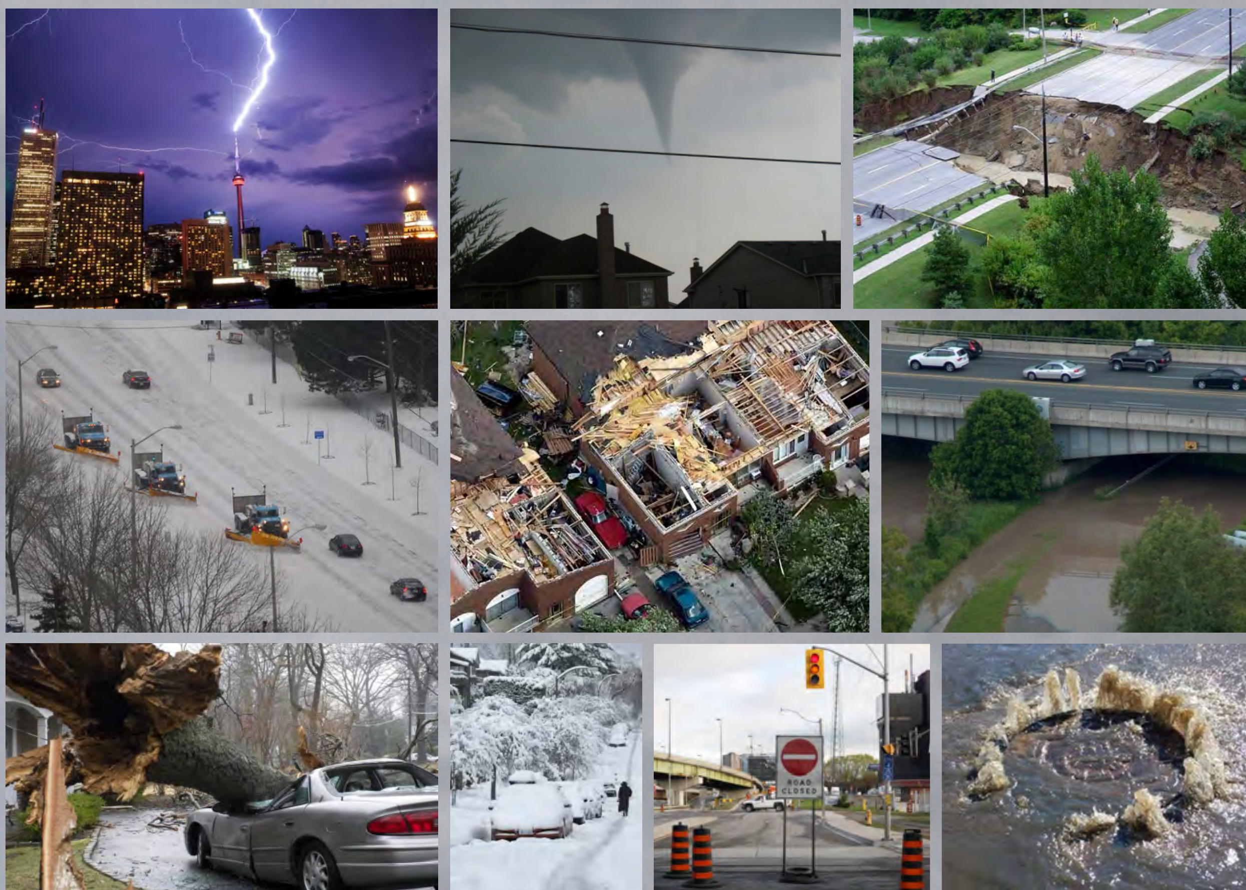
TORONTO'S FUTURE WEATHER AND CLIMATE DRIVER STUDY

Volume 1 - Overview



Prepared For:

The City of Toronto

Prepared By:

SENES Consultants Limited

December 2011

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AND
CLIMATE DRIVER STUDY

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December 2011

EXECUTIVE SUMMARY

The Toronto Climate Drivers Study was conceived to help interpret the meaning of global and regional climate scale model predictions for the much smaller geographic area of the City of Toronto. The City of Toronto recognized that current climate descriptions of Canada and of southern Ontario do not adequately represent the weather that (1) Toronto currently experiences and (2) Toronto cannot rely solely on large scale global and regional climate model predictions to help adequately prepare the City for future "climate-driven" weather changes, and especially changes of weather extremes.

Without the Great Lakes, Toronto would have an "extreme continental climate"; instead, Toronto has a "continental climate", one that is markedly modified by the Great Lakes and other physiographical features. However the Global Climate Models (GCMs) and most Regional Climate Models (RCMs) are not able to properly include the Great Lakes or other relevant local topography and, consequently, cannot adequately predict local future climate change impacts on Toronto and its potentially vulnerable population and public infrastructure.

Large urban centres, such as Toronto, comprise a small percentage of Canada's land area, but are home to a very large percentage of Canada's population, yet the extent of local impacts of future climate on such populations are not sufficiently detailed in the large scale climate models. By improving the level of certainty regarding the magnitude of climate changed weather parameters (temperature, wind speed, rainfall, snowfall), the City hopes to be better guided in its capital works investments and adjustments to operational procedures over time.

Toronto needs to better understand why it gets the climate it does. Just what are the factors and influences that drive the present climate? How will such factors and influences may change in the future – and, when we understand this, hopefully we will see what weather, and especially what future weather extremes, will have to be dealt with in respect to the City's infrastructure and service provision responsibilities.

Why We Get What We Get

The main focus of the work undertaken for the City is an understanding of what the City of Toronto currently experiences and, more importantly, why the City experiences what it does, and why and what the City of Toronto will experience in the future. The key to this is an understanding of what the "drivers" of Toronto's weather are and how they might change in the future. By drivers we are referring to the big picture things – the meandering path of the jet stream, the development and movement of air masses, the position of high and low pressure cells and the associated wind, cloud, heat and moisture characteristics that result in Toronto's weather. This study has developed the data and information needed to appropriately assess and describe the future weather, and especially the expected extremes of temperature and rainfall, to which the City of Toronto must adapt.

When we ask the question – What will the **weather** be like today? – we are asking for a description of the anticipated state of the lower atmosphere in terms of the temperature, the amount of cloud cover and precipitation and whether or not the wind will be blowing in a particular area over a brief period of time in the immediate future.

When we ask the question – What is the **climate** of Toronto? – we are asking for a description of what is commonly regarded as the normally encountered state of the atmosphere over Toronto over an extended period of time in the past. It tells us what the most common weather conditions have been, and are likely to be, for Toronto, season by season, for an assumed "average year".

Emission Scenarios

The climates of the world have always changed "naturally" over time and will continue to do so. However, in the near future further climate changes will also be driven by additional "human" causes at the same time. Predicting future weather is clearly a very difficult undertaking as many uncertainties and unknowns have to be estimated.

One fundamental uncertainty is the amount of (mostly) fossil fuel combustion related emissions that will enter into the atmosphere and at what rate. An international body called the Intergovernmental Panel on Climate Change (IPCC) developed storylines for future greenhouse gas (GhG) emissions as early as 1990. What will actually happen in the future, will be the product of very complex dynamic systems determined by demographic, social, economic, technological and environmental developments. How emissions will actually evolve is highly uncertain. In order to try to come to grips with how our world will change, various storylines were developed by the IPCC to give alternative ideas on how the future might unfold. These storylines are used to develop emissions as inputs to climate models. The outputs from the climate models help people around the world to examine future impacts, and determine appropriate adaptation and mitigation activities.

The IPCC (2000) report identified the A1 family of scenarios as a future characterized by rapid economic growth, by global population increasing to 9 billion by 2050 (after which it gradually declines), by the rapid global dispersion of new and more energy efficient technologies, and where extensive worldwide social and cultural interaction leads to greater parity of incomes and lifestyles among all regions. The A1 scenario family has three members -A1FI, A1B, and A1T, of which the A1B scenario occupies the mid-point between the more fossil fuel intensive (A1FI) scenario and the more technology dependent reliance on non-fossil fuel sources (A1T) scenario.

The A1B scenario is considered to be a "likely" future scenario – and one that is very commonly used for future climate simulations. All such scenarios, when used as part of climate models, produce slightly different future climate forecasts which also differ among regions, and between the time periods, examined. The A1B scenario was selected and used in this study as being representative of a moderate economic outlook yet one that could still be expected to lead to clearly identifiable consequences of the impacts of CO_2 emissions for the 2040-2049 period in southern Ontario

Climate and Weather Models

What is a climate model? It is really the only way to understand the complexities that cause changes in the climate over long timescales. Climate models simulate 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 spatial scale of the boxes in the HadCM3 model is approximately[1] 300x300 km horizontally by 30 km vertically. This scale is much larger than that of some of the key processes that drive Toronto's weather, such as storms and cloud formation. This means that many climate processes have to be approximated at this scale. The approximations, and our incomplete understanding of the climate system, are a major source of uncertainty in climate projections. By using the output of the Hadley global climate model (GCM) to drive a regional climate model (RCM) with a finer scale and with more of the atmospheric processes included (PRECIS was the RCM selected and used in this study), we are able to get a better simulation of the climate over the GTA on a scale of approximately 50x50 km horizontally by 30 km vertically.

However, the scale of weather events over Toronto, like individual storms, and the key influence of the lakes and local topography like the Niagara escarpment, will still not be properly characterized even at this RCM scale. In order to answer the City's questions, a much finer resolution model was required (approximately 2x2 km horizontally) to represent directly some of the key small-scale processes, such as thunderstorm sized rainfall events, weather variability and topographic influences in the Toronto area. For this study, a new and innovative three step process was used. A state-of-the-science weather forecasting model running on a 1x1 km grid covering the GTA (known as FReSH) was also used. Results from a "coarse resolution" HADCM3 climate model (a GCM) were inputted into a "medium resolution" PRECIS climate model (an RCM) to provide results that were them inputted into a "fine resolution" weather-climate model (FReSH). Within the modelling field, this common procedure is called "nesting".

[1] It is impossible to nest perfect squares on a sphere without gaps and overlaps.

Scientists who use climate and weather-climate models do so with confidence because these models are based on well-established physical laws. The science underpinning these laws and the way they are represented in models is continually improving. The models are able to simulate the main features of the current climate and its variability (over an averaging period of about 30 years). 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 hurricanes, 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 successfully simulate the 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.

With a global climate model to correctly identify the long term big picture (30 year and 300x300 km ground resolution) and by feeding that data into a regional climate model (30 year and 50x50 km ground resolution) which then feeds a state-of-the science weather model (hourly, 1x1 km ground resolution), we are able to get the right long term averages and hourly weather statistics on a 1x1 kilometre spacing over the City of Toronto. We will never get a correct prediction of a particular storm on a particular day in a particular location because the weather and its drivers are too variable and chaotic. But a statistical prediction of a storm occurring somewhere within the general area at a particular time of the year can indeed be readily obtained.

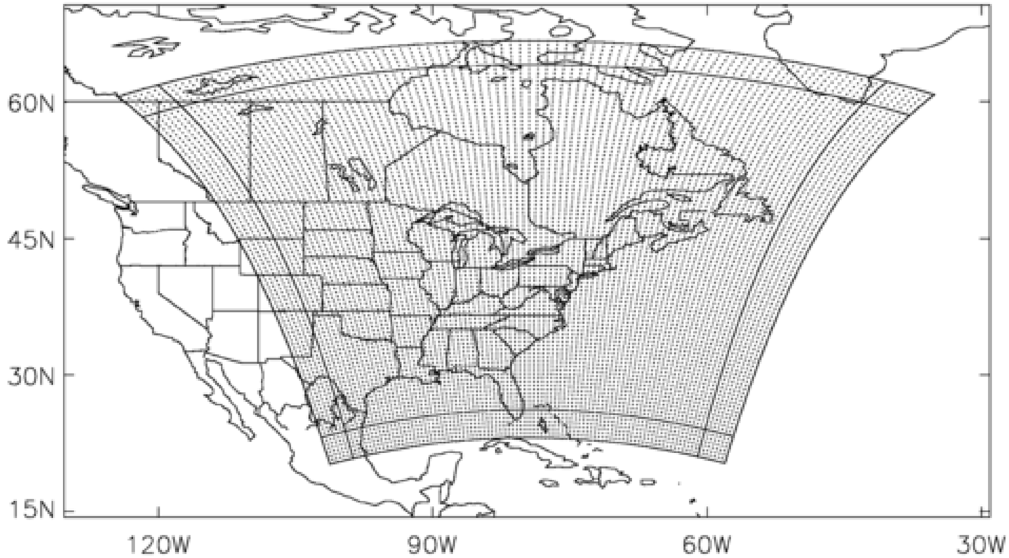
The approach of adding a weather model to the climate model output to obtain more locally relevant future prediction forecasts was completely new and innovative when this project was conceived. One of the main limitations of this approach is simply the computing requirements. This limitation was overcome by SENES' in-house modelling infrastructure. The approach taken has been very successful and the study has demonstrated the value of this approach. It is also an approach that has subsequently been adopted by the National Center for Atmospheric Research (NCAR) for the whole of the USA as well as by the Ontario Ministry of the Environment in partnership with the University of Toronto.

<u>Our Sequenced Approach</u>

For Toronto, the climate and weather modelling and analytical steps involved in preparing the answers, information and associated underlying data developed in association with this report were as follows:

1. Step 1: the **global climate** over the area shown in Figure ES-1 was simulated using the A1B IPCC scenario with the Hadley Climate Model (producing output on a 300x300 km output grid and 6-hour time step) using the Quantifying Uncertainty in Modelling Predictions 15 (QUMP 15) variation. The QUMP 15 variation emphasizes the convective tendency of the atmosphere (occurs when storms are forming) and produces improved estimates of precipitation related extremes;

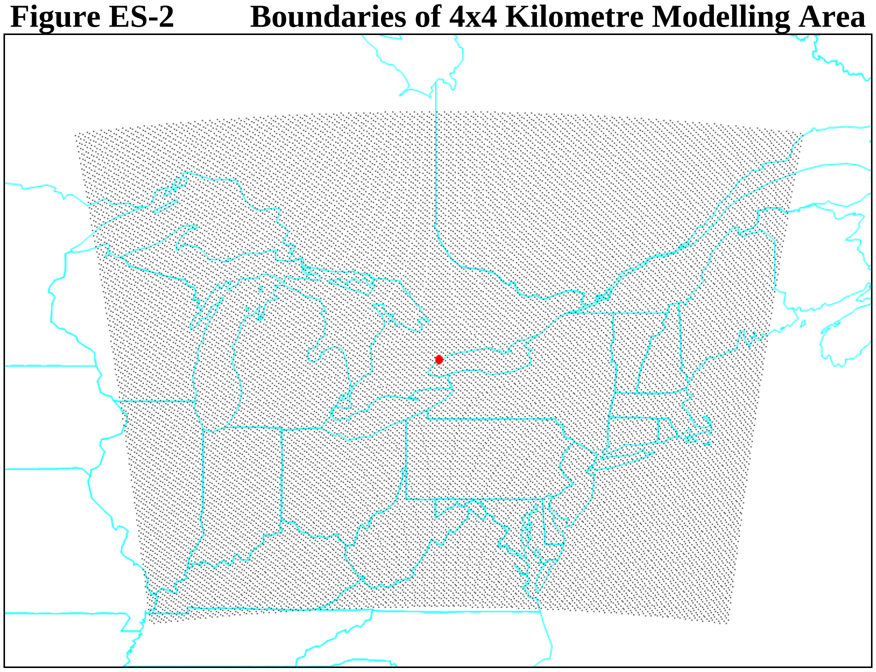
Figure ES-1 Global and Regional Domain Used



2. Step 2: the **regional climate** over the area shown in Figure ES-1 was simulated with the Hadley PRECIS model (a state-of-the-science Regional Climate Model) using the Step 1 output data (producing output on a 50x50 km output grid and 30-minute time step);

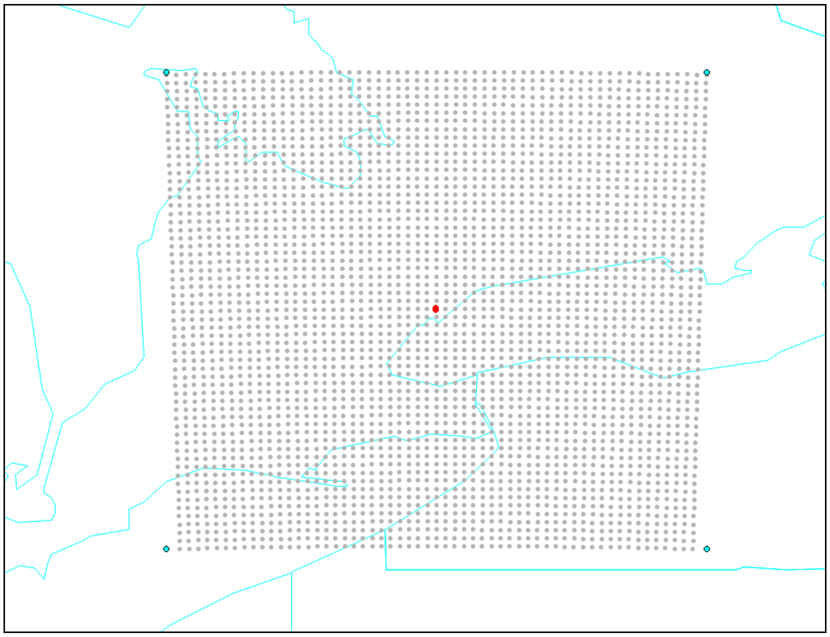
3. Step 3: the **weather drivers over southern Ontario** over the area shown on Figure ES-2 were simulated with FReSH (a state-of-the-science Weather Forecast Modelling System) using Step 2 output data (producing output on a 4x4 km output grid and 20-second time step, aggregated up to 1-hour averages);

Figure ES-2 Boundaries of 4x4 Kilometre Modelling Area



4. Step 4: the **weather details over the GTA** over the area shown in Figure ES-3 were simulated with FReSH using the Step 3 output data (producing output on a 1x1 km output grid and 20-second time step, aggregated up to 1-hour averages); and

Figure ES-3 Boundaries of the1x1 Kilometre Modelling Area



5. Step 5: **10-year descriptive data climate summaries** were prepared for 36 specific output locations around the GTA (not using the closest grid location as other climate models do) using the Step 4 output data as follows:

   i. a "present" climate of 2000-2009 was developed, driven by observed upper air fields, to assess how well the FReSH Weather Modelling System works; and
   ii. a "future" climate of 2040-2049 was developed driven by the PRECIS RCM model.

Accuracy and Sensitivity Tests

Two specific tests were undertaken to evaluate the accuracy and precision of the approaches adopted and were as follows:

1. the period 2000-2009 was simulated using:
   - ❑ observed measurements of broad upper air meteorological fields;
   - ❑ a comparison of predicted versus observed data at specific locations was undertaken; and
   - ❑ a calculation of the error between the modelled and observed weather was prepared; and
2. the Year 2000 was simulated using:

- modelled estimates of upper air fields taken from output of the Regional Climate Model;
- a comparison of predicted versus observed data at specific locations was undertaken; and
- a calculation of the extra error introduced by using a climate model as the driver was prepared.

The data presented in this report illustrate that the approach used for this project gives results that are better than the typical sensitivity range of 2.4 to 5.4°C for future average temperatures achieved by Regional Climate Model analyses. While some approaches estimate the error, by comparing modelled output against comparable monitored data for the same historical time period, and then correct for it, by adding or subtracting the equivalent error, before presenting the results ("bias" correction), SENES feels that it is better to simply document any unknown or inherent bias - but not to hide or remove it. This gives a truer picture of our level of confidence in the model and allows others to independently and more thoroughly assess the model's worth.

The sensitivity tests for the approach used in this study show that the future average temperatures in the 2040-2049 period data, as simulated in this study, may be overestimated by about 2.3°C. The future daily mean maxima and mean minima are also estimated to be high by 2.4 and 2.6°C, respectively. The future extreme maximum temperature could be overestimated by about 7°C and the extreme minimum temperature may be underestimated by about 6°C.

Future total precipitation is estimated to be under-predicted by 35%. Future extreme rainfall seems to be well predicted with an estimated error of only 3% while extreme snowfall is underestimated by about 40%.

Future average wind speeds are estimated to be too low by about 15% while the maximum wind speeds may be underestimated by about 20%. The gust winds may be underestimated by about 10%.

Table ES-1 presents these study generated estimates of possible errors, based on a comparison of model generated and observed values for the year 2000 at the Toronto Pearson Airport.

Table ES-1 Estimated Modelling Errors for Future Weather Parameters

PREDICTED PARAMETER	ESTIMATED ERROR		
	DIRECTION	VALUE	
Average Temperature	too high	2.3	degrees C
Mean Daily Maximum Temperature	too high	2.5	degrees C
Mean Daily Minimum Temperature	too high	2.6	degrees C
Monthly Extreme Maximum Temperature	too high	0.8	degrees C
Monthly Extreme Minimum Temperature	too high	2.6	degrees C
Total Monthly Rainfall	too low	12.5	mm
Total Annual Rainfall	too low	150	mm
Total Monthly Snowfall	too low	5.4	cm
Total Annual Snowfall	too low	65	cm
Extreme Daily Rainfall	too high	2	mm
Extreme Daily Snowfall	too low	4.9	cm
Average Monthly and Annual Wind Speed	too low	0.1	km/hour
Maximum Hourly Wind Speed	too low	15.4	km/hour
Maximum Instantaneous Gust Wind Speed	too low	9.8	km/hour

Future Weather

The study established the current and future weather at 36 different locations around the GTA and across the City of Toronto but for the purposes of detailing the changes, data and information pertaining only to Toronto Pearson International Airport has been examined. The information for all stations can be found in Volume 2 of this report. In general, the other stations, follow a similar set of trends and changes, but can differ somewhat locally both by parameter (e.g. snowfall) and by geography (e.g. proximity to Lake Ontario). The following sections summarize the projected Toronto Pearson International Airport (TPIA) weather for the future period (2040-2049) as compared to the detailed simulation of the current period (2000-2009).

Less snow and more rain in the winter

Figure ES-4 below shows the projected reduction in snowfall in centimetres across Toronto and the GTA for the period 2040-2049. This occurs because higher temperatures will allow less snow to form.

This map also clearly shows that a single data point (as would be derived from a GCM of 300x300 km or an RCM of 50x50 km) does not represent the reality of the geographic variability likely to be experienced within such large "grid cells" across the GTA and Toronto (see Figure ES-5) and hence demonstrates the greater value of the climate-weather model approach for such things as estimating future snow removal budget needs.

Figure ES-4 Projected Change in Snowfall across the GTA by the 2040s (in cm)

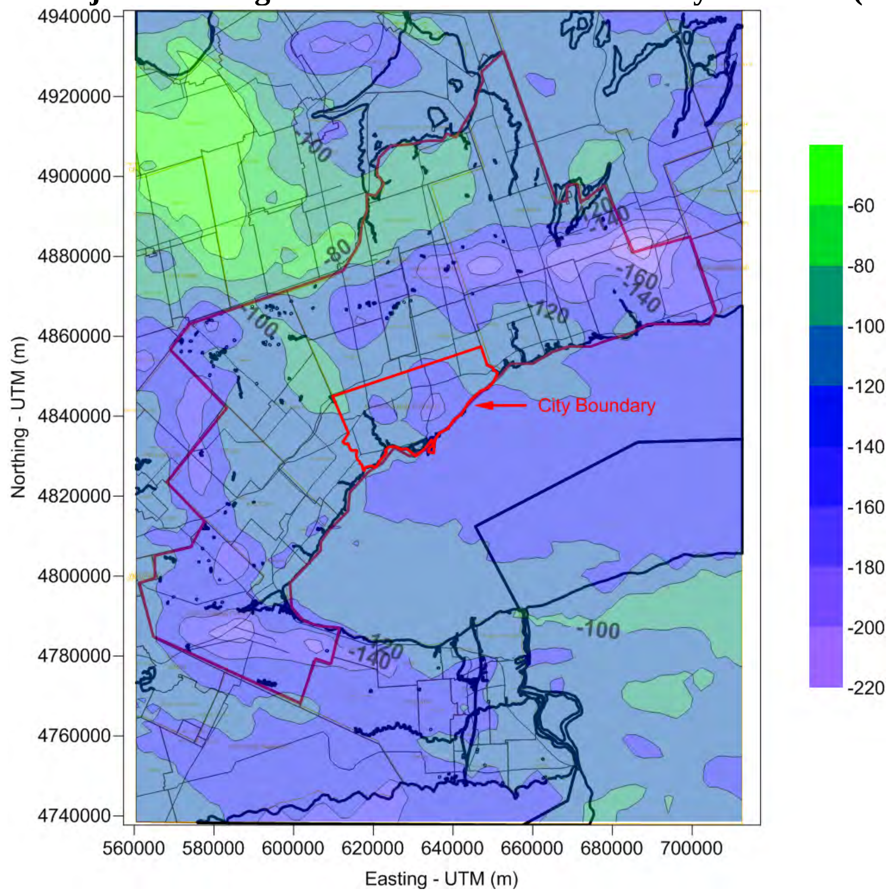
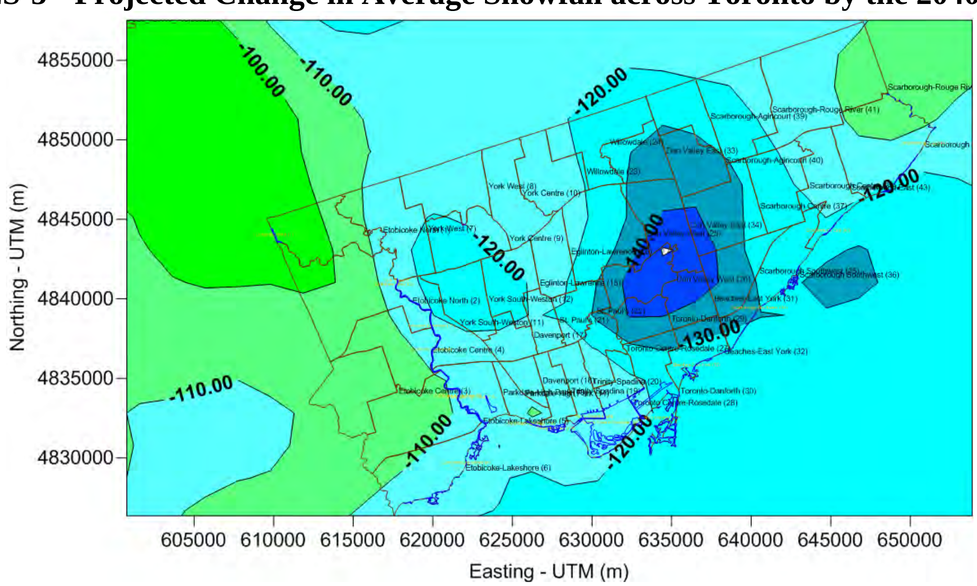


Figure ES-5 presents the details of the projected reduction in snowfall across the City of Toronto for the period 2040-2049 compared to the simulated 2000-2009 period.

Figure ES-5 Projected Change in Average Snowfall across Toronto by the 2040s (in cm)



Slightly more precipitation (snow plus rainfall) overall

Figure ES-6 shows the month by month changes in rainfall amounts showing higher rainfalls during the winter months at Pearson Airport. Precipitation amounts are projected to remain similar to the present for about 8 months of the year but increase markedly in July and August (with 80% and 50% increases caused by extra rainfall over present values respectively). Further analysis shows that the number of days of precipitation per month decrease (except in July and August) with 26 fewer snow days per year (9 less in December). Figure ES-6 presents the projected month-by month differences in average monthly rainfall and snowfall.

Figure ES-6 Projected Change in Monthly Average Rainfall and Snowfall

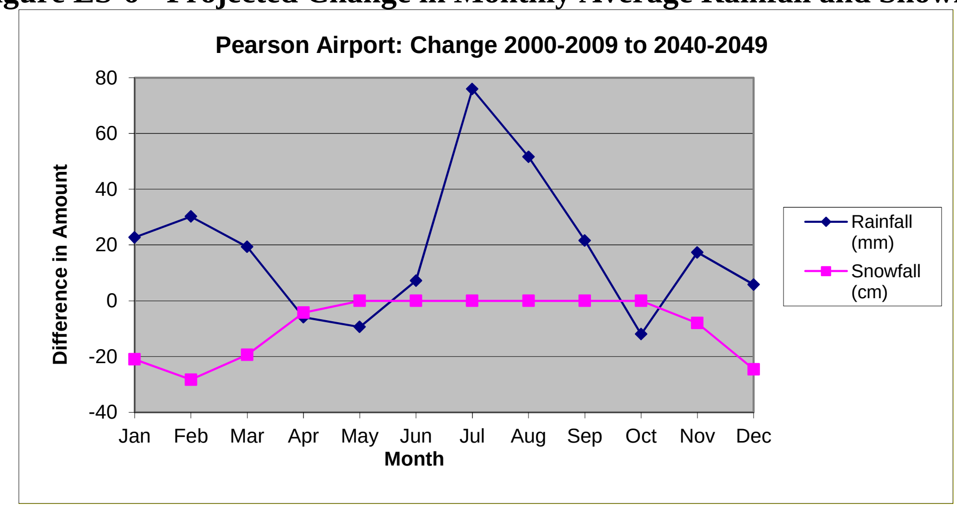
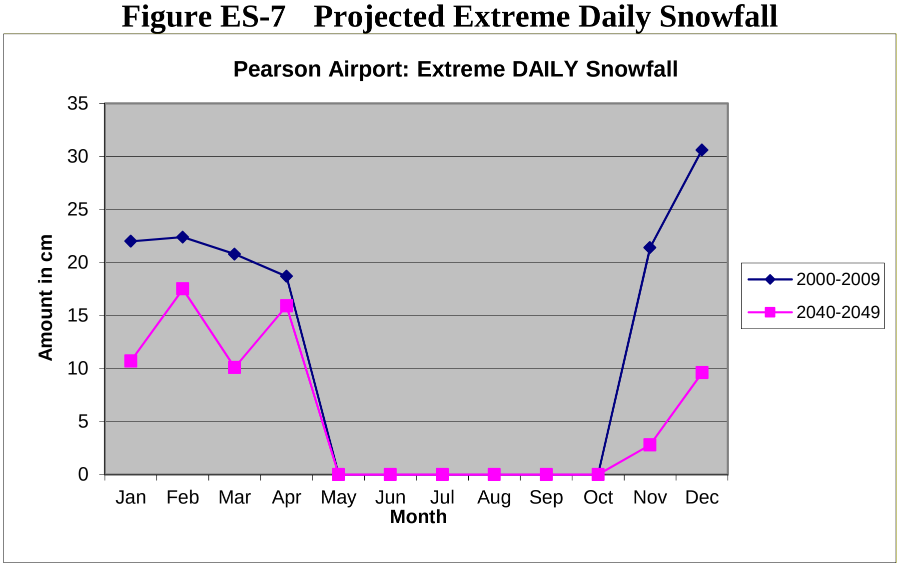


Figure ES-7 presents the projected differences month by month in extreme daily snowfall. The figure shows a lot of variability in the snowfall prediction for the 2040s which is expected since snowfall is traditionally one of the most difficult parameters to predict in all models.

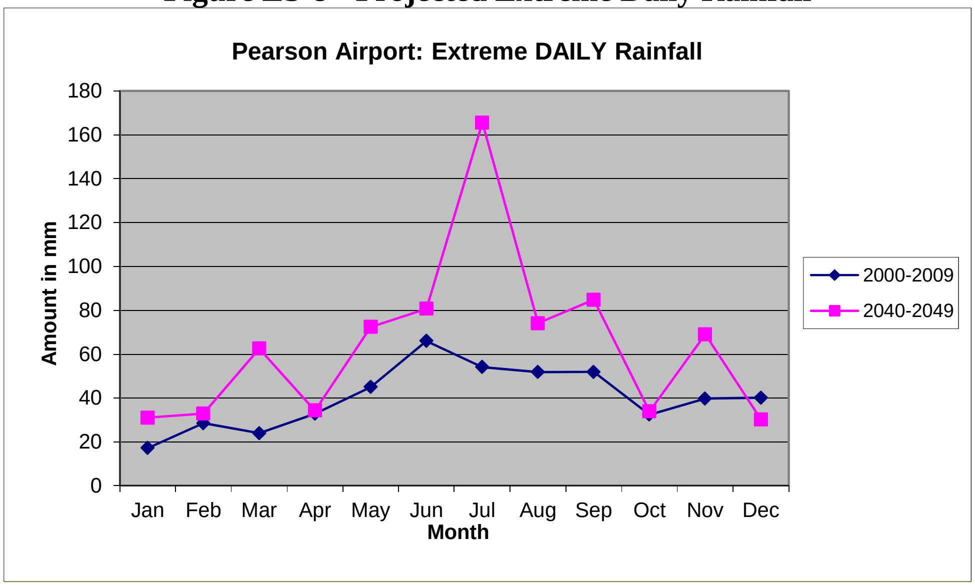
Figure ES-7 Projected Extreme Daily Snowfall



Extreme rainstorm events will be more extreme

The number of days with rain greater than 25mm is projected to decrease while the total precipitation is projected to increase. This means that the future will see a smaller number of storm events but on average each will produce a higher amount of precipitation. Figure ES-8 presents the projected month-by-month extreme rainfall (2040-2049) compared with the present period (2000-2009). It shows a large increase in the magnitude (size) of extreme (daily) rain events during an individual day in July (almost threefold).

Figure ES-8 Projected Extreme Daily Rainfall



An example of an extreme event is the Finch Avenue washout of 19 August 2005. This was simulated with the detailed weather forecast model used in this study (FReSH) and the approach gave a much better simulation of what actually happened on that day than was obtained by any other means. Figure ES-9 presents, for that day, the predicted total daily rainfall amount over part of the City of Toronto and shows that the total forecasted rainfall was in the range 120-140 mm (near red circle) compared to a locally observed 142 mm. The total amount observed at Pearson Airport (Toronto's reference location) on the same day was only 43 mm. This shows the power of the modelling adopted in the present study at a very fine scale of local resolution.

Average annual temperatures increase by 4.4^{o}C

The projected average winter and summer temperatures increase by 5.7^{o}C and 3.8^{o}C, respectively. The extreme daily minimum temperature "becomes less cold" by 13^{o}C. The extreme daily maximum temperature "becomes warmer" by 7.6^{o}C. Figure ES-10 presents the projected average temperature differences for the City of Toronto. It shows that there are differences across the city that would not be evident from a single output point of a climate model. In general, temperatures are the most obvious sign of climate warming. As temperatures rise because of the enhanced greenhouse effect (too much extra CO_2 being emitted into the atmosphere) areas closer to the poles will be affected more than areas near the equator.

Figure ES-9 Modelled Daily Extreme Rainfall for 19 August 2005

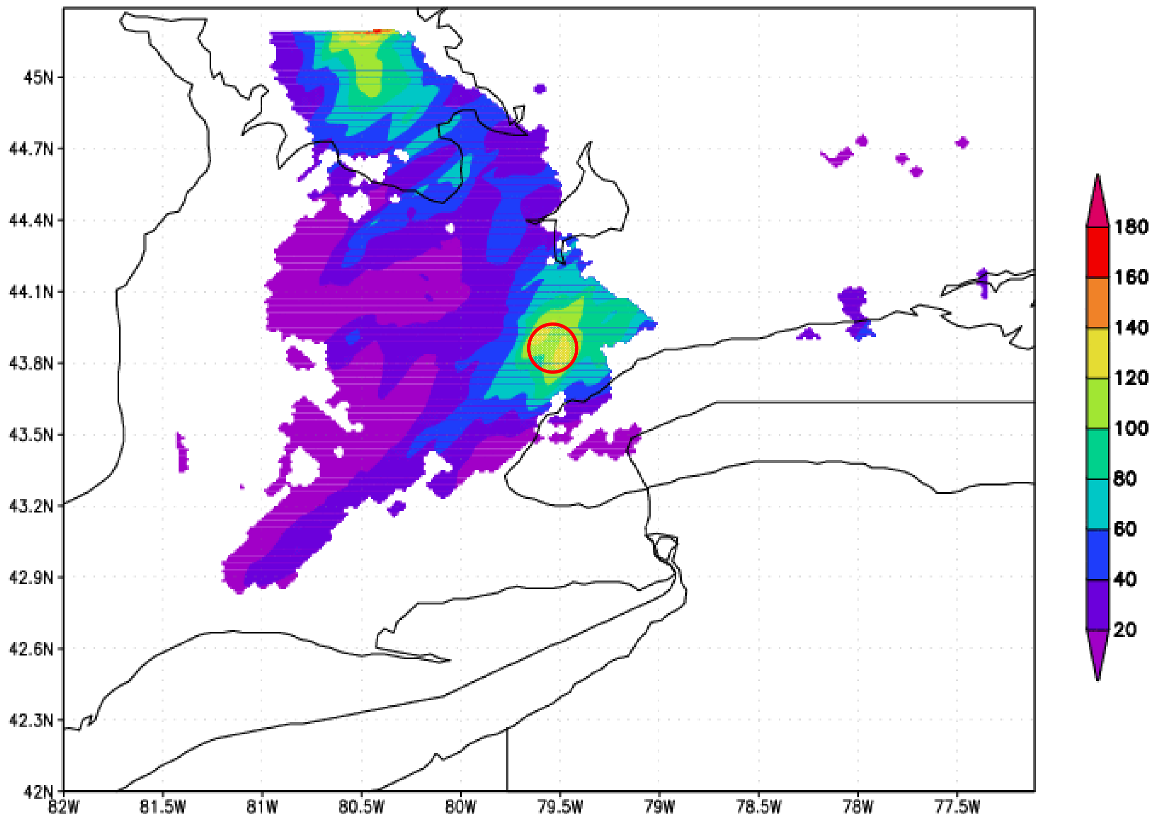
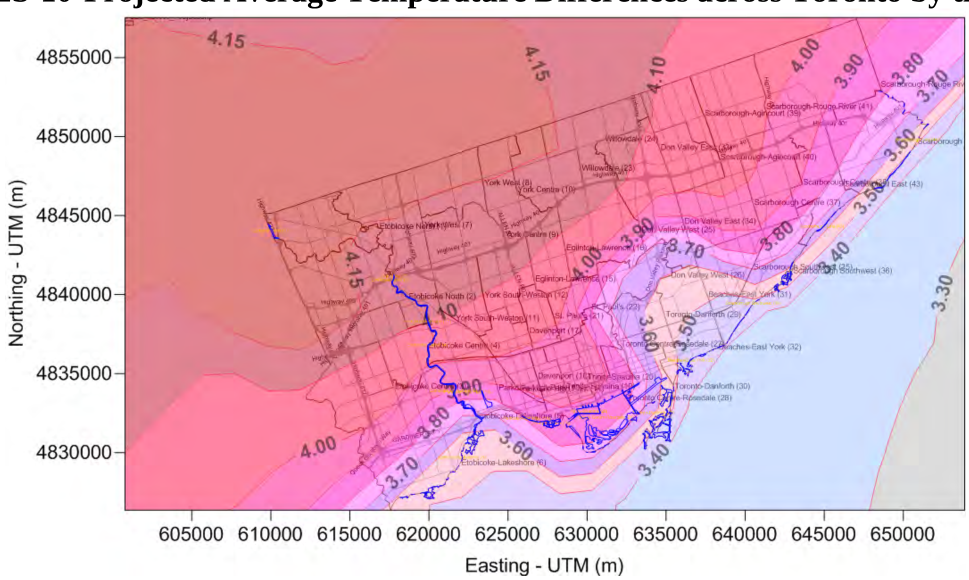


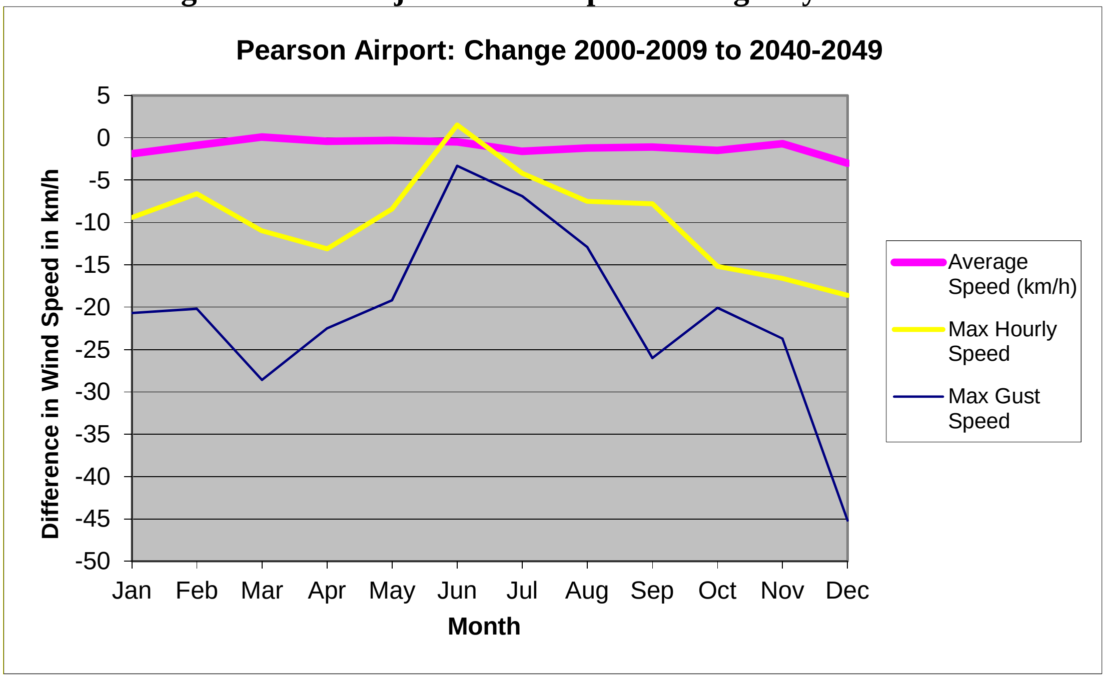
Figure ES-10 Projected Average Temperature Differences across Toronto by the 2040s



Wind speeds will be unchanged on average and maximum wind speeds will be reduced

The maximum hourly winds and maximum wind gusts are projected to be reduced. Figure ES-11 presents the projected wind differences which show the average monthly wind speed almost unchanged and the monthly maximum hourly wind speeds and maximum gusts reduced. This suggests more vertical and less horizontal motion developing stronger storms meaning that there will be more clear skies and calmer periods between storms. But with stronger convective storms (in the summer period) we can expect slightly stronger sustained hourly winds and at least as strong wind gusts during these highly convective storms.

Figure ES-11 Projected Wind Speed Changes by the 2040s



More "comfort" in the winter but less in the summer

Humidity and temperature, taken together as the Humidex, remain similar (within 10% of present values) for most of the year but shows increases in February (up 40%) and in July through to September (up 20%). Wind Chill is reduced by over 50% on average but is reduced to zero (i.e. by 100%) in May, June and September.

How does this projection compare with other estimates?

If we project Environment Canada's observed data linearly into the future, we see that the projected temperature difference between the current period 2000-2009 and the future period 2040-2049 ranges from a low of 1.6ºC to a high of 3.3ºC depending upon the period of observed record that is used. The combination of models and the approach used, which emphasizes the extreme convective cases and takes account of the local topographic and surface features, gives an average difference of 4.4ºC. In terms of reproducibility of the current period 2000-2009, the RCM-FReSH combination approach gave a 10-year average temperature of 8.70ºC at Pearson

Airport compared to an observed 8.73ºC. The best Canadian government model, the Regional CRCM 4.2.3 gave an average temperature of 6.69ºC for the same 10-year period.

Looking at other climate modelling simulations (CCCSN data for the Toronto Pearson location) that include the GTA but at a very coarse resolution, the temperature differences between the current period simulation (2000-2009) and the period 2040-2049 range from -2.7 (i.e. it gets colder) to +6.3 (i.e. it gets even warmer than the current study prediction indicates). A comparison of some of the key parameters is presented in Table ES-2 below.

Table ES-2 Comparison of Projected Changes from the Current to the Future Period

PARAMETER	Differences from Current Period			
	2000-2009 (observed)	2040-2049 (this study)	Value from Other Climate Models	
			Min (2040-2049)	Max (2040-2049)
Total Precipitation in mm/day	0.0	0.1	0.0	2.0
Mean Wind Speed in m/s	0.0	-0.3	-2.8	0.3
Number of Days with Precipitation > 10mm	0.0	-17.2	-20.3	12.7
Mean Temperature in Degrees C	0.0	4.4	-2.7	6.3

Why do we get the weather we get?

The result of the atmosphere being transparent to incoming solar radiation and more absorptive to outgoing long-wave radiation from the Earth is that the Earth's surface is kept at a much higher temperature on average than it would be if there was no atmosphere. The energy radiated outward and absorbed by the atmosphere is partially radiated back to the Earth's surface, increasing the total energy received there. This raising of the Earth's surface temperature because of the back-radiation from the atmosphere is known as the natural greenhouse effect.

Over the long run, the processes of absorption and emission of radiation at the ground and in various layers of the atmosphere have produced a balance between the incoming and outgoing energy, keeping our world a warm enough place to live and providing the driving forces for atmospheric motion.

The latitudinal variation in solar energy means that there is an unequal distribution of heat across surface of the globe. Part of the atmosphere's heating comes from the earth's surface and because there are different types of surfaces the atmosphere is heated unevenly around the globe. Air with different temperatures has different densities. The hotter air becomes lighter and rises, the colder air heavier and sinks. Nature effectively compensates for this unequal distribution of heat (energy) by moving masses of water through ocean currents, and masses of air within the atmosphere mixing it. The ocean and the atmospheric motion sets itself in motion and attempts to distribute the heat more evenly around the globe.

Warm, moist air in the tropics rises and moves poleward transferring energy to higher latitudes while creating a zone of low pressure in the tropics. Around 30°N, air descends, creating a zone of high pressure. The descending air spreads out in the lower atmosphere and some of it flows back to the equator creating a closed loop called the Hadley Cell. Around 60°N, a polar circulation cell is formed as air rises and flows poleward and descends over the high latitudes creating another area of high pressure. This closed loop is called the Polar Cell. A third cell, the Ferrell (or Mid-latitude) Cell, owes its existence to the other two cells. The rotation of the earth causes winds to shift direction. This is known as the Coriolis Effect and it causes winds to shift slowly to the right in the northern hemisphere (clockwise). Three global wind zones result: the polar easterlies; the westerlies; and the easterly trade winds.

Canada is predominantly under the influence of the westerlies. As a result, the prevailing winds in Toronto blow from a westerly direction throughout the year. The prevailing westerlies tend to carry Pacific air to the eastern portions of Canada and are the reason why one of the predominant influences on our climate is the Pacific Ocean. In general, strong upper level westerly air streams (i.e., the Polar jet stream) steer high and low pressure cells which form mostly above areas of cold contracting and sinking air and warm expanding and rising air, respectively, over Canada and the U.S. towards the east, bringing variation to Toronto's day-to-day weather.

There are two types of air masses: travelling air masses and blocking air masses. Air masses that are formed in one geographic area may subsequently move to other areas and are known as travelling air masses. Travelling air masses bring their temperature and moisture characteristics with them and influence the weather of the new areas they encounter. Conversely, air masses with overly strong pressure characteristics may become almost stationary (blocking air masses) for long periods of time and can force other travelling air masses having weak pressure characteristics, to move around them.

Semi-permanent high/low pressure systems become apparent when pressure patterns are averaged over several years for a given region. The winds derived from these regions of high and low pressure are what carry travelling air masses from their source regions into or across Canada.

Toronto summers are dominated by Maritime Polar (i.e., Pacific) and Maritime Arctic air masses from the west that bring warm (sometimes cool), dry air. Occurrences of Maritime Tropical air from the Gulf of Mexico can also arise which bring hot and humid days to Toronto in the summer. In the winter, cold, dry Continental or Modified Continental Arctic air dominates Toronto. Less frequently Toronto receives mild air from the south southwest during the winter months.

The polar front jet stream has been likened to a meandering river winding its way from west to east around the globe's northern latitudes (between 30° and 60° north), but unlike a meandering river, it is also constantly shifting completely from further north to further south as the polar front moves with the seasons and its lobes (i.e., its meanders or turns) correspondingly change in number, shape and position. A typical North American winter polar jet stream pattern, when observed on a weather map, involves a slight northeast turn east of the Rockies, then a dip southeast into the United States and finally, it turns northeast towards the Atlantic coast. This pattern is responsible for the paths taken by many winter storms and it can steer common winter storms such as the Gulf Low (also known as the Texas Low), the Colorado Low and the Alberta Low (also known as an Alberta Clipper) towards Southern Ontario and thus, Toronto.

The significant passage of successions of "lows" (and all their attributes) over Toronto is "driven" by the meeting of tropical air from the south with polar air from the north. The temperature differences of, and between, these air masses create air masses of differing densities and pressures in close proximity to each other. Pressure gradients result; the gradients drive the winds (like water flowing over sloping land) that carry the air masses forward and create the fronts and the sequence of weather associated with their presence.

The location of the invisible line that separates tropical from polar air (of such great importance to Toronto) is itself a dynamic moving wave line, or vertical curtain, extending through the lowest layer of the atmosphere (the troposphere) from the ground to the air aloft at its upper limit the tropopause (or the boundary between the troposphere and the stratosphere above it). The height of the tropopause above Toronto is typically between 10 km and 12 km.

Where the tropical and polar air meet, intense (i.e. steep) pressure gradients are created. These are strongest near the tropopause and give rise to the polar jet stream. The jet stream is a narrow band of very strong winds at height (typically at between 8 and 12 km altitude along the polar front). The polar jet of the northern hemisphere follows (at height) the varying location of the polar front that moves in a wave like manner around the earth. The number of waves within one complete encirclement of the globe can vary from very pronounced amplitude waves, or lobes, to very weak amplitude waves, and can vary in number from as few as two to as many as six – but more typically between three and four "lobes" are present at any given time. The boundary between tropical and polar air and the jet stream between them tends "to be anchored" by the presence of the Rocky Mountains – where the jet stream typically "bends" northwards to cross over them. As such, the jet stream most typically flows south eastwards across western Canada before curving back northwards to complete the lobe form. The location of the polar jet stream across Canada (and indeed cold and warm fronts as well) can be seen in the Globe and Mail and in the Toronto Star on a daily basis.

Although the pattern of the jet stream's meandering motions is variable it does have an average latitudinal location – and if that average location were to change north or south, or the nature and frequency of the amplitudes of the lobes were to change, it would logically bring a change of climate and weather for Toronto with it.

Toronto currently lies within the belt of circumpolar westerly winds (the "westerlies") that dominate the climate of mid-latitude and sub-polar latitude regions. The belt extends from the south west of the USA to the Canadian Arctic. Disturbances flow with that air stream and other air mass streams are also pulled into the main stream. Though the specifics of its make up change, the general flow is fairly constant.

The depiction of tropical air meeting polar air is a simplification and convention that does not fully express the complexity or the nature of the situation in Canada or the Toronto region. True tropical air only enters Canada's air space infrequently (usually only in summer). Much more frequent are subtropical air currents derived from the south eastern United States.

The climate and weather at the surface depends very heavily on the motions of the westerlies and the jet stream, and the disturbances and air streams that are carried along with them.

Topography can have a local or regional impact on climate, or an impact of a much larger scale. On a large scale, extensive mountain chains such as the Rockies can block incoming weather systems from the rest of Canada. However, since the rest of Canada is a large, open land mass, it permits the rapid movement of weather systems through much of the country including Toronto. Topography also influences localized precipitation patterns. Air encountering elevated lands is forced to rise and cool, causing clouds to form and precipitation to occur. This is called orographic precipitation. When air descends along the other side of the elevated region, it is dry and warm and in Western Canada is it commonly referred to as a Chinook Wind. Additionally, in the lee side of elevated lands (such as the Niagara Escarpment, the Oak Ridges Moraine and even Toronto's downtown buildings) there is often a noticeable "rain shadow" effect (an area of reduced rainfall).

Toronto is located within the Great Lakes Lowlands and lies along the north-western shore of Lake Ontario. This has very important implications for Toronto's climate.

Water has a large heat capacity which has two consequences: 1) it requires a large amount of energy to raise the temperature of water and 2) it takes a long period of time for water to release any acquired heat. As a result, Toronto tends to be milder in the fall and winter because the Lakes are warm relative to the air, and the same areas are cooler throughout spring and early summer because the Lakes are cool relative to the air. In other words, the Lakes moderate the occurrence of local temperature extremes in both summer and winter. Theoretically, Toronto should have an extreme continental climate by virtue of its distance from the Pacific Ocean – especially since weather comes to Toronto largely from the west, but also by virtue of its distance from the moderating influences of the Atlantic Ocean as well. In essence, the presence of the Great Lakes reduces the severity of Toronto's cold winters as well as the intensity of its warm summers.

Lake Ontario, being quite deep, requires a larger amount of solar energy and, therefore, time to raise the temperature of even its surface waters, than the amount of energy and time required to raise the temperature of the adjacent land areas. This delay can result in temperature differences of 6 to 12 degrees between the lake and the city in the summer. In the winter, the lake is mostly ice-free which also allows the water to have a moderating effect on the City's temperature over the entire winter season. This moderating effect is most pronounced immediately adjacent to the water, and decreases with distance from the lake.

The moderating effect of Lake Ontario on the climate of Toronto and its environs is as important with regards to the growing season in rural areas surrounding Toronto as it is for vegetation growing within the city. In the spring, lake temperatures keep the surrounding areas cool, preventing vegetation from growing too soon and risking exposure to frost. In the fall, warm lake temperatures also prevent as many damaging frosts from forming as would otherwise happen.

In addition to temperature, lakes also affect local winds, precipitation, cloud cover and fog. As well as being influenced by prevailing winds, areas adjacent to lakes are influenced by lake breezes. Mostly occurring in summer, lake-breezes are a result of large land-lake temperature differences. Often bringing relief on a hot day, cool air from above the lake rushes under and replaces the warm air that is rising above the land. At night, the pattern can reverse, creating a land breeze in which cool air over the land flows out over the warmer water of the lake where it rises. A lake-breeze can only really occur, and be felt, if prevailing winds are light.

During the winter, lake-effect snow (snow that is created, in part, by the presence of a large body of open water, such as Lake Ontario, in the path of a prevailing wind) can develop under conditions of strong, persistent winds and a large difference between the lake's temperature and that of an approaching air mass. For lake effect snow to be created, a large distance of open water over which the air travels is required. Due to Toronto's location in proximity to Lake Ontario, and the prevailing wind direction (NW) in winter, these requirements are not typically met for Toronto. Instead, lake effect snow development predominates to the east of Lake Huron and to the south and east of Lake Erie and Lake Ontario. Sometimes, bands of lake-effect snowfall (from Lake Huron and Georgian Bay) may reach Toronto, but they usually only reach as far as London or Barrie, Ontario.

Depending on the storm track, the Great Lakes may intensify approaching storm systems by adding heat and moisture to the storm system. However, during spring and early summer, it is thought that lakes actually suppress thunderstorms; if the lake surface is cool enough, moisture is returned to the lake through condensation, suppressing convection and thus thunderstorms.

Finally, areas in the vicinity of lakes often experience more days with cloud cover as the lakes provide a source of moisture and heat (in the cooler winter months) which can cause air to rise and the moisture in it to condense. Lakes also encourage fog formation under certain circumstances. These conditions arise if cooler and less turbulent air passes slowly over warm lake water, causing moisture above the surface to condense (creating steam fog) or if warm, moist air passes slowly over cool surface waters (creating advection fog). Advection fog is typical in spring and early summer.

A topographic feature in Southern Ontario that influences climate in the vicinity of Toronto is the Niagara Escarpment. To the east-southeast of Lake Huron and Georgian Bay the escarpment is roughly oriented in a northwest-southeast direction (including the Niagara Region portion) and as a result of its location, prevailing westerly winds are often forced to rise up and over the escarpment. Consequently, areas in close proximity to, and to the west of, the escarpment experience greater amounts of rainfall and a rain shadow is created to the east of it including areas near Toronto.

Not only does local topography impact precipitation patterns, but it also influences local winds and temperature. In the City of Toronto, the land gently slopes towards Lake Ontario and is traversed by many valleys (e.g., the Don and Humber River valleys) which are orientated generally in a north-south direction. Because it is denser, cold air will often drain into these valleys at night which leads to more fog and frost in these areas. Valleys also tend to channel winds making them stronger and gustier than in other parts of the city.

Green areas in cities (parks, gardens, sports fields, etc.) generally have cooler night-time temperatures (and locally a smaller urban heat island) than the surrounding urban areas. Water is able to evaporate from the soils and vegetation in green areas which has a cooling effect. Generally, cities with tall buildings and narrow streets will have a larger heat island effect than cities with lower buildings and broader streets, because more of the heat energy radiated during the night will be reabsorbed by surrounding buildings. The tall bank tower area of downtown Toronto is also an effective topographic, albeit artificial, feature that creates a microclimate, especially in regards to channelling winds and creating its own north and south facing vertical slopes which affect local weather. By removing vegetation and replacing it with man-made structures and surfaces, it changes heat, moisture and momentum exchanges (or fluxes) and thus affects temperature, cloud cover, precipitation and even wind speed. The City of Toronto is no exception; areas of tall buildings as in the high density downtown core have largely asphalt and concrete surfaces and little vegetation and make its climate much different from even lower density surrounding urban areas with more vegetation; equally, even such non-downtown urban areas have more brick, concrete and asphalt than surrounding rural areas.

An Urban Heat Island (UHI) is the name given to an island of warmer air temperatures caused by the extra heat supplied to the air from the urban surface below it, within a generally cooler geographically broad mass of air. Any large metropolitan area, such as Toronto, will exhibit one, or more, urban heat islands (depending on the size and structure of the surface) with higher temperatures than the rural areas surrounding it. It is caused by dense materials (concrete, brick buildings, road surfaces, etc.) preferentially absorbing heat because of their dark colour and then releasing it and heating the air above; as well as being due to heat loss from buildings and vehicles in a city. As a result, significant differences in temperature can occur between Toronto and its surroundings, and this is most noticeable in mid-summer, overnight and during the winter months.

Urban areas also affect other climate parameters such as solar insolation, wind, cloud cover and precipitation. Clusters of tall buildings, like trees in the woods of rural areas, are known to cause shadowing effects creating pockets of cooler temperatures within the city. As well, building configurations significantly alter wind speeds and flow patterns in urban areas. As winds encounter an urban canopy, they are forced to flow up and over tall buildings resulting in a slower, more turbulent flow. However, when winds blow in between tall buildings, a tunnelling effect may result, increasing wind speeds in certain areas of a city.

The consequences in Toronto of the variation in the directions of the general westerly air flow, in the strengths and turbulence of the associated winds, in the temperatures and humidity, and its precipitation, and the ongoing exchange of heat (as sensible and latent heat, and as radiative and convective exchanges) between the air and the land (or lake) surfaces beneath as part of the general circulation - are all very apparent on a day-to-day basis.

Local interactions also influence the air everywhere it travels. In the Toronto areas, the Great Lakes and the seasonal vegetation changes, urban vs. rural land use, urban heat island conditions and impacts, and the topography of the Oak Ridges Moraine and Niagara Escarpment, as well as Toronto's urban canyons all influence the direction and speed of air flow and its basic characteristics of temperatures and water content.

Weather events in Toronto are clearly functions of the general climate and general circulation and the weather system pattern that are created within them, but the weather events in Toronto are also functions of local phenomena and the local interactions between the global and the local phenomena.

The juxtaposition of the general wind direction from west to east and the orientation of the lower Great Lakes (Lakes Erie and Ontario) clearly results in many "snow storms" producing heavy snow in Buffalo but which produce only light snow, or even no snow, in Toronto. Obviously the lake surface over which cold winter winds blow provides extra water to the air, which condenses and ultimately falls as snow. So if the wind blows along the length of Lake Erie picking up moisture which subsequently falls as snow, when the air rises over the land and cools to form snow crystals, as at the eastern end of the lake, then the length of the contact between wind and lake makes a big difference. Whereas cold winter winds that blow across Lake Ontario toward Toronto (unless they blow from the east) do not have as much of a distance to travel over, or exposure to, the lake surface and will gain far less moisture, less snow crystals form and less snow falls. This is a simple comparison known to all Torontonians. But effectively the presence, size and orientation of all the major topographic features (the Niagara Escarpment, the Oak Ridges Moraine, Lake Ontario and Lake Erie, as well as lesser lakes such as Lake Simcoe, and features like the Holland Marsh – can all "localize" the weather experienced by Toronto.

Why Will the Future Be Different?

Generally, the world is going to be a warmer place in the future as a result of the man-made (enhanced) greenhouse effect. Other direct influences will come from El Niño and La Niña, as well as less direct influences from other naturally occurring oscillations.

Oscillations

The El Nino Southern Oscillation (ENSO) occurs every 2-7 years. When it occurs, sea level pressure over the western Pacific Ocean is a little higher and the easterly trade winds are weakened as a result. This causes the warm waters to rise making heat and moisture more available on the surface leading to more uptake of water vapour and more storms and precipitation. This phenomenon alters the location of highs and lows and hence the position of the jet stream. The jet stream shifts southward in the winter giving above normal Spring temperatures and less precipitation in the winter.

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 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. 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 and as a result, cold Arctic air can plunge into North America and storm tracks are maintained over the mid-latitudes.

The Pacific Decadal Oscillation (PDO) is a 20-30 year cycle in sea surface temperature and sea level pressure in the northern Pacific Ocean. When it is in phase with the ENSO, it strengthens the ENSO giving dramatic effects.

The position of the Northern Latitude Storm Tracks affects the frequency and intensity of storms. It has recently been observed to be moving poleward giving stronger storms and an increase in the number of intense storms. Models of future weather all move the storm tracks poleward and show fewer but more intense storms over the GTA. This study shows the same thing. The storm tracks move under the influence of the Arctic Oscillation (AO). When the AO is in a positive phase, the upper air temperatures are cold and the mean sea level pressure is below normal which displaces the storm tracks northward. The AO is currently in a positive phase and is projected to remain so.

Loss of Arctic Sea Ice

The high albedo of the Arctic ice reflects more energy back into space. Water has a low albedo and absorbs more energy. As ice melts, the temperature will rise at a faster rate. This is known as a positive feedback mechanism. Over the short time scale, the arctic water will absorb CO_2 but over the longer term with the rise in water temperature, CO_2 will be released. Also as these waters warm, coastal shelf methane will be released. Methane is 21 times as effective at heat retention as CO_2.

Generally, the future is expected to be different because:

- warming will push the average arctic cold air mass and tropical warm air mass contact zones (and the polar jet stream) further north and the pressure gradient between them will lessen at the latitude of Toronto making for less intense weather in general but exacerbating the likelihood and magnitude of extreme weather in summer;
- a consistent poleward shift in the storm tracks of low pressure cells with frontal rain storms at the latitude of Toronto with greater storm activity at higher latitudes will result in precipitation shifting poleward with the storm track; however, this coupling will be less prominent during the summer when Toronto's precipitation is largely controlled by convection and not the passage of frontal rain storms that are more commonly experienced in the other seasons of the year;
- the number of storms in this region has decreased recently but increased in intensity. This pattern is projected to continue and intensify into the future. This is projected to result in more severe weather occurrences including extreme rain and snowfall events, as well as damaging winds;
- loss of arctic sea-ice will amplify climate warming in the Arctic causing temperatures to increase at an accelerated rate over Toronto; and
- levels of CO_2 will continue to rise in the atmosphere which will significantly influence the distribution of heat and moisture which are the fuel for the weather engine.

These reasons are supported by our analysis of the results obtained as part of the current study and also by other recent studies.

Conclusions

The approach of adding a fine-scale weather model to the climate model output to obtain more locally relevant future prediction forecasts was completely new and innovative when this project was conceived. The approach taken has been very successful and the study has demonstrated the value of the approach. It is also an approach that has subsequently been adopted by the National Center for Atmospheric Research (NCAR) for the whole of the USA as well as by the Ontario Ministry of the Environment in partnership with the University of Toronto.

Climate change will continue into the future, because of the thermal inertia of the oceans and the residence times of GhGs, 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 through 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. However, current national and international emissions-reduction pledges appear to be insufficient to keep global warming below 2.0°C.

While the City could contribute to the global reduction in CO_2 emissions through aggressive emission controls, no matter how much the City does, the climate here is predicted to change as outlined in Table ES-3. This means that the City should start to plan for these changes. Some changes will be positive – a longer growing season and generally more pleasant weather and fewer resources required for winter snow clearance. Other changes will; be negative – fewer but more violent storms with greater extreme rainfall will mean more resources are required for infrastructure (sewers and culverts) upgrades.

In summary, the work undertaken for the City of Toronto, and the results reflected in Table ES-3, has indicated some anticipated changes in extreme weather for the City and the GTA. The comparisons largely speak for themselves.

Table ES-3 Summary of Projected Future Weather Compared to Today

Weather Type	Parameter	2000-2009	2040-2049
Extreme Precipitation	Maximum in One Day (in mm)	66	166
	Number of Days with more than 25 mm	19	9
	Mean Annual Daily Maximum in mm	48	86
	100 year Return Period Maximum Daily (in mm)*	81	204
	10 year Return Period Maximum Daily (in mm)	62	135
	10 year Return Period Maximum Hourly (in mm)	20	39
Extreme Rain	Maximum in One Day (in mm)	66	166
	Number of Days with more than 25 mm	16	9
Extreme Snowfall	Maximum in One Day (in cm)	24	18
	Number of Days with more than 5 cm	16	3
Extreme Heat	Maximum Daily (in °C)	33	44
	Number of Day with more than 30 °C	20	66
Extreme Cold	Minimum Daily (in °C)	-17	-11
	Number of Days with less than -10 °C	24.6	0.3
	Number of Days with minimum less than 0 °C (frost days)	128	70
Wind Chill	Extreme Daily	-24	-17
	Number of Days with less than -20 °C	12	0
Degree Days	Number of Degree Days Greater than 24 °C (air conditioning required)	10	180
	Number of Degree Days Greater than 0 °C	3452	4857
	Number of Degree Days Less than 0 °C (extra heating required)	440	66
Extreme Wind	Maximum Hourly Speed in km/hour	92	48
	Maximum Gust Speed in km/hour	130	75
	Number of Days with Wind Speed Greater than 52 km/hour	0.9	0.0
	Number of Days with Wind Speed Greater than 63 km/hour	0.3	0.0
Humidex	Maximum (in °C)	48	57
	Number of Days greater than 40 °C	9	39
Storms	Average Number of Storms per Year	30	23
	Average Number of Summer Storms in One Year	17	17
	Average Number of Winter Storms in One Year	14	6
	Average SRH (vortices potential) in One Year	1281	691
	Average CAPE (convective energy potential) in One Year	3841	4097
	Average EHI (combination if SRH and CAPE) in One Year	3.6	4.3

* underestimate due to length of record

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1.0 WHAT ARE WE TRYING TO DO AND WHY ARE WE TRYING TO DO IT?

1.1 INTRODUCTION

The City of Toronto needs good information about present local weather and climate, the factors that influence them, and future local weather and climate so that the City can be prepared to address and 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 leading to sewer discharges, roadway and river flooding and strong local pressure gradients and wind events that might occur within Toronto's urban area.

A series of questions form the focus for this project as follows:

1. What is Toronto's current weather and climate? And why?
2. How are Toronto's current weather and climate drivers expected to change? And why?
3. What will be Toronto's future weather and climate? And why?
4. What tools, data and information can be used to adequately determine future climate and weather in Toronto? And why?
5. What magnitudes, frequency and probability of occurrence do present extreme weather events and significant weather events have in Toronto? And why?
6. What magnitudes, frequency and probability of occurrence do future extreme weather events and significant weather events have in Toronto? And why? and
7. Which technology, or technologies, among (1) the one used for the study, (2) using a General Circulation Model (GCM), (3) using a Regional Climate Model (RCM) together with (4) downscaling and (5) other related techniques, holds the best promise of best understanding the future weather and climate of Toronto and the surrounding areas? And why?

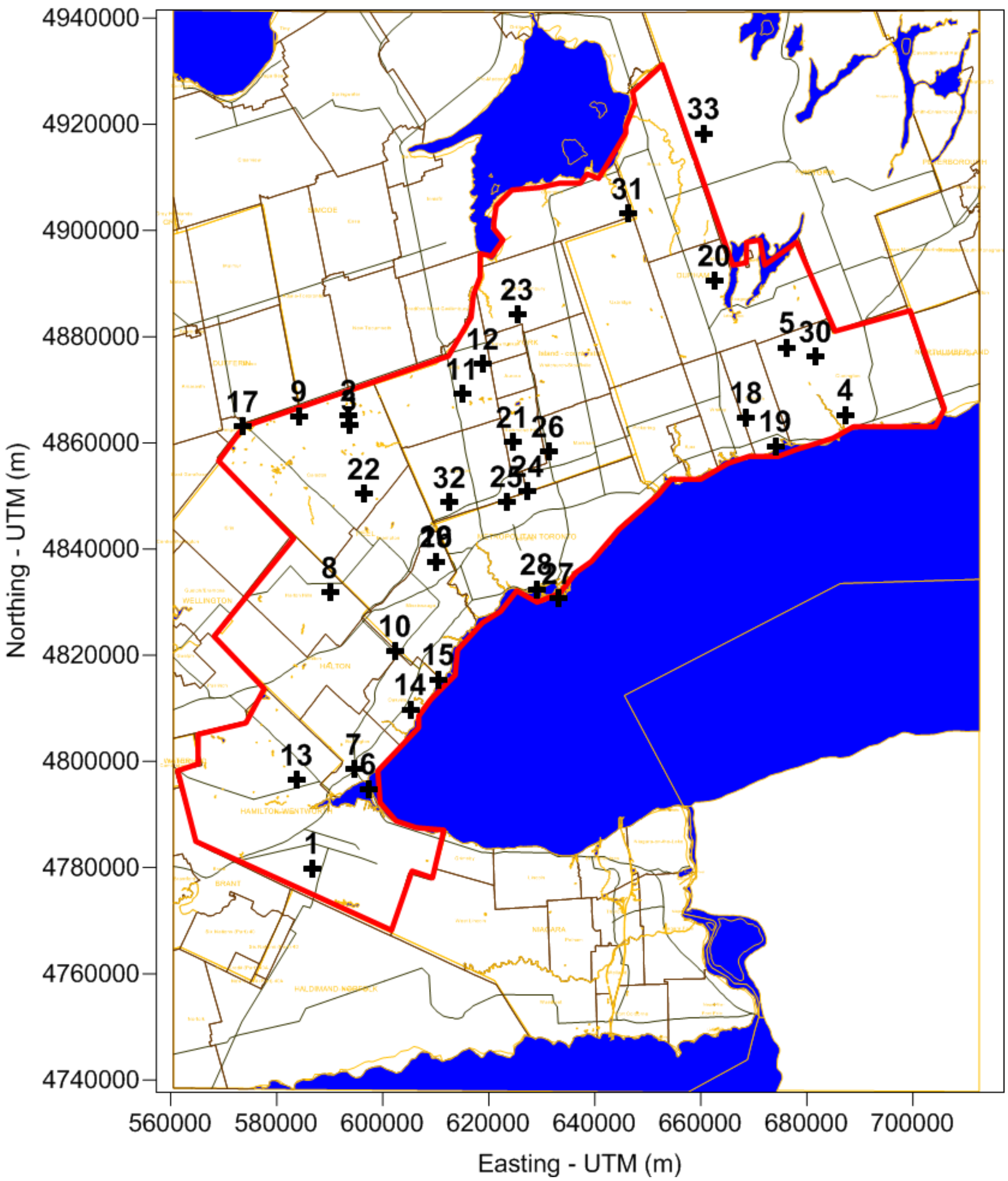
The main deliverable from this project is an understanding of what the City of Toronto currently experiences and, more importantly, why the City experiences what it does now, and why and what the City of Toronto will experience in the future. This study is to develop the data, information and simple and applicable tools to assess weather and climate that the City of Toronto must address and adapt to in the near future.

1.2 WHICH CLIMATE STATIONS ARE USED?

The study area is shown in Figure 1 (outlined in red). It also shows the Climate Stations (numbers) that were available from Environment Canada for use in the analysis. Table 1 gives the names and locations of the Climate Stations that were available for use for the current climate analyses.

Each station in Table 1 measures different parameters and has a different length of record. Analyzing the trends from these stations showed quite different changes over the various periods of record.

Figure 1 Study Area Climate Stations Used



As a result, SENES decided to use Pearson Airport as a reference station for this analysis because it had a long period of record and a high level of data quality. While the trend data for each of the listed stations is available as part of the project record, it will not be presented in this report. SENES decided for consistency and quality purposes to compare model outputs at locations across Toronto and the GTA that were of interest to the client.

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 INT'	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

1.3 DETAILED OUTPUT POINTS

In this document (Volume 1) only the Toronto Pearson International Airport (Pearson Airport) is used to illustrate the results, 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 City of Toronto for the presentation of detailed results. Figure 3 represents points selected by the City throughout the GTA.

Figure 2 Locations Selected for Results Presentation within the City of Toronto

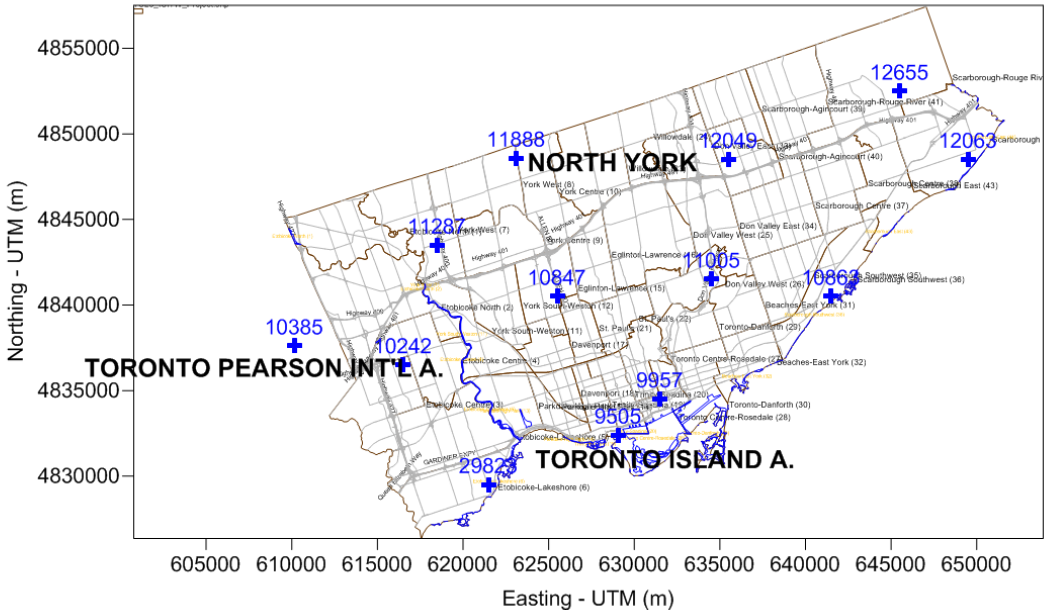


Table 2 lists all of the 36 locations selected along with the Volume 2 table location numbers where detailed results can be found. The table also gives the model output grid location used.

Figure 3 Locations Selected for Results Presentation across the GTA

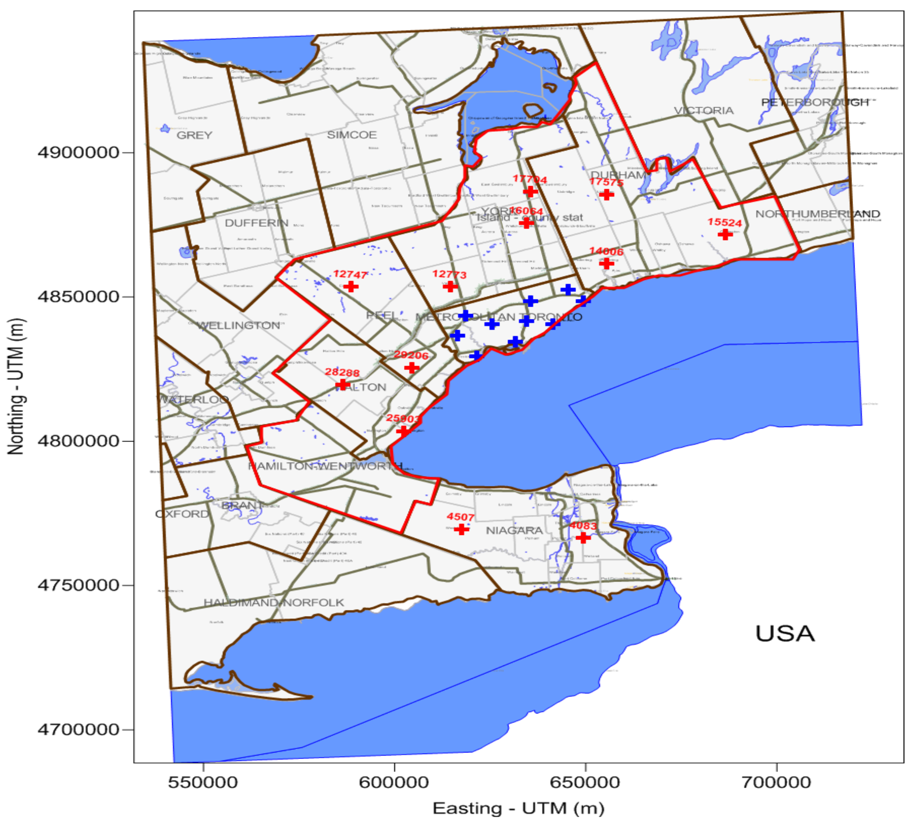


Table 2 List of Grid Points and Tables of Results for Volume 2

Table	Name	Grid Point
1	Toronto Pearson	10385
2	Hamilton	5989
3	Toronto North York	11888
4	Toronto Island	9505
5	Hwy 427-401	10242
6	Beaches-East York	10863
7	York South-Weston	10847
8	DVP-Don Mills Road	11005
9	Etobicoke North	11287
10	Scarborough	12063
11	Don Valley East	12049
12	Scarborough - Rouge River	12655
13	Mississauga	29823
14	Trinity Spadina	9957
15	Pelham -Thorold	4083
16	West Lincoln	4507
17	Caledon	12747
18	Vaughan	12773
19	Pickering	14006
20	Clarington	15524
21	Whitchurch Stouffville	16064
22	Uxbridge	17575
23	East Gwillimbury	17704
24	Burlington	25903
25	Milton	28288
26	Mississauga-Milton	29206
27	Richmond Hill	13677
28	Oshawa	14317
29	Udora	20096
30	Niagara Falls	5608
31	King Smoke Tree	15752
32	Orangeville MOE	14073
33	Georgetown WWTP	29942
34	Oakville Southeast WPCP	27562
35	Burlington Piers	8114
36	Millgrove	8402

1.4 WHY ARE WE DOING IT?

The City of Toronto'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 city of Toronto experiences moderated and less extreme temperatures in both winter and summer. Relative to areas further inland and to what Toronto's temperatures would be like in the absence of Lake Ontario and other nearby Great Lakes, temperatures are cooler during the spring and summer and warmer during the fall and winter. 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 the City's climate.

This purpose of this document is to discuss the factors which influence the weather and climate of the City of Toronto. 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 Toronto. 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 Toronto in the future.

SENES Consultants Limited has predicted, to the degree possible, the likely changes in future weather system patterns that will be experienced in and around Toronto and has 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 City 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. This will help problem avoidance planning undertaken by groups such as Toronto Water and Toronto Transportation. A secondary focus was to look at regional events like heat waves and cold snaps that are ameliorated by the Great Lakes. This information is to be used to corroborate with analyses previously derived by Toronto Public Health.

1.5 HOW DID WE ANSWER THE QUESTIONS?

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 summary for the Greater Toronto Area and addresses and provides insight into Question 1 (What is Toronto's current weather and climate and why?). 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 answer Question 5 (What magnitudes, frequency and probability of occurrence do present extreme weather events and significant weather events have in Toronto and why?).

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. 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 Toronto which was used to answer Question 3 (What will be Toronto's future weather and climate and why?) and Question 6 (What magnitudes, frequency and probability of occurrence do future extreme events and significant weather events have in Toronto and why?) posed in the study.

The third step was to compare the outputs from the present and the future climate simulation in order to provide insight into Question 2 (How are Toronto's current weather and climate drivers expected to change and why?) posed in this study.

The SENES Team, based on their knowledge and current literature, determined the answers to Question 4 (What tools, data and information can be used to adequately determine future climate and weather in Toronto and why?) and Question 7 (Which technology, or technologies, among (1) the one used in this study, (2) using a Global Climate Model (GCM), (3) using an Regional Climate Model (RCM) together with (4) downscaling and (5) other related techniques, holds the best promise of understanding the future weather and climate of Toronto and surrounding areas and why?) of the study.

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 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 the context of the present study, a major portion of the work is to identify the role of "climate drivers" in producing the weather and climate we get now, and to further identify how these same "climate drivers" are expected to change or be modified with the advent of a changing climate, and then subsequently to also identify how the modified climate drivers produce the weather we will get.

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 weather and climate, the logical argument, or story, tries to embrace the following questions:

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

This 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 still have 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.

3.0 WHY IS WEATHER IN TORONTO THE WAY IT IS?

The main factor driving the weather is the exchange of energy between the sun and the earth's atmosphere. This energy exchange generates a global atmospheric circulation pattern which in turn carries air masses and weather systems around the globe and across the land, bringing changes to the weather that we experience day-by-day.

3.1 THE SUN-EARTH ENERGY EXCHANGE

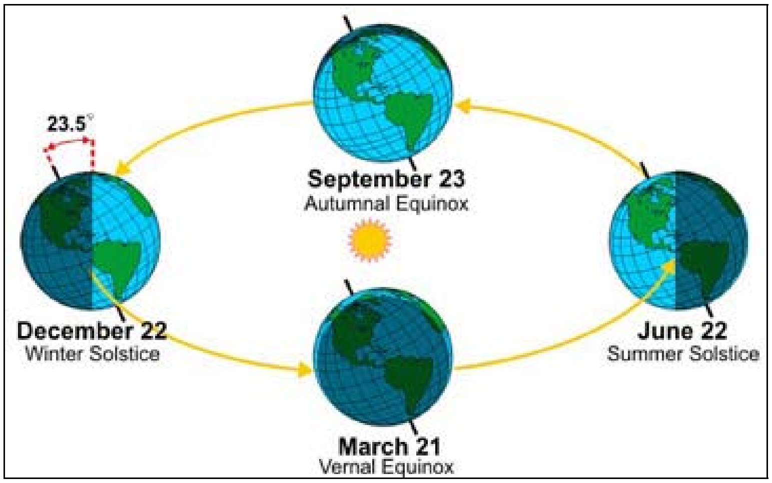
Different locations on earth receive different amounts of solar energy. This is simply a result of geographic location in conjunction with two technical, but fundamental things: 1) the rotation of the earth on its polar axis (which creates differences of day and night); and 2) the tilt of the polar axis relative to the path that the earth travels around the sun along its plane of rotation. This latter effect creates the seasons. Another factor which creates seasonal differences in different areas of the globe includes the elliptic nature of earth's orbit around the sun such that the sun is not at the focal point of the ellipse. As a result, the distance between the earth and sun is not constant causing Toronto to be closer to the sun in January and further away in July.

The tilt of the earth's axis relative to the path it travels around the sun is currently 23.5° (Figure 14). Without this tilt, the sun would be directly overhead the equator all year round meaning that each location on earth would experience the same amount of daylight and darkness each day of the year. Instead, the latitude at which the sun is directly overhead shifts between 23.5°N and 23.5°S (the Tropic of Cancer and the Tropic of Capricorn, respectively) giving rise to changes in the length of day over the course of a year and to the location on earth which receives solar energy from directly overhead during the day. This variation in the length of day and less important, the elliptical path travelled by the earth around the sun, is what causes the seasons.

Not only does the axial tilt affect the length of a day, but it also determines the amount of atmosphere through which the sun's rays must travel through to get to the surface. It also determines the amount surface area which will intercept incoming solar radiation. More of the atmosphere to travel through means less energy reaches the surface because it interacts with, and gets reflected, deflected or absorbed by particles/gaseous components of the atmosphere. Additionally, when the sun's rays are at an oblique angle relative to the earth's surface, solar energy is effectively spread over a larger surface area. Consequently, surface locations tilted away from the sun receive less solar energy because the sun's rays must travel through more of the atmosphere and are dispersed over a larger area once they reach the surface.

Toronto is geographically located north of the Tropic of Cancer and south of the North Polar Circle at latitude 43.75° north. Therefore, the maximum angle that the sun will ever be relative to the horizon in Toronto is 69.75° which occurs at the summer solstice and the minimum angle is 22.75° which occurs at the winter solstice (assuming that the axial tilt of the earth is 23.5°). As a result, the sun will never be directly overhead Toronto (i.e., 90° to the horizon) and Toronto will never experience 24 hours of complete daylight or darkness.

Figure 14 Earth's Orbit and Axial Tilt



Source: NOAA, 2009a

Note that the dates specified in Figure 14 are not constant. Over the next ten years the Winter Solstice will varyingly occur on either the 21st or 22nd of December, the Vernal Equinox on either the 20th or 21st of March, the Summer Solstice on either the 20th or 21st of June, and finally, the Autumnal Equinox will varyingly occur on either the 22nd or 23rd of September. For instance, in 2011 the specific dates of the solstices/equinoxes will be December 22nd, March 20th, June 21st and September 23rd.

There are two basic types of radiation – short wave and long wave. Radiation at temperatures that occur on the Earth's surface is long-wave radiation (this is radiation longer than 4 µm). Radiation reaching the Earth from the sun is short-wave radiation (this is radiation that is shorter than 4 µm). Since the atmosphere has temperatures in the same general range as the Earth's surface, the radiation from the clouds and air molecules is also long-wave radiation. But because the atmosphere is made up of gases, rather than being solid, the atmosphere does not radiate at all wavelengths but only at those at which it can absorb.

The atmosphere is much more transparent for short-wave radiation than for long-wave radiation, particularly in the visible range (0.38-0.77µm). For long-wave radiation, there is a band from 8-11 µm in which the atmosphere absorbs very little radiation. It is in this band, called the "atmospheric window" that heat escapes from the Earth at night. Radiation from the Earth and the cloud-tops in this band passes directly through the atmosphere and almost all goes out into space unimpeded. At other wavelengths, the radiation from the ground is absorbed at various levels in the atmosphere and in turn the atmosphere at these levels radiates this energy up and down. The biggest absorbers of long-wave radiation are water vapour and carbon dioxide. As CO_2 (and other greenhouse gases) increases, less long-wave radiation escapes.

The result of the atmosphere being transparent to incoming solar radiation and more absorptive to outgoing long-wave radiation from the Earth is that the Earth's surface is kept at a much higher temperature on average than it would be if there was no atmosphere. The energy radiated outward and absorbed by the atmosphere is partially radiated back to the Earth's surface, increasing the total energy received there. This raising of the Earth's surface temperature because of the back-radiation from the atmosphere is known as the natural greenhouse effect.

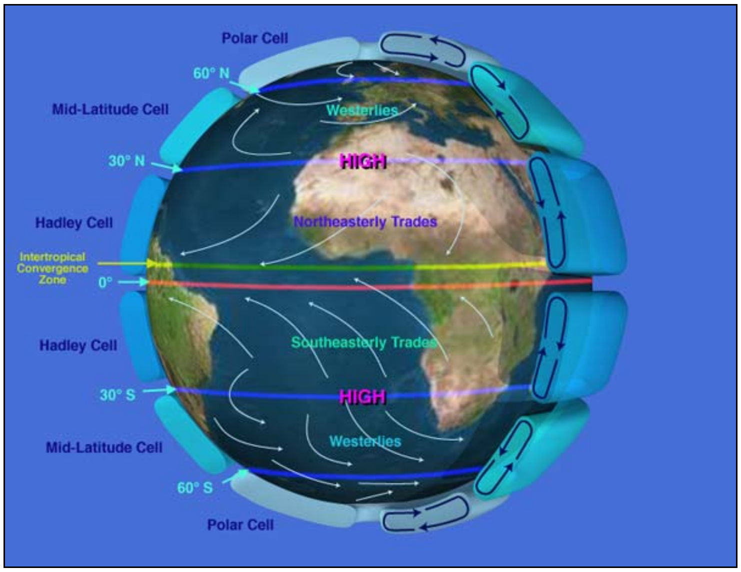
Over the long run, the processes of absorption and emission of radiation at the ground and in various layers of the atmosphere have produced a balance between the incoming and outgoing energy, keeping our world a warm enough place to live and providing the driving forces for atmospheric motion. The problem with climate change is the increase in man-made GhGs is altering this balance, leading to greater absorption of long-wave energy.

3.2 THE GENERAL ATMOSPHERIC CIRCULATION PATTERN

The latitudinal variation in solar energy means that there is an unequal distribution of heat across surface of the globe. Part of the atmosphere's heating comes from the earth's surface and because there are different types of surfaces the atmosphere is heated unevenly around the globe. Air with different temperatures has different densities. The hotter air becomes lighter and rises, the colder air heavier and sinks. Nature effectively compensates for this unequal distribution of heat (energy) by moving masses of water in ocean currents, and air within the atmosphere mixing it. The ocean and the atmospheric motion re-distributes the heat more evenly around the globe. This atmospheric motion is the foundation for the general circulation of the atmosphere.

As shown in Figure 15, warm, moist air in the tropics rises and moves poleward transferring energy to higher latitudes while creating a zone of low pressure in the tropics. Around 30°N, air descends, creating a zone of high pressure. The descending air spreads out in the lower atmosphere and some of it flows back to the equator creating a closed loop called the Hadley Cell. Around 60°N, a polar circulation cell is formed as air rises and flows poleward and descends over the high latitudes creating another area of high pressure. This closed loop is called the Polar Cell. A third cell, the Ferrell (or Mid-latitude) Cell, owes its existence to the other two cells (NASA, 2008). If the earth did not rotate, the large scale circulation cells would just move air in a north-south direction. However, the rotation of the earth causes winds to shift direction. This is known as the Coriolis Effect and it causes winds to shift slowly to the right in the northern hemisphere (clockwise) and shift slowly to the left in the southern hemisphere (counter clockwise). Three global wind zones result: the polar easterlies; the westerlies; and the easterly trade winds. Note that winds are named after the direction from which they blow.

Figure 15 Idealized Global Circulation Pattern



Source: NASA, 2008

Canada is predominantly under the influence of the westerlies. As a result, the prevailing winds in Toronto blow from a westerly direction throughout the year. The prevailing westerlies tend to carry Pacific air to the eastern portions of Canada and are the reason why one of the predominant influences on our climate is the Pacific Ocean. In general, strong upper level westerly air streams (i.e., the Polar jet stream) steer high and low pressure cells which form mostly above areas of cold contracting and sinking air and warm expanding and rising air, respectively, over Canada and the U.S. towards the east, bringing variation to Toronto's day-to-day weather.

3.3 GLOBAL WEATHER DRIVERS

Since the middle of the 20th century, the Earth's climate has been warming rapidly compared to previous centuries, with the rate of warming increasing more significantly over the last 25 years (IPCC, 2007b). Temperature records from thermometers are sufficiently reliable and cover enough of the globe to allow an estimation of global mean temperatures since about 1850. The period from 2000 to 2009 was 0.17 ºC warmer on average than the 1990s[3]. All years since 1998 fall within the top 15 warmest years on record. There is strong evidence that this warming is attributable to human activities, in particular to the emission of greenhouse gases. Further details of the land and marine temperature records are given by Brohan *et al*. (2006) and Rayner *et al*. (2006) respectively. These datasets are continually updated and collected by the World Meteorological Organization (WMO), along with agencies in individual member nations (like Environment Canada).

[3] Reference in this document to periods such as the 1990s and the 2000s always infers the periods 1990-1999 and 2000-2009, respectively.

The Earth is able to support life because naturally occurring levels of greenhouse gases allow the planet's average surface temperature to be approximately 15 ºC rather than the -23 ºC it would be in the absence of the greenhouse effect. Greenhouse gases such as methane (CH_4), carbon dioxide (CO_2), water vapour (H_2O) and nitrous oxide (N_2O) are chemical species which can absorb most of the outgoing long-wave radiation emitted by the surface of the earth inducing a warming of the atmosphere. Humans have, for many years, been modifying the chemical composition of the atmosphere through industrial activity, specifically burning fossil fuels, as well as through agricultural activities which have resulted in increased emissions of greenhouse gases to the atmosphere, and higher levels of those gases in the atmosphere. Such a modification has resulted in increased temperatures in the atmosphere which in turn has allowed more water to be in the form of vapour, a process which has further increased the amount of warming. Even if all the greenhouse gas emissions from human activities were to stop, the presently observed warming trend is highly likely to continue due to the thermal inertia of the climate system and the long lifetimes of some of the greenhouse gases in the atmosphere.

Aerosols are small particles in the atmosphere which have a variety of sources, both natural and anthropogenic. Their impact on the Earth's climate is more complex, because their concentrations vary considerably between different locations of the earth, and they have a range of effects of the Earth's climate. Aerosols which scatter incoming shortwave radiation act to reduce the amount of radiation reaching the Earth's surface. Some aerosols partly absorb incoming radiation, and their overall effect is more complex. Over dark surfaces, such as the oceans and forests, they lead to a cooling of the climate, whereas over bright surfaces, such as snow, ice and crops, they produce an overall warming. The scattering and absorption of radiation is known as the direct effect.

Aerosols can also modify the properties of clouds. They can act as cloud condensation nuclei which encourage water vapour to condense on their surfaces. A polluted cloud (one containing many aerosols) will generally consist of a large number of small water droplets, which makes the cloud highly reflective and have a long lifetime. Non-polluted clouds reflect less radiation and have larger droplets, which are more likely to form rain drops, and so the cloud has a shorter lifetime. Aerosols which absorb incoming solar radiation have another effect on clouds. They act to warm the surrounding atmosphere which changes the stability and humidity of the surrounding air, and may cause clouds to dissipate.

Other global processes are likely to have contributed to global warming. Deforestation, triggered by the need for new arable land to produce the food needed by an ever-growing population, has reduced the ability of the biosphere to store carbon. It is quite likely that the fraction of emitted carbon which remains in the atmosphere will increase in the future (Denman *et al*., 2007). This has the potential to exacerbate the effects that our emissions have on the climate system.

Another potentially important process which could influence future climate is linked to the melting of permafrost. Permafrost consists of soils containing deposits of methane and methane hydrates. If they melt, the methane could be released to the atmosphere. Methane, whose current concentration in the atmosphere is much lower than that of carbon dioxide, is a much more powerful greenhouse gas. A massive release of methane into the atmosphere would dramatically increase the greenhouse effect and trigger a further warming of the climate system (e.g. Thorpe *et al*., 1996; Shindell *et al*., 2005).

3.3.1 Air Masses and Semi-Permanent Pressure Patterns

Air masses are defined as large volumes of air that have mostly horizontally homogeneous properties (i.e., uniform temperature and moisture) in the lower atmosphere (after Phillips, 1990). Persistent levels of incoming solar radiation and moisture occurring over an extensive area having light winds will result in horizontal homogeneity. If air remains over such a location for an extended period of time, its properties will become characteristic of the surface below it. An air mass may have a surplus of energy and moisture (a Tropical air mass) or a deficit of energy and moisture (an Arctic air mass).

There are two types of air masses: travelling air masses and blocking air masses. Air masses that are formed in one geographic area may subsequently move to other areas and are known as travelling air masses. Travelling air masses bring their temperature and moisture characteristics with them and influence the weather of the new areas they encounter. Conversely, air masses with overly strong pressure characteristics may become almost stationary (blocking air masses) for long periods of time and can force other travelling air masses having weak pressure characteristics, to move around them.

Figure 16 and Figure 17 show the common winter and summer air masses which move within Canada (originating in the Arctic) or to Canada (originating from the oceans) and impact various areas of the country. In locations where surface temperatures are hot, the air above it is heated and subsequently rises, creating an air mass with low pressure characteristics. Conversely, where surface temperatures are cold, the air above it is chilled and sinks, creating a high pressure air mass. In locations where excessive heating or cooling occurs for long periods of time relative to adjacent areas, semi-permanent high and low air pressure systems may form.

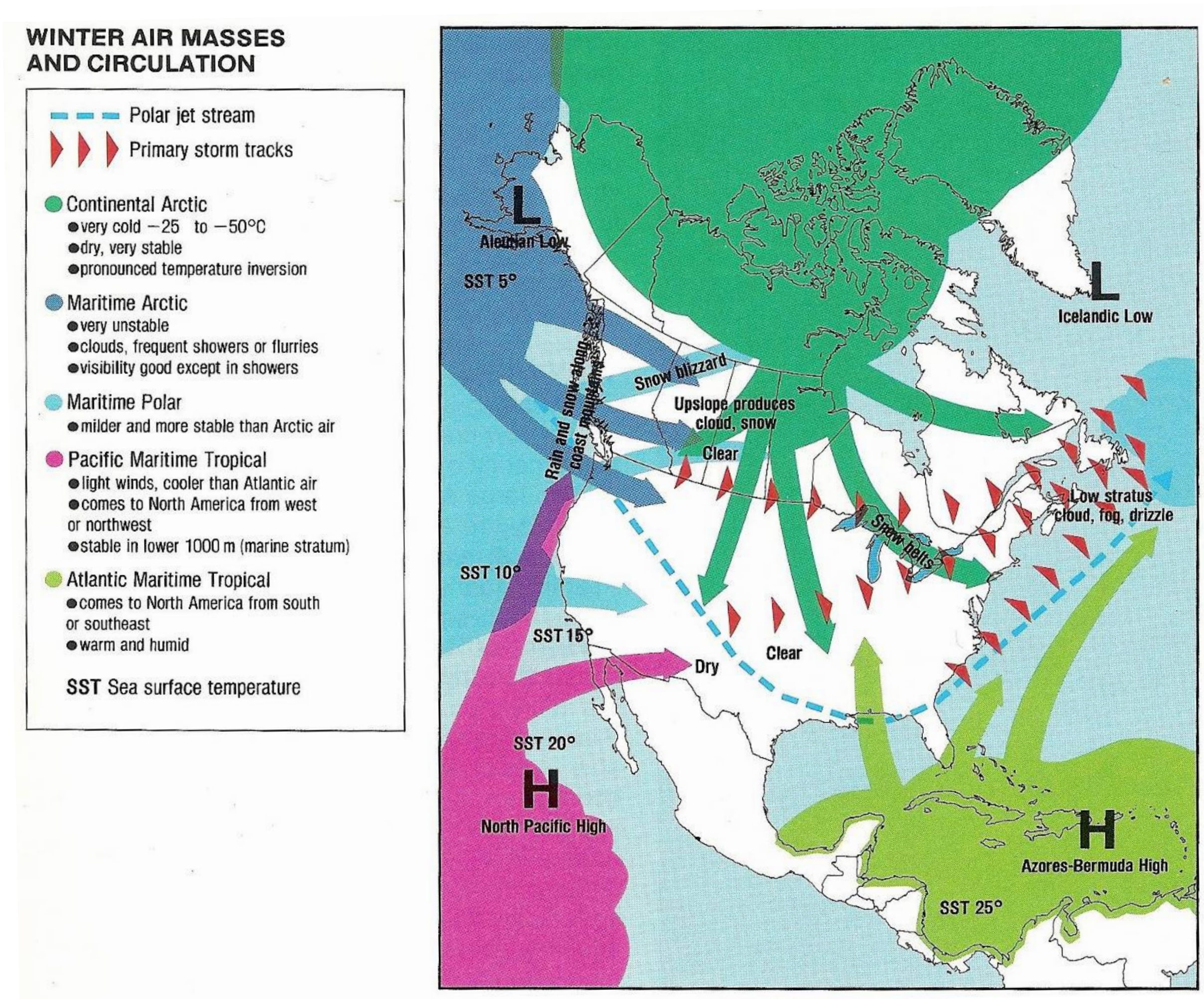
Semi-permanent high/low pressure systems become apparent when pressure patterns are averaged over several years for a given region. The winds derived from these regions of high and low pressure are what carry travelling air masses from their source regions into or across Canada. According to Hare and Thomas (1979), Phillips (1990) and Sanderson (2004), the most common semi-permanent highs and lows are:

- the Aleutian Low - situated in the Pacific near Alaska - it is strongest in winter and brings Maritime Arctic air to the western parts of Canada;
- the Icelandic Low - situated in the Atlantic near Greenland - it is strongest in winter and brings Continental Arctic air into the southern regions of Canada;

- the North Pacific High - situated in the Pacific off the U.S. west coast - it is strongest in winter and brings Maritime Tropical air in summer and winter to the west coast; and
- the Bermuda High - situated in the Caribbean - it is strongest in summer and brings Atlantic Maritime Tropical air to the eastern parts of Canada.

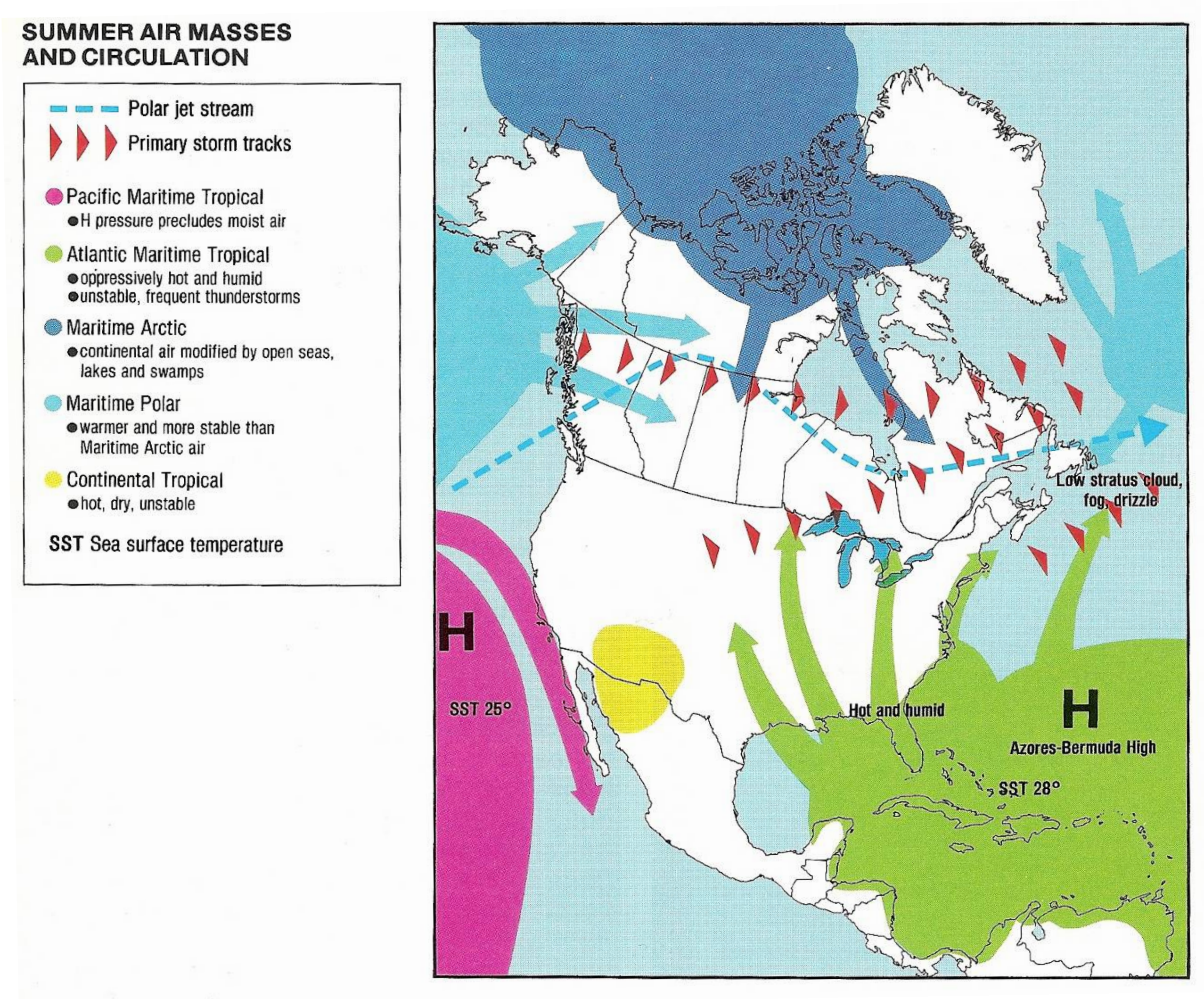
Source regions of air masses at low (equatorial) and high (polar) latitudes experience weather that is almost always the same since these regions experience less variation in incoming solar radiation. In middle latitudes, however, the weather is continually changing as one air mass after another passes overhead. Polar and arctic air masses move predominantly toward the equator and eastward; tropical and equatorial air masses move predominantly poleward and eastward (after Neiburger *et al.*; 1982).

Figure 16 Winter Air Masses and Circulations



Source: Phillips, 1990

Figure 17 Summer Air Masses and Circulations

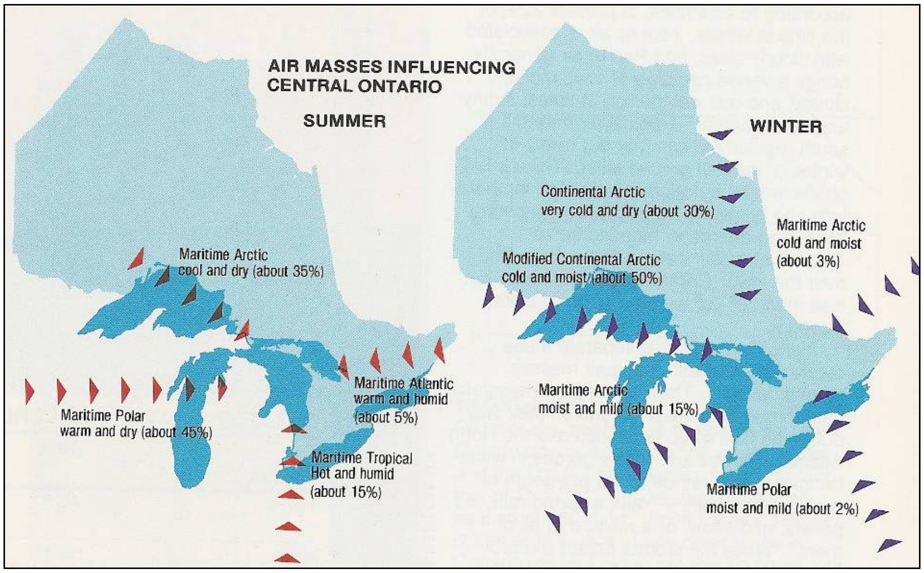


Source: Phillips, 1990

As stated by Phillips and McCulloch (1972), Phillips (1990) and Sanderson (2004), and shown in Figure 17 and Figure 18, Toronto summers are dominated by Maritime Polar (i.e., Pacific) and Maritime Arctic air masses from the west that bring warm (sometimes cool), dry air. Occurrences of Maritime Tropical air from the Gulf of Mexico can also arise which bring hot and humid days to Toronto in the summer.

Figure 16 and Figure 18 shows that in the winter, cold, dry Continental or Modified Continental Arctic air dominates Toronto. Less frequently Toronto receives mild air from the south-southwest during the winter months.

Figure 18 Winter and Summer Air Masses Influencing Ontario



Source: Phillips, 1990

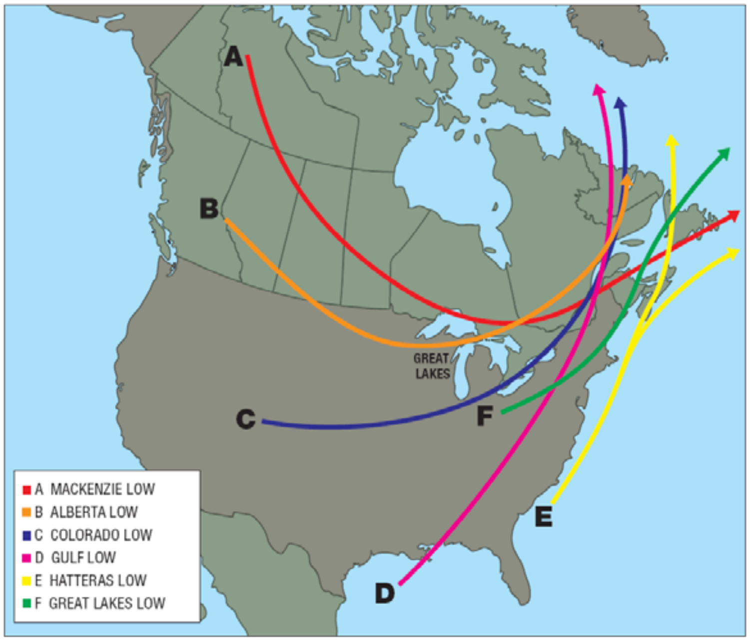
3.3.2 High and Low Pressure Systems

At the boundary between large air masses (known as fronts), the atmosphere becomes unstable and warmer air rises above colder air, and accordingly, smaller low pressure systems may form that are commonly referred to as "Lows". Lows bring unstable weather such as clouds, precipitation, and strong winds. In winter, the contrast between air masses is more pronounced and causes more frequent and more intense or deeper lows to develop. Travelling high pressure systems (commonly referred to as "Highs") bring clear, dry, and often cool weather. The alternating pattern between high and low pressure systems is responsible for the day-to-day weather in Toronto, and is also the reason for relatively consistent precipitation received month-to-month in this region (Boughner and Thomas, 1960; Shenfeld and Slater, 1960; Auld *et al.* 1990).

There are particular locations in North America which favour the development of lows. This is a result of persistent fronts (e.g., the boundary between cold Arctic air and milder Pacific air is called the Polar Front) in addition to large scale topographical features such as the Rockies, and large bodies of water. The regions of North America which favour the development of winter lows as well as their typical storm tracks are shown in Figure 19.

In North America, low pressure systems, and their associated stormy weather along their warm and cold fronts, typically move along tracks associated with strong areas of upper westerly air flow, known most commonly as a jet stream. Jet streams occur in the upper atmosphere at the boundary between two air masses having considerable contrasting characteristics. For example, the Polar Front (known as the Polar Jet), which occurs between 30°N and 40°N, strongly influences weather patterns in Canada, Ontario, and locally in Toronto. We typically observe a much stronger Polar Jet in winter when the contrast between two air masses (Polar Arctic Air and Maritime Air) is greatest.

Figure 19 Common Winter Lows and Typical Storm Tracks of Canada and the U.S.



Source: Klok *et al.,* 2002

The polar front jet stream has been likened to a meandering river winding its way from west to east around the globe's northern latitudes (between 30° and 60° north), but unlike a meandering river, it is also constantly shifting completely from further north to further south as the polar front moves with the seasons and its lobes (i.e., its meanders or turns) correspondingly change in number, shape and position (Neiburger *et al.*, 1982). A typical North American winter polar jet stream pattern, when observed on a weather map, involves a slight northeast turn east of the Rockies, then a dip southeast into the United States and finally, it turns northeast towards the Atlantic coast (Figure 20) (Hare and Thomas, 1979). This pattern is responsible for the paths taken by many winter storms and as shown in Figure 19, it can steer common winter storms such as the Gulf Low (also known as the Texas Low), the Colorado Low and the Alberta Low (also known as an Alberta Clipper) towards Southern Ontario and thus, Toronto. On the other hand, the polar jet stream also usually steers the Hatteras Low along the eastern seaboard, keeping it away from inland locations.

Figure 20 Typical Summer and Winter Jet Streams

Source: University of Maryland, Department of Atmospheric and Oceanic Science (2003)

3.4 REGIONAL WEATHER DRIVERS

As we will see later the greatest warming is projected to occur in northern Canada and Alaska, possibly reaching +10°C in the highest latitudes owing to the positive feedback from reduced snow and ice cover. Snow and ice reflect most of the incoming solar radiation back out to space. This is the reason they appear so brightly white to our eyes. When snow and ice melt, and are replaced by land or sea, a much darker surface is exposed which can absorb a large fraction of the solar radiation, leading to an increase in temperature. A warmed surface induces a warming in the lower atmosphere above which in turn promotes further melting of the snow cover giving rise to one of the most widely known positive feedbacks of the climate system. A related (and very important) phenomenon is the transport of heat from the equator to the poles which occurs through the movements of air masses which exchange heat with the surfaces below them (Barry *et al*., 2002). This transport is partly controlled by the strong temperature gradient between the poles and equator. If this temperature gradient, between the poles and the equator, changes, the rate of heat transport may also change (Caballero and Langen, 2005).

3.4.1 Topography

Topography can have a local or regional impact on climate, or an impact of a much larger scale. On a large scale, extensive mountain chains such as the Rockies can block incoming weather systems from the rest of Canada (Hare and Thomas, 1979). However, since the rest of Canada is a large, open land mass, it permits the rapid movement of weather systems through much of the country including Toronto (Boughner and Thomas, 1960; Shenfeld and Slater, 1960). As noted previously, this allows Toronto to experience variable day-to-day weather and fairly uniform precipitation through the year.

Topography also influences localized precipitation patterns. Air encountering elevated lands is forced to rise and cool, causing clouds to form and precipitation to occur. This is called orographic precipitation. When air descends along the other side of the elevated region, it is dry and warm and in Western Canada is it commonly referred to as a Chinook Wind. Additionally, in the lee side of elevated lands (such as the Niagara Escarpment, the Oak Ridges Moraine and even Toronto's downtown buildings) there is often a noticeable "rain shadow" effect (an area of reduced rainfall).

3.4.2 Regional Geography

3.4.2.1 The Great Lakes

Toronto is located within the Great Lakes Lowlands and lies along the north-western shore of Lake Ontario. This has very important implications for Toronto's climate.

Water has a large heat capacity which has two consequences: 1) it requires a large amount of energy to raise the temperature of water and 2) it takes a large period of time for water to release any acquired heat. As a result, Toronto and other areas in close proximity to the Great Lakes tend to be milder in the fall and winter because the Lakes are warm relative to the air, and the same areas are cooler throughout spring and early summer because the Lakes are cool relative to the air. In other words, the Lakes moderate the occurrence of local temperature extremes in both summer and winter. Theoretically, Toronto should have an extreme continental climate by virtue of its distance from the Pacific Ocean – especially since weather comes to Toronto largely from the west, but also by virtue of its distance from the moderating influences of the Atlantic Ocean as well. In essence, the presence of the Great Lakes reduces the severity of Toronto's winters as well as the intensity of its summers.

Lake Ontario, being quite deep, requires a larger amount of solar energy and, therefore, time to raise the temperature of even its surface waters, than the amount of energy and time required to raise the temperature of the adjacent land areas. This delay can result in temperature differences of 6 to 12 degrees between the lake and the city in the summer (Auld *et al.*, 1990). In the winter, the lake is mostly ice-free which also allows the water to have a moderating effect on the City's temperature over the entire winter season (Phillips, 1990).

The moderating effect of Lake Ontario on the climate of Toronto and its environs is as important with regards to the growing season in rural areas surrounding Toronto as it is for vegetation growing within the city. In the spring, lake temperatures keep the surrounding areas cool, preventing vegetation from growing too soon and risking exposure to frost (Phillips and McCulloch, 1972; Sanderson, 2004). In the fall, warm lake temperatures also prevent as many damaging frosts from forming as would otherwise happen. In general, the number of frost-free days within the vicinity of the Great Lakes is much greater than at locations further inland.

In addition to temperature, lakes also affect local winds, precipitation, cloud cover and fog. As well as being influenced by prevailing winds, areas adjacent to lakes are influenced by lake-breezes. Mostly occurring in summer, lake-breezes are a result of large land-lake temperature differences. Often bringing relief on a hot day, cool air from above the lake rushes under and replaces the warm air that is rising above the land. At night, the pattern can reverse, creating a land-breeze in which cool air over the land flows out over the warmer water of the lake where it rises. A lake-breeze can only really occur, and be felt, if prevailing winds are light. Strong winds will dominate and overcome the lake-breeze effect.

During the winter, lake-effect snow (snow that is created, in part, by the presence of a large body of open water, such as Lake Ontario, in the path of a prevailing wind) can develop under conditions of strong, persistent winds and a large difference between the lake's temperature and that of an approaching air mass. For lake-effect snow to be created, a large distance of open water over which the air travels is required. Due to Toronto's location in proximity to Lake Ontario, and the prevailing wind direction (NW) in winter, these requirements are not typically met for Toronto. Instead, lake-effect snow development is falls to the east of Lake Huron and to the south and east of Lake Erie and Lake Ontario. Sometimes, bands of lake-effect snowfall (from Lake Huron and Georgian Bay) may reach Toronto, but they usually only reach as far as London or Barrie, Ontario.

Depending on the storm track, the Great Lakes may intensify approaching storm systems by adding heat and moisture to the storm system. However, during spring and early summer, it is thought that lakes actually suppress thunderstorms; if the lake surface is cool enough, moisture is returned to the lake through condensation, suppressing convection and thus thunderstorms (Brown *et al.*, 1968, Phillips, 1990).

Finally, areas in the vicinity of lakes often experience more days with cloud cover as the lakes provide a source of moisture and heat (in the cooler winter months) which can cause air to rise and the moisture in it to condense. Lakes also encourage fog formation under certain circumstances. These conditions arise if cooler and less turbulent air passes slowly over warm lake water, causing moisture above the surface to condense (creating steam fog) or if warm, moist air passes slowly over cool surface waters (creating advection fog) (Klok *et al.*, 2002). Advection fog is typical in spring and early summer.

3.5 LOCAL WEATHER DRIVERS

Air masses and weather systems which influence climate are driven by the global atmospheric circulation pattern. As they move, they are further influenced by the surfaces below them. Consequently, topographic features like mountains, bodies of water, and land use all help to shape a region's climate.

3.5.1 Local Geography

3.5.1.1 Niagara Escarpment

A topographic feature in Southern Ontario that influences climate in the vicinity of Toronto is the Niagara Escarpment. To the east-southeast of Lake Huron and Georgian Bay the escarpment is roughly oriented in a northwest-southeast direction (including the Niagara Region portion) and as a result of its location, prevailing westerly winds are often forced to rise up and over the escarpment. Consequently, areas in close proximity to, and to the west of, the escarpment experience greater amounts of rainfall and a rain shadow is created to the east of it including areas near Toronto (Canadian Encyclopedia, 2009). Figure 21 shows the July mean total precipitation in Southern Ontario which shows that Toronto receives less precipitation than areas in the vicinity of the escarpment where elevations are among the highest in Southern Ontario.

3.5.1.2 River Valleys

Not only does local topography impact precipitation patterns, but it also influences local winds and temperature. In the City of Toronto, the land gently slopes towards Lake Ontario and is traversed by many valleys (e.g., the Don and Humber River valleys) which are orientated generally in a north-south direction (Shenfeld and Slater, 1960; Brown *et al.*, 1968; Auld *et al.*, 1990). Because it is denser, cold air will often drain into these valleys at night which leads to more fog and frost in these areas. Valleys also tend to channel winds making them stronger and gustier than in other parts of the city.

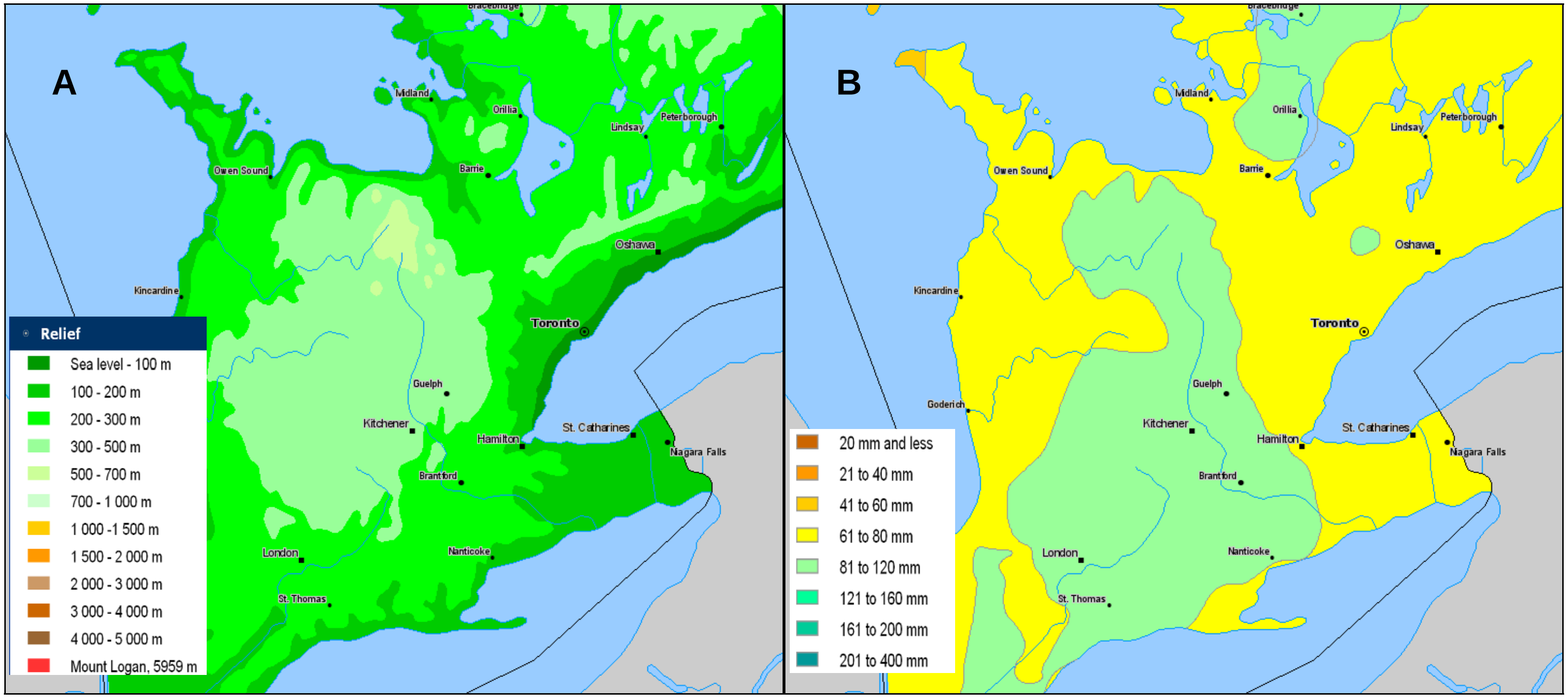
3.5.1.3 Scarborough Bluffs

East of the downtown core, cliffs known as the Scarborough Bluffs also rise to 70 metres above the Lake (Auld *et al.*, 1990). Areas of higher elevation experience colder temperatures during the day, but any south-facing slopes will be warmer than north-facing slopes because they are exposed to more sunlight. Elevated lands can also locally block winds from other areas.

3.5.1.4 Urban Land Use

Green areas in cities (parks, gardens, sports fields, etc.) generally have cooler night-time temperatures (and locally a small urban heat island) than the surrounding urban areas. Water is able to evaporate from the soils in green areas which has a cooling effect. Generally, cities with tall buildings and narrow streets will have a larger heat island effect than cities with lower buildings and broader streets, because more of the heat energy radiated during the night will be reabsorbed by surrounding buildings. The tall bank tower area of downtown Toronto is also an effective topographic, albeit artificial, feature that creates a microclimate, especially in regards to channelling winds and creating its own north and south facing vertical slopes which affect local weather.

Figure 21 Relief Map and Mean July Total Precipitation in Southern Ontario



A: Relief map of Southern Ontario. Note the lighter coloured regions of higher elevation to the west of Toronto.

B: Mean Total Precipitation in July in Southern Ontario. Note that the regions with more precipitation occur near the central regions of Southern Ontario which also have the highest elevations as outlined in Figure A. Toronto lies within the partial rain shadow to the east.

Source: Natural Resources Canada, Atlas of Canada (http://atlas.nrcan.gc.ca/site/english/maps/environment/climate/precipitation/precip)

3.5.2 Toronto's Urban Climate

It is well known that changes in land use can significantly alter the climate of a surrounding area. By removing vegetation and replacing it with man-made structures and surfaces, it changes heat, moisture and momentum exchanges (or fluxes) and thus affects temperature, cloud cover, precipitation and even wind speed. The City of Toronto is no exception; areas of tall buildings as in the high density downtown core have largely asphalt and concrete surfaces and little vegetation and make its climate much different from even lower density surrounding urban areas with more vegetation; equally, even such non-downtown urban areas have more brick, concrete and asphalt than surrounding rural areas. The significance of these differences is discussed below.

An Urban Heat Island (UHI) is the name given to an island of warmer air temperatures caused by the extra heat supplied to the air from the urban surface below it, within a generally cooler geographically broad mass of air. Any large metropolitan area, such as Toronto, will exhibit one, or more, urban heat islands (depending on the size and structure of the surface) with higher temperatures than the rural areas surrounding it. It is caused by dense materials (concrete, brick buildings, road surfaces, etc.) preferentially absorbing heat because of their dark colour and then releasing it and heating the air above; as well as being due to heat loss from buildings and vehicles in a city. As a result, significant differences in temperature occur between Toronto and its surroundings, and this is noticeable both overnight and during the winter months.

Changes in land use as well as daily anthropogenic activities are the main causes of higher urban temperatures. Specifically, the asphalt and concrete-like surfaces of the many roadways and buildings in a city are good absorbers of solar energy. At night, these surfaces release the heat they absorbed during the day thereby reducing and/or slowing the drop in night-time temperature. An additional cause of the UHI is waste heat from energy sources including vehicles as well as residential and commercial heating/cooling units. Due to the insulating effect of clouds, differences between urban and rural temperatures are greatest when skies are clear.

Compared to rural areas surrounding the city, the average **day-time** temperature is approximately 1 degree warmer in Toronto from November to February (Sanderson, 2004). During other months of the year, the average day-time temperature is not that significantly different. However, the average **night-time** temperature is on about 3 degrees warmer in the City of Toronto than in surrounding rural areas for all months of the year (Sanderson, 2004). Although people anecdotally report sensing that UHI also impacts daily temperatures, as in the summer months, implying that the downtown urban core temperatures can be much warmer than the suburban and rural counterparts, this is not always borne out in Toronto and the surrounding rural areas in the available data records (Maloney, 2010). The effect of the UHI can also be quantified by examining the number of frost free-days. In the City, the average number of frost-free days is 191, whereas Pearson Airport has only 149 frost-free days (a difference of 6 weeks) (Sanderson, 2004).

To gain an understanding of the extent of the UHI in the City of Toronto, an experiment was conducted by Koren (1998) in which a temperature sensor was attached to an automobile and driven north overnight along Yonge Street beginning at the lakeshore. He found that temperatures were significantly different from the Pearson Airport reported temperature until he reached Finch Avenue indicating that the UHI effect was present for about 18 kilometres north of the lake.

Urban areas also affect other climate parameters such as solar insolation[4], wind, cloud cover and precipitation. Clusters of tall buildings, like trees in the woods of rural areas, are known to cause shadowing effects creating pockets of cooler temperatures within the city. As well, building configurations significantly alter wind speeds and flow patterns in urban areas. As winds encounter an urban canopy, they are forced to flow up and over tall buildings resulting in a slower, more turbulent flow. However, when winds blow in between tall buildings, a tunnelling effect may result, increasing wind speeds in certain areas of a city. Urban effects on precipitation are less well understood, however, it has been postulated that increased levels of pollution in urban areas create more nuclei for cloud formation which leads to increased levels of precipitation downwind of such urban areas (Oke, 1988).

3.5.3 Toronto Weather Drivers

The significant passage of successions of "lows" (and all their attributes) over Toronto is "driven" by the meeting of tropical air from the south with polar air from the north. The temperature differences of, and between, these air masses create air masses of differing densities and pressures in close proximity to each other. Pressure gradients result; the gradients drive the winds (like water flowing over sloping land) that carry the air masses forward and create the fronts and the sequence of weather associated with their presence.

The location of the invisible line that separates tropical from polar air (of such great importance to Toronto) is itself a dynamic moving wave line, or vertical curtain, extending through the lowest layer of the atmosphere (the troposphere) from the ground to the air aloft at its upper limit the tropopause (or the boundary between the troposphere and the stratosphere above it). The distinction between them is based on temperature. Temperatures decrease with height in the troposphere and increases with height in the stratosphere. The tropopause is found at varying heights – on average at 16 km above the equator and 8 km above the poles, but these heights also change seasonally. The height of the tropopause above Toronto is typically between 10 km and 12 km.

[4] Solar insolation is a measure of the amount of **in**coming **sol**ar radi**ation** or, more colloquially, shortwave radiation from the sun.

Where the tropical and polar air meet, intense (i.e. steep) pressure gradients are created. These are strongest near the tropopause and give rise to the polar jet stream. The jet stream is a narrow band of very strong winds at height (typically at between 8 and 12 km altitude along the polar front). The polar jet of the northern hemisphere follows (at height) the varying location of the polar front that moves in a wave like manner around the earth. The number of waves within one complete encirclement of the globe can vary from very pronounced amplitude waves, or lobes, to very weak amplitude waves, and can vary in number from as few as two to as many as six – but more typically between three and four "lobes" are present at any given time. The boundary between tropical and polar air and the jet stream between them tends "to be anchored" by the presence of the Rocky Mountains – where the jet stream typically "bends" northwards to cross over them. As such, the jet stream most typically flows south eastwards across western Canada before curving back northwards to complete the lobe form. The location of the polar jet stream across Canada (and indeed cold and warm fronts as well) can be seen in the Globe and Mail and in the Toronto Star on a daily basis.

Although the pattern of the jet stream's meandering motions is variable it does have an average latitudinal location – and if that average location were to change north or south, or the nature and frequency of the amplitudes of the lobes were to change, it would logically bring a change of climate and weather for Toronto with it.

Toronto currently lies within the belt of circumpolar westerly winds (the "westerlies") that dominate the climate of mid-latitude and sub-polar latitude regions. The belt extends from the south west of the USA to the Canadian Arctic. Disturbances flow with that air stream and other air mass streams are also pulled into the main stream. Though the specifics of its make up change, the general flow is fairly constant.

The depiction of tropical air meeting polar air is a simplification and convention that does not fully express the complexity or the nature of the situation in Canada or the Toronto region. True tropical air only enters Canada's air space infrequently (usually only in summer) because it is most often modified before it reaches southern Ontario. Much more frequent are subtropical air currents derived from the south eastern United States.

The climate and weather at the surface depends very heavily on the motions of the westerlies and the jet stream, and the disturbances and air streams that are carried along with them.

The consequences in Toronto of the variation in the directions of the general westerly air flow, in the strengths and turbulence of the associated winds, in the temperatures and humidity, and its precipitation, and the ongoing exchange of heat (as sensible and latent heat, and as radiative and convective exchanges) between the air and the land (or lake) surfaces beneath as part of the general circulation - are all very apparent on a day-to-day basis. Further direct influences include El Niño and La Niña, as well as less direct influences such as the North Atlantic

Oscillation, and the Atlantic Multi-Decadal Oscillation (MDO). These are discussed in more detail later.

Local interactions also influence the air everywhere it travels. In the Toronto areas, the Great Lakes and the seasonal vegetation changes, urban land use, urban heat island conditions and impacts, and the topography of the Oak Ridges Moraine and Niagara Escarpment, as well as Toronto's urban canyons all influence the direction and speed of air flow and its basic characteristics of temperatures and water content.

Weather events in Toronto are clearly functions of the general climate and general circulation and the weather system pattern that are created within them, but the weather events in Toronto are also functions of local phenomena and the local interactions between the global and the local phenomena.

The juxtaposition of the general wind direction from west to east and the orientation of the lower Great Lakes (Lakes Erie and Ontario) clearly results in many "snow storms" producing heavy snow in Buffalo but which produce only light snow, or even no snow, in Toronto. Obviously the lake surface over which cold winter winds blow provides extra water to the air, which condenses and ultimately falls as snow. So if the wind blows along the length of Lake Erie picking up moisture which subsequently falls as snow, when the air rises over the land and cools to form snow crystals, as at the eastern end of the lake, then the length of the contact between wind and lake makes a big difference. Whereas cold winter winds that blow across Lake Ontario toward Toronto (unless they blow from the east) do not have as much of a distance to travel over, or exposure to, the lake surface and will gain far less moisture, less snow crystals form and less snow falls. This is a simple comparison known to all Torontonians. But effectively the presence, size and orientation of all the major topographic features (the Niagara Escarpment, the Oak Ridges Moraine, Lake Ontario and Lake Erie, as well as lesser lakes such as Lake Simcoe, and features like the Holland Marsh – can all "localize" the weather experienced by Toronto.

3.6 OVERVIEW BY SEASON

Table 4 presents a summary, by season, of Toronto's weather in terms of the major and minor influences.

Table 4 Toronto's Seasonal Weather Summary

<table>
<tr><th rowspan="3">Season</th><th rowspan="3">Typical Weather</th><th colspan="6">What Affects the Weather in Toronto?</th></tr>
<tr><th colspan="3">Large Scale Factors</th><th colspan="3">Local Factors</th></tr>
<tr><th>Air Masses and Circulation</th><th>High/Low Pressure Systems</th><th>Hurricanes</th><th>Great Lakes</th><th>Topography</th><th>Urban Heat Island</th></tr>
<tr><td>Spring</td><td>• Cool days and nights
• Alternating periods of dry, sunny weather with periods of rain</td><td>• Transitioning into summer, the spring months become more influenced by warmer air masses such as Maritime Polar air</td><td>• Periods of cool, dry, sunny weather are associated with high pressure systems.
• Low pressure systems bring overcast skies and precipitation and often milder temperatures.</td><td>Not Applicable</td><td>• After a long winter, Lake Ontario's cold waters prolong cooler temperatures in Toronto
• Can also cause advection fog [3] during the spring</td><td rowspan="4">• Toronto is bound to the west by the Niagara Escarpment and the Oak Ridges Moraine to the North which casts a rain shadow on the city and causes Toronto to receive less precipitation than areas to the west and north of these land features
• The Humber and Don River valleys create pockets of cooler air which often leads more fog and frost in the spring and fall. The valleys also channel winds.
• Tall buildings in Toronto's downtown core are an artificial topographic feature which can either slow down or channel winds. Shadowing from buildings also creates pockets of differing temperatures.</td><td rowspan="3">• Artificial surfaces such as asphalt and brick absorb more heat during the day than vegetated surfaces. On calm, cloudy nights, this heat cannot escape. As a result, the average night-time temperature in the city is higher compared to surrounding rural areas</td></tr>
<tr><td>Summer</td><td>• Warm to hot days and nights
• Moderate to high humidity
• Convective precipitation common</td><td>• Dominated by cool to warm, dry air masses from the Pacific
• Bermuda high strengthens in summer which brings hot and humid air from the Gulf of Mexico to Southern Ontario. Prolonged periods of southerly winds can cause several days of high temperatures and humidity.</td><td>• Low pressure systems can cause periods of mild, wet weather. Intense thunderstorms can also occur with the passage of the cold front.
• Periods of high pressure create clear, sunny skies. Blocking highs can often result in a heat wave (an extended period of hot weather).</td><td rowspan="2">• Beginning in August and extending to late fall, tropical storms have the potential to impact Canada, but rarely reach as far inland as Ontario
• Tropical storms can bring large amounts of rain and strong winds
• The frequency of tropical storms in Ontario is 11.1 years [2]</td><td>• In early to mid-summer, Lake Ontario is quite cool relative to inland temperatures which creates lake-breezes during the day, and land-breezes at night
• Creates more cloud cover and convective precipitation as it is a source of moisture, especially in late summer when the lake has warmed</td></tr>
<tr><td>Fall</td><td>• Cool days and cool to cold nights
• Alternating periods of dry, sunny weather with periods of rain</td><td>• Transitioning into winter, the Bermuda high begins to weaken, and the Arctic lows strengthen, bringing outbreaks of cold air into Southern Ontario</td><td>• Periods of cold, dry, sunny weather are associated with high pressure systems.
• Low pressure systems bring overcast skies and precipitation and often milder temperatures.</td><td>• After the summer has passed, Lake Ontario is warm relative to the air above it. This keeps Toronto warmer longer than without the presence of the Lake.
• Warmer lake temperatures keeps frost at bay in the fall
• Cloud is more common in the vicinity of the lake as it is a source of heat and moisture</td></tr>
<tr><td>Winter</td><td>• Cool to cold temperatures
• Alternating periods of dry, cold days with periods of precipitation (usually snow)
• Winter storms common</td><td>• Dominated by Continental Arctic air masses which are cold and dry. This air mass can also be modified by passing over lakes, making it moist.
• Moist and mild air from the southwest US sometimes influences southern Ontario</td><td>• High pressure in the winter creates dry, clear skies and cold night time temperatures as heat easily escapes through a cloudless sky
• Low pressure systems (or winter storms) often pass by, bringing milder air and sometimes large amounts of snow. Gulf [1] Lows bring heavy amounts of snow as they draw upon heat and moisture from the Gulf of Mexico. Alberta clippers are another common winter low affecting Toronto, but are much drier.</td><td>Not Applicable</td><td>• Cloud is more common in the vicinity of Lake Ontario in early winter when the lake is still warm relative to areas inland
• Lake-effect snow typically develops over Lake Huron rather than Lake Ontario. Sometimes this snowfall can reach Toronto, but it usually only extends as far east as Middlesex County
• Storms approaching Toronto from a southerly direction, can draw upon heat and moisture from Lake Erie or Lake Ontario and intensify storms
• Lake ice will block the transfer of heat and moisture to the atmosphere</td><td>• Due to residential and commercial heating, the heat island effect results in higher day-time and night-time temperatures compared to rural areas</td></tr>
</table>

Notes:

1. Also known as Texas Lows
2. Environment Canada. 2005. *Atmospheric Hazards – Ontario Region: Hurricanes and Tropical Storms*. Available online: <http://ontario.hazards.ca/maps/background/Hurricane-e.html> [2010 October 4].
3. Advection fog occurs when warm, moist air pass slowly over cool surface waters causing the moisture in the air to condense.

2.0 WHAT IS TORONTO'S WEATHER AND CLIMATE NOW?

2.1 INTRODUCTION

When one asks "What will the weather be like today?" we are inherently asking for a description of the current state of the lower atmosphere in terms of the temperature, the amount of cloud cover and precipitation and whether or not the wind will be blowing. Weather also includes extremes (the maxima and minima) and how they contribute to floods, heat waves, cold snaps and other "important events". Recent important events are presented in the next section.

Climate, on the other hand, is commonly regarded as the mean state of the atmosphere over an extended period of time[2]. It tells us what the most common weather conditions are likely to be for a given location and the time of year. During a Canadian winter, for example, we typically think of coastal cities like Vancouver as being cool and wet, and interior cities such as Toronto as being cold and dry.

Weather is what we experience day-to-day, while climate is what we can expect.

The World Meteorological Organization selected a 30 year period of record as representative of climate Normals by analyzing about 125 years of observed data and looking at its variability. The data for temperature, for example, showed that it takes about 45 years for the standard deviation of annual temperature anomaly (difference between the average for a single year and the long term average) to stabilize but the WMO was content to select 2/3 of the stable value or 30-years. Temperature varies up and down, a time series has a lot of natural variation, and a cold spell could last six years, or even twelve years. A short period of data doesn't tell us anything about what the long-term trends in climate are doing.

For this project, we examined the 30-year climatology for the Toronto area and we selected the most recent 10-year period to look at in detail because 2000-2009 is a key period for recent extreme weather events.

[2] A more complete definition of climate comes from the Intergovernmental Panel on Climate Change:

> "*Climate in a narrow sense is usually defined as the "average weather," or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.*" (IPCC, 2007a)

2.2 IMPORTANT EVENTS IN THE PERIOD 2000-2009

While this study focuses on the GTA and the City of Toronto in particular, weather impacts often cover an area much broader than the GTA. For this reason, a summary of important events for the period 2000-2009 covering that portion of southern Ontario that is close to, or immediately surrounds the GTA, is presented in Appendix A and summarized in this section. It was adapted from information developed by Environment Canada and available in the following website: http://ontario.hazards.ca/docs/collected-docs-e.html.

The period 2000-2009 was selected as the baseline against which future weather was examined because this period exhibited a significant number of extreme weather events. A summary of these is presented in Table 3 below.

Table 3 Summary of Extreme Weather Events for 2000-2009

Year	Extreme Event Recorded
2000	Wettest summer in 53 years with 13% more precipitation than normal
2001	Driest growing season in 34 years; first ever "heat alert"; 14 nights with temperatures above 20°C (normal is 5 nights)
2002	Driest August at Pearson Airport since 1937; warmest summer in 63 years; 5th coldest Spring
2003	Rare mid-Spring ice storm – Pearson Airport used a month's supply of glycol de-icer in 24-hours
2004	Year without a summer; May rainfall in Hamilton set an all-time record; and another all-time record 409 mm rainfall was set at Trent University in July which was equivalent to 14 billion litres of water in 5 hours (a 200 year event)
2005	Warmest January 17 since 1840; January 22nd blizzard with whiteouts; warmest June ever; number of Toronto days greater than 30°C was 41 (normal is 14); August 19 storm washed out part of Finch Avenue
2006	23 tornadoes across Ontario (14 normal); record year of major storms; record one-day power demand of 27,005 MW due to summer heat
2007	Protracted January thaw; 2nd least snow cover ever in Toronto of ½ the normal amount; snowiest Valentine's Day ever; chunks of ice fell from CN Tower; 2-3 times the normal number of hot days in the summer; record latest-in-season string of +30°C days around Thanksgiving
2008	Toronto's 3rd snowiest winter ever; record for highest summer rainfall
2009	3rd rainiest February in 70 years; Hamilton had a 100-year storm; one of the wettest summer on record; tornados hit Vaughan-Woodbridge area in late August; an unusually mild and storm-free November in Toronto – Downtown had a record no snow for the first time ever – first snow-free November at Pearson Airport since 1937

The table shows that the climate has already started to change around the GTA and that we had better start to prepare for even more change.

2.3 THE BIG PICTURE

2.3.1 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 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.

2.3.2 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).

2.4 THE GTA'S CURRENT CLIMATE

2.4.1 Introduction

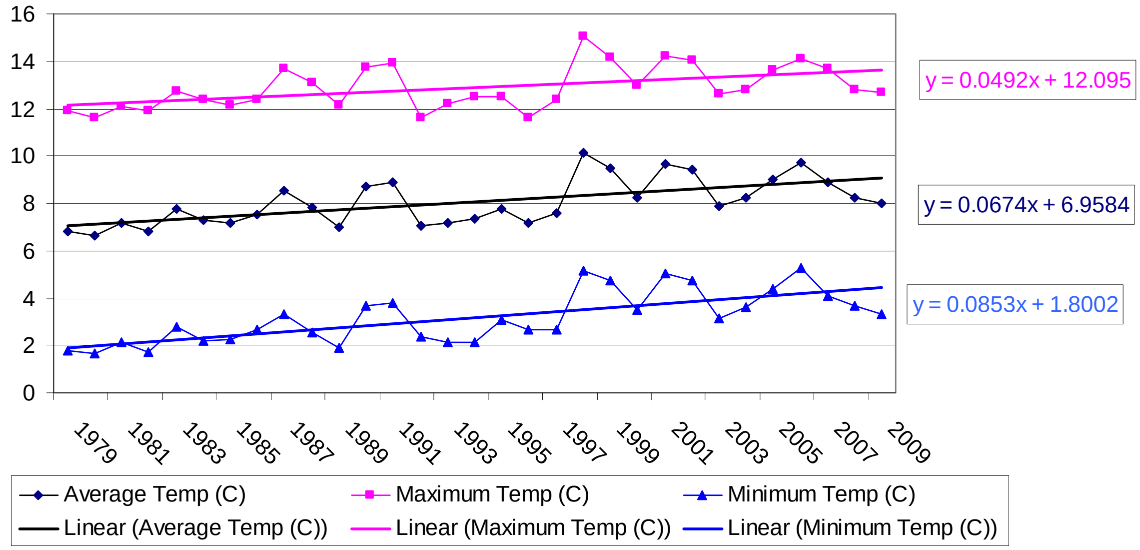
The climatology over the period 1979-2009 for the Greater Toronto Area was reviewed using all available records from the Environment Canada monitoring stations. Because of the varying length of records and uneven data quality, SENES decided to use Pearson Airport as a reference location for this study because of its extended period of record and high data quality.

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 across the GTA.

2.4.2 Average, Minimum and Maximum Temperature Trends

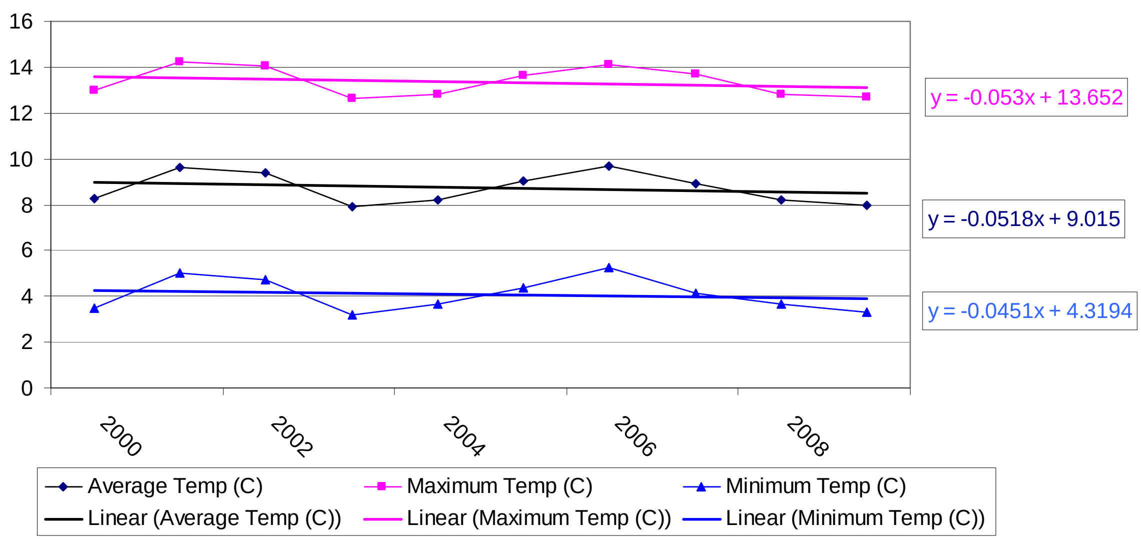
While the analysis was completed for all stations listed in Table 1, an example of the Pearson Airport (as one of the most complete stations) was selected to show the form of the results. The most recent 30-year climate trend was assessed (1979-2009) and compared to the study reference period (2000-2009). Figure 4 and Figure 5 present the annual average temperature data well as a linear trend line.

Figure 4 Average Temperature 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°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. Final report is available at http://www.ouranos.ca/Ontario/Results_html/index.htm).

Figure 5 Average Temperature 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, as indicated earlier by the World Meteorological Organization (WMO) in Section 2.1.

2.4.3 Extreme Temperatures

The extreme maximum and minimum temperature trends over 30 and the last 10 years are presented in Figure 6 and Figure 7, respectively. In Figure 6 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 staying about the same and the minimum temperatures are becoming much less severe.

Figure 6 Extreme Temperature – Pearson Airport (1979-2009)

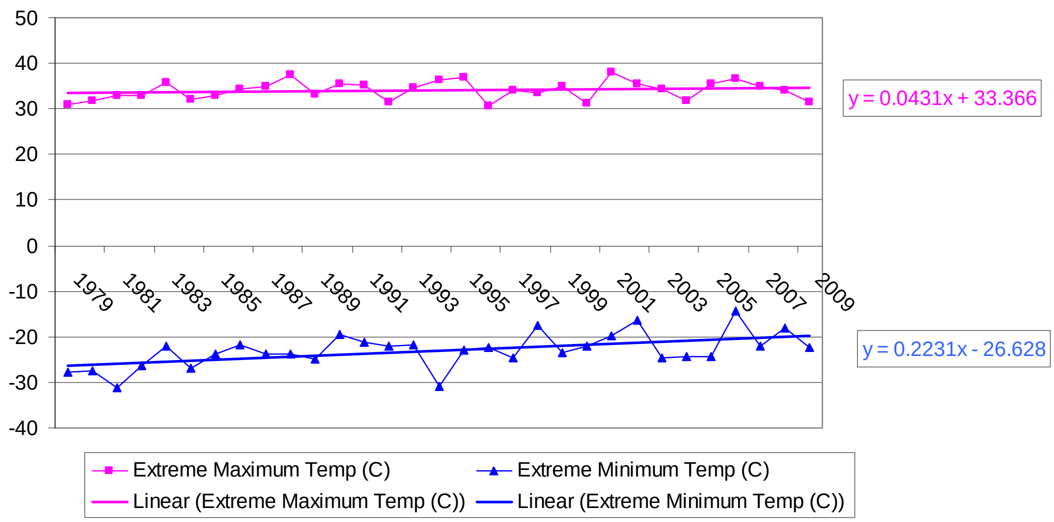


Figure 7 shows that, over the most recent 10-years, there is a negative trend in the extreme maximum temperature while the extreme minimum has remained virtually flat. This is another indication of the variability in our climate over shorter timescales.

2.4.4 Rainfall, Snowfall and Total Precipitation

Trends in precipitation are presented here, for the thirty year and the ten year period. Figure 8 and Figure 9 represent the trends in precipitation for these two periods, respectively.

Figure 7 Extreme Temperature - Pearson Airport (2000-2009)

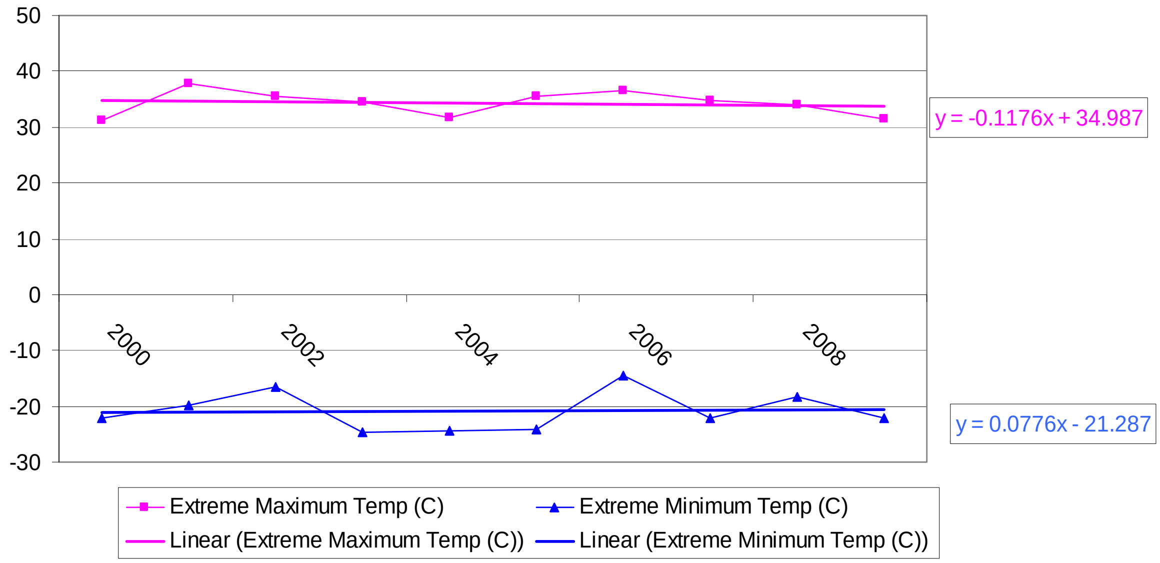
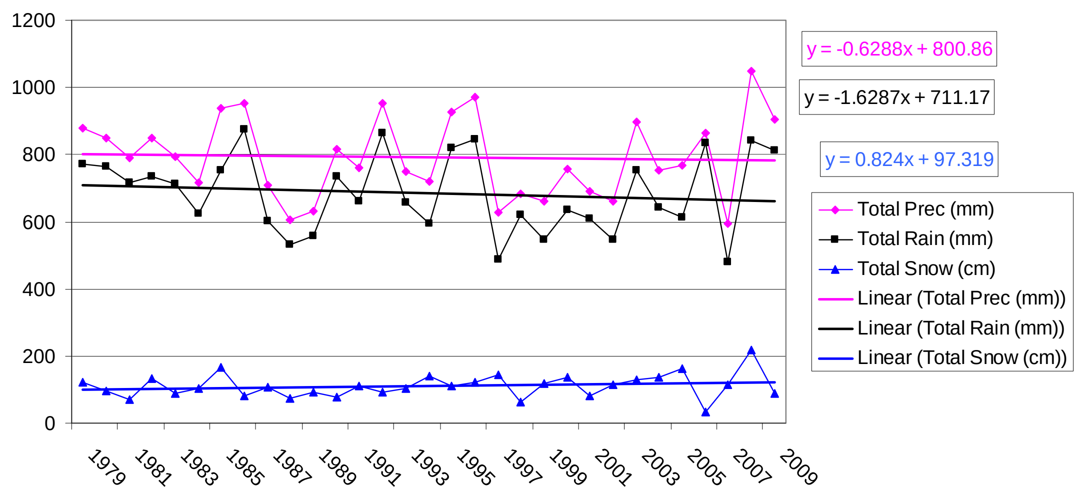
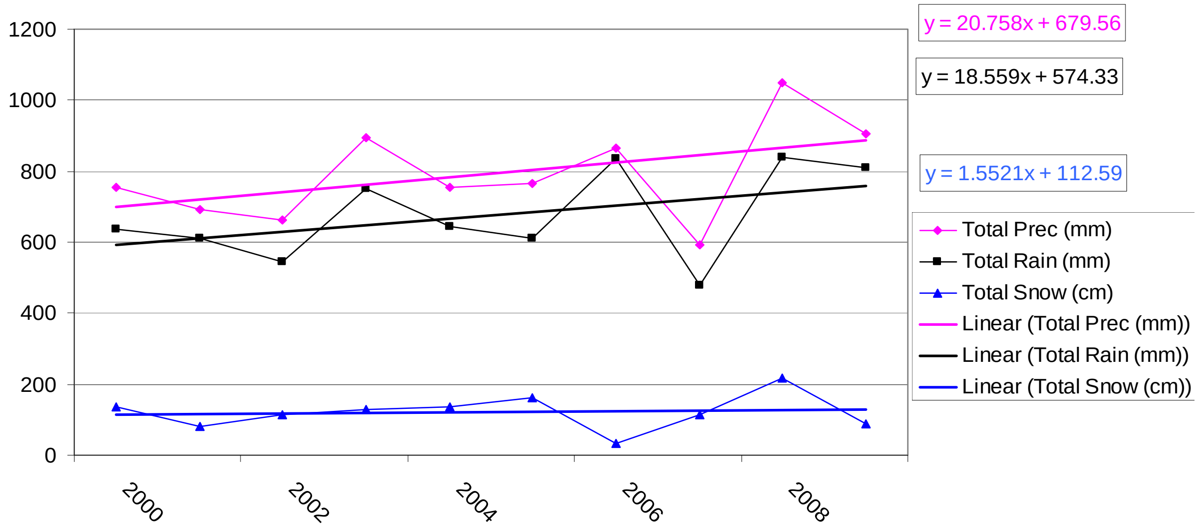


Figure 8 Precipitation at Pearson Airport (1979-2009)



Based on the 30-year period of data (Figure 8), there is a decreasing trend of rainfall and total precipitation, while snowfall is increasing, while the most recent 10-year period (Figure 9) has different trends, with all three parameters indicating an increase. Again, the conflicting trends can be explained by the different time periods being considered.

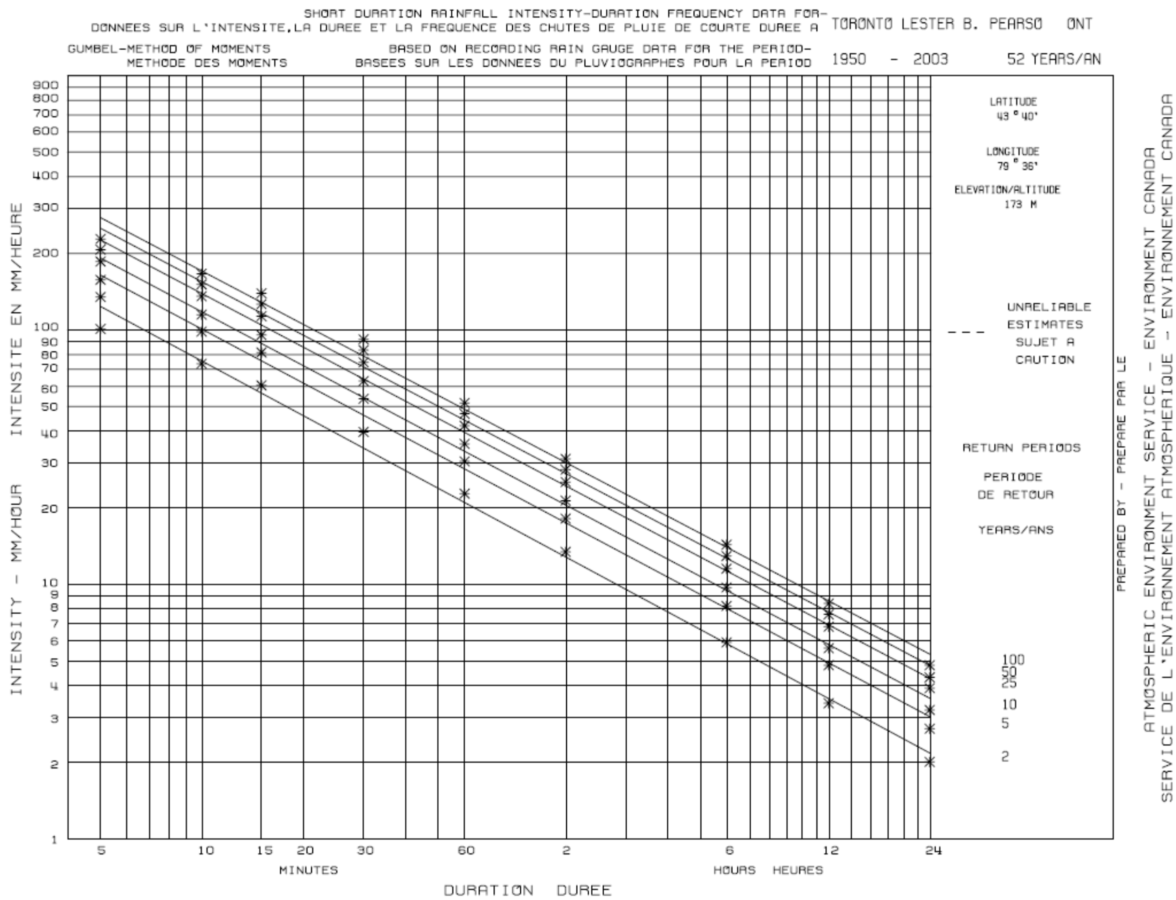
Figure 9 Precipitation at Pearson Airport (2000-2009)



2.4.5 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 10 on which similar storms with similar intensity and duration characteristics are used to calculate their 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 10. This IDF graph will be used as the base reference for comparisons with the predicted return periods of the future period to be modelled as part of this study. IDF curves are of particular interest to water engineers and conservation authorities charged with providing water infrastructure given our precipitation characteristics. These characteristics are projected to change in our future climate and should be considered now given the expected lifespan of this type of infrastructure.

Figure 10 Intensity Duration Frequency Graph - Pearson Airport (1950-2003)

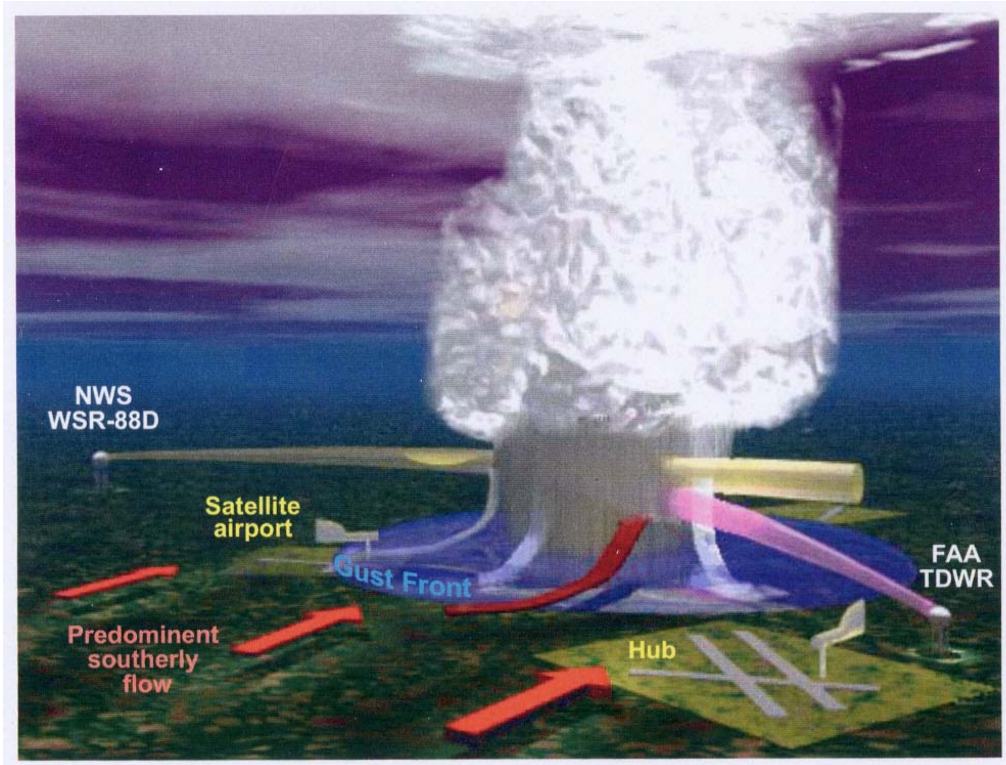


2.4.6 Gust Winds

Around thunderstorm cells there are strong vertical movements called updrafts and downdrafts. Those downdrafts create local fronts which generate gusting winds. Such frontal systems are quite difficult to detect. This downdraft phenomenon is thought to be the most likely cause of the majority of observed damage. 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 11 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 11 Cool Outflow from Thunderstorms Produces a Gust Front



The long term tendency of gust winds is presented in Figure 12 (30-year period) and Figure 13 (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 that associated with instantaneous wind speeds caused by storm downdrafts and other atmospheric phenomena.

Figure 12 Gust Wind Trend for the 1979-2009 Period

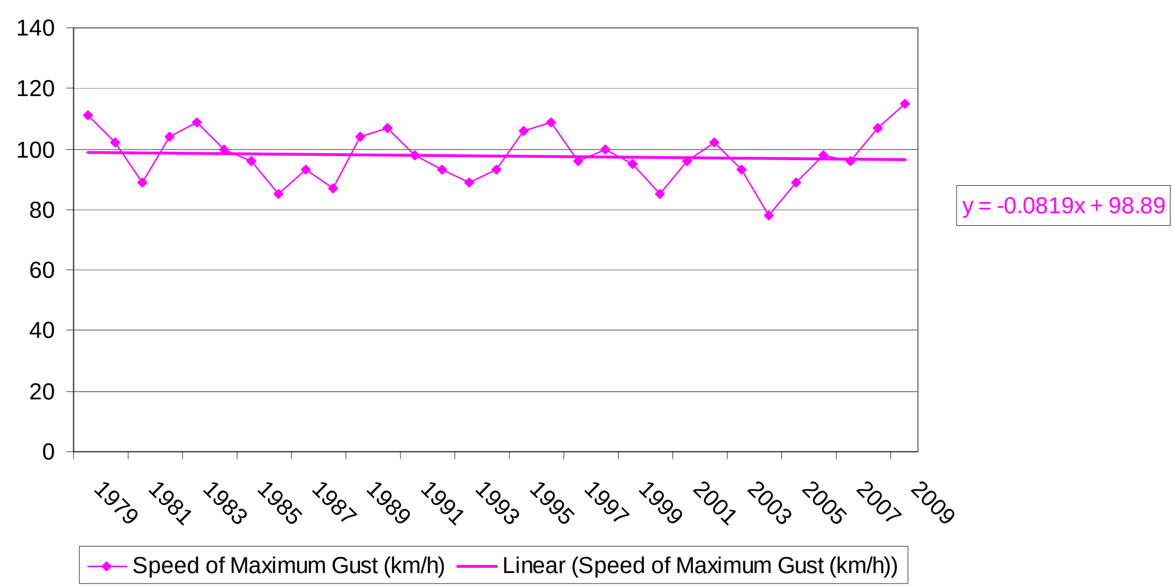
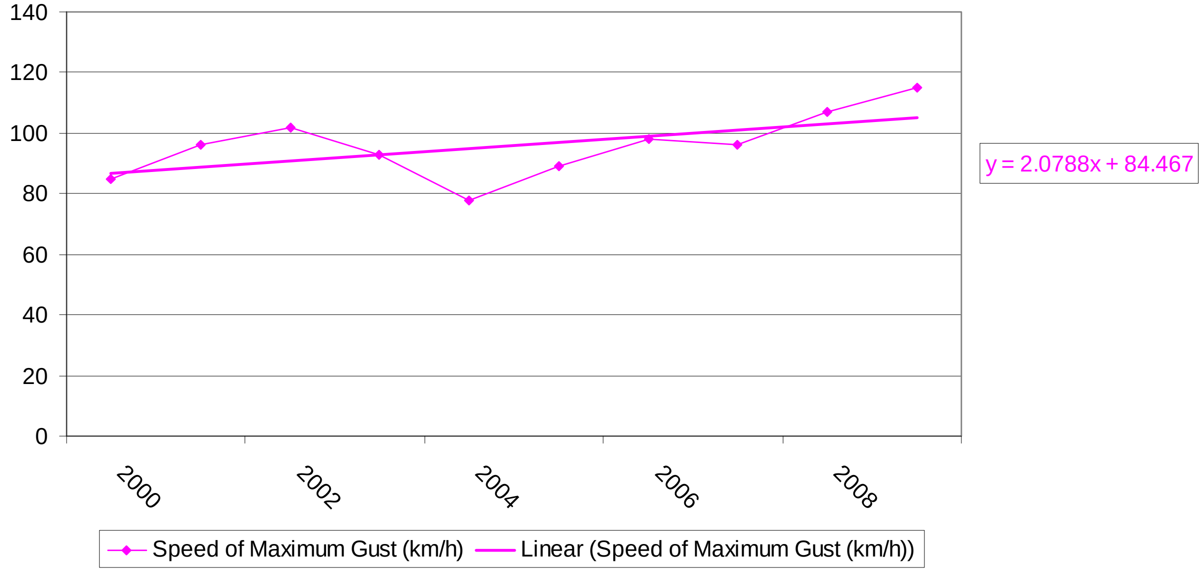


Figure 13 Gust Wind Trend for the 2000-2009 Period



The figures show, based on the thirty year period (Figure 12) that the gust trend is slightly negative (gust wind will decrease in the future), while the most recent 10 years (Figure 13) 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.

4.0 HOW DO WE FIND THE FUTURE WEATHER?

4.1 INTRODUCTION

The climates of the world have always changed "naturally" over time and will continue to do so. However, in the near future further climate changes will also be driven by additional "human" causes. Predicting future weather is clearly a very difficult undertaking as many uncertainties and unknowns have to be estimated.

One fundamental uncertainty is the amount of (mostly) fossil fuel combustion related emissions that will enter into the atmosphere and at what rate. An international body called the Intergovernmental Panel on Climate Change (IPCC) developed storylines for future greenhouse gas (GhG) emissions as early as 1990. What will actually happen in the future, will be the product of very complex dynamic systems determined by demographic, social, economic, technological and environmental developments. How emissions will actually evolve is highly uncertain. In order to try to come to grips with how our world will change, various storylines were developed by the IPCC to give alternative ideas on how the future might unfold. These storylines are used to develop emissions as inputs to climate models. The outputs from the climate models help people around the world to examine future impacts, and determine appropriate adaptation and mitigation activities.

The IPCC (2000) report identified the A1 family of scenarios as a future characterized by rapid economic growth, by global population increasing to 9 billion by 2050 (after which it gradually declines), by the rapid global dispersion of new and more energy efficient technologies, and where extensive worldwide social and cultural interaction leads to greater parity of incomes and lifestyles among all regions. The A1 scenario family has three members -A1 FI, A1B, and A1T, of which the A1B scenario occupies the mid-point between the more fossil fuel intensive (A1FI) scenario and the more technology dependent reliance on non-fossil fuel sources (A1T) scenario.

The A1B scenario is considered to be a "likely" future scenario – and one that is very commonly used for future climate simulations. The A1B scenario was selected and used in this study as being representative of a moderate economic outlook yet one that could still be expected to lead to clearly identifiable consequences of the impacts of CO_2 emissions for the 2040-2049 period in southern Ontario

Using a climate model is really the only way to understand the complexities that cause changes in the climate over long timescales. Climate models simulate 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 spatial scale of the boxes in the HadCM3 model is approximately 300x300 km horizontally by 30 km vertically. This scale is much larger than that of some of the key processes that drive Toronto's weather, such as storms and cloud formation. This means that many climate processes have to be approximated at this scale. The approximations, and our incomplete understanding of the climate system, are a major source of uncertainty in climate projections. By using the output of the Hadley global climate model (GCM) to drive a regional climate model (RCM) with a finer scale and with more of the atmospheric processes included (PRECIS was the RCM selected and used in this study), we are able to get a better simulation of the climate over the GTA on a scale of approximately 50x50 km horizontally by 30 km vertically.

However, the scale of weather events over Toronto, like individual storms, and the key influence of the lakes and local topography like the Niagara escarpment, will still not be properly characterized even at this RCM scale. In order to answer the City's questions, a much finer resolution model was required (approximately 2x2 km horizontally) to represent directly some of the key small-scale processes, such as thunderstorm sized rainfall events, weather variability and topographic influences in the Toronto area. For this study, a new and innovative process was used. A state-of-the-science weather forecasting model running on a 1x1 km grid covering the GTA was used. Results from a "coarse resolution" HADCM3 climate model (a GCM) were input into a "medium resolution" PRECIS climate model (an RCM) to provide results that were them input into a "fine resolution" weather-climate model (FReSH). Within the modelling field, this common procedure is called "nesting".

With a global climate model to correctly identify the long term big picture (300x300 km ground resolution) and by feeding that data into a regional climate model (50x50 km ground resolution) which then feeds a state-of-the science weather model (1x1 km ground resolution), we are able to get the right long term averages and hourly weather statistics on a very fine spacing over the City of Toronto. We will never get a correct prediction of a particular storm on a particular day because the weather and its drivers are too variable. But a prediction of a particular storm occurring somewhere within the general area at a particular time of the year can be obtained.

The approach of adding a fine-scale weather model to the climate model output to obtain more locally relevant future prediction forecasts was completely new and innovative when this project was conceived. The approach taken has been very successful and the study has demonstrated the value of the approach. It is also an approach that has subsequently been adopted by the National Center for Atmospheric Research (NCAR) for the whole of the USA as well as by the Ontario Ministry of the Environment in partnership with the University of Regina, and by the University of Toronto.

4.2 WHAT EMISSIONS OF CO_2 DRIVE THE FUTURE?

The Intergovernmental Panel on Climate Change (IPCC) developed future greenhouse gas (GhG) emissions 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 relationships between emissions and their driving forces in the world in 2100. Each storyline represents different demographic, social, economic, technological, and environmental developments and are named A1, A2, B1, and B2 (see Figure 22). 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.

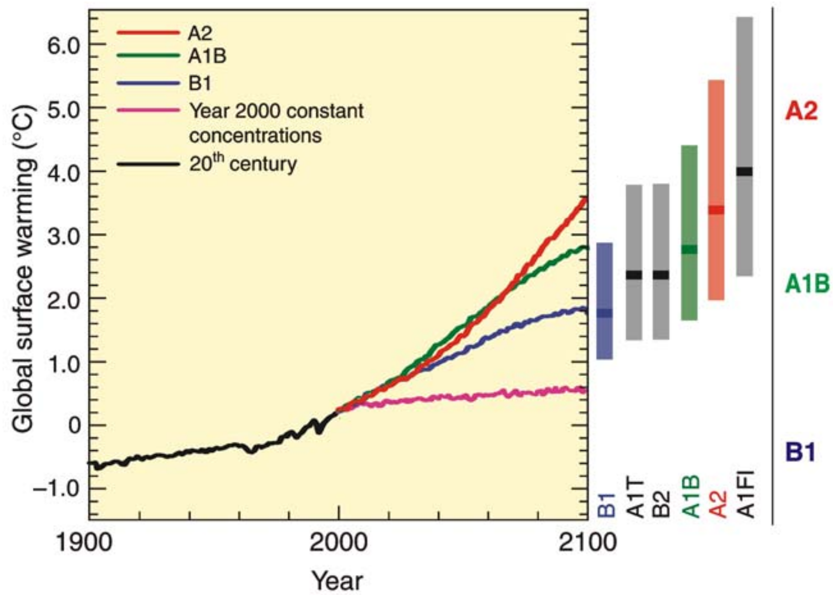
The B1 storyline and scenario is similar to the A1 scenario but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

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.

Greenhouse gas emissions are the largest in the A1FI and A2 scenarios. The A1B scenario might be considered to have moderate emissions, and the B1 low emissions. There are several different scenarios in each storyline, of which one is referred to as a 'marker' scenario. The marker scenarios from the A1FI, A2, A1B and B1 storylines are most commonly used in climate models for projections of future climate. Each of these scenarios is considered to be an equally likely projection of future greenhouse gas emissions.

The IPCC (2000) report identifies the A1B scenario as the worst reasonable case (highest warming impact of CO_2) within the balanced energy sources family for the 2040-2049 period. This can be seen graphically in Figure 22. This scenario was selected for this study.

Figure 22 Impact of Various Climate Change Scenarios



4.3 APPROACHES TO MODELLING THE FUTURE

4.3.1 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 levels 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.

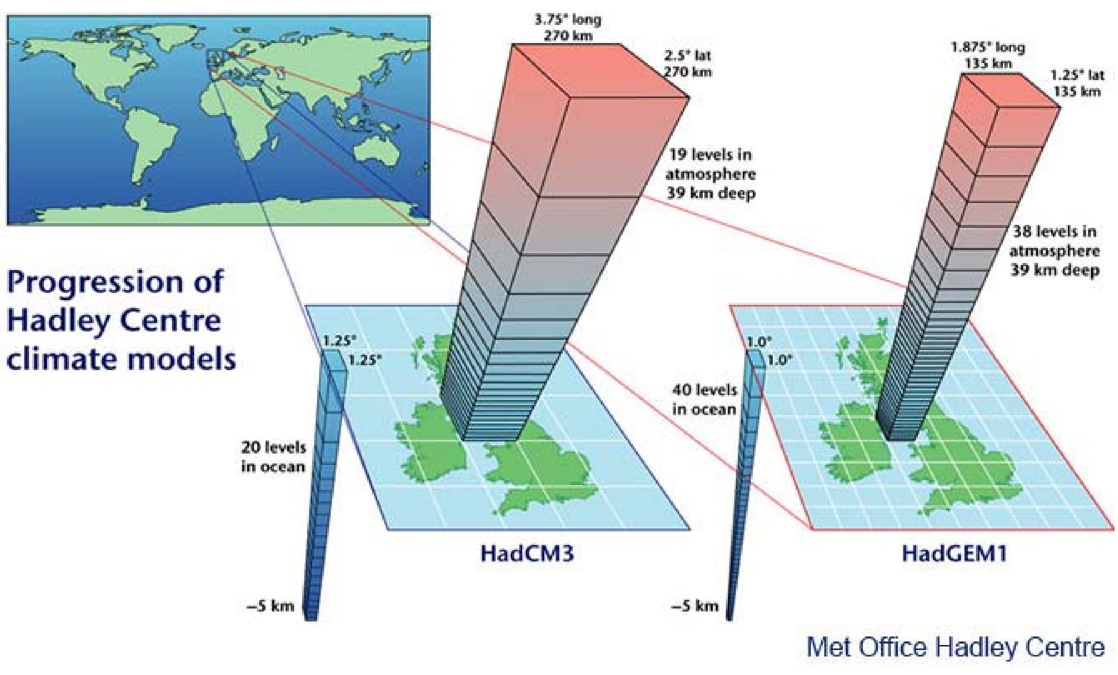
One common question asked is how reliable are climate models, and can we be confident in their projections of future climate? There are three reasons for placing confidence in projections of future climate from these models. The first reason is because climate models are based on well-established physical 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 23. 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 23 Progression of the Hadley Centre Climate Models



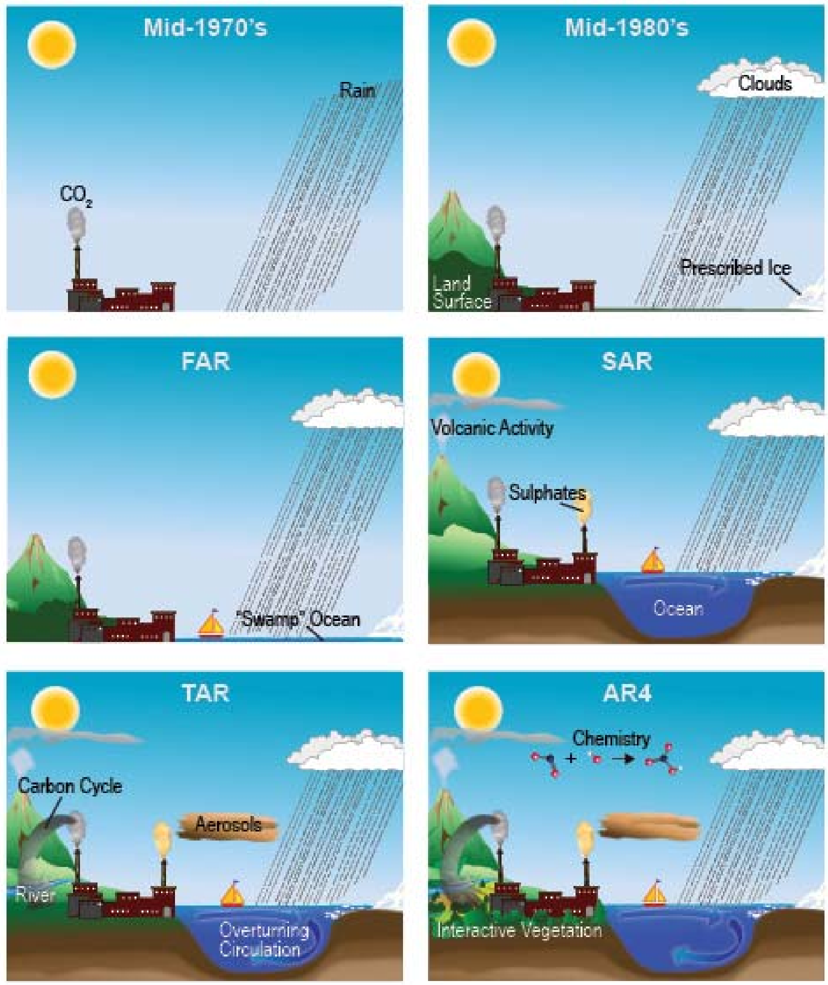
4.3.2 Evolution of Climate Models

Climate models have been, and continue to be, improved. Our knowledge of the atmosphere 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 24. 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.

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.

Figure 24 Evolution of climate models between the 1970s and 2000s



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 across and up to northern Europe, and has a strong effect on the temperatures that the United Kingdom 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 like Canada's north, when 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 include 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 24 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).

4.3.3 Types of Climate Model

There are many different types of climate model of varying complexity which may be used to project future climate. They may be divided into three classes: complex, intermediate and simple models. For simulation of recent climate (1860 – 2000) and near-future climate (to 2100, or, in some cases, to 2300), complex climate models are used. Both HadCM3 and the more recent HadGEM series of climate models could be classed as complex. These models contain representations of the atmosphere, oceans and interactions between the two. The atmospheric components have horizontal resolutions of the order of 150 km, and represent the vertical structure of the atmosphere with many levels, between 19 and 70. Some climate models also include a representation of the stratosphere, as interactions between the circulation patterns in the stratosphere and troposphere are known to influence surface climate (e.g., the winter climate of northern Europe; Scaife *et al*., 2005). The ocean components generally have higher resolutions than the atmosphere. Many of these models also represent other components of the earth system, such as the carbon cycle (interactions between trees, grasses, other vegetation types, and soils with climate) and gaseous chemistry (which controls the levels of methane, ozone and other trace gases). Much higher resolution versions of some of these models have also been created (e.g. HiGEM; Shaffrey *et al*., 2009).

An intermediate class of climate models also exist, which are called Earth System Models of Intermediate Complexity (EMICs). These models have been developed to investigate climate change over long periods of time (e.g. 100s – 1,000s of years, or, in some cases, a glacial cycle which has a time span of 100,000 years). Complex climate models cannot be used for such studies owing to their high computational costs. EMICs have reduced resolutions and simplified representations of physical processes, and so can only project climate change over continental and global scales. Large ensembles of EMICs (i.e. different EMICS or variations of one EMIC) can be used to investigate uncertainty in long-term climate projections, owing to their lower computation costs. Many EMICs are based on and are validated using results from complex climate models. There is no universal definition of an EMIC, and EMICs themselves can differ considerably. For example, some EMICs have few interacting components and may be used in long simulations to study climate variability. Others have simplified representations of many processes and are used to study feedbacks in the climate system.

Simple climate models (SCMs) can only simulate hemispheric and global climate change, and are used to study the temperature and sea level implications of different scenarios of future greenhouse gas emissions. One such model is MAGICC (IPCC, 2007, Ch.8), which represents the land and ocean in each hemisphere and the vertical structure of the ocean. MAGICC can be tuned to represent the climates produced by many different complex climate models, and then used to simulate global climate over 100s – 1000s of years. For the IPCC 4th Assessment Report, the complex climate models only produced future climate projections using three scenarios. MAGICC was used to produce global projections for the period 2000 – 2100 for additional scenarios. After tuning to each complex climate model, MAGICC was used to produce climate projections under three additional scenarios for each model.

All the types of models discussed so far have been global, that is, they represent the oceans and the entire atmosphere between the surface and a predefined upper level, e.g. 40 km. Regional climate models (RCMs) also exist. They generally only represent the atmosphere, and simulate the climate over a region of the Earth at a higher resolution than can be achieved with a global model. For example, the Hadley Centre regional climate model PRECIS can be run with a resolution of 25 km or 50 km (the global model has a resolution of ~300 km). Regional climate models require meteorological data at the boundaries of the region of interest, which is supplied by a global climate model. The RCM generates a climate which will be the same as that simulated by the global model, but at much higher resolution. RCMs include more accurate representations of the topography of the region and so generate an improved climate simulation compared to a global climate model.

4.3.4 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 (see Section 4.2 What Emissions of CO2 Drive the Future?).

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.

4.3.5 Main Sources of Uncertainty

4.3.5.1 Global Scale

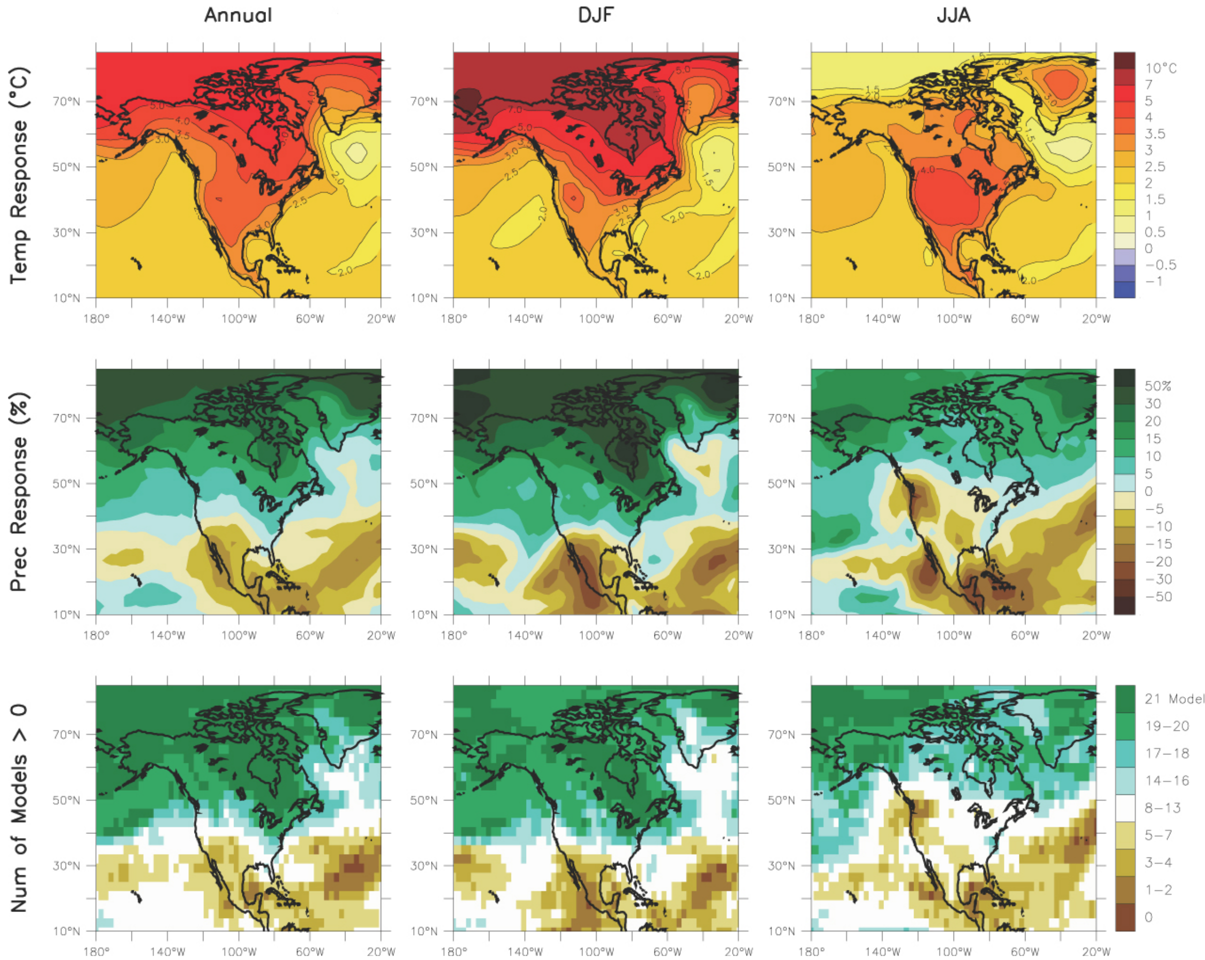
Uncertainty, in global climate projections, originates from many sources. These sources may be categorised into four main areas: (1) the regional climate response to global warming, including the climate sensitivity of the model used to make the projections, (2) the formulation of the model used, (3) natural variability, and (4) feedbacks between the biosphere and climate. Each of these sources of uncertainty is discussed in more detail below.

Climate projections are based on global climate model integrations. Compared to weather forecast models, climate simulations normally use coarser resolutions but they frequently include more complex descriptions of the ocean and surface processes. The climate projection is usually obtained from the long term averages of model results in which the concentration of greenhouse gases has been prescribed to rise following a predetermined emission scenario. The long-term warming associated with a specific increase in the concentration of greenhouse gases is typically model-specific. The global mean temperature response to a doubling of CO_2 concentrations (when the model has reached a new equilibrium) is termed climate sensitivity. The current generation of global climate models cover a range of climate sensitivities between 2.1 ºC and 4.2 ºC, with a mean value of 3.2 ºC (IPCC, 2007).

However, the response of the regional climate to global climate change is the main source of uncertainty in regional climate projections, especially in the near-term (Hawkins and Sutton, 2009). Modelled changes in temperature and precipitation over North America from 21 regional climate models have been assessed by the IPCC (Denman *et al.,* 2007), and are summarised in Figure 25. The three columns show annual, DJF (December, January and February) and JJA (June, July and August) mean changes between 1980-1999 and 2080-2099. The top row presents temperature changes between the two scenarios. The middle row shows percentage changes in precipitation and the bottom row shows the number of models which project an increase in precipitation. The green colours in the bottom row indicate areas where 66% (14 out of 21) or more of the models project an increase in precipitation. In winter (DJF), the model agreement over the Great Lakes region is good, but in summer (JJA) model agreement is very poor. There is no clear signal for the change in summer precipitation from the models.

The second source of uncertainty in climate projections originates from the climate models themselves. Climate models contain mathematical representations of many different processes within the atmosphere. These representations use many parameters, some of whose values are uncertain. Murphy *et al*. (2004) used the climate model HadAM3 and perturbed 29 key parameters individually away from their standard variables and calculated the climate sensitivity for each new version of the model. The climate sensitivities lay in the range 2.4 to 5.4 ºC.

Figure 25 Average Temperature and Precipitation Changes (21 RCMs)



The Earth's climate system is characterised by natural fluctuations (periodic, semi periodic and random). This represents the third important source of uncertainty as, up to now, climate simulations have generally not been initialised with current conditions in the atmosphere and ocean. This means that each model integration is likely to sample differently the internal variability of the climate system. This is one of the reasons why climate model projections make sense only when averaged over a long period. It is commonly accepted that a simulation of 30 years for a non-initialised climate model is the minimum time period required (Jones *et al*., 1997).

The fourth source of uncertainty in global climate projections comes from the concentrations of GhGs in the atmosphere. Although these are prescribed in most climate models (often using the SRES scenarios developed by the IPCC), there is a growing set of evidence suggesting feedback mechanisms occur and that the ability of the biosphere and ocean to absorb carbon dioxide is affected by climate change and direct representations of the relevant processes must be included in the models (e.g. Huntingford *et al.,* 2009; Gregory *et al.,* 2009). GhG concentration uncertainty represents the main source of uncertainty for centennial time scales.

Further uncertainty in climate projections arises from processes not represented in models. For example, major volcanic eruptions cannot be predicted. Such eruptions place large amounts of material into the stratosphere which acts to cool the earth for 2-3 years after the eruption. Atmospheric chemistry, which controls the levels of methane and ozone (both are important greenhouse gases), is not usually included in projections of future climate. Johnson *et al*. (2001) showed that projections of methane and ozone levels in the 21st century were strongly impacted by changes in climate.

4.3.5.2 Region Specific Uncertainty and Limitations

In order to fully capture the climate and its modification in the Great Lakes Region it is very important to correctly characterise the lakes and their interaction with the atmosphere. Although the Great Lakes are resolved by the current generation of regional climate models, their resolution is still not adequate to represent the fine details of the coastlines which are likely to play an important role in local climate. Furthermore, the absence of a specific model for lakes means that biases on both sea ice extension and location can be expected.

4.4 THE APPROACH USED FOR THIS PROJECT AND WHY

4.4.1 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, our contributors from the Hadley Centre are 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.

4.4.2 Downscaling of Projections of Future Climate

Climate models are based on well-established physical laws and principles and are the best tools available to project future changes in climate. Climate change at any given location will be the result of a complex interaction between global warming, atmospheric and oceanic circulation changes, increases in the humidity of the atmosphere, cloud properties, and many other factors. There are no other ways of correctly projecting future climate. However, future climate at specific locations has been estimated using techniques which downscale the climate change data from a model to the required location. These downscaling techniques cannot replace climate models, as they require projections of future climate.

Wilby (2003) constructed a statistical model of the urban heat island of London, England. This model was created using a stepwise multiple linear regression procedure with the observed urban heat island and other meteorological variables. The future heat island was estimated using values of the meteorological variables projected by a climate model. This technique assumes the relationship between the urban heat island and the meteorological variables used in the regression does not change, which may not be the case.

Another technique for estimating the impact of climate change at a specific location is called morphing (Belcher *et al*., 2005), and is usually applied to sub-daily (hourly) observed climate data. An existing climate data set for a given location (e.g. hourly observations of temperature, rainfall, wind, etc.) is modified (or "morphed") using specified mathematical operations to create an equivalent data set for the future. For example, if a climate model projection suggested that temperatures would rise by 2ºC in April; the observed temperatures for April could be increased by 2ºC to create hourly climate data representative of the future.

Different mathematical operations are used on each variable of interest. Precipitation is multiplied by a factor. If the climate projections suggested that rainfall will increase by 5%, then the observed rainfall data would be multiplied by 1.05 to create the future rainfall data set. Morphing is a simple technique for producing sub-daily climate data which is representative of the future climate. However, the overall characteristics of the climate are not changed. If the particular observed data were made when a given month was unusually cool and wet, for example, then that month will always be cool and wet in the morphed time series. Morphing cannot easily incorporate trends in climate. For example, Jenkins *et al*. (2008) analysed observed temperature and rainfall data for the UK and found that, for the period 1960-2006, winter rainfall had increased and summer rainfall had decreased. In this instance, the morphing procedure could be applied on a monthly basis, but some "blending" of the morphed data between each month would be necessary to remove any step-changes in climate variables. However, if the original data set recorded rainfall between 6th and 10th June, any morphed data will always have rainfall between the same dates at the same times, even if the climate model projection suggested that rain in early June would be highly unusual in the future. It is possible that the morphed data may be physically unrealistic. For example, morphed rainfall could be inconsistent with morphed temperatures and cloud cover.

It has been suggested that a proxy for a future climate could be used for adaptation studies, e.g., the future climate of London, England will be like the present-day climate of Marseilles, France. However, this method is not recommended, as the meteorological characteristics of the proxy city are very different to those of the city under study. In this example, the proxy city, Marseilles, is at a much lower latitude than London. The lengths of the days will be very different between the two cities, particularly around the solstices. The origin of weather in London is mainly controlled by low pressure systems which form in the Atlantic Ocean and travel north eastwards to the UK, whereas in Marseilles low pressure systems form directly in the Mediterranean area. Marseilles is sometimes impacted by the hot dry winds of the sirocco, which originates in the Sahara, whereas London is not.

4.4.3 Overview of Approach Used

As outlined in the previous section, 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 (Version 1.8.2) 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 (Version 1.8.2) 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.

SENES started with the climate Normals[6] 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

[6] 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.

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.

This set of statistics formed the baseline summary of current climate for the Greater Toronto Area and addresses and provides new insight into Question 1 (What is Toronto's current weather and climate and why?). This baseline period was also used for model validation against the current observational data.

The second step was to use the 50x50 km output from the Regional Climate Model (RCM) called PRECIS (Version 1.8.2) 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 (Version 1.8.2) 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 from RCMs 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 resulting averages and statistics form the future period climate summary for Toronto and the GTA and is used to answer Question 3 (What will be Toronto's future weather and climate and why?) and Question 6 (What magnitudes, frequency and probability of occurrence do future extreme weather events and significant weather events have in Toronto and why?) posed in the study.

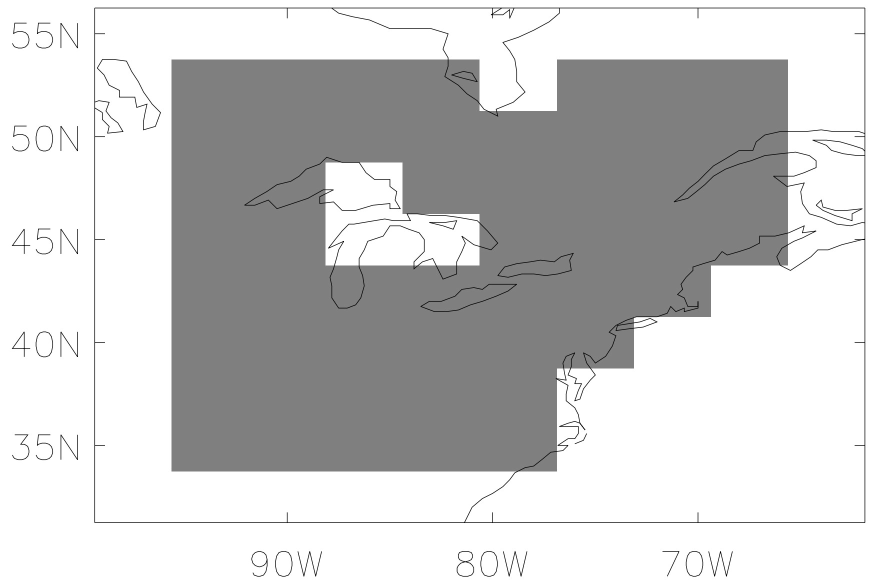
The third step was to compare the outputs from the present and the future climate simulation in order to provide insight what Toronto's future weather and climate will be thereby directly answering Question 3's what will be Toronto's future weather and climate, as well as providing insight into Question 2 (How are Toronto's current weather and climate drivers expected to change and why?).

4.5 INTRODUCTION TO THE CLIMATE MODEL USED

4.5.1 Introduction

Not all climate models show the same thing. Because of this 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 Figure 26 for the distribution of land and water grid cells of HadCM3) 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 (Version 1.8.2). However, the projected future change in climate from this ensemble member may not necessarily be the most representative of the future; it is just one illustrative projection of many. 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 was also 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 26 Great Lakes Region Used to Assess the Perturbed Physics Ensemble



4.5.2 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.

4.5.3 Comparisons of Climate Model Ensemble with Observations

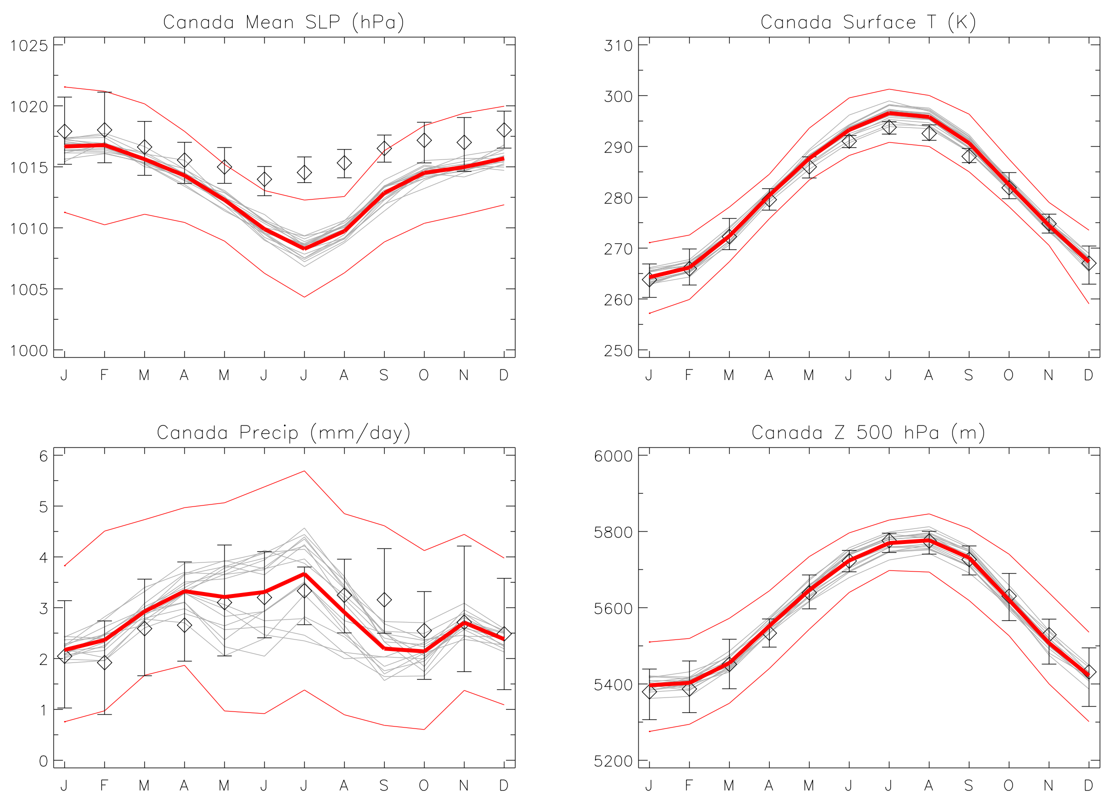
Observations and model data for the shaded region shown in Figure 26 were extracted and used in the assessment of the global climate model, as this area was simulated in more detail using the regional climate model, PRECIS. A comparison of the entire perturbed physics ensemble with the four sets of observations is shown in Figure 27.

The data shown in Figure 27 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 according to Hadley.

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 (QUMP 15) was selected to drive the regional climate model for the 2040s simulation.

In Figure 27, 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 27 Comparison of Modelled vs. Observed Parameters (1961-1990)



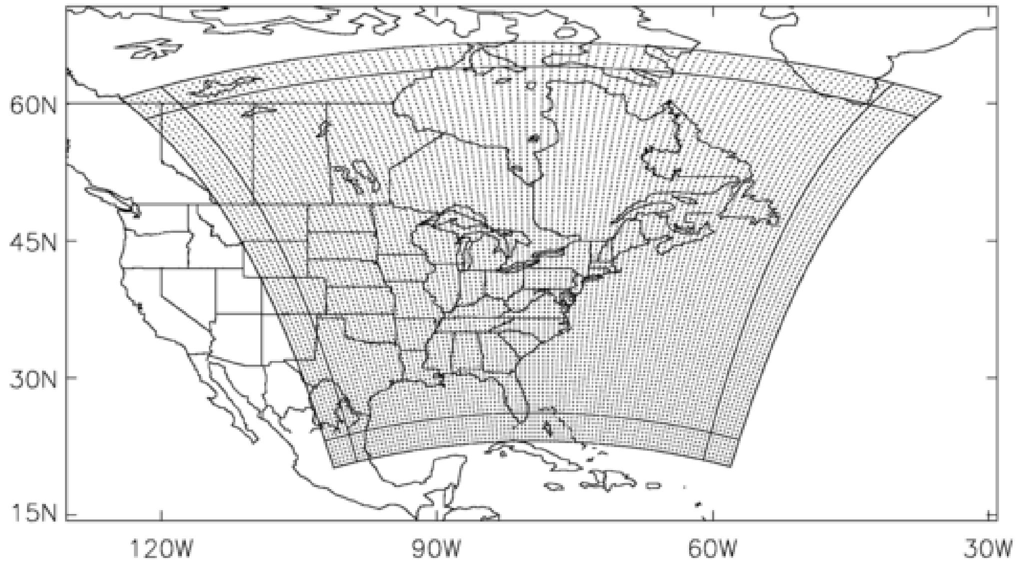
4.5.4 Global and Regional Models

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 (Version 1.8.2). 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). Earlier versions of PRECIS itself have 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 (Version 1.8.2) is shown in Figure 28. The inner region of Figure 28 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 is 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 28 Map Showing the Regional Climate Model (PRECIS) Domain



4.5.5 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.

4.6 INTRODUCTION TO THE WEATHER MODEL USED

4.6.1 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.

4.6.1.1 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 29 which also shows the extent of the computational grid used.

Figure 29 Terrain Data Used for the FReSH Small Modelling Domain (1x1 km)

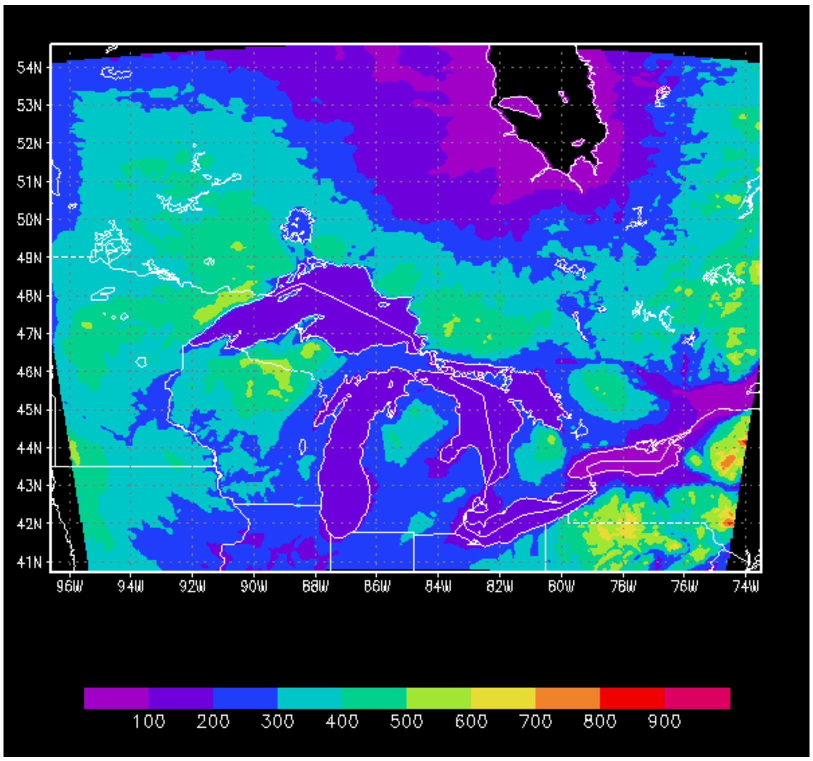
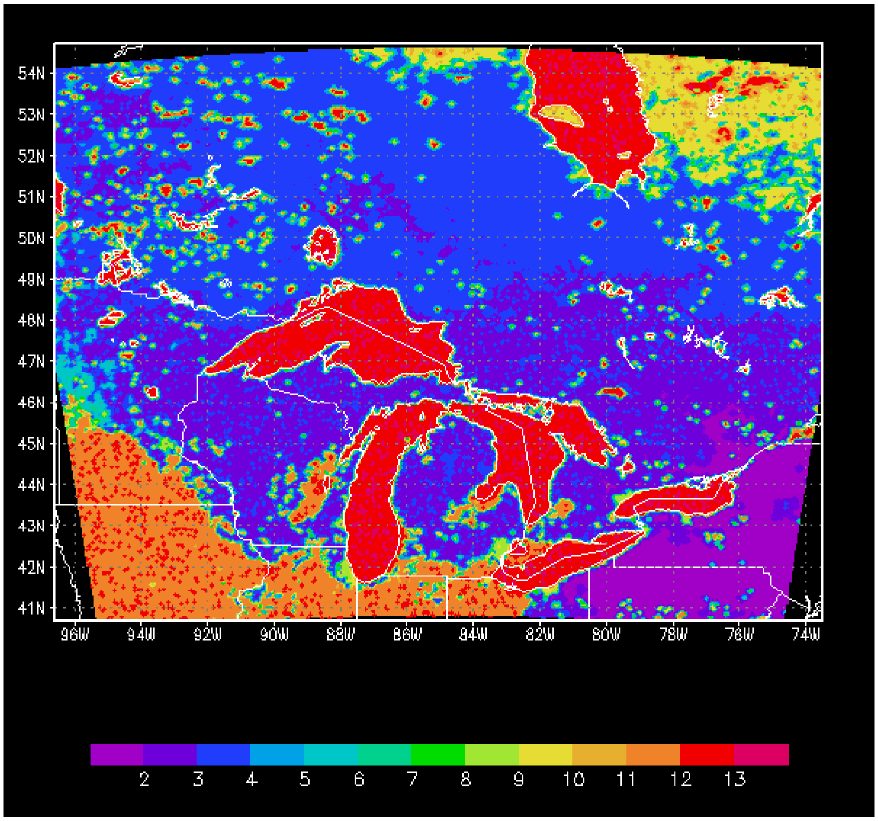


Figure 30 shows the vegetation data used as an input to FReSH system, based on GTOPO-30 global USGS land use data.

Figure 30 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

4.6.1.2 The Weather Forecast Model

The main component of FReSH system is the NMM[7] 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 31) over a larger area to ensure that the inflow to the GTA was correct and a 1x1km grid (Figure 32) over the GTA to allow local details to be properly incorporated.

[7] 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 31 4x4 Kilometre Grid Used for Upwind FReSH Modelling

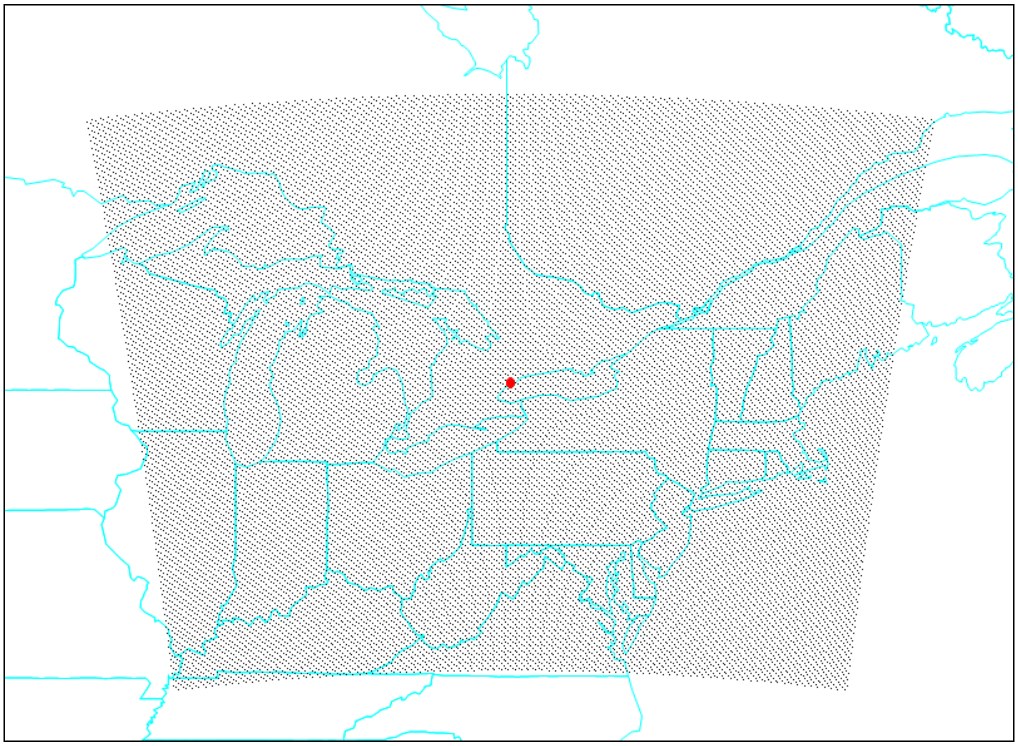
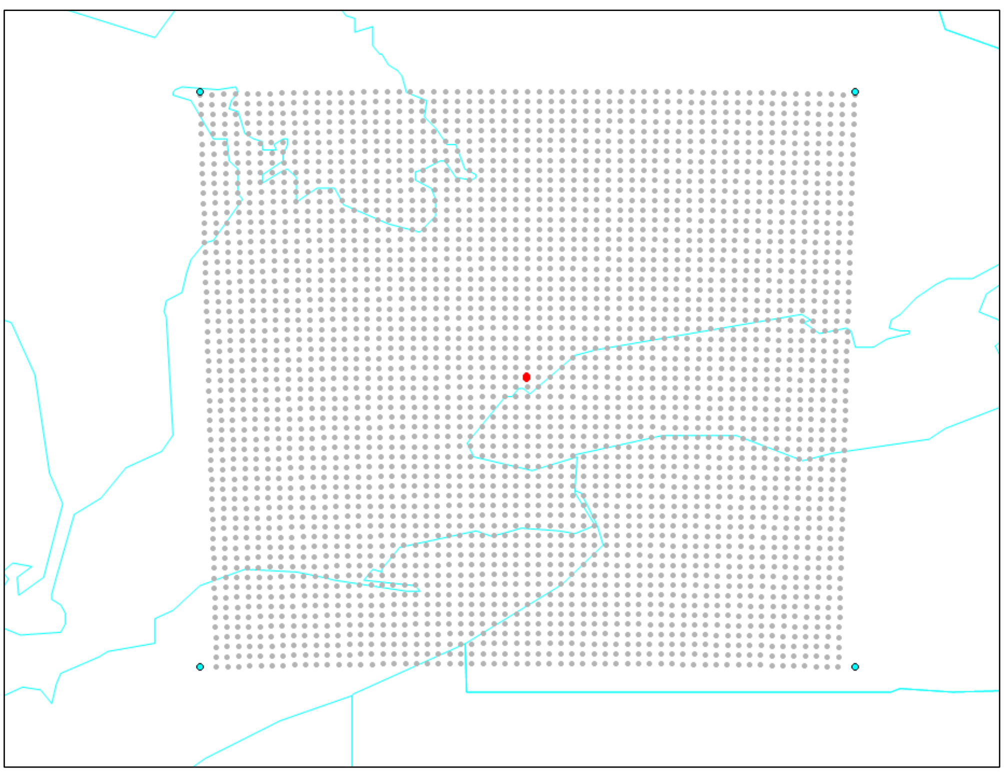


Figure 32 1x1 Kilometre Grid Used for Detailed GTA FReSH Modelling



4.6.1.3 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.

4.6.1.4 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 31) resolution and was nested down to 1x1 km (Figure 32) to refine and resolve thunderstorms 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.

4.6.2 How is FReSH Driven?

Table 5 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-dimesional 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 to the City of Toronto. Table 5 also shows for future conditions, that 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 5 How the Climate and Weather Model was Used

Approach	Observations	Data	Model	Produces	Model	Produces	City Forecasts
Weather Forecasting System							
SENES HISTORICAL WEATHER	world-wide every 12 hours on a spacing of ~350km	4-dimensional balancing of forces to produce global analysis fields every 12 hours	global forecast	use 365 days of 6-hourly analysis fields out to 24-hours	WRF-NMM	every hour on a 4x4 km grid over area of interest	nest WRF-NMM down to give 1x1 km outputs every hour (or less)
Climate Weather Forecasting System							
SENES CLIMATE CHANGE			Global Climate Model driving a Regional Climate Model	6-hourly fields for one year based on a climate scenario on a 50x50 km grid	WRF-NMM	every hour on a 4x4 km grid over area of interest	nest WRF-NMM down to give 1x1 km outputs every hour (or less)

The key attributes of the FReSH Forecasting System compared to other weather forecast models are given in Table 6.

Table 6 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

4.7 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.

4.7.1 How Well Does the Local Weather Model Work?

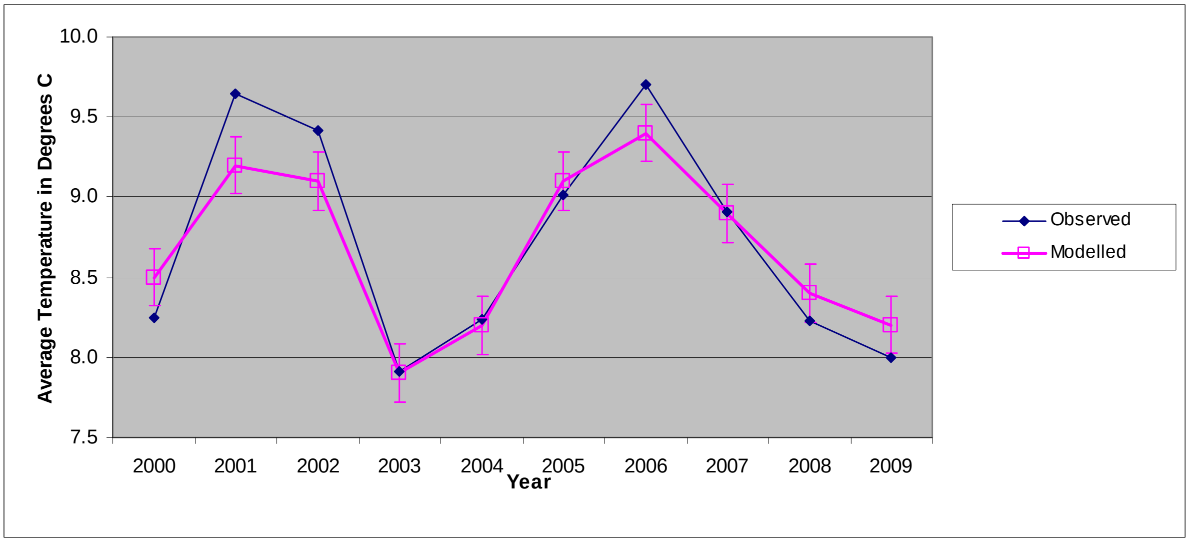
This section will present the weather model's capability to reproduce real observations. It confirms that the modelling approach is capable of correctly simulating the weather and climate over the GTA. The comparison shows that weather parameters can be correctly simulated when weather driving parameters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

4.7.1.1 Temperature

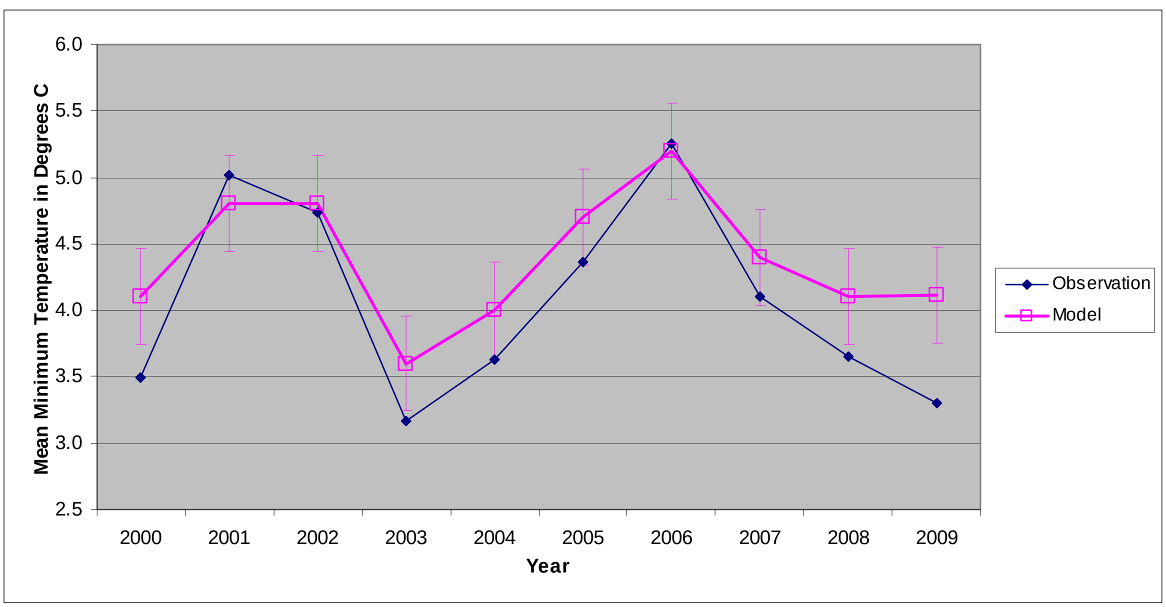
Figure 33 presents annual average, mean minimum and mean maximum temperatures for Pearson Airport vs. FReSH modelling simulations (at the Pearson Airport output point) based on the analysis data. The figure also presents the mean absolute error (difference between modelled and observed values) for the model results.

Figure 33 Model vs. Observations – Pearson Airport

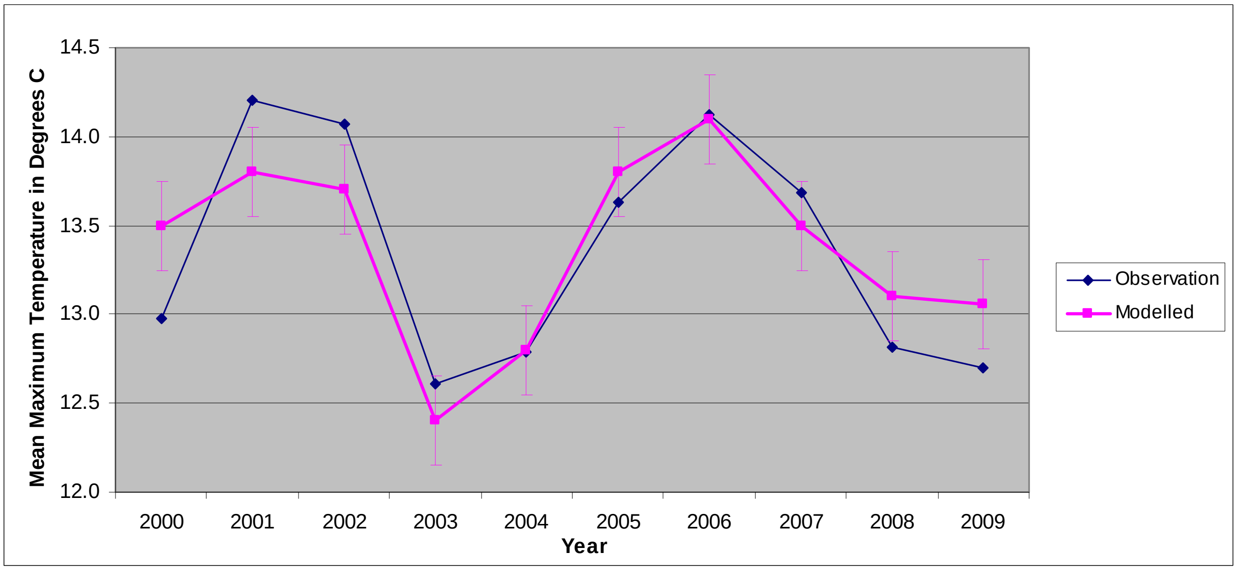
a) Average Temperature



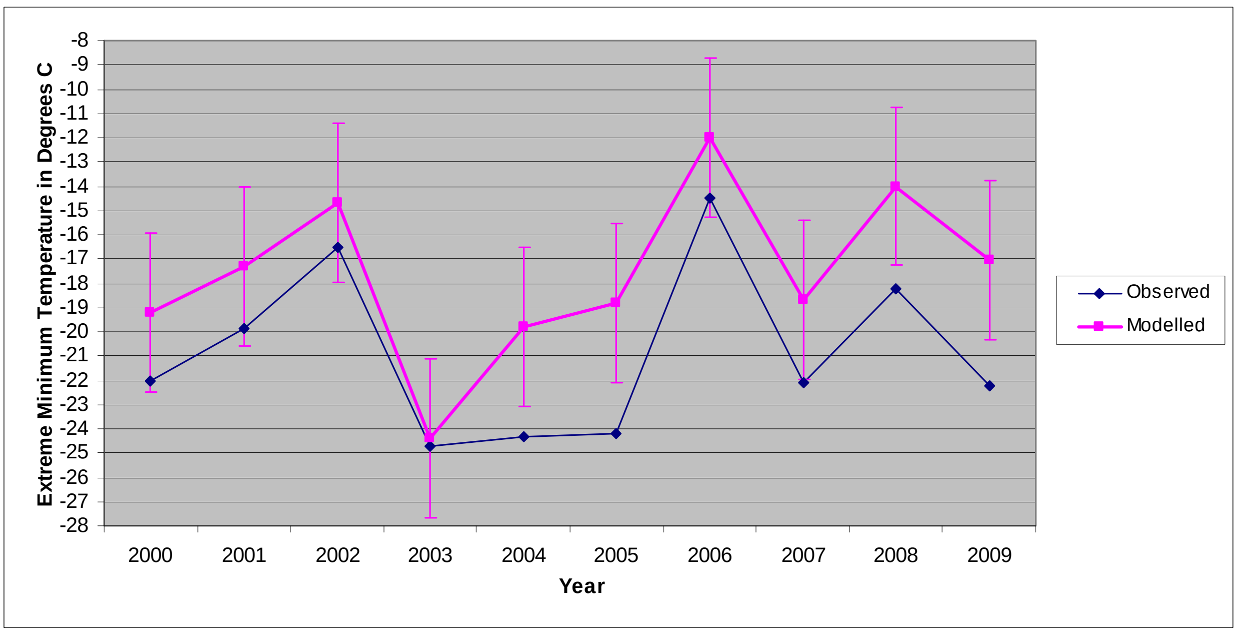
b) Mean Minimum Temperature



c) Mean Maximum Temperature



d) Extreme Minimum Temperature



e) Extreme Maximum Temperature

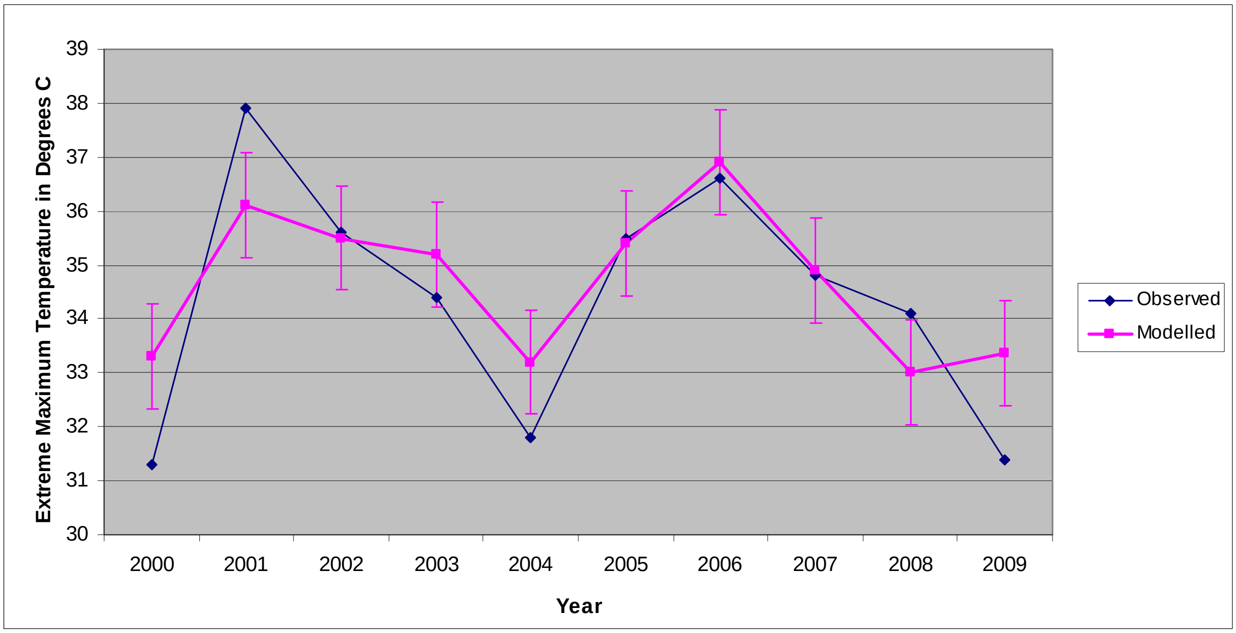


Figure 33a through Figure 33e demonstrate that the model reproduces the average, minimum and maximum temperatures quite well, as well as the extreme maximum, while the extreme minimum temperatures are under-estimated by about 19% on average over the 10 year period.

4.7.1.2 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 metres.

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 (as in our case 1 km) then the precipitation parameterization will simulate more successfully the smaller, convective scale type of precipitation and extreme precipitation events. This was demonstrated here for the case of the re-simulation of the August 19, 2005 – Finch Avenue washout storm. 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 because the corrections will just cancel each other out.

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

The results for total annual precipitation are presented in Figure 34. Figure 35 presents total rainfall in comparison with observed data and Figure 36 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 34 Total PRECIPITATION – Model vs. Observations – Pearson Airport

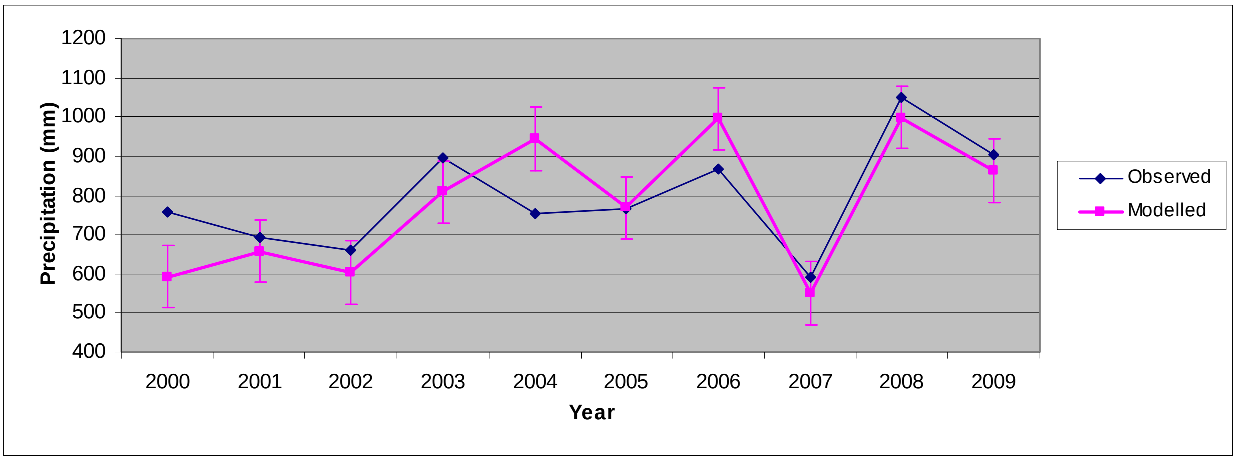


Figure 35 Total RAINFALL – Model vs. Observations – Pearson Airport

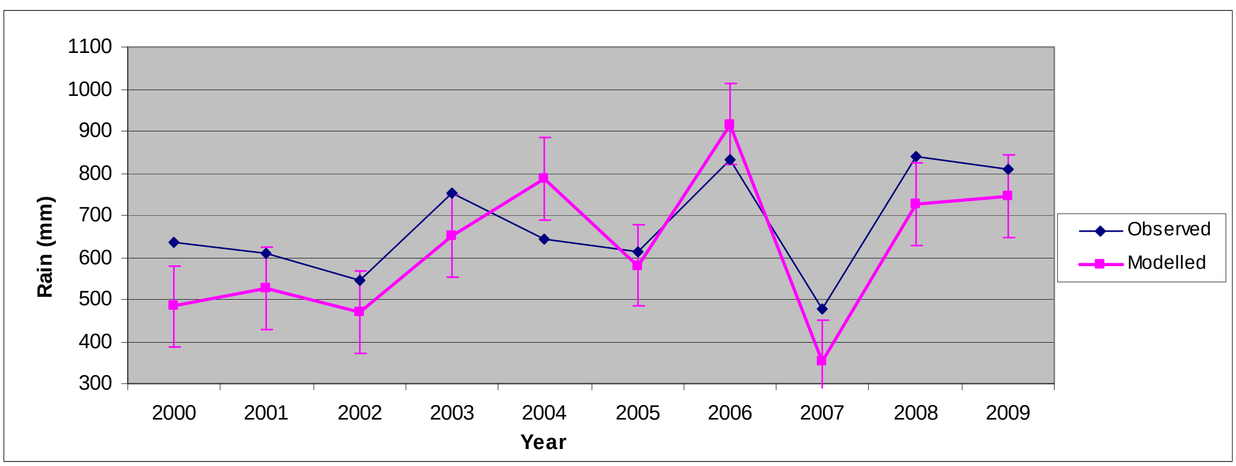
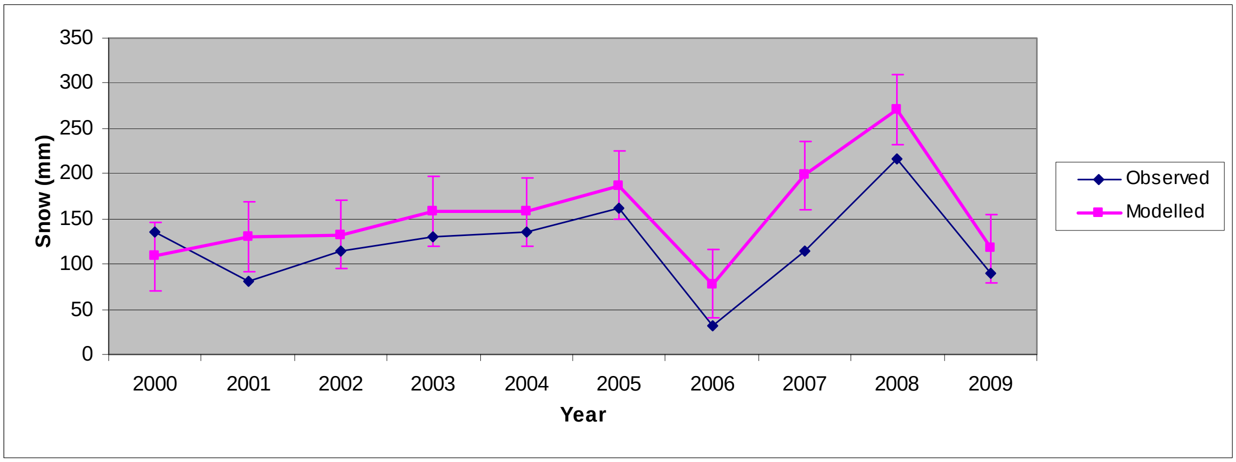


Figure 36 Total SNOWFALL - Model vs. Observations – Pearson Airport



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

4.7.1.3 Wind

The results for average wind speed are presented in Figure 37. Figure 38 presents maximum wind speed compared to observed data and Figure 39 shows predicted gust winds in comparison with measurements. The figures also present the mean absolute error (difference between modelled and observed values) for the model results. It should be noted that the average model error for wind speed is expected to be about 1 metre/second or 4 km/hour based on current comparisons between weather model predictions and observed winds. Figure 37 shows that the average error for this project is about 2 km/hour.

Figure 37 Average Wind Speed – Model vs. Observations – Pearson Airport

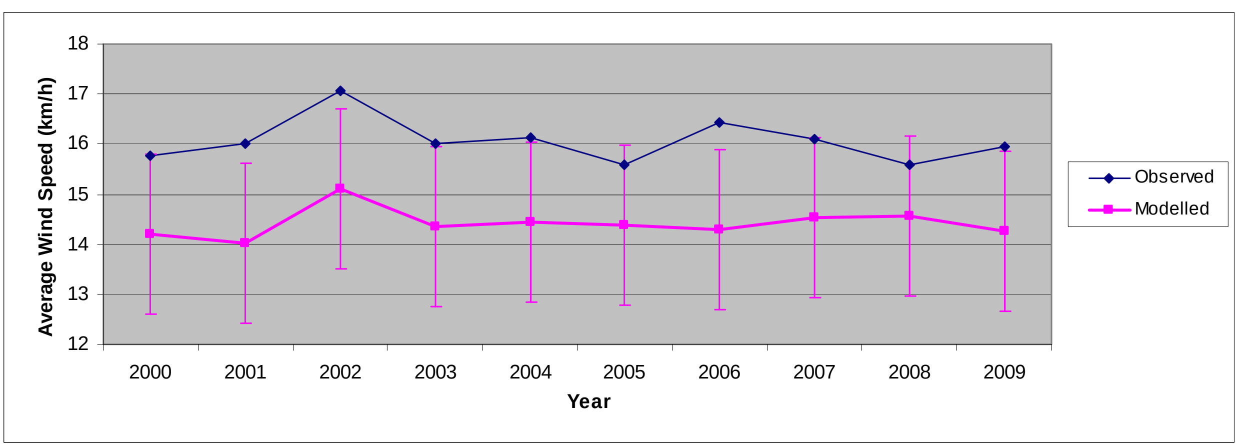


Figure 38 Maximum Wind Speed – Model vs. Observations – Pearson Airport

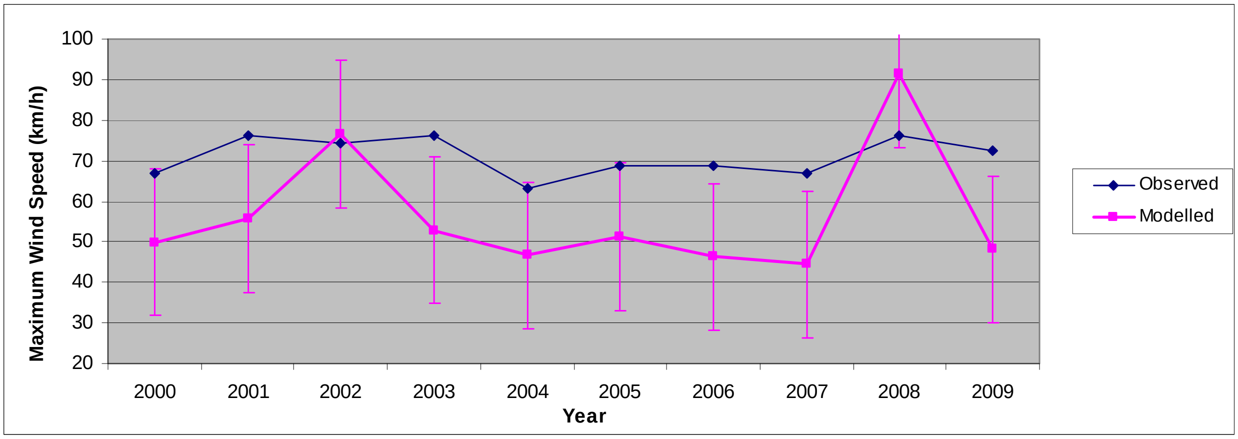
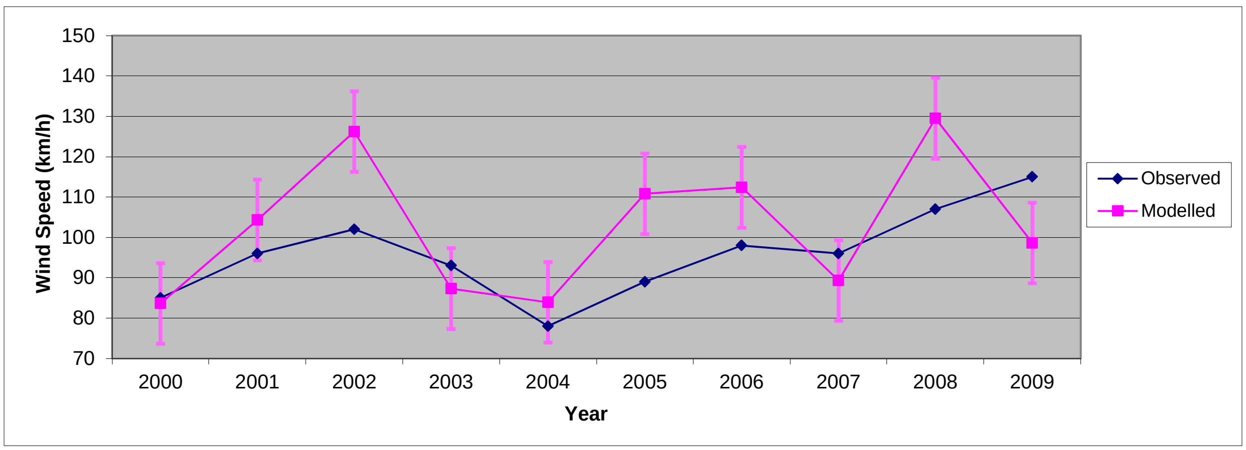


Figure 39 Gust Wind Speed – Model vs. Observations – Pearson Airport



The model predicts well the average wind speed. The 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.

4.7.1.4 Specific Historical Event

19 August 2005 – The Finch Avenue Washout

On 19 August 2005, a small scale micro-burst event that occurred over Toronto washed out a culvert on Finch Avenue. As part of this study, SENES Consultants Limited re-analyzed that particular storm. Figure 40 and Figure 41 present the results of a 1x1 kilometre grid simulation of that day for the Finch and Dufferin Streets area. The pink dot represents the total observed rainfall for that day from a single point observation near the location.

Figure 40 Cumulative Hourly Rainfall Simulation near Finch and Dufferin

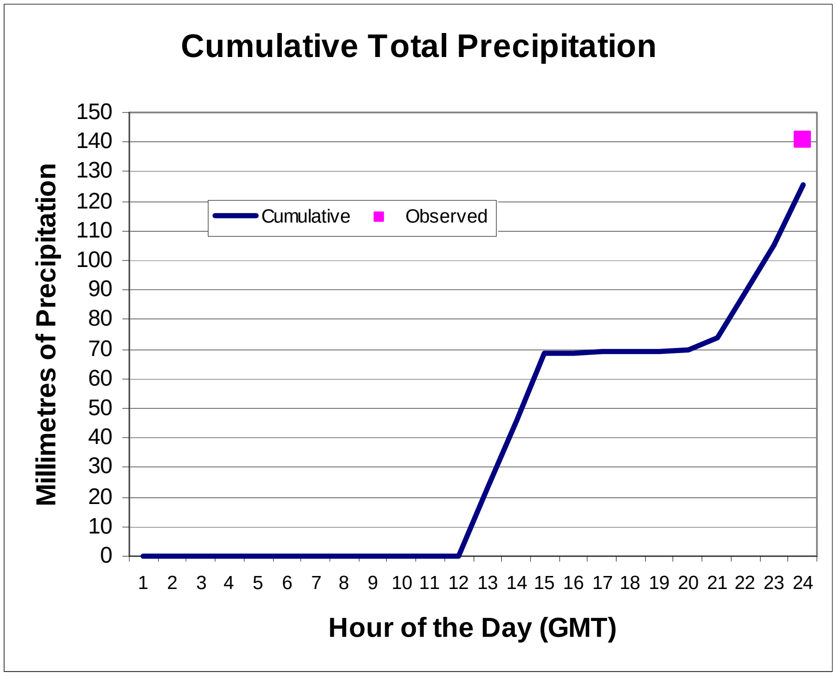


Figure 41 Hour-by-hour Rainfall Simulation near Finch and Dufferin

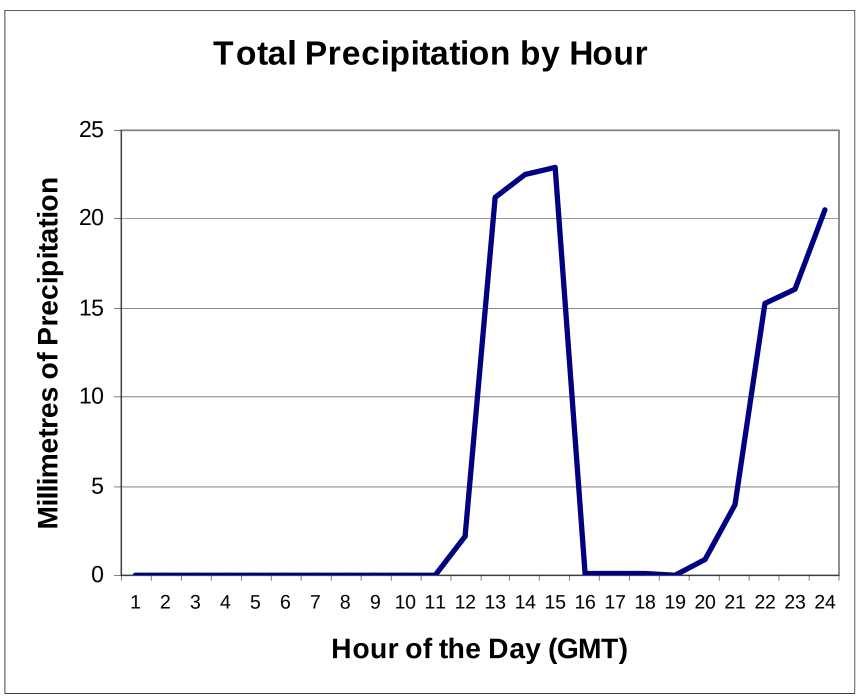
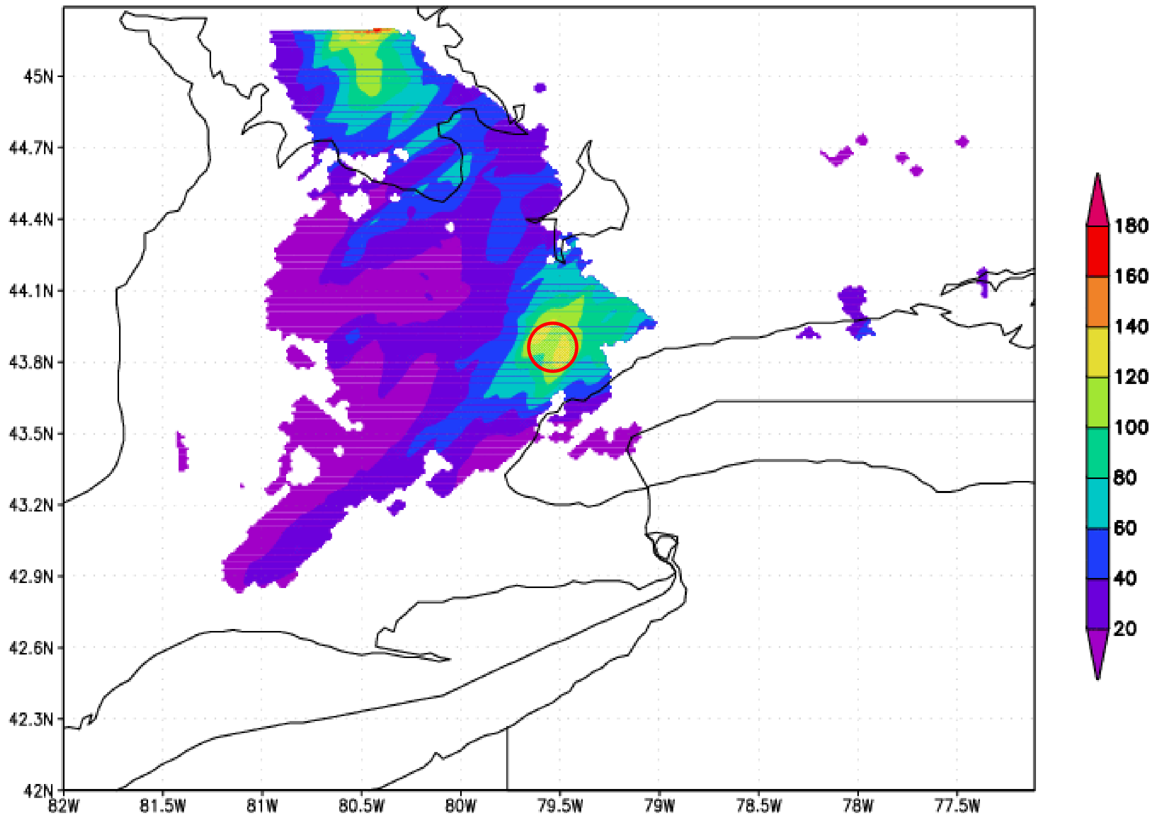


Figure 40 shows the cumulative hourly forecast details for a point close to the washout and Figure 41 shows the hour-by-hour details. Figure 42 presents the modelled total precipitation over the day for the GTA with the heavy rainfall over the area within a few kilometres of the washout (see red circle).

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 on a fine grid. From Figure 42 we see that the total rainfall during this day over the GTA was up to 180 mm. The simulation reflects the fact that under the high winds that were occurring two storm cells merged and additional convective rain was produced. This means that during the 2-hour period, from 1700-1900 local time, a total of 69 mm of rain was predicted to fall in the Finch-Dufferin area (well over half the rain that was observed to fall in that day).

What is important to note here is that while the official measurement made at Pearson Airport for this day was a total of 43 mm of precipitation, significantly more than that actually fell in the Dufferin-Finch area. It should also be pointed out that additional monitoring that was in place just north of the affected area did show the higher levels of precipitation in the same range shown in Figure 42 from the model simulation. This figure also points out that the model and grid size used better simulates these extreme conditions.

Figure 42 Map of Total Precipitation over the GTA on 19 August 2005



4.7.2 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.

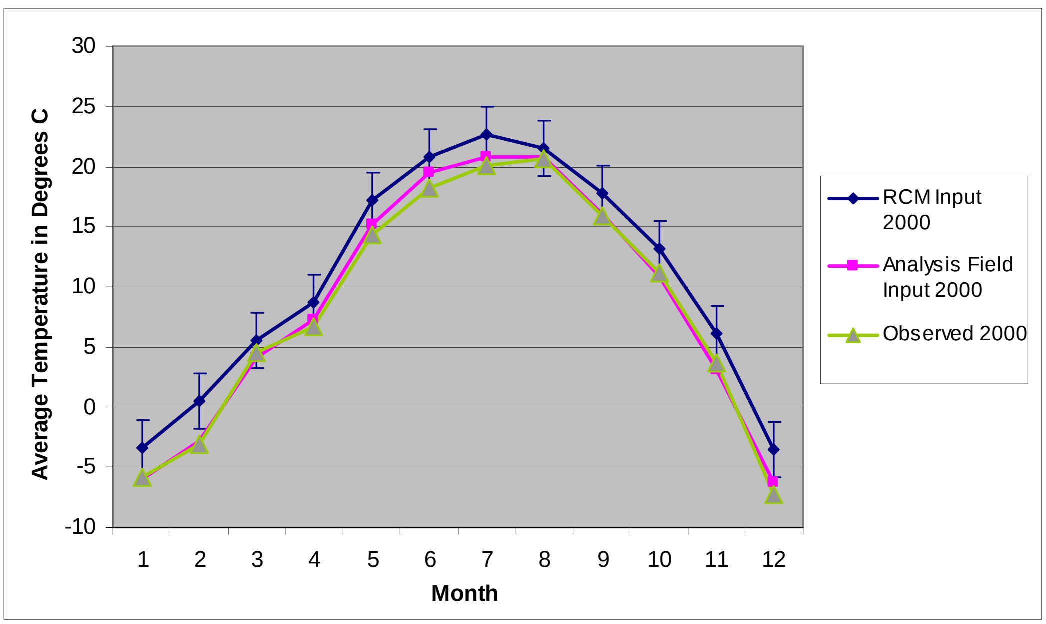
It should be noted that, since FReSH is driven by the output from the PRECIS Regional Climate Model (RCM), hour-by-hour comparisons with observational (single station) data are not expected to match, but the descriptive statistics of the hour-by-hour output for the period simulated is expected to provide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

4.7.2.1 Temperature

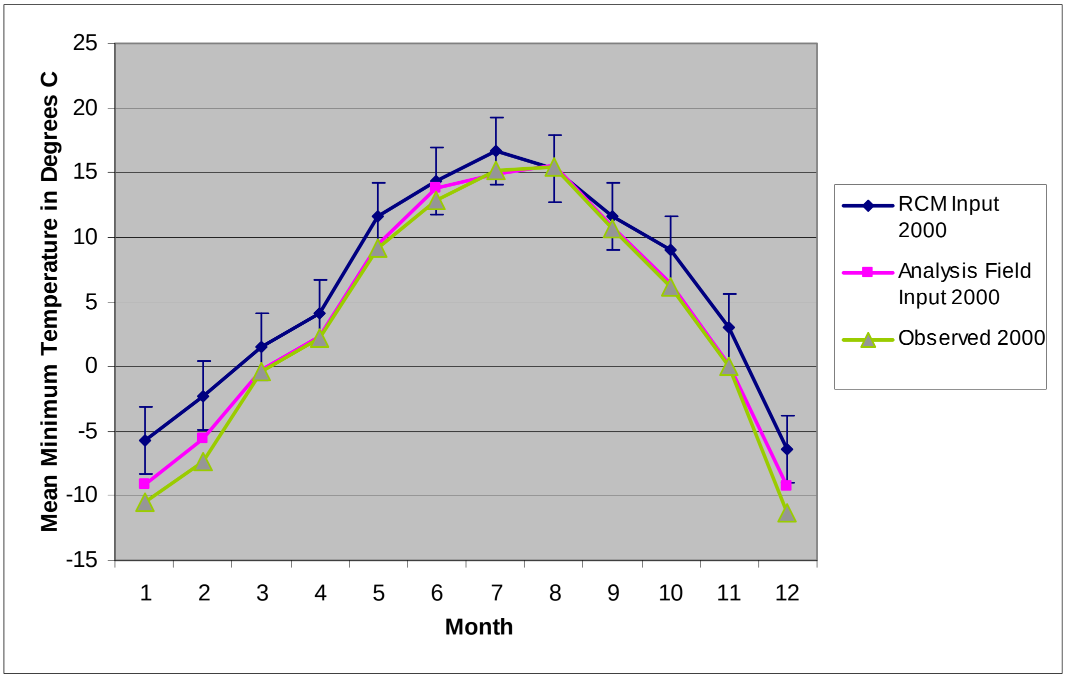
Figure 43 presents the average, mean minimum and mean maximum temperatures for the year 2000 for the Pearson Airport vs. FReSH modelling simulation driven by (1) the analysis fields (Analysis Field Input) and (2) the regional climate model (RCM Input). This comparison shows the capability of the combined 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 43 Pearson Airport - Observed vs. Modelled Temperatures - 2000

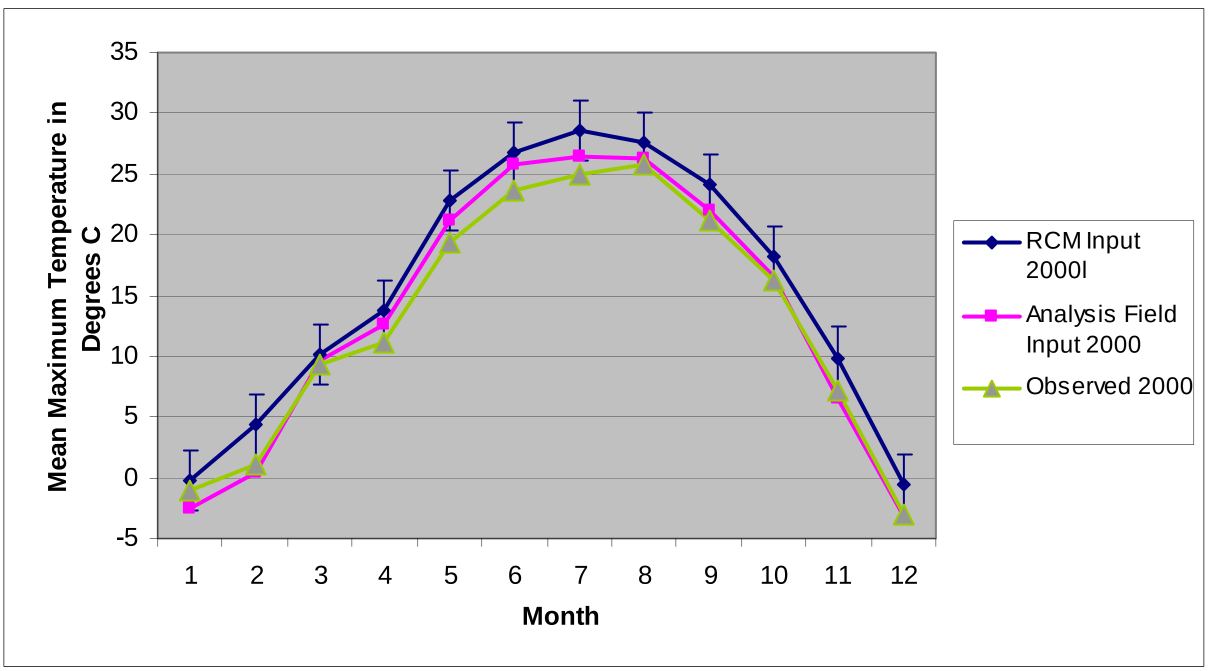
a) Average Temperature



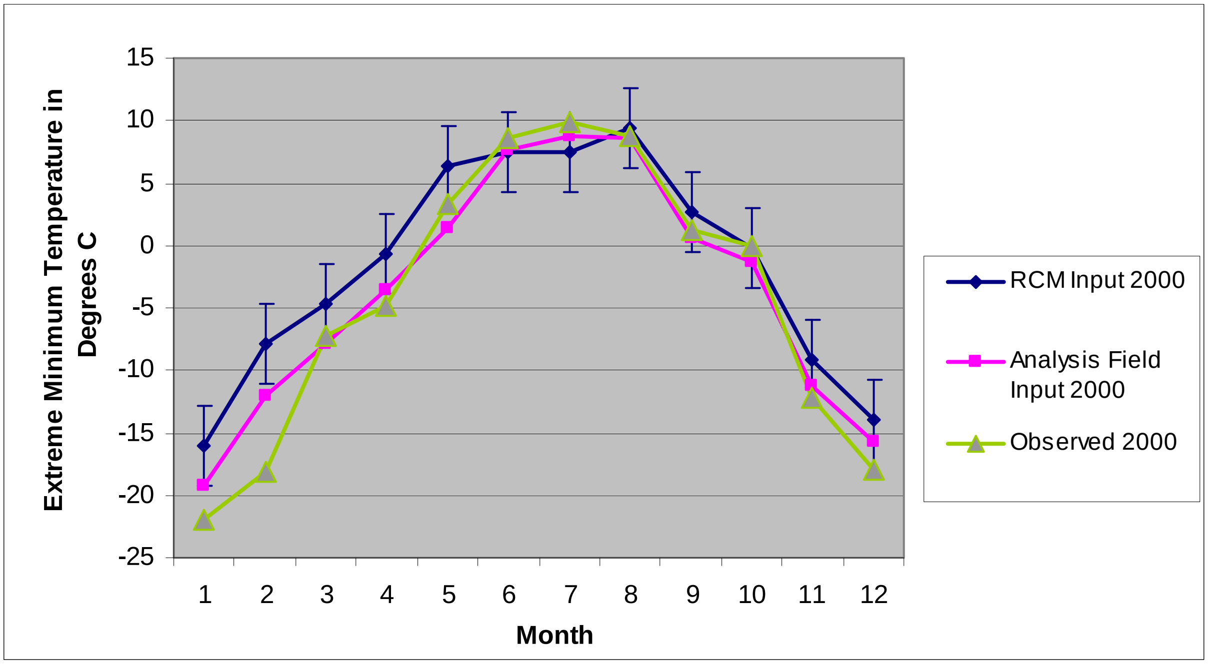
b) Mean Minimum Temperature



c) Mean Maximum Temperature



d) Extreme Minimum Temperature



e) Extreme Maximum Temperature

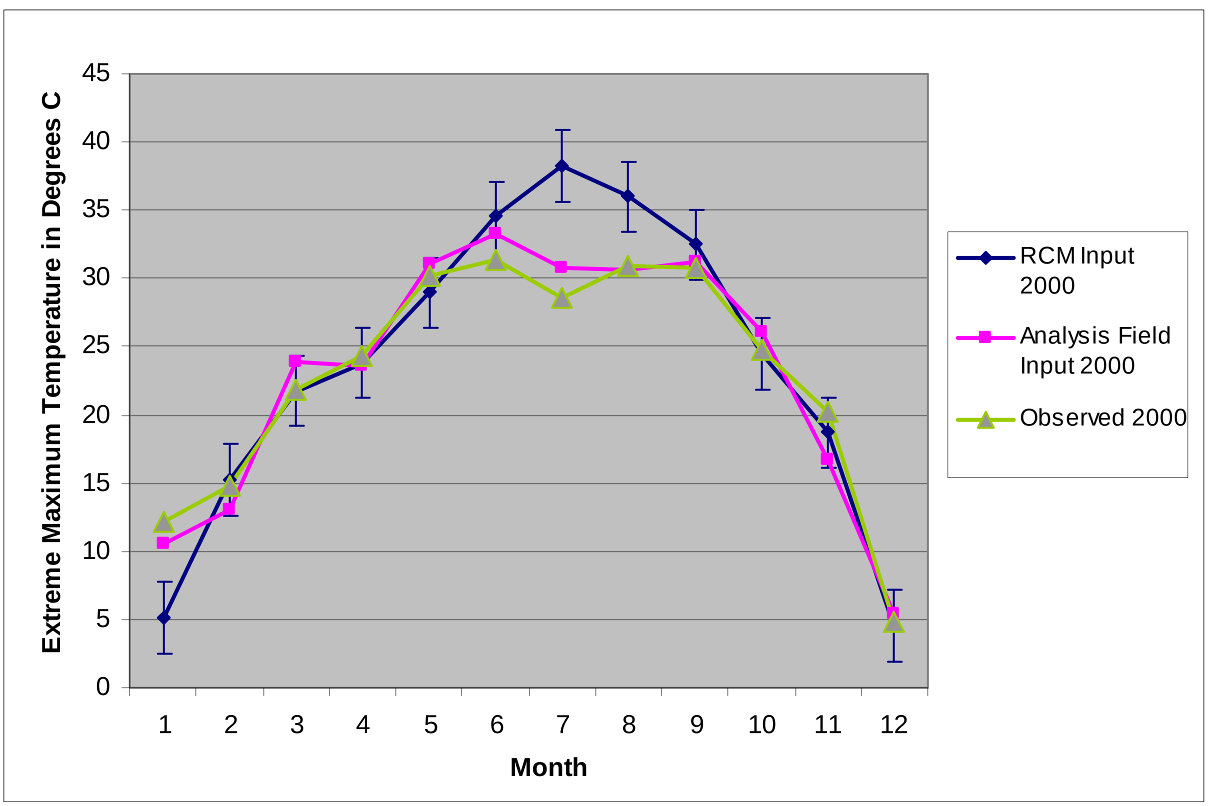


Figure 43a through Figure 43e demonstrate that the model driven by the analysis fields can reproduce the average, mean minimum, mean maximum and extreme maximum temperatures quite well, while the extreme minimum temperatures are under-estimated by about 13% for year 2000. Figure 43e does show the weakness 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 - Main Sources of Uncertainty).

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. While climate models are often adjusted to remove this bias, SENES prefers to simply present the model error/bias rather than hiding or removing it so that the reader gets a better sense of how well the model performs and how much confidence we can have in it.

4.7.2.2 Precipitation

The results for total precipitation for 2000 are presented in Table 7. This table summarizes the rain, the snow and total precipitation for year 2000. Variability on a monthly basis is larger.

Table 7 Pearson Airport - Observed vs. Modelled Precipitation – Year 2000

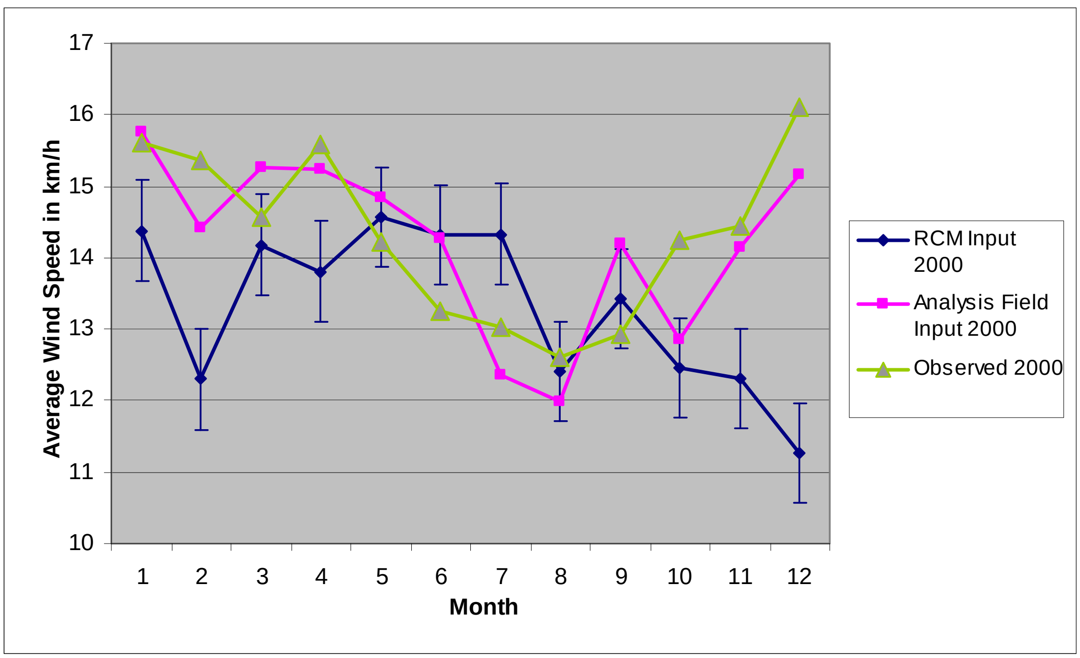
Parameter	Model Driven by		Observed
	Analysis Fields	RCM Fields	
Rainfall (mm)	483.3	485.4	635.2
Snowfall (cm)	108.5	71.0	135.7
Precipitation (mm)	591.9	556.4	755.7
Extreme Daily Rainfall (mm)	47.6	61.4	59.4
Extreme Daily Snowfall (cm)	16.3	7.5	12.4
Extreme Daily Precipitation (mm)	47.6	61.4	59.4

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 extreme daily snowfall is better predicted using the analysis data (within ~31%). For the purpose of estimating the uncertainty of the future extreme snowfall, the data 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 34) 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.

4.7.2.3 Wind

The results for average wind speed are presented in Figure 44. Figure 45 presents maximum wind speed in comparison with observed data and Figure 46 shows predicted gust speed in comparison with measurements. The figure also presents the mean absolute error (difference between modelled and observed values) for the model results. It should be noted that current weather models are only expected to predict winds within about 4 km/hour of the correct value. The mean absolute error is just over 1 km/hour and even for the specific year (2000) under test the error ranges from about 0.5 to 5 km/hour.

Figure 44 Pearson Airport - Observed vs. Modelled Average Wind Speed - 2000



The model predicts well the average wind speed observed at Pearson Airport. Again Figure 44 shows the weakness of using a climate model to simulate a particular year or month in that December wind speeds have not been properly projected even though the error is within that expected from a weather forecast model (4 km/hour). 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. It should be noted that maximum wind speeds will be controlled by local obstacles and we should not expect a model with a grid spacing of 1 kilometre to accurately reflect the maximum wind speed at a specific point.

Figure 45 Pearson Airport - Observed vs. Modelled Maximum Wind Speed - 2000

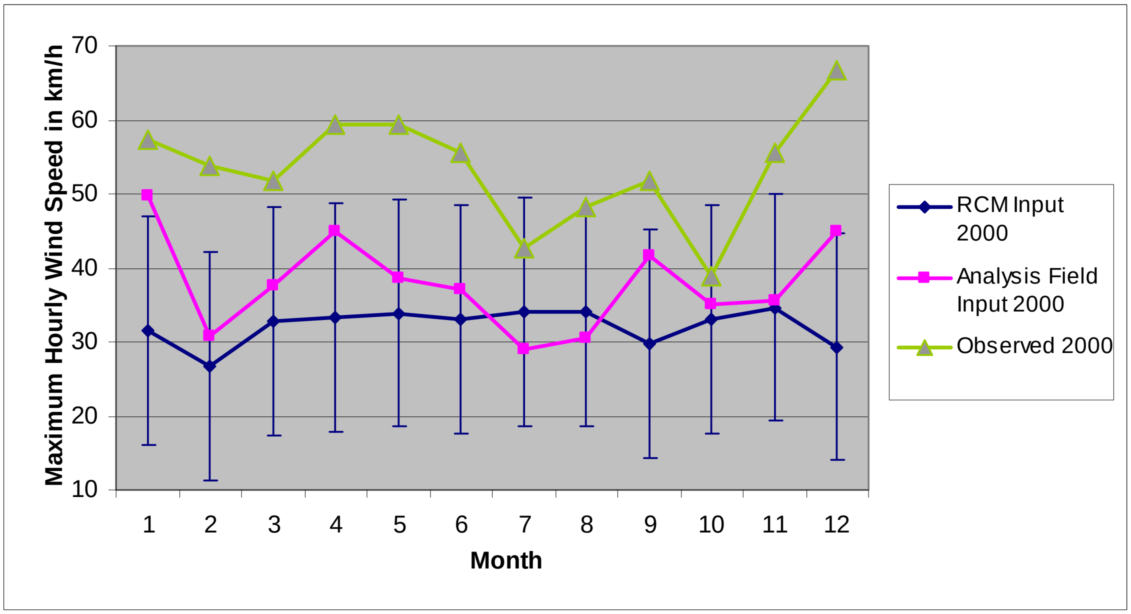
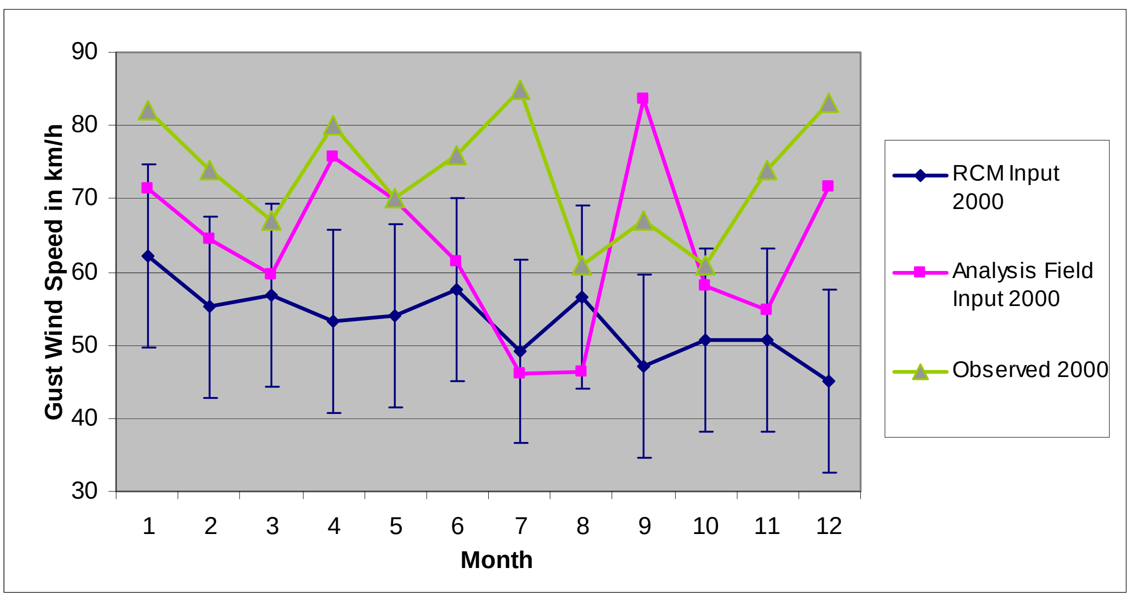


Figure 46 Pearson Airport – Observed vs. Modelled Gust Wind – 2000



4.8 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 climate can produce a very good representation of the current weather with precision and accuracy that can be quantified as presented in Table 8. This means that using the same approach to infer future detailed local weather statistics will likely have the same precision and accuracy.

Table 8 Bias Statistics for NMM vs. Observation –Pearson Airport - 2000

Measure of Bias	WS	WD	TEMP
	km/hour	degrees	°C
Good Performance	< ±7.2	< ±45	<±2
Fair Performance	< ±14.4	< ±.90	<±4
Poor Performance	> ±21.6	> ±90	<±6
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 best sensitivity commonly identified for Regional Climate Model analyses of 2.4 to 5.4°C. The data shows that future average temperatures will be overestimated by about 2.3°C which is the best performance one expects from a Regional Climate Model. The future daily mean maxima and mean minima are also estimated to be high by 2.4 and 2.6°C, respectively. The future extreme maximum temperature is overestimated by ~7°C and the extreme minimum temperature is underestimated by ~6°C.

Future total precipitation is estimated to be under-predicted by 35%. Future extreme rainfall seems to be well predicted with an error of only 3% while extreme snowfall is estimated to have an error of about 40%.

Future average wind speeds will be underestimated by about 15% while the maximum wind speeds will be underestimated by about 20%. The gust winds will be underestimated by about 10%.

5.0 WHAT IS THE FUTURE (2040-2049) WEATHER EXPECTED TO BE?

This chapter presents some illustrative results for one station, Pearson Airport, extracted from the hour-by-hour simulations of the future period (2040-2049) driven by the A1B climate change scenario that gives the largest convective response. A comparison is made with the current climate statistics (2000-2009). Volume 2 of this report presents results for the other selected locations across the GTA.

5.1 TEMPERATURE

An example of the results from the NMM simulation for 2000-2009 is presented in Table 9 for Pearson Airport.

An example of the results from the NMM simulation for 2040-2049 is presented in Table 10 for Pearson Airport.

Table 11 presents the differences between the future period and the present period.

Table 9 Pearson Airport Data - Temperature Summary for 2000-2009

Temperature	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Daily Average (°C)	-4.6	-4.5	-0.1	7.3	13.4	19.5	21.7	21.4	17.4	10.2	4.5	-2.0	8.7
Standard Deviation of Daily Average (°C)	4.5	3.8	4.6	4.8	3.9	3.7	2.6	2.9	3.5	4.3	3.8	3.6	3.8
Daily Maximum (°C)	-1.6	-1.1	4.2	12.7	19.3	25.4	27.5	27.0	22.9	14.9	8.3	0.7	13.3
Standard Deviation of Daily Maximum (°C)	4.5	3.9	5.4	6.0	4.9	4.3	3.1	3.3	3.9	5.1	4.5	3.7	4.4
Daily Minimum (°C)	-7.2	-7.4	-3.6	2.4	7.5	13.5	15.8	15.8	12.4	6.2	1.5	-4.4	4.4
Standard Deviation of Daily Minimum (°C)	4.7	4.0	4.5	4.1	3.9	3.9	3.2	3.2	3.7	4.3	3.6	3.8	3.9
Extreme Maximum (°C)	14.5	13.1	23.9	29.6	34.0	35.2	36.2	36.9	32.7	31.2	19.3	16.4	36.9
Extreme Minimum (°C)	-20.5	-20.2	-24.4	-9.8	-1.2	0.7	6.1	8.0	0.7	-2.0	-11.2	-19.8	-24.4

Table 10 Pearson Airport Data - Temperature Summary for 2040-2049

Temperature	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Daily Average (°C)	1.3	2.2	5.1	10.2	17.3	22.9	25.5	25.5	21.0	14.9	8.2	2.7	13.1
Standard Deviation of Daily Average (°C)	3.1	3.3	3.3	4.2	3.7	3.6	2.7	2.8	3.9	4.1	3.3	3.1	3.4
Daily Maximum (°C)	4.1	5.4	9.3	15.1	22.9	29.0	31.7	31.5	26.5	20.0	12.0	5.9	17.8
Standard Deviation of Daily Maximum (°C)	3.3	3.8	4.0	5.0	4.5	4.4	3.3	3.3	4.4	4.8	3.4	3.2	4.0
Daily Minimum (°C)	-0.9	-0.2	1.6	5.6	11.6	16.7	19.7	20.1	16.2	10.5	5.2	0.2	8.9
Standard Deviation of Daily Minimum (°C)	3.2	3.4	3.1	4.1	3.7	3.5	2.7	2.9	4.0	4.2	3.6	3.2	3.5
Extreme Maximum (°C)	16.0	17.7	21.1	29.2	39.9	42.7	44.1	44.4	36.9	33.7	21.3	16.1	44.4
Extreme Minimum (°C)	-10.0	-9.6	-6.4	-4.3	2.9	5.1	11.7	11.7	3.7	0.4	-5.7	-11.4	-11.4

Table 11 Pearson Airport – Temperature Difference 2040-2049 to Present

Temperature	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Daily Average (°C)	5.9	6.7	5.2	2.9	3.9	3.4	3.8	4.1	3.6	4.8	3.7	4.7	4.4
Standard Deviation of Daily Average (°C)	-1.4	-0.5	-1.4	-0.6	-0.2	-0.1	0.1	0.0	0.4	-0.2	-0.6	-0.6	-0.4
Daily Maximum (°C)	5.8	6.6	5.1	2.4	3.5	3.6	4.2	4.5	3.6	5.1	3.7	5.2	4.4
Standard Deviation of Daily Maximum (°C)	-1.2	-0.2	-1.4	-1.0	-0.4	0.2	0.2	0.0	0.5	-0.3	-1.1	-0.4	-0.4
Daily Minimum (°C)	6.3	7.1	5.3	3.2	4.1	3.2	3.9	4.3	3.8	4.3	3.7	4.6	4.5
Standard Deviation of Daily Minimum (°C)	-1.5	-0.6	-1.5	0.0	-0.1	-0.4	-0.5	-0.3	0.3	0.0	0.0	-0.5	-0.4
Extreme Maximum (°C)	1.5	4.6	-2.8	-0.3	5.9	7.4	7.9	7.6	4.2	2.4	2.0	-0.3	7.6
Extreme Minimum (°C)	10.5	10.6	18.0	5.5	4.1	4.4	5.6	3.8	3.0	2.4	5.5	8.3	13.0

Figure 47 shows the temperature differences between the current and future period, over the entire GTA.

Comparing Table 9 with Table 10 indicates that the future period is projected to be about 4.4 degrees warmer on average at Pearson Airport (i.e. 13.1°C – 8.7°C = 4.4°C) and that the extreme maximum and minimum temperatures could be 11.5 and 13.0 degrees warmer than today, respectively. A more detailed look at the monthly average differences, between the current and future period for the Pearson Airport location, is presented in Chapter 6.

Table 12 and Table 13 present the number of days [8]of temperatures experienced within certain ranges. Examining these tables we see that in the current period, the number of days per year above 20 ^{0}C is 132.7 days and in the future period this is increased to 160.3 days, an increase of about 28 days. The number of days per year above 0 ^{0}C is increased by approximately 16%. The number of days per year below 10 ^{0}C is reduced from 24.6 days, to 0.3. These tables can give valuable results for future building code design parameters.

Table 12 Pearson Airport - Temperature Day Summary - 2000-2009

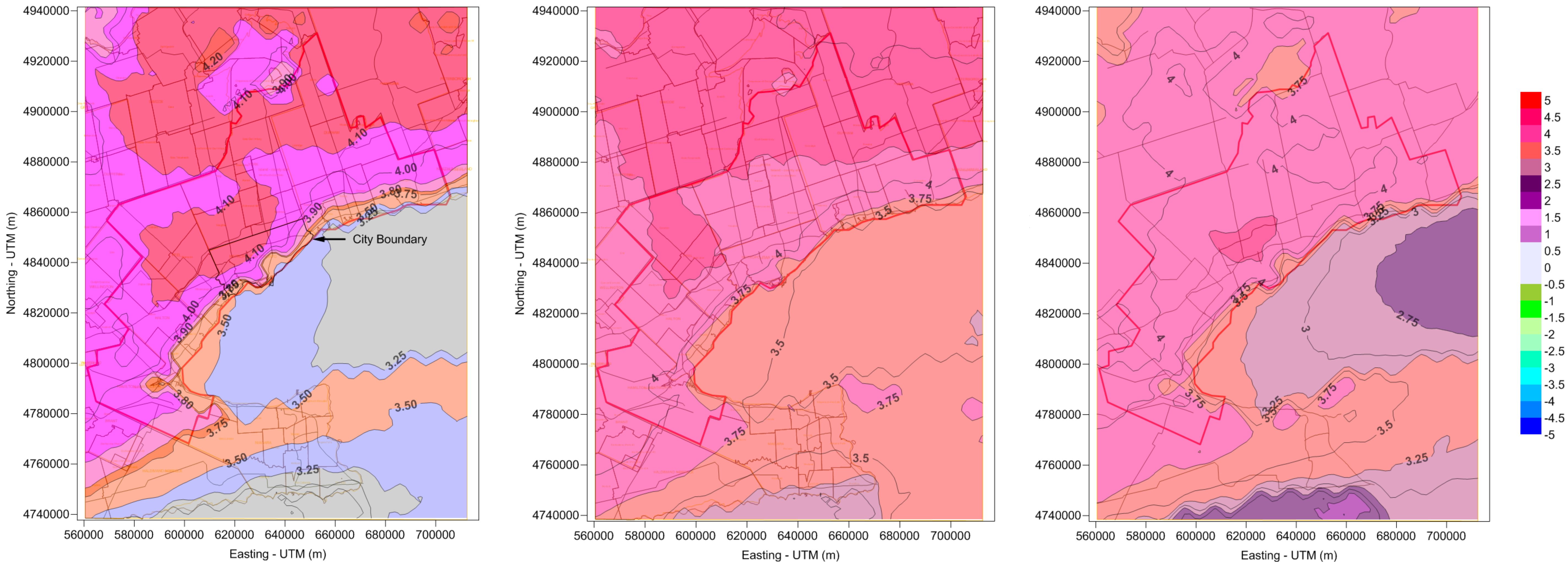
Max Temp (deg C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
<= 0 C	19.1	17.0	7.5	0.4	0.0	0.0	0.0	0.0	0.0	0.0	1.3	13.0	58.3
> 0 C	11.8	11.3	23.5	29.6	31.0	30.0	31.0	31.0	30.0	31.0	28.7	18.0	306.9
> 10 C	0.7	0.4	5.6	19.4	30.3	30.0	31.0	31.0	29.9	24.2	10.4	0.8	213.7
> 20 C	0.0	0.0	0.4	4.5	13.1	25.7	30.7	30.6	22.1	5.6	0.0	0.0	132.7
> 30 C	0.0	0.0	0.0	0.0	0.7	5.5	7.2	5.3	1.3	0.2	0.0	0.0	20.2
> 35 C	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.3	0.0	0.0	0.0	0.0	0.8
Min Temp (deg C)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
> 0 C	2.9	1.5	7.1	21.3	30.1	30.0	31.0	31.0	30.0	28.8	18.6	4.9	237.2
<= 2 C	30.1	27.6	27.1	15.3	3.2	0.1	0.0	0.0	0.2	6.5	17.6	29.7	157.4
<= 0 C	28.1	26.8	23.9	8.7	0.9	0.0	0.0	0.0	0.0	2.2	11.4	26.1	128.1
< -2 C	24.5	25.1	18.4	3.9	0.0	0.0	0.0	0.0	0.0	0.1	5.1	21.2	98.3
< -10 C	10.0	8.0	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	3.4	24.6
< -20 C	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
< -30 C	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 13 Pearson Airport - Temperature Day Summary - 2040-2049

Max Temp (deg C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
<= 0 C	3.7	3.6	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	9.7
> 0 C	27.3	24.4	30.5	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	29.2	355.3
> 10 C	2.2	4.8	14.4	25.0	31.0	30.0	31.0	31.0	30.0	30.9	19.9	4.8	255.0
> 20 C	0.0	0.0	0.3	5.9	21.7	29.3	30.9	31.0	26.6	14.2	0.4	0.0	160.3
> 30 C	0.0	0.0	0.0	0.0	2.2	12.6	21.7	21.0	8.3	0.4	0.0	0.0	66.2
> 35 C	0.0	0.0	0.0	0.0	0.4	3.9	4.8	4.5	0.4	0.0	0.0	0.0	14.1
Min Temp (deg C)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
> 0 C	10.8	12.8	18.8	26.7	31.0	30.0	31.0	31.0	30.0	31.0	26.9	15.5	295.5
<= 2 C	24.5	21.3	19.3	8.1	0.0	0.0	0.0	0.0	0.0	0.5	6.6	22.8	103.1
<= 0 C	20.2	15.2	12.2	3.3	0.0	0.0	0.0	0.0	0.0	0.0	3.1	15.5	69.5
< -2 C	11.3	8.5	4.4	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.8	7.3	33.2
< -10 C	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3
< -20 C	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
< -30 C	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

[8] It should be noted that the current period was driven by the analysis fields and covered all the days of the year. The future case (2040-2049) was driven by the output of the Regional Climate model which simulates months as having 29 days and February 27 days. All future model simulations of the number of days have been corrected for the actual number of days in each month so that they can be compared correctly against the 2000-2009 period.

Figure 47 Mean Daily Temperature Differences 2040-2049



Mean Daily Temperature Difference (°C) **Mean Daily Minimum Temperature Difference (°C)** **Mean Daily Maximum Temperature Difference (°C)**

5.2 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 of heating degree-days 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 14 and Table 15 present a summary of degree days for the periods 2000-2009 and 2040-2049, respectively.

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 10 degree days above 24 ^{0}C every year and in the future period this is increased to 179.9, an increase of about 18 times. The category of above 0 ^{0}C increases by approximately 41%. And the degree days below 18 ^{0}C are reduced by approximately 32%, while the category of below 0 ^{0}C is reduced by approximately 85%.

Table 14 Pearson Airport - 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	0.0	0.0	0.9	7.2	12.1	10.6	1.7	0.0	0.0	0.0	32.5
Above 22 C	0.0	0.0	0.0	0.0	2.7	19.5	33.4	28.8	5.7	0.1	0.0	0.0	90.3
Above 18 C	0.0	0.0	0.0	1.2	12.4	73.5	119.0	110.5	35.8	3.6	0.0	0.0	356.0
Above 15 C	0.0	0.0	0.0	5.3	31.4	141.6	208.1	197.2	90.6	14.2	0.0	0.0	688.4
Above 10 C	0.2	0.1	1.4	28.9	119.4	284.4	363.0	352.1	223.7	60.5	5.6	0.4	1439.6
Above 5 C	2.7	0.7	13.7	97.6	260.9	434.4	518.0	507.1	372.1	166.2	42.9	2.8	2419.1
Above 0C	16.3	9.4	61.5	222.1	415.6	584.4	673.0	662.1	522.1	315.5	143.5	26.7	3652.1
Below0 C	158.1	136.6	65.6	4.6	0.0	0.0	0.0	0.0	0.0	0.0	8.6	88.7	462.2
Below5 C	299.0	269.4	172.8	30.1	0.3	0.0	0.0	0.0	0.0	5.8	58.0	219.8	1055.2
Below10 C	450.9	410.3	315.5	111.4	13.8	0.0	0.0	0.0	1.7	55.0	170.7	372.4	1901.7
Below15 C	605.2	551.7	469.1	237.8	80.8	7.2	0.2	0.1	18.6	163.7	315.2	527.0	2976.5
Below18 C	697.9	636.6	562.1	323.7	154.8	29.0	4.1	6.4	53.8	246.1	405.2	620.0	3739.7

Table 15 Pearson Airport - 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	0.0	0.0	3.8	33.5	62.5	64.7	15.3	0.1	0.0	0.0	179.9
Above 22 C	0.0	0.0	0.0	0.3	9.4	63.1	111.7	113.4	37.5	1.8	0.0	0.0	337.1
Above 18 C	0.0	0.0	0.0	2.7	40.3	153.0	231.7	231.2	112.0	22.0	0.0	0.0	793.0
Above 15 C	0.0	0.0	0.1	10.4	90.4	238.8	324.6	324.2	186.3	56.2	0.5	0.0	1231.7
Above 10 C	0.5	1.6	6.1	59.4	226.4	387.9	479.6	479.2	331.1	159.7	23.3	1.1	2156.1
Above 5 C	9.8	18.4	50.5	165.0	381.2	537.9	634.6	634.2	481.1	307.9	108.8	18.5	3348.0
Above 0C	64.5	83.5	162.0	306.2	536.2	687.9	789.6	789.2	631.1	462.9	247.2	96.4	4856.7
Below0 C	25.6	21.1	4.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.6	13.8	65.9
Below5 C	125.8	96.0	48.0	9.1	0.0	0.0	0.0	0.0	0.0	0.0	12.2	91.0	382.1
Below10 C	271.6	219.3	158.5	53.4	0.2	0.0	0.0	0.0	0.0	6.8	76.8	228.6	1015.2
Below15 C	426.0	357.6	307.6	154.4	19.2	0.9	0.0	0.0	5.2	58.4	204.0	382.5	1915.9
Below18 C	519.0	441.6	400.5	236.8	62.1	5.2	0.1	0.0	20.8	117.1	293.5	475.5	2572.1

5.3 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 projected to cause a change in the humidex. Table 16 and Table 17 present the humidex summary for the periods 2000-2009 and 2040-2049, respectively.

The tables show that, in the current period, extreme humidex is 47.9; while in the future period the extreme humidex is 56.5. The category of above 30 is increased by approximately 63%. For the category >=45, there is an increase from 0.6 to 12.7.

Table 16 Pearson Airport - Humidex Summary for 2000-2009

Humidex	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Extreme Humidex	17.8	14.8	28.3	36.8	44.5	44.8	45.7	47.9	40.6	38.2	22.3	18.7	47.9
Days with Humidex > =30	0.0	0.0	0.0	0.7	2.9	13.3	20.6	20.4	7.4	1.4	0.0	0.0	66.7
Days with Humidex > =35	0.0	0.0	0.0	0.2	1.0	7.4	10.0	10.2	2.5	0.3	0.0	0.0	31.6
Days with Humidex >= 40	0.0	0.0	0.0	0.0	0.3	2.7	3.0	2.7	0.3	0.0	0.0	0.0	9.0
Days with Humidex >= 45	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.2	0.0	0.0	0.0	0.0	0.6

Table 17 Pearson Airport - Humidex Summary for 2040-2049

Humidex	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Extreme Humidex	18.6	20.4	25.8	35.5	46.7	51.3	56.5	55.7	47.3	38.9	27.0	19.8	56.5
Days with Humidex > =30	0.0	0.0	0.0	0.8	7.2	19.8	29.4	28.6	18.2	4.6	0.0	0.0	108.6
Days with Humidex > =35	0.0	0.0	0.0	0.1	3.0	14.6	23.7	22.6	10.8	0.5	0.0	0.0	75.3
Days with Humidex >= 40	0.0	0.0	0.0	0.0	0.7	7.4	12.9	14.1	3.3	0.0	0.0	0.0	38.6
Days with Humidex >= 45	0.0	0.0	0.0	0.0	0.2	3.2	4.3	4.8	0.2	0.0	0.0	0.0	12.7

5.4 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 and total precipitation.

5.4.1 Rainfall, Snowfall and Total Precipitation

Table 18 and Table 19 present, for Pearson Airport, the precipitation summaries for the 2000-2009 and the 2040-2049 periods, respectively. Table 20 presents the precipitation differences at Pearson Airport between the 2040s and the present period.

Table 18 Pearson Airport – Precipitation Summary for 2000-2009

Precipitation (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rainfall (mm)	15.0	16.8	31.9	63.4	84.9	80.4	68.4	51.3	58.1	55.2	61.9	36.9	624.2
Snowfall (cm)	35.5	42.0	24.7	7.2	0.0	0.0	0.0	0.0	0.0	0.0	8.4	36.0	153.8
Precipitation (mm)	50.5	58.8	56.6	70.6	84.9	80.4	68.4	51.3	58.1	55.2	70.3	72.9	778.0
Std of Precipitation	3.2	3.9	3.7	5.0	5.5	6.6	5.5	4.9	4.9	3.9	5.4	5.0	4.8
Extreme Daily Rainfall (mm)	17.2	28.5	23.9	32.8	45.0	66.0	54.1	51.8	51.9	32.4	39.7	40.1	66.0
Extreme Daily Snowfall (cm)	22.0	22.4	20.8	18.7	0.0	0.0	0.0	0.0	0.0	0.0	21.4	30.6	30.6
Extreme Daily Precipitation (mm)	22.0	28.5	23.9	32.8	45.0	66.0	54.1	51.8	51.9	32.4	39.7	44.2	66.0

Table 19 Pearson Airport - Precipitation Summary for 2040-2049

Precipitation (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rainfall (mm)	37.7	47.0	51.2	57.5	75.5	87.6	144.3	102.9	79.7	43.2	79.2	42.7	848.3
Snowfall (cm)	14.5	13.7	5.3	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.4	11.4	48.1
Precipitation (mm)	52.2	60.6	56.5	60.4	75.5	87.6	144.3	102.9	79.7	43.2	79.5	54.1	896.4
Std of Precipitation	3.1	4.0	4.3	3.8	6.8	7.7	12.2	9.4	6.9	3.7	7.6	4.0	6.1
Extreme Daily Rainfall (mm)	31.0	32.9	62.5	34.3	72.4	80.7	165.6	74.1	84.8	33.9	69.0	30.2	165.6
Extreme Daily Snowfall (cm)	10.7	17.5	10.1	15.9	0.0	0.0	0.0	0.0	0.0	0.0	2.8	9.6	17.5
Extreme Daily Precipitation (mm)	31.0	32.9	62.5	34.3	72.4	80.7	165.6	74.1	84.8	33.9	69.0	30.2	165.6

Table 20 Precipitation Differences between the 2040s and the Present

Precipitation (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rainfall (mm)	22.7	30.2	19.3	-5.8	-9.4	7.2	75.8	51.6	21.6	-12.0	17.3	5.7	224.1
Snowfall (cm)	-21.0	-28.3	-19.4	-4.3	0.0	0.0	0.0	0.0	0.0	0.0	-8.1	-24.6	-105.7
Precipitation (mm)	1.7	1.9	-0.1	-10.2	-9.4	7.2	75.8	51.6	21.6	-12.0	9.2	-18.9	118.4
Std of Precipitation	-0.1	0.1	0.6	-1.2	1.2	1.0	6.7	4.5	2.0	-0.2	2.2	-1.1	1.3
Extreme Daily Rainfall (mm)	13.8	4.5	38.6	1.5	27.5	14.8	111.5	22.3	32.9	1.5	29.2	-9.8	99.7
Extreme Daily Snowfall (cm)	-11.3	-4.9	-10.7	-2.9	0.0	0.0	0.0	0.0	0.0	0.0	-18.6	-21.0	-13.1
Extreme Daily Precipitation (mm)	9.0	4.5	38.6	1.5	27.5	14.8	111.5	22.3	32.9	1.5	29.2	-14.0	99.7

Table 21 presents the expected change in total precipitation by season. The table shows increasing rainfall in all seasons peaking in the summer and a reduction in snowfall in the winter, spring and fall. The table also shows increases in the extreme daily maximum rainfalls in all seasons.

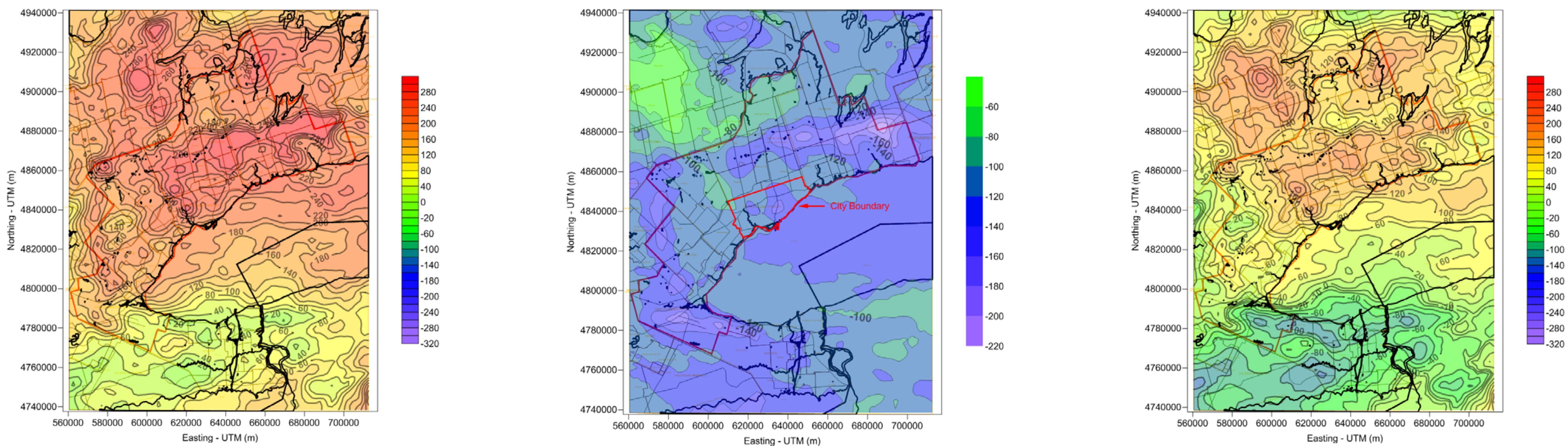
Table 21 Seasonal Precipitation Change from 2000-2009 to 2040-2049

Precipitation (mm)	Winter	Spring	Summer	Fall
Rainfall (mm)	58.5	4.1	134.6	26.9
Snowfall (cm)	-73.9	-23.7	0.0	-8.1
Precipitation (mm)	-15.3	-19.7	134.6	18.8
Extreme Daily Rainfall (mm)	2.8	22.5	49.5	21.2
Extreme Daily Snowfall (cm)	-12.4	-4.5	0.0	-6.2
Extreme Daily Precipitation (mm)	-0.2	22.5	49.5	21.2

Based on the predicted current and future scenario (2040-2049) for Pearson Airport, total annual rainfall will increase by 36%, snowfall is predicted to be reduced by 69% 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 69 (Appendix B1). Figure 48 presents the differences in rainfall, snowfall and total precipitation between the two periods.

Figure 48 shows increasing precipitation over downtown Toronto but very clearly shows an enhanced precipitation downwind of the GTA to the east and northeast. This is simply a reflection of the orographic (Oak Ridges Moraine) and/or lake effects, the prevailing storm tracks.

Figure 48 Rainfall, Snowfall and Total Precipitations Differences 2040s to Present



Rainfall Difference (mm)

Snowfall Difference (cm)

Total Precipitation Difference (mm)

5.5 NUMBER OF PRECIPITATION, SNOWFALL AND RAINFALL DAYS

The numbers of days for rainfall, snowfall and precipitation are presented in Table 22 and Table 23 for current (2000-2009) and future (2040-2049) scenario model outputs, respectively.

Table 22 Pearson Airport – 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	17.9	15.7	14.0	12.3	13.2	12.1	10.0	8.5	9.3	12.8	14.0	17.4	157.2
>= 5 mm	5.2	6.0	6.0	6.2	6.4	5.6	4.7	3.5	5.0	5.5	6.0	6.3	66.4
>= 10 mm	2.7	3.3	3.0	4.0	5.0	4.0	3.5	2.7	3.0	3.3	3.5	4.3	42.3
>= 25 mm	0.9	1.0	1.0	2.2	2.3	2.1	2.0	1.3	1.6	1.1	2.1	1.4	19.0
>= 50 mm	0.0	0.0	0.0	0.1	0.7	0.7	0.4	0.5	0.3	0.3	0.3	0.4	3.7
>= 100 mm	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.4
>= 150 mm	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
>= 200 mm	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
>= 250 mm	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
Snowfall (cm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
>= 0.2 mm	16.0	13.7	8.8	2.2	0.0	0.0	0.0	0.0	0.0	0.0	3.5	13.1	57.3
>= 5 mm	3.8	4.5	2.9	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	3.5	16.4
>= 10 mm	1.8	2.5	1.1	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.8	8.0
>= 25 mm	0.4	0.7	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.5	2.3
Rainfall (mm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
>= 0.2 mm	5.0	3.5	7.1	11.2	13.2	12.1	10.0	8.5	9.3	12.8	11.8	7.1	111.6
>= 5 mm	1.4	1.8	3.0	5.3	6.4	5.6	4.7	3.5	5.0	5.5	5.4	3.2	50.8
>= 10 mm	1.0	0.9	1.7	3.7	5.0	4.0	3.5	2.7	3.0	3.3	3.2	2.3	34.3
>= 25 mm	0.4	0.3	0.5	1.9	2.3	2.1	2.0	1.3	1.6	1.1	1.9	0.7	16.1

Table 23 Pearson Airport – 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	16.1	15.6	12.8	11.9	9.7	9.1	13.3	10.9	9.3	9.5	13.3	13.8	145.4
>= 5 mm	4.4	4.0	3.2	4.1	4.3	3.9	6.2	5.0	3.7	2.4	3.9	3.5	48.7
>= 10 mm	1.2	1.8	1.6	1.8	2.4	2.3	4.3	3.1	2.5	1.3	1.8	1.3	25.1
>= 25 mm	0.1	0.3	0.2	0.1	0.7	1.0	1.9	1.8	0.8	0.4	0.7	0.4	8.7
>= 50 mm	0.0	0.0	0.1	0.0	0.3	0.4	0.4	0.3	0.2	0.0	0.4	0.0	2.2
>= 100 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
>= 150 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
>= 200 mm	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
>= 250 mm	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
Snowfall (cm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
>= 0.2 mm	7.5	6.4	3.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.3	4.0	21.9
>= 5 mm	1.0	0.8	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	3.1
>= 10 mm	0.1	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
>= 25 mm	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
Rainfall (mm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
>= 0.2 mm	10.0	11.1	11.2	11.7	9.7	9.1	13.3	10.9	9.3	9.5	13.1	11.2	130.2
>= 5 mm	3.1	2.9	2.9	3.9	4.3	3.9	6.2	5.0	3.7	2.4	3.8	2.9	45.0
>= 10 mm	1.0	1.5	1.6	1.7	2.4	2.3	4.3	3.1	2.5	1.3	1.8	1.2	24.4
>= 25 mm	0.1	0.2	0.2	0.1	0.7	1.0	1.9	1.8	0.8	0.4	0.7	0.4	8.6

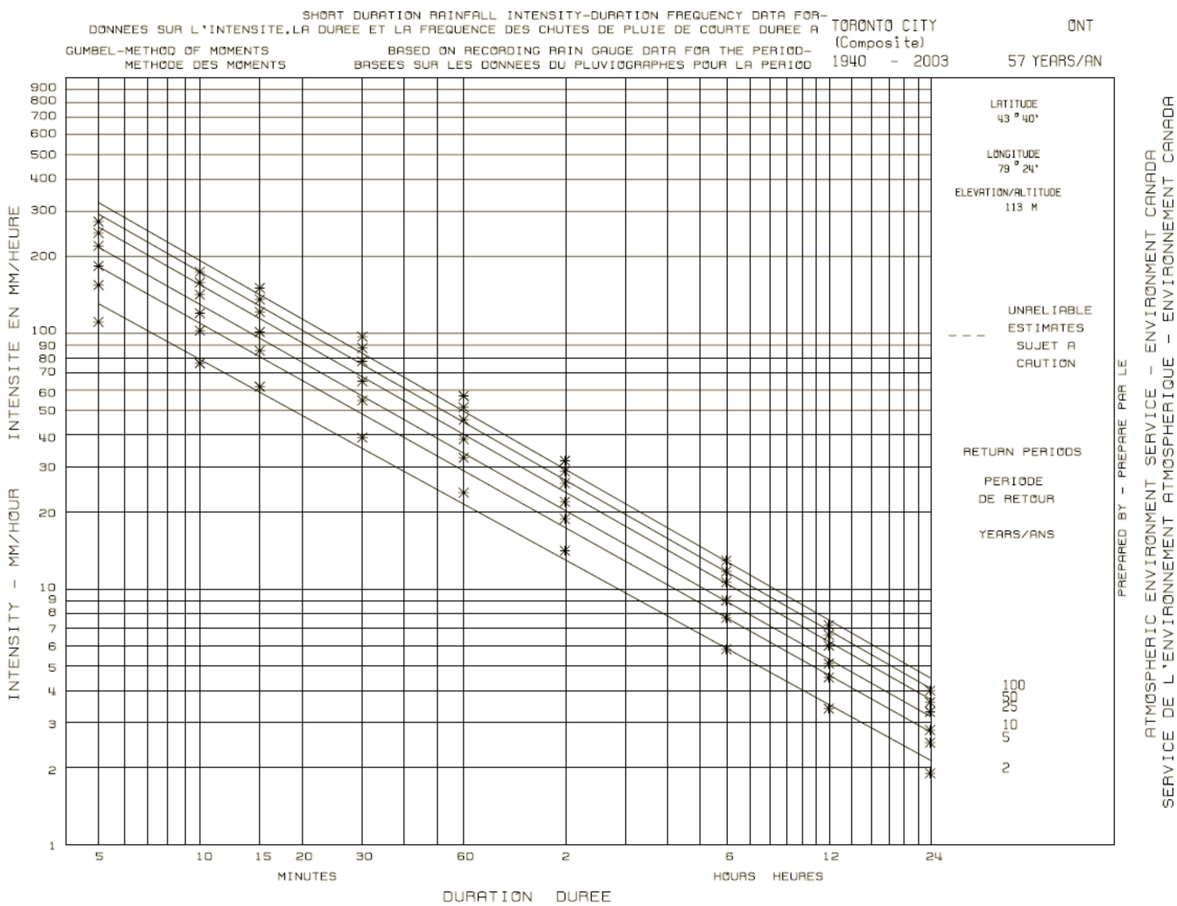
While the number of days with rain greater than 25mm is decreasing, the total precipitation is increasing. The details show increasing summer and winter rainfalls for all categories up to and including >25mm (which shows an average increase of ½ day per year).

The data also shows that there are currently no days with greater than 150mm of precipitation but for the future case we get 1 additional day every 10 years. 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 overall.

5.6 RETURN PERIODS

Return periods have only been calculated only for Pearson Airport but the database provided allows such a calculation for any of the 36 locations modelled. The current IDF curve for Pearson Airport is presented in Figure 49.

Figure 49 IDF Curves for Pearson Airport (1940-2003)



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.

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 24 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 24 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

5.6.1 Summary Statistics

Table 25 provides a statistical summary of the annual maximum precipitation data shown in Table 24 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 25 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

5.6.2 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 26. 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 25 (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 26 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 Table 27. 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 (greater than 10-years) are under-estimated.

The key observation is that the future scenario (2040-2049) is exhibits a consistent doubling of the current return period values. This is potentially very important for infrastructure design purposes.

So, considering the comparison in Table 27, 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 (204.4 mm) estimated in Table 26 for a return period of 100 years should be increased to a value 286 mm (204.4*1.4). This is quite critical in design, and demonstrates that future local climate and its effects should be considered carefully.

Another way to look at these values is by rainfall intensity. Table 26 was converted to rainfall intensity and values for the period 1940-2003 were extracted from Figure 49 for return periods of up to 10-years. These are shown in Table 28. The table shows for 2040-2049 storms lasting longer than 2-hours that the rate of rainfall will essentially be double that of the current period.

Table 27 Return Period Comparison for Pearson Airport

Current (2000-2009)						
Return Period	**1-hour**	**2-hour**	**6-hour**	**12-hour**	**24-hour**	**Number of Years**
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 (1940-2003)						
2-year	22.7	26.8	35.6	41.3	47.0	62
5-year	30.4	36.3	49.0	57.2	65.2	62
10-year	35.6	42.5	57.9	67.8	77.3	62
25-year	42.0	50.5	69.2	81.1	92.5	62
50-year	46.8	56.3	77.5	90.9	103.8	62
100-year	51.6	62.2	85.8	100.8	115.1	62

Table 28 Rainfall Intensity Comparison

Maximum Precipitation Intensity over the Period in millimetres / hour															
Return Period	1-Hour			2-Hour			6-Hour			12-Hour			24-Hour		
	1940-2003	2000-2009	2040-2049	1940-2003	2000-2009	2040-2049	1940-2003	2000-2009	2040-2049	1940-2003	2000-2009	2040-2049	1940-2003	2000-2009	2040-2049
2-Year	22.0	12.7	22.0	14.0	9.9	18.4	5.8	5.4	9.3	3.5	3.3	5.5	2.2	1.9	3.3
5-Year	29.5	17.2	32.2	18.0	12.6	25.0	7.6	7.3	14.8	4.7	4.2	8.0	2.9	2.3	4.7
10-Year	35.0	20.2	39.0	20.0	14.3	29.4	9.0	8.6	18.4	5.2	4.7	9.7	3.3	2.6	5.6

5.7 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, while wind direction is presented at selected locations in the form of wind roses. Wind roses are generated only for average wind speeds. Using this standard approach, a general picture of the winds and wind changes can be seen effectively.

5.7.1 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 29 and Table 30 for the periods 2000-2009 and 2040-2049, respectively. It should be noted that the future results have been corrected for the number of modelled days. 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 29 Pearson Airport –Wind Summary for 2000-2009

Wind	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Speed (km/h)	15.6	15.4	14.6	15.6	14.2	13.3	13.0	12.6	12.9	14.3	14.4	16.1	14.3
Maximum Hourly Speed	49.9	48.2	49.7	52.0	46.8	46.2	41.3	47.1	44.1	52.7	53.8	56.7	56.7
Maximum Gust Speed	83.4	90.3	98.6	86.2	85.3	78.0	63.4	65.3	84.5	85.2	86.5	112.4	112.4
Days with Winds >= 52 km/h	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.3	0.8
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	0.2	0.2

Table 30 Pearson Airport –Wind Summary for 2040-2049

WIND	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Speed (km/h)	13.7	14.5	14.7	15.2	13.9	12.8	11.4	11.4	11.8	12.8	13.7	13.1	13.3
Maximum Hourly Speed	40.5	41.6	38.7	38.9	38.4	47.7	37.1	39.6	36.3	37.5	37.2	38.1	47.7
Maximum Gust Speed	62.7	70.1	70.0	63.7	66.1	74.7	56.5	52.4	58.5	65.1	62.8	67.2	74.7
Days with Winds >= 52 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
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 ~ 7%, while maximum wind speeds are reduced by ~ 48% and the gust speeds by ~ 42%. 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 horizontal wind speed will decrease. Vertical wind speeds may increase in local storms and some of that is projected to be increasingly converted to horizontal winds but this effect is a sub-grid scale phenomenon and is not captured within the model scale (1x1 km).

Figure 70 (Appendix B1) presents the average wind speed in the form of a contour plot.

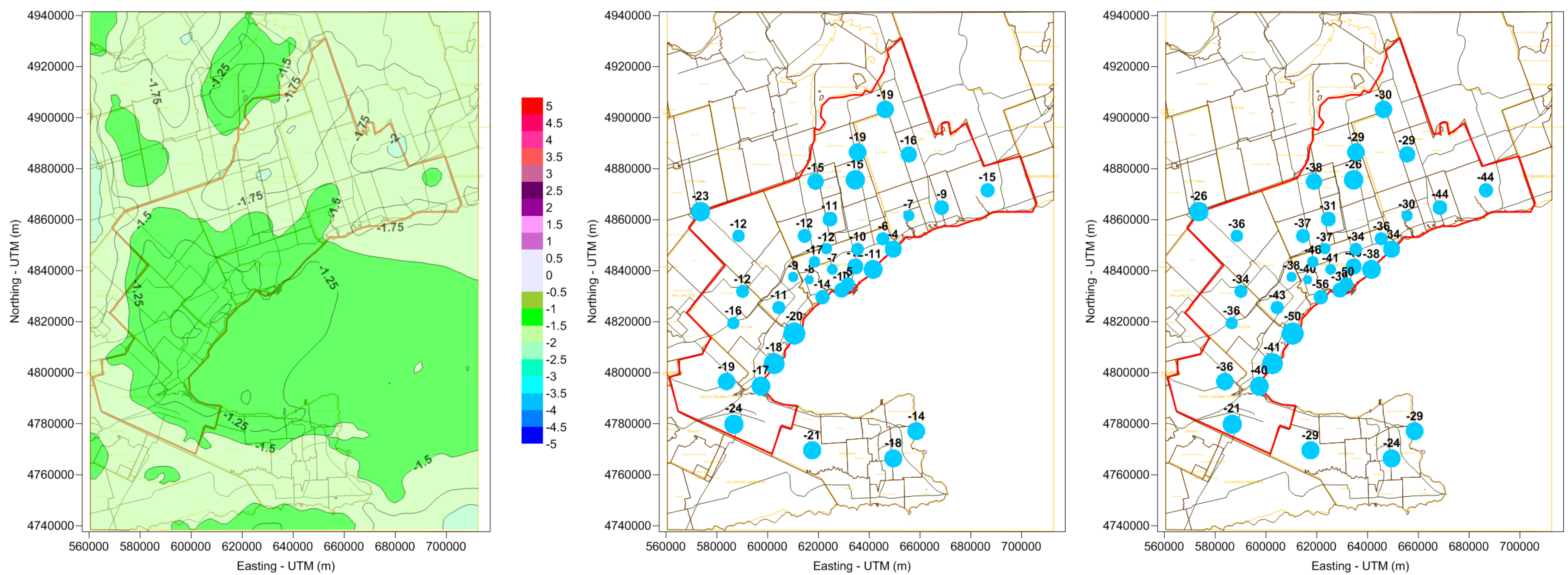
Figure 71 (Appendix B1) shows maximum wind speed over the GTA, as a discrete variable, because for grid points the contour plots are difficult to read. The maximum wind speed and gust are function of surface roughness, and the spatial variability is quite large. Figure 72 (Appendix B1) shows the gust wind speed over the GTA.

Figure 50 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 (jet stream and storm tracks) further north and the pressure gradient will change at the latitude of the GTA.

Figure 50 Wind Speed Differences between the 2000-2009 and 2040-2049 Periods



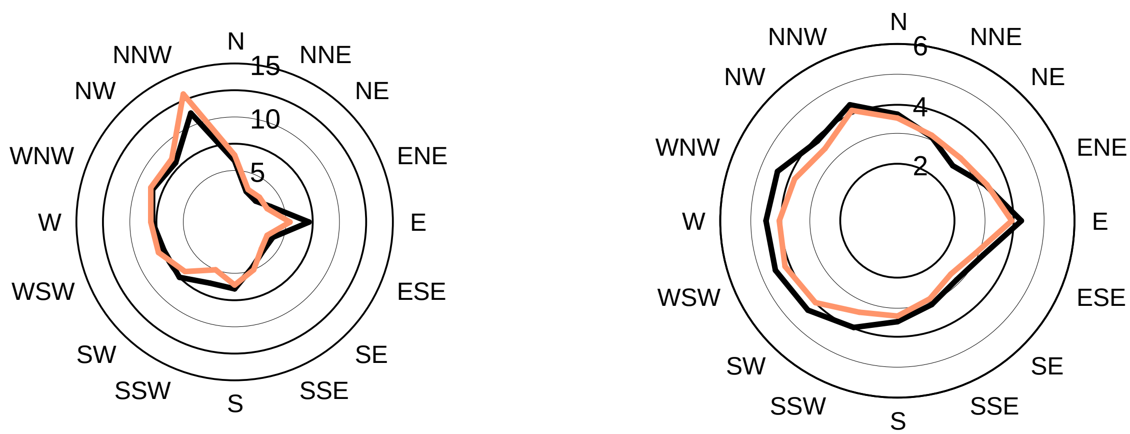
Average Wind Speed Difference (km/h) **Maximum Wind Speed (km/h)** **Wind Gust Difference (km/h)**

5.7.2 Wind Roses

Wind direction change is typically presented in the form of "wind rose" diagrams. Figure 51 presents the wind direction and average wind speed as wind roses for Pearson Airport for the current and future period. There is essentially no change in wind direction and only a slight reduction in average wind speed between these two periods.

Figure 51 Wind Roses for Pearson Airport

Wind Direction Frequency (%) **Average Wind Speed (m/s)**



Note: This is direction wind blows **from**

Percentage Calms = 11.2% - (2000-2009)
Percentage Calms = 13.3% - (2040-2049)

— 2000-2009 — 2040-2049

However, the percentage of calms (periods of time with no discernible wind) is predicted to increase by about 2%.

5.7.3 Wind Chill

Summarised data of wind chill events are presented in Table 31 and Table 32 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 projected to occur; indeed the total number of days with wind chill less than -20 is projected to decrease from 13.1 to zero.

Table 31 Pearson Airport – Wind Chill Summary for 2000-2009

Windchill	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Extreme Windchill	-31.1	-29.5	-36.1	-16.8	-5.0	-3.2	0.0	0.0	-3.3	-7.2	-17.2	-24.5	-36.1
Days with Windchill < -20	5.1	4.9	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	13.1
Days with Windchill < -30	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
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 32 Pearson Airport – 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	-15.7	-17.0	-12.6	-11.1	-0.1	0.0	0.0	0.0	0.0	-2.1	-10.3	-15.6	-17.0
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

5.8 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 occurrence.

5.8.1 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

5.8.2 Convective Available Potential Energy

CAPE (Convective Available Potential Energy) is a measure of the atmospheric instability (or buoyancy) 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).

If the instability is larger (greater buoyancy), the CAPE is higher. The units of CAPE are Joules per kilogram (energy per unit mass). Increasingly unstable air is associated with the generation of convective events like thunderstorms and tornadoes.

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

CAPE	
1 - 1,500	Positive (weakly unstable)
1,500 - 2,500	Large (moderately unstable)
2,500+	Extreme (highly unstable)

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.

5.8.3 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 City of Toronto, 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, and the final *Summary Table for Toronto* for that report is presented in Volume II of this report.

For 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 (and the criteria levels elucidated above) would not miss anything significant.

The correction made for the number of storms is really not a correction but rather the average of three different approaches for estimating 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 33 summarizes the number of storms based on a detailed observational analysis for the current period, for Pearson Airport. Table 34 summarizes the current period (2000-2009) and the future based on the adjusted derived criteria. Table 35 and Table 36 show the SRH indexes for the current and future periods. Table 37 and Table 38 show the CAPE indexes for current and future (2040-2049) periods.

Table 33 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 34 Pearson Airport - Derived Number of Storms by Year

Current Period (2000-2009)				Future Period (2040-2049)			
Year	**Total**	**Summer**	**Winter**	**Year**	**Total**	**Summer**	**Winter**
2000	28	16	12	**2040**	15	10	5
2001	26	16	10	**2041**	23	14	7
2002	39	23	16	**2042**	22	14	8
2003	30	16	14	**2043**	21	18	4
2004	32	16	15	**2044**	27	19	8
2005	28	16	11	**2045**	32	26	5
2006	32	18	14	**2046**	21	15	6
2007	32	16	16	**2047**	24	19	5
2008	30	16	14	**2048**	27	21	6
2009	26	15	11	**2049**	21	17	4
Average	**30**	**17**	**13**	**Average**	**23**	**17**	**6**

Based on the average of the derived criteria results, 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 35 Pearson Airport - Number SRH Days for 2000-2009

Srheli	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Days with Srheli 150-300	13.7	12.1	10.4	10.8	11.8	8.1	7.5	9.7	10.3	12.8	12.2	12.8	**132.2**
Days with Srheli 300-450	6.4	4.8	5.5	4.8	3.6	2.6	1.3	1.2	2.4	5.1	5.3	5.9	**48.9**
Days with Srheli >450	4.4	5.4	6.1	5.4	2.4	1.3	0.7	0.7	1.4	2.9	4.6	5.0	**40.3**

Table 36 Pearson Airport – Number of SRH Days for 2040-2049

Srheli	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Days with Srheli 150-300	11.9	12.0	10.5	11.5	10.3	8.8	9.9	6.7	6.5	9.0	12.0	10.7	119.8
Days with Srheli 300-450	2.4	2.6	2.0	1.9	1.1	2.3	1.4	1.6	1.0	1.5	1.8	1.8	21.3
Days with Srheli >450	0.4	1.1	1.1	1.6	0.6	0.4	0.1	0.7	0.2	0.4	0.9	0.5	8.2

Table 37 Pearson Airport - 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	1.2	1.8	4.7	8.1	6.6	3.0	1.0	2.1	5.8	5.9	4.7	2.2	**47.1**
Days with Cape 0-1000	30.9	28.3	30.9	29.0	27.3	19.5	16.5	19.2	26.4	30.3	30.0	31.0	**319.3**
Days with Cape 1000-2500	0.0	0.0	0.1	0.9	3.2	8.1	11.1	9.2	3.5	0.7	0.0	0.0	**36.8**
Days with Cape 2500-3500	0.0	0.0	0.0	0.1	0.3	2.1	2.8	2.0	0.1	0.0	0.0	0.0	**7.4**
Days with Cape >3500	0.0	0.0	0.0	0.0	0.2	0.3	0.6	0.6	0.0	0.0	0.0	0.0	**1.7**

Table 38 Pearson Airport – 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	2.8	3.1	5.1	5.2	5.3	3.6	0.9	0.5	1.7	6.1	5.8	1.7	41.8
Days with Cape 0-1000	31.0	28.0	31.0	29.4	28.0	18.8	13.8	12.7	21.5	30.1	30.0	31.0	305.4
Days with Cape 1000-2500	0.0	0.0	0.0	0.6	3.0	8.5	11.8	12.1	7.6	0.7	0.0	0.0	44.2
Days with Cape 2500-3500	0.0	0.0	0.0	0.0	0.0	2.4	4.3	4.5	0.7	0.1	0.0	0.0	12.0
Days with Cape >3500	0.0	0.0	0.0	0.0	0.0	0.3	1.2	1.7	0.2	0.0	0.0	0.0	3.4

The CAPE index based results are presented in Table 38 and show that the number of days for CAPE > 1000 goes up slightly, from 36.8 to 44.2 (an increase of about 20%). This is also in the agreement with the precipitation days >150mm (see Table 23 above) which appears in the future, but is not shown in the current period. The data confirms that the total number of storms is going down, but the potential for severe future summer storms is going up.

Table 39 shows the extreme indices year-by-year for Pearson Airport 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 B1 in Figure 73, Figure 74 and Figure 75. The percent differences between the current and future periods are presented in Figure 52.

Table 39 Summary of Extreme Indexes (Current and Future Scenario)

Storm Indices – Pearson Airport

Year	SRH	CAPE	EHI	Year	SRH	CAPE	EHI
2000	1720	2713	3.4	**2040**	597	3369	1.6
2001	1346	3766	2.0	**2041**	838	4001	6.9
2002	1189	5200	4.4	**2042**	634	3879	4.6
2003	917	3260	2.3	**2043**	575	4570	5.1
2004	1553	3074	2.7	**2044**	726	4346	4.6
2005	1038	3603	4.0	**2045**	825	4379	4.9
2006	1317	5664	5.4	**2046**	759	3439	3.3
2007	1352	3963	4.3	**2047**	649	4807	3.7
2008	1107	3317	3.4	**2048**	561	4265	4.0
2009	1274	3847	3.9	**2049**	746	3916	4.2
Maximum	1720	5664	**5.4**		838	4807	**6.9**
Average	1281	3841	**3.6**		691	4097	**4.3**

Based on Figure 73 though Figure 75 (Appendix B1), 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. The Pearson Airport seems to be influenced by the lower values found over Lake Ontario showing that the lake will have a significant effect on Toronto's future climate and weather.

As an interesting example, Figure 53 shows a distribution of the CAPE Index values for 10 years of the current (2000-2009) and the future period (2040-2049) for Pearson Airport. The future data was corrected for the difference in the number of days per year simulated. As can be seen from Figure 53, the frequency of CAPE values greater than 30 are increasing for the future 2040-2049 period (with large increases in the most severe categories), which is consistent with previous conclusions.

A comparison to the other results is presented in Appendix A of Volume II 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.