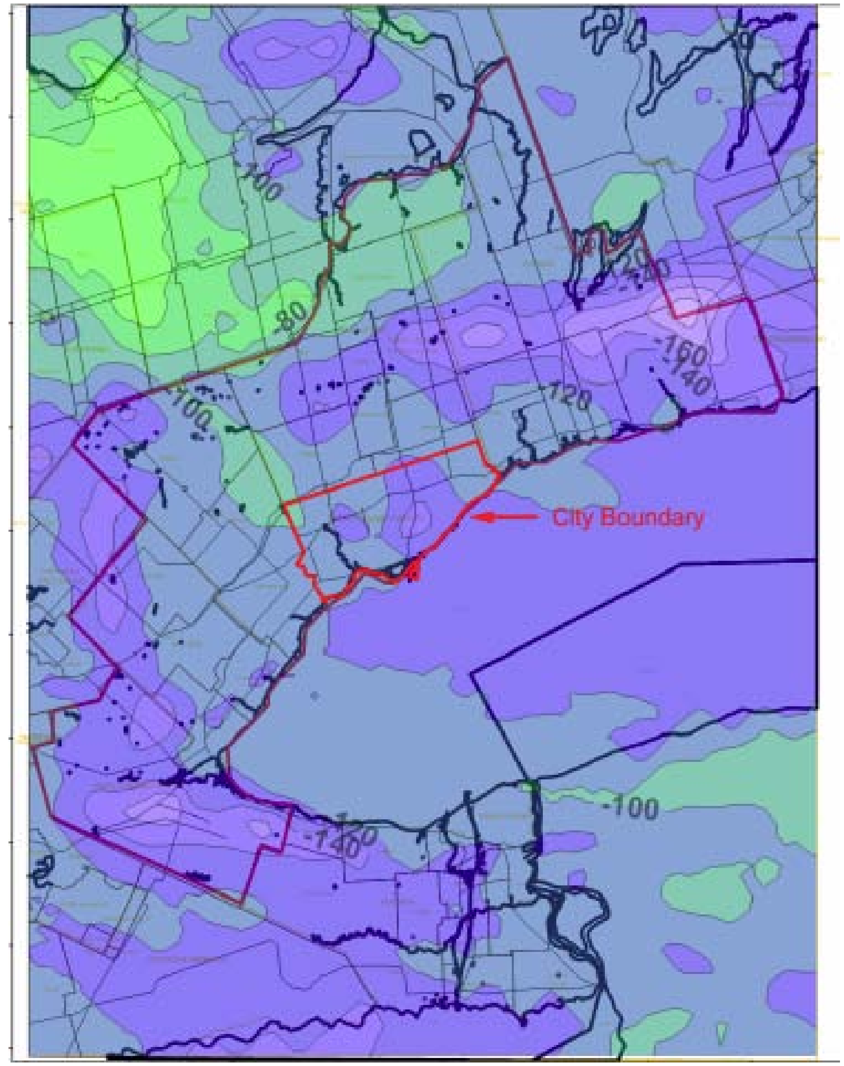
TORONTO'S FUTURE WEATHER & CLIMATE DRIVER STUDY:

OUTCOMES REPORT

Summary of the SENES Consultants Ltd Study by Toronto Environment Office October 30, 2012



Less Snowfall Expected in 2040-2049 (in centimetres)

- 140 centimetres less in parts of Toronto
- 160 centimetres less on parts of the Oak Ridges Moraine

Why We Did What We Did

Clear Direction *from City Council re: policies and actions including*

Climate Change Action Plan (2007)
Ahead of the Storm (2008)

To Prepare the City for the Future

The City needed Toronto & GTA specific Weather & Climate Information unavailable from Environment Canada.

Toronto Environment Office uses an innovative approach to modelling climate and weather.

We combine modelling technologies
Global Climate Models (GCM)
Regional Climate Models (RCM)
Local Weather Models (WRF)

Advisors: *Environment Canada, Ministry of Environment, Toronto Region Conservation Authority*

Consultants*: SENES + Hadley UK*

INTRODUCTION

In order to more effectively plan municipal infrastructure investment and provision of services, the City of Toronto needs to know what currently influences Toronto's present weather and climate. The City needs to determine how these influences are likely to change, and how severe the consequences are likely to be in the future. In simple terms, the City of Toronto needs a better understanding of why Toronto gets the weather and climate it gets now and what weather and climate it can expect to get in the future.

For large cities with high density populations and concentrated critical infrastructure, climate and weather can have a significant impact on economic activity and municipal services. Existing global and regional climate models have not provided cities, such as Toronto, with sufficiently tailored information to understand and address specific local future impacts.

The *Toronto's Future Weather & Climate Driver Study* aims to help understand what projections on future climate mean for the City of Toronto. By improving the level of certainty about climate related weather changes, the City will be better guided in making investment and budgetary decisions regarding infrastructure and service provision responsibilities.

The study was undertaken by SENES Consultants, based in Richmond Hill. SENES works on projects around the globe and specializes in climate modelling. The Toronto Environment Office commissioned the study to support the City's climate change policies.

WHY DID THE CITY UNDERTAKE THE CLIMATE DRIVERS STUDY?

There are three reasons why the City cannot solely rely on the existing climate projections derived from Global and Regional Climate Models to fully understand current and future climate and weather patterns for Toronto:

1) ***The Great Lakes*** – The Great Lakes have an important influence on Toronto's climate and weather. Without the Great Lakes, Toronto would have an extreme continental climate instead of its more moderate continental climate. Global and regional climate models do not adequately represent the moderating effect of the Great Lakes on the City's climate and weather. The implication is that the City cannot adequately predict future climate change impacts for Toronto from these models alone.

2) ***Lack of focus on urban climate and weather impacts*** – Large urban centres, such as Toronto, comprise a small percentage of Canada's land mass. However, they are home to a substantial percentage of Canada's economic activity and population (80% of the Canadian population live in urban areas). Local impacts of future climate changes on city and urban populations are not sufficiently detailed in the global and regional climate models to inform cost effective infrastructure planning and adaptation.

3) ***The need for weather and climate 'extremes' rather than 'averages'*** – The operation of critical infrastructure such as the electrical grid, water treatment plants, sewers and culverts, public transport and roads are sensitive to particular temperature and weather thresholds. Beyond these thresholds infrastructure may have reduced capacity or may not function at all. While we cannot ignore gradual climate change, variation in the patterns of extreme weather pose a particular challenge to the operation of municipal and provincial infrastructure. The focus of global and regional climate models on climate averages are unlikely to provide cities, such as Toronto, with adequate insight into extreme weather projection changes necessary for prudent infrastructure management.

Monitored weather events identified in Table 1 below (Environment Canada) show an increasing occurrence of record years between 2000 and 2009. This data suggests that extreme weather events are changing more rapidly than predicted by the models built around the standard 30-year climate averages.

New Approach

The approach was new and innovative *when this project was conceived.*

The approach *taken has been* ***very successful (proved*** *value of approach).*

Approach subsequently adopted by *the National Center for Atmospheric Research, and by the Ministry of the Environment with the University of Toronto.*

To Answer New Questions

Included Influence of the ***Great Lakes, Niagara Escarpment*** *and the* ***Oak Ridges Moraine****.*

Examined a ***10 Year Period*** *(not 30 Years)*

Wanted data and information concerning the ***future "extremes"-of-weather*** *rather than the* ***future "means"-of-climate****.*

Recent Empirical Data

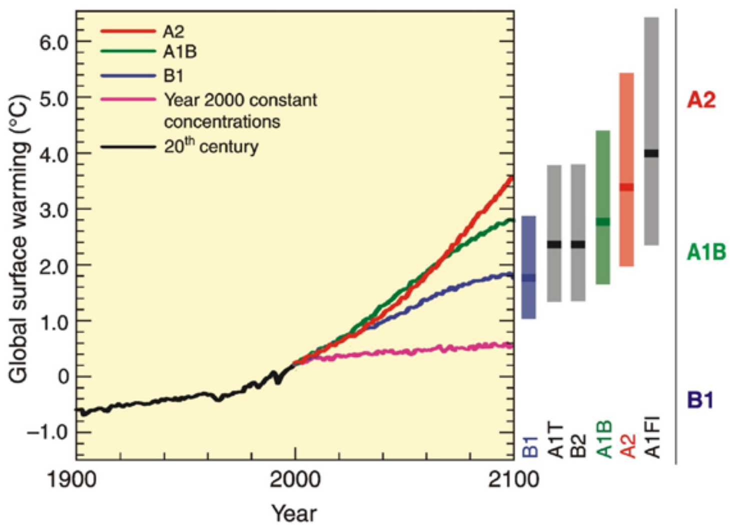
Globally, ***2010*** *ranked as the* ***warmest year on record****, as was 2005 and 1998 before it.*
The ***10 warmest years on record*** *have* ***all*** *occurred* ***since 1998****.*

Over the ten years from ***2001 to 2010****, global temperatures have averaged 0.46°C above the 1961-1990 average, and are* ***the highest temperature increase ever recorded for a 10-year period*** *since the beginning of instrumental climate records.*

Table 1: Record Weather Events in Toronto by Year in the Period 2000-2009 Provide Rationale For Study

Year	Record Events
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 (half 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 summers 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.
2012	Toronto's earliest ever official heat wave (June 19-21)
Also	Three 1 in 100 year storms in Toronto in less than 12 years: July 2000, August 2005, July 2012.

International Panel on Climate Change (IPCC) Scenarios of Future Climate Driven by Population, Economics, and Technology Adoption[1]



IPCC Emission Scenarios

B1 ***Low Growth (Integrated World)***

A1B ***Moderate Growth (Balanced Energy Use)***

A2 ***High Growth (Divided World)***

The City's approach adopted Scenario A1B regarded as an upper-middle of the road scenario (i.e., not an extreme scenario) into the future. Also note that A1B & A2 are essentially similar until 2060.

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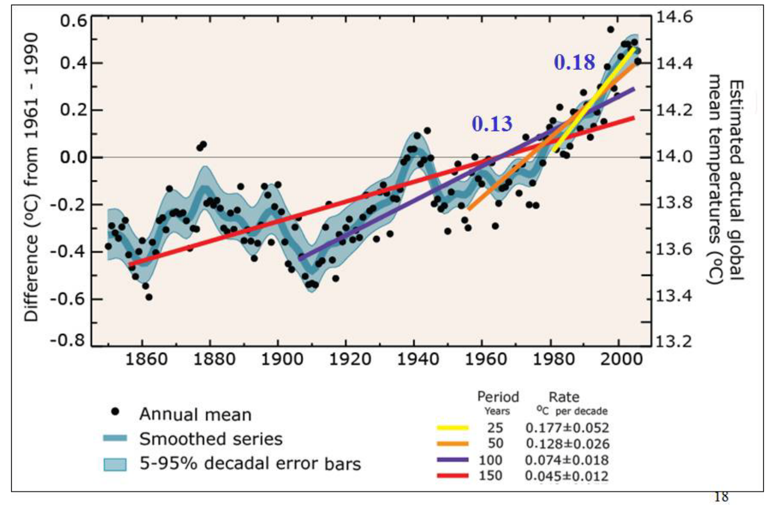
[1]From Pachauri, R.K. and Reisinger, A. (Eds.)"Climate Change 2007: Synthesis Report Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (2007) at p 46. Accessed at ***http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf***

Exponentially Increasing Rates of Temperature Change in the recent past and into the Future[2]



Showing different rates (slopes) of change from the same monitored temperature data set (1860-2010)

This shows that the changes are occurring more rapidly now than before and that they should also be examined on smaller and more recent time intervals in respect to City responsibilities.

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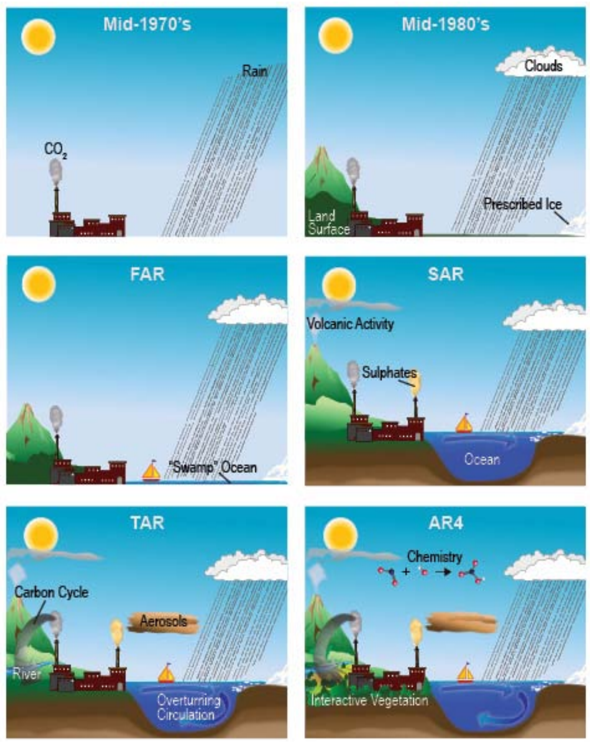
[2] *From Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, US at Technical Summary 3.1 - Accessed at*http://www.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-3-1-1.html

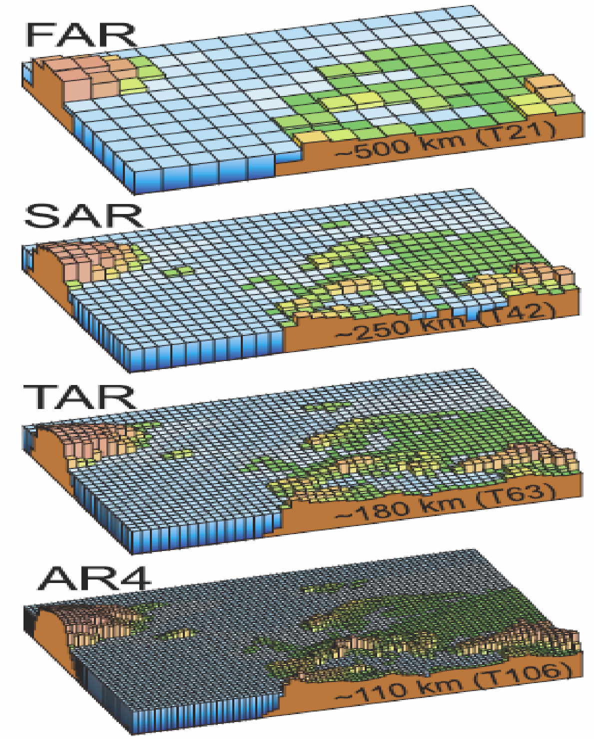
Global and Regional Climate Model Improvements (from 1970 to 2010) in Physical and Chemical Complexity[3]



More processes and better chemistry were included sequentially and created increasing certainty in the results obtained.

[3] *From Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson and M. Prather, 2007: Historical Overview of Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Chapter 1.2*

Model Improvements of Geographic Scale and Three Dimensional Computational Grid Resolution (1990-2007)[4]



Scale & Resolution of IPCC Assessment Reports (AR)
FAR = 1st – 1990 SAR = 2nd - 1996
TAR = 3rd - 2001 AR4 = 4th - 2007

[4] *From Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, US at Chapter 1.5* Accessed at http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch1s1-5.html

HOW DID WE APPROACH THIS STUDY?

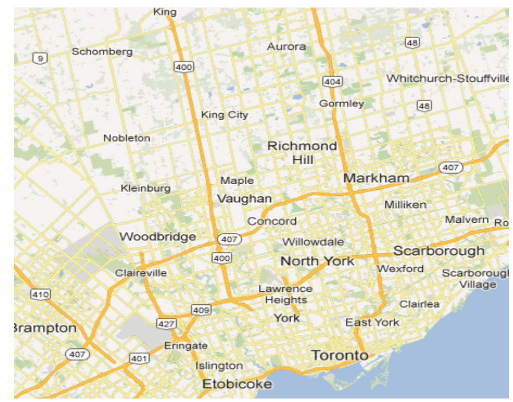
Overcoming the limitations of global and regional climate models in understanding localized climate and weather requires a unique approach. In consultation with climatologists, meteorologists, hydrologists and climate adaptation specialists from Environment Canada, the Ontario Ministry of the Environment and Toronto Region Conservation Authority, SENES and the City of Toronto used existing Environment Canada and United Kingdom Meteorological Office - Hadley Centre results from global and regional climate models as input into a local-scale, weather forecasting research model.

To appreciate the distinctiveness of the Toronto Climate Drivers Study approach it is necessary to understand the basics of global and regional climate models:

Global Climate Model (GCMs) - The standard approach to climate modeling has been to use global climate models linked to data of climate averages for 30 year time periods. These models operate at a course spatial resolution: a **300 km^2** grid scale. While remaining relevant to understanding climate impacts on national scale, this modelling makes no differentiation in projected future climate averages for Toronto, London, North Bay, or Muskoka due to its coarse grid scale, nor does it distinguish between lakes versus lands, or high-lands versus low-lands, or urban versus rural lands – all areas and conditions within a grid cell are described by their mean condition.

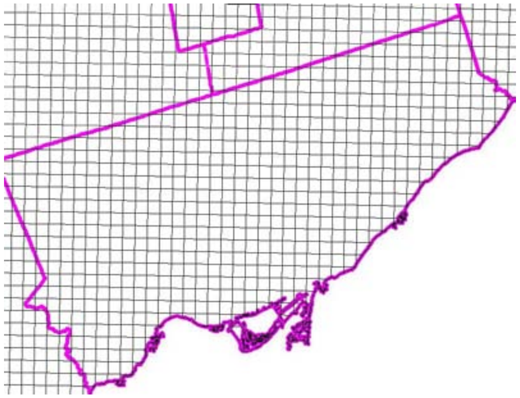
Regional Climate Model – Allows refinement of global model results by introducing Regional Climate Models (RCMs) of medium resolution (typically in the range of **40 - 100 km^2** or larger). While providing greater geographic differentiation than global models, they still do not adequately represent features such as the Great Lakes which are critical to explaining Toronto's weather and climate.

An example of a single grid cell within a <u>Global Climate Model</u> of 300 km x 300 km resolution.



An example of a single grid cell within a <u>Regional Climate Model</u> of 40 km x 40 km resolution.

These two maps show the equivalent area of one grid cell in which all weather data is considered uniform. The maps do not necessarily represent actual modelling grid cells



An example of grid cells in a Weather Research Forecast (WRF) model of 1 km x 1 km resolution used in evaluation of Toronto's future climate and weather.

Weather Research Forecasting (WRF) Model - Developed jointly by the US National Centre of Atmospheric Research, the US National Oceanic and the Atmospheric Agency this model allows the output of spatially variable mean and extreme weather predictions that account for the influence of local geography and topography.

The *Toronto's Future Weather & Climate Drivers Study* uses a sequential combination of these models. Results from global and regional models were fed into the Weather Research Forecasting (WRF) model of much finer spatial resolution to provide detailed estimates of Toronto's future local weather between **2040 and 2050** – a time horizon relevant to a large range of infrastructure replacement activities that City staff can reasonably envisage.

The result is a *climate-weather* model capable of operating at a very fine resolution (**1 km^2**). This allows different climate and weather projections to be established for even small areas within Toronto (e.g. equivalent in area to small individual postal code areas or smaller areas within Scarborough, North York or Downtown) rather than only large regional areas such as southern Ontario or even larger provinces and nations.

Having climate and weather projections physically down-scaled to this level is critical to addressing infrastructure impacts caused by extreme weather events similar to those that caused the Finch Avenue culvert collapse and road wash out of August 19 2005.

The results of the City's climate-weather model were compared against output from more traditional global and regional model combinations to verify performance. The City's results for were judged to be very good and within the range of theoretically expected results and in keeping with global and regional model output.

WHAT ARE "CLIMATE DRIVERS"?

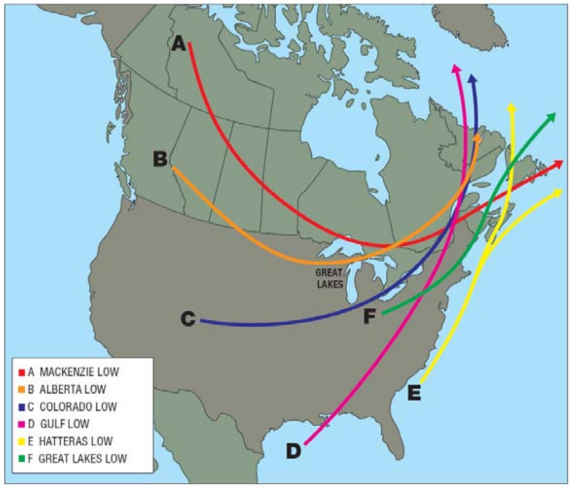
The SENES Study references "Climate Drivers" in its title (*Toronto's Future Weather & Climate Driver Study)* to reflect the significance of large scale meteorological features and processes that determine or "drive" Toronto's day-to-day weather such as the location of the Jet Stream and movement of major air masses. Climate models such as global and regional climate models can predict potential climatic changes into the future. These potential changes need to make sense and be consistent with our understanding the laws of physics and known behaviours of weather systems.

Models that run equations and provide climate data output need to make sense in light of our understanding of physical meteorological processes that we know operate in the atmosphere now. For example:

- Does the average position of the polar front jet stream move northward in keeping with the predicted average temperature changes?
- Are predictions of more intensive but fewer summer storms logically consistent with increased occurrence of updrafts of warm air?
- Does the influence of Lake Ontario and other Great Lakes continue to modify summer temperatures?
- Is a reduction in winter snowfall accompanied by a corresponding increase in winter rainfall?

Identifying the climate drivers that control Toronto's present weather is a major part of the study and an important way to corroborate the overall integrity of model data and computer program assumption.

Common Winter Low Depressions - Sources and Storm Tracks



Source: Klok *et al.*, 2002

Summer and Winter Jet Streams

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

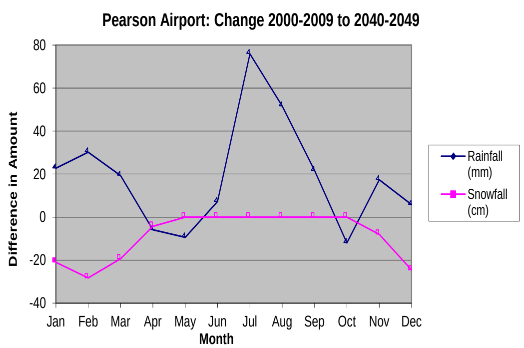
Confidence in Results using Mean Temperature as an example

Compared with Monitored Means *(2000-09)*
1) Toronto's Climate-Weather Model v.1= ***8.70°C***
2) Environment Canada's Canadian Regional Climate Model v.4.2.3 = ***6.69°C***
3) Monitored Data from Pearson = ***8.73°C***

Compared with Other Models *(2040-49) GTA*
Our forecast change of ***4.4°C*** *compares favourably with Low Resolution Models showing changes from* ***-2.7°C*** *to* ***6.3°C***

Snowfall and Rainfall

- Less Snow & More Rain -- in Winter
- More Rain in July (80%) & August (50%)



SUPPORT FOR TORONTO'S APPROACH

Toronto's approach of adding output from climate models into a weather model in order to obtain more locally relevant future weather predictions was cutting edge and innovative when conceived. It has been subsequently 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.

THE RESULTS FOR TORONTO

The study predicts that climate change will continue to create different weather patterns across Toronto in the future. Some changes can be regarded as being positive - longer growing season, generally more pleasant weather and fewer City resources required for winter snow clearance. However, other changes can be regarded as being negative. Though a similar number of storms per year are projected a fewer number of "heavy" storms (>25mm/day) are expected. However, a small number of those "heavy" storms" will produce "very intense" storms and produce much greater amounts of rainfall in short periods than previously seen with clear impacts on city infrastructure (culverts and drainage management) and an increased potential for flooding.

The changes (comparing 2000-2009 monitored data with modelled results for 2040-2049) **are predicted** to be as follows:

Precipitation - Snow and Rain

- Less snow and more rain in the winter
- 26 fewer snow days per year, 9 less in December
- Slightly more precipitation (snow plus rainfall) overall
- Marked rainfall increases in July (80%) and August (50%)
- Extreme rainstorm events, fewer in number but more extreme

Temperature

- Average annual temperatures increase by 4.4°C
- The projected average winter temperature increase by 5.7°C.
- The projected average summer temperature increase by 3.8°C.
- The extreme daily minimum temperature rises by 13°C (i.e., becomes less cold).

Wind

- Unchanged average wind speeds
- Reduced maximum wind speeds
- No changes in wind direction

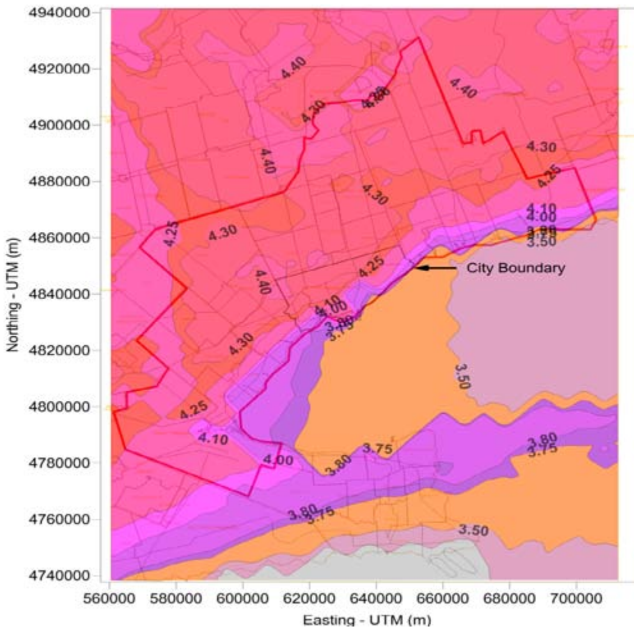
Comfort Measures

- Reduced occurrences of Wind Chill
- Virtual disappearance of Wind Chill events with temperatures below -20°C;
- Humidex events greater than 20°C increase more than 60%
- The maximum Humidex increases from 48°C to 57°C

Temperature Degree Days

- Values below 18°C can be used to estimate the heating requirements of buildings. The occurrence of such degree days are expected to reduce by almost a third - 31%
- Values above 24°C can be used to estimate the cooling requirements of buildings. The occurrence of such degree days are expected to increase by more than five times - 560% (i.e., from 32 degree-days to 180 degree days per year)

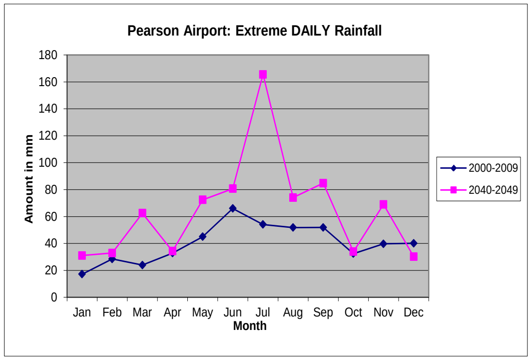
4.4°C Average Annual Temperatures Increase in Toronto



- The extreme daily maximum temperature "becomes warmer" by 7.6°C (i.e., becomes warmer).

Extreme DAILY Rainfall

- Fewer Precipitation Storms >25 mm in Winter
- Same Number of Storms in Summer
- **BUT the Summer Storms will be Much More Intense**



CHANGES IN "EXTREMES"

Most global climate models assess changes in the averages that typify a climate. The *Toronto Future Weather & Climate Drivers Study* assessed these climate averages but also extended the study to assess potential changes in the "extremes" of weather (maximums and minimums). This included examining the changing likelihood, severity and durations of "extremes" such as heat waves and intense rainstorms.

Table 2 summarizes the changes expected to occur between the period **2000-2009** and the period **2040-2049**. Key projections include:

- Though the number of storms that occur in winter decrease, the number of storms that occur in summer remains the same – but the maximum amount of rainfall expected in any single day and in any single hour more than doubles.
- The number of days when the humidex exceeds 40^{o}C is expected to increase fourfold.
- The number of degree days >24^{o}C (a degree-day[5] occurs when the temperature is higher than 24^{o}C for 24 hours) - which is typically used as the measure of air conditioning being required - increases six-fold.
- The number of "heat waves" (i.e., events with more than 3 consecutive days of temperatures greater than 32^{O}C) is expected to increase from an average of 0.57 occurrences per year, as in the period 1971-2000, to 5 occurrences per year in the period 2040-2050.

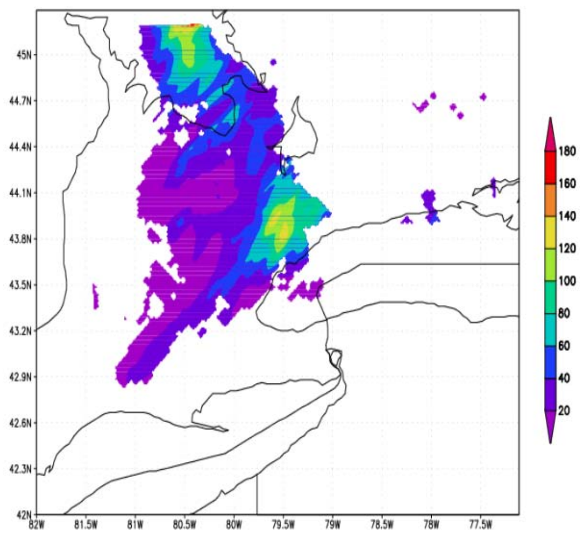
[5]For an explanation of what is meant by "degree days" please see: http://www.oahpp.ca/resources/documents/Accumulated%20Degree%20Days.pdf

Table 2: Projected Future Weather Changes Compared to Recent Weather

Weather Type	**Parameter**	**Units**	Annual Weather **2000-2009**	Annual Weather **2040-2049**
Extreme Precipitation	Maximum Amount in One Day	mm	66	166
	Number of Days with More Than 25mm	days	19	9
	Mean Annual Daily Maximum	mm	48	86
	100 year Return Period Maximum Daily	mm	81	204
	10 year Return Period Maximum Daily	mm	62	135
	10 year Return Period Maximum Hourly	mm	20	39
Extreme Rainfall	Maximum Amount in One Day	mm	66	166
	Number of Days with More Than 25mm	days	16	9
Extreme Snowfall	Maximum Amount in One Day	cm	24	18
	Number of Days with More Than 25cm	days	16	3
Extreme Heat	Maximum Daily Temperature	^{o}C	33	44
	Number of Days with Temperature > 30 ^{o}C	days	20	66
	Number of heat waves" (>3 consecutive days > 32^{O}C*	events	0.57**	2.53
Extreme Cold	Minimum Daily Temperature	^{o}C	- 17	-11
	Number of Days with Temperature < -10 ^{o}C	days	25	0
	Number of Days with Temperature < -0 ^{o}C	days	128	70
Wind Chill	Extreme Daily Wind Chill	^{o}C eq.	-24	-17
	Number of Days with Temperatures > 20 ^{o}C	days	12	0
Degree Days	Number of Degree Days > 24 ^{o}C (A/C required)	degree-days	31	180
	Number of Degree Days > 0 ^{o}C	degree-days	3452	4587
	Number of Degree Days < 0 ^{o}C (Heat required)	degree-days	440	66
Extreme Wind	Maximum Hourly Wind Speed	km/hr	92	48
	Maximum Wind Gust Speed	km/hr	130	75
	Number of Days with Winds > 52 km/hr	days	1	0
Humidex	Maximum Humidex	^{o}C eq.	48	57
	Number of Days with Humidex > 40 ^{o}C	days	9	39
Storms	Average Number of Storms per Year		30	23
	Average Number of Summer Storms per Year		16	17
	Average Number of Winter Storms per Year		14	6

* Note: This data is not included in SENES Report Volume I. It is included in subsequent data extraction and analysis by SENES for the City.
**Derived from Meteorological Services Canada data recorded at Toronto Pearson International Airport.

Modelling Future Extreme Storms is Much Harder…. but ….



Storm of August 19th, 2005

a) Highest Rainfall is shown over Finch Avenue

b) Captured by Modelling, but NOT by Standard Environment Canada Monitoring at Pearson International Airport (the best weather monitoring station for Toronto) because the centre of the storm was distant from the airport monitoring station.

c) Monitoring stations can only identify what happens at a particular station. Modelling can identify what happens between stations. This example typifies the benefits of not relying purely on monitored data.

THE BENEFITS OF THE FUTURE WEATHER PREDICTIONS

The study provides projections that can inform present and future infrastructure and service decisions (e.g., water pipe sizing, heat resistance of road surface materials) and policy development planning (e.g., heat wave responses, pest infestations).

By improving the level of certainty regarding the magnitude and frequency of expected climate change, and particularly extreme weather events, the City is better guided in making decisions regarding capital works investments and adjustments to operational procedures. This may reduce the risk of unsustainable investment and loss associated with infrastructure construction, maintenance and operations that do not take into account extreme weather events and climate change projections.

THE CERTAINTY OF THE FUTURE WEATHER PREDICTIONS

The study predicts potential future outcomes based on the data and the modelling capabilities of the recent past. The weather of the future will continue to change rapidly and at an accelerating rate into the future. With the passing of years the certainty surrounding the outcomes in the study will need to be reassessed and the study will need to be re-examined. The City can address this by maintaining a watching brief of:

1. The changing state of climate change science and predictions; and
2. The ongoing changes in weather extremes and means for Toronto; and
3. The significance, value and needs of timely adaptation and financing its costs.

SUMMARY AND CONCLUSIONS

Using a weather-climate model approach, this study projects the future weather changes that Toronto may expect in 2040-2049. The model combined an ensemble of large-scale global and medium-scale regional climate model data as inputs to a local scale Weather Research Forecast (WRF) model to predict successive hourly weather conditions into the future, in and around Toronto.

The study is unique as it goes beyond the standard modelling means of rainfall and temperature and assesses extremes of temperature and precipitation. On average in 2040-2049, warmer annual average temperatures of 4.4°C are expected. For seasonal averages winter temperatures are projected to increase by 5.7°C and summer temperatures by 3.8°C. Extreme daily maximum temperatures are projected to increase by 7.6°C, but extreme daily minimum temperatures are projected to also rise by 13°C (i.e., becomes less cold). Less snow and more rain in the winters (26 fewer snow days per year) and fewer rainstorm events per year are anticipated. However, the model predicts more extreme rainstorms and marked rainfall increases in July (80%+) and in August (50%+).

Considering these results as part of City Council's decision making processes may aid the City and the community better prepare and adapt to future climate change.

Future Warmer Temperatures

- Average annual temperatures increase by **4.4°C**
- Projected average winter temperature increases by **5.7°C**.
- Projected average summer temperature increases by **3.8°C**.

- The extreme daily minimum temperature - "becomes less cold" by **13°C**.
- The extreme daily maximum temperature - "becomes warmer" by **7.6°C**

Future Extreme Heat

- Mean Maximum Daily Temperature between **(2000-2009)** and **(2040-49)** changes from . . . **33°C** to **44°C**

Maximum daily air temperature is recorded at a weather station by selecting the highest 1-hourly air temperature within each 24-hour period. (Averaged here over 10 years).

- Number of days per year with temperatures greater than 30°C between **(2000-2009)** and **(2040-49)** changes from . . . **20 days** to **66 days**

Future Rain, Storms and Snowfall

Less snow, more rain in winter.
Fewer snow days per year

Fewer rainstorms per year
But more extreme rainstorms
More rainfall in July (80%+) and August (50%+)