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SELECTING A GLOBAL CLIMATE MODEL FOR UNDERSTANDING FUTURE PROJECTIONS OF CLIMATE CHANGE

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ABSTRACT: There is a wide selection of climate models available to provide projections of future climate change. All are mathematical models that simulate the functioning of the global climate system varying in size, scope, scale and complexity. The fourth, and most recent, assessment of the Intergovernmental Panel on Climate Change (IPCC) provides projections of future climate change using twenty-four global climate models under three major greenhouse gas emission scenarios. These provide for a wide range of possible outcomes when trying to inform managers about possible future climate changes. In order to narrow the projections to a handful of models that could be used in a climate change impact study, three approaches are taken – extremes (max/min) approach; ensemble approach; and validation approach. The extremes (max/min) approach suggests that it is best to plan within the full range of possibilities that the ~72 GCM scenarios present. The approach takes the projection for the maximum change, as well as the projection for the minimum change, and uses both as the range of consideration when planning. The ensemble approach suggests that it is best to plan for the average change of all the models. The approach uses a mean or median of all the models (or many models) to reduce the uncertainty associated with any individual model. The validation approach suggests that those models that compare well to historical climate observations should be the ones used for planning. The approach takes the historical climate observations over a thirty-year period from a global gridded dataset (for example, the National Centres for Environmental Prediction (NCEP)) and compares this against all models to see which ones reproduce the values best. Subsequently, only the four or five best-agreement models are used to produce the validated projections for planning. Using all three approaches, the future projections of climate for Halton Region are presented. Climate models remain the best option available for projections of future climate change. Impact or adaptation studies may require the application of additional downscaling methods (such as dynamical or statistical) to provide more robust results.

Keywords: climate change, climate models, future climate scenarios, approaches to selecting a global climate model

1. Introduction

There is a wide selection of climate models available to provide scenarios of future climate change. All are mathematical models that simulate the functioning of the global climate system varying in size (computer space), scope (atmosphere, ocean, sea-ice and land-surface components), scale (horizontal spacing and grid size) and complexity (parameterization schemes). Our present understanding of the climate system and how it is likely to respond to increasing concentrations of greenhouse gases in the atmosphere would be impossible without the use of global climate models (GCMs) (Environment Canada, 2002). GCMs are powerful computer programs that use physical processes to replicate, as accurately as possible, the functioning of the global climate system.

GCMs use mathematical equations to simulate the functioning of the global climate system in three spatial dimensions and in time (Figure 1). Modern climate models include coupled atmosphere, ocean, sea-ice and land-surface components. Coupled GCMs must operate at modest resolutions due to the constraints on the availability of computing resources. For example, the atmospheric component of the Canadian global climate model is a 3-dimensional grid with a horizontal spacing (grid cell size) of about 312 km and 31 vertical atmospheric layers. The model simulates atmospheric temperature, pressure, winds and humidity at each grid point. The ocean component of the GCMs has a higher resolution, using 29 layers of vertical grid points with a horizontal resolution of about 150km (grid cell size). The model simulates the density, salinity and velocity of the ocean water at each grid point. The land-surface component has one layer, uses the same horizontal grid as the atmosphere (about 312 km), and simulates the temperature and moisture content of the soil. The sea-ice component, which also has one layer, uses the horizontal grid of the atmosphere and simulates the temperature and thickness of the ice pack.

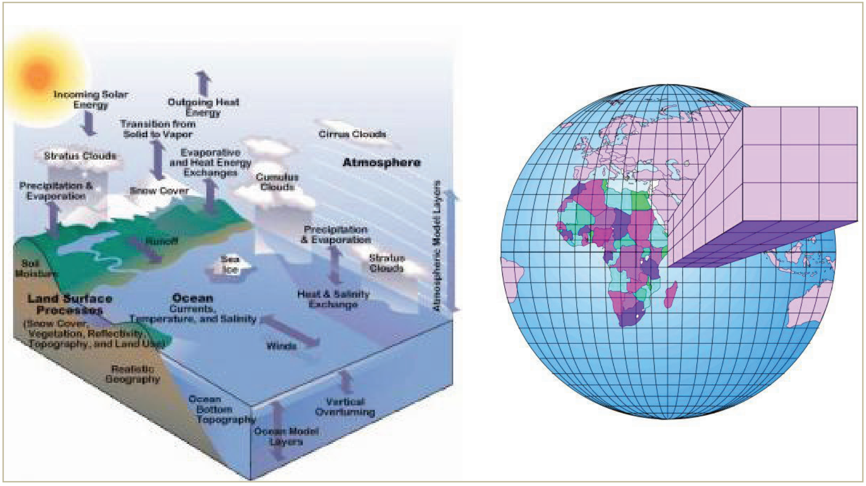

FIGURE 1
On left, climate system to be modeled by Global Climate Model (GCM); on right, gridded horizontal and vertical layers of a GCM. Source: National Center for Atmospheric Research

Improving the simulation of regional climates continues to be one of the biggest challenges facing climate modellers. For meaningful climate change impact studies, realistic simulations of the local climate are needed (Machenhauer *et al.*, 1996). Much higher resolution GCMs would provide a solution to this problem but would also require considerably more computer capacity. Doubling the resolution in three dimensions and reducing the time step for calculations, for example, increases computational requirements by a factor of more than sixteen. In addition to the coarseness and computational issues, there is the concern of compatibility of GCM results at regional scales. The results of GCMs from around the world often agree well with each other and with historical surface air temperature data over large scales such as global, hemispheric and zonal. However, when the model results are examined on successively smaller and smaller scales, eventually focusing on sub-continental regions containing only relatively few gridpoints, some studies (Grotch, 1988) show that significant differences arise. A leading question for climate impact assessment is how to resolve these differences and select a model, or handful of models, to provide adequate projections of future climate change.

2. Approaches to Selecting a Global Climate Model

2.1 Projections Using the Twenty-Four Global Climate Models Used in the IPCC AR4

The results from twenty-four global climate models were used in the deliberations of the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) (see Table 1). Each of the modelling centres has provided future projections for at least two, sometimes three, emission scenarios

TABLE 1

GCMs from the IPCC's Fourth Assessment Report (AR4)

CENTRE	MODEL
Bjerknes Centre for Climate, Norway	BCM2.0
Canadian Centre for Climate Modelling and Analysis (CCCma), Canada	CGCM3T47
Canadian Centre for Climate Modelling and Analysis (CCCma), Canada	CGCM3T63
Centre National de Recherches Meteorologiques, France	CNRMCM3
Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia	CSIROMk3.0

TABLE 1

GCMs from the IPCC's Fourth Assessment Report (AR4) cont...

CENTRE	MODEL
Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia	CSIROMk3.5
Max Planck Institute für Meteorologie, Germany	ECHAM5OM
Meteorological Institute, University of Bonn Meteorological Research Institute, Germany	ECHO-G
Institute of Atmospheric Physics, Chinese Academy of Sciences, China	FGOALS-g1.0
Geophysical Fluid Dynamics Laboratory (GFDL), USA	GFDLCM2.0
Geophysical Fluid Dynamics Laboratory (GFDL), USA	GFDLCM2.1
Goddard Institute for Space Studies (GISS), USA	GISSAOM
Goddard Institute for Space Studies (GISS), USA	GISSE-H
Goddard Institute for Space Studies (GISS), USA	GISSE-R
UK Meteorological Office, United Kingdom	HADCM3
UK Meteorological Office, United Kingdom	HADGEM1
National Institute of Geophysics and Volcanology, Italy	INGV-SXG
Institute for Numerical Mathematics, Russia	INMCM3.0
Institute Pierre Simon Laplace, France	IPSLCM4
National Institute for Environmental Studies, Japan	MIROC3.2 hires
National Institute for Environmental Studies, Japan	MIROC3.2 medres
Meteorological Research Institute, Japan Meteorological Agency, Japan	MRI-CGCM2.3.2
National Center for Atmospheric Research (NCAR), USA	NCARPCM
National Center for Atmospheric Research (NCAR), USA	NCARCCSM3

(scenarios that describe how greenhouse gas emissions could evolve over the next 100 years). Thus, there are about 72 possible future outcomes for the climate of Halton Region when using the 24 GCMs used in the IPCC AR4 (see Figures 2 and 3).

When beginning any impact assessment, choosing which climate model to use is an important question more easily addressed with the advent of the Canadian Climate Change Scenarios Network (CCCSN.CA), Environment Canada’s tool for accessing global climate model results. The CCCSN.CA translates the tera-bytes of global climate model output into useable information displayed in, for example, readable map and graphics formats from all two dozen international global climate models, and several regional climate models, with customized results for all regions of Canada (Note: GCM output is available in the system for across the globe, but mapping only available for Canada).

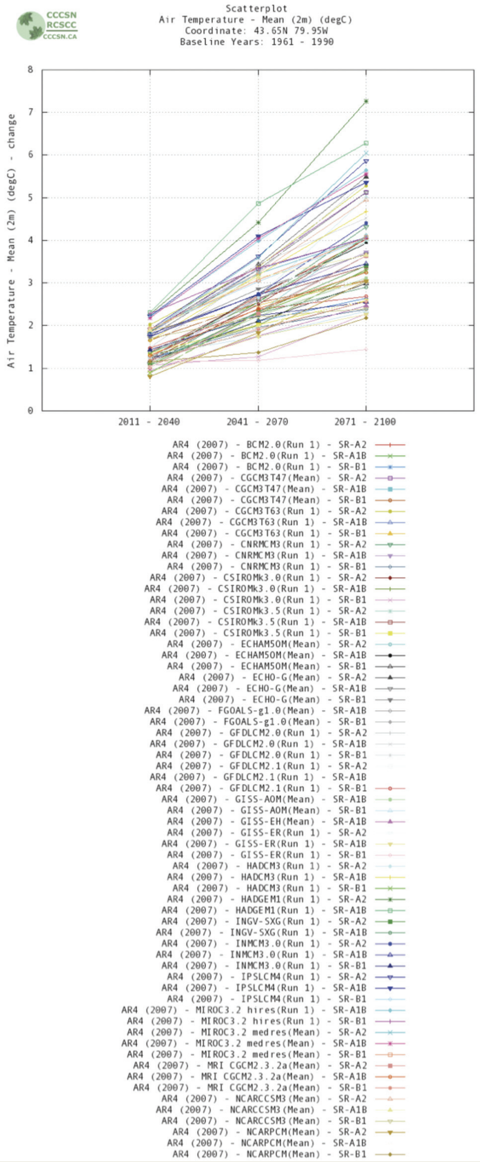

FIGURE 2

Projected future annual mean temperature increases for Halton Region for 2020s, 2050s and 2080s using twenty-four IPCC AR4 GCMs and available emission scenarios. Source: CCCSN, 2007.

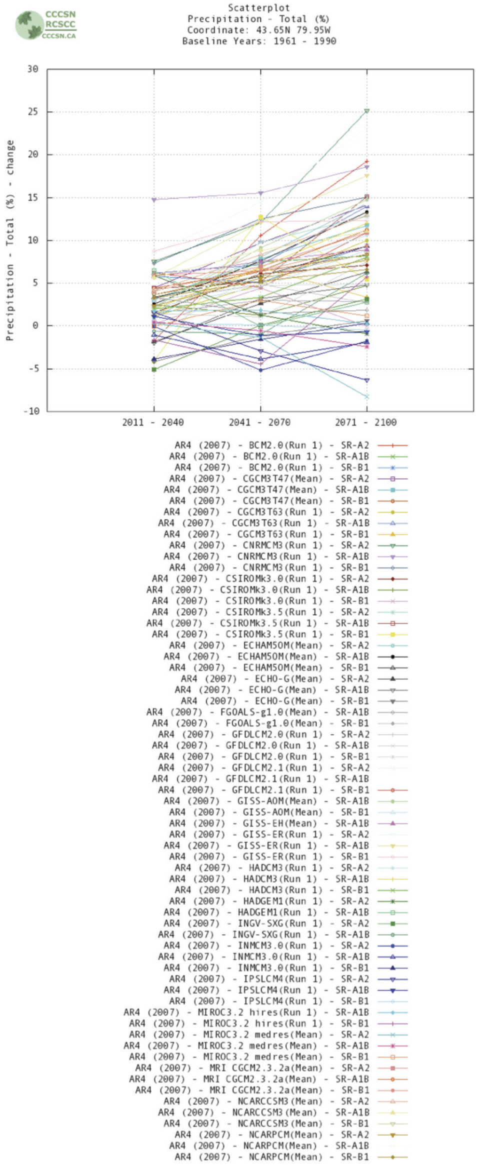

FIGURE 3

Projected future annual total precipitation changes for Halton Region for 2020s, 2050s and 2080s using twenty-four IPCC AR4 GCMs and available emission scenarios. Source: CCCSN, 2007.

While the models are in agreement with the direction of temperature change, results between models can vary widely, and models each contain their own inherent biases (some are too warm, others are too cold; some are too wet, others are too dry compared to historical climate). The differences in results exist because of the differences between each GCM's model resolution, model formulations and model parameterization. Differences are also found as a result of which emission scenario of future greenhouse gases is selected.

2.2 Greenhouse Gas Emission Scenarios

Greenhouse gas emission scenarios provide a "storyline" of possible futures based on key characteristics - such as human population growth, economic development, and energy technology change - that influence climate. Each storyline assumes a distinctly different direction for the future development of these characteristics, such that the storylines differ in increasingly divergent ways over time. The plausibility or feasibility of each storyline should not be considered solely on the basis of an extrapolation of current economic,

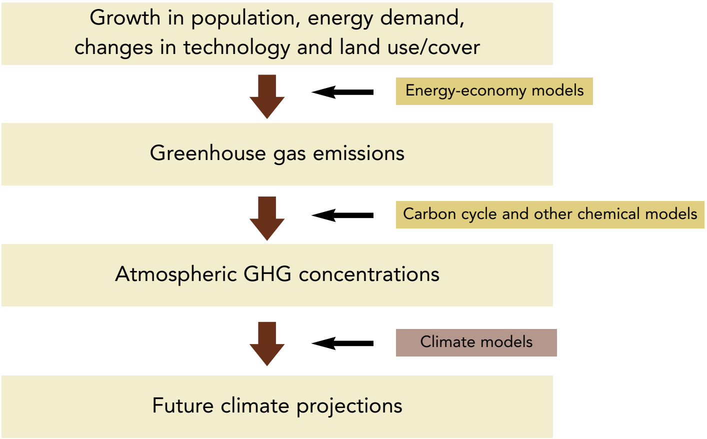

FIGURE 4
The steps in producing future climate projections.

technological, and social trends (CCCma, 2007). A schematic (Barrow *et al.*, 2003) of the production of future climate projections is shown in Figure 4.

Six alternative IPCC scenarios (IS92 a to f) were published in the 1992 Supplementary Report to the IPCC Assessment. These scenarios embodied a wide range of assumptions affecting how future greenhouse gas emissions might evolve in the absence of climate policies beyond those already adopted. The different "futures" that the scenarios imply, in terms of economic, social and environmental conditions, vary widely and the resulting range of possible greenhouse gas futures spans almost an order of magnitude. The premises for the IS92a and IS92b scenarios most closely resemble and update those underpinning the original SA90 scenario used in the IPCC First Assessment Report (FAR) in 1990. IS92a was widely adopted as a standard scenario for use in climate change impact assessments back in the 1990s.

The so-called IS92 scenarios were the first global scenarios to provide estimates for the full suite of greenhouse gases (IPCC, 2001). Much changed in the understanding of possible future greenhouse gas emissions and climate change, so the IPCC decided in 1996 to develop a new set of emissions scenarios that provided input to the IPCC Third Assessment Report (TAR). This new set provided improved emission baselines and the latest information on economic restructuring throughout the world; examined different rates and trends in technological change; and expanded the range of different economic-development pathways, including narrowing of the income gap between developed and developing countries. Overall, there were 40 different scenarios prepared for the IPCC TAR, and subsequently used again in the IPCC 4th Assessment Report (AR4). The scenarios were categorized into four storylines – A1, A2, B1, B2 – and are described briefly in Table 2. Figure 5 shows how these scenarios differ in their atmospheric response over time – in this case, global mean temperature change. The range of IPCC SRES climate change scenarios A2 (high), A1B (mid) and B1 (low) are used for climate change vulnerability, impact and adaptation studies.

TABLE 2

Summary of major categories of IPCC Special Report on Emissions Scenarios (SRES)

A1 - The A1 scenarios are of a more integrated world. The A1 family of scenarios is characterized by: rapid economic growth; a global population that reaches 9 billion in 2050 and then gradually declines; the quick spread of new and efficient technologies; a convergent world – income and way of life converge between regions; and extensive social and cultural interactions worldwide. There are subsets to the A1 family based on their technological emphasis: A1FI - an emphasis on fossil-fuels; A1B - A balanced emphasis on all energy sources; and A1T - emphasis on non-fossil energy sources.

A2 - The A2 scenarios are of a more divided world. The A2 family of scenarios is characterized by: a world of independently operating, self-reliant nations; continuously increasing population; regionally oriented economic development; and slower and more fragmented technological changes and improvements to per capita income.

B1 - The B1 scenarios are of a world more integrated, and more ecologically friendly. The B1 scenarios are characterized by: rapid economic growth as in A1, but with rapid changes towards a service and information economy; population rising to 9 billion in 2050 and then declining as in A1; reductions in material intensity and the introduction of clean and resource efficient technologies; and an emphasis on global solutions to economic, social and environmental stability.

B2 - The B2 scenarios are of a world more divided, but more ecologically friendly. The B2 scenarios are characterized by: continuously increasing population, but at a slower rate than in A2; emphasis on local rather than global solutions to economic, social and environmental stability; intermediate levels of economic development; and less rapid and more fragmented technological change than in B1 and A1.

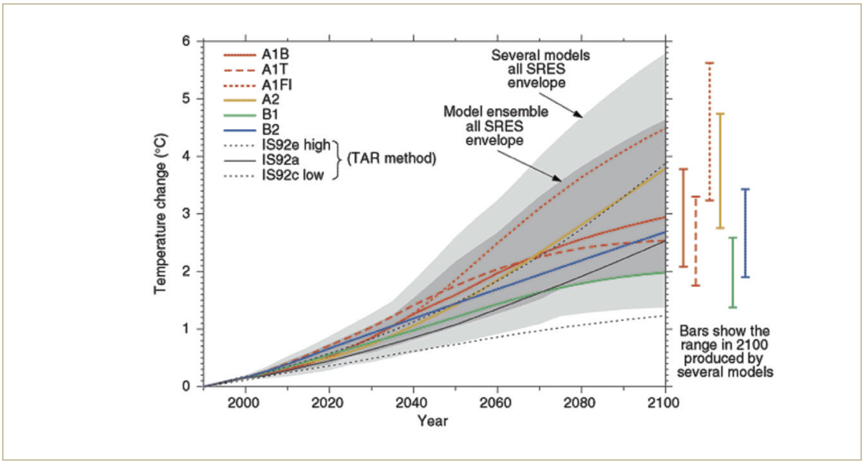

FIGURE 5

Projected global mean temperature change under different SRES and IS92 scenarios. Source: IPCC 2001.

2.3 Model Selection Approaches and Projection Results

There are three approaches that have been developed in order to provide some direction for determining which of the ~72 future projections of climate from the IPCC 4AR should be used in planning – the extremes (max/min) approach; the ensemble approach; and the validation approach. The extremes (max/min) approach suggests that it is best to plan within the full range of possibilities that the ~72 GCMs present. The approach takes the projection for the maximum change, as well as the projection for the minimum change, and uses both as the range of consideration when planning. The ensemble approach suggests that it is best to plan for the average change of all the models. The approach uses a mean or median of all the models (or many models) to reduce the uncertainty associated with any individual model. The validation approach suggests that those models that compare well to historical climate observations should be the ones used for planning. The approach takes the historical climate observations over a thirty-year period from a global gridded dataset (for example, the National Centres for Environmental Prediction (NCEP)) and compares this against all models to see which ones reproduce the values best. Subsequently, only the four or five historically best-agreement models are used to produce the validated projections for planning – in the case of Halton Region, these are GISSEH, ECHAM5OM, NCARCCSM3 and CGCM3T47.

Using all three approaches, the future projections of climate for Halton Region are presented (see Figures 6 and 7). Using the ensemble approach (and others in parentheses), results suggest that the future changes in annual mean temperature are 1.5°C for the 2020s (0.6°C minimum, 2.3°C maximum, 1.4°C validated); 2.7°C for the 2050s (1.3°C minimum, 4.8°C maximum, 2.6°C validated); and 3.9°C for the 2080s (1.6°C minimum, 7.2°C maximum, 3.6°C validated). Future changes in annual total precipitation are projected at an increase of 2.4% for the 2020s (decrease of 6.4% minimum, increase of 14.8% maximum, increase of 3.2% validated); an increase of 4.7% for the 2050s (decrease of 5.2% minimum, increase of 15.6% maximum, increase of 7.4% validated); and an increase of 7.5% for the 2080s (a decrease of 7.5% minimum, an increase of 25% maximum, an increase of 11.9% validated). Note that some studies will require projections at a finer temporal scale than annual – perhaps seasonal, monthly or even daily – requiring different approaches such as those below.

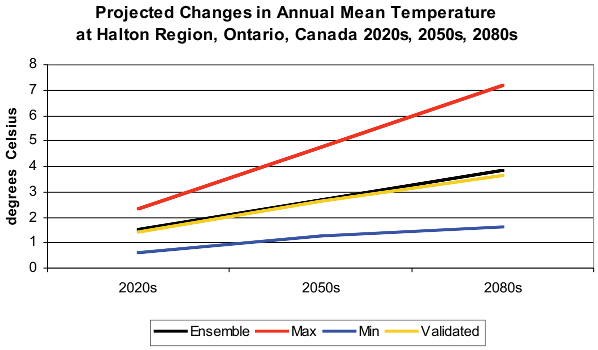

FIGURE 6

Future Projections of Annual Mean Temperature Changes at Halton Region, Ontario, Canada Grid Cell in the 2020s, 2050s, 2080s – Extremes (Max/Min), Ensemble and Validated (change in degrees Celsius from 1961-90 baseline period).

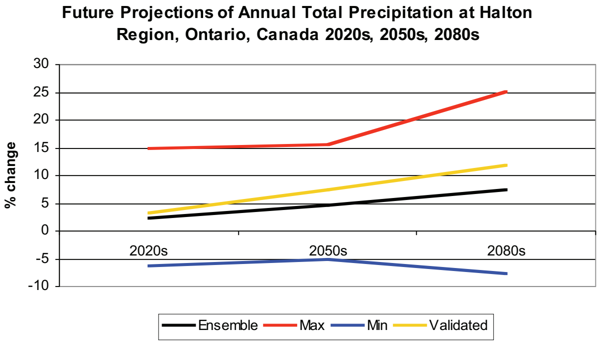

FIGURE 7

Future Projections of Annual Total Precipitation Changes at Halton Region, Ontario, Canada Grid Cell in the 2020s, 2050s, 2080s Extremes (Max/Min), Ensemble and Validated (change in percentage from 1961-90 baseline period).

2.4 Issues with Using GCM Output for Future Projections

There are many caveats to using GCMs for future projections. The resolution of the models varies and is completely determined by the modelling centre, that is, there is no 'standard' grid size or projection method. The output from the model represents an average value of the entire grid cell area – a grid cell with a large resolution of about 250 by 250 kilometers. In Ontario, this means there are about 25 grid cells (it depends on the model). This approximation means that even the distribution of land/water grid cells differs between models. For Halton Region, this can have important implications since its climate is influenced significantly by the Great Lakes which not likely to be represented by most GCMs because of their scale.

A number of methodologies have been developed for deriving more detailed regional and site scenarios of climate change for impact studies. These downscaling techniques are generally based on GCM output and have been designed to bridge the gap between the information that the climate modelling community can currently provide and that required by the impacts research community (Wilby and Wigley, 1997). The literature presents downscaling techniques as generally divided into spatial (deriving local scenarios from regional scenarios) and temporal (deriving daily data scenarios from monthly or seasonal information) classes (Giorgi and Mearns, 1991; Robock *et al.,* 1993; Hewitson and Crane, 1996; Wilby *et al.,* 1998; Murphy, 1999; IPCC, 2001).

There are three main classes of spatial downscaling:

- Transfer functions - statistical relationships are calculated between large-area and site-specific surface climate, or between large-scale upper air data and local surface climate.
- Weather typing - statistical relationships are determined between particular atmospheric circulation types (for example, anti-cyclonic or cyclonic conditions) and local weather.
- Stochastic weather generators - these statistical models may be conditioned on the large-scale state in order to derive site-specific weather.

There are many different types of statistical downscaling of climate model software available for climate impact studies, namely the Statistical Downscaling Model (SDSM) (Wilby *et al.,* 2002), the Long Ashton Research Station (LARS) Weather Generator (LARS-WG). (Racsko *et al,* 1991; Semenov *et al.,* 1998; Semenov and Brooks, 1999) and the Automated Statistical Downscaling (ASD) tool (Hessami *et al.,* 2006). As a next step in the research, these approaches could be applied to Halton Region to determine their value in simulating climate values. Many of these approaches are limited in their transferability, however, due to their intellectual complexity or their need for expensive software as a platform.

References

CCCma. 2007. *Canadian Centre for Climate Modelling and Analysis*. Environment Canada. **www.cccma.bc.ec.gc.ca/**

CCCSN. 2007. *Canadian Climate Change Scenarios Network.* Environment Canada. **www.cccsn.ca**

Environment Canada. 2002. Poster 5: Climate Modelling: Predicting Global Climate Change in series *Science for Sustainable Development* presented at the 2002 World Summit on Sustainable Development at Johannesburg, South Africa.

Giorgi, F. and L.O. Mearns. 1991. Approaches to the simulation of regional climate change: a review. *Reviews of Geophysics* 29, 191-216.

Grotch, S.L. 1988. *Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data.* US Department of Energy. Washington, D.C.

Hessami, M., P. Gachon, T.B.M.J. Ouarda and A. St-Hilaire. 2006. Automated regression-based Statistical Downscaling Tool. *Environmental Modelling & Software* (in review).

Hewitson, B.C. and R.G. Crane. 1996. Climate downscaling: techniques and application. *Climate Research* 7, 85-95.

IPCC. 2001. *Special Report on Emissions Scenarios.* Intergovernmental Panel on Climate Change.

Machenhauer, B., Windelband, M., Botzet, M., Jones, R.G., and Déqué, M. 1996. *Validation of Present-Day Regional Climate Simulations over Europe: Nested LAM and Variable Resolution Global Model Simulations with Observed or Mixed Layer Ocean Boundary Conditions.* Max Planck-Institut fur Meteorologie. Hamburg, Germany.

Murphy, J. 1999. An evaluation of statistical and dynamical techniques for downscaling local climate. *Journal of Climate* 12, 2256-2284.

Racsko, P., L. Szeidl and M.A. Semenov. 1991. A serial approach to local stochastic weather models. *Ecological Modelling* 57:27-41.

Robock, A., R. Turco, M. Harwell, T.P. Ackerman, R. Andressen, H.-S. Chang and M.V.K. Sivakumar. 1993. Use of general circulation model output in the creation of climate change scenarios for impact analysis. *Climatic Change* 23, 293-335

Semenov, M.A., R.J. Brooks, E.M. Barrow and C.W. Richardson. 1998. Comparison of the WGEN and LARS-WG stochastic weather generators for diverse climates. *Climate Research* 10:95-107.

Semenov, M.A. and R.J. Brooks. 1999. Spatial interpolation of the LARS-WG stochastic weather generator in Great Britain. *Climate Research* 11:137-148.

Wilby, R.L. and T.M.L. Wigley. 1997. Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography* 21, 530-548.

Wilby, R.L., T.M.L. Wigley, D. Conway, P.D. Jones, B.C. Hewitson, J. Main and D.S. Wilks. 1998. Statistical downscaling of General Circulation Model output: a comparison of methods. *Water Resources Research* 34, 2995-3008.