Future realities of climate change impacts: an integrated assessment study of Canada

Mohammad Khaled Akhtar*

River Engineering and Technical Services,
Alberta Environment and Parks,
Edmonton, Alberta, Canada
Email: khalediwm@yahoo.com
Email: Khaled.Akhtar@gov.ab.ca
*Corresponding author

Slobodan P. Simonovic

Department of Civil and Environmental Engineering,
The University of Western Ontario,
London, Ontario, Canada
Email: ssimonovic@eng.uwo.ca

Jacob Wibe

PricewaterhouseCoopers,
Calgary, Alberta, Canada
Email: jacob.wibe@gmail.com

James MacGee

Department of Economics,
The University of Western Ontario,
London, Ontario, Canada
Email: jmacgee@uwo.ca

Abstract: This paper presents an integrated assessment model for use with climate policy decision making in Canada. The feedback based integrated assessment model ANEMI_CDN represents Canada within the global society-biosphere-climate-economy-energy system. The model uses a system dynamics simulation approach to investigate the impacts of climate change in Canada and policy options for adapting to changing global conditions. The disaggregation techniques allow ANEMI_CDN to show results with various temporal resolutions. Two Canadian policy scenarios are presented as illustrative examples to map policy impacts on key model variables, including population, water-stress, food production, energy consumption, and emissions under changing climate over this century. The main finding is a significant impact of a carbon tax on energy consumption. Two policy scenario simulations provide additional insights to policy makers regarding the choice of adaptation/mitigation options along with their implementation time.

Keywords: system dynamics simulation; climate change; integrated assessment modelling; society-biosphere-climate-economy-energy system; water resources management; disaggregation; global warming; Canada.

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Biographical notes: Mohammad Khaled Akhtar has over 15 years of progressively increasing experience in organising, planning, designing and managing of water resource projects including; flood forecasting, sub-watershed studies, hydrodynamic modelling, flood control and drainage study, integrated water resources management, storm water management, and serious game development for basin management. He is also experienced with various climate change impact studies including formulation of adaptation and mitigation strategies. He received his BSc in Civil Engineering from Bangladesh University of Engineering and Technology, MSc in Water Resources Engineering from UNESCO-IHE, and PhD from the University of Western Ontario. He is currently working as a River Forecast Engineer with the Alberta Environment and Parks.

Slobodan P. Simonovic has made seminal contributions to the development of systems engineering approaches to the planning, designing and managing of complex water resources systems in the search for sustainable and robust physical and societal solutions, based on stakeholders' value systems and ethical principles. He has utilised probabilistic and fuzzy simulation and optimisation for addressing subjective and objective uncertainties in managing water resources systems. Moreover, he has contributed to the solution of complex reservoir operations problems; developed effective flood management measures; improved assessment of climate change impacts on local scales; and developed decision support for integrated water resources management. He has published over 530 professional publications (219 in peer reviewed journals) and three major textbooks.

Jacob Wibe is currently a Transfer Pricing Consultant at PricewaterhouseCoopers in Calgary, Alberta. He has a PhD in Economics from the University of Western Ontario with extensive research and consulting experience in international macroeconomics, international trade, and environmental economics.

James MacGee is an Associate Professor of Economics at the University of Western Ontario, where he has been a faculty member since 2002. He received his BBA and MA in Economics from the University of New Brunswick and his PhD in Economics from the University of Minnesota. His research interests include consumer credit and bankruptcy, the role of international and monetary shocks in the great depression, and has been supported by the Social Science and Humanities Research Council of Canada. He has published in leading academic publications, including the *American Economic Review*, the *Review of Economic Studies*, the *American Economic Journal: Macroeconomics*, the *Journal of Monetary Economics*, and *Review of Economic Dynamics*.

1 Introduction

The scientific consensus is that climate change is ongoing with the potential for catastrophic impacts (IPCC, 2014, 2007). To mitigate the negative impacts of climate change, policy makers in Canada and other countries need models which can help them analyse the extent and impact of climate change so as to develop adaptation strategies (Navazi et al., 2017). One approach to better understand the risk trade-offs associated with complex interactions between the climate system, the economy, ecosystems, and human activities is to use scenario analyses to examine the future socioeconomic and climatic conditions associated with alternative emission paths of greenhouse gases (Moss et al., 2010).

Integrated assessment models (IAMs) provide a useful structure for a simulation-based approach to assess climate risk as they combine socioeconomic conditions with the physical processes that determine climate change. Kelly and Kolstad (1999) define an IAM as one that combines scientific and socioeconomic aspects of climate change for the purpose of assessing policy options for adaptation to climate change. Some examples include Akhtar et al. (2013), Davies and Simonovic (2010), Dowlatabadi and Morgan (1993, 1995), Kolstad (1996), Lempert et al. (1996), Manne et al. (1995), Nordhaus (1994) and Peck and Teisberg (1992).

Climate change projected impact on the geographical distribution and extent of rainfall is expected to increase pressure on freshwater resources and make sustainable water resource management more challenging in the face of population growth and ongoing land use change. Motivated by these concerns, the ANEMI modelling effort at the University of Western Ontario, Canada develops a system dynamics simulation approach for integrated assessment of climate change impacts (Akhtar et al., 2013; Davies and Simonovic, 2011, 2010). The second version of the global ANEMI model, ANEMI_2 (Akhtar et al., 2013) includes nine sectors (climate, carbon cycle, land-use, population, food production, hydrologic cycle, water demand, water quality, and energy-economy) which interact through a number of feedback relationships. However, the global version of ANEMI_2 cannot be used on a regional or local scale. In order to evaluate mitigation and adaptation strategies for Canada, the ANEMI_CDN model was developed. This model also illustrates how ANEMI_2 can be extended to examine regional impacts of climate change with appropriate spatial and temporal resolutions.

The regional assessment ANEMI model of Canada (ANEMI_CDN) separates Canada from the rest of the world (ROW). As the climate, carbon and a portion of the hydrologic cycle system components deal with global processes, they remain in the model on a global scale. The rest of the system components are regionalised based on available data since they represent the driving force of the regional energy-economy, hydrologic cycle, and food production sectors. The regional rainfall and temperature change are computed from global data due to the lack of long-term regional historical hydrometeorological observations. Here a disaggregation technique is employed to establish a relationship between global and regional temperature and rainfall data based on available GCM models.[1,2]

The ANEMI_CDN links global conditions with regional implications to develop a system dynamics simulation model for analysing the behaviour of the social-energy-economy-climate system. In this study, two types of objectives are considered; modelling effort and climate policy development. The specific modelling objectives include:

1 regionalisation of the model's global system components to a regional scale for Canada (land-use, population, food production, portion of the hydrologic cycle, water demand, water quality, and energy-economy)

2 implementation of disaggregation/downscaling modeling techniques to generate regional precipitation and temperature from the global scale to Canada

3 implementation of endogenous market response of fossil energy production in Canada in response to changes in world commodity prices.

The specific policy objectives of ANEMI_CDN development include:

1 provide a framework for organising and assessing knowledge about climate change

2 help differentiate among policy options

3 help inform the research planning process

4 understand the interactions of components of the modeled systems

5 climate impact analysis including computation of the social cost, emission response and economic implications of carbon and carbon pricing

6 integrated mitigation and impacts analysis.

Given these modelling and policy objectives, the ANEMI_CDN model is expected to provide insights into the complex global system and climate policy development. This paper describes the ANEMI_CDN structure in detail and illustrates its performance in emulating historical trends along with its use through the analyses of two illustrative regional policy scenarios.

Section 2 of the paper briefly outlines the Canadian climate change policy environment. Section 3 briefly describes the ANEMI_CDN model. Section 4 describes the model simulations undertaken to analyse two policy scenarios. Section 5 summarises and evaluates the significant results of model simulations against research objectives. The final section concludes with recommendations for future research.

2 Climate change policy context

Canada has experienced warmer average temperatures in recent decades, with an approximately 1.5°C increase in annual temperature from the 1951 to 1980 climate normal. In addition, there is suggestive evidence of a trend towards lower maximum and minimum river flows over 1970-2005 in southern Canada, with increases in minimum flows in western Nunavut, Northwest Territories, Yukon, and northern British Columbia (Warren and Lemmen 2014).

The challenge of dealing with the impacts of climate change is often framed in terms of *adaptation* and *mitigation*. Mitigation refers to an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases (IPCC, 2001a). Adaptation involves actions that lower our vulnerability to climate change, while not necessarily dealing with the underlying cause. Adaptation and mitigation are complementary, as mitigation alone will not prevent climate change from occurring. Adaptation is thus necessary to complement mitigation strategies.

3 Modelling

Global climate models (GCMs) are the basic tools for understanding the dynamics of the climatic system, whereas regional climate models (RCMs) provide more detailed insights for regional socioeconomic policy analyses. The horizontally integrated assessment system dynamics model ANEMI_CDN was developed to allow modellers and policy makers to investigate the effects of global climate change on Canadian water resources, energy supply and demand, population and land-use, and economic performance. Applications of the ANEMI_CDN IAM span both the past and possible future climates on a regional scale;

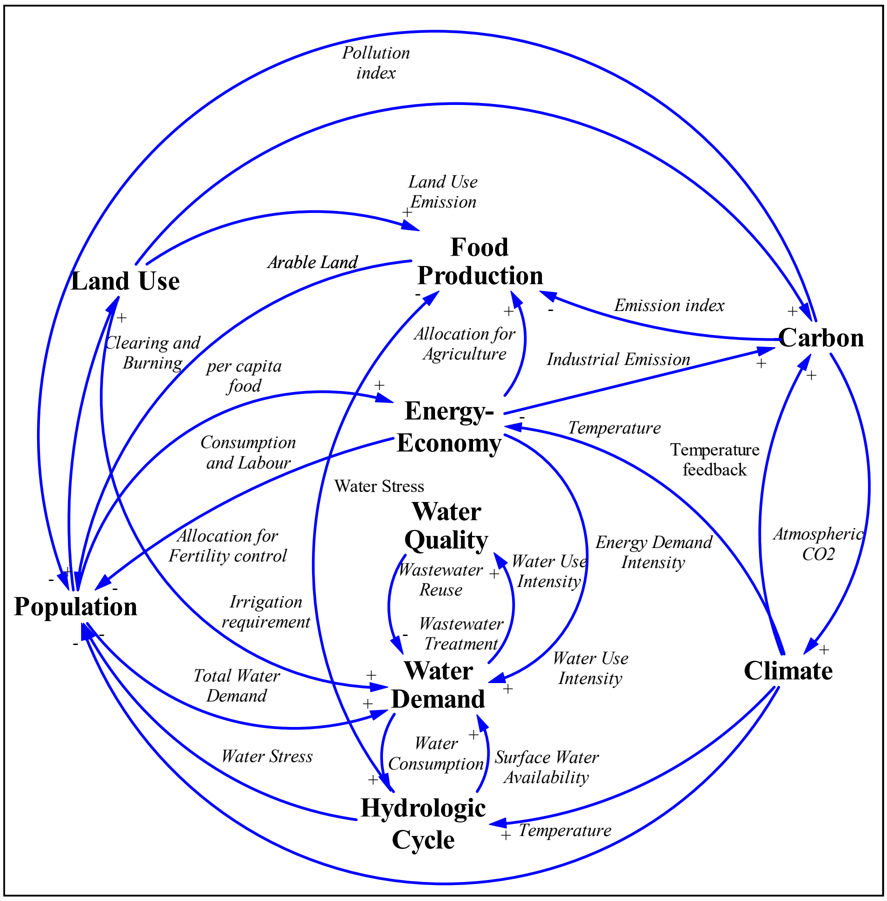
1 facilitating climate impact studies

2 providing information to climate policy

3 supporting investigation of adaptation options for Canada.

As the climate system has no geographic boundaries, the climate in any region is affected by global conditions.

Figure 1 Causal loop diagram of the ANEMI_CDN model (see online version for colours)



ANEMI_CDN consists of nine sectors. The climate, carbon and a portion of the hydrologic cycle related model sectors deal with global processes, hence they remain on a global scale. Figure 1 displays the causal loop diagram of ANEMI_CDN, with sector names in bold font and feedbacks represented as arrows which connect system components in a closed-loop structure. Each arrow connecting system components bears the name of the element which causes a change in the connected system component, known as intersectoral feedback. For example, the connection between water demand and hydrologic cycle components, called 'water consumption', indicates that a rise in water consumption causes a fall in water quantity, a key output of the water sector.

The carbon sector has two major feedbacks producing radiative forcing that leads to higher temperatures. In the climate sector, atmospheric CO_2 is converted to radiative forcing, see equation, equation (1). The other sources of radiative forcing arise from methane, nitrous oxide, chlorofluorocarbons, and other Montreal protocol gases. F_{co_2}, the radiative forcing from carbon dioxide, and F_{other}, the radiative forcing from methane, chlorofluorocarbon, nitrous oxide, and other Montreal protocol gases, are added together and enter the climate sector as total radiative forcing, F_{total}:

$$F_{total} = F_{co_2} + F_{other} \tag{1}$$

The climate sector impacts almost all sectors in the ANEMI_CDN model. The population, food production, hydrologic cycle, land-use, water demand, and water quality sectors are connected with the climate sector through the global temperature. The model follows Nordhaus and Boyer (2000) and captures the impact of climate change on the energy-economy sector via the climate damage function (D_t):

$$D_t = \theta_1 \cdot \Delta T_t + \theta_2 \cdot \Delta T_t^2 \tag{2}$$

where D_t is the damage from climate change, as a fraction of output and ΔT_t is the atmospheric temperature increase (in degree Celsius) since 1900, and θ_1 and θ_2 are parameters of the damage function.

The increase in temperature affects the global hydrologic cycle by changing the intensity and magnitude of evaporation, precipitation pattern, starting day of snow melt, and so on. Huntington (2006) argues global precipitation increases by 3.4% per 1^{o}k surface temperature increase. This leads to the following functional relationship:

$$P_{mult} = P_{mult,base} \cdot \Delta T_s \tag{3}$$

$$T_{feedback} = 1 + \left(P_{mult} / 100 \right) \tag{4}$$

where $T_{feedback}$ is the temperature multiplier, which depends on P_{mult}, the precipitation multiplier ΔT_s is measured in Kelvin, which denotes the change in surface temperature; $P_{mult,base}$ is a fixed value of 3.4% K^{-1}. The temperature multiplier equation, equation (4), computes the temperature feedback which determines the dynamic feedback relationship between climate, water use, water demand, evaporation calculation, and CO_2 absorption capacity of the ocean.

Population is linked to land-use following the approach of Goudriaan and Ketner (1984). Emissions from the energy-economy sector are directly added to the carbon sector. Carbon emissions from each energy source are calculated based on energy consumption and carbon content. The following equation computes the CO_2 emissions in 10^6 tons C.

$$CO_{2i} = P_i \cdot FO_i \cdot C_i \tag{5}$$

where subscript i indicates the fuel, P_i = annual production in 10^6 tons of fossil fuel equivalent, FO_i is the effective fraction oxidised in year t and C_i is carbon content in tons C per ton coal equivalent.

Each of the three water related sectors interacts with food production and population through the 'water-stress' variable. The annual withdrawals-to-availability (wta) ratio is the most used indicator of water-stress. Alcamo and Henrichs (2002) report that 'wta' values of 0.2 indicate 'mid-stress' and values of 0.4 and higher indicate 'severe stress'. The concept of water scarcity is most meaningful at the watershed or sub-watershed level.

3.1 Methodological approaches

This paper presents two new methodological approaches: the regionalisation of system components to capture Canada, and introduction of disaggregation modelling for temporal and spatial downscaling of the GCM data. The temporal disaggregation extends the ANEMI_CDN so as to generate monthly data, while the model simulation is performed with a yearly time step. To evaluate market and non-market costs and benefits of climate change, the model integrates an economic sector, with a focus on the international energy stock and fuel price, with climate interrelations and temperature change in Canada.

The ANEMI_CDN differs from other IAMs [MERGE (Manne et al,. 1995), REMIND (Leimbach et al. 2010; Luderer et al., 2009), MiniCAM (Edmonds et al., 1996, 1994) etc.] in merging a system dynamics simulation approach with a neo-classical economic growth model. In the energy-economy sector, the price of fuel and the capital stocks for energy production are simulated based on the optimal value of GDP, energy production and energy use across sectors. The values of these components are selected by an optimisation scheme linked to population and climate as well as the energy-economy sector. Based on the calculated objective functions, the optimisation algorithm selects new sets of control parameters to be evaluated. This process is repeated until no further improvement can be made. The optimisation scheme of ANEMI_CDN takes labour supply and the climate damage function as given.

The ANEMI_CDN model separates Canada from the ROW. Since the climate and carbon system sectors of ANEMI_CDN remain at a global scale, the model does not directly generate regional temperature change. Regional rainfall and temperature change are computed using global values and downscaling techniques. The relationship between global and regional temperature and rainfall data is established based on the outputs of GCM models using a disaggregation technique.[3] The hydrologic cycle involves global and regional scales, as marine atmosphere and ocean drive at a global scale. Whereas, variables such as surface flow, available water, and ground water operate at a regional scale. The downscaled physical variables drive the regional energy-economy, hydrologic cycle, and the food production sectors.

3.1.1 Regionalisation of model sectors

As this paper focuses on the regional assessment model, ANEMI_CDN, our discussion of the underlying global model ANEMI_2 is kept brief.[4] Below we outline the regionalised model sectors: population, land-use, hydrologic cycle, water demand, water quality, food production, and energy-economy.

3.1.1.1 Population

Annual deaths are the sum of deaths per age group, computed as the product of that age's population (P_{agr}) and age-specific mortality (P_{mor}).

$$D_{er} = \sum_{agr} P_{agr} \cdot P_{mor} \tag{6}$$

Births per year (B_{er}) depend on a demographic factor, the number of women of child bearing age (half the population between ages 15 and 44), and the average number of births per woman annually.

$$B_{er} = F_{total} \cdot \frac{0.5 \cdot P_{15-44}}{R_{life}} \tag{7}$$

where F_{total} is total fertility, R_{life} is the reproductive lifetime of 30 years, and P_{15-44} is the population of age 15 to 44. Total fertility is a function of the maximum total fertility (F_{Mtotal}), desired fertility (F_{Dtotal}), and fertility control effectiveness (F_{econt}):

$$F_{total} = MIN\left(F_{Mtotal}, F_{Mtotal} \cdot \left(1 - F_{econt}\right) + F_{econt} + F_{Dtotal}\right) \tag{8}$$

Each year we update the total population by the change in the population (P_total), given by the integral of births (B_{er}) less deaths over the year (D_{er}).

3.1.1.2 Hydrologic cycle

The hydrologic cycle tracks atmospheric water content over the ocean (A_M) and land (A_L):

$$A_M = \int \left(E_M - Adv - P_0\right) \cdot dt \tag{9}$$

$$A_L = \int \left(Adv + ET - P_R - P_s\right) \cdot dt \tag{10}$$

where E_M is evaporation from oceans, Adv is the advective flow of moisture from the marine atmosphere, P_O is ocean precipitation, ET is evapotranspiration from the land surface, and P_R and P_S are precipitation over land in the form of rain and snow, respectively. Water storage in the terrestrial environment (LS) is:

$$LS = \int \left(P_R - ET - SF - GP\right) \cdot dt \tag{11}$$

where SF is the surface flow of water to the oceans, and GP is percolation.

Water storage in the oceans (O) is:

$$O = \int \left(SF + GD + P_0 + M - E_M \right) \cdot dt \tag{12}$$

where *GD* is groundwater discharge, and *M* is ice sheet melting. Groundwater storage (GS) and ice storage (*IS) are* expressed as:

$$GS + IS = \int (GP - GD) \cdot dt + \int \left(P_S - M \right) \cdot dt \tag{13}$$

3.1.1.3 Water demand and water quality

Water withdrawals and consumption depend on the population (P_{total}), industrial structural water intensity (ISWI), technological change, electricity production (E_p), irrigated land (A_{tirr}), per hectare water withdrawal (W_{phw}) and consumption (W_{phc}). A significant fraction of agricultural water is sourced from treated wastewater (W_{atwr}) and ground water withdrawal (W_{wgw}).

Desired industrial water withdrawal and consumption are driven by the ISWI, technological change and electricity production (E_p). In calculating 'industrial water withdrawal', we subtract treated industrial water for reuse (W_{itwr}) to avoid double counting, as well as the reuse of treated water (W_{dtwr}) and desalinated water (W_{ddsw}):

$$W_{dw} = P_{total} \cdot W_{pcw} - W_{dtwr} - W_{ddsw} \tag{14}$$

$$W_{dc} = P_{total} \cdot W_{pcc} \tag{15}$$

where W_{pcw} and W_{pcc} represents per capita water withdrawal and consumption, respectively.

$$W_{iw} = f\left(E_p\right) \cdot ISWI \cdot TFP - W_{itwr} \tag{16}$$

$$W_{ic} = f\left(E_p\right) \cdot ISWI \cdot TFP \tag{17}$$

$$W_{aw} = A_{tirr} \cdot W_{phw} - W_{atwr} - W_{wgw} \tag{18}$$

$$W_{ac} = A_{tirr} \cdot W_{phc} \tag{19}$$

where desired agricultural water withdrawal and consumption are denoted by W_{aw}, and W_{ac}, respectively.

Water quality is proxied by water-stress which measures the pressure on water resources by how much is left for ecosystem health. Water quality accounts for water withdrawal as well as the return of unused water.

$$wta = {W_w}/{(SF + GD)} \tag{20}$$

where W_w is surface water withdrawal and *(SF+GD)* is total surface runoff available for human use. The other option to calculate water-stress is as a fraction of total runoff, called Q_S;

$$wta = {W_{SW}}/{Q_S} \tag{21}$$

where W_{SW} is the effective surface water withdrawal.

3.1.1.4 Food production

Annual food production is a function of cultivated land and land yield:

$$F_p = L_y \cdot A_l \cdot L_{fh} \cdot (1 - P_l) \tag{22}$$

where F_p denotes food production, L_y is land yield, A_l is net arable land, and the fraction of land cultivated is denoted by L_{fh}. In the simulations, the processing loss (P_l) is set to 10%. The land yield L_y is the average weight of crop production on a hectare of land per year:

$$L_y = L_{yf} \cdot L_{fert} \cdot L_{ymc} \cdot L_{ymw} \tag{23}$$

where L_{yf} is the land yield factor, L_{fert} is land fertility, L_{ymw} is water-stress to land yield, and L_{ymc} is the land yield multiplier from capital.

3.1.1.5 The energy-economy

The energy-economy sector of ANEMI_CDN models Canada as a small open economy that takes energy prices and the global mean temperature as given. Thus, fossil fuel prices and the global mean temperature are exogenous to the region's energy-economy system component. The path of fossil fuel prices and the global mean temperature are endogenously determined by the ANEMI_2 (global version) model.

Aggregate energy services, E, are produced from heat and electric energy. Electric energy is produced from fossil fuels, nuclear and hydro power, where nuclear and hydro power are exogenous policy variables. Each period the representative firm solves the following problem:

$$\min_{F_{El,i}} ATC_{El}\left(F_{El,Coal}, F_{El,Oil}, F_{El,Nat.Gas}\right)$$

Subject to

$$E_{El} \geq \overline{E_{El}} \tag{24}$$

$$P_{El} = ATC_{El}$$

K_{Coal}, K_{Oil}, $K_{Nat.Gas}$ given.

where

$$E_{El} = A_{El}\left(a_1 F_{El,Coal}{}^{\vartheta} + a_2 F_{El,Oil}{}^{\vartheta} + a_3 F_{El,3}{}^{\vartheta} + a_4 \overline{E}_{El,Nucl.}{}^{\vartheta} + a_5 \overline{E}_{El,Hydr.}{}^{\vartheta}\right)^{1/\vartheta}$$

and

$$a_i = \left(1/\omega\right)\left(g_i - \left(F_{El,i}/K_i\right)^2\right), \text{ for } i = 1, 2, 3.$$

Given the capital stocks for fossil fuels and the available nuclear and hydro power, the firm chooses $\{F_{El,Coal}, F_{El,Oil}, F_{El,Nat.Gas}\}$ to minimise the average cost of electricity. Here,

A_{El} is a productivity term specific to electricity production, $F_{El,i}$ is the fuel input used for fuel type i in electricity production, ATC_{El} is the average cost of electric energy, $\overline{E_{El}}$ is the threshold value for electric energy, P_{El} is the price of electric energy and ϑ is the elasticity parameter, with elasticity of substitution of $E_s = 1/(1-\vartheta)$.

The a_i functions for the fossil fuels are decreasing in the fuel-to-capital ratio to capture diminishing returns as capital is a fixed factor. The parameters a_4 and a_5 are fixed, while ω and g_i are calibrated to match the relative levels of fossil fuels in electricity production.

Heat energy is produced from fossil fuels and alternative energy sources. We do not directly model capital in the heat energy sector, but implicitly assume that the capital for heat energy is part of the aggregate capital stock. Each period the representative firm chooses the quantity of each fuel type i, $\{F_{H,Coal}, F_{H,Oil}, F_{H,Nat.Gas}, F_{H,Alt}\}$, to minimise the average total cost of heat energy.

$$\min_{F_{H,i}} ATC_H \left(F_{H,Coal}, F_{H,Oil}, F_{H,Nat.Gas}, F_{H,Alt.}\right)$$

subject to

$$E_H \geq \overline{E_H} \tag{25}$$

$$P_H = ATC_H$$

where

$$E_H = A_H \left(b_1 F_{H,Coal}{}^{\mu} + b_2 F_{H,Oil}{}^{\mu} + b_3 F_{H,Nat.Gas}{}^{\mu} + b_4 F_{H,Alt}{}^{\mu}\right)^{1/\mu}.$$

Here, A_H is a productivity term specific to heat energy production, $F_{H,i}$ is the input of fuel type i for heat energy production, b_i is the weight for fuel type i, and μ is the elasticity of substitution.

The fossil fuel price functions are increasing in the ratio of base year reserves relative to its current value.

$$P_{F_{i,t}} = \tau_{i,t} + P_{F_{i,t=1980}} \left(\frac{R_{i,t} + D_{i,t} - F_{El_{i,t}} - F_{H_{i,t}}}{R_{i,t=1980}}\right)^{\rho} \tag{26}$$

Subscripts i and t refer to fossil fuel type and year, respectively. $P_{Fi,t}$ is the fuel price, $\tau_{i,t}$ is the fuel specific carbon tax, $P_{F_{i,t=1980}}$ is the price of fuel at the base year (1980), $R_{i,t}$ is current reserves, $R_{i,t=1980}$, is reserve in the base year, and $D_{i,t}$ is new discoveries of fossil fuel. $F_{El_{i,t}}$ and $F_{H_{i,t}}$ is extraction of fuel for electricity and heat energy production, respectively. $\rho < 0$ is an elasticity parameter.

In the energy-economy sector, extraction decisions are based on fossil fuel prices from the global energy sector. Fossil fuel prices are exogenous to Canada, so the amount of fossil fuel extracted is obtained through the inverse of the price functions:

$$F_{TE,i,t} = R_{i,t} + D_{i,t} - \upsilon_i R_{i,t=1980} \left(\frac{\overline{P_{F_{i,t}}}}{P_{Fi,t=1980}} \right)^{1/\rho} \tag{27}$$

where $F_{TE,i}$ is the total extraction of fossil fuel type i at time t, given the current world price $\overline{P_{F_{i,t}}}$. $R_{i,t}$ is the current reserve value, $R_{i,t=1980}$ is the reserve value at the base year, $D_{i,t}$ is new discoveries, and $P_{Fi,t=1980}$ is the world price of fossil fuel i at the base year. ρ is an elasticity parameter, and υ_i is a parameter which adjusts the amount extracted.

Since Canada contributes roughly 2% of total global greenhouse gas emissions (ECCC 2016; Akhtar, 2011), we assume that Canadian energy consumption and greenhouse gas emissions do not significantly impact global emissions. The difference between Canadian demand and extraction in each period yields the net exports of fossil fuel i, $NX_{i,t}$:

$$NX_{i,t} = F_{TE,i,t} - F_{H,i,t} - F_{El,i,t} \tag{28}$$

Since the price for fossil fuels is exogenous, regional demand and supply for fossil fuels are determined independently. If supply is greater (less) than demand, the excess is exported (imported).

ANEMI_CDN merges a system dynamics approach with a neo-classical growth model, where a trust-region method (Conn et al., 2000) is utilised to solve the nonlinear system of equations of the energy-economy sector. Because of its unique system dynamics based feedback structure, within each simulation time step the ANEMI_CDN solves an optimal allocation problem. Thus, unlike other IAMs which take the path of carbon fuel used as an input, ANEMI_CDN generates an endogenous path of energy produced and emissions.

The path of prices depends on the stock of recoverable fossil fuels and the path of future discovery of fossil fuels. Although Canada has large reserves of oil, economic, political, and technological constraints make it difficult to predict what share of the oil sands will be viable to extract. In 2007, for example, the Alberta Energy and Utilities Board estimated that economic conditions and technological restraints implied that only 10% of the oil was recoverable (ERCB, 2008; Zandi, 2011). In our simulations, we account for these constraints by assuming that total recoverable oil in Canada is 410 billion barrels, approximately 25% of the oil estimated in the Alberta's oil sands (conversion factor from the EIA is 1 barrel of oil = 6.119 GJ). A similar assumption underpins the natural gas reserves. Discovery and extraction depend upon technological improvements and the increase in price. The reserves for Canada used in the simulations in Section 4 are reported in Table 1.

Table 1 Assumed future fossil fuel discovery in Canada (billion GJ)

	1980 assumed initial reserves	*1980 reserves (EIA & Statistics Canada)*	*1980–2005 discoveries (EIA & statistics Canada)*	*2006 assumed discoveries*
Coal	140	90	50	-
Oil	2,500	40	1,180	1,280
Natural gas	400	77	133	190

Model initialisation and parameterisation

The ANEMI_CDN simulation is initialised in 1980. The initial regional population is based on UN population data for 1980 (DESA, 2011), with the initial population growth rate set to that of 1975 to 1980.

Population is the main factor determining land-use as the land transfer rate is proportional to population growth. ANEMI_CDN thus requires the regionalisation of the global land transfer matrix (provided by Goudriaan and Ketner, 1984) and the available land area for the region. This approach can introduce measurement error into the land transfer matrix due to data limitations. To address potential measurement error, the calibration was repeated multiple times with several parameters.

The hydrologic cycle describes interactions among land, water, and atmosphere. This sector estimates the balance between water supply and water demand within Canada, and the effects of water deficiency on other model sectors. The atmospheric and oceanic portions of the hydrologic cycle are on a global scale, and include physical, chemical, and ecological processes. Precipitation is regionalised by the disaggregation technique described in Section 3.1.2, where the calibrated parameters based on historical observations are transferred to the disaggregation model.

Population, energy-economy and the hydrologic cycle contribute to water demand, water consumption, water use intensity, water quality, wastewater treatment, and water availability. The initialisation of water demand targets irrigated area and electricity production based on data from World's Water 2008–2009 (Pacific Institute, 2009) and the EIA database (EIA, 2006), respectively. The regional distribution of desalinated water supply capacity and waste water treatment is from the World's Water 2006–2007 (Pacific Institute, 2007) and the Food and Agriculture Organization of the United Nations database (http://faostat.fao.org/, last accessed October 2014), respectively. The initial treatment percentage is selected using information from Environment and Climate Change Canada (ECCC, 2008) for 1980.

The food production sector of ANEMI_CDN is connected to a number of other system components. Despite this complexity, the regionalisation of this model sector is straightforward as most of the inputs from other sectors are already on the regional scale.

3.1.2 Disaggregation modelling of precipitation and temperature

Salas et al. (1980) defines disaggregation modeling as a process by which time series are generated from an existing time series. The ANEMI_CDN model use temporal disaggregation to generate monthly rainfall using annual rainfall data, and generates regional temperatures using spatial disaggregation of global data.

Disaggregation models can generally be articulated in linear form as:

$$Y = AX + B\varepsilon \tag{29}$$

where Y is the time series to be generated, X the independent series, ε is white noise, and A and B are matrices of parameters. To avoid redundancy and reduce the number of parameters, the following form of temporal disaggregation is adopted from (Mejia and Rousselle, 1976; Lane, 1979):

$$Y_\tau = A_\tau X + B_\tau \varepsilon + C_\tau Z_{\tau-1} \tag{30}$$

where C is a parameter matrix with the same dimensions as Y, and Z is a column matrix containing monthly values from the previous year. τ and $\tau - 1$ denote the current and previous year, respectively.

In disaggregating annual rainfall, X, inputs are allocated into monthly values so Y has dimensions of 12 by 1 (12 monthly values). Z incorporates the linkage between the current month and the previous month of the previous year (e.g., in calculating December 1980 rainfall, Z represents November, 1979 rainfall). Thus, C and Z have dimensions of 12 by 11 and 11 by 1, respectively. The estimated values of Y, A, B, and C are denoted as $\hat{Y}, \hat{A}, \hat{B}, \hat{C},$ respectively.

$$\hat{Y}_\tau = \hat{A}_\tau X + \hat{B}_\tau \varepsilon + \hat{C}_\tau Z_{\tau-1} \tag{31}$$

A spatial disaggregation approach is employed to disaggregate global temperature to the regional level:

$$V = EU + F\varepsilon + GW \tag{32}$$

where V is the generated regional annual values, U the global annual temperatures, W is the lagged regional annual values, and E, F, G are matrices of parameters. The estimation uses the linear dependence model method and the Choleskey decomposition algorithm.[5]

Performance evaluation

The parameter values are estimated using data spanning 1901 to 2000 (the average results of 17 GCMs). Comparing the simulated values with the data in Table 2 and Figure 2, one sees that the model fit is reasonably good.

Figure 2 Basic monthly temperature comparison between analysed and simulated data (see online version for colours)

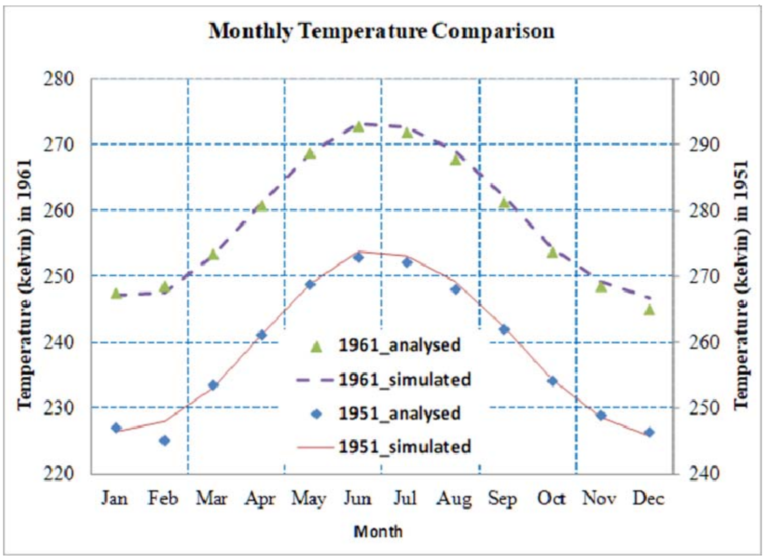


Table 2 Comparison of the average temperature (Kelvin), Canada

Year		*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1951													
	Analysed	247.10	245.15	253.57	261.18	268.84	272.94	272.17	268.10	262.04	254.18	248.98	246.41
	Simulated	246.38	247.97	253.04	261.05	268.83	273.74	273.08	269.25	262.40	254.40	248.66	245.78
1961													
	Analysed	247.52	248.62	253.45	260.83	268.78	272.82	271.87	267.77	261.25	253.74	248.55	245.03
	Simulated	247.09	247.54	253.12	260.96	268.63	273.14	272.56	268.98	262.08	254.34	249.24	246.71
1971													
	Analysed	246.20	249.27	253.53	261.16	269.39	272.83	272.23	268.36	261.38	254.78	249.63	246.61
	Simulated	247.87	249.28	253.57	261.14	268.51	272.91	272.10	268.50	261.89	254.31	249.57	247.20

3.1.3 Limitations

ANEMI_CDN represents Canada without explicitly modelling the distribution of its six model sectors across Canadian provinces. As a low-resolution model, ANEMI_CDN is not designed to capture phenomena at the watershed level, such as flooding, drought, snow cover, or provincial agricultural production. ANEMI_CDN does not model the chemical composition of water or local industrial pollution or algae blooms. Thus, the model only indicates the overall health of water resources, including the availability of sufficient water supply for human survival via the 'water-stress' parameter. Although the regionalisation does not produce regional atmospheric water content, it does disaggregate regional discharge and surface water availability using historical rainfall data and land characteristics.

4 Model experimentation

The regional assessment model ANEMI_CDN can evaluate how alternative policy scenarios impact the nine model sectors. Before examining the illustrative policy scenarios, the model performance is assessed by comparing the baseline simulation with historical data. The simulation runs from 1980 to 2085, and the evaluation period covers the first 30 years (i.e., 1980 to 2010). Due to data limitations, in some cases only a few (or single) observations are used to evaluate the model's performance.

4.1 Model validation

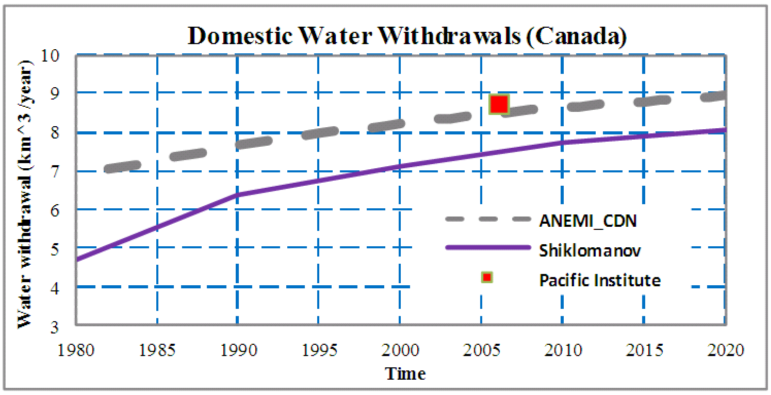
System dynamics (SD) modelling is iterative and relies on the problem being well conceptualised and the prior identification of causal relationships. Thus, SD validation is not performed to solely replicate the past (observed) system behaviour, but to capture the key patterns of system behaviour that originate in system structure, feedbacks, and delays (Sterman, 1984). This section examines the ANEMI_CDN model's ability to represent the components of the social-energy-economy-climate system.

The simulated Canadian water consumption in agriculture, as well as for domestic and industrial purposes are reasonably close to data reported by the Pacific Institute (Pacific Institute, 2014) for 2006. Although the level of Canadian water use implied by ANEMI_CDN (and the Pacific Institute) differ from the historical estimates and projections to 2030 of total domestic and industrial water use of Shiklomanov and Rodda's (2003), the overall trend in water use generated by the model simulation tracks their estimates (see Figure 3).

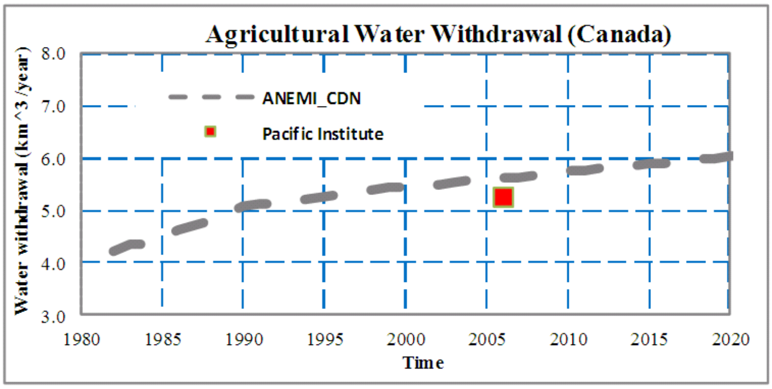
The simulation matches UN population estimates for Canada until 2005, after which the UN reports projected rather than actual data. However, as illustrated in Figure 4(a), the ANEMI_CDN population simulation track the projections reported by the International Institute for Applied Systems Analysis (IIASA, 2007).

The simulated path of real GDP of ANEMI_CDN does not take into account the recession of the early 1990s. However, the early 2000s level (prior to the 2008 recession) are close to those reported in World Development Indicators.[6,7] The results thus satisfy the calibration of the energy-economy system component of the model [Figure 4(b)].

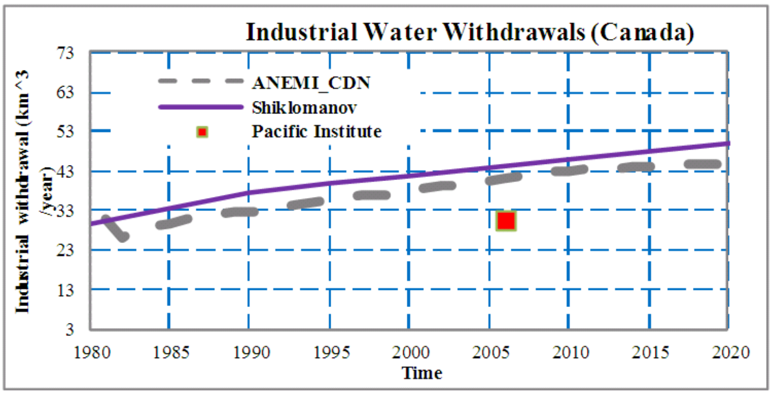
Figure 3 Water withdrawal comparison, (a) domestic (b) agricultural (c) industrial (see online version for colours)



(a)

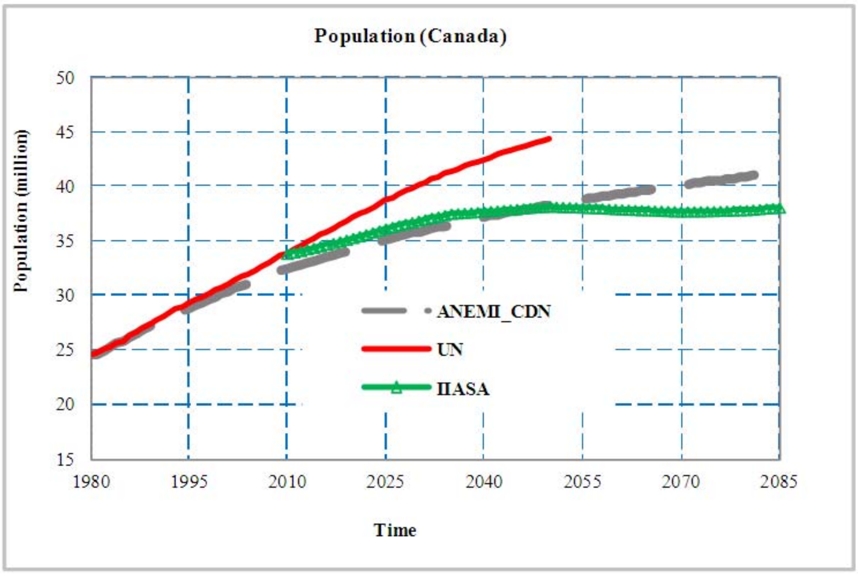


(b)

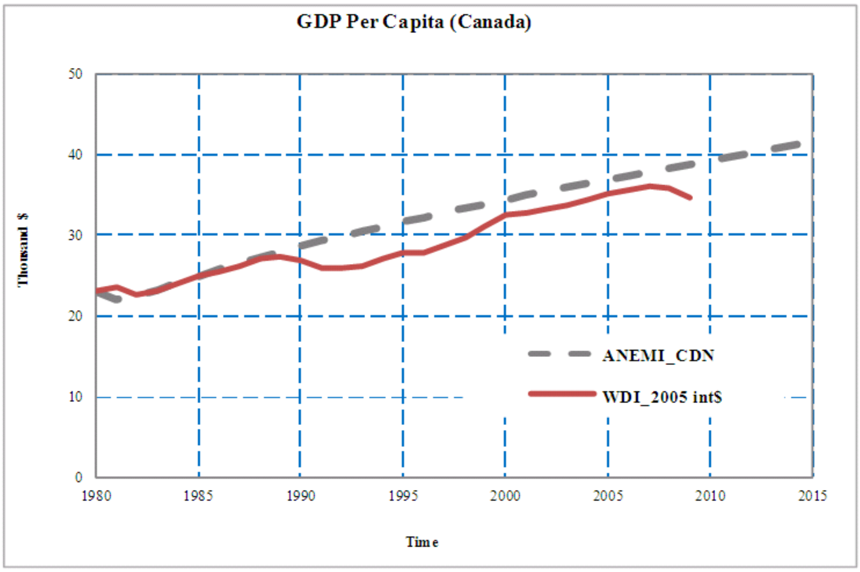


(c)

Figure 4 Validation plot, (a) population (b) GDP per capita (see online version for colours)



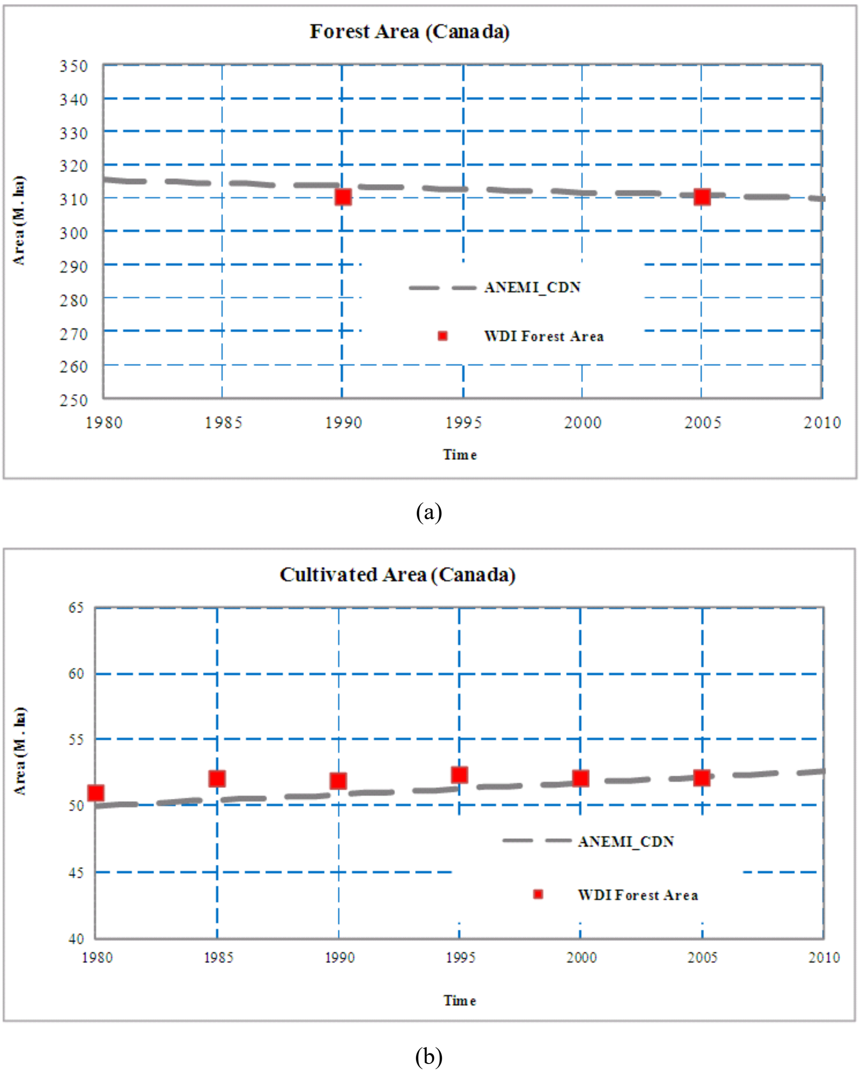
(a)



(b)

The ANEMI_CDN land-use sector generates a land conversion rate based on population growth. Two verification graphs (Figure 5) show future land-use change (i.e., conversion of forest area into cultivated/agricultural area). The simulated results from ANEMI_CDN are similar to those reported in the WDI database.[8,9]

Figure 5 Land-use comparison, (a) forested area (b) cultivated area (see online version for colours)



Overall, the comparison graphs suggest that the ANEMI_CDN model provides a reasonable platform for evaluating different Canadian policy scenarios.

4.2 Scenario development and analysis

The term *scenario* refers to any projected course of action used to understand possible future paths of the social-energy-economy-climate system. Scenario development is used in policy planning to test strategies against the uncertain future impacts of climate change. Therefore, the purpose of ANEMI_CDN is not to forecast the future but to assist policy makers in understanding the complexity of the system and to provide insights into the possible impacts of changing climate conditions.

ANEMI_CDN provides policymakers and scientists with a tool that can help answer many 'what if' questions. A process of communication with the climate change policy community resulted in the identification of over five policy scenarios [details are available in Popovich et al. (2010)]. Although the identified socioeconomic policy scenarios were all examined, due to space constraints only two illustrative examples are presented here:

1 carbon tax

2 increase food production.

It is worth emphasising that these scenarios are intended to illustrate the potential use of the model rather than being based on internationally available policy scenarios.

Both of the illustrative policy scenarios are compared with the baseline scenario. The baseline represents business as usual and is based on commonly used projections which assume that future trends track historical data and no changes in policies (IPCC, 2001b).

Table 3 Policy scenarios

Scenario title	*Objective*	*Parameter changed*	*Parameter reference value*	*Experimental value (post-2013)*
1 Carbon tax	Less fossil fuel burning	Carbon tax switch	0(off)	1(on)
2 Increased food production	More food	Increase land conversion to agriculture	BA	15%

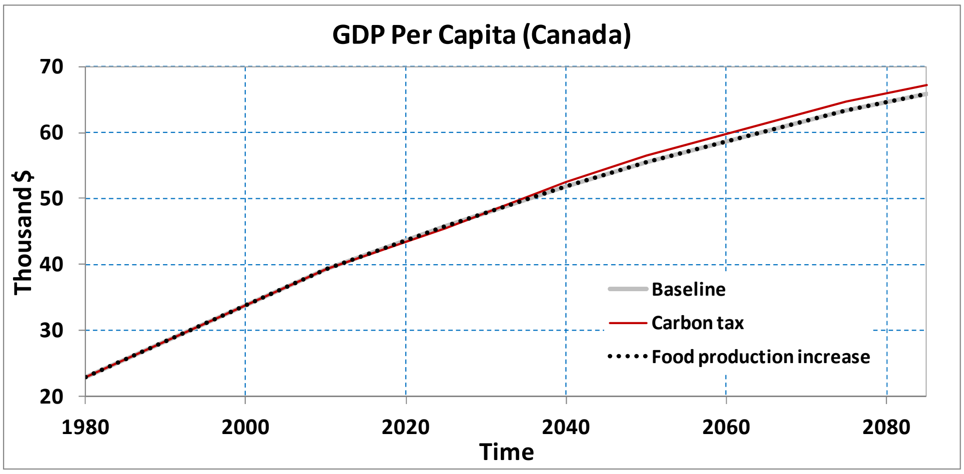
Table 4 ANEMI_CDN model simulation result

Variables	*Scenario*	*1980*	*2010*	*2025*	*2040*	*2050*	*2075*	*2085*
Food Production (*Trillion kilocalorie/yr*)	Baseline	105.79	112.08	135.69	166.64	184.83	211.55	218.04
	Carbon tax	105.79	112.08	142.21	176.70	191.97	205.43	209.36
	Food production increase	105.79	112.08	139.02	176.52	199.34	235.04	245.75
Available surface water (*km^3*)	Baseline	1,022.57	818.23	784.78	748.26	720.58	643.56	614.48
	Carbon tax	1,022.57	818.23	785.66	755.14	734.92	681.36	659.99
	Food production increase	1,022.57	818.23	784.77	748.25	720.55	643.46	614.33
Water-stress (*unit less*)	Baseline	0.165	0.214	0.231	0.248	0.261	0.301	0.322
	Carbon tax	0.165	0.214	0.230	0.244	0.262	0.308	0.327
	Food production increase	0.165	0.214	0.233	0.253	0.267	0.312	0.335
Population (million)	Baseline	24.52	32.37	35.06	37.13	38.25	40.46	41.20
	Carbon tax	24.52	32.37	35.06	37.13	38.24	40.45	41.18
	Food production increase	24.52	32.37	35.06	37.13	38.25	40.46	41.20

Table 4 ANEMI_CDN model simulation result (continued)

Variables	*Scenario*	*1980*	*2010*	*2025*	*2040*	*2050*	*2075*	*2085*
CO_2 emission from fossil fuel (*Gt*)	Baseline	0.376	0.685	0.721	0.674	0.598	0.326	0.226
	Carbon tax	0.376	0.685	0.410	0.340	0.340	0.282	0.240
	Food production increase	0.376	0.685	0.721	0.674	0.599	0.328	0.228
GDP (*billion $*)	Baseline	562	1271	1607	1925	2125	2566	2714
	Carbon tax	562	1271	1597	1951	2159	2615	2764
	Food production increase	562	1271	1607	1925	2125	2566	2715
Total energy used in the production of aggregate energy services (billion GJ)	Baseline	7.31	13.39	14.48	14.21	13.42	10.33	9.86
	Carbon tax	7.31	13.39	8.90	8.60	9.00	9.80	10.31

Figure 6 GDP per capita under two scenarios (see online version for colours)



4.2.1 *Carbon tax illustrative scenario*

Policy scenario 1 features the introduction of a global carbon tax in 2013 that slowly ramps up to $100 per tonne of CO_2 over 30 years. This is the only policy scenario in which there are significant changes in GDP per capita (Figure 6), as the tax distortion initially reduces Canada's Gross Domestic Product (GDP) (Table 4). However, the reduction in climate damages and the changes in fossil fuel prices gradually offset the negative impacts of the tax so that GDP increases slightly relative to the baseline (Figures 6 and 7). The net benefits from the carbon tax is somewhat offset in the regional model, since fossil fuel extractions and net exports decrease under the tax. However, as reported in Table 4, the carbon tax results in a significant fall in CO_2 emissions from reduced fossil fuel consumption (Figure 7). For the baseline (no tax implemented), the hump shape in total energy used in aggregate energy services in Canada is a result of increasing fossil fuel prices, which are generated from the global model (see Figure 8). The carbon tax has a significant impact on energy consumption in the regional model.

Figure 7 Model results with and without carbon tax scenario (see online version for colours)

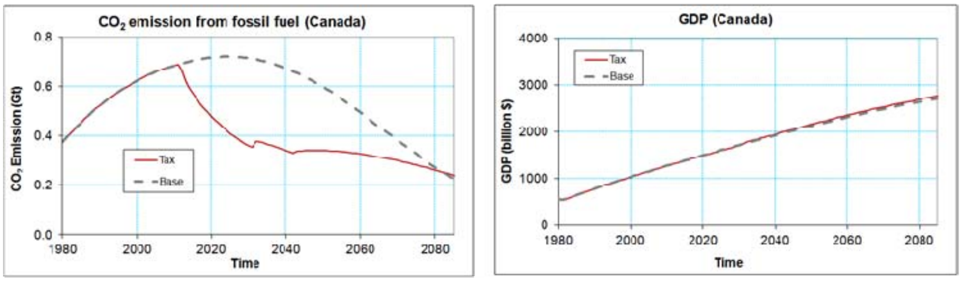
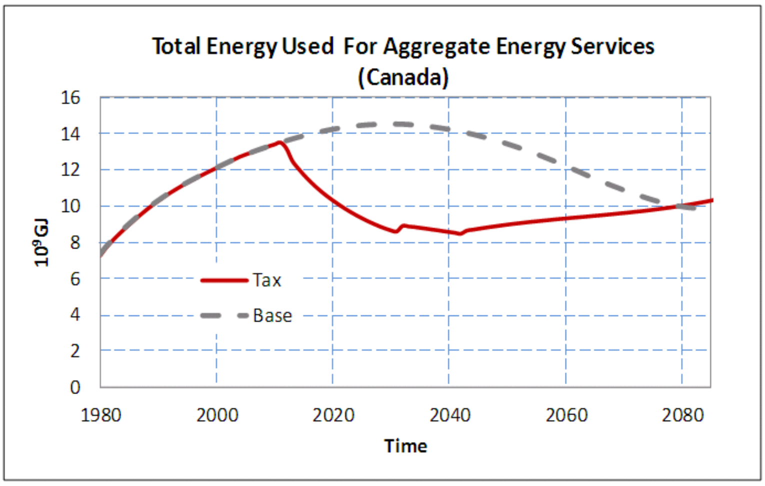


Figure 8 Total energy used in the production of aggregate energy services (see online version for colours)

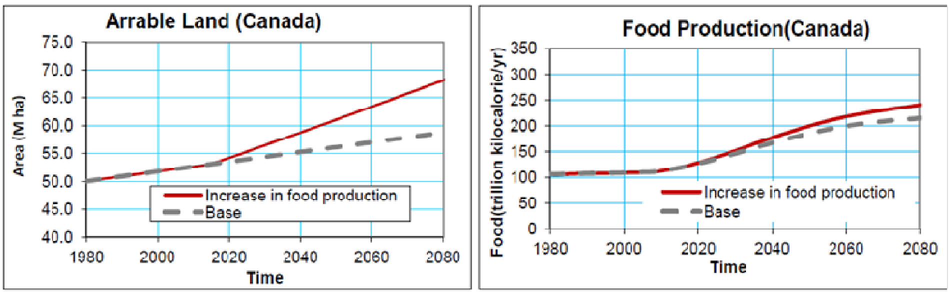


Climate change is projected to increase competition for water resources and reduce the water supplied to agriculture. This has led some to argue that the provision of sufficient food supplies will be a key issue of the 21st century (Khan et al., 2015; Pereira et al., 2002). Although Canadian farms have become larger and more productive, it may be essential to expand the agricultural land to remain food self-sufficient and to satisfy the needs of the ROW.

4.2.2 Increased food production illustrative scenario

The second scenario examines the consequences resulting from increased food production which entails the conversion of forest into agricultural land. In this scenario, the agricultural land conversion rate in Canada is increased by 15% to raise food production by 2100. In ANEMI_CDN, this increase in land conversion generates a roughly 13% rise in Canadian food production (Table 4, Figure 9). Although this increase in agricultural land use increases water use, the high level of water availability relative to water demand in Canada implies that the rise in water consumption is barely noticeable (Table 4). Hence, water-stress remains below the critical threshold level. And yet surprisingly, the regional model results do not show any noticeable population growth (Table 4). Such insensitive behaviour in population growth of Canada can be explained by sufficient food production and/or the optimum availability of per capita food-energy. A further increase in per capita food production does not change the life expectancy of Canadians. The total population in Canada remains almost unchanged, even with the 13% increase in food production. With no change in population, there is also no increase in human induced fossil fuel based emissions, and both GDP and fossil fuel based emissions thus remain almost unchanged (Table 4). However, in this model immigration is not considered explicitly as it is heavily driven by immigration policy. Canada as a country depends on immigration to fill shortages in its labour market.

Figure 9 Model results with and without food production increase scenario (see online version for colours)



5 Discussion

To effectively simulate climate policy, this IAM utilises an optimisation procedure and has an energy supply sector which accounts for the effects of non-renewable resource depletion. The ANEMI_CDN model is implemented on a regional scale (Canada) to analyse behaviours of the society-energy-economy-climate system for Canada. The model features a one-period nonlinear optimisation program for the energy-economy system, while a part of this system component is going through the simulation process. The introduction of market clearing within the energy-economy sector makes the ANEMI_CDN model unique in the field of integrated assessment modeling of climate change.

The disaggregation technique in ANEMI_CDN illustrates a potential method for resolving the incongruity in spatial and temporal resolution without sacrificing the statistical properties of standard deviation, skewness coefficient, and lag-one correlation coefficient. The same approach can be applied to generate further local and weekly time series data.

The model provides an inclusive summary of the availability of water resources, food production, population, emissions, global atmospheric temperature, as well as energy demand and supply across several system components. However, these results are valid only at the national scale and may not be indicative of changes at a regional level, and cannot capture the impacts of water shortages or drought events which may be significant by the end of this century. The two policy scenarios examined illustrate the potential use of the model in climate policy development.

The carbon tax scenario simulation indicates a considerable impact on Canada's energy production as extraction, domestic consumption, and exports are reduced. The tax distortion initially reduces Canada's GDP; however, as a result of benefits from lower climate damages and relative changes to fossil fuel prices GDP growth eventually increases. The relative change in fossil fuel consumption also lowers Canadian fossil fuel based industrial CO_2 emissions. Since Canada has the world's largest reserve of freshwater resources and a relatively modest population, a 15% increase in water consumption has little impact on total water reserves or the level of water-stress.

These policy scenarios demonstrate the consequences of the activities on future behaviour of the society-biosphere-climate-economy-energy system through feedback based interactions. ANEMI_CDN can provide a framework for understanding the climate change problem and for informing judgements about the relative value of different options for dealing with climate change by informing the research planning process, and understanding the interaction of components of the modeled systems. Hence, the use of ANEMI_CDN may facilitate both increased scientific understanding and socioeconomic climate change policy development for Canada.

The methodology and knowledge developed during the model development can help policy makers understand the behaviour of the society-biosphere-climate-economy-energy system under climate change scenarios and thereby help them to develop long term preparation for a) irrigation planning, b) emission control and planning by introducing carbon taxes, c) water policy development, d) vulnerability assessments, e) compute the optimal trajectory of global GHG emissions, and the corresponding prices to change for those emissions, f) compute the social cost of carbon, g) structural changes to the energy system, h) adaptation and mitigation policy planning, and so on.

6 Future work

The energy-economy sector of the ANEMI_CDN model offers opportunities for further improvements. At the current stage of model development, the modeling of electric energy production is myopic, as the simulated investment decisions do not consider the future expected returns. The inclusion of an optimal capital stock adjustment mechanism in combination with forward looking behaviour is the natural next step to enrich the model's energy-economy sector. Since the model's water sectors are not yet fully linked with the economy sector, extending the model to include a pricing mechanism that equilibrates water demand and supply would allow for the examination of policies which focus on dealing with increased water stress resulting from climate change and population growth.

The major limitation of the ANEMI_CDN model is that it cannot capture processes occurring on a local scale. In order to develop suitable mitigation strategies for different regions of Canada, a model must be able to describe local impacts of climate change. Hence, one of the future research steps would be the regionalisation of the ANEMI_CDN to an appropriate local scale. Some anticipated challenges of regionalisation to a local scale are lack of historical data on trade, unknown factors of migration, and regional climate forcing.

A limited number of policy scenarios derived through discussions with the study partners were implemented. While these discussions provided important insights, further policy scenarios are under consideration. In addition, further research on international and local climate change policy will be important for the design of model simulations required for the assessment of local consequences.

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Notes

1 The disaggregation technique is discussed in Section 3.1.2.

2 The following GCM models are used for the disaggregation: CCSM3, CGCM3.1_T47, CGCM3.1_T63, CSIRO-CCSM3Mk3.0, CSIRO-Mk3.5, ECHAM5/MPI-OM, ECHO-G, GFDL-CM2.0, GISS-AOM, GISS-EH, GISS-ER, INM-CM3.0, IPSL-CM4, MRI-CGCM2.3.2, PCM, UKMO-HadCM3, and UKMO-HadGEM1. Details are available in Table 5.5, Akhtar 2011.

3 The disaggregation technique is discussed in Section 3.1.2.

4 Background information on the global climate and carbon sectors are available in Akhtar (2011) and Akhtar et al. (2013).

5 See Section 5.2, Akhtar 2011 for details of the estimation.

6 http://databank.worldbank.org, last accessed, September 2014.

7 GDP is reported in constant 2005 international dollar value.

8 World Development Indicators, The World Bank, http://databank.worldbank.org, last accessed, October 2014.

9 FAO data from AQUASTAT database (Food and Agriculture Organization of the United Nations Global Water Information System, http://www.fao.org/nr/water/aquastat/data/query/index.html, last accessed, October 2014.

Nomenclature

ANEMI	Physical system model of the world
ANEMI_2	Physical system model of the world version 2
ANEMI_CDN	Physical system model of Canada
AQUASTAT	Food and Agriculture Organization's global water information system
^{0}C	Temperature on the Celsius scale
CCSM3	Community Climate System Model version 3
CGCM3.1_T47	Third generation coupled global climate model with spatial resolution of roughly 3.75 degrees lat/lon
CGCM3.1_T63	Third generation coupled global climate model with spatial resolution of roughly 2.80 degrees lat/lon
CO_2	Carbon dioxide
CSIRO-Mk3.0	Commonwealth Scientific and Industrial Research Organisation SIRO climate model version designated Mk3.0
CSIRO-Mk3.5	Commonwealth Scientific and Industrial Research Organisation SIRO climate model version designated Mk3.5, with reduced errors and climate drift than the Mk3.0 model
DESA	Department of Economic and Social Affairs of the United Nations
ECCC	Environment and Climate Change Canada
ECHAM5/MPI-OM	Ffth-generation Climate model developed at the Max Planck Institute for Meteorology
ECHO-G	Global coupled atmosphere-ocean climate model whose component models are the ECHAM atmosphere general circulation model and a global version of the Hamburg Ocean Primitive Equation model
EIA	U.S. Energy Information Administration

ERCB	Energy Resources Conservation Board of Alberta
FAO	Food and Agriculture Organization
GCM	Global climate model
GDP	Gross Domestic Product
GFDL-CM2.0	Second-generation Global coupled atmosphere-ocean General Circulation Models used at National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory
GISS-AOM	Atmosphere-Ocean Model at Goddard Institute for Space Studies
GISS-EH	Climate model coupled to the HYbrid Coordinate Ocean Model at Goddard Institute for Space Studies
GISS-ER	Climate model coupled with the Russell ocean model at Goddard Institute for Space Studies
GJ	Gigajoule, unit of energy
IAM	Integrated Assessment Model
IIASA	International Institute for Applied Systems Analysis, conducts policy-oriented research into problems of a global nature
INM-CM3.0	Institute of Numerical Mathematics Climate Model Version 3
IPCC	Intergovernmental Panel on Climate Change, scientific and intergovernmental body under the auspices of the United Nations
IPSL-CM4	A version of the coupled climate system model at the Institut Pierre-Simon Laplace, which considers both feedbacks from ocean and vegetation
^{0}K	Temperature on the Kelvin scale
MERGE	A Model for Evaluating the Regional and Global Effects of greenhouse gas Reduction Policies
MiniCAM	Mini-Climate Assessment Model, an integrated assessment model of moderate complexity focused on energy and agriculture sectors
MRI-CGCM 2.3.2	A version of the coupled climate system model at the Meteorological Research Institute, Japan Meteorological Agency
PCM	Parallel climate model
RCM	Regional climate model
REMIND	Regional Model of Investments and Development, which is a global energy-economy-climate model
ROW	Rest of the world

SD	System dynamics
UKMO-HadCM3	Hadley Centre Coupled Model version 3, at United Kingdom Met Office
UKMO-HadGEM	Hadley Centre Global Environmental Model, at United Kingdom Met Office
UN	United Nations