Projecting Future Climate Scenarios for Canada Using General Circulation Models: An Integrated Review

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Abstract This chapter provides an overview of the General Circulation Models, Regional Models, and "downscaling" techniques which can improve model resolution at the local level. Authors review the available literature on projections of precipitation over the next 100 years for Canada. The future projections of Canada as a whole are considered, followed by a more detailed survey of precipitation projections including the possibility of dry spells. The stream-flow projections for the major river basins of Canada are also considered. Finally a detailed treatment of projections by regions, such as the North, southern Ontario, southern Quebec and New Brunswick, and western Canada, is presented. Authors conclude that: (a) from the literature reviewed, it appears that changes to the Canadian climate are projected to occur under virtually all scenarios and with all models and (b) the northern and western parts of Canada may be affected most severely by climate change. There are some obvious policy implications.

Keywords Canada precipitation, Future climate scenarios, General circulation models, Statistical downscaling

Contents

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1 Introduction

This chapter provides an in-depth survey of the readily available body of research papers offering scenarios for possible future climate in Canada. These projections cover the period up to year 2100 and are based on projected changes in greenhouse gas concentrations and sulfate aerosol loadings using General Circulation Models and Atmosphere-Ocean General Circulation Models (AOGCM), which are complex models coupling various components of the climate system. A comparison of responses from several models can indicate the degree of uncertainty in the projections. Agreement among most model simulations allows a number of findings to be classed as “virtually certain” or “very likely.” This chapter states the various climate change scenarios that have been accepted by the Intergovernmental Panel on Climate Change (IPCC). A brief guide to the work of the IPCC is presented in the Appendix.

This chapter is organized as follows. The first section explains the meanings of the General Circulation Models as well as Regional Climate Models. Because of their coarse resolution, both require some method of incorporating the effects of local topological features, which are usually carried out by some statistical methods, called “statistical downscaling.” In Sect. 3, the future projections of Canada as a whole are considered. Section 4 is a more detailed survey of precipitation projections including the possibility of dry spells. This is followed, in Sect. 5, by the stream-flow projections for the major river basins of Canada. Section 6 is a detailed treatment of projections by regions, such as the North, southern Ontario, southern Quebec and New Brunswick, and western Canada. Section 7 draws some conclusions.

2 Projections of Climate Change for Canada

Climate models are used for making projections of what the future climate will look like under human influence. As with any other kind of modeling, it is necessary to establish that the model being used is an adequate representation of the underlying system, in this case the very complex climate system. Thus, firstly the present day climate is simulated without any changes in external influences (such as radiative forcing). This is often referred to as a "validation simulation," and is usually carried out for the 1961–1990 period. It is important to assess the quality of simulations by comparing the simulated conditions to the ones that are actually observed. Once it is established that a specific model is reliable in its ability to simulate observed climate conditions, projections of future climate scenarios can be built.

There are two main approaches to making climate change projections. One is the so-called equilibrium climate simulation (or equilibrium-response experiment). The basic principle is to double the carbon dioxide concentration and then run a simulation until the model reaches a new equilibrium. This new equilibrium is then compared to the results obtained from the original (validation) simulation to get an idea of how the climate responds and is sensitive to radiative forcing. This type of simulation is time-independent in the sense that simulations are not run for specific time periods, but rather for specific blocks of time. For example, a simulation marked as "1900–2100" refers to a simulation of a 200-year period, but this could be any 200-year period. A great advantage of equilibrium climate simulations is that they are not very demanding in terms of computational power requirements, largely due to a very simplistic representation of ocean bodies in these models, or slab ocean models, in which the ocean is represented as a fixed-depth layer of water without any currents. Due to the simple representation of the ocean, however, these models reach a new equilibrium in a much shorter time frame than more complex models such as fully coupled atmosphere-ocean models.

The other approach is referred to as transient climate simulations, which are much more computationally demanding, but owing to great advancements in computing technology, have become more accessible in recent years. This approach requires that a set of predefined "scenarios" be established, where each scenario reflects some key assumptions about global population growth and the use of fossil fuels, which lead to greenhouse gas emissions. The IPCC has created several such scenarios. Originally these were called the "IS92 scenarios" [1], which were later replaced and updated in the IPCC *Special Report on Emission Scenarios* (SRES) [2]. These new SRES scenarios establish a time profile of greenhouse gas emissions and aerosol concentrations. Thus, this simulation shows how the climate would respond to potential changes in the initial conditions for real world situations.

The most commonly considered scenario in the literature is the so-called A2 scenario. One reason for it to be the most commonly considered scenario is due to the fact that models forced with the A2 scenario tend to project the greatest global warming, and as such are in a way a "worst-case" scenario. The A2 emissions scenario is characterized by continuous global population growth, and regionally focused economic growth. What follows is a brief description of the four scenario families (A1, A2, B1, and B2) as defined by the IPCC in the *Special Report on Emissions Scenarios* [2], in order to give the reader an overview of the major assumptions underlying future projections.

The A1 Storyline and scenario family can be divided into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), nonfossil energy sources (A1T), or a balance across all sources (A1B), where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies.

The A2 Storyline and scenario family considers a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.

The B1 Storyline and scenario family considers a convergent world with the same global population, that peaks in mid-twenty-first century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate change initiatives.

The B2 Storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

The IPCC also makes note of the fact that these scenarios do not take into account climate change *mitigation* initiatives such as the United Nations Framework Convention on Climate Change, or the emissions targets set out by the Kyoto Protocol, which is due to expire at the end of 2012.

It is common practice to run simulations with an ensemble of models as opposed to using only single model on its own. This is done with the aim of reducing the systematic biases of individual models.

2.1 General Circulation Models

General Circulation Models (GCMs) are mathematical models composed of complex equations “representing physical processes in the atmosphere, ocean, cryosphere, and land surface."[1] They are used to make projections for climate change under various forcing scenarios. The most complex models from this family are referred to as Atmosphere-Ocean General Circulation Models (AOGCMs), which include the complex interactions between oceans and the atmosphere. These models have proved to be very useful in simulating the large-scale features of observed climate, and for this reason they are widely used today to make projections for future periods. GCMs are essentially the same models as are used to make weather forecasts, but they also include the effect of greenhouse gases, and divide up the earth into "grid boxes." Division into grid boxes of a fairly large size is necessary in order to ease the computational requirements of these models. Thus, GCMs are mainly used to make climate projections at the continental scale, and other methods are employed when more detailed information is required. These other methods are discussed below.

Most major developed countries have produced a GCM. In Canada, for example, the Canadian Centre for Climate Modeling and Analysis[2] has developed a coupled global climate model, CGCM, currently in its fourth version (CGCM4). The GCM developed by the UK is called HadCM, currently in the third version (HadCM3) and Germany has ECHAM, currently in its fifth version (HadCM5). Australia and Japan also have their GCMs; for more information, the reader may consult the website of the IPCC Data Distribution Centre.[3]

General Circulation Models cover a large number of climate variables. These include the following: mean temperature, maximum temperature, minimum temperature, diurnal temperature range, precipitation, snow water content, relative humidity, specific humidity, sea ice, mean sea level pressure, vapor pressure, surface temperature, incident solar radiation, wind speed, evaporation, potential evapotranspiration, soil moisture, and fractional cloud cover. In this review we concentrate mainly on precipitation.

On a global basis, the results from all models generally yield comparable results. One of their shortcomings, however, is their inability to reproduce observed climate patterns on a regional level. In fact, large discrepancies among GCMs exist with respect to regional projections. For example, Aubeeluck and Dore [3] found that the Australian GCM was in general better at projecting precipitation patterns for southern hemisphere locations whereas the Canadian GCMs were better for Canadian locations.

GCMs have limitations for regional predictions partly due to their coarse resolution which do not include topological features of landmasses, and also partly due to limitations in surface physical parametrization. For example, some parts of the Canadian Arctic Archipelago are misrepresented in GCMs, potentially causing large biases in the temperature regimes simulated by these models [4]. Like most models, GCMs provide a simplified view of the earth and its climate. The projected

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[1] *Source*: IPCC website (http://www.ipcc-data.org/ddc_gcm_guide.html).

[2] Canadian Centre for Climate Modelling and Analysis: http://www.cccma.ec.gc.ca/.

[3] See http://www.mad.zmaw.de/IPCC_DDC/html/IS92A/index.html.

climate abstracts from real topological features of the earth. For example, the grid boxes representing Canada do not have the Rocky Mountains or the Great Lakes as a feature of the terrain.

Because these local features are not included in the GCMs, for realistic purposes, the projections for each grid box have to be “downscaled” using a variety of techniques, of which the simplest and the cheapest is some form of statistical approach to downscaling, to capture the real topological features located within particular grid boxes [5].

2.2 Regional Climate Models

Regional climate models (RCMs) offer a higher spatial resolution than GCMs. These models are “driven by atmospheric data from long coupled GCM simulations” [6]. In effect, RCMs perform dynamic downscaling of data simulated by a GCM.

For the purposes of impact and adaptation studies, information about climate change is required at a much finer spatial resolution than what GCMs are able to provide. The spatial resolution of RCMs is an improvement, but often the equivalent of station-specific data is required.

2.3 Statistical Downscaling

Statistical downscaling methods provide detailed site-specific data which can be crucial for climate change impact studies. Furthermore, they are computationally inexpensive. Given dissatisfaction with the existing statistical downscaling methods Dore and Burton [5] developed two downscaling models using autoregressive integrated moving average (ARIMA) methods. A detailed description of the ARIMA downscaling method can be found in Appendix A at the end of this chapter. Some other downscaling methods include the Statistical DownScaling Model [7] and the Long Ashton Research Station Weather Generator – LARS-WG [8].

Even though a great degree of agreement among models exists, there are some areas where a large variation in the projected results shows up. Models have a tendency to agree with respect to global projections; however, there is more uncertainty for regional projections. This can be partially attributed to the details of the simulated climate processes and the sensitivity of projections to spatial patterns of aerosol concentrations. For greater detail about various models, as well as uncertainties in projections, see the IPCC Third Assessment Report [9].

With the above background in mind, this chapter considers future climate projections for Canada, with the intention of identifying both areas of convergence and areas of disagreement. It is not our intention to present quantified estimates of future climate variables, as these are discussed in great detail within each respective study. The focus here is on the major directions of change and on identifying consistent patterns in projections over the vast area that Canada covers. We do, however, present a significant amount of detail for the Sooke Reservoir in British Columbia (Sect. 6.4). This is done to give the reader a better idea of how much variation among individual model projections exists for any given area.

3 Canada as a Whole

There is a great deal of evidence that climate change is already well under way, and many studies have been devoted to analyzing the changing patterns in climate variables around the globe. Dore [10] provides an extensive review of the literature pertaining to changing patterns of precipitation observed in the data across the globe. One of the main conclusions of his work is that there is increased variance in precipitation everywhere, and dry areas are getting dryer, while wet areas are getting wetter. Some further patterns that emerged from this review were increased precipitation in high latitudes (Northern Hemisphere); reductions in precipitation in China, Australia, and the Small Island States in the Pacific; and equatorial regions becoming more variable. These observed changes are said to be a “signature of global climate change.”

Specifically for Canada, Vincent and Mekis [11] consider a number of temperature and precipitation indices, during two time periods namely 1950–2003 and 1900–2003. The general trends observed for both these time periods are similar. For precipitation, the observations reveal significant trends for days with precipitation as well as days with rain, that is there will be more days with precipitation, and also more days with precipitation falling as rain. Significant decreasing trends, on the other hand, were found in maximum number of consecutive dry days, as well as the simple day intensity index of precipitation and rain across Canada. The study indicates a significant increase in the number of warm events (warmer than average), and a significant decrease in the number of cold events for both studied time periods. Furthermore, over the considered time period, nighttime warming was observed to be more intense than daytime warming, resulting in a decrease of the diurnal temperature range.

The results presented above are in agreement with the results of an earlier study by Zhang et al. [12], who analyzed temperature and precipitation trends over the 1900–1998 period for southern Canada, and over the 1950–1998 period for the whole country. Their results showed that the Canadian climate has been getting warmer and wetter over the 1950–1998 period.

In the following sections, we turn our attention to actual projections of climate change. A great deal of work is done by the IPCC Working Groups who produce their own reports. Based on these reports the IPCC produces its own summary in an “IPCC Assessment Report.” The most recent assessment report is the *Fourth Assessment Report* (AR4) (IPCC [13], and the Fifth Assessment Report (AR5) which is due to be completed in 2014. The assessment reports published so far cover climate change projections on a global scale, and do not include a great deal of detail at the regional level. Thus, our focus here is on projected changes in precipitation across different regions of Canada, as well as projected changes in stream-flows of various river basins in Canada. Thus, this paper brings together the findings of a number of research works with a geographical focus on Canada. It is expected that presenting these findings together in one place will make any potential patterns more obvious, and thus will contribute to our confidence in the projections. It will also be useful for comparisons with projections for other northern hemisphere countries.

4 Precipitation

Changes in precipitation patterns are key indicators of changes in climate. There are numerous variables that cover precipitation, such as mean annual rainfall and mean annual days with rainfall. Additionally, there are other measurements of precipitation that are more concerned with the frequency and intensity of extreme events. Precipitation extremes are often expressed as return periods of annual maximum events. For example, a 30-year event is said to occur with probability 1/30 in a given year on average. If the return period decreases, then a more extreme event (one with a larger amount of precipitation) is likely to happen with a greater probability; that is such an extreme event is likely to become more frequent. Extreme events can have very serious implications, and global projections point to an increased occurrence of these events. For example, precipitation events that were considered extreme in the year 2000 may be twice as likely to occur by the end of the twenty-first century under conditions of climate change scenarios [14].

The Canadian Climate Change Adaptation Project (CCAP) published a report in 2010 [15]. Within this report, projections for major Canadian cities were presented. The projections were obtained using an ensemble of 24 GCMs, put together by the Canadian Climate Change Scenarios Network (CCCSN). All GCMs were forced with the A1B emissions scenario, so as to provide “medium” projections of the future climatic conditions. Winter precipitation was projected to increase in all regions, which is especially pronounced for the Winnipeg area, further increasing the sensitivity of this region to spring flooding. Precipitation in the summer months is likely to experience only small changes in most regions of Canada, with the exception of southern British Columbia and Alberta, where a substantial decrease in precipitation is projected to occur by 2050. As noted in the report, this may have serious implications for forest fire risk within lower mainland and B.C. interior – areas which are already considered at-risk. Although not as substantial as in the case of B.C., summer drying is also projected for southern Ontario, Quebec, and Prairie regions, potentially affecting drinking water supplies, as well as hydroelectric power generation.

Sushama et al. [6] compared simulations performed with two different versions of the Canadian regional climate model (CRCM) for the IS92a and A2 scenarios.

Although the magnitude of projected changes in precipitation differs between the two versions of the CRCM, there is agreement on the direction of change. Five of the six studied river basins (Fraser, Mackenzie, Yukon, Nelson, and Churchill) were found to exhibit increases in annual precipitation. The largest increase in annual precipitation is projected to occur in the Yukon basin, while no increase is expected for the Mississippi basin. These findings are in good agreement with other studies, as the Yukon basin is located furthest North, while the Mississippi basin is located furthest south of the six studied basins.

Wang and Zhang [16] estimate changes in the risk of winter extreme precipitation over North America using statistical downscaling of a GCM forced with the SRES A2 scenario. Largest increases in the 20-year return level of daily precipitation were projected to occur in the central and southern United States and the Pacific Northwest (Oregon, Washington, Idaho, Montana, British Columbia, and Alberta). They found a lower risk of extreme precipitation in the Canadian prairies, northern Alaska, and southern Mexico, but it was pointed out that the confidence in these predictions is low.

This result for the Canadian Prairies is further reinforced by the findings of Mailhot et al. [17] who projected no decrease in the return periods of annual maximum precipitation events in this region, over the period 1850–2100. This means that extreme events are not going to occur more often than they do in today's climate. However, their findings pointed to a shift in the occurrence of these events, projecting that they will tend to occur earlier in the year (a shift from the summer months to the spring months). Seasonal shifts in precipitation patterns can have serious implications for agriculture, as less precipitation is projected to occur in the summer growing months, but also for flooding, since more springtime precipitation can translate into an increased probability of flooding due to spring ice jams.

Mailhot et al. [17] analyzed simulation results of the CGCM3. The analysis focused on the evolution of intensity and frequency of daily and multiday precipitation in a future Canadian climate. Three scenarios were considered (A1B, B1, and A2), and the most severe effects were observed under the A2 scenario, under which all of Canada saw decreases in return periods of annual maximum events, except for the Prairies as already noted above. The seasonal shift of precipitation patterns that was projected for the Prairies was also noted for most other regions of Canada. Generally projections show a decrease in the frequency of occurrence of annual maximum events in the summer months, and an increase in the spring and/or winter months. A shift away from the summer months is also projected for the northern region of Nunavut, but the shift is toward the autumn months in this case. North West Territories and the western parts of BC and Yukon were the only regions where no change in the seasonal occurrence of precipitation events was noted.

Mladjic et al. [18] carried out simulations using the Canadian Regional Climate Model (CRCM) to evaluate and assess future (2040–2071 period) changes to precipitation characteristics for the April–September period over Canada corresponding to the SRES A2 scenario. Namely, they consider the return levels of single and multiday annual maximum precipitation amounts. They utilized two techniques in their analysis: the Regional Frequency Analysis (RFA) and the Grid

Box Analysis (GBA). The largest percentage increases are projected to occur in the northern climatic regions, even though in absolute terms these are the smallest. The largest changes in absolute terms are projected to occur along the west coast. Decreases in annual maximum precipitation amounts were projected to occur mainly in the southern regions (albeit sporadically), but no clear patterns at the regional level were observed.

It is noteworthy that the CRCM tends to underestimate (negative performance errors) extreme weather events over most of Canada, the one exception being Yukon where positive performance errors are observed. The relatively short (30 year) sample size may negatively affect the statistical significance of changes to return levels for the 50- and 100-year return periods. An increase in the severity and duration of extreme precipitation events will have severe implications especially for water-related infrastructure such as combined sewer systems. These consequences of climate change were pointed out in Mladjic et al. [18] as well as in a Brock University Honors Economics Thesis by Shah, supervised by Dore [19].

4.1 Dry Spells

An alternative approach to looking at precipitation patterns is to consider the frequency and length of dry spells. These are defined as periods of a certain number of consecutive days in which precipitation does not exceed a predetermined threshold (i.e., 0.5, 1, or 2 mm)

Sushama et al. [20] studied the dry spell characteristic over Canada for two future time periods (2041–2070 and 2071–2100) and compared them to dry spell characteristics over the 1971–2000 period. They utilized simulations from the fourth generation of the Canadian Regional Climate Model (CRCM), driven by the third generation Canadian General Circulation Model (CGCM3) forced with the SRES A2 scenario. They found an increase in the mean number of dry days for southern regions in Canada, suggesting a dryer climate in these regions, but an opposite trend for the rest of Canada. Furthermore, they found a decrease in the mean number of dry spells in the southern regions, but an increase in other regions of Canada. Together this seems to imply a higher chance of droughts in the south, since fewer dry spells together with an increase in dry days indicate fewer but longer periods of dry weather throughout the year. The rest of Canada may expect to see a wetter climate on average, but also more variability in precipitation.

Schwalm et al. [21] note that the devastating drought which occurred in North America during the 2000–2004 period may actually be considered “an outlier of extreme wetness” toward the latter half of the twenty-first century, when more severe drought periods can be expected. This is a very worrying projection given that the 2000–2004 drought was the worst event in 800 years.

The results of various studies summarized in this section uncover a few distinct patterns of future changes in precipitation within Canada. It appears that most regions will see increases in the amount of precipitation throughout the year.

Most notable changes are likely to occur in the north and western regions. These regions will likely see not only an increased amount of precipitation, but also an intensification of extreme precipitation events. The southern parts of Canada and the Prairies will likely observe very little if any changes to precipitation patterns. However, there is some evidence that these regions will be more prone to droughts under future climate scenarios.

Changes in precipitation patterns can have serious and expensive implications for social infrastructure. A thorough analysis of climate change projections for a number of Canadian cities, and a quantification of its financial implications for social infrastructure was carried out by Dore and Burton [5]. The main focus was on estimating the impacts of climate change on the availability of drinking water supply and capacity for treating wastewater, and also the impact on road networks. In their analysis, the CGCM1 model was utilized, forced with the GG emissions scenario (the GG scenario is an older scenario which was used before the Special Report on Emissions Scenarios was published in 2000). The outputs from the CGCM1 were downscaled using the so-called *proportional downscaling* method. It was found that precipitation will likely increase in higher latitudes, especially in the winter months. The Great Lakes may experience a lowering of water supplies and lake levels, even though precipitation is projected to increase in the Toronto area. The changes for Toronto include a notable increase in maximum precipitation (by a factor of 4 compared to the baseline period of 1961–1990) and an increase in the variability of precipitation (an increase in the standard deviation by a factor of 1.7 compared to the baseline period). The analysis showed a wet autumn in the Niagara region, followed by a wetter winter. A dramatic increase in maximum precipitation is projected to occur in the Halifax area, especially from the baseline period to the 2010–2039 time period.

5 Stream-Flow

Projections of future stream-flows are important for various sectors of the economy, such as agriculture and hydroelectric power. Stream-flow data are also important for ensuring that existing infrastructure is adequate for dealing with changes in flow rates, as there will be a need for planning for flood events in the future.

Seasonal flooding of the Chateauguay River Basin in southern Quebec under future climate scenarios was evaluated by Roy et al. [22]. Using a coupled hydrology–hydraulics model of the basin in conjunction with results from the CGCM1, the authors consider potential future changes in the volume of runoff, maximum discharge, and water level. It was found that for the summer and fall periods, discharge levels will likely increase in the future (2020–2040 and 2080–2100). The summer and fall discharges are projected to surpass the current maximum flows observed during the spring snowmelt period. Since the spring maximum flows are already associated with flooding, an exceedance of these levels will likely result in more flooding in the future.

Quilbe et al. [23] carried out projections for the Chaudiere River in Quebec using three GCM models: (a) CGCM3, with scenarios A2 and B1, (b) HadCM3 with A2 and B2, and (c) ECHAM4 with A2 and B2. All models pointed to a small decrease in annual runoff over the projection period 2010–2039. Monthly projections were found to exhibit more variance among models, but generally increased winter discharge and decreased summer and fall discharge are projected for the 2010–2039 period. Furthermore, slight decreases in spring peak flows along with unchanged summer base flow are projected by statistical downscaling methods.

Choi et al. [24] investigated potential changes to stream-flows in river basins in central parts of Canada (Northern Manitoba, in the Taylor, and Burntwood River basins). Their study used two GCMs which fed into a hydrological model to assess potential impacts of climate change for the 2041–2070 and 2071–2099 periods under the SRES A2 and B2 scenarios. Regardless of the emission scenario, the projections pointed to increases in mean annual runoff, as well as high and low flow quintiles, for all GCMs. The number of days with extreme low flows is consistently projected to decrease by all simulations. It is noted, however, that the projections for autumn and summer runoff tend to vary greatly for different scenarios.

Shepherd et al. [25] discuss the impact of climate change on river flows of Rocky Mountain Rivers. They consider both empirical trend projections and hydroclimatic modeling. The use of this “composite analysis” allows greater confidence in the projected results. What emerged from their analysis is a considerable decline in summer flows and a modest increase in winter flows, resulting in an overall reduction in annual flows.

Poitras et al. [26] investigated projected changes in average and extreme stream-flows of ten river basins across western Canada, namely the Nelson, Churchill, North Saskatchewan, South Saskatchewan, Peace, Athabasca, Mackenzie, Yukon, Fraser, and Columbia basins. The stream-flows were derived from climate simulations performed with the fourth generation of the CRCM forced with the A2 emission scenario. Stream-flows are projected to increase in all basins, with the largest (26%) increase occurring in the most northerly basin (Yukon), and the smallest (6%) increase occurring in the Columbia basin, which is furthest south out of the ten basins. An increase in 10-year return levels of high flows is projected, especially for the basins further north, while some of the southern basins (Columbia for example) are projected to experience a decrease.

6 Regional Focus

Canada is divided into ten distinct eco-climatic provinces which are further subdivided into eco-climatic regions [27]. It would be useful to have projections for each of these regions. However, it appears that research has been mostly carried out in a somewhat sporadic manner. The research papers which we examined for this review mostly focus on specific watersheds, river basins, or geographic regions. In this section some findings for key regions of interest are presented. Most notably the northern region of Canada, which is geographically a very complex and heterogeneous region, as well as a few other areas have received attention in the regional-level research.

6.1 Northern Regions

Northern regions of Canada are complex to model owing to heterogeneous surface conditions and the large presence of sea ice, which greatly modifies "the exchange of heat, water, and momentum between the air and the underlying surface, affecting mostly the characteristics of the local and regional climate states" [4]. Using statistical downscaling and input data from two GCMs (forced with the A2 and B2 scenarios), Gachon and Dibike [4] considered temperature change signals for the 2070–2099 period. They found a consistently lower warming in the summer months than in the other months, as well as a lower warming with the B2 than the A2 scenario (for example, in the winter months, the temperature increase as projected using the A2 scenario is in the range of 4–7°C compared with a projected warming of 3–4.5°C with the B2 scenario). The main goal of their paper was to compare the predictions of the statistical downscaling model to raw-GCM outputs, and as such it is important to note that "all downscaled results gave a higher convergence and physically plausible temperature change signal in comparison with the raw-GCM anomalies." See also Dibike et al. [28] for an uncertainty analysis of statistically downscaled climate regimes (precipitation and temperature) in the Canadian north.

Extensive work focusing on northern regions of Canada has been carried out by Prowse et al. [29–31]. Their studies provide a comprehensive review of outputs from seven AOGCMs and six emission scenarios for three 30-year periods between 2010 and 2100. They found that significant variability among model predictions exists, both for temperature as well as precipitation, and variability is even more pronounced with the latter. However, there appears to be an agreement among all models of an increasing trend of both air temperature and, for the most part, precipitation, with larger percentage increases in the northern regions of the Canadian Arctic. The authors specifically noted a "general poleward gradient of temperature increase, which will likely lead to a more uniform, future temperature climate over northern land areas" [29]. Certain seasonal patterns also emerge from their study. Largest increases in temperature are projected for the winter and fall seasons, while precipitation is projected to increase the most in winter. It is important to note that projections of future precipitation are more uncertain than temperature. Significant variability among models exists, and even though the median projections show an increase in precipitation over the Canadian North, some actually predict a decline. This is in line with the findings of other investigations, which seem consistently to point to a more pronounced warming in the North, and in the winter months (see for example, Plummer [32]).

One must be cautious when interpreting climate change projections for northern Canada because of the geographical complexity of this region. This is especially true when the projections under consideration are outputs from a GCM model, which tend to have limitations for a number of reasons, as already noted above. Furthermore, Plummer [32] noted large differences in projected winter precipitation over the Canadian Archipelago between the CGCM and CRCM. These differences are largely due to the different representations of the distribution of land and sea throughout this region. Furthermore, a lack of high-quality observational records of the past for the northern regions of Canada makes model validation difficult.

6.2 Southern Ontario

Grillakis et al. [33] consider projections from a number of hydrologic models for the Spencer Creek watershed in southern Ontario. The authors assessed potential hydrologic impacts of climate change for the watershed by imposing changes in precipitation and temperature derived from the North American Regional Climate Change Assessment Program. All models were forced with the SRES A2 scenario, and climate was simulated for the 2050–2068 period, using an equally long past period (1990–2008) for comparison purposes. Despite the variability among projections from different models, they find that "all simulations show an increase in the average inter-annual discharge, but also a noteworthy change in the seasonal distribution of the discharges" [33].

The change in seasonal distribution of discharges can be attributed to the nonuniform increases in temperature and precipitation throughout the year. In certain months, the projected increase in flows can be attributed to increased precipitation (January for example). In other months, the origin of increased flows is more complex, and can occur even where precipitation is not projected to increase. For example, no increases in precipitation were projected for the month of February, but increased discharges were projected nevertheless. In this case, the change in discharges can be attributed to the higher temperatures projected for this month, resulting in more snowmelt which occurs earlier compared to past climate. Overall, flow rates are projected to increase in winter and autumn, with the largest increases projected to occur in the months of January and February. This result confirms the findings of Dore and Burton [5] whose analysis of projections for the Niagara region in Southern Ontario showed a wet autumn, followed by a wetter winter in future periods (as described in "Precipitation").

6.3 Southern Quebec and New Brunswick

An analysis of extreme precipitation events under the influence of climate change in the southern Quebec area was performed by Mailhot et al. [34]. By examining intensity–duration–frequency curves, they show what precipitation patterns may look like under a future (2041–2070) climate in the studied area. Annual maximum amounts of precipitation for the May–October period were considered. Projections were made using the CGCM2 forced with the A2 emissions scenario. Although the uncertainty in projections increases at larger return periods and durations, certain expected increases are noted at the 90% confidence level. Namely, the 2-h rainfall amounts for May–October annual maximum of return periods between 2 and 25 years as well as 24-h rainfall for May–October annual maximum of 2- and 5-year return periods are expected to increase. Furthermore, the return periods of 2- and 6-h precipitation events which were considered to be annual maxima in the period 1961–1990 are projected to be approximately halved in the future (2041–2070). This means that extreme precipitation events will intensify under a future climate, and events that were considered to be extreme in the past will occur more often in the future.

Groleau et al. [35] performed a trend analysis of winter (January–February) rainfall over the regions of southern Quebec and New Brunswick. The analysis is carried out using data from 60 weather stations located in the studied regions. They found an increased probability of occurrence of winter rainfall, with clearer trends emerging in the south. As noted by the authors, increased winter rainfall can have significant implications for potential flooding, especially in the presence of extensive snow cover.

Boyer et al. [36] studied potential hydrological impacts of climate change on five St. Lawrence tributaries. Their study utilized the HSAMI hydrological model developed by Hydro Quebec, which was run with climate projections generated by three GCMs under the A2 and B2 scenarios. The focus was placed on the winter and spring seasons. An increase in winter discharges and a decrease in spring discharges relative to the reference period (1961–1990) were projected to occur by most simulations. Another trend apparent from the analysis was an earlier "center-volume date" in future climate regimes. The center-volume date is the date by which half of the annual flow volume has passed through a river. Thus, an earlier center-volume date indicates that the first half of the year could become wetter. Warmer temperatures and a reduction in the snow to precipitation ratio were cited as the main contributors to hydrological changes. The results of this study are similar to the results found by Grillakis et al. [33] (presented above), which makes sense given the geographic proximity of the studied areas.

6.4 Western Canada and the Rocky Mountains

A number of studies have focused on the impact of climate change on water resources in British Columbia. A review of these studies was presented by Merritt et al. [37]. Besides providing a review of several studies, Meritt et al. also carried out simulations for the Okanagan Basin. Using three GCMs and the University of British Columbia Watershed Model, projections corresponding to the SRES

A2 and B2 scenarios were carried out for a number of subwatersheds within the basin. All three models utilized for making projections indicate earlier onset of the spring "freshet" – the spring snow thaw. This is consistent with the findings of other studies (as per the summarized results in Merritt et al. [37]), which also found an earlier occurrence of the freshet, and a shift of the spring peak flows to earlier in the year [38–40]. Furthermore, all models agree on a "more rainfall dominated hydrograph" and reduced flow volumes in a future climate. As indicated by the authors, their results were consistent with other studies for this geographical area.

Larson et al. [41] use climate change scenarios to estimate spring stream-flow within the St. Mary Watershed for the 1961–2099 period. Although this watershed is not fully situated in Canada, as part of it is across the border in the United States, it is of importance to agriculture in Southern Alberta, where it provides "almost 200,000 ha of downstream irrigation" [41, p. 37]. Substantial warming is predicted under both scenarios (A1 and B1), but only a modest increase in winter and spring precipitation is projected. However, an increase in the rain to snow ratio and higher snowmelt frequency in winter (due to warming) in future periods are identified as contributing factors to reduced spring stream-flow. The authors point to significant implications for water storage facilities in the projected future, with potentially severe water shortages occurring during drought years.

Changing patterns of precipitation at the Sooke reservoir in B.C. were investigated by Dore et al. [42]. Using statistical techniques, they analyzed daily precipitation data covering the period 1914–2004, in an effort to identify possible signals of climate change. Their analysis showed a change in at least three of the moments of the distribution of precipitation. Most notably, a change in the variance of precipitation was identified, prompting the Victoria local authorities to take action by expanding the capacity of the reservoir at a cost of significant capital investment of $23 million [42].

Considering the signals of climate change observed in existing data, Dore [43] did extensive work on future projections for the Sooke Reservoir located in British Columbia. Using statistical downscaling methods (outlined in the Appendix), projections from four GCMs were downscaled to obtain projections of daily and monthly precipitation for this reservoir. The four GCMs consisted of two Canadian models (CGCM2 and CGCM3), the U.S. developed NCAR[4] model, and the U.K. HadCM3[5] model. Below is a summary of the results for both daily precipitation and extreme projections quoted directly from their study. The results for the Sooke Reservoir are presented in detail in order to give the reader a glimpse at how projections differ depending on the model used. The differences are many, but nevertheless there still are patterns that emerge. These patterns are presented after the detailed summary of results for projections of the Sooke Reservoir.

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[4] For information on the NCAR model see http://ncar.ucar.edu/community-resources/models.

[5] For information on the HadCM3 model see http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadcm3.

6.4.1 Daily Projections

1. Future precipitation projections were downscaled from the Canadian general circulation models, CGCM2 and CGCM3. These projections show that annual precipitation is expected to increase by up to 12% over the next 100 years.
2. Precipitation could decline for the 2020s time slice according to results from Runs 1 and 2 of the CGCM3 model. However, this decline is very small (approximately 1%).
3. The CGCM2 projections over the next 100 years suggest that precipitation levels would increase by about 8% for the next 30 years (2011–2040), continue along this pattern for another 30 years (2041–2070), and increase by 12% for another 30 years (2071–2100).
4. For the NCAR model, annual precipitation for the next 100 years is expected to increase between 13% and 17%.
5. The NCAR model projects a 17% increase during the period 2010–2039s, the highest of all GCM projections for the period while HADCM3 model projects an 18% increase for the 2070–2099 time slice (also the highest increase of all GCMs for that time slice).
6. There seems to be a consistent indication for the 2070–2099 time slice that annual precipitation is projected to increase between 10% and 13% for the NCAR model while the HADCM model predicts an increase of about 18% for the same time period.
7. When the daily projections were converted to monthly projections, it was found that the CGCM2, NCAR, and HADCM3 models show an increase (both in percentage and absolute terms) in precipitation for historically "wetter" and a decrease in precipitation for the historically drier months.
8. January, February, March, September, October, and November all showed increases (absolute and percentage) while for historically "drier" months May, June, and July precipitation is projected to decrease (for CGCM2, NCAR, and HADCM3).
9. For all runs in the CGCM3 model, they found that in general precipitation is projected to decline during the first 5 months of the year while latter 5 months of the year was projected to have an increase in precipitation.
10. The CGCM3 model projects an increase in precipitation for (the "drier") May and June but an increase for July and August contrary to the CGCM2, NCAR, and HADCM3 projections.
11. Both the CGCM2 and CGCM3 models predict a large increase in precipitation for September, October, and November.
12. The NCAR and HADCM3 models project a larger percentage and absolute decrease in precipitation during the summer months than the CGCM models. However, the HADCM3 model predicts an even greater degree of precipitation decline for the summer months than the NCAR for the 2070–2099s time period.

13. The NCAR model projects a higher percentage increase in precipitation than the CGCM models for the months of January, February, and March for all time slices.
14. On the other hand, the NCAR model projects a greater degree of precipitation decline than the CGCM model between the months of June–September.
15. The CGCM2 model has similar trends in percentage differences as the NCAR model has unlike the CGCM3 model; in general precipitation is expected to increase (in percentage terms) in the first third of the year, decline during the spring and summer months, and increase during the winter months for the CGCM2.
16. The CGCM2 model shows a percentage increase in precipitation beginning in August while NCAR and HADCM3 show an increase from October onward (for all time periods).
17. For all runs in the CGCM3 model an increase in precipitation (in percent) is expected between the months of July–October during all time periods.
18. The CGCM3 model projects a relatively low percentage decline in precipitation for the first 6 months of the year for all time periods.
19. Compared to all other models, the NCAR and HADCM3 models project the largest percentage decline in precipitation for the summer and other months with historically low precipitation.
20. All models project large increases in absolute precipitation during the latter months of the year while NCAR and HADCM3 also show large increases in absolute precipitation during the earlier months of the year.
21. As expected, absolute changes in precipitation for all three runs of the CGCM3 show similar patterns. The CGCM3 model shows the largest absolute increase in precipitation for the month of October during the 2041–2070 time period.
22. The NCAR model shows the largest absolute increase in precipitation for November (during the 2050s) while the HADCM3 model shows the largest absolute increase for December (during the 2080s).
23. HADCM3 shows the largest absolute increases in precipitation for the first 3 months during the 2080s while NCAR shows this during the other two time slices.

6.4.2 Extreme Projections

1. February and November are projected to have the largest absolute decline in monthly (extreme) low totals followed by March and December for the CGCM2 model.
2. For all GCMs, during the 2010–2040 period, there is a greater difference between the observed monthly totals and the projected extreme low monthly totals for the first 3 and last 2 months of the year than for the other months of the year.
3. Since the summer months contained very low (some close to zero precipitation) many models were not able to capture this feature in the projections.

The NCAR and HADCM3 models were the only two models which were able to produce zero precipitation totals during the summer months.

4. Nevertheless, CGCM2 and CGCM3 both produced very low totals (between 1 and 5 mm per month as an extreme low projection).
5. For all models, the months of February and November are generally expected to have the largest millimeter decline in total precipitation for an extreme low precipitation scenario.
6. The CGCM2 generally predicts a lower extreme precipitation than the CGCM3 model on average for the 2071–2100 time period.
7. Both the HADCM3 and NCAR project an extreme low of zero precipitation during September for the 2070–2099 period.
8. For the extreme maximum projections, the CGCM models generally project higher extreme maximum precipitation during the latter months of the year while the NCAR predicts higher extreme precipitation during the earlier months.
9. For extreme maximum projections, a greater millimeter increase in precipitation in an extreme scenario during the wetter months than during the summer months is expected.
10. For the 2010–2039 period, the NCAR model projects the highest maximum extreme precipitation for January, March, and April while the CGCM3 Run 3 predicts the highest maximum extreme for February and May. The CGCM3 Run 2 projects the maximum extreme precipitation for June and August while CGCM Run 1 projects the maximum extreme precipitation for July, September, and October. The CGCM2 model projects the maximum extreme for November and December.
11. For the 2011–2040 period, the summer months can expect between 5 and 60 mm above the observed maximum while autumn and winter months can expect between 40 and 140 mm of precipitation above the observed maximum. Spring months can expect between 10 and 110 mm above the observed maximum.
12. For the 2040–2069 period, the NCAR model projects the highest extreme precipitation for March and April. CGCM3 Run 1 projects the highest extreme for January alone while CGCM3 Run 2 projects the highest extreme for July, September, November, and December. CGCM3 Run 3 projects the highest extreme precipitation for June and October. CGCM2 projects the highest maximum extreme for February, May, and August.
13. For the 2040–2069 period, the summer months can expect between 5 and 90 mm above the observed maximum while autumn and winter months can expect between 40 and 160 mm of precipitation above the observed maximum. Spring months can expect between 5 and 150 mm above the observed maximum with the highest extreme precipitation projected for March (for spring).
14. For the 2070–2099 period, the NCAR model projects the highest extreme for January while the HADCM3 model projects the highest extreme for February, March, April, November, and December. The CGCM3 Run 1 projects the highest extreme for May and July while CGCM3 Run 2 projects the highest

extreme for June and September. CGCM3 Run 3 projects the highest precipitation for August and October.

15. For the 2070–2099 period, the summer months can expect between 0 and 150 mm above the observed maximum while autumn and winter months can expect between 25 and 230 mm of precipitation above the observed maximum. Spring months can expect between 5 and 150 mm above the observed maximum with the highest extreme precipitation projected for March (for spring).

For the most part, the models agree on the direction of change of future precipitation. An exception to this consistency among models is observed for the annual precipitation projection for the 2020s time period. Runs 1 and 2 of the CGCM3 model predict a possible decline in annual precipitation, contrary to what all the other models predict. Nevertheless, the projected decline is rather small, in the order of 1%. Although differences in the magnitude of projected changes among models exist, all models consistently point to a pattern of historically drier months receiving less precipitation in the future, while historically wetter months are projected to see increases in precipitation. Specific patterns can also be observed for precipitation extremes. Generally speaking, regardless of the model used the months of February and November are projected to see the largest absolute decreases in total monthly precipitation for an extreme low precipitation scenario. Wetter months are projected to experience a larger absolute increase in precipitation in an extreme event as compared to the summer months.

Clearly, although projections of future climate change are highly uncertain, and exhibit a lot of variation between different models, when everything is considered together common patterns emerge. In this chapter, we have presented a number of studies which use a variety of models in their analyses. In this way, it may be easier to notice common patterns of climate change projections. As we summarize the results in the following section, it becomes clear that climate change in one form or another is projected to occur in all regions of Canada.

7 Conclusions

From the literature reviewed above, it is obvious that changes to the Canadian climate are projected to occur under virtually all scenarios and with all models. Although regional differences exist, with some areas being affected more severely or in different ways than others, changes are projected to occur everywhere. Thus, it is important for policymakers to take this into account, and develop adequate policies for adapting to climate change; adaptation usually means improving all infrastructures to make it more resilient to the impacts of extreme climate events, from extreme precipitation to extreme heat waves.

The implications of climate change may be very different for various regions of Canada. As is evident from the projections currently available, the northern and western parts of Canada may be affected most severely by climate change. In light of the regional differences that persist, it may be useful to develop a comprehensive study which will consider climate change projections for each of the eco-climatic regions of Canada. This would allow one to get the full picture of how Canada's diverse regions may be affected by future climate scenarios.

Climate change is a reality that has been taking place for a number of years, and is projected to continue into the future under many potential scenarios. Thus, much effort should be exerted on the part of policymakers to develop mitigation and adaptation strategies. Mitigation means reducing the emissions of greenhouse gases, possibly by international cooperation through binding treaties, such as the Kyoto Protocol. For adaptation, it means, for example, strengthening of building codes to reflect the future climate's impact on infrastructure. Comprehensive mitigation strategies at the national level need to be enhanced, especially as the future of the Kyoto Protocol remains uncertain. For example, Canada should implement mitigation policies that are consistent with Western Europe, which seems to making rapid progress not only in adaptation but also by pursuing serious mitigation policies to reduce the use of fossil fuels.

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Appendix A: Description of Dore's ARIMA Downscaling Method

Details of how downscaled projections are obtained using Dore's ARIMA method are described below. These steps are also presented in a thesis by Ashwina Aubeeluck (2006) supervised by Dore [3].

Step 1

We fit the best ARIMA model to the base years (1961–1990) of the respective GCM models. The fitted values obtained for the base years can be denoted as Arima(m, y) where m is the month and y is the year. We also divide each GCM models into three time slices, the 2020s, 2050s, and 2080s, from which one time slice is considered at a time.

Step 2

Find the mean of each month over the 30-year period for the fitted values, Arima (m, y). For example, mean of January can be calculated as follows:

$$\text{mean}_1 = \frac{\text{Arima}_{1,1961} + \text{Arima}_{1,1962} + \cdots + \text{Arima}_{1,1990}}{30\ \text{years}}$$

The same procedure is carried out to calculate the mean for the other 11 months.

Step 3

Divide the mean of the fitted values, mean_m obtained in step 2 by the 2020s GCM values to obtain the multipliers. We also find the maximum, $\text{max}_\text{arima}\text{mul}_m$, and minimum, $\text{min}_\text{arima}\text{mul}_m$, multipliers for each month.

Step 4

Multiply the maximum multiplier by the observed base, $\text{obs}_{m,y}$, to obtain the High Downscaled values and the minimum multiplier by the observed base to obtain the Low Downscaled values.

$$\text{High Downscaled values} = (\text{max}_\text{arima}\text{mul}_m) \times \text{obs}_{m,y}$$

$$\text{Low Downscaled values} = (\text{min}_\text{arima}\text{mul}_m) \times \text{obs}_{m,y}$$

The High and Low Downscaled values are plotted. We can also extend our analysis by finding the average of the High and Low Downscaled values. We then repeat the same steps to obtain 2050s and 2080s Downscaled values.

Appendix B: Guide to the IPCC Literature

The contents of this appendix have been taken from the IPCC website, and are presented here to give the interested reader a brief overview of the IPCC and its work. It is recommended that the reader should consult the IPCC website for further information.

Background

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. It was established by the United

Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socioeconomic impacts. In the same year, the UN General Assembly endorsed the action by WMO and UNEP in jointly establishing the IPCC.

Activities

One of the main IPCC activities is the preparation of comprehensive assessment reports about the state of scientific, technical and socioeconomic knowledge on climate change, its causes, potential impacts, and response strategies. Four assessment reports have been prepared by the IPCC since 1988. There is a Fifth Assessment (AR5) due to be finalized in 2014. Compared with previous reports, the AR5 will put greater emphasis on assessing the socioeconomic aspects of climate change and implications for sustainable development, risk management, and the framing of a response through both adaptation and mitigation.

In addition to these comprehensive assessment reports, the IPCC also publishes special reports from time to time (such as the Special Report on Renewable Energy Sources and Climate Change Mitigation and Special Report on “Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation”). Furthermore, the IPCC helps coordinate the development of new scenarios. The IPCC recommends the use of these scenarios for climate projections to allow international comparison among projections. In the past, the IPCC coordinated the development of new scenarios for its assessment reports directly, and one of the results of this work was the Special Report on Emissions Scenarios (SRES) published in 2000 (these superseded the older IS92 scenarios). The scenarios defined in the SRES (such as scenarios A1, A2, and so on as described in the main chapter) are often mentioned in the climate projections literature because these scenarios are a vital part of transient climate change simulations. However, in 2006 the IPCC decided to leave future scenario development to the scientific community. A presentation on the new process underway for developing new scenarios was provided at the 35th Session of the IPCC in June 2012.

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