Potential Hydrologic Impact of Climate Change to Athabasca River Basin based on Dynamically Downscaled Climate Scenarios of IPCC

by

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Abstract

To investigate the potential hydrologic impact of climate change on the Athabasca River Basin (ARB) of Alberta, Canada, the fully distributed physically based model, Modified Interactions Soil-Biosphere-Atmosphere (MISBA) land surface scheme of Kerkhoven and Gan (2006) was driven with two SRES climate change scenarios (A1B and A2) of four General Circulation Models (GCMs) of IPCC (2007) dynamically downscaled by MM5, to simulate the future water availability of ARB for 2050s and 2080s. MM5 is the Fifth-generation Mesoscale Model jointly developed by the Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR). The four GCMs selected were ECHAM5 (wettest), MIROC3.2 (warmest and driest), CGCM3 and CCSM3 (moderate). Due to warming, the future streamflow of ARB simulated by MISBA show that ARB is generally expected to experience a decrease in streamflow. The management of ARB's water resources system should be adjusted to augment against possible shortfall to various users relying on ARB for water supply. The results of this study based on climate scenarios of GCMs dynamically downscaled by MM5 are compared with results of Kerkhoven and Gan (2011) for ARB based on climate scenarios that were statistically downscaled.

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List of Abbreviations

Acronym	Definition
2050s	2040-2069
2080s	2070-2099
20c3m	The 20th century experiment
ABSE	Absolute Standard Error
AR4	Fourth Assessment Report of IPCC
AR5	Fifth Assessment Report of IPCC
ARB	Athabasca River Basin
ASTM	American Society of Testing and Materials
AVHRR	Advanced Very High Resolution Radiometer
CCCma	Canadian Center for Climate Modeling and Analysis
CCSM3	Community Climate System Model version 3
CCSRNIES	Center for Climate System Research, University of Tokyo and National Insititute for Environmental Studies
CFS	Climate Forecast System
CGCM3	Canadian Global Climate Model version 3
CRR	Conceptual Rainfall-runoff
CRU	Climatic Research Unit
D1	Domain 1
DEM	Digital Elevation Model
Dfb	Warm summer continental or hemiboreal climates of Köppen climate classification
Dfc	Continental subarctic or boreal (taiga) climates of Köppen climate classification

DJF	December January Febuary (winter)
ECHAM5	ECMWF-Hamburg version 5
ECMWF	European Center for Medium-Range Weather Forecasts
Ef	Nash-Sutcliffe coefficient of efficiency
EIONET	European Environment Information and Observation Network
ERA-Interim	A third generation re-analysis data of the European Center for Medium-range Weather Forecasts
FAR	First Assessment Report of IPCC
GCM	General Circulation Model or Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory model
GIS	Geographic Information System
GISS	Goddard Institute for Space Studies model
GNP	Gross National Product
IPCC	Intergovernmental Panel on Climate Change
IRMB	Integrated Runoff Model-F. Bultot
ISBA	Interaction Soil Biosphere Atmosphere
JJA	June July August (summer)
KINEROS	Kinematic Runoff and Erosion Model
LARS-WG	Long Ashton Research Station Weather Generator
MDGs	Millennium Development Goals of the United Nations
MIKE SHE	MIKE Model emerged from System Hydrologique European
MIROC3.2	Model for Interdisciplinary Research on Climate version 3.2
MISBA	Modified Interaction Soil Biosphere Atmosphere
MM5	The fifth-generation Mesoscale Model

MOHC	Met Office Hadley Center
MPI-M	Max Planck Institute for Meteorology
MRBB	The Mackenzie River Basin Board
NAM	The North American Mesoscale Model
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NIES	National Institute for Environmental Studies
NOAA	National Oceanic and Atmospheric Administration
RCM	Regional Climate Model
ppm	Parts per million
PSU	Pennsylvania State University
R	Coefficient of correlation
R^2	Coefficient of determination
RAMP	Regional Aquatics Monitoring Program
RCPs	Representative Concentration Pathways
RMSE	Root Mean Square Error
SAR	Second Assessment Report of IPCC
SCS	Soil Conservation Service
SDSM	Statistical Downscaling Model
SMAR	Soil Moisture Accounting and Routing model
SRES	Special Report on Emissions Scenarios
SSRB	South Saskatchewan River Basin
TAR	Third Assessment Report of IPCC
UEA	University of East Anglia
UNCED	United Nations Conference on Environment and Development

UNDESA	United Nations Department of Economic and Social Affairs
UNEP	United Nations Environmental Program
USDA	United States Department of Agriculture
WATBAL	Integrated Water Balance Model
WMO	World Meteorological Organization

List of Symbols

Symbol	Definition (Unit)
$\boldsymbol{\alpha}$	Monthly adjustment factors
$\boldsymbol{\beta}$	An empirical parameter
$\boldsymbol{w}$	The soil water content
$\boldsymbol{w}_{\mathbf{r}}$	The residual water content
$\boldsymbol{w}_{\mathbf{sat}}$	The saturated water content
$\mathbf{F(x)}$	The cumulative probability distribution of x
$\mathbf{O}$	The observed value
$\boldsymbol{\bar{O}}$	The observed mean monthly precipitation (mm)
$\mathbf{P}$	The predicted value
$\boldsymbol{\bar{P}}$	The ERA-Interim mean monthly precipitation (mm)
$\mathbf{P}^*$	The corrected precipitation amounts (mm)
$\mathbf{S}$	Soil water retention
$\mathbf{\bar{S}}$	Mean value of soil water retention
$\mathbf{x}$	The moisture capacity of the soil (meters)
$\mathbf{\bar{x}}$	The mean value of x (meters)
$\mathbf{x_{max}}$	The maximum value of x (meters)

CHAPTER 1

Introduction and Research Objectives

1.1 Background

Climate change and climate variability could have significant impacts on the hydrologic regime of a watershed, especially for mountainous watersheds with extended lowlands (Mauser and Bach, 2009). These hydrologic effects could impact many facets of our society, such as agricultural productivity, energy use, flood control, municipal and industrial water supply, fisheries and wildlife management (Xu and Singh, 2004).

According to IPCC (Intergovernmental Panel on Climate Change), climate change is very likely the result of anthropogenic activities which resulted in the emissions and increasing concentration of carbon dioxide (CO_2) and other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O). It is essential to understand feedbacks and interactions between climate change and basin scale water and energy fluxes so that it will be possible to predict the spatial and temporal variations of these fluxes in a watershed for the management of our future basin-scale water resources and for mitigating the potential threat of climate change impact to our water resources.

The Athabasca River Basin (ARB) is one of the largest watersheds of Alberta and it is located along the eastern slopes of the Canadian Rocky in central Alberta. Kerkhoven and Gan (2011) showed that ARB is susceptible to the hydrologic impact of a changing climate. ARB is of vital importance to Alberta because it has abundant natural resources that are easily accessible, such as forestry, fisheries, aggregate mining, and most notably, oil sands, and natural gas. The Athabasca Oil Sands, in combination with the nearby Peace River Oil Sands and Cold Lake Oil Sands, comprise the third-largest proven crude oil reserve in the world, next to Saudi Arabia and Venezuela (Alberta Energy, 2014).

The mining of oil sands accounts for the largest consumption of water in the ARB (Alberta Environment, 2014). This dependency on water resources causes ARB to be one of the most vulnerable watersheds to the potential hydrologic impact of climate change. In its Fourth Assessment Report (AR4), the Intergovernmental Panel on Climate Change (IPCC) provides an integrated view of climate change, which indicates that the Rocky Mountain watersheds along the eastern slopes of western Canada are predicted to be exposed to warming, possibly increased precipitation during the 21st century (IPCC, 2007). However, Kerkhoven and Gan (2011) showed that warmer temperatures lead to increased evaporation that may offset the effects of increased precipitation. Therefore, understanding climate change impact on the hydrological cycle within ARB is of significant value to both the environment and economy of Alberta and probably western Canada.

Hydrologic models have become an indispensable tool for hydrologic studies, for a better understanding of hydrologic processes and for predicting the behavior of hydrologic systems. With respect to the details of physical processes and the degree of simplifications considered in modeling the spatial and temporal fluxes at watershed scales, hydrologic models can be broadly classified from simple, lumped conceptual to fully distributed, physically based models (Refsgaard, 1997). The lumped conceptual models use conceptual hydrologic relationships that are empirically derived to describe hydrologic processes of a watershed in a lumped approach, without considering the spatial variability of such processes. In contrast, distributed physically based models use known scientific laws to model detailed hydrologic processes in a spatially distributed manner. The spatial variations of watershed characteristics and hydrologic fluxes are modeled at every grid point of a watershed represented by a set of computational grids of appropriate resolutions (Refsgaard, 1997). With the rapid development of the geographic information system (GIS), the distributed physically based land surface schemes have gained popularity in recent years.

In this study, the Modified Interactions Soil-Biosphere-Atmosphere (MISBA) model was applied to simulate the potential hydrologic impact of climate change on the ARB. It is a fully distributed, physically based model modified by Kerkhoven and Gan (2006) from the Interactions Soil-Biosphere-Atmosphere (ISBA) land surface scheme of Météo France (Noilhan and Planton, 1989; Habets et al., 1999). MISBA was then linked to a Muskingum-Cunge routing model (Cunge, 1969), which was applied to route the grid-based runoff simulated by MISBA to obtain the basin streamflow under the impact of climate change. For the control run of 1979-2007, MISBA was driven by the ERA-Interim re-analysis data dynamically downscaled by a regional climate model, the Fifth-generation Mesoscale Model (MM5), jointly developed by the Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR). The ERA-Interim re-analysis dataset is a global atmospheric re-analysis dataset developed by the European Center for Medium-range Weather Forecasts (ECMWF). By comparing with the observed streamflow data of the Athabasca River, streamflow simulated by MISBA for ARB for 1979-1988 was used as the basis for calibrating MISBA. The calibrated MISBA was independently validated by comparing its simulated streamflow for 1989-2007 against the observed counterpart. The results are presented in Chapter 3.

After validating MISBA's performance for ARB, MISBA was driven by the Special Report on Emissions Scenarios (SRES) climate change scenarios of some selected General

Circulation Models (GCMs) of IPCC dynamically downscaled by MM5 to simulate the impact of climate change to the hydrology of ARB. GCMs, or Global Climate Models are the primary tool for projecting future large-scale climate patterns under the anthropogenic impact of increasing greenhouse gases.

Six emission scenario families (A1T, A1B, A1F1, A2, B1, and B2) for the 21st century were issued in the SRES climate scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2007) which represent different projections about regional economic and technologic development patterns until the end of the 21st century. In this study, two SRES climate scenarios (A1B and A2) of four GCMs were selected to represent the projected climate over ARB for the 21st century. With reference to the climate normal of 1979-2007, future hydrology of ARB was simulated by MISBA which was driven by a total of 7 SRES climate change scenarios (four A1B and three A2) dynamically downscaled by MM5, which provided the framework for simulating the future impacts of climate change to ARB for 2050s (2040-2069) and 2080s (2070-2099). To study the difference between statistically downscaled versus dynamically downscaled climate data, climate change projections of MISBA for ARB driven with climate data that were statistically downscaled by Kerkhoven and Gan (2011) are compared with that obtained from climate data dynamically downscaled by MM5. The results are described in Chapter 4.

1.2 Literature Review

Although projecting long-term climate changes involve large uncertainties, over the years IPCC has shown substantial scientific evidences to demonstrate that a consistent increasing temperature trend, along with changes in temporal and spatial patterns and intensity of precipitation at a global scale is due to the greenhouse effect of anthropogenic greenhouse gases. Climate change impact has gained the attention of scientists and politicians across the world, and in recent years many regional hydroclimatic issues have become hot research topics at international levels. In other words, many studies have been conducted to investigate the potential impact of climate change on water resources, especially in semi-arid to arid regions already threatened with recurrent water shortage problems.

This review begins by providing the background information regarding the science behind climate change. As the primary tool to determine the impacts of climate change, Global Climate Models (GCMs) are involved in most climate change studies. However, due to coarse resolutions, outputs of GCMs are generally inappropriate for studying regional scale impact studies. Thus, it is necessary to downscale the outputs of GCMs before applying them for regional studies. Herein, a review of various downscaling approaches and issues related to a mismatch between temporal and spatial scales of available climate information of GCMs, and scales appropriate needed to drive hydrologic models for evaluating site-specific climate change impact studies, are presented.

1.2.1. Climate Change Impact Assessment

Climate change impact is or will be a serious challenge to our modern society. To help policymakers and the public understand issues on climate change, the Intergovernmental Panel on Climate Change (IPCC) was created by the World Meteorological Organization (WMO) and the United Nations Environmental Program (UNEP) in 1988. Until now, the IPCC has published five assessment reports commencing with the First Assessment Report (FAR) in 1990 (IPCC, 1990), followed by the Second Assessment Report (SAR) in 1995 (IPCC, 1995), the Third Assessment Report (TAR) in 2001 (IPCC, 2001), the Fourth Assessment Report (AR4) in 2007 (IPCC, 2007), and the Fifth Assessment Report (AR5) in 2014 (IPCC, 2014). Because of AR4, IPCC won the 2007 Nobel Peace Prize. All assessment reports of IPCC have been vocal on the human-induced emissions of greenhouse gases and various aspects of climate change. IPCC's first four assessment reports on climate change have become a standard reference for scientists, researchers, and the general public all over the world. Subsequently, the Fifth Assessment Report (AR5) released in 2013-2014 (IPCC, 2014) has likely presented the most comprehensive assessment of scientific knowledge on climate change.

Global warming has been detected since the mid-1970s (IPCC, 2013). Over the past 100 years, the global land-ocean surface average temperature has increased by nearly 0.8 ^{o}C, with about two-thirds of this warming occurred since 1980s (National Research Council, 2011). Brohan et al. (2006) indicated that the mean Earth temperature has been increasing by about 0.15 ^{o}C per decade. The IPCC's fourth assessment report (AR4) made a strong statement about the warming of the mean global air temperature as well as that of the oceans (IPCC, 2007):

> "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, wide-spread melting of snow and ice, and rising global average sea level."

As the leading international organization on climate change science, the IPCC concluded in its AR4 in 2007 that the mean global temperatures had increased by about 0.74 ^{o}C (0.56 ^{o}C to 0.92 ^{o}C) between 1906 and 2005 (IPCC, 2007). The IPCC Special Report on

Emissions Scenarios (SRES) issued six commonly used climate change scenarios (Figure 1.1) with respect to the emissions of greenhouse gases. For projection of climate change in the 21st century, a subset of B1, A1B, and A2 scenarios is concluded in the AR4, which represents low, medium, and high scenarios respectively with respect to the greenhouse gas emission concentrations (Meehl, et al., 2007).

Under the A2 scenario, IPCC projected that the global mean surface temperature will increase by 3.4 ^oC (2.0 ^oC to 5.4 ^oC) at the end of the 21st century. The A2 scenario describes an intensification of economic development, global population, and the hydrologic cycle with a general global increase of the mean precipitation, water vapor, and evaporation. The IPCC also predicted a future rise in surface temperature by 1.8 ^oC (1.1 ^oC to 2.9 ^oC) for the B1 scenario, which projects a global convergent world with more emphasis on global solutions to economic, social, and environmental sustainability. The A1B scenario is considered as a balance across all six scenarios. Through the A1B scenario, the IPCC predicted an increase in surface temperature by 2.8 ^oC (1.7 ^oC to 4.4 ^oC). Under the B1 scenario, the sea level is expected to rise by 0.18 to 0.38 meters, under the A1B scenario by 0.21 to 0.48 meters, and under the A2 scenario by 0.23 to 0.51 meters (IPCC, 2007). Due to warming which enhances evaporation loss, drought has become more common throughout the world even though the northern hemisphere has experienced increased precipitation especially in higher latitude areas (IPCC, 2007).

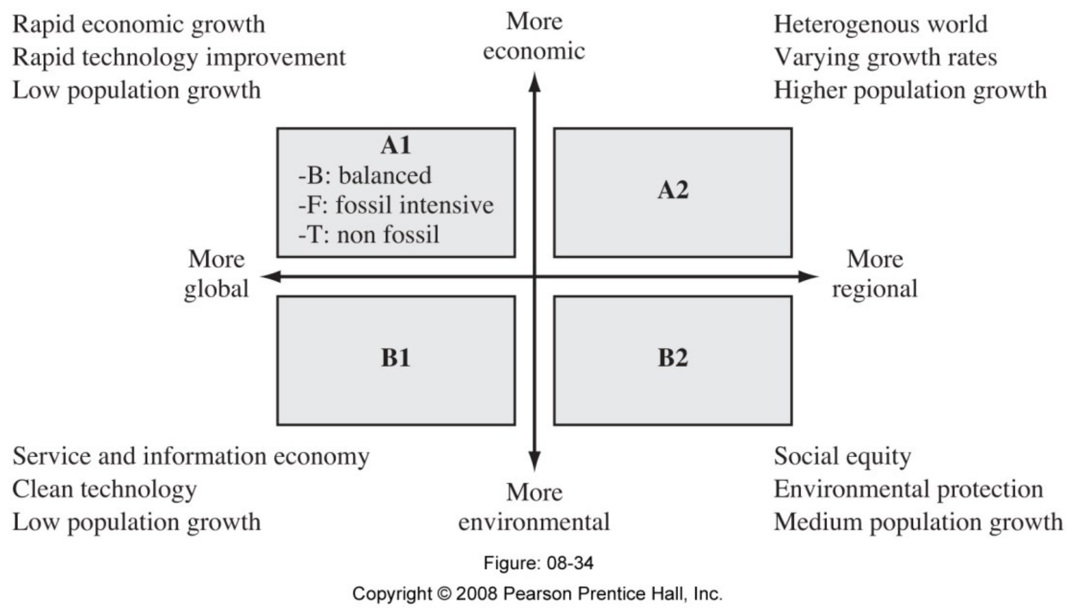

Figure 1.1: SRES Climate Change Scenarios of IPCC (2007).

The IPCC has just released its Fifth Assessment Report (AR5). It announced that the globally averaged combined land and ocean surface air temperature had increased by 0.85 ^{o}C $\pm$ 0.21 ^{o}C, and twice as much in the Arctic, over the period 1880 to 2012 (IPCC, 2013). A warming of 0.05 ^{o}C per decade since 1998 is probably related to a strong El Niño which is an increased uptake of heat in the deep ocean, a decline of radiative forcing, and natural climate variability (IPCC, 2013). The findings of AR5 are based on a new set of scenarios that replace the Special Report on Emissions Scenarios (SRES) employed in the TAR and AR4. The new set of scenarios, denoted as Representative Concentration Pathways (RCPs), consists of RCP8.5, RCP6, RCP4.5, and RCP2.6 (or RCP3-PD) (The numbers refer to radiative forcing for each RCP; PD stands for Peak and Decline) (Moss et al, 2008). These four RCPs were selected, defined, and named according to their total radiative forcing in 2100. The details are shown in Table 1.1. Under all RCP scenarios, the global surface temperature change projected for 2081-2100 is greater than 1.5 ^{o}C relative to 1850 to 1900 except for the RCP3-PD and greater in the Arctic (IPCC, 2013). The AR5 projected a decrease of the area of Arctic sea ice, and the

Arctic sea ice cover will continue to shrink and thin as the global mean surface temperature rises. A projection of a nearly ice-free Arctic Ocean in September before 2050 is likely for RCP8.5 (IPCC, 2013). Along with the melting of glaciers, the global mean sea level will rise by up to 0.98 meters by the year 2100 for RCP8.5 (IPCC, 2013), creating massive problems for coastal cities.

Table 1.1: Types of Representative Concentration Pathways (Moss et al, 2008).

Types	Radiative Forcing[1]	Concentration[2]	Pathway shape
RCP8.5	>8.5 W/m^2 in 2100	>~1370 CO_2-eq in 2100	Rising
RCP6	~6 W/m^2 at stabilization after 2100	~850 CO_2-eq (at stabilization after 2100)	Stabilization without overshoot
RCP4.5	~4.5 W/m^2 at stabilization after 2100	~650 CO_2-eq (at stabilization after 2100)	Stabilization without overshoot
RCP3-PD	peak at ~3W/m^2 before 2100 and then decline	peak at ~490 CO_2-eq before 2100 and then decline	Peak and decline

Notes:

1 Approximate radiative forcing levels were defined as ±5% of the stated level in W/m^2. Radiative forcing values include the net effect of all anthropogenic GHGs and other forcing agents.

2 Approximate CO_2 equivalent (CO_2-eq) concentrations. The CO_2-eq concentrations were calculated with the simple formula Concentration = 278 * exp(forcing/5.325). Note that the best estimate of CO_2-eq concentration in 2005 for long-lived GHGs only is about 455 ppm, while the corresponding value including the net effect of all anthropogenic forcing agents (consistent with the table) would be 375 ppm CO_2-eq.

The most widely used indicator of climate change is that of annual-average global-mean near-surface temperature which commonly is referred to as global temperatures. Despite the fact that there are a few different global datasets, a series of IPCC assessments since the first in 1990 have used the data produced by the Met Office

Hadley Center (MOHC) and the Climatic Research Unit (CRU) of the University of East Anglia (UEA). This dataset is used to plot Figure 1.2, showing the individual annual average differences from the 1961-1990 baseline periods (the latest WMO baseline period), as well as the estimated error in each value (Brohan et al., 2006). Figure 1.2 shows that up to 2006, 1998 was the warmest year (almost exactly 14 ^{o}C) with nearly 0.55 ^{o}C above the norm calculated for the range from 1961 to 1990 (Jones et al., 1999). In 1992, the United Nations Conference on Environment and Development (UNCED), also known as the Rio Summit or Earth Summit, was held at Rio de Janeiro, Brazil; 172 governments participated to discuss the threat of global warming (Taib, 1997).

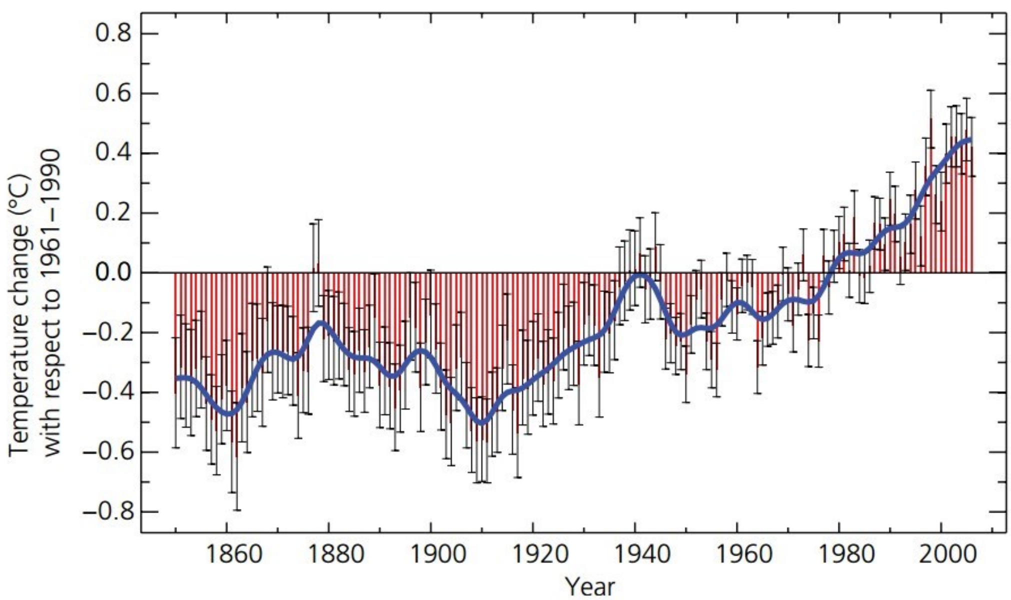

Figure 1.2: Annual-average global-mean near-surface temperature (red bars) from 1850-2006, as an anomaly from the average over the 1961-1990 baseline period. The error bars shown for each year indicate the 5% to 95% confidence range; the true value is more likely to be towards the middle of the error bar. The blue curve shows the data smoothed to emphasize decadal variations (MOHC/CRU/UEA).

1.2.2. Hydrologic Modeling

As evidence mounts that global warming is a likely future scenario, there has been increasing interest in simulating and predicting the impact of climate change to global water resources. In December 2003, the United Nations General Assembly officially declared the years 2005-2015 to be the International Decade for Action with "Water for Life" as the UN theme. This theme aims to promote efforts to fulfill international commitments made on water and water-related issues in the United Nations Millennium Development Goals (MDGs) by 2015; all of these actions raise worldwide awareness (UNDESA, 2014). In Canada, Alberta is facing significant pressures on its water resources. The Government of Alberta proposed 'Water for Life' as Alberta's Strategy for Sustainability which they believe to be a wise management plan for Alberta's water quantity and quality for the benefit of Albertans now and in the future.

Many studies have focused on forecasting climate change in relation to water resources planning and relevant hydrologic designs. By using climate data from two GCMs on the Great Lakes region, namely the Geophysical Fluid Dynamics Laboratory (GFDL) model and the Goddard Institute for Space Studies (GISS) model, Cohen (1986) found that there would be a decrease in the net basin water supply by 15% to 30% due to the CO_2-induced warming. In 1987, water balance models were used to study the potential impacts of climate change on surface runoff of the Great Basin region located in Nevada and Utah in the United States during the 21st century (Flaschka et al., 1987). Flaschka et al. (1987) found that there would be a 17% to 28% decrease in runoff for a 2 ^{o}C temperature rise and a 10% decline in precipitation. In 1990, Lettenmaier and Gan investigated the hydrologic sensitivities of four medium sized mountainous catchments in relation to global warming. These catchments include McCloud, Thomes Creek Basin and North Fork American and Merced which are all located in the Sacramento-San Joaquin River Basin, California. They found a major shift in accumulation pattern in snow, more rainfall and runoff in winter, less spring snowmelt runoff, and a significant increase in the annual flood maxima and its timing (Lettenmaier and Gan, 1990).

Many studies have used different types of numerical hydrologic models such as distributed, semi-distributed, and lumped models in combination with various GCMs' projected climate scenarios to predict the possible future hydrologic impact of climate change in different river basins. In 1994, the performance of three different models were tested and compared on the Walnut Gulch watershed with a semi-arid climate, including a complex distributed model named KINEROS, a simple distributed model based on the Soil Conservation Service (SCS) method, and a simple lumped model based on SCS method (Michaud and Sorooshian, 1994). They found that the performance of the complex distributed model was similar to the simple distributed model with calibration, but better than models without calibration. In 1996, three different models, namely the lumped conceptual model called NAM, a distributed physically based model called MIKE SHE, and an intermediate complex model called WATBAL, were applied on three catchments in Zimbabwe (Refsgaard and Knudsen, 1996). They found that all three models performed equally well after calibration, but MIKE SHE performed better than the other two models without calibration; similarly, Michaud and Sorooshian's (1994) found that the complex distributed model KINEROS performed better than other models. In 1997, Gan et al. tested five types of conceptual rainfall-runoff (CRR) models of different complexity on three medium-sized dry catchments in Africa and the United States. The models used were the Pitman model of South Africa, the Sacramento model of the United States, the NAM model of Europe, the Xinanjiang model of China, and the SMAR model of Ireland. Performance of models depended on the model structure and data quality, and dry catchments were generally more difficult to model than wet catchments. The Xinanjiang model performed best among these models, due to its non-uniform distribution of runoff (Gan et al., 1997). In 1998, a conceptual model called Integrated Runoff Model-F. Bultot (IRMB) was applied in combination with the climate scenarios projected by six GCMs on eight different types of Belgian catchments. They found an increase in the winter flood frequency in most cases (Gellens and Roulin, 1998). Since the 21st century, many hydrological models have been applied to study hydrologic impact of climate change (for example: Mimikou et al., 2000; Bruce et al., 2000; Ashmore and Church, 2001; Kamga, 2001; Alberta Environment, 2002; Singh and Bengtsson, 2004; Lac, 2004; Barrow and Yu, 2005; Alberta Environment, 2005; The Government of Canada, 2006; Kerkhoven and Gan, 2006; Martz et al., 2007; Jiang et al., 2007; Sauchyn and Kulshreshtha, 2008; Tanzeeba and Gan, 2011; Kerhkhoven and Gan, 2010; Chen et al., 2011; Troin et al, 2012; Vansteenkiste, 2013; Islam and Gan, 2014; Lei, et al., 2014). The rapid applications of a wide range of hydrologic models for predicting water availability are expected to contribute to improved water resources management under climate change impact.

1.2.3. Downscaling of GCM output

As mentioned earlier, due to coarse resolutions, outputs of GCMs are generally inappropriate for investigating regional scale impact of climate change. Thus, it is necessary to downscale the outputs of GCMs before applying them for regional studies. Dynamic and statistical downscaling are two approaches commonly employed to downscale climate change scenarios.

Statistical downscaling of GCMs outputs is usually based on statistical models linking local scale instrumental data collected from climate stations with climate data simulated by GCMs. Because this technique is relatively simple and computationally modest, it has been widely used to derive daily and monthly precipitation at higher spatial resolution for climate change impact assessments (Semenov and Barrow, 1997; Wilby et al., 2002). Statistical Downscaling Model (SDSM) and the stochastic Weather Generator (LARS-WG) are two popular statistical downscaling methods. SDSM relies on empirical relationships established between large-scale predictors and local-scale processes (Wilby et al., 2002). On the other hand, assuming weather to be stochastic processes, LARS-WG can downscale daily climate variables of multiple climate scenarios of GCMs to data at local stations useful for risk assessment (Semenov and Barrow, 2002).

In contrast, dynamical downscaling involves the application of high-resolution, regional climate models (RCMs) to simulate finer resolution climate information from climate scenarios projected by large-scale GCMs for certain selected domains that covers an area of interest (IPCC, 2001). Because they provide highly resolved spatial and temporal climate information, RCMs are much more computationally demanding than statistical downscaling approaches (Hay and Clark, 2003). RCMs are generally set up to simulate climate processes of selected sites represented by a 2 or 3-domain framework and are driven with the initial and lateral boundary conditions of GCMs. This nesting technique is presented in Figure 1.3.

Dynamic downscaling of climate data for hydrological impacts studies using RCMs is a promising tool with several advantages over statistical downscaling (Fowler et al., 2007). A major drawback of a RCM is its complicated design and high computational cost. Globally, there are some public-domain, portable RCMs. Seven RCMs were applied to dynamically downscale the Climate Forecast System (CFS) seasonal prediction over the conterminous U.S. (Yoon et al., 2012). MM5, the Fifth-generation Mesoscale Model of the Pennsylvania State University (PSU) and the National Center for Atmospheric

Research (NCAR) has been chosen for this study. MM5 is selected as the dynamic downscaling tool in this study because it has been applied successfully to dynamically downscale NCAR/NCEP reanalysis data for regional scale, hydroclimatic studies (Kavvas et al., 2013; Chen et al., 2011; Ohara et al., 2011), and for studies on the assessment of climate change impact on regional water resources (Shaaban et al., 2011).

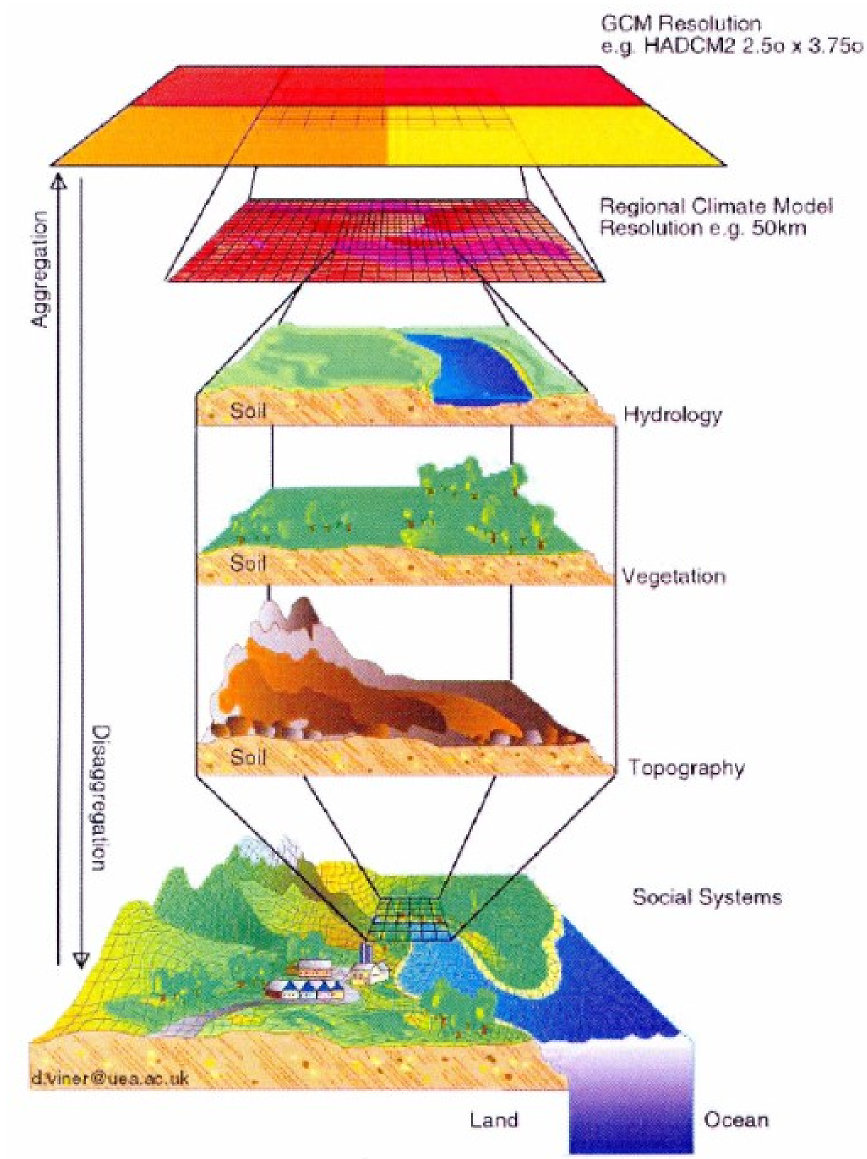

Figure 1.3: Nesting from GCMs to RCMs to a watershed (Le Treut et al., 2007).

1.3 Research Objectives

The primary objectives of this study are:

i) To investigate possible changes to streamflow of the Athabasca River Basin (ARB) under the potential impact of climate change based on the streamflow of ARB simulated by MISBA, a fully distributed, physically based land surface scheme under two SRES emission (A1B and A2) scenarios projected by four Global Climate Models (GCMs) of IPCC (2007) and dynamically downscaled by MM5 (a RCM) for 2050s and 2080s.

ii) On the basis of results obtained from (i) involving seven climate change test cases (four A1B and three A2), assess uncertainties associated with long-term projections on the hydrologic impact of climate change on ARB, and differences between streamflow simulated by MISBA driven with GCM-scale climate data downscaled by dynamic versus statistical approaches.

1.4 Research Methodology

The procedure of this research is outlined as follows:

The RCM, MM5, was first set up with a one-way, one-domain framework of 27 km resolution and forced with ERA-Interim re-analysis data of ECMWF (European Centre for Medium-Range Weather Forecasts). Input ERA-Interim data are geopotential height, temperature, wind field, relative humidity, mean sea level pressure, and sea surface temperature which provide the necessary initial and lateral boundary conditions for MM5 to model the regional climate of ARB.

The aforementioned variables from ERA-Interim re-analysis data (data-portal.ecmwf.int) were used to drive MM5 for the simulations of precipitation, precipitable water, 2-m air temperature, and other climate variables in the 27-km domain. These data are available every 6-h since 1979 at a spatial resolution of 1.5^o latitude x 1.5^o longitude. The minimum required 10 pressure levels (100, 150, 200, 250, 300, 400, 500, 700, 850, 1000 mb) data were used for the pre-processing phase of MM5.

Next, MISBA, was first calibrated and then independently validated using 1979-1988 and 1989-2007 climate data dynamically downscaled by MM5 from ERA-Interim re-analysis data for ARB, respectively. After calibration and validation, MM5 was driven with initial and boundary conditions taken from four selected General Circulation Models (GCM) of IPCC (2007) for ARB for the climate normal period of 1971–2000, and the simulated precipitation and temperature of MM5 were compared with observed data. Next, after validated MM5, the simulated climate data of MM5 for the climate normal period was used to drive MISBA and the simulated streamflow was compared with available observed streamflow data of ARB to ensure that MISBA's simulation for the climate normal period for the four GCMs is consistent with observed streamflow data of ARB.

After validated MM5's simulated precipitation and MISBA's simulated streamflow for the climate normal period, MM5 was used to downscale future climate projections of ARB based on the SRES (Special Report on Emission Scenarios) (A1B and A2) climate scenarios of the four selected GCMs of IPCC (2007), which are CGCM3 (Canada), CCSM3 (USA), ECHAM5 (Germany), and MIROC3.2 (Japan) for two 30-year periods, 2040-2069, and 2070-2099, and the downscaled climate data were used to drive MISBA to investigate the impact of climate change on the hydrology of ARB.

1.5 Organization of Thesis

This thesis consists of five chapters. Chapter 1 provides an overview of the impact of climate change on hydrology, research objectives and research methodology. A description of study site at ARB, the MM5 and MISBA models, and the data requirements of those models are summarized in Chapter 2. The calibration and validation of MISBA, and the results from MISBA, the bias correction of MM5 downscaled data are presented in Chapter 3. Detailed discussion on GCMs and their climate scenarios, the future streamflow of ARB under the potential impact of climate change simulated by MISBA based on climate scenarios dynamically downscaled by MM5, versus climate scenarios that were statistically downscaled, are presented in Chapter 4. Finally, conclusions and recommendations for future work are presented in Chapter 5.

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CHAPTER 2

Study Area and Data

2.1. Basin Description

The Athabasca River Basin (ARB), a sub-basin of the Mackenzie River Basin of Canada, has a watershed area of 133,000 km^2 and a main channel length of about 1154 km according to the Water Survey Canada (Kellerhals et al., 1972). It provides vital water resources to vegetation, animals, and people living in northern Alberta. After originated from the Canadian Rocky Mountains, the Athabasca River extends eastward through central-northern Alberta and northern Saskatchewan. Therefore, the ARB encompasses diversified landscapes ranging from snow-capped mountains, boreal forest, wetlands, agricultural plains, and urban centers (RAMP, 2014a). Therefore as a major river system of Alberta, the Athabasca River is influenced by a variety of climate, terrain and landscape characteristics found within the ARB (RAMP, 2014b).

The Athabasca River which is undammed, is the longest river within Alberta, and the second largest in terms of volume (RAMP, 2014a). The river originates from the snow and ice of the Columbia glacier in the Jasper National Park, and it meanders through urban centers of Jasper, Hinton, Whitecourt, Athabasca and Fort McMurray and eventually drains into Lake Athabasca located at the northeastern corner of Alberta.

The Athabasca River exhibits strong climatic seasonality between cold winters and warm summers. During cold winters, most of the precipitation falls as snow. During springs, water from melting snow and ice begins to trickle from the headwaters at the Rocky Mountain. During summer, water from the headwaters will combine with runoff from localized snowmelt and rainfall events occurring throughout individual sub-basins of ARB before it ends up at Lake Athabasca (RAMP, 2014b).

ARB experiences a continental climate with significant seasonal variation in temperature. The daily mean temperature drops below freezing after mid-October and remains below zero until early April. Typical January temperature is around −20 °C while that of July (warmest month) is about 17 °C (Kerkhoven and Gan, 2006). Typically the wet months are from June to October with an average seasonal precipitation of about 300 mm, while winter and spring are relatively dry with an average seasonal precipitation of about 150 mm, in an average year respectively (Kerkhoven and Gan, 2010).

Other than temperature and precipitation, the vegetation cover, soil types and terrain features in ARB also play a significant role in its land surface hydrology. The hydrologic responses of ARB essentially consists of canopy interception of precipitation, plant transpiration and evaporation from intercepted precipitation and water stored in the soil layer, spring snowmelt, soil infiltration, and predominantly subsurface runoff. ARB can be broadly classified under the following six eco-regions (Mitchell and Prepas, 1990):

- Rocky Mountain (Alpine, Subalpine, Mountain);
- Boreal Foothills;
- Boreal Mixed Wood (dry and wet);
- Boreal Uplands;
- Boreal Lowlands; and,
- Canadian Shield (Athabasca Plains).

The top soil layers of ARB are dominated by glacial soils (silt, clay and sands), glaciolacustrine soils (clay loam to heavy clay), and glaciofluvial soils (sandy loam to sands) (Kerkhoven and Gan, 2010; Fulton, 1995). However, peat soils are also found in many parts of ARB, which vary in depth from 0.3m to over 1m for the upland and lowland terrains of ARB, respectively. Thick peat soils with near surface groundwater level are normally found in lowland areas. On an average, typical ground slopes of upland parts of ARB are 0.5% or more, while those of lowland parts of ARB are less than 0.5% (Kerkhoven and Gan, 2010). Under such terrain characteristics, interflow tends to constitute a significant component of the sub-surface runoff for lowland areas which are dominated by muskeg (Golder Associates, 2002).

2.2. Description of Climate and Hydrologic Models

2.2.1. MM5 Model

The Fifth-Generation Mesoscale Model (MM5) was jointly developed by the Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR) in the early 1970's (Anthes and Warner, 1978). It is a three-dimensional meteorological prognostic Eulerian model and mostly written in Fortran. The last version of MM5 was Version 3-7-4 released on 16 October 2006 (MM5 Community Model, 2014a).

Over the years, many changes have been added to broaden the applications of MM5. Its key features include: (i) a multiple-nest capability, (ii) non-hydrostatic dynamics, which allows the climate model to be used at high spatial resolution, e.g., several kms, (iii) multi-tasking capability on shared and distributed memory machines, (iv) a four-dimensional data-assimilation capability, as well as (v) cloud parameterization schemes and other physical options. MM5 is portable to a wider range of computing platforms. It is best described as a limited-area, non-hydrostatic, sigma-coordinate, regional climate model designed for the simulation and prediction of mesoscale and regional scale atmospheric circulations. Sigma surfaces near the ground follow the terrain, and the higher-level sigma surfaces tend to approximate isobaric surfaces (MM5 Community Model, 2014a).

In this study, MM5 was set up and fine-tuned to dynamically downscale the coarse resolution, SRES climate change scenarios of GCMs (≈ 150 to 400 km) to 27 km resolution for driving MISBA to simulate future water resources of ARB subjected to the impact of climate change. It is a mesoscale model widely used for numerical weather prediction, air quality studies, and hydrological studies.

2.2.2. MISBA Model

The Modified Interactions between the Soil-Biosphere-Atmosphere (MISBA) model is a fully distributed physically based, soil-vegetation-atmosphere transfer model (SVAT) that considers interactions between the soil-biosphere-atmosphere. ISBA was developed by Météo France (Noilhan and Planton, 1989; Habets et al., 1999), and modified by Kerkhoven and Gan (2006) to more accurately simulate the water and energy fluxes of the Athabasca River Basin (ARB). This model is designed to simulate exchange of heat, mass and momentum fluxes between the land or water surface and the overlying, lower atmosphere. MM5 accounts for the basic physics that controls regional energy balance and water budget, but with minimum number of parameters that require calibration (Kerkhoven and Gan, 2006). In other words, the model consists of two basic types of parameters which include four primary and twenty-two secondary parameters. The primary parameters are percentage of sand, percentage of clay, vegetation cover types and land-water ratio that are specified at each grid point. The secondary parameters are related to the primary parameters (Kerkhoven and Gan, 2006). Both two types of parameters are listed in **Appendix**. Because MISBA is a 1-D model, it is set up to model the hydrology of ARB at 27 km resolution which is the same as that of the meteorological forcing data.

MISBA is a grid-based land surface scheme designed to model hydrologic processes of large watersheds in a distributed, grid-based manner. For each grid, it further accounts for the sub-grid variability of soil, vegetation and elevation of ARB using a mosaic approach. It considers subsurface water fluxes in a three-layer soil storage. The interception of precipitation is modeled using the Deardorff (1978) relationship, while evaporation from soil and transpiration from vegetation are based on energy balance and an aerodynamic method. The sub-grid runoff scheme (Habets et al., 1999) considers the sub-grid heterogeneity of soil moisture, x (meters) using the Xinanjiang distribution presented below (Zhao, 1992):

$$F(x) = 1 - \left(1 - \frac{x}{x_{max}}\right)^{\beta} \quad 0 \leq x \leq x_{max} \tag{2.1}$$

$$\frac{\bar{x}}{x_{max}} = \frac{1}{\beta + 1} \tag{2.2}$$

Where, F(x) is the cumulative probability distribution of x, defined by the maximum (x_{max}) and mean ($\bar{x}$) values of x, and β is an empirical parameter. The maximum soil depth in each grid is effectively defined by the parameter β determined by the modeler. In MISBA, β is calculated internally using the following equations,

$$\beta = \frac{1}{\bar{\bar{S}}} - 1 \tag{2.3}$$

$$S = \frac{w - w_r}{w_{sat} - w_r} \tag{2.4}$$

Where, S is the soil water retention, w is the soil water content, w_r is the residual water content, and w_{sat} is the saturated water content. In ISBA, the sub-surface runoff is modeled using a gravity drainage scheme following a linear reservoir, while in MISBA the sub-surface runoff is modeled using a nonlinear function of soil water to more accurately account for the interflow and subsurface flow of ARB (Kerkhoven and Gan, 2006).

2.3. Model Data Requirements

2.3.1. Data Requirement of MM5 Model

MM5 has proven to be a powerful tool for simulating three-dimensional high-resolution meteorological fields for various climatic regions of North America (e.g., Spak et al., 2007; Zhang et al., 2007; Hwang et al., 2011; Jang and Kavvas, 2013). Data required to run the modeling system include topography and land-use datasets, radiosonde and surface observation data, regional gridded atmospheric data that have at least these variables: 3D forecast fields including U-winds, V-winds, heights, temperature, water vapor mixing ratio, and 2D forecast fields including sea surface temperature, sea level pressure, and snow cover for surface (MM5 Community Model, 2014b). The recommend temporal resolution of MM5 input data is about three times the temporal resolution of the outer domain of the study site. Typically, MM5 uses a horizontal resolution ranging from 1 km to 90 km, and a vertical resolution of 20m for elevations that are below 100m and 100-500m for elevations above 100m (EIONET, 2014).

2.3.2. Data Requirement of MISBA Model

Topographic, land-use, meteorological, and hydrometric data are required to simulate the hydrologic processes of a river basin. In this study, the meteorological data for MISBA includes ERA-Interim historical re-analysis dataset of 6-hourly duration from 1979 to 2007 with a spatial resolution of 1.5^{o} latitude and 1.5^{o} longitude. The ERA-Interim data developed by the European Center for Medium-range Weather Forecasts (ECMWF) was used to fine tune MM5 as explained in Section 1.4 and its simulated climate data was used to drive MISBA. Other input data to MISBA includes DEM data obtained from the USGS National Elevation Dataset to determine the drainage area, drainage network and flow direction of the rivers of ARB. The land-use data for ARB was taken from 30 arc seconds ecoclimap dataset derived from combining land cover maps, climate and Advanced Very High Resolution Radiometer (AVHRR) satellite data (Masson et al. 2003). Other input data to MISBA include initial soil moisture, soil ice content, soil temperature, surface albedo, and others (Kerkhoven and Gan, 2006).

The 1979-2007 ERA-Interim re-analysis dataset of ECMWF was the baseline data used to run the first experiment of MM5. The output of MM5 was compared with the 1979-2007 observed data of Canadian Meteorological Center (CMC) for the Athabasca River Basin (ARB). Next, the second and the third numerical experiments involving MM5 were the SRES A2 and SRES A1B emission scenarios for two 30-year periods (2040-2069 and 2070-2099) of ECHAM5, CGCM3, CCSM3, and MIROC3.2, respectively.

The hydrometric data for ARB was collected from the gauging station at the Athabasca River below McMurray, Station # 07DA001 of Environment Canada, which is located near the outlet of ARB (see Table 2.1) and its location is shown in Figure 2.1.

Table 2.1: The hydrometric station of Environment Canada selected for the study.

Station Name	**Athabasca River below McMurray**
Station Number	07DA001
Latitude	56°46'49" N
Longitude	111°24'7" W
Gross drainage Area [km^2]	133000
Drainage Area [km^2]	130000
Period of record	1957-2011

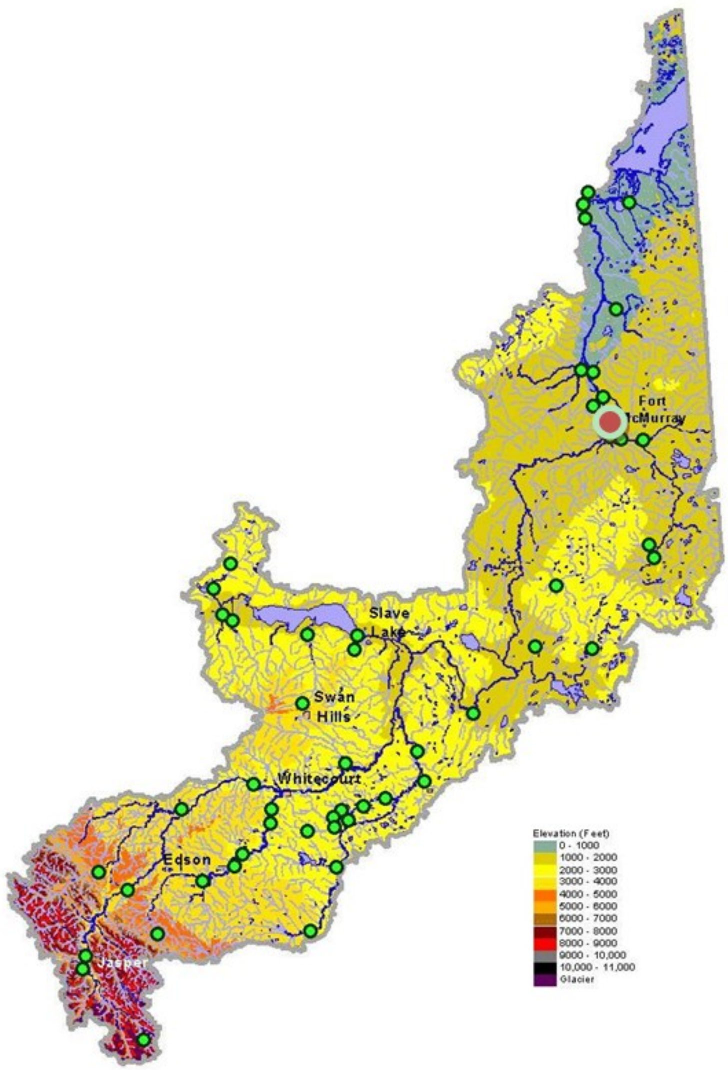

Figure 2.1: Study basin and study flow stations (Station Athabasca River below McMurray is shown in Red) (Alberta Environment, 2014).

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CHAPTER 3

Research Procedure

3.1. Calibration and Validation of MISBA

According to the Standard Practice for Evaluating Environmental Fate Models of Chemicals of the American Society of Testing and Materials (ASTM, 1984), the definitions of calibration and validation are as follows:

- Calibration is a test of the model with known input and output information that is used to adjust or estimate factors for which data are not available.
- Validation is a comparison of model results with numerical data independently derived from experiments or observations of the environment.

MISBA was first calibrated for ARB using ten years of climate and hydrologic data of 1979 to 1988. After calibration, keeping all model parameters of MISBA unchanged, MISBA was independently validated using data for 1989 to 2007. The performance of MISBA was assessed by comparing its simulated streamflow for ARB with that observed at the Athabasca River below McMurray gauging station.

Because MM5 and most climate models are simplified version of nature and are driven by coarse resolution input data, etc., they tend to over simulate precipitation, which therefore requires bias correction before they are comparable to rain gauge measurements (e.g., Berg et al., 2012; Teutschbein and Seibert, 2012). Similar problems were encountered by Chiew et al. (1995), Kamga (2001), and Kuo et al. (2014). Therefore, precipitation data simulated by MM5 were adjusted by a linear bias correction method (Lafon et al., 2012). In this method, the daily precipitation simulated by MM5 was adjusted with twelve monthly adjustment factors, represented as $\alpha_i = \bar{O}/\bar{P}$, which is the ratio between mean monthly observed value ($\bar{O}$) and the MM5 simulated mean monthly value ($\bar{P}$) for 1979-1988 for each month.

Five goodness-of-fit statistics or measures were calculated to assess the performance of MISBA in both calibration and validation stages. Those measures are coefficient of determination (R^2), Absolute Standard Error (ABSE), Root Mean Square Error (RMSE), Nash-Sutcliffe coefficient of efficiency (Ef), and log error (Equations 3.1 to 3.5). The results presented below show that MISBA performed well in both calibration and validation stages. Given that MISBA could simulate the historical streamflow of ARB accurately in both stages, and by assuming physical conditions of ARB remaining unchanged to the end of the 21st century, there is sufficient basis to employ MISBA to investigate the long-term impact of climate change on the hydrology of ARB.

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2}} \right)^2 \quad (3.1)$$

$$\text{ABSE} = \frac{\sum |O - P|}{\sum O} \quad (3.2)$$

$$\text{RMSE} = \frac{\sqrt{\sum (O - P)^2}}{\sum O} \quad (3.3)$$

$$\text{Ef} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \quad (3.4)$$

$$\log \text{error} = \frac{\sum |\ln O - \ln P|}{\sum \ln O} \quad (3.5)$$

Where O and P are observed and predicted values, and $\bar{O}$ and $\bar{P}$ are their mean values, respectively.

The simulated outflows and naturalized observed outflows for calibration and validation periods for the Athabasca River Basin are shown as Figure 3.1 and 3.2, respectively. Values of R^2, Ef and three other coefficients for calibration and validation stages for MISBA are listed in Table 3.1. Figure 3.3 provides range of values of R and R^2 recommended by Donigian (2002) for determining the performance of a hydrologic model under daily and monthly time scales. Based on Figure 3.3, with a R^2 of 0.71, MISBA is considered to perform reasonably well in the validation stage and therefore can be used to assess the impact of climate change to ARB.

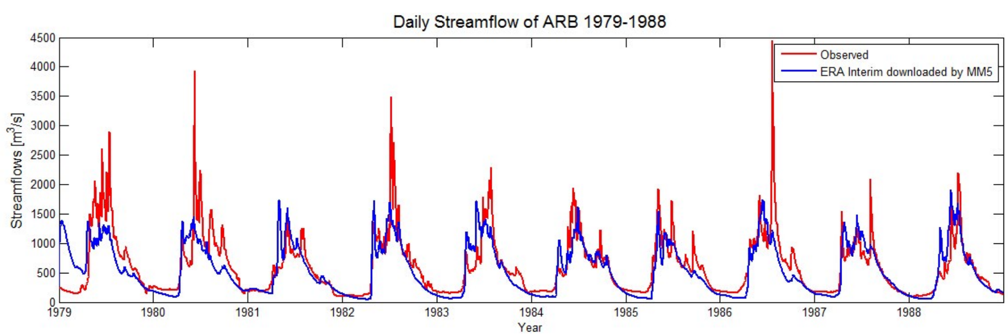


Figure 3.1: Calibration plots of Athabasca River below McMurray using MISBA (R^2 = 0.5965).

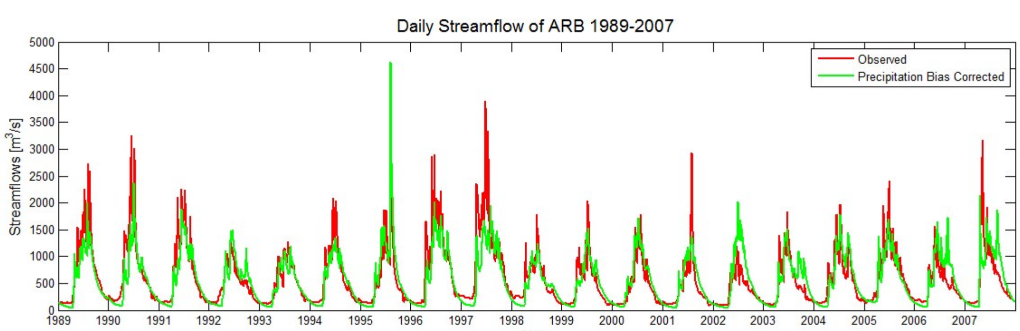


Figure 3.2: Validation plots of Athabasca River below McMurray using MISBA (R^2=0.7055).

Table 3.1: Statistics of calibration and validation runs using MISBA for the Athabasca River below McMurray gauging station.

Station Name	Runs	Period	R^2	ABSE	RMSE	Log error	Ef
Athabasca River below McMurray	Calibration	1979-1988	0.5965	0.3303	0.009	0.0654	0.5749
	Validation	1989-2007	0.7055	0.3066	0.0059	0.0626	0.6998

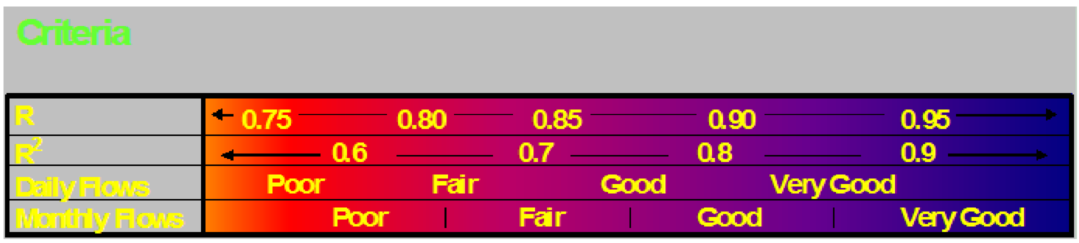


Figure 3.3: Typical accepted performance of hydrologic models based on R and R^2 values obtained between simulated and observed streamflow (Donigian, 2002).

3.2. Discussions of Results

3.2.1. MISBA Simulated Runoff

MM5's simulated precipitation was bias corrected using the bias correction technique of Lafon et al. (2012) before it was used to drive MISBA to simulate the runoff of ARB. The average annual runoff hydrograph of ARB, observed and simulated by MISBA based on bias corrected precipitation data of MM5 at daily time steps for 1979-2007, are shown in Figure 3.4. There are two peaks in Figure 3.4, with the first smaller peak representing runoff resulted from melting of the snowpack of ARB in spring, while the second, larger peak represent summer runoff. Overall, the summer peak flow simulated by MISBA matches well with the observed, but the spring and autumn runoffs simulated by MISBA show some discrepancies from the historical runoff.

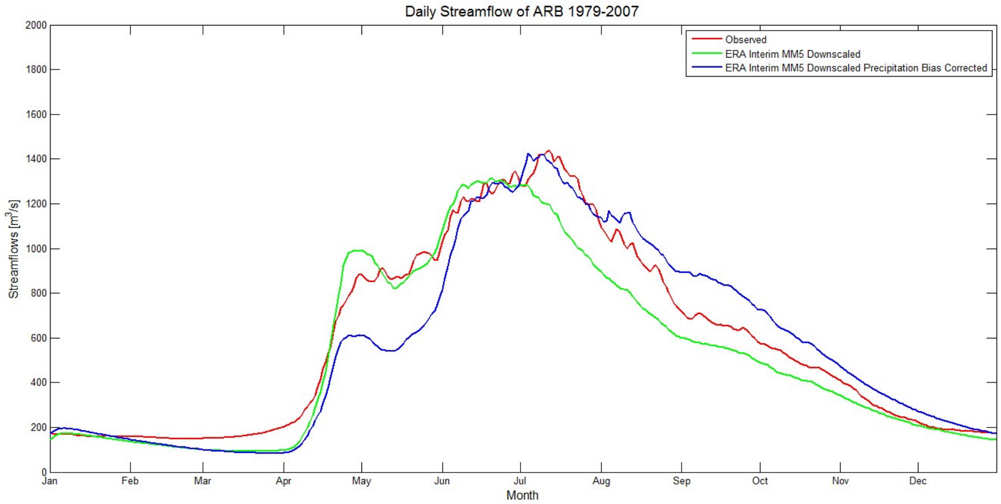


Figure 3.4: MISBA Annual Mean Daily Simulated Streamflow at Athabasca River below McMurray for 1979-2007.

3.2.2. Biases in MM5 Dynamic Downscaled Precipitation Data

Lafon et al. (2012) described various bias correction techniques for precipitation simulated by climate models. Among those techniques, a relatively simple, linear bias correction method was implemented in this study based on monthly precipitation data recorded in ten historical rain gauges located within ARB. Details about these ten rain gauges such as Station ID, name, longitude and latitude, etc., are shown in Figure 3.5 and Table 3.2.

From information given in the CMC website (http://climate.weather.gc.ca/), there are 707 climate stations located inside Domain 1 (D1) of MM5 located within longitudes -119^o to -107^o, and latitudes 52^o to 59^o (Figure 3.6). However, only 61 out of the 707 stations contain monthly precipitation data from 1979 to 2007 and most of these 61 stations only contain data between April and September. Only 10 out of these 61 stations have precipitation data for twelve months (Figure 3.5). These 10 rain gauge stations were selected to implement the bias correction of MM5's simulated precipitation. These 10 stations are: Athabasca 2, Calling Lake RS, Campsie, Cross Lake, Fort McMurray A, Jasper East Gate, Kaybob 3, Shining Bank, Wabasca RS, and Whitecourt A.

Figure 3.5: Ten rain gauge stations distribution inside ARB

Table 3.2: Ten rain gauge stations information

Lon	Lat	Station
-113.54	54.82	ATHABASCA 2
-113.18	55.25	CALLING LAKE RS
-114.68	54.13	CAMPSIE
-113.91	54.63	CROSS LAKE
-111.22	56.65	FORT MCMURRAY A
-117.82	53.23	JASPER EAST GATE
-116.63	54.11	KAYBOB 3
-115.97	53.85	SHINING BANK
-113.83	55.97	WABASCA RS
-115.79	54.14	WHITECOURT A

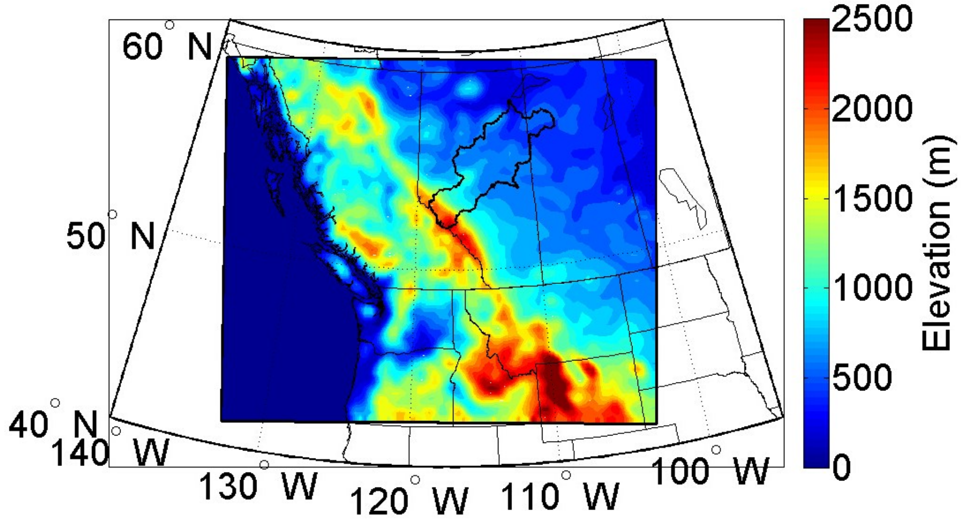


Figure 3.6: The Domain 1 (D1) of MM5 set up for the climate change impact study of ARB.

According to the linear bias correction method of Lafon et al. (2012), a scaling factor alpha (Equation 3.6), which is a simple ratio of the mean observed versus simulated precipitation, is used to correct MM5's simulated precipitation P to the corrected amount, P*, using Equation 3.7.

$$a = \overline{\mathrm{O}}/\overline{\mathrm{P}} \tag{3.6}$$

$$\mathrm{P}^* = a\mathrm{P} \tag{3.7}$$

Where, $\overline{\mathrm{O}}$ and $\overline{\mathrm{P}}$ are the monthly mean observed and MM5's precipitation.

Even though a simple approach, the bias corrected precipitation obtained are generally reasonable and accurate (Figure 3.7). By implementing this bias correction method to MM5's simulated precipitation (P to P*), the runoff of ARB simulated by MISBA driven by P* has improved (see Figure 3.4).

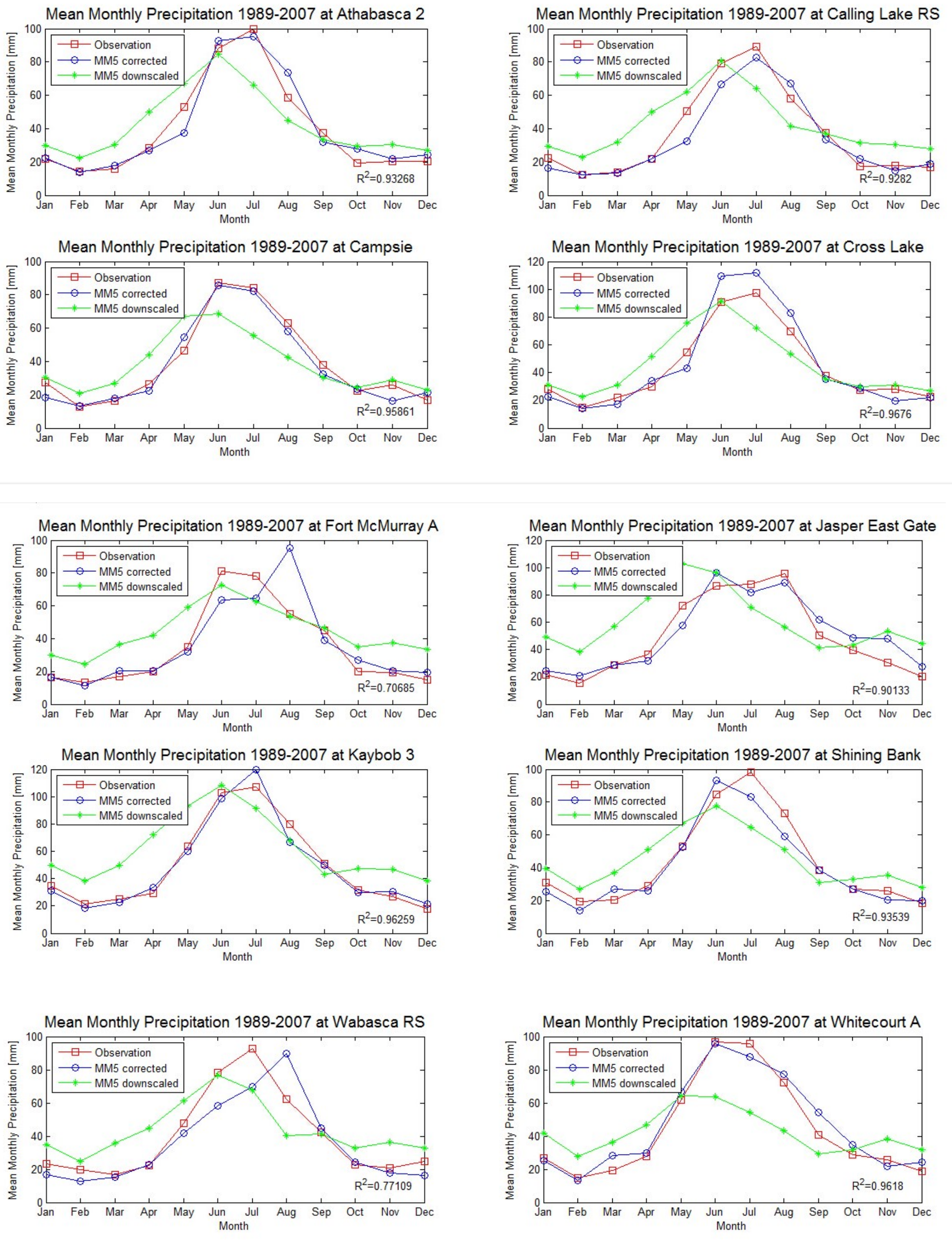
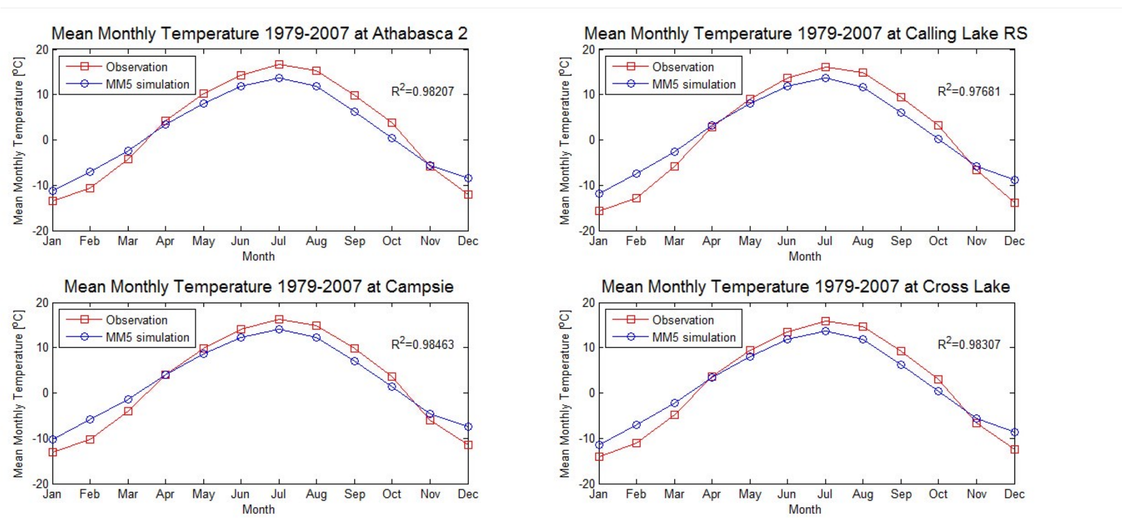


Figure 3.7: Comparison of monthly, 1989-2007 precipitation data downscaled by MM5 before and after bias correction, with observed data of rain gauging stations: Athabasca 2, Calling Lake RS, Campsie, Cross Lake, Fort McMurray A, Jasper East Gate, Kaybob 3, Shining Bank, Wabasca RS, and Whitecourt A. R^2 represents goodness-of-fit between

MM5 bias corrected and observed, station precipitation data.

3.2.3. MM5's Simulated Temperature Data

MM5's simulated temperature data are compared with the mean monthly observed temperature data (Figure 3.8). Apparently there is good agreement between MM5's mean monthly temperature data with that of the observed at Station Athabasca 2, Calling Lake RS, Campsie, Cross Lake, Fort McMurray A, Jasper East Gate, Kaybob 3, Shining Bank, Wabasca RS, as well as at Station Whitecourt A. Therefore, unlike precipitation data of MM5, temperature of MM5 does not require bias correction.



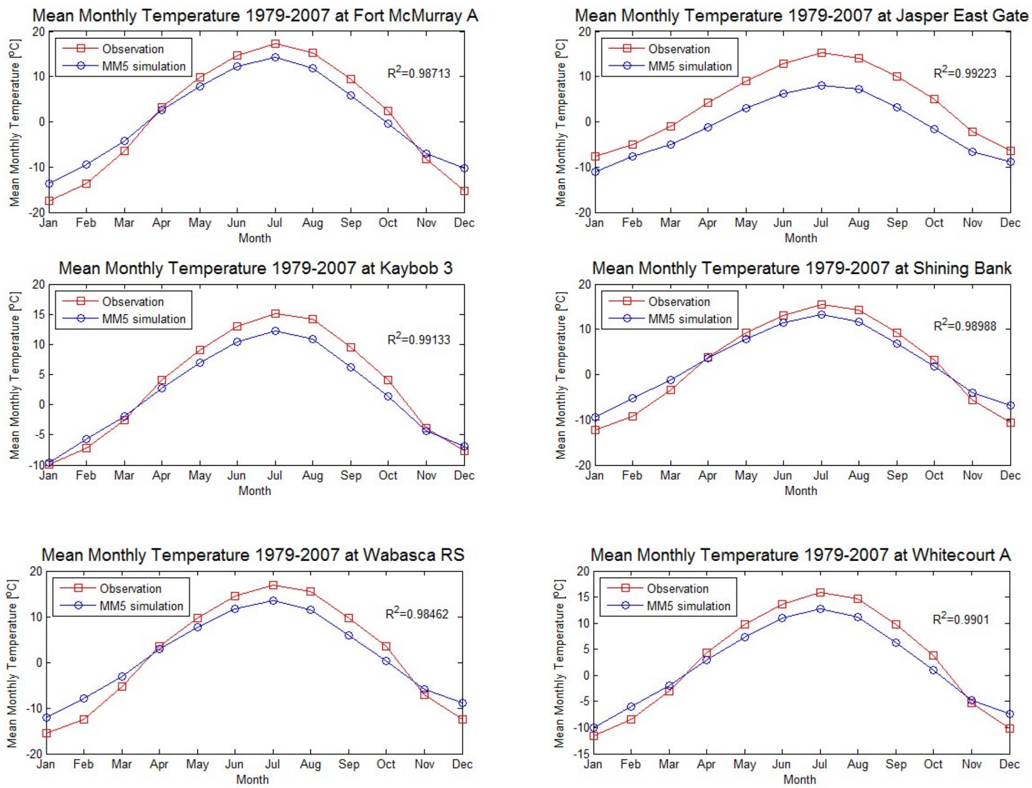
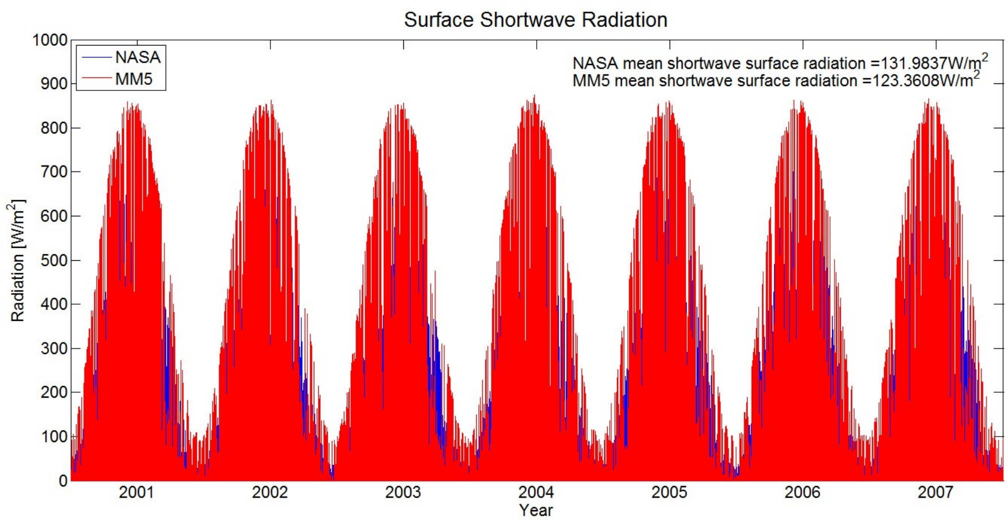


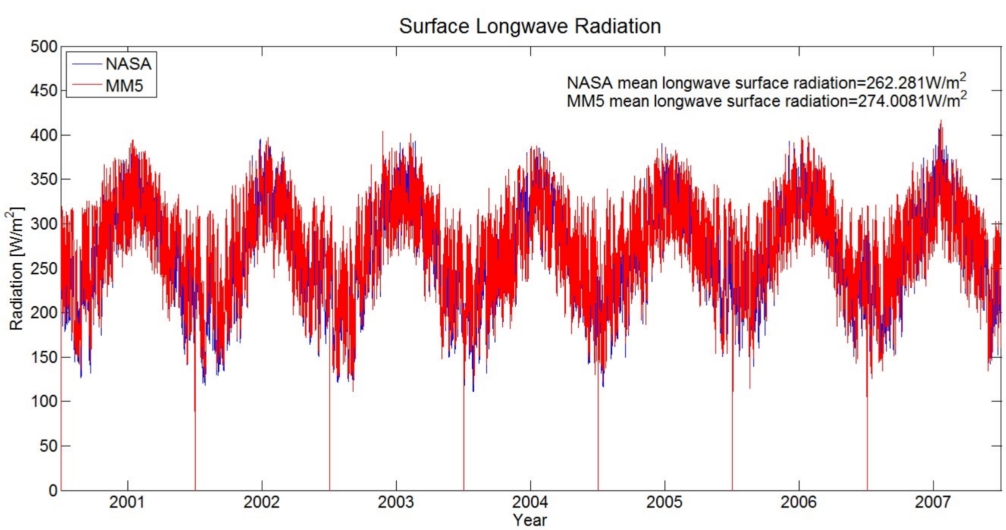
Figure 3.8: Comparison of the 1979-2007 mean monthly air temperature observed and simulated by MM5 at stations: Athabasca 2, Calling Lake RS, Campsie, Cross Lake, Fort McMurray A, Jasper East Gate, Kaybob 3, Shining Bank, Wabasca RS, and Whitecourt A.

3.2.4. MM5's Simulated Radiation Data

Energy fluxes a watershed receives consist of the shortwave, solar radiation and the downward longwave radiation from the atmosphere. The 2001-2012 radiation data downloaded from National Aeronautics and Space Administration (NASA) is a 3-hourly radiation data at the top of the atmosphere (TOA) acquired by the Clouds and the Earth's Radiant Energy System (CERES) sensor, one of the high priority scientific satellite instruments developed for NASA's Earth Observing System (EOS). The 6-hourly, radiation data for 2001-2007 that MM5 downscaled from ERA-Interim reanalysis data for ARB was compared with the radiation data of NASA (see Figure 3.9). The mean shortwave radiation of NASA (131.98 W/m^2) is about 10 W/m^2 higher than that of MM5 (123.36 W/m^2) but the mean longwave radiation of NASA (262.28 W/m^2) is about 12 W/m^2 lower than that of MM5 (274.00 W/m^2). On a whole, the total amount of energy fluxes between that of NASA and MM5 are about the same and therefore no attempt was made to bias correct the radiation data of MM5.



a)



b)

Figure 3.9: a) 6-hourly shortwave radiation data of NASA and MM5; b) 6-hourly

downward longwave radiation data of NASA and MM5 over ARB for 2001 to 2007.

3.3. Summary and Conclusions

In this study, the Fifth-Generation Mesoscale Model (MM5) jointly developed by the Pennsylvania State University and the National Center for Atmospheric Research was set up to dynamically downscale ERA-Interim re-analysis data and SRES climate changes scenarios of four GCMs to simulate the hydrologic impact of climate change to the Athabasca River Basin of central Alberta using a fully distributed land surface scheme, MISBA, of Kerkhoven and Gan (2006). Because MM5 tends to over-simulate the precipitation data of ARB, the precipitation data of MM5 was first bias corrected before it was applied to MISBA to simulate the streamflow of ARB. MISBA was first calibrated using the 1979-1988 climate data that MM5 downscaled from ERA-Interim re-analysis data for ARB and then it was independently validated using the 1989-2007 data. The conclusions are listed as follows:

1) By bias corrected the precipitation data that MM5 dynamically downscaled using a linear bias correction method and rainfall measurements from ten selected rain gauges stations located in ARB, the performance of MISBA (assessed in terms of its simulated streamflow data for ARB) improve marginally in the calibration stage, but significantly in the validation stage. Due to the limitations of regional climate models such as MM5, it seems in most cases precipitation data dynamically downscaled by a RCM will have to be bias corrected with respect to observed rain gauges data before applying the data to MISBA to simulate the hydrology of the study basin.

2) In contrast, by comparing with temperature data of 10 climate stations locate in

ARB, and radiation data of NASA, it seems unnecessary to bias correct temperature and radiation data dynamically downscaled by a RCM such as MM5 before such data are applied to MISBA to simulate the hydrology of ARB.

3) A fully distributed, physically based land surface scheme, MISBA, driven by coarse-scale ERA-Interim re-analysis data or climate data of GCMs dynamically downscaled by MM5, can accurately simulate the hydrologic processes of a regional scale, Athabasca River Basin of central Alberta.

4) The mean annual outflows of ARB under warming are expected to decline because the winter snowfall season is shorter while snow sublimation increases, which together lead to a decline in the spring snowpack (Kerkhoven and Gan, 2011), and increased evaporation loss, which together could offset the increase in the overall precipitation of ARB. Detailed discussions on the future streamflow of ARB will be presented in Chapter 4.

3.4. References

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CHAPTER 4

Hydrologic Impact of Climate Change on the ARB

4.1. Global Trend in Climate Change

Climate change is an ongoing phenomenon of global scale and it is expected to get worse in response to ever increasing greenhouse gas concentrations in the atmosphere. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), from 1880 to 2012, the globally averaged, combined land and ocean surface air temperature had increased by 0.85 ^{o}C $\pm$ 0.21 ^{o}C (IPCC, 2013). In its Fourth Assessment Report (AR4), IPCC reported the global average surface air temperature has increased by about 0.74 ^{o}C $\pm$ 0.18 ^{o}C over the last 100 years (1906-2005) (IPCC, 2007), which is greater than the reported warming of 0.6 ^{o}C $\pm$ 0.2 ^{o}C between 1901 and 2000 given in its Third Assessment Report (TAR) (IPCC, 2001). Differences in global scale warming reported by different ARs of IPCC are due to several factors, which include the availability of additional datasets that are independently produced, new improved analysis approaches, more sophisticated climate modeling capabilities (IPCC, 2007), and the ongoing increase in atmospheric greenhouse gases (IPCC, 2013).

Climate change is affecting and will continue to affect many aspects of water resources worldwide, including that of Athabasca River Basin (ARB), which has a humid continental climate (Köppen climate classification Dfb) that borders on a subarctic climate (Köppen climate classification Dfc) (Peel et al, 2007). According to MRBB (2012), between 1950 and 1998, the average annual temperature of the Mackenzie river basin (MRB) had increased by about 2 ^{o}C while the average winter temperature had increased by about 4 ^{o}C which are much higher than the global warming trend reported by IPCC (2001, 2007, 2013). Further, MRBB (2012) also reported that between 1950 and 1998, the number of extreme warm days had increased while the number of extreme cold days had decreased in MRB. This would result in an earlier thawing of the snowpack in spring but a later freeze-up in the fall in MRB. Since ARB is the southern sub-basin of MRB, we would expect similar changes had also happened to ARB. In other words, the earlier onset of peak spring runoff and increased evaporation could affect the summer runoff of ARB.

4.2. Historical Trend in Meteorological and Hydrometric Data of ARB

There is a scientific consensus that climate change is occurring, e.g., Assessment Reports of IPCC, and based on projections of global climate models, Northwestern North America will become increasingly warmer and drier in the 21st century (USDA, 2004). One of the most significant climate change impacts may be on hydrological processes, particularly streamflow regimes of river basins. According IPCC (2007), under the impact of climate change, more GCMs project the precipitation of ARB to increase by the end of the 21st century (though some project decrease in precipitation), but the increase in evaporation loss due to warmer temperatures could offset the increase in precipitation, so that the streamflow of ARB is mostly projected to decrease, which would affect the water supply of ARB (Kerkhoven and Gan, 2011).

A simple linear regression fitted to historical time series of precipitation, temperature and naturalized flow of ARB indicates that there has been a decreasing trend in precipitation and streamflow discharge but an increasing trend in the temperature over ARB (see Figure 4.1). The climate data recorded at Fort McMurray A, shows a decrease trend of 0.26 mm/year in precipitation and an increasing temperature trend of 0.021 °C/year between 1979 and 2007. Based on the 1958-2011, mean annual naturalized streamflow data collected at the gauging station, Athabasca River below McMurray, ARB has experienced a decreasing trend by about 3.326 m^3/s per year.

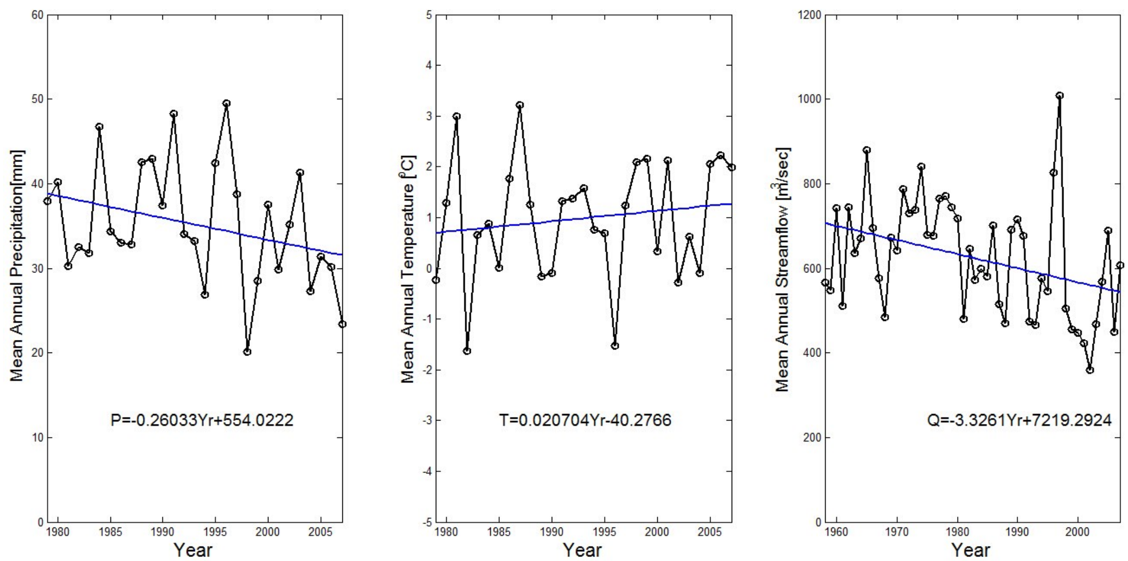


Figure 4.1: Observed trends in historical precipitation, temperature at the Fort McMurray A climate station and naturalized streamflow at the Athabasca river below McMurray gauging station, for different time periods as shown in respective diagrams.

Given the aforementioned decreasing streamflow and increasing temperature trends of ARB, and the mean annual streamflow of ARB based on the 1958-2011 is about 618.67m^3/sec, it means that an increase in temperature of 1^{o}C $\approx$ 25% decrease in runoff $\left\{\frac{3.326\ m^3/s/yr}{618.67\ m^3/s/yr \times 0.021℃/yr} \times 100\%\right\}$, which is about three times that of Kerkhoven and Gan (2011) who estimated that for ARB, based on the SRES climate scenarios of 7 GCMs, an increase in temperature of $1^{o}C \approx 8\%$ decrease in runoff even though precipitation is predominantly projected to increase. Given the decreasing precipitation trend has been about 0.26mm/year and the area of ARB is about 133,000 km^2, the decrease in streamflow due to decreasing precipitation alone should be about 1.12 m^3/s per year, which has been increased to about 3.326 m^3/s per year because of increased evaporation loss due to warming.

4.3. Climate Change Scenarios

Primarily climate change scenarios based on future climate projections of Global Climate Models (GCMs) of IPCC have been applied in climate change impact studies. GCMs are three-dimensional mathematical models that simulate atmospheric circulations using the momentum, continuity, and energy equations which are based on known physical laws of atmosphere, ocean, ice cap and land surface processes (Tanzeeba and Gan, 2012). Changes to future climate of ARB are based on projected SRES emission scenarios (A2 and A1B) of four GCMs (ECHAM5, CGCM3, CCSM3 and MIROC3.2) of IPCC (2007). The outputs of GCMs are of relatively coarse resolutions both spatially and temporally. Therefore SRES climate scenarios of GCMs were first dynamically downscaled by MM5 and used to drive a land surface scheme, MISBA to predict the possible hydrologic impact of climate change to the Athabasca River Basin under a wide range of possible future climate conditions. Brief information of the four GCMs selected in this study is given in Table 4.1 while their climate scenarios are explained briefly in Table 4.2. Two future periods are considered in study, namely the 2050s (2040-2069) and the 2080s (2070-2099).

Table 4.1: Information of four Global Climate Models selected for this study.

Climate Modeling Center	Country	Model	SRES Scenarios	Resolution
Canadian Center for Climate Modeling and Analysis (CCCma)	Canada	CGCM3	A1B, A2	3.75^o x 3.75^o
University Corporation for Atmospheric Research (UCAR)	USA	CCSM3	A1B, A2	3.75^o x 3.75^o
Max Planck Institute for Meteorology (MPI-M)	Germany	ECHAM5	A1B, A2	1.875^o x 1.87^o
National Institute for Environmental Studies (NIES)	Japan	MIROC3.2	A1B	2.8125^o x 2.8^o

Table 4.2: Information of climate scenarios considered in this study.

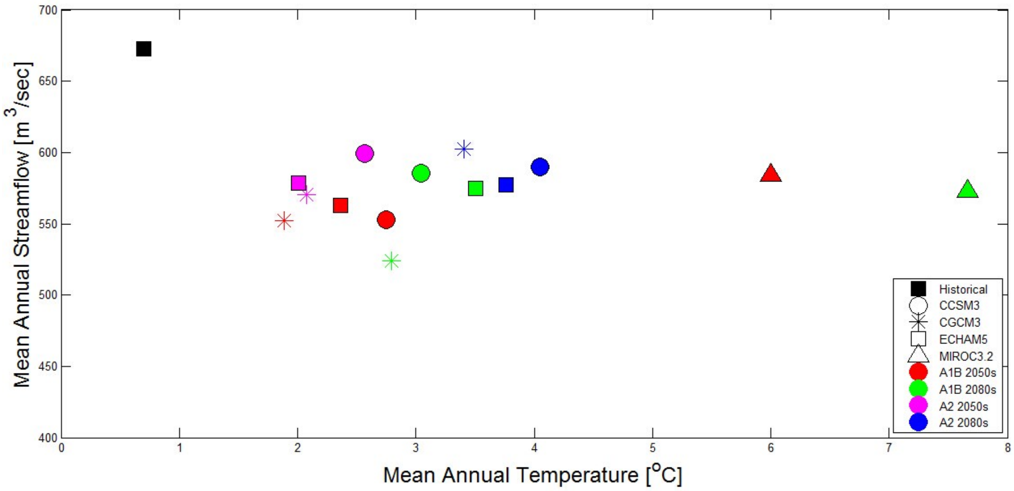
scenarios	Dataset	Description	Duration
20C3M	Climate of the 20^{th} century	Atmospheric CO_2 concentrations and other input data are based on historical records or estimates beginning around the time of the Industrial Revolution.	1971-2000
SRES A1B	720 ppm CO_2 maximum	Atmospheric CO_2 concentrations reach 720 ppm in 2100 in a world characterized by low population growth, very high GDP growth, very high energy use, low land-use changes, medium resource availability and rapid introduction of new and efficient technologies.	2040-2100
SRES A2	850 ppm CO_2 maximum	Atmospheric CO_2 concentrations reach 850 ppm in 2100 in a world characterized by high population growth, medium GDP growth, high energy use, medium/high land-use changes, low resource availability and slow introduction of new and efficient technologies.	2040-2100

4.4. Impact of Climate Change to Streamflow of ARB

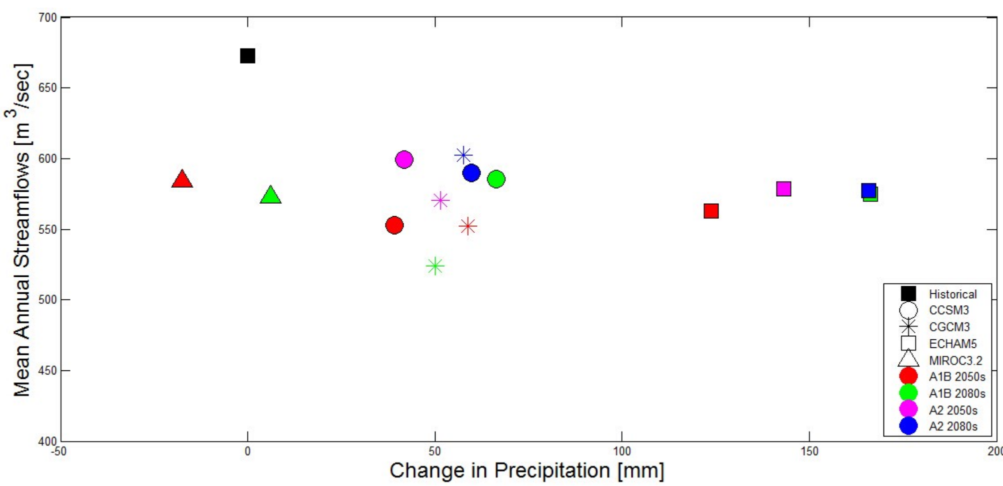
4.4.1. Mean Annual Streamflow

The primary climate change factors considered are 6-hourly air temperature and precipitation with reference to the base period of 1979-2007. According to the four A2 scenarios, the average annual temperature of the ARB is projected to rise by 2.13 ^oC (1.88 ^oC to 2.37 ^oC) in 2050s, and 3.62 ^oC (3.31 ^oC to 3.94^oC) in 2080s, and for the A1B scenarios, to increase by 3.77^oC (1.67 ^oC to 5.88 ^oC) in 2050s, and 5.15 ^oC (2.66 ^oC to 7.63 ^oC) in 2080s. While the average annual precipitation of the ARB is projected to change by 7.59% to 22.55% in 2050s, 10.26% to 24.47% in 2080s for the A2 scenarios; and -2.66% to 21.99% in 2050s, and 0.90% to 29.26% in 2080s for the A1B scenarios.

In response to these projected climatic change, SRES scenarios (A2 and A1B) of four GCMs (ECHAM5, CGCM3, CCSM3, and MIROC3.2), the future streamflow of ARB was simulated by MISBA for 2040-2069 (2050s) and 2071-2099 (2080s). To simulate the streamflow of ARB for the base period (1979-2007), MISBA was driven by the ECMWF ERA-Interim re-analysis data. The streamflow of ARB simulated by MISBA for the 2050s and 2080s are compared to that of the 1979-2007 base periods (black squares shown in Figure 4.2). According to these SRES climate scenarios, the mean annual temperature of ARB is projected to increase by up to 7.63 ^oC and the mean annual precipitation by up to 29.26% for the 21st century, respectively. However, the mean annual streamflow of ARB is predominantly projected to decrease for all SRES climate scenarios tested in this study. Apparently for ARB, the enhanced evaporation loss caused by the projected increase in temperature could offset the projected increase in precipitation, leading to the projected decrease in the mean annual streamflow of ARB.



a)



b)

Figure 4.2: Mean annual streamflows simulated by MISBA at the Athabasca River below McMurray of ARB for 2050s and 2080s under SRES emissions scenarios (A2 and A1B) projected by four GCMs (ECHAM5, CGCM3, CCSM3, and MIROC3.2) of IPCC (2007), with respect to (a) mean annual temperature, and (b) mean annual precipitation. The streamflow of ARB observed for the base period are plotted with black squares.

The percent changes in the mean annual precipitation versus percent changes in annual temperature projected by the four GCMs are shown in Figure 4.3. In general, both the temperature and precipitation are projected to increase with respect to the 1979-2007 base period. However, compared to the base period, MIROC3.2 projects a decrease in precipitation in the 2050s and almost no increase (0.90%) in the precipitation in 2080s. Between the four GCMs, MIROC3.2 projects the warmest and the driest climate, ECHAM5 projects the wettest climate, whileCGCM3 and CCSM3 project changes that are in between, for ARB.

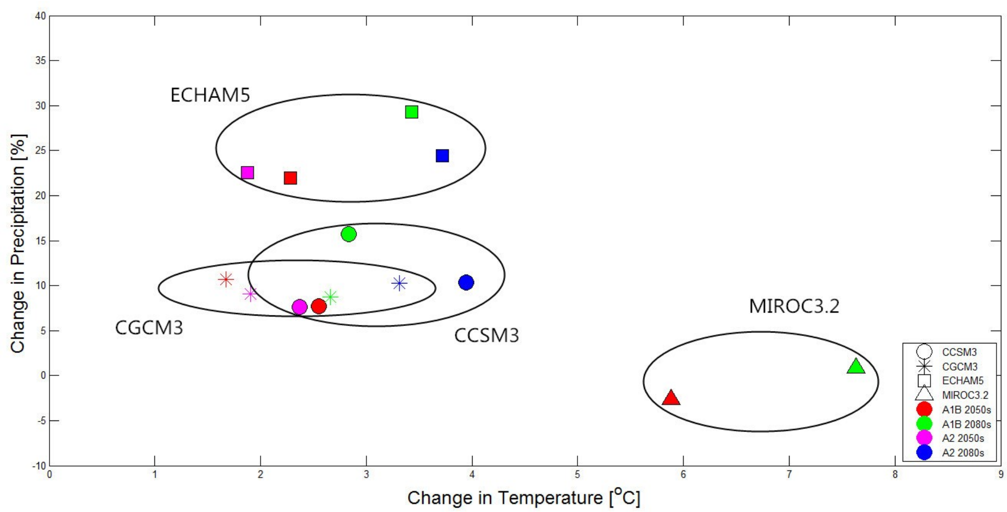


Figure 4.3: Projected changes to temperature and precipitation for ARB in the 2050s and 2080s by two SRES scenarios (A1B and A2) of four GCMs (ECHAM5, CGCM3, CCSM3, and MIROC3.2) with respect of the 1979-2007 base period.

The average daily streamflow projected by MISBA for ARB based on the MM5 downscaled 20c3m scenario of the four GCMs for of 1971-2000 periods are compared to the observed mean daily streamflow at the Athabasca River below McMurray gauging station (see Figure 4.4). Apparently there are some discrepancies between the streamflow simulated by MISBA for the control run climate of the four GCMs with respect to the observed streamflow. However, the mean annual streamflow simulated for the control run of the four GCMs are comparable to that of observed (656.33 m^3/sec), e.g., CCSM3 (663.70 m^3/sec), ECHAM5 (658.96 m^3/sec), and MIROC3.2 (661.29 m^3/sec);

CGCM3 (653.15 m^3/sec). Apparently, compared to the observed streamflow, all 20c3m scenarios of four GCMs resulted in a smaller snow melting streamflow simulated by MISBA, while the streamflow of ARB from late July to middle October are over simulated.

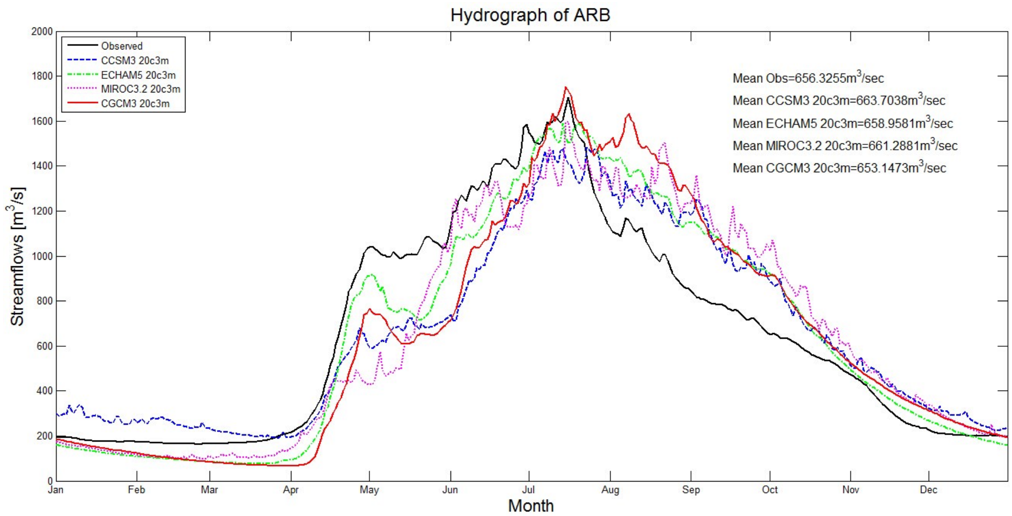


Figure 4.4: Mean daily streamflow simulated by MISBA for ARB based on the 20c3m scenario of four GCMs for the 1971-2000 base period, with respect to the observed mean daily streamflow at the Athabasca River below McMurray gauging station.

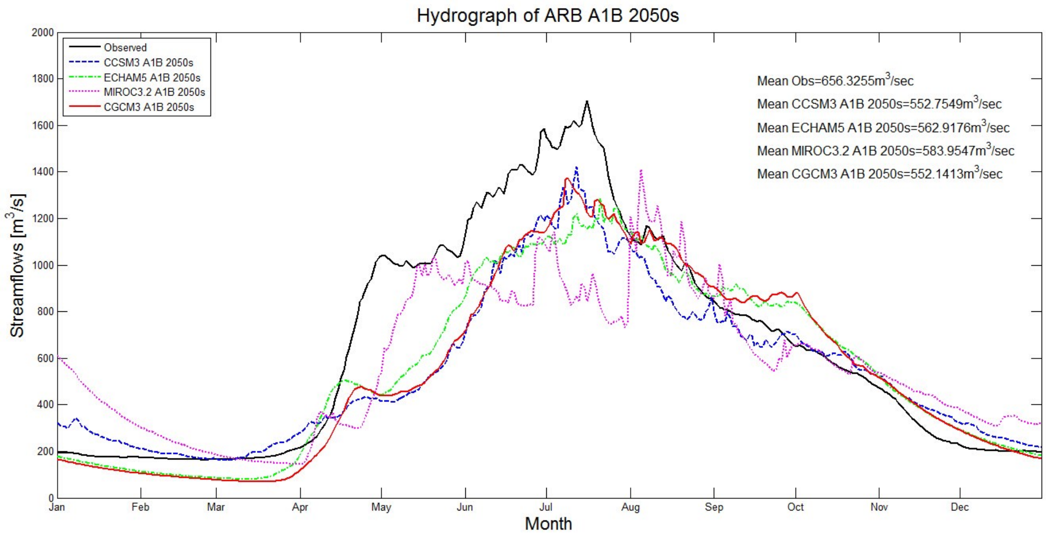
4.4.1.1. Changes in Streamflow by 2040-2069 (2050s)

The mean annual streamflow projected by MISBA for ARB based on the MM5 downscaled SRES climate scenarios of the four GCMs for 2050s are compared to the 1979-2007 base periods (Table 4.3). Apparently, MISBA driven by all downscaled SRES climate change scenarios unanimously projects to a decrease in the streamflow of ARB in 2050s. The maximum projected decrease in the mean annual streamflow for the Athabasca River below McMurray is about 17.9% (based on the CGCM3 A1B scenario), and the minimum is 10.9% (based on the CCSM3 A2 scenario).

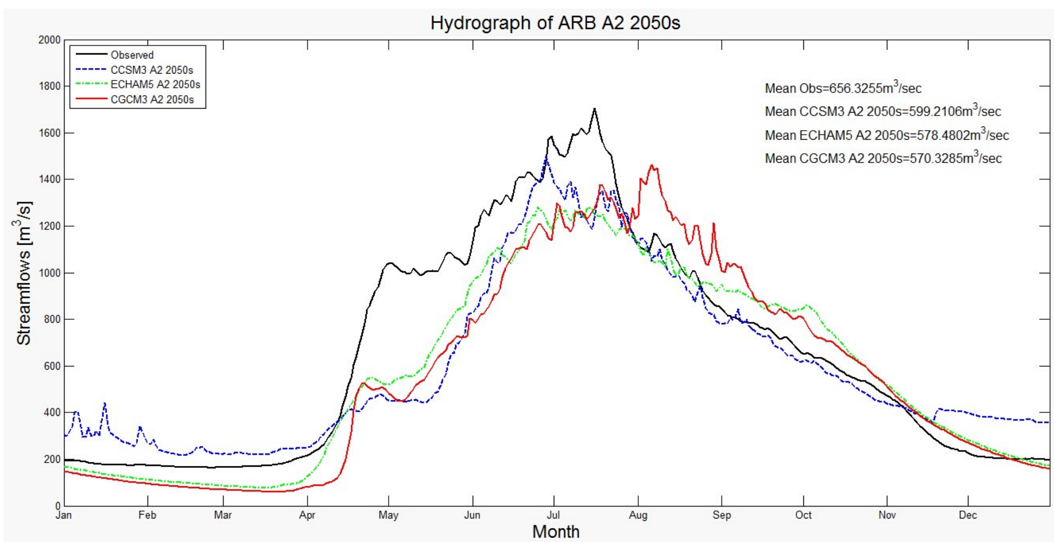
Table 4.3: Changes (%) in the mean annual streamflow of 2050s with respect to the 1979-2007 base period for ARB simulated by MISBA forced by SRES climate change scenarios.

	2050s
CCSM3_A1B	-17.8%
CCSM3_A2	-10.9%
CGCM3_A1B	-17.9%
CGCM3_A2	-15.2%
ECHAM5_A1B	-16.3%
ECHAM5_A2	-14.0%
MIROC32_A1B	-13.2%

With respect to the 1979-2007 base period, Figure 4.5 shows the mean daily streamflow of 2050s for ARB projected by MISBA forced by the A2 and A1B SRES scenarios of four GCMs. Apparently, spring snowmelt could occur earlier but also lower, summer streamflow could also decrease, but the August to December streamflow could be comparable to that of the observed. Based on the MIROC3.2 A1B climate scenario, MISBA projected the lowest daily streamflow throughout the summer but the highest daily streamflow in the beginning of each year. Under the CGCM3 A2 scenario, MISBA projected the summer peak streamflow to occur in August which is about one month later than SRES climate scenarios.



a)



b)

Figure 4.5: Mean daily streamflow under a) A1B and b) A2 climate scenarios simulated by MISBA for ARB in 2050s.

4.4.1.2. Changes in Streamflow by 2070-2099 (2080s)

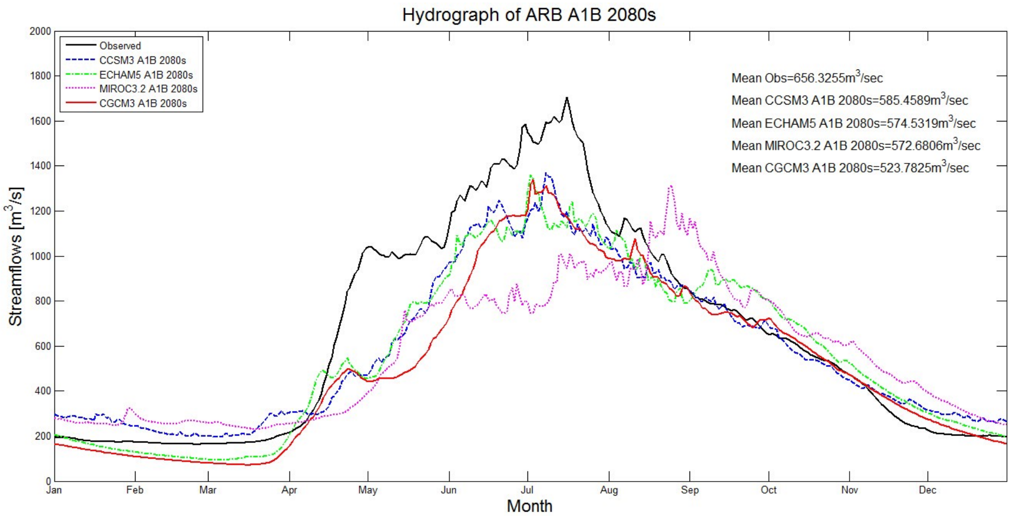
The mean annual streamflow projected by MISBA for ARB based on the MM5 downscaled SRES climate scenarios of the four GCMs for 2080s are compared to the

1979-2007 base periods (Table 4.4). Apparently, MISBA consistently projects a decrease in the streamflow of ARB in 2080s. The maximum projected decrease in the mean annual streamflow for the Athabasca River below McMurray is about 22.2% (CGCM3 A1B scenario), and the minimum is 10.5% (CGCM3 A2 scenario).

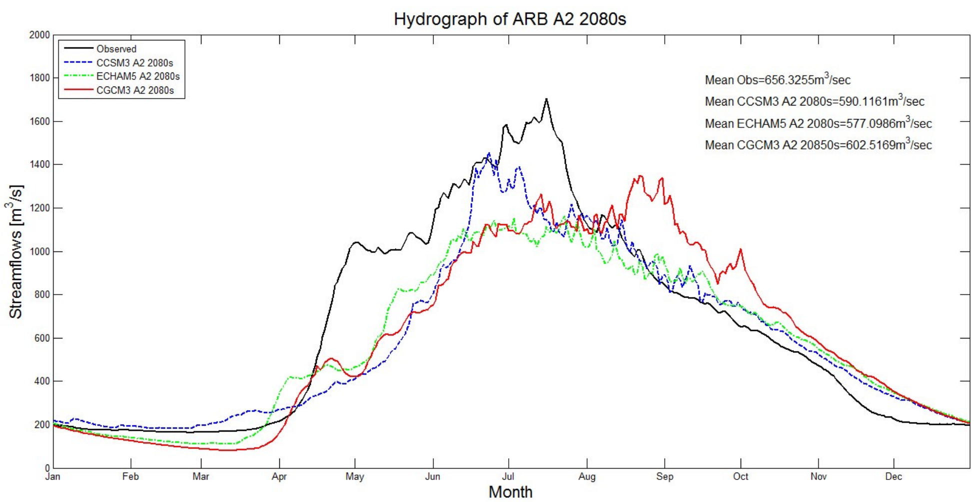
Table 4.4: Changes (%) in the mean annual streamflow of 2080s with respect to the 1979-2007 base period for ARB simulated by MISBA forced by SRES climate change scenarios.

	2080s
CCSM3_A1B	-13.0%
CCSM3_A2	-12.3%
CGCM3_A1B	-22.2%
CGCM3_A2	-10.5%
ECHAM5_A1B	-14.6%
ECHAM5_A2	-14.2%
MIROC32_A1B	-14.9%

With respect to the 1979-2007 base period, Figure 4.6 shows the mean daily streamflow of 2080s for ARB projected by MISBA forced by the A2 and A1B SRES scenarios of four GCMs. Again, MISBA consistently projected an earlier spring snowmelt and lower summer streamflow except for the MIROC3.2 A1B scenario of which the summer peak streamflow is projected to occur from late August to early September.



a)



b)

Figure 4.6: Mean daily streamflow under a) A1B and b) A2 climate scenarios simulated by MISBA for ARB in 2080s.

4.4.2. Sensitivity of Changes in Streamflow

With respect to the 1979-2007 base period, under the forcing of all SRES climate change scenarios considered in this study, MISBA consistently projects a decrease in the mean annual streamflow of ARB. A sensitivity analysis is performed to estimate the overall rate of decrease in the streamflow of ARB per °C rise in temperature over the 21st century. Figure 4.7 shows projected changes to the runoff coefficient (ratio of mean annual runoff and mean annual precipitation) with respect to a rise in temperature based on the SRES climate projections of three GCMs (ECHAM5, CGCM3 and CCSM3). It shows that an increase in temperature of 1 °C $\approx$ 5.3 % decrease in runoff even though precipitation is predominantly projected to increase.

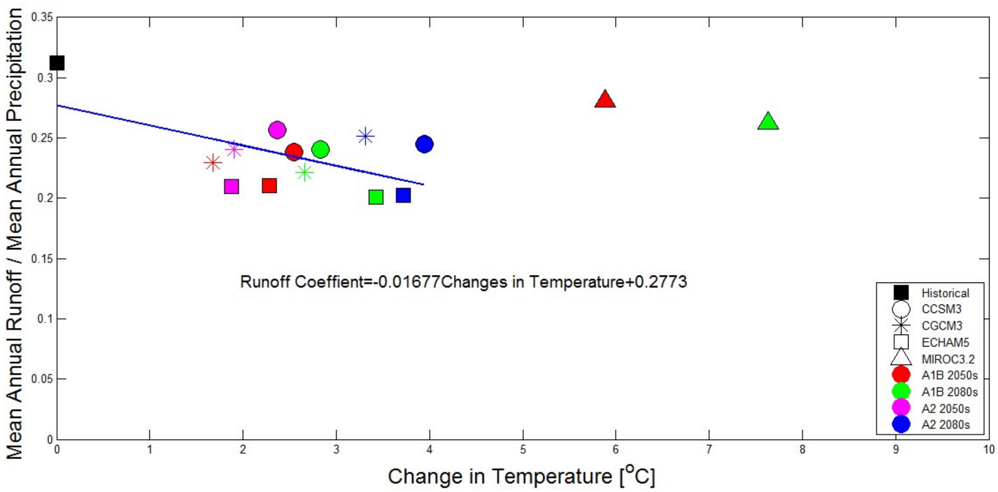


Figure 4.7: Changes to the runoff coefficient of ARB with respect to projected increase in temperature.

The annual evaporation loss of a river basin is basically the difference between the annual precipitation and the annual runoff. The mean annual evaporation loss, mean annual precipitation, and mean annual runoff for ARB subjected to climate change impact based on the SRES climate scenarios of four GCMs downscaled by MM5 are shown in Figure 4.8. The projected mean annual evaporation loss for ARB differs among the climate projections considered. Based on ECHAM5's SRES scenarios, ARB is projected to experience higher mean annual evaporation loss, especially under the A2 scenarios. In contrast, MIROC3.2's SRES scenarios resulted in the lowest projected mean annual evaporation loss for ARB, which is partly because its projected precipitation is the lowest among the four GCMs. The SRES scenarios of CGCM3 and CCSM3 lead to mean annual evaporation losses that are in between those of ECHAM5 and MIROC3.2. Under the climate projections of the four GCMs, MISBA simulated comparable future streamflow for ARB that are lower than the observed partly because that the enhanced evaporation loss offset the projected increase in future precipitation in ARB.

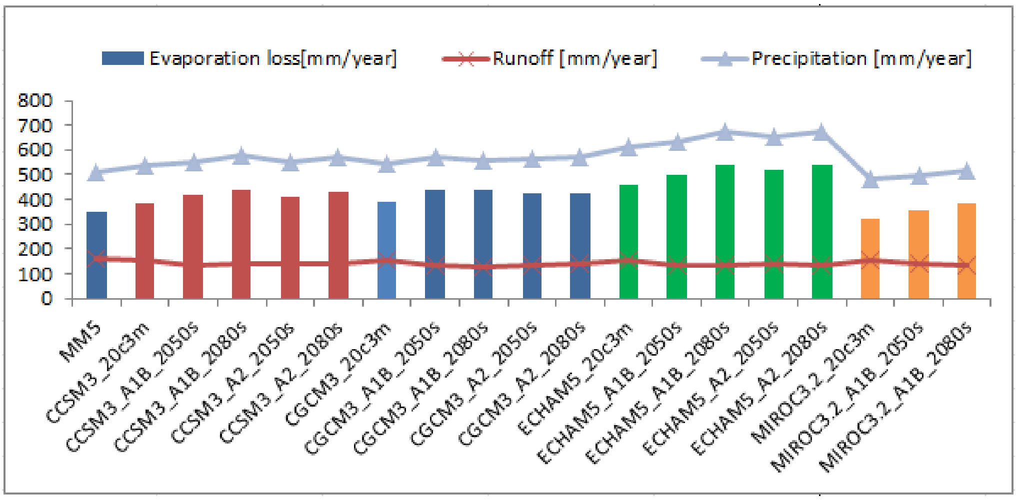


Figure 4.8: The mean annual evaporation loss, mean annual precipitation and mean annual runoff of all GCMs projections.

4.4.3. Precipitable Water and 2-m Temperature Analysis

Precipitable water is defined as the depth of water in an atmospheric column, if all the water vapor in that column were precipitated as liquid. Quantifying the atmospheric precipitable water vapor is important for the understanding of water vapor related processes, which include precipitation, evaporation, and convective activity. The summer precipitable water (May to August) for ARB under both A1B and A2 climate scenarios are projected to consistently increase from 2040 to 2100 (see Figure 4.9) though the projected range of change in precipitable water for A1B are larger than those of A2. Figure 4.10 shows the projected increasing trends of 2-m temperature for summer (May to August). Both A1B and A2 scenarios lead to comparable increasing 2-m temperature trends but the projected changes in temperature for A1B show larger fluctuations than those of A2.

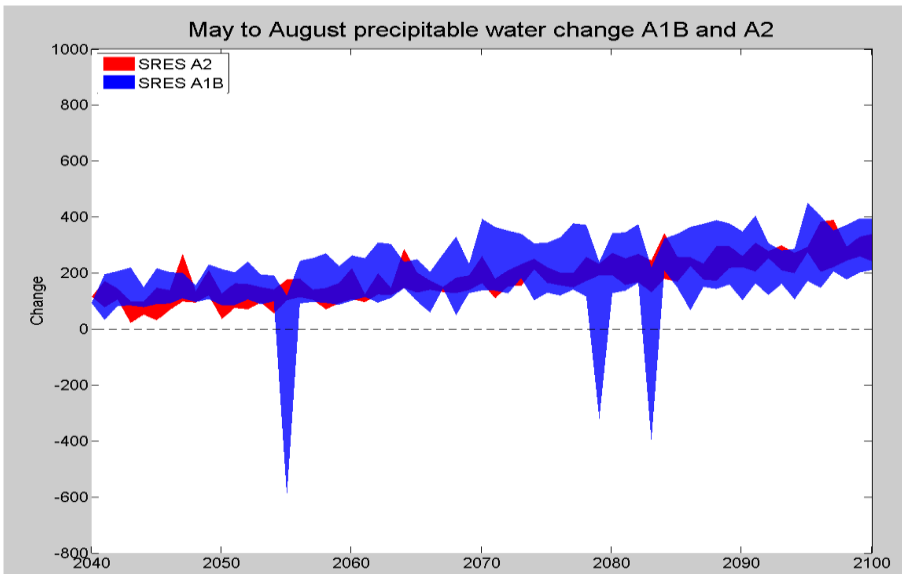


Figure 4.9: Projected change to the summer (May-August) Precipitable Water (in g/m^2) of ARB under both A1B and A2 SRES scenarios.

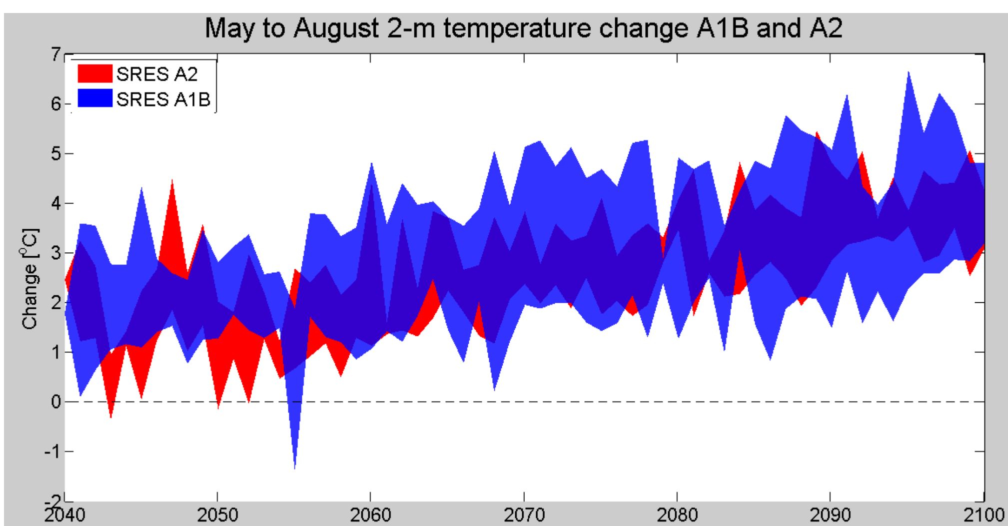


Figure 4.10: Projected change to the summer (May-August) 2-m Temperature Change (in ^{o}C) of ARB under both A1B and A2 SRES scenarios.

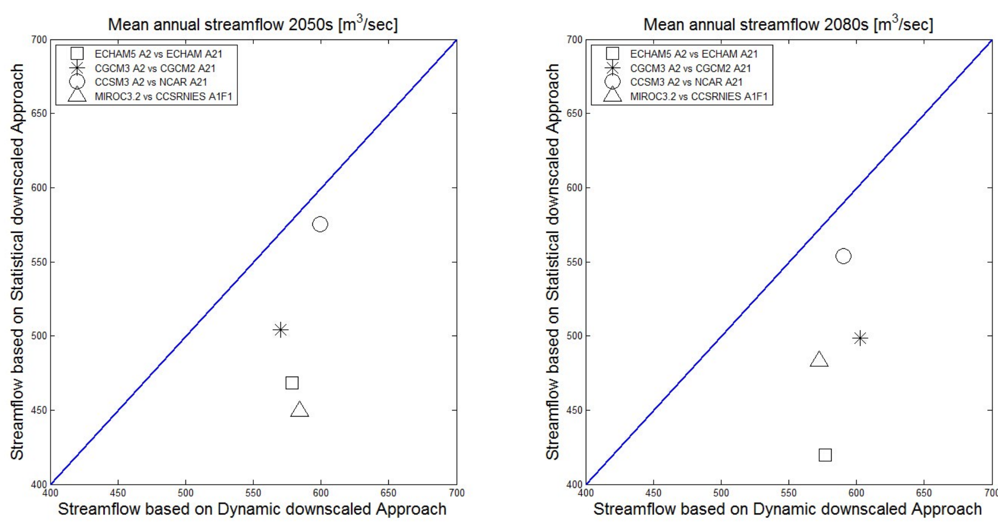
4.5. Different Methods to Downscale Climate Data

Because the spatial resolutions of most (if not all) GCMs are relatively coarse (150 to 400km), climatic variables such as precipitation, temperature, wind speed, surface air pressure, long-wave and short wave radiation simulated by GCMs have to be downscaled to sub-grid scales before they can be adequately applied for simulating basin scale processes. In general, the downscaling of GCMs' outputs can be done statistically or dynamically.

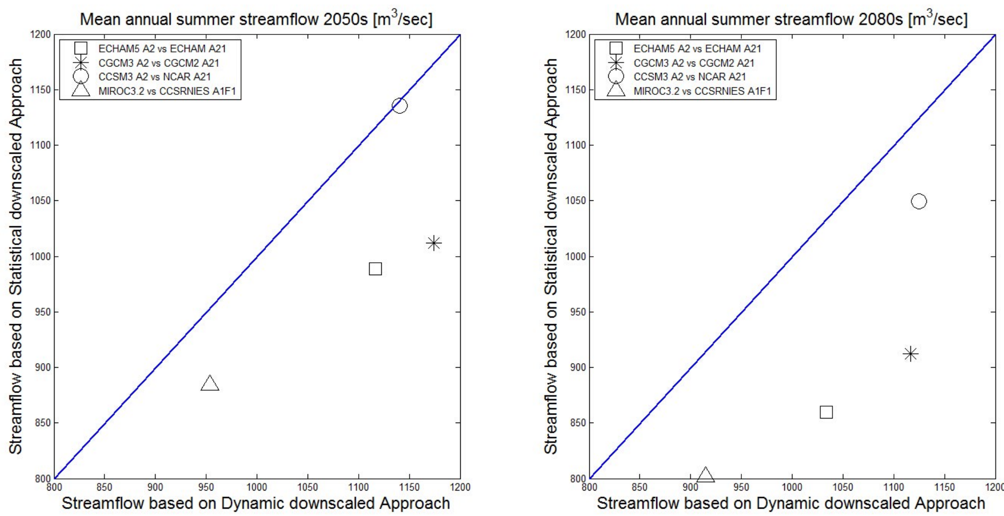
The statistical downscaling method is based on established empirical, statistical relationships between GCM-scale climate variables and local-scale meteorological variables. In their study, Kerkhoven and Gan (2011) applied a simple statistical method to downscale the climate data for the Athabasca River Basin. Islam and Gan (2013) also statistically downscaled the climate change scenarios from GCMs outputs for the South Saskatchewan River Basin (SSRB) using a delta change approach. However in this study, a computationally intensive, dynamic downscaling method based on a Regional Climate Model (MM5) was used to simulate higher resolution climate data from coarse resolution, climate scenarios of GCMs for ARB.

In terms of scatterplots, Figure 4.11 compares the streamflow of ARB simulated by MISBA driven by climate data that were dynamically downscaled by MM5 with climate data that were statistically downscaled by Kerkhoven and Gan (2011) for 2050s and 2080s, respectively. Figure 4.11 shows that the mean annual, summer (JJA) and winter

(DJF) streamflow simulated by MISBA driven with daily precipitation data that MM5 dynamically downscaled from the four GCMs are generally higher than those simulated by MISBA driven with data that were statistically downscaled by Kerkhoven and Gan (2011) for both 2050s and 2080s. Even though in this study the same GCMs as that of Kerkhoven and Gan (2011) are selected, the climate projections of this study are taken from AR4 of IPCC (2007) while that of Kerkhoven and Gan (2011) were taken from AR3 of IPCC (2001) and there a fair comparison cannot be achieved, e.g., climate projections of CGCM3, ECHAM5, CCSM3 and MIROC3.2 versus climate projections of CGCM2, ECAHM4, NCAR and CCSRNIES. As a result, different versions of the same GCMs are expected to project different climate scenarios for the 2050s and the 2080s. These factors together with different downscaling approaches lead to results of this study to be different from that of Kerkhoven and Gan (2011).



a)



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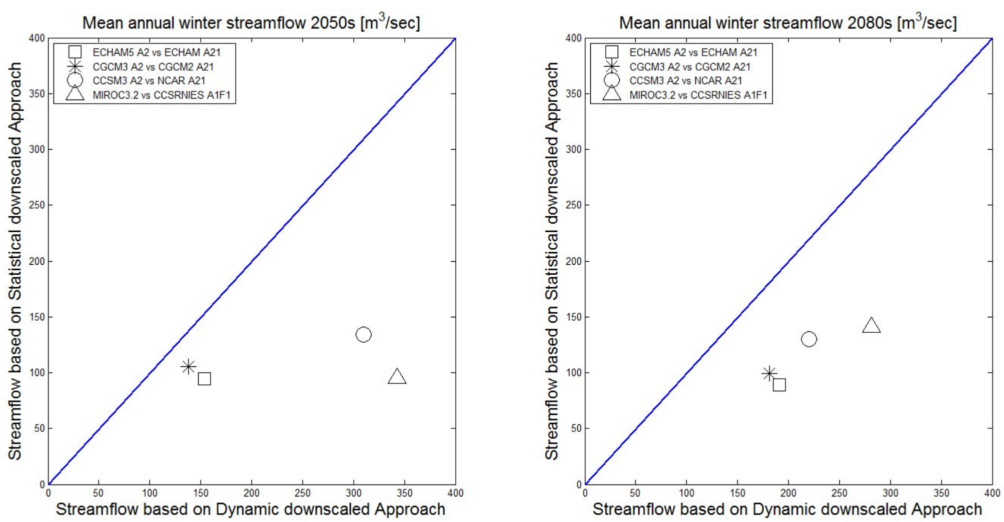

c)

Figure 4.11: Comparison of a) Mean annual streamflow, b) Mean annual summer streamflow, c) Mean annual winter streamflow of ARB simulated by MISBA using daily precipitation dynamically downscaled by MM5 with the streamflow simulated by MISBA using data statistically downscaled by Kerkhoven and Gan (2011) for 2050s and 2080s.

4.6. Summary and Conclusions

The MISBA model was used to simulate possible hydrologic changes to the Athabasca River Basin (ARB) of Alberta subjected to climate change impact based on the climate projections, SRES A1B and A2 scenarios of four General Circulation Models (GCMs) of AR4 (IPCC, 2007) for the 2050s and 2080s. MISBA was forced by the above coarse resolution climate scenarios dynamically downscaled by MM5.

MISBA was first calibrated with the ERA-Interim re-analysis data dynamically downscaled by MM5 for the 1979-2007 climate normal period with respect to the observed streamflow of the Athabasca River below McMurray gauging station. After calibration and validation, MISBA was set to predict the streamflow of ARB for 2050s and 2080s, based on the above climate projections of IPCC (2007). Among the four GCMs selected, Japan's MIROC3.2 projected the warmest and the driest climate for the ARB; Germany's ECHAM5 projected the wettest climate; and Canada's CGCM3 and USA's CCSM3 projected changes for ARB that are in between.

In addition to the projected hydrologic changes, decreased mean annual streamflow and changes in the timing of streamflow provide evidence that ARB's water cycle is changing. The volume of ARB's streamflow has decreased and will likely continue to decrease towards the end of the 21st century. In view of these possible changes to ARB, it will be prudent for the management of the water resources of ARB to begin implementing adaptive measures to mitigate potential impact expected from its dwindling water resources because of climate change impact.

4.7. References

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CHAPTER 5

Conclusions and Recommendations

5.1. Summary and Conclusions

The primary objective of this thesis is to assess the potential impact of climate change on the water resources of the Athabasca River Basin (ARB) of Alberta for the 21st century based on the simulation of the basin-scale, physically based, distributed land surface scheme or hydrological model, the Modified Interactions Soil-Biosphere-Atmosphere (MISBA) of Kerkhoven and Gan (2011). The performance of MISBA was assessed by comparing the simulated streamflow of ARB for 1979-2007 base period with the streamflow data recorded at the gauging station located at Athabasca River below McMurray.

After calibration and validation, MISBA was driven with the SRES climate scenarios (A2 and A1B) of four GCMs (ECHAM5, CCSM3, CGCM3, and MIROC3.2) dynamically downscaled by MM5, the Fifth-generation Mesoscale Model jointly developed by the Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR), to study the possible hydrologic impact of climate change on ARB in 2050s (2040-2069) and 2080s (2070-2099).

Even though GCMs can simulate of the global atmospheric processes and major circulations, the spatial and temporal resolutions of the climate variables simulated by GCMs are too coarse to be applied reliably to predict the basin scale hydrologic processes at daily or smaller time steps. GCMs' simulated climatic variables used for the hydrologic impact studies are more reliable at seasonal or monthly scales (Schulze, 1997; Xu, 1999). Therefore in this study, the climate data of GCMs are first dynamically downscaled to reliably obtain climate data of adequate spatial and temporal resolutions.

Among the four GCMs selected for this study, ECHAM5 projected the wettest climate for ARB, MIROC3.2 projected the warmest and the driest, and the projections of CGCM3 and CCSM3 are in between. On the basis of the future simulations of MISBA, it seems that the mean annual streamflow of ARB is sensitive to the change in temperature. As expected, a warmer climate will lead to the shortening of the snowfall season of ARB. On a whole, an earlier snow melting with less discharge was predicted by MISBA for most of the climate change scenarios tested in this study. This is not a surprise given a warmer climate will enhance the evaporation loss, causing ARB to become drier and less streamflow will find its way to the local drainage network of ARB (Kerkhoven and Gan, 2011). A long term decline in the winter snowpack of ARB and enhanced evaporation loss which offset the possible increase in precipitation under a warmer climate could have adverse effect on the future water resources of ARB, and impact its oil sands and industrial development. On a whole, the Athabasca River Basin could become drier and drier in the 21st century.

5.2. Recommendations for Future Work

The results presented in this thesis project have provided useful understanding of the possible threats to the future water resources availability in the Athabasca River Basin under the potential impact of climate change. Recommendations to the future works are suggested below:

- In addition to the four GCMs involved in this study, climate scenarios of other GCMs of IPCC (2007), should also be considered in the future.
- New set of climate scenarios announced by IPCC's Fifth Assessment Report (AR5), RCP8.5, RCP6, RCP4.5, and RCP2.6 (or RCP3-PD) (IPCC, 2013), should be downscaled by MM5 and applied to MISBA.
- In addition to MM5 used in this study, different dynamic downscaling approach or different RCMs such as the WRF of NCAR could be considered.
- Other reanalysis dataset, such as that of NCEP/NCAR from NOAA Research, can be tested to compare with the ERA-Interim reanalysis data.
- In addition to climate change impacts that have been discussed in this study, impact due to climate anomalies and landuse changes (such as the expansion of industries, the development of municipals, and the changes of vegetation) can also exert significant hydrologic to ARB, and they should be investigated in future studies.

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APPENDIX

MISBA Parameters

Primary Parameters	Percentage of Sand Percentage of Clay Vegetation Types Land-Water Ratio
Secondary Parameters	Saturated Volumetric Moisture Content Wilting Point Volumetric Water Content Saturated Matric Potential Saturated Hydraulic Conductivity Slope of the Retention Curve Soil Thermal Coefficient at Saturation Two Force Restore Coefficients for Soil Moisture Two Coefficients of Surface Volumetric Moisture at the Balance of Gravity and Capillary Forces The Superficial or Top Soil Depth The Depth of the Rooting Layer Fraction of Vegetation Minimum Surface Resistance Maximum Surface Resistance Leaf Area Index Roughness Length for Momentum Roughness Length for Heat Transfer Albedo Emissivity Time Constant of the Day