Assessing the sensitivity of Canadian hydro and wind power production potentials to climate variability and change

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Abstract

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Increasing population, limiting fossil fuels, along with looming effects of climate change and environmental degradation have forced the energy industry to look for alternative energy sources, most particularly from renewable resources, including wind, solar and hydro. Among these, hydropower is the dominant renewable energy source in Canada in terms of production, with enormous potential for further growths due to large water availability. Wind power also constitutes the fastest growing renewable energy source in Canada during the recent past. Both hydro and wind power productions are largely dependent on local and regional climate conditions. As a result, climate variability and change can greatly affect their availability in time and space. This study aims at providing a first-hand analyses of the sensitivity of hydropower and wind energy to climate variability and change across Canadian regions using a suite of statistical techniques and inference approaches. More specifically for hydropower production, trends in effective climate variables along with the dependencies and causalities of these variables with monthly hydropower production is assessed. These analyses lead to the development of a set of predictive statistical models, with which the expected future monthly hydropower production can be projected in light of the existing trends in effective climate variables across Canadian political jurisdiction. For wind energy, the dependency between temperature and wind speed is explored at the local scale with a greater goal of understanding how gradual changes in temperature during the recent past has

resulted into trends in wind speed across different time scales and/or Canadian regions. Our results show that Canada has become warmer, slightly wetter with more contribution from rain than snow, and less windy. In addition, provincial monthly hydropower productions demonstrate strong dependence with effective climate variables, however the sign and magnitude of such dependencies are subject to spatial and temporal differences. Our results show that depending on the province, climate variables in a given time step can cause changes in the hydropower production between up to 20 months ahead. The sensitivity analyses made by developed predictive models also show that continuation of the existing trends in climate variables can cause some changes in the expected annual pattern of hydropower production across Canadian providences and territories, which are more intense during the warmer seasons. Although net effect of climate change over the entire Canadian landmass is suggested to be positive, there are significant seasonal and regional losses in hydropower production, for instance in Alberta and British Columbia. With respect to the wind speed, negative trends in wind speed were found for most of the stations throughout the country. Although during the same period, positive trends are also observed in temperature, it is shown that in majority of cases there is no significant dependency between local temperature and wind speed; yet, it should be noted that this, to some extent, is governed by the threshold used to account for the significance of the dependency. Considering stations that are shown significant dependency between the local temperature and wind speed, the negative influences of increasing local temperature on the local wind speed are quantified across northern, western, eastern and Atlantic Canada. Our results provides a fresh look at the future of hydro and wind energy productions in Canada under climate variability and change, which have enormous implications to natural resource management. The statistical frameworks developed due to the course of this thesis can be used in other parts of the globe, where data support is available, to address the sensitivity of hydropower and wind energy to climate variability and change.

Acknowledgment

I would first like to express my special thanks and gratitude to my supervisor Professor Ali Nazemi of the BCCE department at Concordia. The door to Professor Nazemi office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this research to be my own work, but steered me in the right direction whenever he thought I needed it.

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Symbols and Abbreviation

E	Expected value
VAR	Variance
Z	Z Statistic
α	Significant level
P	Probability value
Cov	Covariance
σ	Standard deviation
ρ_P	Pearson correlation coefficient for population
r_P	Pearson correlation coefficient for sample
r_s	Spearman's rank coefficient
τ	Kendall's rank correlation coefficient
RSS	Residual sum of squares
AR	Autoregressive model
ARX	Autoregressive Exogenous model
f	Function
BIC	Bayesian information criterion
Ln	Natural logarithm
F *test*	F Statistic

1 Introduction

1.1 Hydro and wind power production and their climatic drivers

Renewable energy sources are those that are collected from sunlight, wind, water, biomass, and geothermal heat, and can be converted easily to electricity. These sources cannot be exhausted and they are constantly replenished. The International Renewable Energy Agency (IRENA) has reported that renewable energy sources have been occasionally ignored at great socio-economic and developmental expense [1]. In contrast to fossil fuels, the energy collected from renewable sources is clean and do not have large emission footprint; and therefore, they are important for building sustainable economy. According to the Paris agreement, Canada and 174 other countries have agreed on the mitigation of greenhouse gas emissions [2]. The International Energy Agency highlights that in order to cut the current level of emissions in half by 2050, renewable sources should become the source for producing 46% of global power [3].

Renewable energy provides about 18% of Canada's total primary energy supply. Thus, Canada ranks 7th in the world in terms of proportion of renewable energy production. Hydropower is the key renewable energy source. The electricity generated from hydroelectric plants fulfills 66.9% of Canada's electricity needs, which makes hydropower the primary source of renewable energy production in Canada [4] – see Figure 1.1. This amount ranked Canada third as the largest hydro generator in the world during late 20th century and early 21st century. The Canadian hydroelectric sector has a long history and is supported by a large network of reservoirs and run-off-river dams. However, the most hydropower generation relies on large reservoirs in Canada, such as the Behemoth La Grande dam, with a hydropower production capacity of 15000MW, located in Québec. Much of Canada's hydropower plants are located in the provinces of Quebec and British

Columbia and Ontario [5-7] that are also the most populated regions in Canada with large concentration of socio-economic activities. Hence, Canada is very dependent on hydro resources in terms of both internal usage and exportation. In terms of production, the province of Québec, located in the eastern part of Canada, and is the most significant hydropower producer in the country both in terms of the internal usage and exportation. Québec accounts for more than half of the installed hydro capacity in Canada and generates roughly 60% of the country's hydroelectricity [12]. Québec consist of 60 hydro plants with a total capacity of 36,671 MW [7]. Similarly to other parts of the world, levels of both total electricity and hydropower generation have changed in Canada. According to Natural Resources Canada's annual report, from 1990 to 2006, increases in total electricity and hydropower generation happened simultaneously, but the total level of generation of hydropower decreased in proportion to that of the total generation of electricity [9]. In 2008, the total hydropower produced in Canada constituted 26.4% of Canada's total energy consumption; this amount came in as a close second to petroleum's 31.3% contribution. In 2009, Canada exported 51.1 KBWh of electric power [8]. In 2011, hydroelectricity generated in Canada was equivalent of consuming 85.2 megatons of oil [10]. Also in 2015, Canada generated 10% of the world's hydroelectricity, making it the second largest hydroelectric producer in the world during that year [4]. The electricity generated from hydropower in 2015 reached to 95% of the electricity need in Québec, 97% in Manitoba, 95% in Newfoundland and Labrador, and 86% in British Columbia [11].

Moving water is the key to generating hydroelectric power. The kinetic energy of water is transformed into mechanical energy when the moving water makes the generators turbines turn. So, one could argue that the river runoff plays the most essential role in hydropower production, which itself depends on climate variables, in particular precipitation and temperature [14]. As a result alteration in climate variables can affect river runoff both in terms of volume and timing, which consequently leads to changes in hydropower production. For instance, precipitation changes affect the amount of water availability. Furthermore, increasing temperature has a direct impact on earlier snowpack melting, which causes the reduction of annual regular spring and early summer stream flows [15,16].

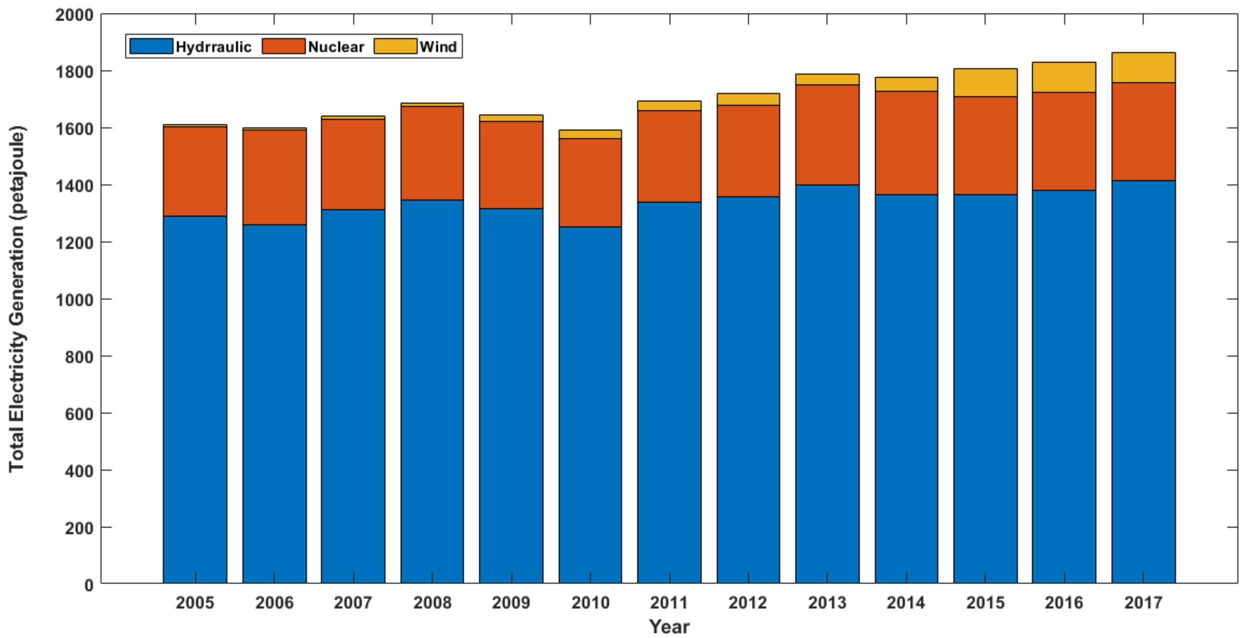

Figure 1.1 *Proportion of electricity generation separated by renewable sources in Canada. Colors indicate source of production in each column [13]*

Wind power is the fastest growing renewable source globally and competes with other renewable energy sources due to being highly subsidized – see Figure 1.2. In 2016 more than 54 gigawatts of wind power capacity were installed over the globe across more than ninety countries [17]. The Global Wind Energy Council presents the outlook reports that the wind power could reduce 3 billion tons of CO_2 emission per year by 2030 as wind power production can reach to 2,000 gigawatts by 2030, which can generate up to 19% of total global electricity demand. This can reach to 30 % of total global electricity supply by 2050 [18].

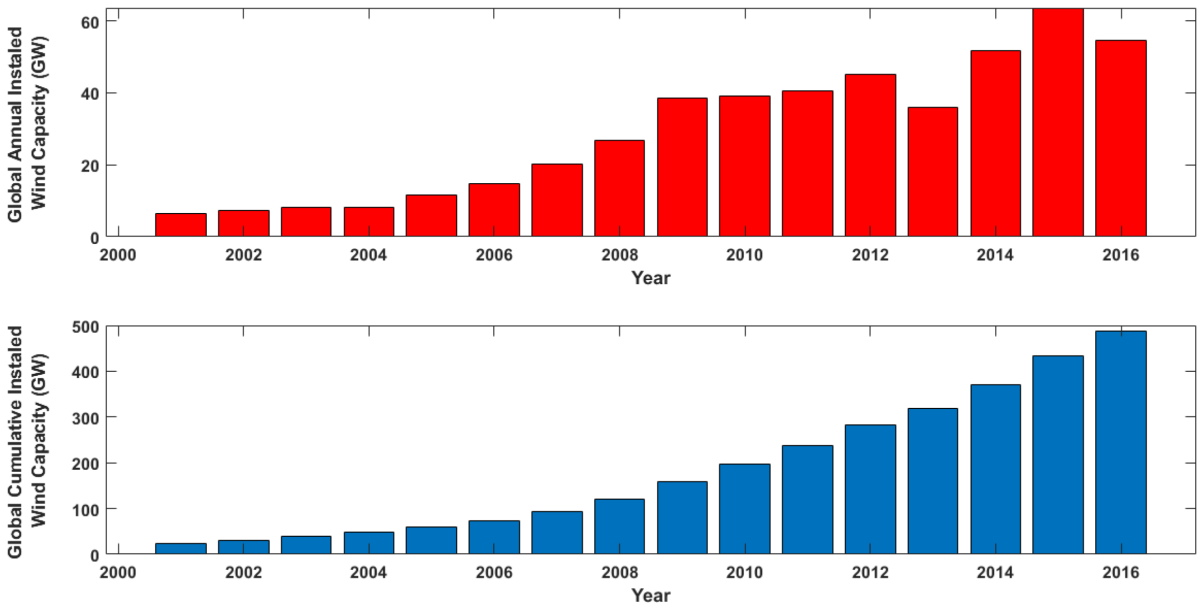

Figure 1.2 *annual (up) and cumulative (down) wind capacity installed at the global scale (2001-2016) [17]*

In the Canadian context, the Canadian Wind Energy Association highlights that the electricity generated from wind is equivalent to the amount of electricity consumed by over 3 million average Canadian homes. Today the wind power produce about 6% of Canada electricity demand and this amount rated Canada as the 8th in the world for the installed wind energy capacity. Based on data from the National Energy Board, during 2012 to 2018, the wind energy has become, by far, the fastest growing sector of electricity generation in Canada with 18% annual growth rate – Figure 1.3. Only in 2016, nearly 12 gigawatts new wind energy capacity installed in the country [19]. Québec is the second biggest wind energy producer in Canada with 3,510 megawatts of installed energy capacity. It houses 30% of Canada's installed wind energy capacity. In 2016, 249 megawatts of installed energy capacity were added to the existing total of installed plants. The electricity generated by wind power in Québec supports approximately 4% of total electricity demands in the province. The number of wind power turbines in the province was recorded as 1,897 as of December 2015 [19].

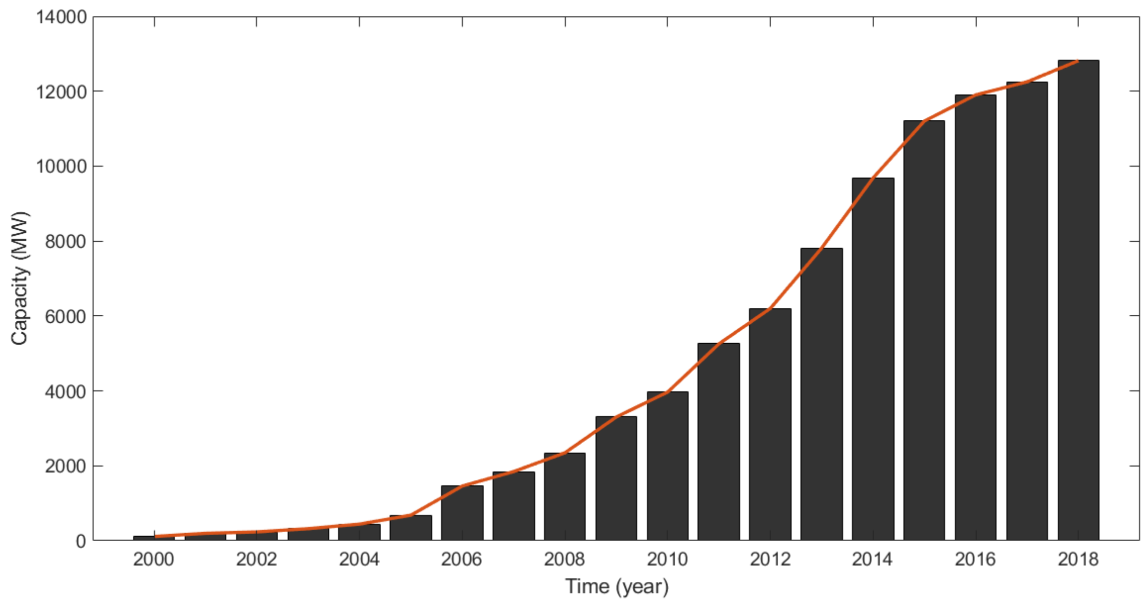

Figure 1.3 *wind power capacity installed in Canada (during 2000-2018)[20]*

Wind power generation is obviously dependent majorly on the wind speed [21]. The kinetic energy of blowing wind is converted to mechanical energy by wind turbines. Wind blowing leads to the rotation of the turbine's blades, and the kinetic energy inherent to these rotations is converted into electricity by generators. The movement of air however is largely driven by temperature gradients and therefore temperature changes can affect wind speed. Therefore power production is dependent on the state of the temperature and its changes in time and space [22].

1.2 Background and problem definition

As noted above, the harnessing of energy from water and wind is largely dependent on climate conditions. In recent decades, research has concluded that the climate may be altered by both its internal randomness (i.e. natural variability) and external anthropogenic affects. Most importantly, the world's energy sector is confronting different challenges due to human-induced climate change [23], as the increasing temperature leads to permanent changes in water cycle and wind distribution [24]. Therefore, changes in climate conditions could significantly affect renewable energy production and could also have a strong direct and indirect impact on energy demand and distribution [25]. Hence, the understanding of effect of changing climate on wind and hydropower energy variables is not only tempting for scientific discovery, but also is necessary for energy security and resource management.

Previous studies have mainly represented the influences of climate change on hydropower generation in terms of respective variation in runoff volumes. In other words, runoff was modeled based on hydrological models, considering runoff as a function of precipitation, evapotranspiration, and temperature. The results obtained from top-down assessments are limited due to uncertainties in modeling solutions. In addition, these studies mostly focused on local hydropower plants. Therefore, the information obtained from these assessments cannot be readily translated into knowledge across jurisdictional scales, where policy decisions are made.

In terms of the wind power, many studies have addressed the effects of future climate changes on wind by looking at the projection of wind speed and wind distribution. Some other papers have made wind speed projections under different scenarios to clarify the influences of different forms of climate change on wind power potential. Based on literature review, one can conclude that wind speed is altered by changes in temperature, and it appears that temperature levels have been increasing. However, the nature and extent of the relationship between wind speed and temperature at local scale still needs to be investigated.

1.3 The aim and objectives of this thesis

This research aims to understand the effect of climate variability and change on hydro and wind power production in Canada. The main objectives of this research are (1) to inspect the key changes in climate variables that drive hydro and wind power productions; (2) to clarify the dependency between climate variables, hydropower production and/or wind speed; and (3) to identify how changes in climate conditions can lead to alteration in hydro and wind power production potential across Canadian regions.

Detecting the changes occurring in terms of specific variables can contribute to understanding the impact of changes in climate pattern on hydro and wind energy productivity potential. This study provides an opportunity to apply statistical tools to investigate the relationship between climate and hydropower generation, as well as the relationship between temperature and wind speed. The information and tools presented here would be helpful to provide a clear picture of current hydro and wind power dependence to climate in Canada and understand the sensitivity of their production to climate variability and change. The proposed statistical framework, allows detecting the effects of changing climate on hydro and wind power without considering any complex and uncertain modeling. The straightforward approach of this study presents a set of executive knowledge for decision makers to be able to understand the vulnerability or resilience of production potential under different climate conditions. Providing this information would be useful in defining whether future climate has resulted in conditions which need to modify resource management strategies and/or infrastructural developments.

1.4 Thesis organization

The remainder of the thesis is organized as follows: Chapter 2 will review the previous studies which focused on the link between climate and energy variables. Furthermore this chapter contains the summary of studies that addressed the impact of climate variability and change on hydro and wind power production at the global scale and in Canada. The critical review of previous work is necessary to obtain the existing gaps in understanding climate-hydropower and climate-wind speed dependencies. Chapter 3 will provide information about climate and hydropower data, as well as related details concerning these sources – such as their background and required pre/post processing. Chapter 4 will describe the methodology and the proposed research framework to investigate the sensitivity of hydro and wind power to climate variability and change. For instance, a trend test is used to address the changes in climate variables and measure the magnitude of the change. A dependency test is applied to investigate the relation between hydropower and climate variables as well as the relation between wind speed and mean temperature. Also, a causality test is used to confirm the existence of causal relation between climate variables and hydropower. Chapter 5 contains a review of the obtained results for climate trends and the dependency test between climate variables and hydropower as well as between temperature and wind speed. Moreover, this chapter discusses the climatic driver of hydropower generation in Canadian provinces and the impacts of climate variability and change on both hydro and wind power production. Finally, in Chapter 6 the summary of the key findings on climate-hydropower and climate-wind power dependency will be outlined and the limitations and recommendations for future research work are presented.

2 Literature review

The literature review performed in this chapter aims at illustrating the link between climate and hydro and wind power and investigating the impact of changing climate on these energy sources. Particular focus is given on understanding the coevolution in relevant climate variables including temperature, total precipitation, rainfall, snowfall, and wind speed on the one hand, as well as hydro and wind energy on the other hand. The discussion and the review of the literature is pursued globally as well as across Canada and Quebec. This review will lead to the discussion of the gap in knowledge and rationalizing the necessity of this research.

2.1 The link between climate and hydropower

The vitality and magnitude of hydropower production is controlled by local and regional water resources as well as the installed capacity [26]; yet the expected volume and variability of running water remain the most important driver of the hydropower generation. Runoff itself is largely dependent on climatic variables [25], in particular temperature and precipitation [27]. It has been shown that changes in climate variables affect quantity, timing, and the performance of the hydropower production [28]. However, it should be noted that changes in climate variables can involve both natural variability (i.e. seasonality and/or interannual variability) and gradual shifts in climate normals and extremes [29]. It has been noted the climate impacts on hydropower generation is mainly manifested across three different temporal scales. Firstly, seasonal variability in climate affects runoff generation and therefore hydropower production. Secondly, interannual hydroclimatic events such as droughts and floods can cause enormous changes in hydropower production. Thirdly, profound yet gradual shifts in climate variables can completely change the water availability in time and space and therefore hydropower production outlook [30]. The life cycle of the climate impact on the hydropower production is therefore complex and multi-faceted. Figure 2.1 schematically shows various forms of impacts on hydropower production, caused by changes in the temperature and precipitation [31]. In this figure, red boxes indicate negative effects on hydropower generation, whereas blue boxes indicate positive impacts. Terminal boxes represent the change in river discharge, determining the potential of hydropower generation. It should be noted that this life cycle is subject to massive regional and local differences that are imposed by the geography [28] along with human intervention in land and water processes.

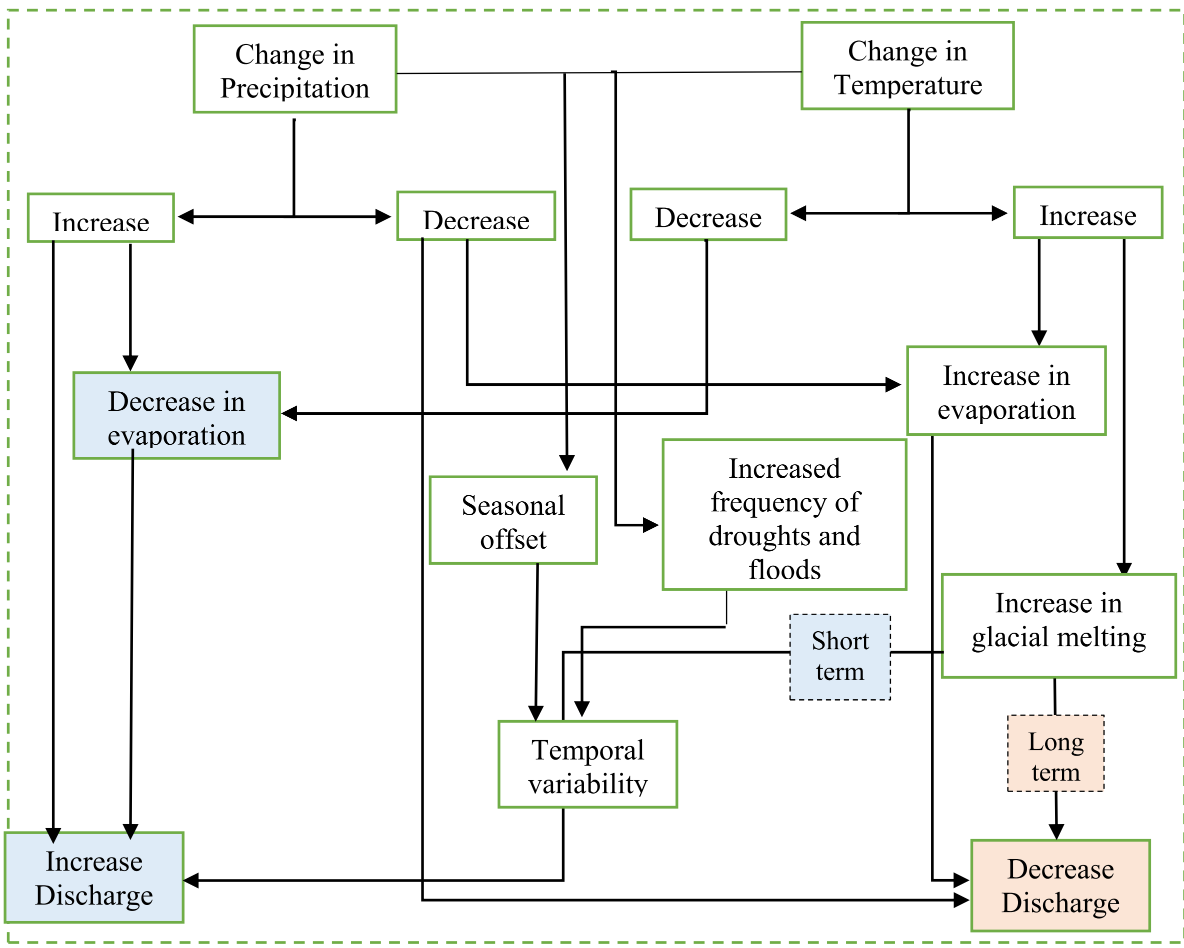

Figure 2.1 *The impact of change in climate variables on hydrological discharge, which is the key driver of hydropower production. Blue and red boxes shapes indicate the positive and negative impacts*

2.1.1 Change in climate and hydroelectric variables at the global scale

The Intergovernmental Panel on Climate Change (IPCC) has been analyzing the historical temperature data available from the late of 19th century [32]. The IPCC reported that the global mean temperature has been rising and the last three decades have been warmer than any previous decades during the historical record. In addition, the recent paleoclimatology data showed that the air temperatures and rate of warming during the course of the twentieth century have been higher than any other time within the previous 1000 years [33,34]. The analyses of trends in the global temperature shows that the global temperature has increased by 0.13˚ C per decade in the last fifty years, which is double of the temperature trend during the last 100 years [35]. In another study, Nicholls et al. reported that the mean surface temperature of the globe increased by around 0.3˚ C and 0.6˚ C in the late 19th century and between 0.2 and 0.3 per decade over the last four decades [36]. Other than mean temperature, there are some studies focusing on the changes in maximum and minimum temperatures. Nicholls et al. found that the minimum temperature increases with higher magnitude than maximum temperature for several regions of world during the 19th century [36]. In its third assessment report, the IPCC mentioned that both minimum and maximum temperature have increased between 1950 to 2004 globally over the Planet Earth's surface [37]. The rate of increase of the minimum temperature is greater (0.204˚C/decade) than that of the maximum (0.141˚C/decade). These rates of warming are progressively increasing in time and are more intensified over the land surface. For example, Vose et al. performed a trend analysis on the maximum and minimum temperature data obtained from a large number of climate stations for the period of 1979 to 2004. The estimated magnitude of trends showed that the rate of warming in minimum temperature is more than maximum temperature [38].

The changes in temperature can make a wide range of domino effects in other climate variables. Most importantly, the spatial and temporal characteristics of precipitation, rainfall, runoff, and evaporation can be impacted by increasing global temperature [14]. In brief, precipitation is expected to increase globally due to the expected increase in temperature, yet the magnitude of increase can be subject to geographic differences [14]. The physics behind the phenomena is quite straightforward: The amount of rainfall is strongly dependent on the level of atmospheric moisture. Therefore, given increases in temperature, the atmospheric moisture will also increase due to enhanced evaporation [39]. Such an intensification of water cycle can lead to increase precipitation [40]. Empirical data confirm this. Jones et al. mentioned that the world total levels of precipitation have increased by approximately 2% since the start of the twentieth century [41,42]. Kunkel et al. argued that increases in temperature will not only cause increases in total precipitation, but also render extreme events of precipitation more frequent [43]. Solomon argued that the precipitation trend has increased in some parts of the globe like northern Europe, Asia, and the eastern region of America. On the other hand, the southern regions of Africa and Asia, as well as the Mediterranean, have experienced a decrease in precipitation over the past fifty years [35]. After synthesizing a large literature review focused on precipitation patterns changes around the world, Dore et al concluded that precipitation in the middle and high latitude of the northern hemisphere – except for the eastern region of Asia – has kept on increasing between 0.5 - 1% per decade. The subtropical region has experienced a decrease in precipitation about 0.3% per decade. Average precipitation increased between 0.2 - 0.3% per decade in tropical regions over the past century[44].

The warming of air temperature and its consequent effects on other climate variables are expected to be more intensified under future conditions. The IPCC provided a complete assessment of climate change projections with large numbers of simulations under different scenarios. In general, among climate models, the changes in direction and magnitude of temperature are more consistent than those of precipitation [45]. These analyses showed that the global average surface temperature increases in all simulations for the period of 2090-2099 relative to 1980-1999 climate conditions. The changes are supposed to be greater in northern latitudes and parts of the North Atlantic Ocean. During the same period, increases in precipitation for the higher latitudes and decreases in the tropical regions are expected – see Figure 2.2. In the same report, the IPCC projected about a 0.2˚C increase in temperature per decade under several Greenhouse Gas (GHG) emission scenarios for the next twenty years [46]. In terms of precipitation, Emori and Brown observed that the global mean rainfall increased by 6% from 1981 to 2000, and projected that it would increase by 13% from 2081 to 2100 [47]. Kharin and Zwiers projected that the mean annual precipitation would increase by 1% from 2040-2060, and 4% from 2080-2100 [48]. Bates et al mentioned that precipitation increments of at least 20% are to be expected in the higher latitudes of both hemispheres, while mid-latitude regions will experience dryer climates [49].

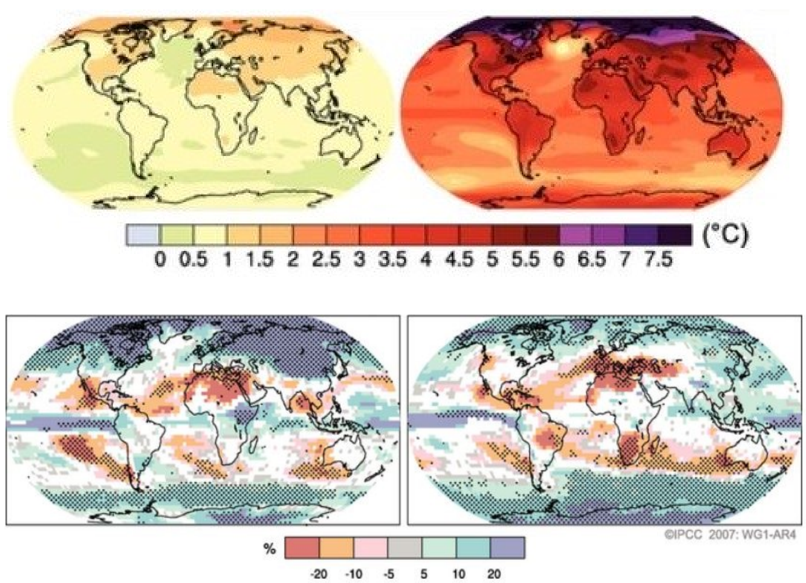

Figure 2.2 *Projection of surface temperature (up) and precipitation (down)[46]*

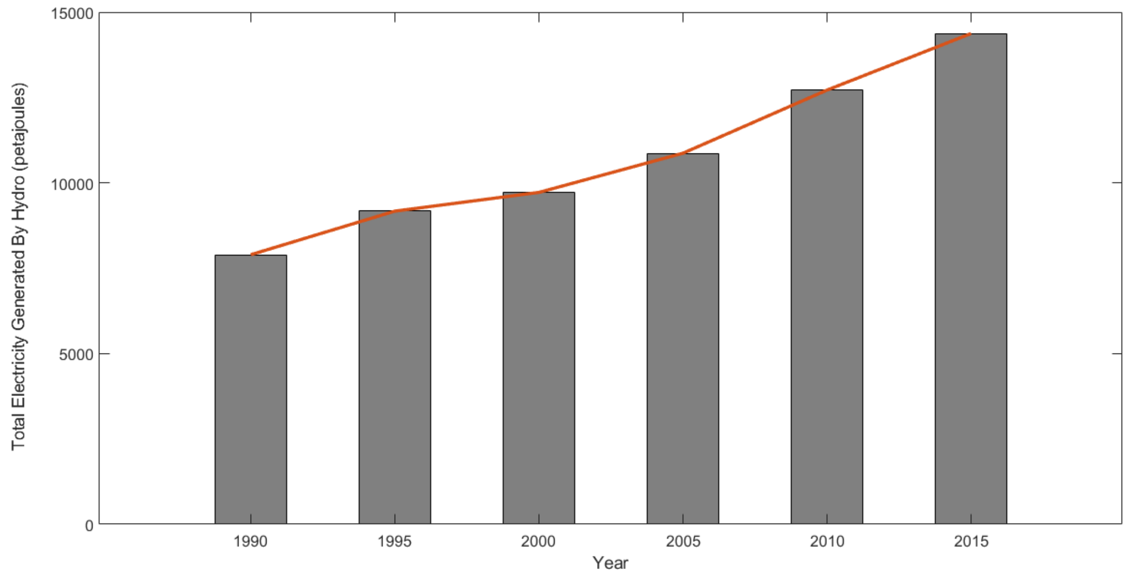

Figure 2.3 *Total hydropower generation trend [53]*

2.1.2 The impact of climate variability and change on hydropower generation

Shu et al performed a comprehensive survey on direct and indirect impacts of climate change on hydropower generation [54], which indicated that climate change has already affected hydropower production, with increasing impacts under future conditions. In this line, there are a number of studies focusing on assessing the impact of climate variability and change on hydropower generation by looking at the historical data. In most studies, the repercussions of climate variability and change on hydropower generation have manifested themselves in terms variations in precipitation, rainfall, and temperature that are diagnosed at the regional or national scales. For instance, Contreras-Lisperguer looked at the precipitation and temperature trends in Caribbean regions. It was understood that hydropower generation decreased due to drought conditions in the 1990s across this regions [25]. Another study evaluated the impact of climate variability on hydropower in Sri Lanka [55], in which multi-year rainfall trend analysis was performed in order to evaluate the possible impact of shift in precipitation pattern on hydropower generation. Madani and Lund used an energy-based hydropower optimization model and considered observed runoff data to estimate impacts of climate warming on high-elevation hydropower plants in California [56]. They understood that the system is sensitive to the both inflow's quantity and timing. Also, both warming and dry- warming climate leads to decrease in hydropower revenues while, wet-warm climate could increase the revenues of hydropower. In other study, Kabo-Bah used multiyear temperature and rainfall trends in order to address the potential impact of climate change on hydropower generation in Ghana [57]. It was understood that decrease in rainfall and increase in temperature across various stations affect water availability and water accessibility, which consequently have negative effects on hydropower generation. Another study considered rainfall, temperature, inflow, storage, and turbine discharge along with hydropower generation data to find the relation between climate and hydropower generation to address the impact of climate on hydro generation in Nigeria [58]. Mann-Kendal trend analysis was used to investigate the existence of trends and correlation coefficient to find the relationship between variables. Furthermore, the regression model was used to find the linear trend between temperature and rainfall, rainfall and inflow, temperature and storage, also between inflow and energy generated. The analysis confirmed that the increase in temperature and the decrease in rainfall lead to a decrease in inflow. These changes consequently affect hydropower generation. Similar analyses in a basin at northwest of China as well as Nepal showed that annual streamflow and therefore hydropower generation decreased due to decrease in total precipitation and increase of potential evapotranspiration [59]. Boadi used multiple regression and considered mean total basin rainfall, El Niño–Southern Oscillation (ENSO) index, lake elevation and net lake inflow as predictor variables to model annual power production in Ghana [60]. It was found that, rainfall variability accounted for 21% of the inter-annual fluctuations in power generation from 1970 to 1990 while, the majority (around 72.5%) of inter-annual fluctuation occurred due to ENSO and lake level fluctuations during 1991 to 2010.

Apart from analyses of the historical link between climate and hydropower generation, there are several studies that focus on the future impacts of climate change on hydropower generation at local or national scale but the number of studies at global scale is limited. As an example, at the global scale, Kumar mentioned that the changes in climate pattern particularly in precipitation and temperature leads to change in river flow and therefore hydropower generation [29]. Projections of runoff show expected increase in higher latitude and wet tropics while decrease in mid-latitudes and some dry tropics by the end the 21st century. In another study, 12 sets of output from Global Climate Models (GCMs) were used to project river flow and consequently simulate hydropower generation under future scenarios of climate change [52]. In general, hydropower production increases in the majority of regions except in Europe and a lesser extent in Africa by 2050. In a more recent study, integrated hydrological and dam models were used to address the vulnerability of hydropower generation to climate change [61]. It was understood that hydropower production decreased around 40% in the Mediterranean countries in southern Europe, northern Africa and the Middle East by the end of the century under a high emission scenario. On the other hand, countries in Scandinavia and central Asia will experience an increase in total hydropower production.

At the regional scale there are a number of studies that focus on the impacts of future climate change on hydropower in US. For instance, using a multi-model ensemble of GCMs' outputs, increasing variability in water availability and therefore hydropower generation was revealed in Flordia [62]. Ehsani et al used a high-resolution, fully coupled model that integrates hydrology with water management and energy production at the northeast of the US. The results showed that hydropower production may decrease due to a decline in water availability by up to 8% [63]. Another study focusing on California indicated that hydropower generation will decrease due to an increase in winter and spring runoff and therefore an increase in unproductive spills. Also, a temporal shift in runoff generation leads to an increase in generation in the winter, while a decrease during the summer [64].

Using temperature and rainfall data, it was shown that hydropower is largely sensitive and vulnerable to climate fluctuations in China [62]. Based on GCM outputs, it was shown that future impacts of climate change on hydropower production in China is very much dependent on the scenario of change manifested by emission (or concentration) of GHGs [63]. Based on the run-off data obtained from GCMs and inputting them to a hydropower generation models, it was shown that rainfall will increase during the period of 2016 to 2050 and consequently hydropower generation will increase in the Yangtze River in China [65]. In another case, the impacts of climate change on hydropower generation in Himalayan region was studied. It was proven that during the spring season, the growth in the glacial melt will increase the streamflow and therefore hydropower generation. Meanwhile, in the summer time and during monsoon precipitation, the flow cannot be fully utilized due to the hydropower generation constraints and unproductive spill [66]. In another study the effect of climate change on hydropower in India was conducted. It was understood that seven large hydropower plants experienced significant warming and a decrease in precipitation and stremflow during the observed period of 1951-2007 [67]. However, all the hydropower plants experience increase in production due to increase in precipitation and annual streamflow under future climate condition (2070-2099)

In Switzerland, it has been shown that climate change can have complex impacts on hydropower generation [68]. In general, wet years lead to increase in inflow and revenues from hydro while, dry years become drier and have negative effects on hydropower generation. Another study, focused on the runoff generation in the Periglacial regions in Switzerland, showed the potential of new hydropower plants under future climate due to glacier retreat and increase in runoff in this region [69]. Killingtvei et al. have analyzed the impacts of the climate change on hydropower generation in Romania using the HBV model [70]. They demonstrated that the runoff and hydropower would decrease in the period of 2065-2099 due to the increase in temperature and consequently evaporation. Similar results were obtained in Portugal [71], where it was demonstrated that by 2050 the hydropower generation would decrease up to 41% due to the changes in climate and decline in water availability.

A study, focused on a mountainous basin in New Zealand, showed that inflow to reservoirs will increase during winter and early spring. However, the inflow will decrease during the summer time [72]. A research on the impacts of climate change and variation in temperature on hydropower energy in the region of Mozambique indicated that the increase in temperature has negatively affected the production potential of hydropower [73]. Another study in the Rio Jubones Basin in Ecuador showed that the change in climate will decrease the hydropower potential in the wet seasons and the plant will face a significant power shortage during the dry season [74]. A research on the effects of climate change on the streamflow and consequently on hydropower potential in Grande river basin, Southeastern Brazil was conducted [75]. It was demonstrated that in the future there would be a decrease in the streamflow due to the change of the climate parameter and as a result there would be a reduction in hydropower generation to 58.6% throughout the 21st Century. Chery reviewed the existing research on the climate change impacts on hydropower generation in far north regions (Canada, Norway, Russia, Sweden, Alaska, and Finland) and then a template for application of current techniques for management and decision-making was proposed [76]. It was found that hydropower generation will increase due to increase in precipitation. Also increase in temperature leads to more melt and more water availability in these regions generally.

2.1.3 Changes in climate and hydroelectric variables in Canada

Climate in Canada has changed with the rate approximately twice of the global average and therefore has caused significant impacts on the landscape including water availability [36]. Zhang et al. studied the trend analysis for temperature and precipitation in Canada over the twentieth century [77]. The investigation contains six characters: maximum, minimum, and mean temperature, diurnal temperature range, total precipitation, and the ration of snow to precipitation. He observed that the mean temperature in southern Canada has increased yearly by an average of 0.9˚C between 1900 and 1998. This observation demonstrates the rate of increase in daily minimum temperature was higher than that of the maximum daily temperature. The incremental increase in temperature was more significant during spring and summer in western Canada. Whitfield and Cannon compared the meteorological data for Canada during two different time periods (1976-1985 and 1986-1995) and found that temperature increased in western and northern Canada – except during the winter [78]. The northeast part of Canada has experienced decreasing trends in maximum, minimum, and mean temperatures of the same magnitude. These trends are also consistent with the North American climate model projection studied by Meehl et al. [79]. Precipitation in the fall and winter increased in northern and western Canada, while it decreased in the east. The Prairies demonstrated blended outcomes [78]. Déry and Wood observed that precipitation in northern Canada decreased from 1964 to 2000 [80]. Zhang et al found that total annual precipitation and snowfall levels increased by about 20% in the northern part of the country [77]. Also, total precipitation levels increased between 5 – 35% in northern Canada between 1900 and 1998. The proportion of snowfall increased in the winter and autumn, but in some parts of the southern region, a negative trend is observed during the spring. Generally, they concluded that the climate became warmer and wetter across Canada as a whole during the last fifty years of the twentieth century. Similarly, Stone et al noticed an increasing trend in the total annual level of precipitation throughout the southern parts of Canada during the twentieth century [81]. This observation also applies to southern Québec, where increases in fall and winter precipitations were recorded.

The studies focusing on the impact of climate change on hydropower production in Canada are limited and they are mainly based on using GCMs in conjunction with hydrological models. As an example, Filion looked at the changes in runoff, precipitation and evaporation to address future impacts of hydroclimatic changes on hydropower production [82]. The areas investigated include the interior of British Columbia and southern Yukon, the basins surrounding James Bay in Québec, the Great Lakes Basin in Ontario, and the Saskatchewan sub-basin which transects the provincial borders of Alberta, Saskatchewan and Manitoba. In general, annual runoff and therefore potential for hydropower production will increase in northern parts of the country, while it will decrease in southern parts. In a report published by government of Canada, it was noted that hydropower generation will increase in the period of 2013 to 2050; however there is a considerable uncertainty in terms of the magnitude, as findings based on different models and/or scenarios can be quite divergent. In fact by changing the energy simulation model only, the results can change more than 50% by the end of 2050 [83]. Canada's Energy Future, published by National Energy Board highlights that hydroelectric capacity increases by nine GW, or 12 per cent from 2015 to 2040 in Canada [84]. In more recent study, Shevnina used annual runoff projections of the arctic countries including Canada and mentioned that, the potential of hydropower has increased by 14.0 to 18.0 % due to increase in annual runoff in these regions [85]. Considering future hydroclimate projections, the potential for increase in hydropower generation will be 4% to 9% accross Canada.

2.1.4 Changes in climate and hydroelectric variables in Québec

Based on its climatic conditions, Québec is divided into four zones. The northern part of Québec has an arctic climate with very cold winters and cool summers. The southern part has a humid climate with cold winters, hot summers, and high precipitation. The central part has a subarctic climate with very long, cold winters and short, warm summers. The eastern part has an eastern climate with cool summers and mild winters [86]. Thus, the climate varies significantly across different regions of Québec. Vincent et al performed a trend analysis which observed variations in climatic variables all over Canada, including Québec [87]. They found that the mean temperature during the fall increased in the arctic and northern parts of Québec between 1948 and 2014. During the same period, total annual precipitation increased in northern Québec, but there is no significant seasonal precipitation trend was observed in the southern part of the province. A negative snowfall trend was observed during the winter in southern Québec. The ratio of snowfall significantly decreased in northern Québec due to an increase in mean temperature in this region. Allard et al analyzed the data collected from several stations throughout Québec and suggested that the climate has warmed up faster in the northern part of province rather than in other parts during the twentieth century [88]. In another study, Yagouti et al. observed a significant increase in temperature in some parts of southern Québec during 1960 to 2003 [89]. More specifically, annual mean temperature has significantly increased by 0.5 to 1.2˚C in southwestern and south-central Québec. Insignificant rates of increase (less than 0.5˚C) were also observed in the southeastern part of province. The recorded information showed that temperatures have been increasing more rapidly since 1995. When tracking seasonal changes, various studies observed significant increases in temperature in winter and summer.

With respect to understanding the future outlook of hydropower production in the province, the general results confirms that hydropower production is expected to increase across the Québec due to inflow increase. The changes in the southern part were minor while it is very significant in northern part of the province [90]. However, such findings are subject to large uncertainty. For instance, Minville et al. fed the results of three climate models into a distributed hydrological model to investigate the impact of climate change on the management of Peribonka River basin, including hydropower production [91]. The results illustrated that annual mean hydropower would decrease by 1.8% for the period 2010–2039 and then increase by 9.3% and 18.3% during the periods 2040–2069 and 2070–2099, respectively. In other study, Minville et al used thirty climate projections including five climate models, two greenhouse gas emission scenarios and three temporal horizons with one lumped conceptual hydrological model over Peribonka River to investigate the most likely impacts of climate change on hydropower generation [92]. Results demonstrated that hydropower could be systematically affected by changes in hydrological regimes and annual mean flow. Also it was highlighted that unproductive spillage increased from upstream to downstream due to low storage capacities in upstream reservoirs with the increased flow, due to increased melt as well as precipitation.

2.2 The link between climate and wind power

The amount of electricity generated by the wind is proportional to the turbine's power curve [93], which is a function of cubic wind speed [21]. This has been the basis for the design of wind energy facilities based on air density, turbine surface area, and cubed wind speed [94-96]. As a result, small changes of wind speed can have large effects on wind power generation as well as the timing and period of operation [97]. Since wind energy cannot be stored and there is no output regularization on this type of energy, the natural variability of wind speed across different time spans can significantly affect wind energy productivity [98]. In fact, wind is formed due to uneven warmings of the world's surface by the sun [97]. Thus, different temperature gradients affect characteristics of wind, which affect the potential of energy production [25]. From such a perspective, both natural variability in temperature gradient as well as systematic warming can alter wind characteristics, most importantly wind direction and speed [94].

2.2.1 Observed and future changes in wind characteristics at the global scale

There are a number of studies, focusing on analyzing the variations in wind characteristics across the world during the recent past. These studies shows decreasing wind speed in Italy[99], China [100], Nepal [101], US [22,102] and Australia [103,104]. Globally, Lynch et al reported increasing trend in wind speed from 1921 to 2001 in high latitude regions of both hemispheres [105], however based on McVicar et al.'s work, it can be concluded that wind speeds in tropical and mid-latitude regions of both hemispheres are decreasing [106]. Such understandings however are subject to large regional and seasonal variability. For instance, using North American Regional Reanalysis (NARR) dataset for 1979 to 2009, Holt and Wang identified significant positive trends in wind speed in the southeastern and northern states of US [107].

Several studies also looked at the impact of future climate change on wind speed particularly in Europe. The general understanding of wind speed change in the 21st century is that on the annual scale and within the whole European continent, wind speed remain stable [108]. This however is subject to enormous seasonal and regional variability. For example, Nolan et al. projected wind speed variations in Ireland using regional climate models (RCMs) under four different climate scenarios from 2021-2060 [109]. Their results showed that wind energy will increase in the winter and decrease during the summer across Ireland. Najac et al. used the same methodology and predicted the wind speed across France [110]. The results show that wind speed will increase by up to 2.6% in northwestern regions and decrease by about 6% in the central region between 2046 and 2065. Pryor and Barthelmie used wind speed projections from GCMs across northern part of Europe for the period 2071 to 2100 [111]. It was found that wind speed is higher in comparison with the control period (1961–1990) in most of the regions. In another work, Weber et al. looked at the high resolution climate simulations in order to address the impact of climate change on wind power resources and its potential in Europe [112]. The probability and persistence of different wind regimes and seasonal variability of wind speed was evaluated in this study. The results show that, the wind speed distribution shifts from high speed to low speed in most of the parts. Also seasonal wind variability mostly increase in west and north western regions. It was also noted that there is a need for an increase of backup energy and storage in most of central, north and north western Europe [113]. Based on using the projections of 22 GCMs, Reyers et al. showed that the future wind energy will most likely not increase over northern and central Europe but decrease over southern parts.

In the US, Breslow and Sailor noted that wind energy is vulnerable to variations in wind speed as a result of global warming [114]. They used a range of different global climate model (GCM) outputs to investigate the possible impact of climate change on the mean magnitude of wind across the continental US for current and future conditions. The result shows that wind speed decreases by about 1–4.5% over the next hundred years. The results of another study over northwest states in US show that summertime wind speeds may decrease by 5–10%, while wintertime wind speeds may decrease insignificantly. Also, it is expected that wind power generation decrease around 40% in summertime by the end of 2050 [115]. Similar analyses for Brazil illustrated that wind speed will increase by over 20% in northeastern Brazil, but also decrease by more than 20% in northwestern regions of the country from 2071-2100 [93]. Over Chile, the results reveal that wind speed will likely become more intense while the variability of wind speed will also increase and this is significant in some part of northern and southern part of country [116].

Using multi-model ensemble of eight RCMs under two emission scenarios over the period 2011-2040, the wind power potential in east Africa was investigated [117]. The results show that wind power potential will increase across all area with higher values during summertime. Another research was conducted to find the effects of climate change on wind potential in Nigeria [118]. The results show that wind power density varied with season across the country. The highest potential for wind power was found in north eastern regions during dry seasons. A study over the Mediterranean region and the Black Sea showed future decrease in wind speed in most of the regions [119]. Over the Republic of Korea, it was understood that future wind speed can vary between -9.53% to 29.80% depending on the location and season. Also, the strong wind speed decreased during cold seasons while it increased in warm seasons.

2.2.2 Observed and future changes in wind characteristics across Canada

Surface observation data acquired by some of the review studies found a decreasing trend in wind speed over various parts of Canada. Tuller analyzed wind speed trends across four stations on the west coast of Canada [120]. The trends of mean annual and winter wind speeds in three of these stations were negative from 1940 to 1990. However it seems to be conflicting results between inland and coastal stations. For instance, using meteorological buoys' data for trend analysis across the Canadian west coast and the adjacent United States, an increasing trend in monthly wind speed was understood during 1972 to 1999 [121]. The analyses of trend in wind speed has been also performed in other parts of Canada. Keimig and Bradley studied trends in afternoon wind speed for fifteen Alaskan and northern Canadian stations in order to track changes in wind chill temperature between 1953 and 1993 [122]. They observed that 64% of all monthly wind speed trends are negative. A study based on wind speed observations in Whitehorse (Yukon) showed that wind speed during 1956 to 2005 and the potential for wind power has increased, particularly during the winter [123]. Another study over north Atlantic regions, however, showed an increase of 0.1-0.5 (m/s) per decade during 1978–1992 [124].

There is evidence that the wind speed has altered in Québec. Wan et al. used wind speed data from 117 stations across Canada to analyze the changes in wind speed during 1953-2006 [125]. They detected linear trends of wind speed for eight regions in Canada. The results based on thirteen

Québec stations showed that wind speed in Québec and Baffin Island decreased during the study period. These results were consistent and statistically significant across all seasons and on an annual basis. Based on the observed magnitude of these trends, the largest decrease in wind speed occurred during summer. Ilinca et al presented a comprehensive study of wind potential in Québec for the period between 1955- 1995 [126]. It was found that the potential of wind power is low in most of the regions. Higher wind power potential was observed in coastal locations and certain interior regions of the province. The highest wind power potential were found in the Gaspe Peninsula, the northeastern coast of St. Lawrence near Blanc Sablon, and the Magdalene Islands.

In terms of future projections of wind power potential in Canada, Yao et al. used a high resolution regional climate model (PRECIS) and dynamic downscaling to predict wind speeds across Ontario [127]. The results illustrated that wind speed may decrease from 2071 to 2100 in southern Ontario. In a more recent paper, Cheng analyzed the possible impact of climate change on wind gust events across Canada [128]. They developed hourly and daily wind gust simulation models to statistically downscale future station-scale hourly wind speed data. The result clearly showed that wind gust events of greater magnitude and intensity than those historically recorded are expected to occur during the late twenty-first century across Canada.

2.3 Gaps in knowledge and thesis statement

2.3.1 Current gaps in understanding the effects of climate variability and change on hydropower production

Based on the literature review provided in Section 2.1, historical evidences for direct and indirect impacts of climate variability and change on hydropower productions can be seen globally, regionally and locally. However, the form and nature of impacts are subject to large temporal and spatial variability and can be different among studies. This indeed includes some inherent natural variability due to natural differences in the Earth System processes as a result of geographical and/or temporal differences; but it also refers, to a certain extent, to methodological frameworks with which the impacts of climate variability and change on hydropower production has been assessed. First, majority of current studies are performed at local and/or catchment scales and therefore they are not regionally explicit across political jurisdictions, in which information are needed for taking important water and energy management decisions. The other issue is the lack of common study periods, which hinders direct intercomparison between research results obtained from independent sources of findings. This is an important gap because the geographic differences in the impacts of climate variability and change on hydropower production can be mixed with the temporal difference due to consideration of multiple time periods. Another issue is the fact that the effect of climate variability and change are often observed through variations in streamflow. Although streamflow is largely determined by climate, however, it is controlled significantly by natural land and human processes. Moreover, hydrological models that convert the climate forcing to streamflow sequences and then to time series of hydropower production have significant uncertainties. As a result, the empirical statistical dependence between climate and hydropower production might be exaggerated or dampened due to land-based hydrological processes and/or limitations in current hydrological models. The uncertainty in understanding the impact of climate variability and change on hydropower production are more severe under future conditions due to the incorporation of uncertain projection of GCMs, whether raw or downscaled. Therefore the total uncertainty in future climate projections can be large, particularly due to the use of hypothetical scenarios that portray the future emissions or concentration of GHGs.

Based on the survey made on the current understanding of climate variability and change on Canadian hydropower production, it can be argued that there is a lack of an homogeneous study that looks at empirical changes and links between climate and hydropower production across Canadian provinces and territories, where management decisions are usually made. In addition, it seems that there is a methodological departure between the studies focusing on the past changes and those concerning future conditions. While analyses of historical data are mainly based on applying trend analyses on observed data, future findings are mainly based on simulation results, without incorporating what is learnt from historical analyses using the observed data.

2.3.2 Current gaps in understanding the effects of climate variability and change on wind power production

With respect to understanding the wind speed patterns, there are clear evidences for spatial and temporal changes in wind speed that coincide with changes in other climate variables such as temperature globally and in Canada. However, current understanding are rather regionally spare and lack homogeneous time periods for investigating historical changes in wind characteristics to address geographic differences with or without considering other climate variables. In addition, it is not clear how changes in local temperature and wind speed are connected across different regions, including in Canada. If this link is understood, then there would be a possibility for quantifying the impact of warming on wind speed at the local scale, without considering the projections obtained from climate models. Addressing this gap requires rather a comprehensive study to formally inspect the direct dependence between wind and temperature at the local scale and to analyze the potential links between historical trends in temperature with those observed in wind speed at the same location.

2.3.3 Aims and specific research objectives

This research aims at providing a holistic understanding of the dependencies between climate variables and hydro and wind production in Canada. Using empirical observed data of climate and hydroelectric production, the first aim of this study is to provide a statistical understanding of the sensitivity of hydropower production to climate variability of change at the monthly scale and across Canadian jurisdictions. The second aim of this study is to understand whether there is a direct link between local temperature and local wind speed across Canadian landmass and if so, whether it would be possible to link the trends in local wind speed to the trends in the local temperature at monthly, seasonal and annual scales and across Canadian regions.

More specifically, with respect to hydropower production, the objectives of this research are as the following:

- Studying the trend in relevant climate variables to hydropower production, namely temperature, precipitation, rainfall and snowfall across Canadian provinces and territories.
- Analyzing the dependence between climate variables and hydropower production at the homogeneous temporal scale across Canadian jurisdictions.
- Understanding the climatic causes of hydropower production in each province and territories

- Using this knowledge to create predictive models to quantify changes in monthly hydropower production at each province and/or territory, based on changes in climate variables within the same region.

With respect to wind power production, the specific objectives of this research are as the following:

- Understanding the co-evolution of change in monthly, seasonal and annual in temperature and wind speed across a number of Canadian stations during a common period.
- Understanding the statistical dependence between local temperature and local wind speed.
- Analyzing the link between trends in temperature and wind speed across monthly, seasonal and annual scales within four key Canadian regions, i.e. northern, western, eastern and Atlantic Canada.

3 Available data and post processing

This research involves analysis of both climatic and energy data across the Canadian landmass. This chapter outlines the type and sources of the implemented data in this thesis. The first part introduces the energy and climatic data, their sources, and their temporal and spatial availability and distribution across Canada. There is also a brief background about the previous work that has been done with the data. The difference between spatial scales of these data leads to an additional data post processing to fix the scaling mismatch.

3.1 Provincial hydropower production data

The data related to hydropower production is obtained from Statistics Canada's key socioeconomic database (CANSIM) (http://www5.statcan.gc.ca/cansim). In terms of temporal scale, the datasets are recorded on a monthly basis, and in terms of spatial scale, they are lumped at the provincial scale. The data covers the period from January 1977 to December 2007. The measurements for the Northwest Territories and Nunavut were counted together before April 1st, 1999, when they were separated juristically. Therefore, the hydropower generation in these territories are lumped into one single measure. It should be also noted that there is no recorded data available for Prince Edward Island due to unnoticeable production compared to other provinces and territories in Canada. Figure 3.1 shows the available monthly time series of hydropower production in Canada.

3.2 Climate data

The historical climate data used in this study includes total monthly precipitation, rainfall, snowfall, as well as monthly mean temperature and wind speed across a large number of Canadian climate stations that have data during the period of 1977 to 2007, which is corresponding with available energy data. This is necessary for formally understanding the statistical dependence and causal relationship between climate variables and hydropower production. The historical data used is the official Environment and Climate Change Canada (ECCC) data created to be used in climate research [129-131]. The data can be accessed at https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/climate-trends-variability/adjusted-homogenized-canadian-data.html. The stations with more than 15% of missing data (1 month a year on average) are removed from the analyses. The missing months are gap filled using the mean value of the observed data during the same month.

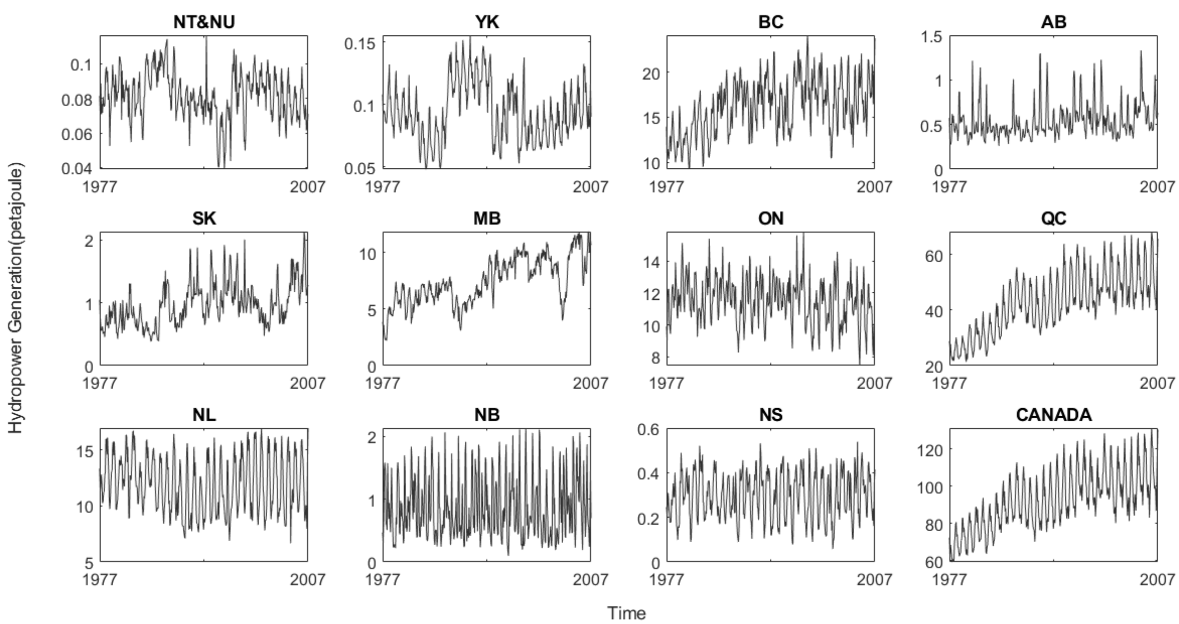

Figure 3.1 *Monthly hydropower production in Canada along its provinces and territories*

3.2.1 Precipitation

Precipitation data is gathered from the second generation's adjusted precipitation for Canada's (APC2) dataset for over 450 locations, as prepared by Mekis and Vincent [130]. The original climate data is on a daily scale, including daily rain and snowfall amounts. Mekis and Vincent upscaled and harmonized the collected data to correspond with season and annual monthly estimates. The amounts of rainfall and snowfall were adjusted based on certain measurement factors such as wind under catch, evaporation and wetting losses for each type of rain-gauge, snow water equivalents of ruler measurements, and trace observations. The adjusted daily total precipitation was calculated by the sum of the adjusted rainfall and adjusted snow-water equivalent. After removing stations with more than 15% missing data, 379 precipitation stations from a total of 463 are chosen. The distribution of stations within Canadian landmasses and their corresponding locations are shown in Figure 3.2.

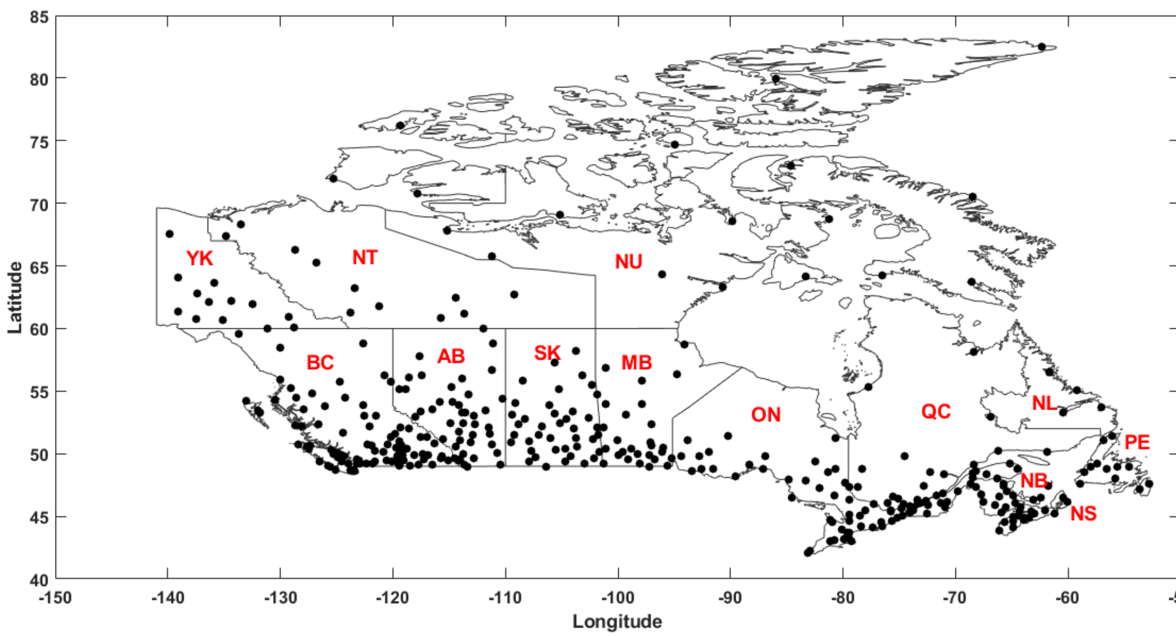

Figure 3.2 *Distribution of precipitation stations over Canada*

3.2.2 Temperature

Temperature data is collected from the second generation of homogenized temperature datasets, prepared by Vincent and Wang [131], in which the observation data of nearby stations are combined to create a long term time series suitable for climate change studies. As mentioned for the case of precipitation data, the stations with more than 15% missing data during 1977 to 2007 are discarded from the analyses. Accordingly, 308 stations from 338 are selected. The distribution of chosen temperature stations and their locations is shown in Figure 3.3.

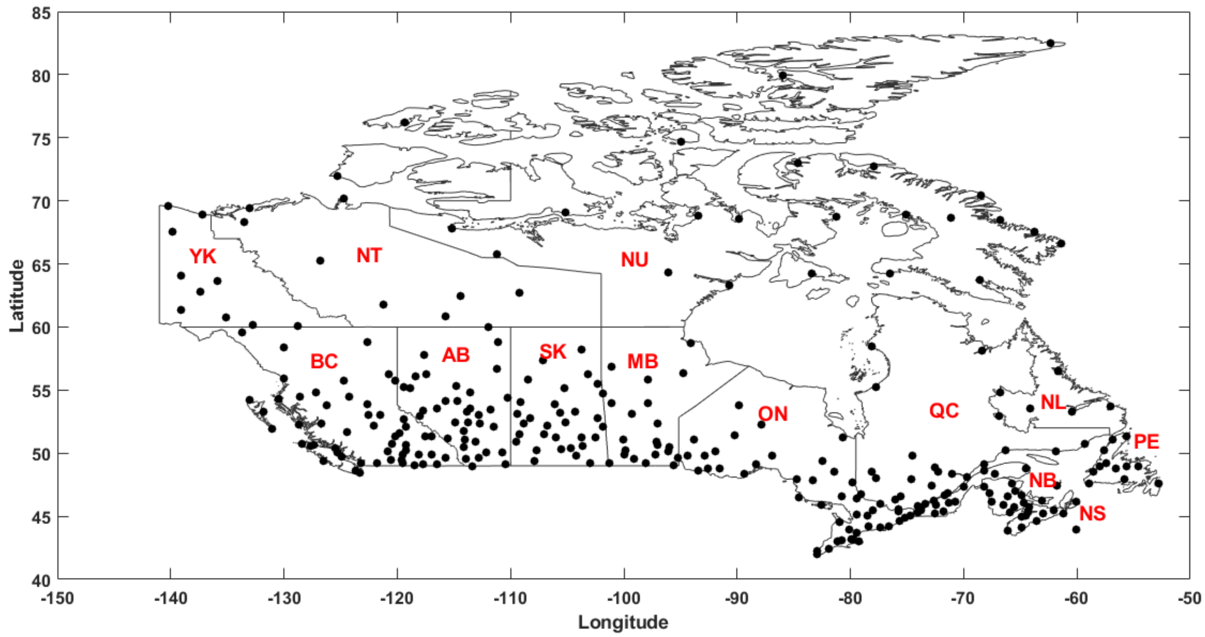

Figure 3.3 *Distribution of temperature stations over Canada*

3.2.3 Wind

The monthly homogenized surface wind speed data was prepared from hourly data observations by Wan et al. [125]. The data was organized to approximate surface wind speed trend analysis across Canada. The metadata and logarithmic wind profiles were applied to adjust hourly data due to nonstandard anemometer height measurements. Consequently, the monthly mean wind speed series was extracted from the adjusted hourly wind speeds. Then, monthly datasets were tested for homogeneity by using a statistical inhomogeneity model based on regression models suggested by Wang [132]. After removing the stations with high amounts of missing values, 88 stations are selected which cover both temperature and wind speed during 1968-1998. This includes the 30-

year episode in the total data availability period in which the largest number of stations having both monthly wind and temperature data is available. The distribution of chosen stations is illustrated in Figure 3.4.

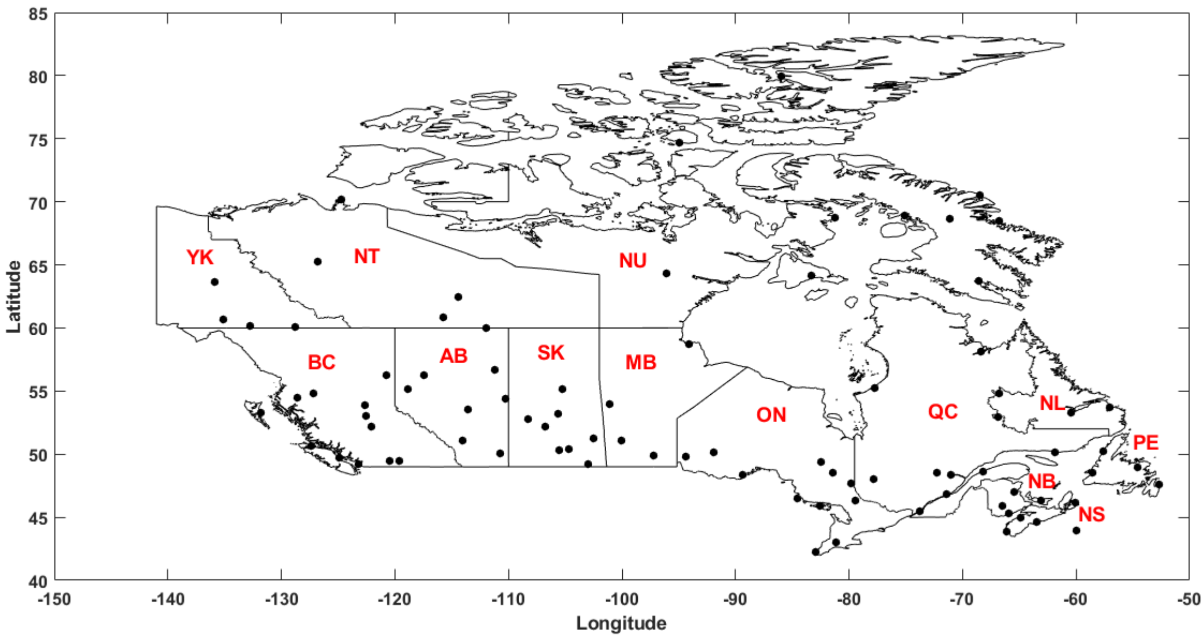

Figure 3.4 *Distribution of stations with paired temperature-wind speed data over Canada*

3.3 Spatial data adjustment

As mentioned earlier, the spatial scales of climatic variables and hydropower are different. The same spatial scale between variables is needed to perform dependency and causality analysis – see Chapter 4. Hence, an upscaling attempt is required to convert the station-scale climate data to the provincial and territorial scales, in which hydropower data are available. Here the Grid Method proposed by Han et al. was used to interpolate climate data from station scale to provincial scale [133]. The method is based on dividing the total landmass into a number of grids and calculating the weight of each climatic station to be able to interpolate them into the gridded system. The grid size is dependent to the total area and the number of climate stations available – see Equation 1:

$$Grid\ size = \sqrt{\frac{Total\ area}{200 \times Number\ of\ stations}} \quad (1)$$

Here the grid size was considered as 0.3° degree in latitude and longitude. Weighting is based on the distance between the centre of each cell and all stations. Each cell is allocated to its corresponding station based on the minimum squared Euclidian distance squared (d^2). The weight of each station is calculated by adding the number of allocated cells to each station.

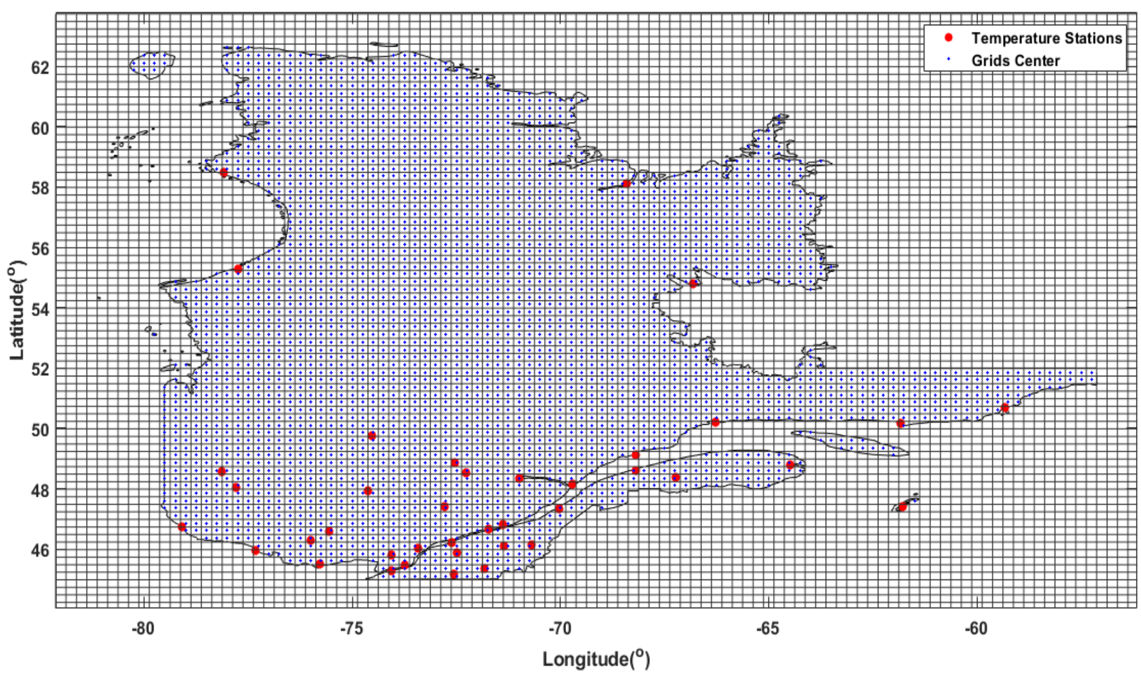

Figure 3.5 *Demonstration of the gridding system for upscaling spare temperature data over Québec*

After estimating the station's weight, the interpolated value for each climate variable is calculated for each province, as the following:

$$\bar{P} = \frac{P_1W_1 + P_2W_2 + P_3W_3 + \cdots + P_nW_n}{W_1 + W_2 + W_3 + \cdots + W_n} = \frac{\sum_{i=1}^{n} P_iW_i}{\sum_{i=1}^{n} W_i} \quad (2)$$

Where $\bar{P}$ is the upscaled (interpolated) value of each corresponding variable, P_i is the climatic value of each station, W_i is the weight of the stations, and *n* is the number of stations.

4 Methodology

Pursuing the aims and objectives of this study, as illustrated in Section 2, requires two different types of methodology regarding each types of energy separately, i.e. hydropower and wind energy. Two statistical frameworks are proposed, each combining various statistical methodologies and tools, which together make an integrated workflow to address the specific objectives, laid down for analyses of climate sensitivities in hydropower and wind energy production in Canada. In this chapter, information concerning the proposed statistical frameworks and their corresponding tools will be respectively introduced. It should be noted that the link between climate variables and hydropower production as well as wind speed and hydropower production are inspected at monthly, seasonal and annual resolutions. For analyzing climate-hydropower dependency, the year is considered from October to September, which corresponds to a typical hydrological year.

4.1 The proposed framework and assumptions for understanding the dependency between climate and hydropower at the provincial scale

This section describes a statistical framework and its procedure for integrating and explaining the relation between climate and hydropower generation in Canada. The proposed framework consists of four different steps, the implementation of which is illustrated in Figure 4.1. The first step would be detecting the change, and measuring the magnitude of the change in climatic variables. Hence, the Mann-Kendall trend test is used to investigate the changes and subsequently, Sen's slope is applied to measure the magnitude of the monotonic changes in climate time series across monthly, seasonal and annual scales. The next step is to assess the dependency between climate variables and hydropower generation at common temporal and spatial scales.

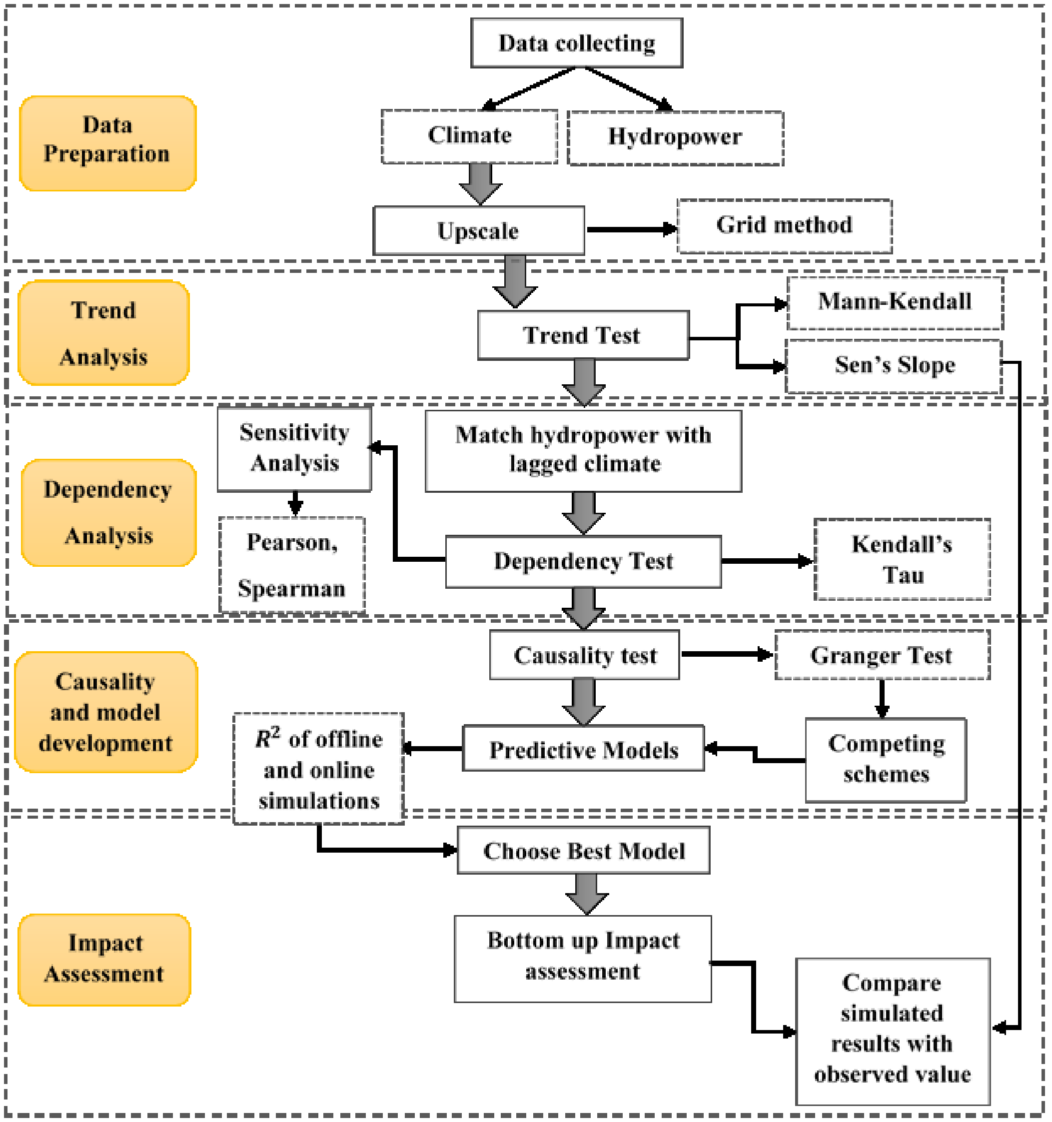

Figure 4.1 *Proposed statistical procedure to address sensitivity of hydropower production to climate variability and change*

For this purpose, Kendall's tau is used, which is a popular method to formally quantify the dependence between two ordinal random variables [134]. To find the sensitivity of the dependency results to Kendall's tau, two other dependency tests, namely Spearman and Pearson are used. Furthermore, the dependency between hydropower and lagged climate is analyzed considering 0 to 11 months lag to understand intra-annual links between climate drivers and hydropower production, whether they are causal or not [135]. A formal causality test based on the Granger hypothesis [136] is further applied to investigate the causal relation between climate variables and hydropower generation. After understanding specific climatic causes of hydropower generation at each jurisdictional region, different predictive modeling schemes based on autoregressive multivariate regression is proposed to build competing hypotheses for simulating monthly hydropower generation. The best predictive model is then selected based on the coefficient of determination (R^2). To showcase the practicality of the proposed methodology for impact assessment, the historical trends in climate variables are inputted to the predictive models to come up with a bottom-up assessment of how continuation of the historical trend can result into gain/loss in expected monthly hydropower production. This can provide an alternative methodology to address the sensitivity of hydropower production to climate variability and change without using climate and/or hydrological models.

Few assumptions are considered in order to investigate the dependency between hydropower production and climate variables across Canadian provinces. These assumptions are divided into two terms which they are the main drivers of hydropower production. In terms of water availability, the effects of both natural and anthropogenic physical landscape informations of the provinces are ignored. For instance, the characteristics of watershed, number and location of the dams are declined. On the other hand, in terms of water demand, the amount of water which is allocated for hydropower production is not considered as an individual variable in the analysis. Furthermore, the hydropower demands from different sectors is accumulated to the total hydropower production. Hence, the relation between the water availability and the hydropower demand is considered to be constant for each province.

4.2 The proposed framework for understanding the dependency between local temperature and wind speed

The proposed framework for investigating the temperature and wind energy dependency starts from analyses of co-evolution of observed data at the station scale and implements regional upscaling to investigate the link between trends in temperature and wind where local dependencies are significant. Figure 4.2 shows the workflow of the proposed methodology. In brief, the Mann-Kendall trend test is used to study the changes in temperature and wind speed data. Then the dependency between them is analyzed by using Kendall's tau. The effect of altering the significance level on number of cases with significant dependence between temperature and wind speed is studied by considering different confidence levels for identifying the significant dependence. Then, the relations between Sen's slopes of temperature and corresponding values related to the wind speed are analyzed across northern, western, eastern and Atlantic Canada using the first order simple linear regression. Below the methodological details of the proposed frameworks are discussed.

4.3 Methodological elements of the proposed frameworks

4.3.1 Trend test

In this study, trend test is applied to investigate changes in climatic variables. Trend analysis is one of the simplest, yet most robust and powerful methods for detecting monotonic temporal changes in environmental variables [137]. Generally, a trend refers to a monotonic change, which might occur over time in a particular variable. These changes can be described by magnitude, direction, and significance level. The direction shows the sign of trend as a positive (increasing) or negative (decreasing) values. The magnitude of monotonic change is represented by the slope of change over time and the p-value of formal dependence test can provide a proxy for assigning the significance of potential trends in climate variables.

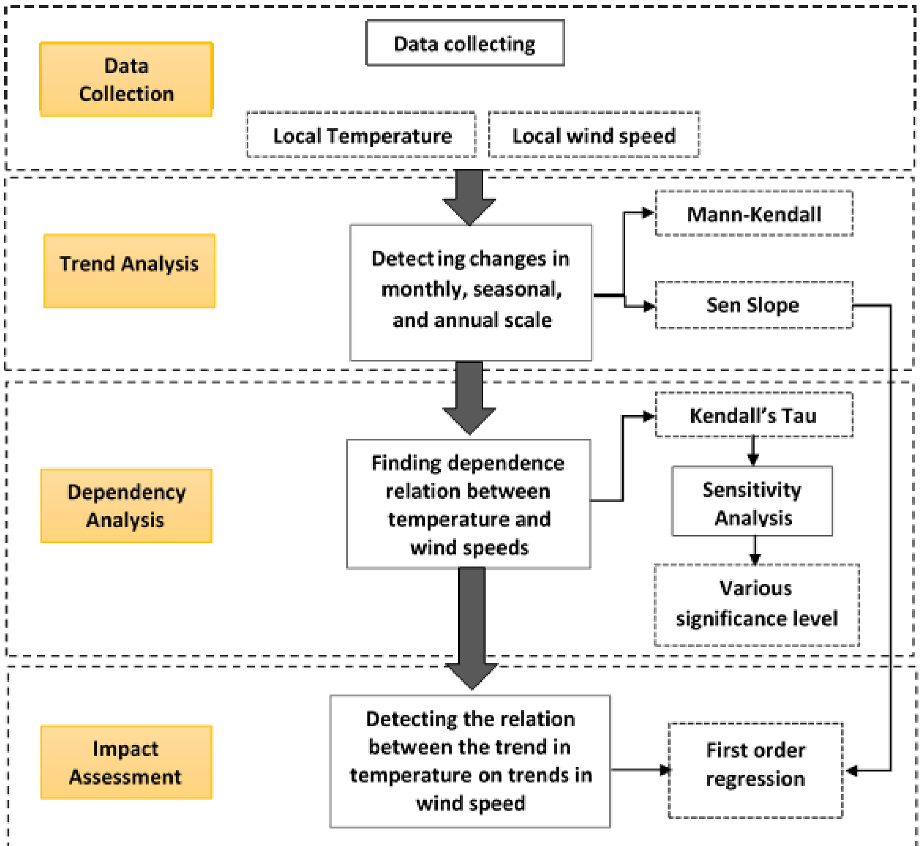

Figure 4.2 *Proposed statistical procedure to address sensitivity of wind speed to trends in local temperature*

Trend analysis is divided into two types, involving parametric and non-parametric approaches to trend analyses. Parametric statistical tests make assumptions based on the parameters of the population distribution, which is often assumed to be a normal distribution. On the other hand, there is no distribution assumption in non-parametric statistical tests which can be useful for non-normal data, common in vast majority climate time series [138]. In this study, the Mann-Kendall trend test, which is one of the most common methods of non-parametric trend analysis, is employed to detect a monotonic trend in a series of climate data. The test is initially proposed by

Mann [139], who suggested an innovative application of Kendall's dependency test to detect monotonic trends [140]. The main advantage of this method is in its low sensitivity to unexpected break changes in heterogeneous time series [141] as well as the non-stationarity and skewed distributions [142-144]. Therefore so far, many studies have used the Mann-Kendall trend test in the context of detecting gradual changes in hydroclimatic data across the globe [145-149].

The null hypothesis of the Mann-Kendall trend test is that the dataset is independent to time and therefore there is no trend. The rejection of this null hypothesis requires the existence of a significant upward or downward trends, characterized as the following: Considering the data time series as $x_1, x_2, x_3, \dots to\ x_n$, where x_i is the datum at time i, a comparison can be made between each value and other subsequent values. If the values in higher (lower) time steps are bigger than the value of the lower (higher) time step, the indicator function Sign will be 1 (-1). If the two values are equal, then Sign takes 0, as described below:

$$Sign(x_j - x_k) = \begin{cases} +1\ if\ x_j - x_k > 0 \\ 0\ if\ x_j - x_k = 0 \\ -1\ if\ x_j - x_k < 0 \end{cases} \tag{3}$$

Where x_j , x_k are the values in time j and k respectively when $j > k$. Accordingly, the Mann-Kendall *S* statistics, which is the sum of the Sign across the whole time series, can be calculated as the following:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} Sign(x_j - x_k) \tag{4}$$

Where x_i denotes the data value and n is the length of the time series. The value of S would be the maximum, if $x_1 < x_2 < x_3 < \cdots < x_n$ [150]. It has been shown that for $n \geq 10$ the S statistic is normally distributed with zero mean and constant variance, which can be calculated as the follows [140,151]:

$$VAR(S) = \frac{1}{18}[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(p)(p-1)(2p+5)] \tag{5}$$

Where t_p represents the number of ties. Using the estimated S and *VAR(S)*, the standardized Z statistics can be calculated to formally assign the significance and direction of the trend:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & if \quad S < 0 \end{cases} \tag{6}$$

The null hypothesis of no-trend will be rejected if the absolute value of computed standardized Z is greater than the $Z_{\alpha/2}$ of the normal distribution, where α represents the chosen significance level and is the probability of rejecting a null hypothesis when it is true. Positive (negative) values of Z indicate that the direction of the trend is upward (downward) [151]. Figure 4.3 shows two examples with regard to increasing and decreasing forms of monotonic change in energy production.

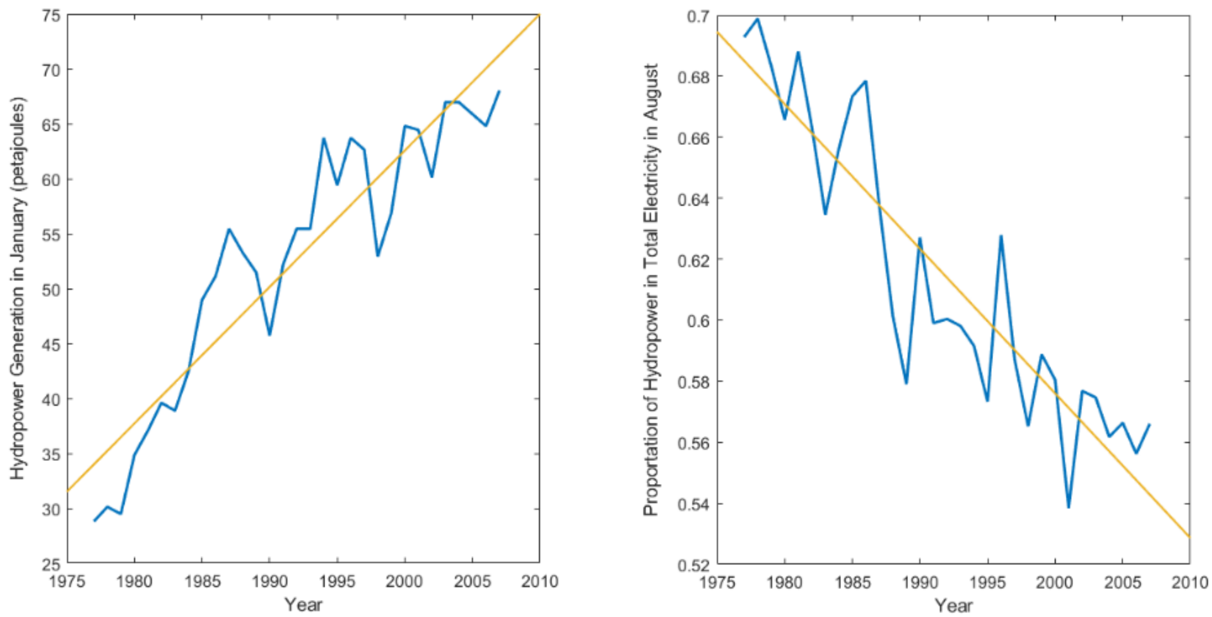

Figure 4.3 *Monotonic increasing trend in total hydropower generation in month January in Quebec (right), monotonic decreasing trend in the proportion of hydropower to total electricity generation in August in Canada*

In Mann-Kendall trend test, the linear slope (change per unit time), characterizing the magnitude of the trend, is often calculated by the Sen's slope estimator. Sen' slope describes the magnitude of trend and is estimated by a non-parametric procedure [152]. In brief having a trendy process of f(t) as $f(t) = Qt + b$, where $f(t)$ is the linear model and Q is the slope and b is a constant, a robust estimate of Q can be calculated as:

$$Q_i = \frac{Xj - Xk}{j - k}, \qquad i = 1,2, \ldots, N, j > k \tag{7}$$

Where X_j, X_k are parameter concentrations at time j and k. For n values of x, we get $N = \frac{n(n-1)}{2}$ slope estimates of Q_i, hence the median of these N values of slopes (Q_i) is Sen's slope estimation:

$$Q = \begin{cases} Q_{\frac{N+1}{2}} & If\ N\ is\ odd \\ \frac{1}{2}\left[Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}\right] & If\ N\ is\ even \end{cases} \tag{8}$$

The advantages of using Sen's slope estimator is its insensitivity to extreme values within the time series that can dampened or exaggerate the true trend. Due to the different scales and/or dimension of climate variables, the trend test is performed on the anomaly of the time series, so that the results from various regions and/or variables can be comparable. The anomaly can be calculated as the following, in which $\dot{X}_i$ and X_i are the transferred and the raw data, $\bar{X}$ is the mean and σ is the standard deviation of the raw data:

$$\dot{X}_i = \frac{X_i - \bar{X}}{\sigma} \tag{9}$$

4.3.2 Dependency test

The dependency test is used to define the statistical dependency between a pair of datasets. There are several studies that use dependency analyses to understand relationships between hydroclimate data. For instance, Feng et al. used dependence methodology to analyze the relation between extreme temperature and precipitation in China [153]. Hennemuth et al considered dependency measures to analyze the association between observed and simulated climate data [154]. Assani and Guerfi used dependency analysis to address the link between extreme temperature and precipitation in three hydroclimate regions of Southern Québec [155].

Here, three different measures of dependency are considered: Pearson's correlation, Spearman's rank and Kendall's tau. These measures have a value between +1 and −1. The absolute values of the dependency measures show the magnitude, and their signs indicates the direction. Where 1 is the complete positive dependence, 0 is no dependence, and -1 is the complete negative dependence. Generally, the Pearson correlation is used to detect the linear relation between two variables, while Kendall's tau and Spearman's rank are suitable for detecting non-linear relations between data.

The Pearson correlation coefficient, also known as the Pearson Product-Moment Correlation or coefficient of correlation, is the most widely used method to detect the linear relation between variables [156]. In 1877, the concept was introduced by Galton [157] and was later developed by Pearson [158]. Figure 4.4 shows three possible cases for dependence, i.e. no dependence (Pearson correlation is equal to zero), negative dependence (Pearson correlation is less than zero) and positive dependence (Pearson correlation is more than zero).

When the Pearson correlation coefficient is applied to the population data, it is described by the letter ρ (rho), and can be calculated using the following equation, where X and Y are the variables of population, cov is the covariance and σ is the standard deviation.

$$\rho_{X,Y} = \frac{\mathrm{cov}(X, Y)}{\sigma_X \sigma_Y} \tag{10}$$

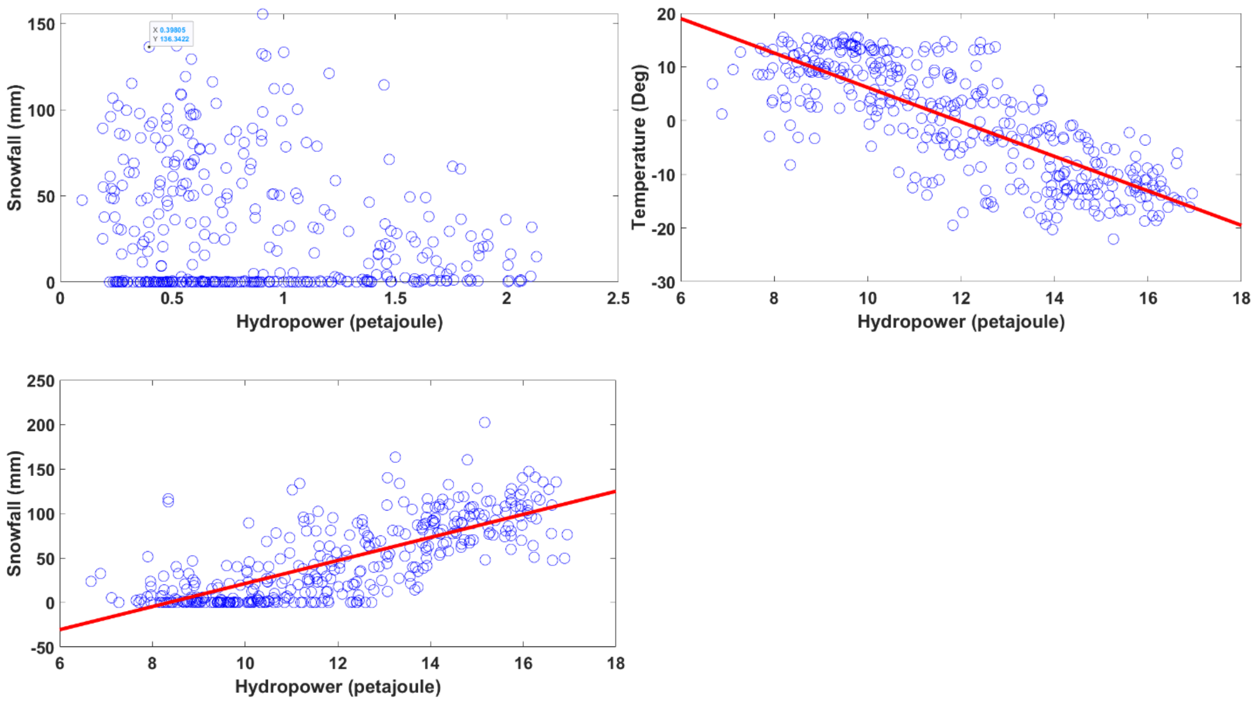

Figure 4.4 *Different conditions for Pearson correlation coefficient: No correlation between monthly snowfall hydropower generation and in New Brunswick (left-up).The negative dependency between monthly rainfall and monthly hydropower generation in Newfoundland (right-up). The positive dependency between monthly snowfall and hydropower generation in Newfoundland (left-down).*

However, Pearson correlation coefficient is often applied to samples rather than data populations. In such cases, it is represented by the letter r and can be calculated as the following, where x_i and y_i are the samples, $\overline{x_i}$ and $\overline{y_i}$ are the average values, and n is the number of sample data:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{11}$$

Like any other formal statistical test, the significance of correlations can be objectively inspected using the *p*-value. In most cases, a *p*-value ≤ 0.05 is considered as the level of significance, which means that there is a probability of 95% and more than the inspected dependence is not created by random chance.

Spearman and Kendall rank correlations are similar to correlation coefficients, but they work on the ranked variables rather than original raw variables. Spearman's rank coefficient was originally introduced by Spearman in 1904 [159] as a non-parametric statistical test. In simple terms, Spearman's rank correlation is the Pearson correlation coefficient that is applied to ranked data [160,161]. Suppose that there are two sets of variables X_i and Y_i with length of n and their ranked values are determined by rg_X and rg_Y. Accordingly, Spearman's rank coefficient r_s between X and Y is defined as:

$$r_s = \rho_{rg_X, rg_Y} = \frac{cov(rg_X, rg_Y)}{\sigma_{rg_X}\sigma_{rg_Y}} \tag{12}$$

Where ρ is the Pearson's correlation coefficient but applied on ranked values, $cov(rg_X, rg_Y)$ is the covariance of the ranked variables, and $\sigma_{rg_X}, \sigma_{rg_Y}$ is the standard deviation of the ranked values. Since Spearman's correlation measures the association between ranked observations rather than raw variables, monotonic transformations of initial variables do not affect the estimation of dependence; in contrast, estimates of Pearson's correlation stay unaffected only by linear transformations [162]. Similar to Pearson's correlation, the statistical significance of Spearman Rho can be formally inspected by using the p-value, which is often placed at 0.05, representing 95% confidence.

Similar to Spearman's Rho, Kendall's tau is also a non-parametric measure that evaluates the degree of similarity between two sets of ranked random variables [140]. The calculation in Kendall's tau is based on concordant and discordant pairs, which is different from Spearman's Rho as the latter is based on calculating the deviations between pairs. Let (X_i, Y_i) and (X_j, Y_j) be a pair of data observations and $i < j$. If $(X_j - X_i)$ and $(Y_j - Y_i)$ have the same sign, the pairs are concordant. If they have opposite signs, the pairs are discordant. There are $\frac{1}{2}n(n-1)$ pairs in a sample data set with size n for$1 \leq i < j \leq n$. If C represents the number of concordant pairs and D stands for the number of discordant pairs, then Kendall's tau (τ) can be calculated as:

$$\tau = \frac{2(C - D)}{n(n^2 - 1)} \tag{13}$$

Where *n* is the size of observation dataset. The maximum positive value (+1) of correlation occurs when all $\frac{1}{2}n(n-1)$ pairs are concordant. Consequently, the minimum correlation is achieved when all data pairs are discordant. Like previous methods, the statistical significance of correlations should be objectively inspected by using the *p*-value, and the significance level is often placed at 0.05.

4.3.3 Causality test

As mentioned earlier, the dependency analysis does not necessarily reveal causality. Testing causality requires exclusive statistical framework to quantify the significance of how occurrence of one event (cause) makes another event (effect) happens. One of the most intuitive explanations of causal relation between two time series was introduced by Wiene [163] and later formalized by

Granger in 1969 as a formal statistical test, known as "Granger causality" [136]. The test has been used in several hydroclimatology studies as it can be more effective than conventional lag-correlation analyses. Most importantly, the Granger test is used to find the causal effect of CO_2 on the global warming [164,165] as well as other important causal effects within the Earth System such as the effect of El Nino's southern oscillation on the Indian monsoon [166], the effect of sea surface temperature on the northern Atlantic oscillation [167], and the effect of snow and vegetation cover on the local climate [168] and vice versa [169].

Granger causality is based on prediction using linear autoregressive models [136]. There are two principles in this method: first, the cause is always prior to effect and second, the cause makes unique changes to the effect and if it is known can improve the prediction. To better understand the concept of Granger's causality, let's assume $x_1(t)$ and $x_2(t)$ are two separate time series. If we are better able to predict $x_1(t)$ by using the past value of both $x_1(t)$ and $x_2(t)$ rather than using the value of $x_1(t)$ alone, $x_2(t)$ should be the Granger cause of $x_1(t)$ [170]. Thus, the past values of $x_2(t)$ should contain information to predict $x_1(t)$ more accurately than using only the information contained in past values of $x_1(t)$. The procedure of Granger causality starts from modeling a particular effect (e.g., hydropower) only based on its own past values. For the regression model of order p, for $x_1(t)$ with $t = 1, 2, \dots, T,$ we have:

$$x_1(t) = \sum_{k=1}^{p} a_1(k)x_1(t-k) + u_1(t) \qquad (14)$$

Where $x_1(t)$ is the predicted time series, $u_1(t)$ is the prediction error, and $a_1(k)$ is the model coefficient. The order of the model can be empirically investigated by analyzing the autocorrelation of $x_1(t)$. The quality of the representation of $x_1(t)$ for the AR model may be assessed with the corresponding unbiased variance of prediction error. The variance of the prediction error based on simple auto regression would be:

$$\Sigma_{x_1|x_1^-} = \frac{1}{T-p}\sum_{t=1}^{T} u_2^2(t) = \frac{RSS_{x_1|x_1^-}}{T-P} \tag{15}$$

Where the prediction error of x_1 ($\Sigma_{x_1|x_1^-}$) depends only on its own past, T is the length of the time series, p is the order of the model, and $RSS_{x_1|x_1^-}$ is the residual sum of squares in the autoregressive model.

Alternatively, a bivariate AR model, including an exogenous variable (ARX), of order p can be used to simulate x_1 (hydropower) by considering both values of x_1 and x_2 (e.g. a climate variable) to build a Granger causal model [136]:

$$x_1(t) = \sum_{k=1}^{p} a_{1.1}(k)x_1(t-k) + \sum_{k=1}^{p} a_{1.2}(k)x_2(t-k) + w_1(t) \tag{16}$$

Where $x_1(t)$ is the predicted time series, $w_1(t)$ is the prediction error, $a_{1.1}(k)$ and $a_{1.2}(k)$ are the model coefficients. The variance of the prediction error of $x_2(t)$ for the ARX model would be:

$$\Sigma_{x_2|x_2^-,x_1^-} = \frac{1}{T-2p}\sum_{t=1}^{N} w_2^2(t) = \frac{RSS_{x_2|x_2^-,x_1^-}}{T-2p} \tag{17}$$

Where the prediction error of x_2 ($\Sigma_{x_2|x_2^-,x_1^-}$) depends on the past values of two signals (both hydropower and climate). According to the definition of Granger causality, if the prediction error for x_1 calculated in the ARX model is smaller than the prediction error that is calculated in the AR model, it then indicates that x_2 could be a cause of x_1 [136].

Two separate conditions are defined to decide whether x_2 is the cause or not. The first condition is based on the Bayesian Information Criterion (BIC), which is a measure to evaluate the complexity and performance of the model at the same time:

$$BIC = n \times ln(\frac{RSS}{n}) + k \times ln(n) \tag{18}$$

Where n is the sample size, RSS is the sum of squared residuals, and k is the number of free parameters in the model. The lower BIC indicates the better performance. By comparing the BIC between corresponding AR and ARX models, it would be possible to understand whether adding x_2 can make any improvement in the predictability of x_1 or not.

The second condition is based the formal statistical *F*-test, which quantifies the relative improvement in prediction when moving from the AR model to the ARX model [171]. The *F*-test estimator can be formulated as the following:

$$F\ test = \frac{(RSS_R - RSS_U) / (p_2 - p_1)}{RSS_U / n - p_2} \tag{19}$$

Where RSS_R and RSS_U is the sum of squared residuals for the AR and ARX models respectively, p_1 and p_2 are the number of regression parameters for the AR and ARX model respectively, and n is the number of observations. The probability value of the F-test is calculated as the following, where F is the value of the F-test, and $fcdf$ is the cumulative distribution function of the standard F distribution:

$$p = 1 - fcdf\ (F) \tag{20}$$

The value of $p \leq 0.05$ is considered a statistically significant event.

4.3.4 Statistical models for monthly prediction of hydropower generation

Having the climatic causes of monthly hydropower production identified at each province, various predictive models can be developed by combining past values of hydropower production (i.e. endogenous term) and climate causes (i.e. exogenous term). Here, four schemes are considered that differ from one another in terms of how climate causes are considered. In the Scheme A, hydropower is simulated as a function of hydropower generation at previous time steps and the dominant climate causes of hydropower generation at each time lag. Dominant climate cause at each time step is the climate variable that makes the most improvement in the prediction of AR model, if included as an exogenous variable in the ARX model. Scheme B is similar to Scheme A, however not only the dominant climate causes at each time step are considered, but also their values in the previous time steps are also considered. In scheme C, hydropower is modeled as a function of hydropower values in previous time steps and all the climatic causes of hydropower at each time lag. Scheme D is similar to Scheme B but apart from the dominant climate cause at each time step, all climate causes are considered. Hence, scheme A is the simplest model and scheme D is the most complex model in comparison with the others. Table 4.1 summarizes the details and description of the four scheme considered for building predictive models.To systematically develop and test predictive models, the available data is divided into two parts, related to calibration and validation of predictive models. The first 80% of the data is used as a “training period” and the last 20% is selected as a “testing period.” During the training period, the coefficients of the predictive models are identified and the predictive performance is evaluated using a set of measure. Using the extracted parameters during the training period, monthly hydropower is simulated for the remaining 20% of data.

Table 4.1 *Four setups for developing predictive models for monthly hydropower production of hydropower*

Scheme ID	Endogenous component	Exogenous component	Model formulation
A	Hydropower in previous time steps	dominant climate causes of hydropower at each previous steps	$H_t = \sum_{i=1}^{p} [a_i H_{t-i} + b_i C_{t-i}]$
B	Hydropower in previous time steps	dominant climate causes of hydropower at all previous time steps	$H_t = \sum_{i=1}^{p} [a_i H_{t-i} + b_i C_{t-i}] + \sum_{j=1}^{i-1} c_j C_{t-j}$
C	Hydropower in previous time steps	all climate causes of hydropower at each previous time steps	$H_t = \sum_{i=1}^{p} [a_i H_{t-i} + \sum_{j=1}^{d} b_{i,j} C_{j,t-i}]$
D	Hydropower in previous time steps	all climate causes of hydropower at all previous time steps	$H_t = \sum_{i=1}^{p} a_i H_{t-i} + \sum_{j=1}^{d} b_{i,j} C_{j,t-i} + \sum_{k=1}^{i-1} c_j C_{t-j}]$

Competitive predictive models are compared based on their error measures during the testing period. Apart from BIC, other goodness-of-fit indices namely Root Mean Square Error (RMSE) and coefficient of determination (R^2) are also considered to ensure the integrity of the developed models. In brief, RMSE and R^2 can be calculated as the following:

$$RMSE = \sqrt{\frac{RSS}{n}} \tag{21}$$

$$R^2 = 1 - \frac{RSS}{SS_{Tot}} \tag{22}$$

Where RSS is the sum of the squared residual, n is the number of sample data and SS_{Tot} is the total sum of squares, calculated as follows, where x_i and y_i are the observed and predicated values:

$$SS_{Tot} = \sum_{i=1}^{n} (x_i - \bar{x}_i)^2 \tag{23}$$

5 Results and discussion

This chapter is divided into two main sections. The first section summarizes and discusses the findings with regard to sensitivity of the provincial hydropower production to climate variability and change. The second section is dedicated to findings with respect to links between local wind speed and local temperature. The results in both sections are organized in a way that correspond directly to the specific objectives in Chapter 2.

5.1 Sensitivity of provincial hydropower production to climate variability and change

The findings in this section are organized by (1) assessing the reliability of the upscaling methodology for converting the station-based climate observations to lumped province-wide estimates; (2) analyzing the trend in province-wide climate variables across monthly, seasonal and annual time scales; (3) analyzing the dependency between climate variable and hydropower production at the provincial scale with consideration of lag up to 1 year; (4) inspecting climate causes of provincial hydropower production; (5) developing predictive models for monthly hydropower production; and finally (6) assessing the impact of existing provincial climate trends on expected monthly hydropower production at the provincial scale.

5.1.1 Assessing the reliability of upscaling methodology

Before going through specific analyses of trends, dependency and casualty between climate variables and hydropower generation, the reliability of the upscaling methodology, used to transfer multiple station-scale data to a lumped provincial-scale estimate, should be assessed. To explore this, four experiments are performed to compare the upscaled climate with station-based data. First, the monthly upscaled data at each province and/or territory are compared with the station-scale data as well as the arithmatic mean of all stations (i.e. expected province-wide estimate) – see Figure 5.1 as an example for the analysis for the mean monthly temperature in Québec. The grey boundary indicates the envelope of a time series of mean temperature in Québec stations. The red lines indicate the upscaled mean temperature obtained from the gridding method used for upscaling. The blue dashed lines indicate the arithmetic mean temperature. Both mean and upscaled value confirm the pattern, altough there are obvious differences between the arithmatic mean and upscaled values in warm and cold months. Such differences can be traced in the mechanism of upscaling using the gridding method and the hetrogenity in the distribution of climate station over a provincial landmass. For example, Figure 5.2 shows the distrubtion of temperature stations over the province of Québec, with which Figure 5.1 is created.

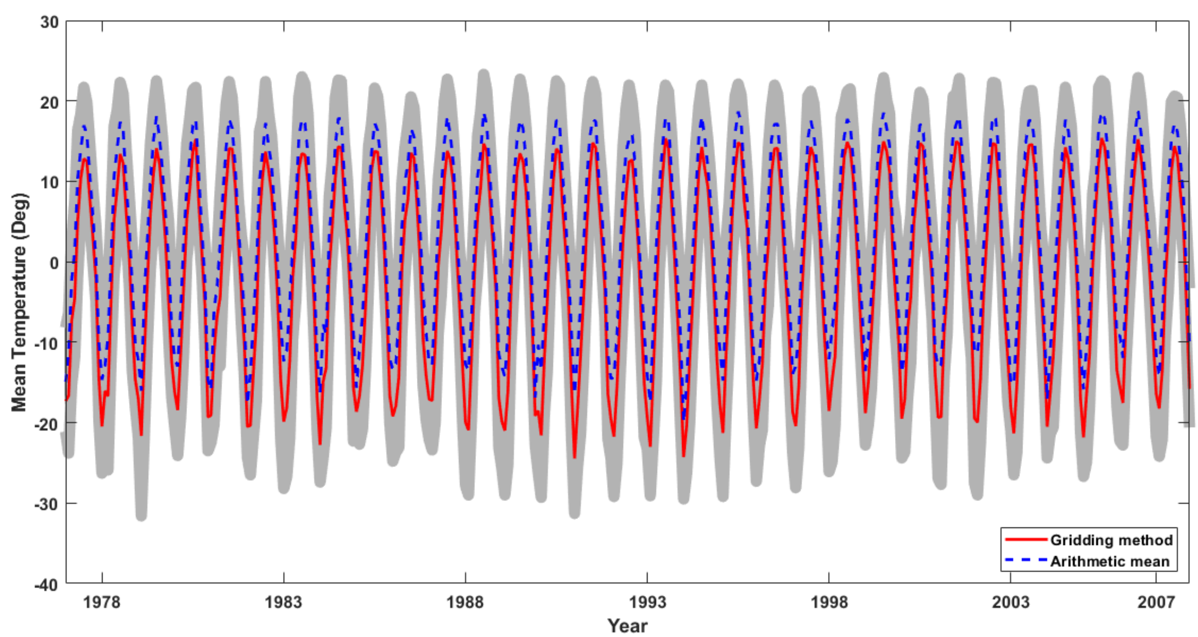

Figure 5.1 *Monthly time series of mean temperature across climate stations in Québec (grey envelope) along monthly upscaled provincial temperature calculated using the arithmetic mean (dashed blue line) and gridding method (solid red line).*

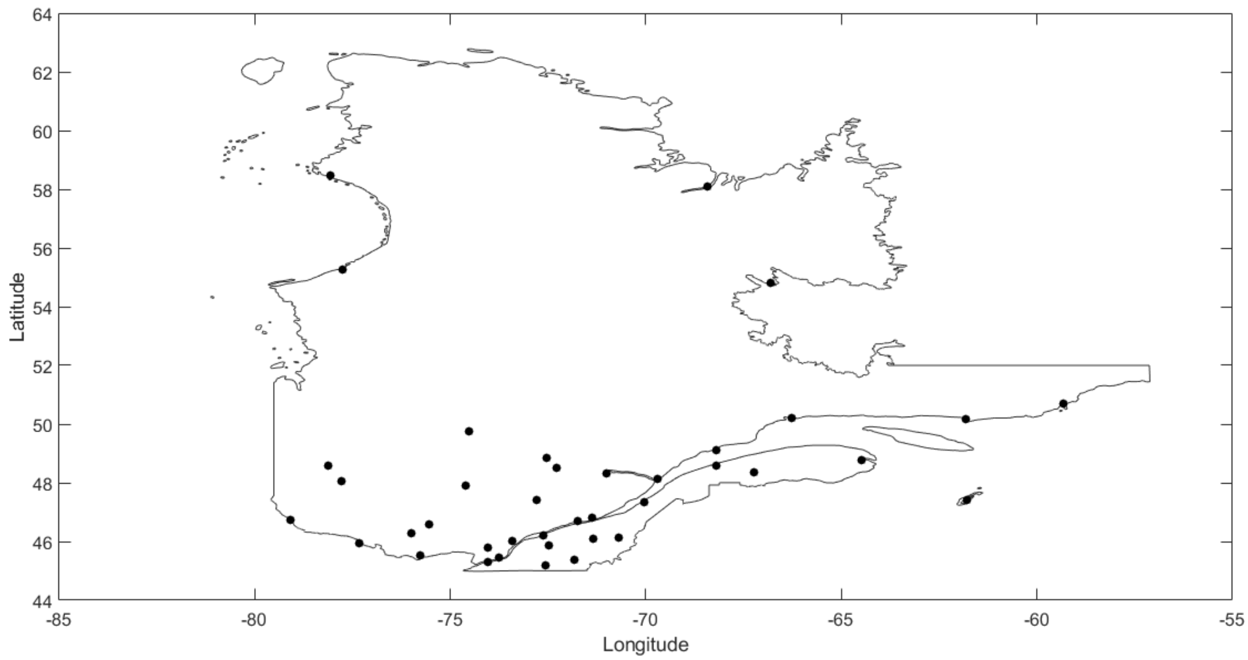

Figure 5.2 *Heterogeneous distribution of temperature stations across Québec*

As figure 5.2 shows, the majority of stations are located in the southern parts and northern regions include a sparse set of stations. As a result, the gridding method inclines to colder temperature due to the higher weights of northern stations. More homogenious distribution of climate stations can be seen in New Brunswick (see Figure 5.3), in which stations across the provinicial landmass are more evenly distributed and threfore has similar weights. This leads in more agreement between the results of the gridding method and arithmatic mean – see Figure 5.4. As a result, the distribution of the stations across the provincial region causes the differences in the estimates. This analysis is repeated for other climate varibales and for all regions. It is occurred that differences between arithmatic mean and upscaled values are very limited in the case of precipitation, snowfall, and rainfall.

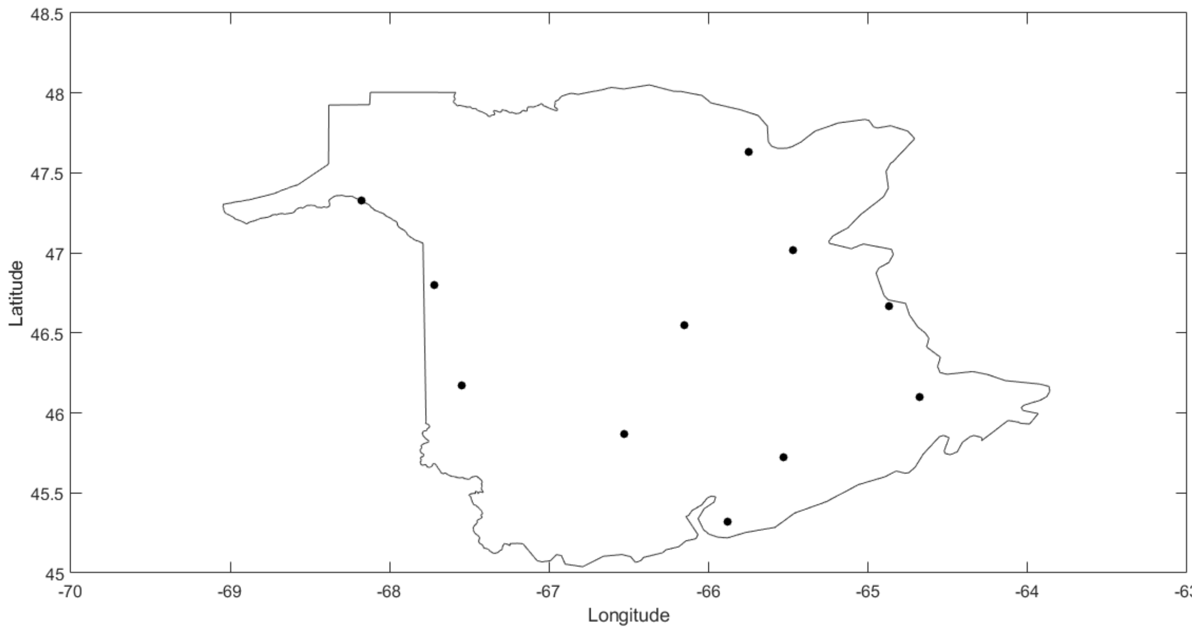

Figure 5.3 *Homogeneous distribution of temperature stations across New Brunswick*

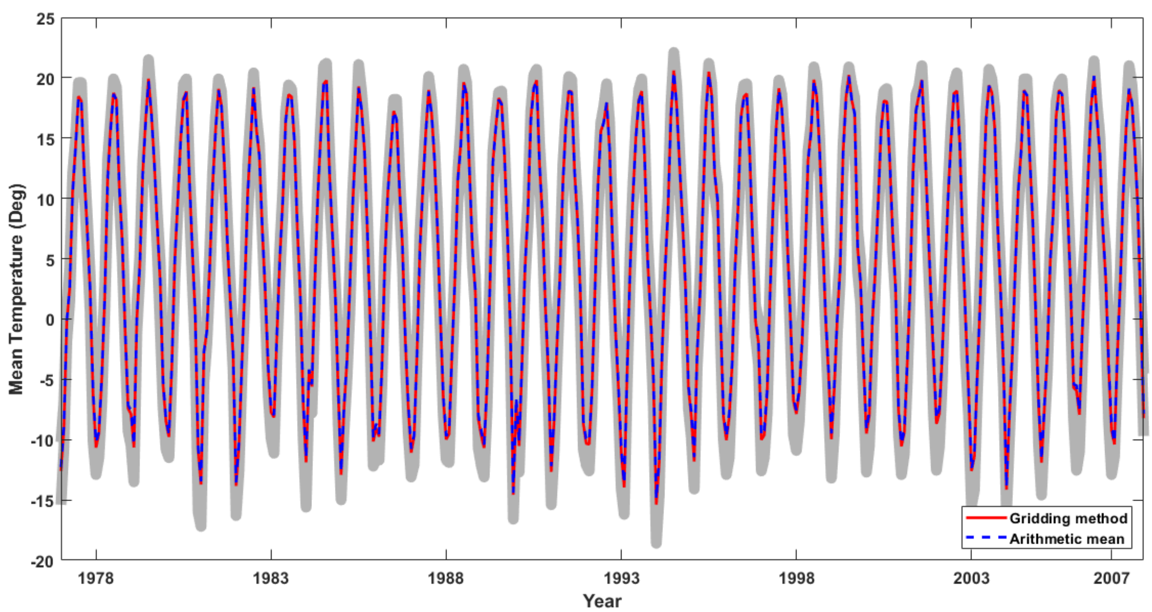

Figure 5.4 *Monthly time series of mean temperature across climate stations in New Brunswick (grey envelope) along monthly upscaled provincial temperature calculated using the arithmetic mean (dashed blue line) and gridding method (solid red line).*

To better inspect the performance of upscaling using the gridding method, the anomaly in annual climate variables at station scales are compared with upscaled provincial values – see Figures 5.5 to 5.8 for temperature, precipitation, snowfall, and rainfall respectively. In these figures, the annual time series at the station-scale are shown by the grey envelope and the estimated provincial-scale climate variable obtained by the gridding method is demonstrated by the red line. As it can be inspected for all climate variables and/or provinces, the upscaled annual variables are within the envelope and there is no under- or over-estimation beyond the variability observed at the station-scale.

To better understand how the gridding method can maintain the same pattern of change in station-scale variables, the trend in anomaly of climate data at each station is calculated for all considered climate variables across all provinces. Simultaneously, the trend of the upscaled anomaly is also calculated and compared with their corresponding station-scale trends in anomalies. The results are depicted in Figures 5.9 to 5.12 for temperature, precipitation, snowfall, and rainfall respectively. In these figures, the distribution of station-scale trends are shown by box plots, while stars illustrate the trend of the upscaled anomaly time series. The results confirm that the trends of upscaled climate anomalies are in the range of station trends in all cases, expect for NU&NT for the mean temperature in which there are very sparse stations within a large landmass that are distributed unevenly. In general, the results demonstrates the liability of the upscaling methodology in estimating a lumped climate estimate over a large region using an arbitrary distribution of climate stations. In the following sections, the upscaled monthly climate values are used for inspecting trends in climate variables at the provincial scale as well as the understanding the dependency between climate variables and hydropower production.

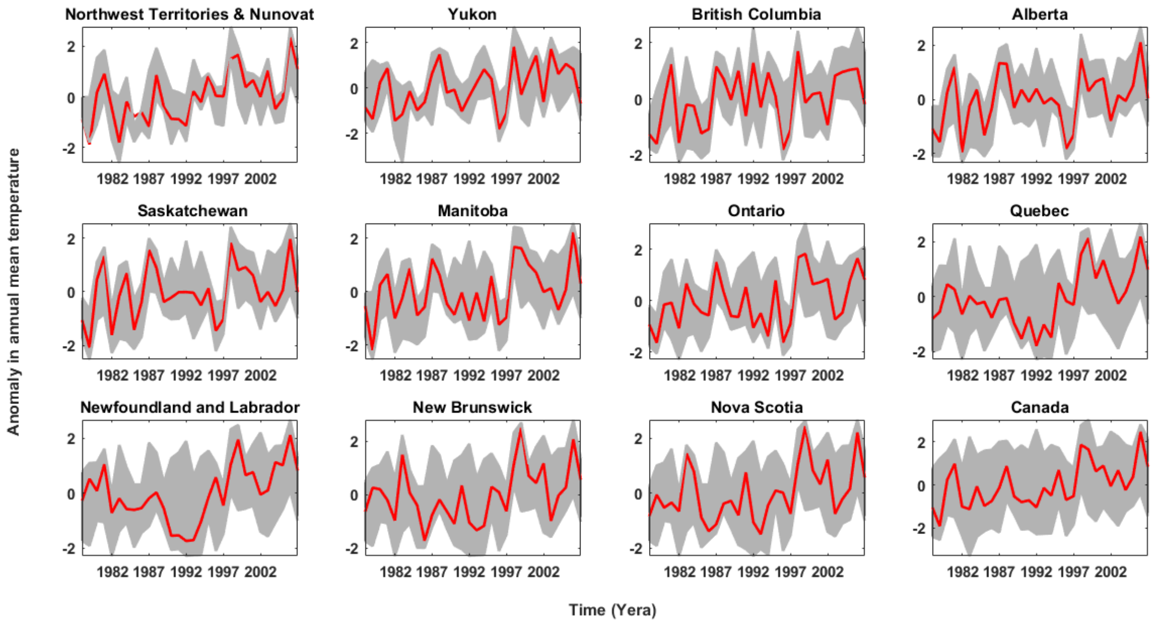

Figure 5.5 *Anomaly in annual mean temperature at stations (grey envelope) versus anomaly in the upscaled provincial temperature (red line).*

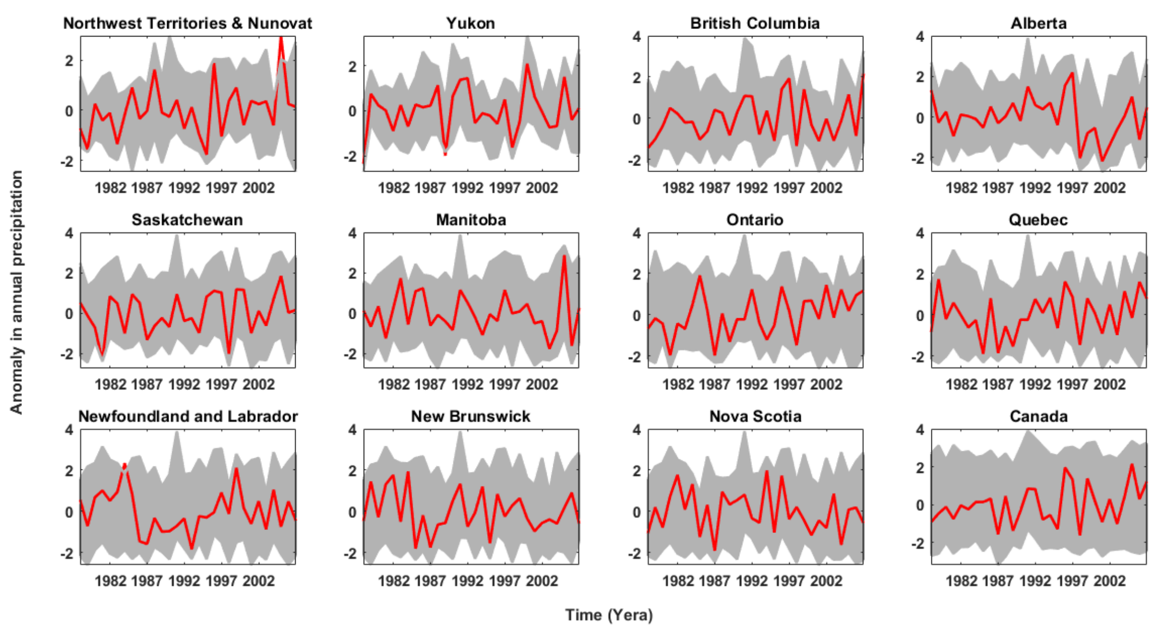

Figure 5.6 *Anomaly in annual mean precipitation at stations (grey envelope) versus anomaly in the upscaled provincial precipitation (red line).*

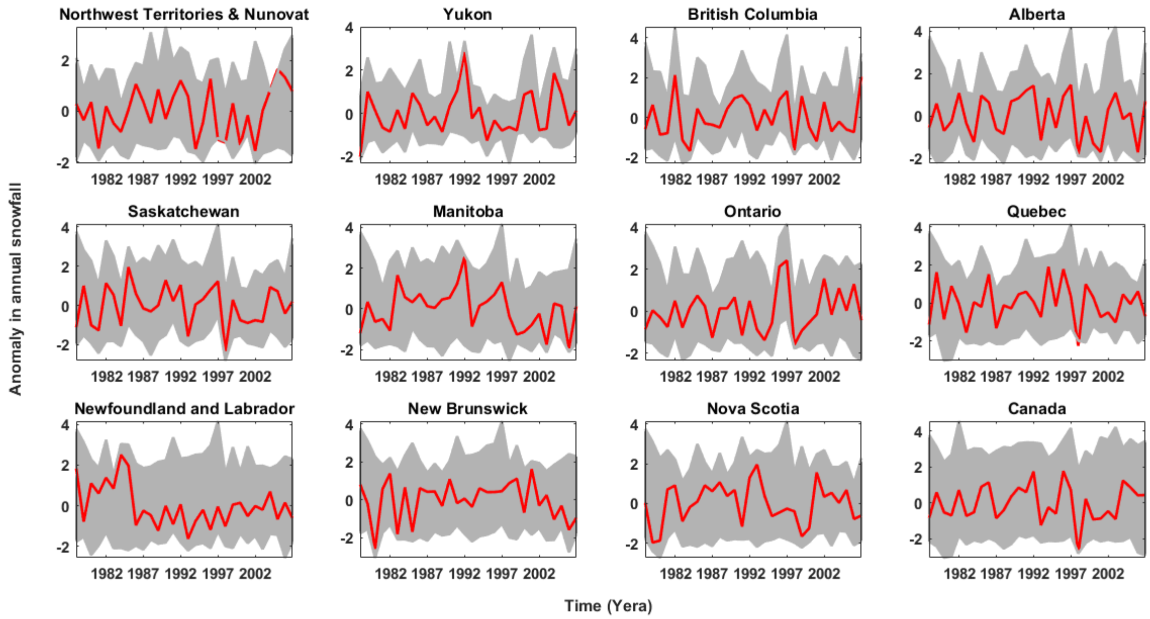

Figure 5.7 *Anomaly in annual mean snowfall at stations (grey envelope) versus anomaly in the upscaled provincial snowfall (red line).*

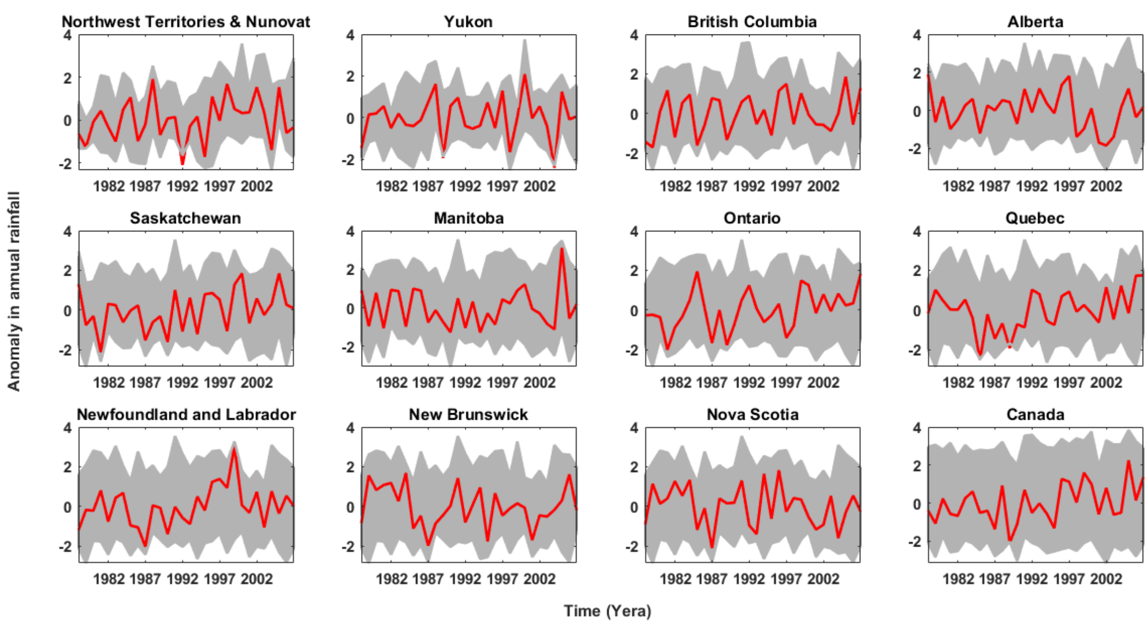

Figure 5.8 *Anomaly in annual mean rainfall at stations (grey envelope) versus anomaly in the upscaled provincial rainfall (red line)*

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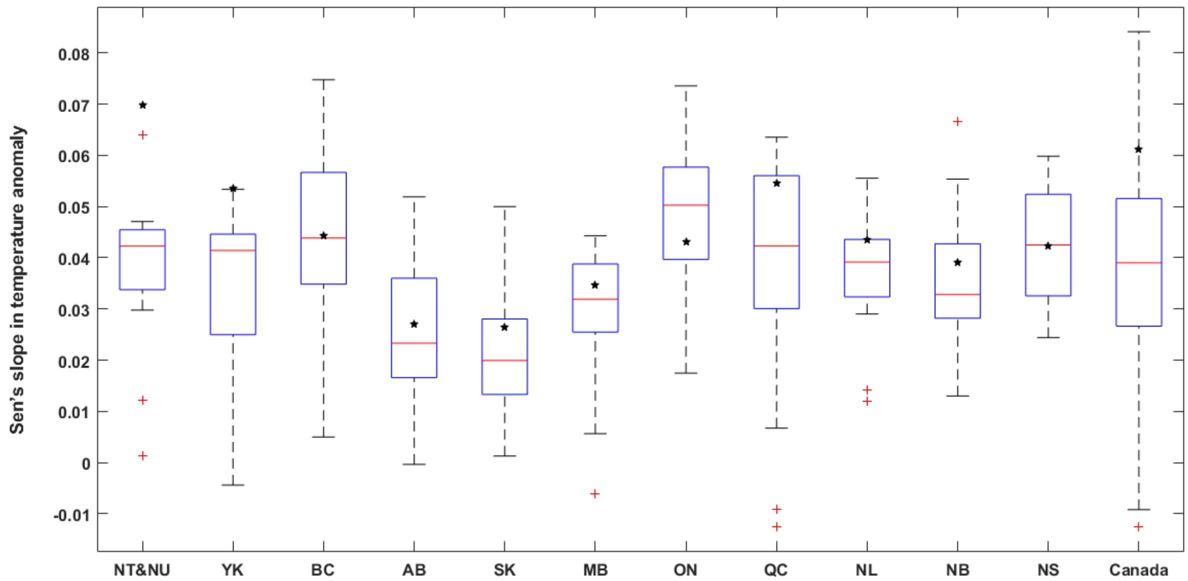

Figure 5.9 *Trend in the station-scale anomaly of mean temperature (boxplots) versus anomaly in provincially upscaled temperature (black stars).*

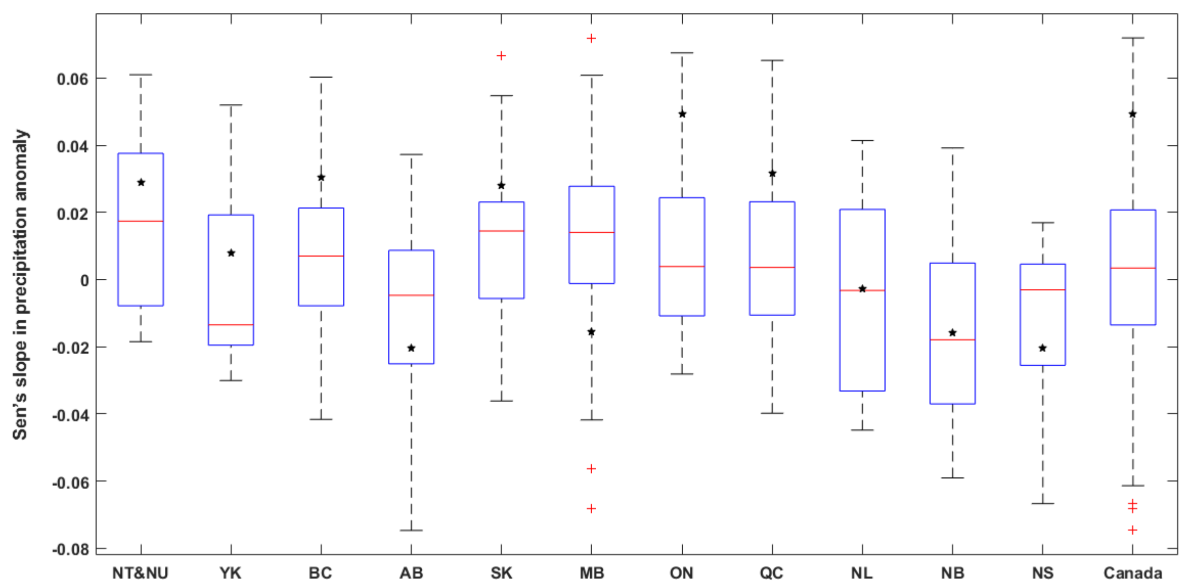

Figure 5.10 *Trend in the station-scale anomaly of annual mean precipitation (boxplots) versus anomaly in provincially upscaled annual precipitation (black stars).*

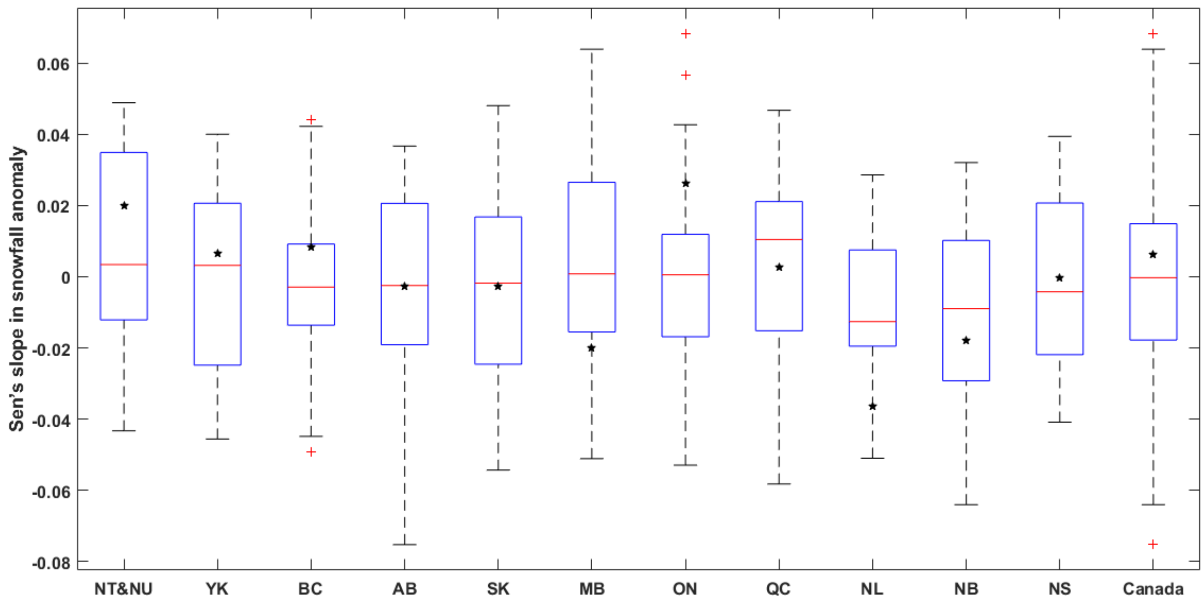

Figure 5.11 *Trend in the station-scale anomaly of mean annual snowfall (boxplots) versus anomaly in provincially upscaled annual snowfall (black stars).*

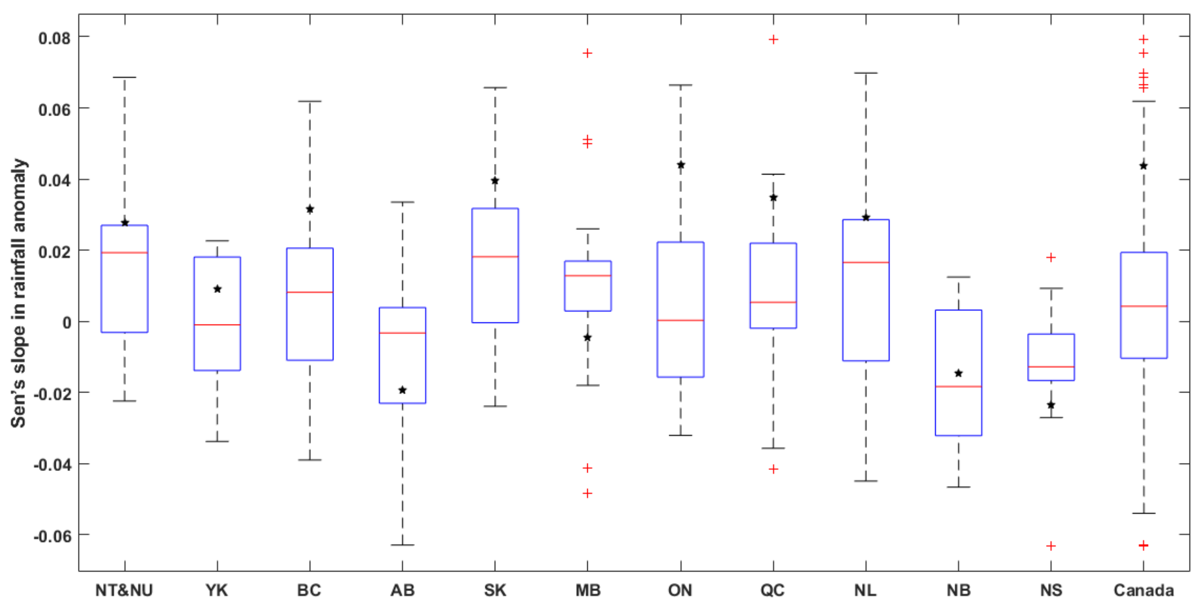

Figure 5.12 *Trend in the station-scale anomaly of mean annual rainfall (boxplots) versus anomaly in provincially upscaled annual rainfall (black stars).*

5.1.2 Analysis of climate trends across Canadian regions

In the following, the result of the Mann-Kendall trend analysis on the anomaly of upscaled climate variables are illustrated at monthly, seasonal, and annual scales using a set of standardized heat maps, in which x-axes indicate the time scale. Provinces are ordered in the y-axis based on their location. From top to bottom, it starts with the northern territories, then goes from western Canada to East and finally presents values for Canada as a whole. In each cell, upside triangles indicate the positive trend and downside triangles represent a negative trend and the significant events at 95% confidence are illustrated by filled triangles. The magnitude of trend in region-wide anomalies in climate variables are represented by colors.

5.1.2.1 Mean temperature

Figure 5.13 represents the results of Mann-Kendall trend analysis on provincial, territorial, and country-wide anomalies in mean temperatures at monthly, seasonal, and annual scales. As the figure clearly shows, the majority of trends are positive across various temporal and spatial scales. All significant events are positive and no significant negative event can be captured. During the winter, all provinces experienced an increase in mean temperature, with significant increases in NT&NU, BC, and Canada. During spring, the trend was significant and positive in YK and BC; but it was insignificant and negative in SK and MB, and insignificant and positive in other provinces. The mean temperature increased during the summer across all provinces. The captured trends were significant in all provinces except for in YK, AB, and SK. It is also shown that the mean temperature increased in the fall across all provinces. These increasing trends were significant in NT&NU, QC, and the Atlantic provinces. In the annual scale, significant and positive trends were captured in all provinces except in MB, which is still positive but not significant. Based on the trend analysis performed, it can be vividly highlighted how Canada is warming, which can cause significant alteration in hydrological processes that form runoff generation.

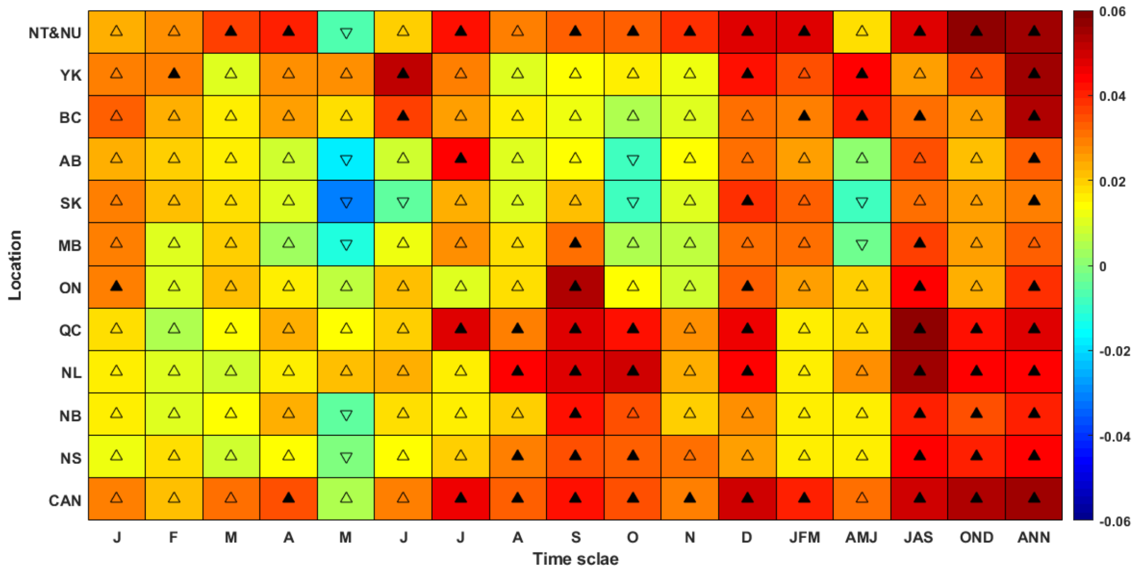

Figure 5.13 *Results of the Mann-Kendall trend test for provincial, territorial and country-wide anomalies in mean temperature at monthly, seasonal and annual scales. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of Sen's slope is shaded by* the color code in the side bar. *Significant level is considered at 95% confidence.*

5.1.2.2 Total precipitation

Figure 5.14 shows the results for the Mann-Kendall trend analysis for provincial, territorial, and country-wide anomalies in total precipitation at monthly, seasonal, and annual scales. In the monthly analysis, the trend in precipitation can be divergent across various spatial and temporal scales. For instance, in the northern territories, it is positive in January, March, June, July, November, and December but negative in April and October. Also, in the western provinces, precipitation increased mainly in January and May, but decreased in February, July, and December. The trends are also positive in the eastern provinces through May to July, as well as

September to November. In terms of seasonal analysis, northern territories experienced increases in total precipitation during the winter. The trend was also positive in MB, QC, and NL, but the significant trend event occurred in NT & NU. The rest of provinces (i.e. BC, AB, SK, OB, NB, and NS) experienced insignificant negative trends in total precipitation. In the spring, positive trends were captured in NT&NU, BC, and ON and other regions show insignificant negative trends. During the summer, most provinces experienced an increase in total precipitation except in AB, MB, NB, and NS; but captured trends are insignificant during this season. Total precipitation increased across the northern territories, BC, SK, as well eastern provinces but decreased in others during the fall. The only significant event took place in ON with a positive trend. In annual scale, northern territories experience an increase in total precipitation, which is significant in NT&NU. In the AB, the precipitation significantly decreased, while ON experienced a significant increase.

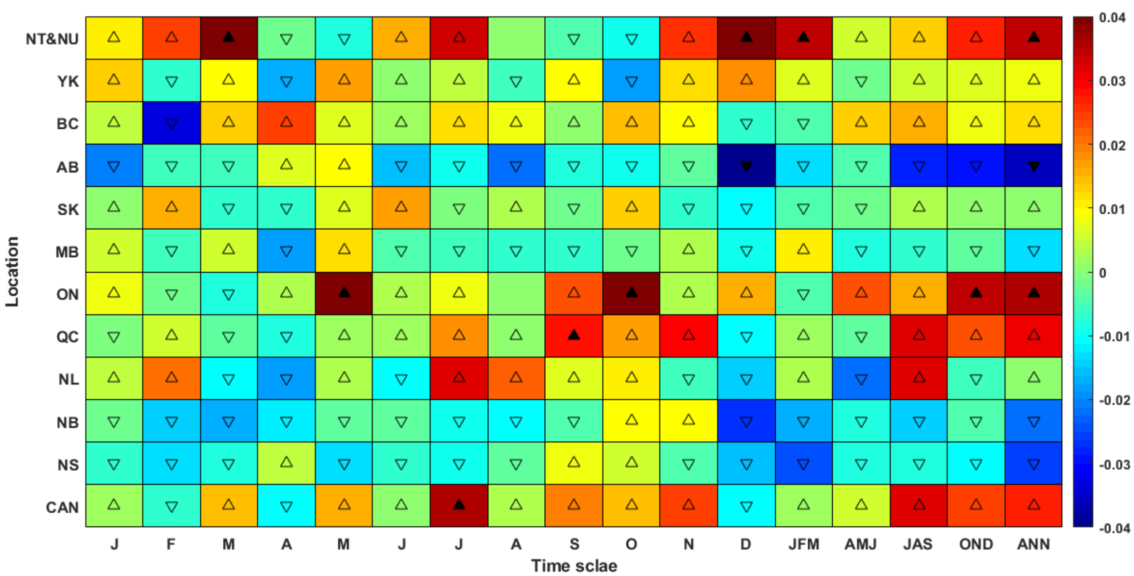

Figure 5.14 *Results of the Mann-Kendall trend test for provincial, territorial and country-wide anomalies in total precipitation at monthly, seasonal and annual scales. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of Sen's slope is shaded by t*he color code in the side bar. *Significant level is considered as 95% confidence.*

5.1.2.3 Total snowfall

Figure 5.15 presents the Mann-Kendall trend analysis for provincial, territorial, and country-wide anomalies in snowfall at monthly, seasonal, and annual scales. Similar to precipitation, the trends of snowfall anomalies show different patterns across various temporal and spatial scales; however, it is clear that significant trends are mostly negative. In general, during the winter, the amount of snowfall increased in the northern territories, but the observed trends remain insignificant. Snowfall has decreased along western, eastern, and Atlantic Provinces except in MB, QC, and NL. However both negative and positive trends are insignificant. In spring, all regions show negative trends in anomalies of snowfall except in ON, which shows an insignificant positive trend. During the summer, northern territories show negative trends, which is significant in NT&NU. The amount of snowfall decreased during fall across the whole country except in the northern parts of Canada and ON. However, the only significant event in this season occurred in NL. In the annual scale, the snowfall increased in NT&NU but insignificantly. On the other hand, snowfall decreased over western, eastern, and Atlantic provinces except in ON. The negative trend was significant in NL and NB.

5.1.2.4 Total rainfall

Figure 5.16 represents the Mann-Kendall trend analysis for provincial, territorial, and country-wide anomalies in rainfall at monthly, seasonal, and annual scales. Similar to precipitation and snowfall, the pattern of change in rainfall is not the same across various spatial and temporal scales, however, it seems that the number of positive events outnumber negative trends and increasing trends are stronger in summer and fall. Total rainfall increased across the country except in ON, QC, and NS during the winter. Having said that, the only significant trend captured in SK.

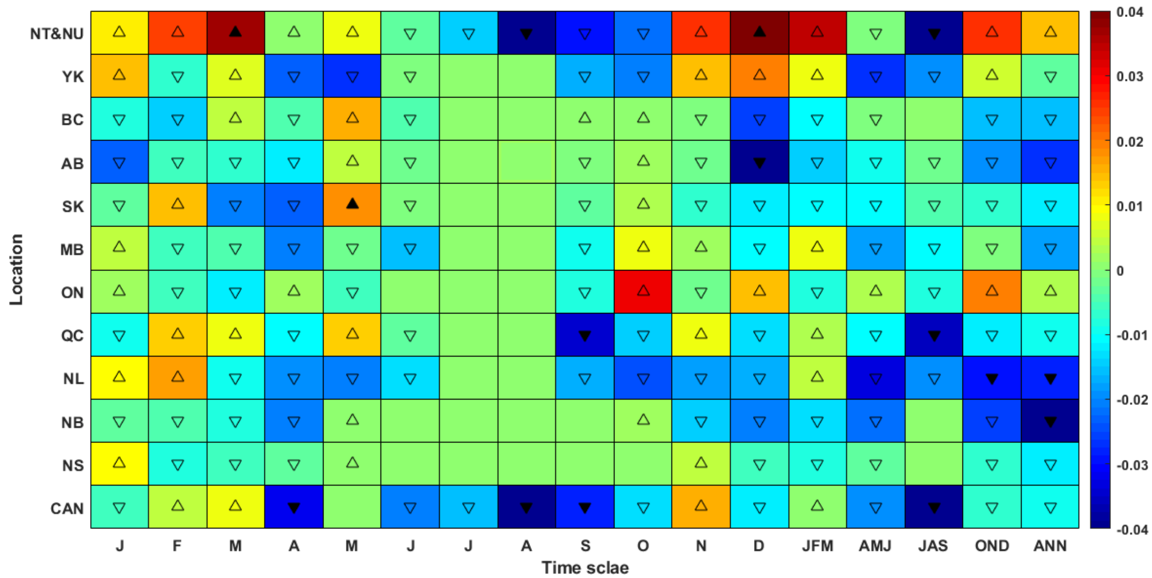

Figure 5.15 *Results of the Mann-Kendall trend test for provincial, territorial and country-wide anomalies in snowfall at monthly, seasonal and annual scales. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered as 95% confidence.*

Total rainfall increased across entire provinces except in AB, NL and NS during the spring; however all trends occurred to be insignificant. During the summer, all provinces experienced increased rainfall except for AB, NB, and NS. The captured increasing trends were significant in NT&NU, QC, and NL. During the fall, trends in rainfall were positive in all provinces except in AB, MB, and NS. These trends were significant over QC and Canada as a whole. In the annual scale, trends were positive in northern regions, which is significant in NT&NU. In the western provinces, BC and SK experienced an increase in rainfall, but decreased trend were observed in AB and MB. The positive trend in BC occurred to be significant. At the annual scale, rainfall also increased significantly in the eastern provinces; however across Atlantic provinces, only NL experienced a significant increase in rainfall. Generally speaking, it can be concluded that Canada is gradually becoming a wetter country.

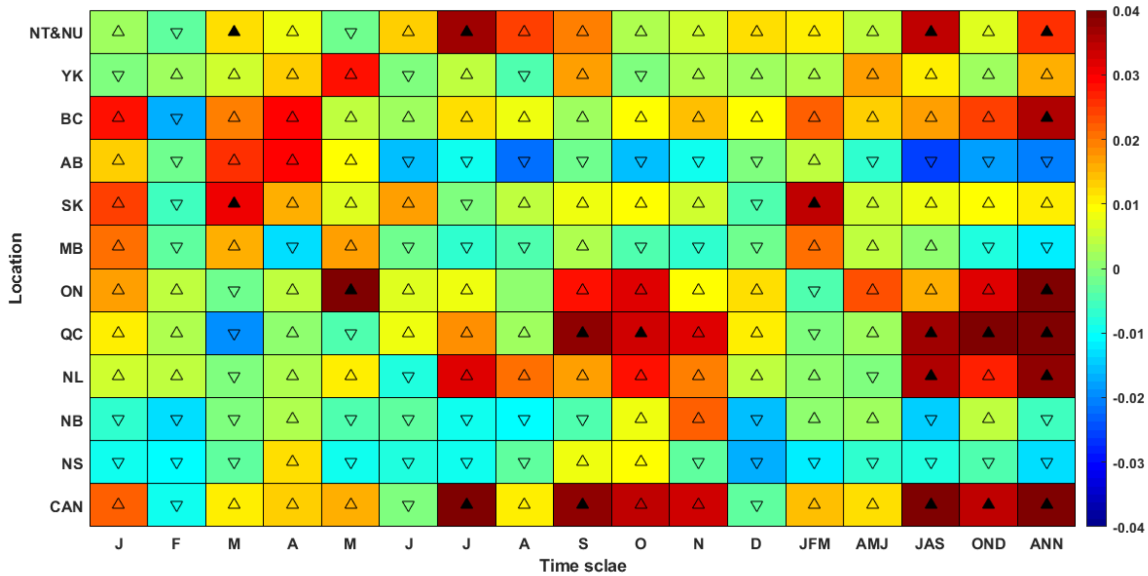

Figure 5.16 *Results of the Mann-Kendall trend test for provincial, territorial and country-wide anomalies in rainfall at monthly, seasonal and annual scales. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered as 95% confidence.*

5.1.3 Analysis of climate-hydropower dependency across Canadian regions

This section presents the results of dependency analyses between the four considered climatic variables and hydropower generation across Canadian regions. Similar to the analyses of trends presented in the previous section, the results are summarized in heatmaps that are organized very similar to those for trend analysis. The only difference is related to the arrangment of x-axes that are indicating the lagged climate variables sorted from 0 to 11 months. The reason for consideration of lag up to 11 months is the fact that hydrological processes that affect runoff generation have annual occuance. Positive and negative dependencies are shown with upward and downward triangulars. Significant dependencies (p-values ≤ 0.05) are shown with filled triangles.

5.1.3.1 Mean temperature and hydropower production

Figure 5.17 shows the results of the Kendall tau test for monthly lagged dependencies between mean temperature and hydropower production across various regional scales. Except for AB, the relation between mean temperature and hydropower generation is significantly negative in all provinces in the first months, excluding Saskatchewan in which the dependence is negligible. After a few months. However, the negative dependency becomes positive. The behavior in AB is inverted as the relation is significantly positive in first months, and then becomes negative.

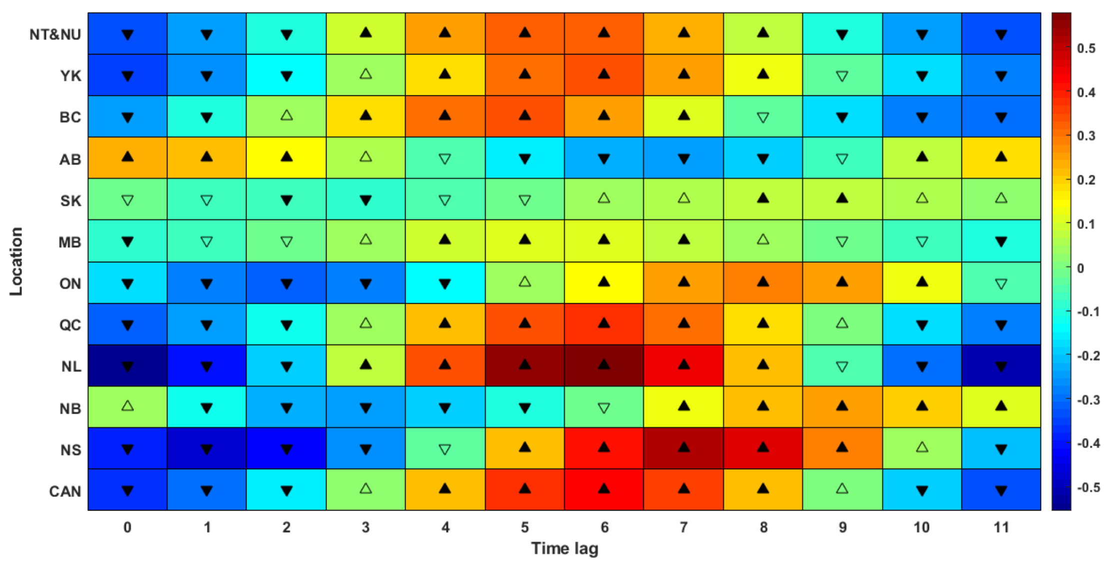

Figure 5.17 *Results of the Kendall tau test for identifying lagged dependency between temperature and hydropower production at provincial, territorial and country-wide scales. For each case, the direction and significance of dependency is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of dependency is shaded by the color code in the side bar. Significant level is considered at 95% confidence limit.*

The results obtained are justifiable as the water from snow/ice melting is not immediately used for power generation. In other words, the life cycle of snow melt-runoff-storage-hydropower generation takes a few months.

5.1.3.2 Precipitation and hydropower production

Figure 5.18 shows the results of the Kendall tau test for identifying lagged dependency between precipitation and hydropower production at provincial, territorial and country-wide scales. The figure vividly illustrates the significant dependency between precipitation and hydropower generation is majority of time scales and/or spatial regions.

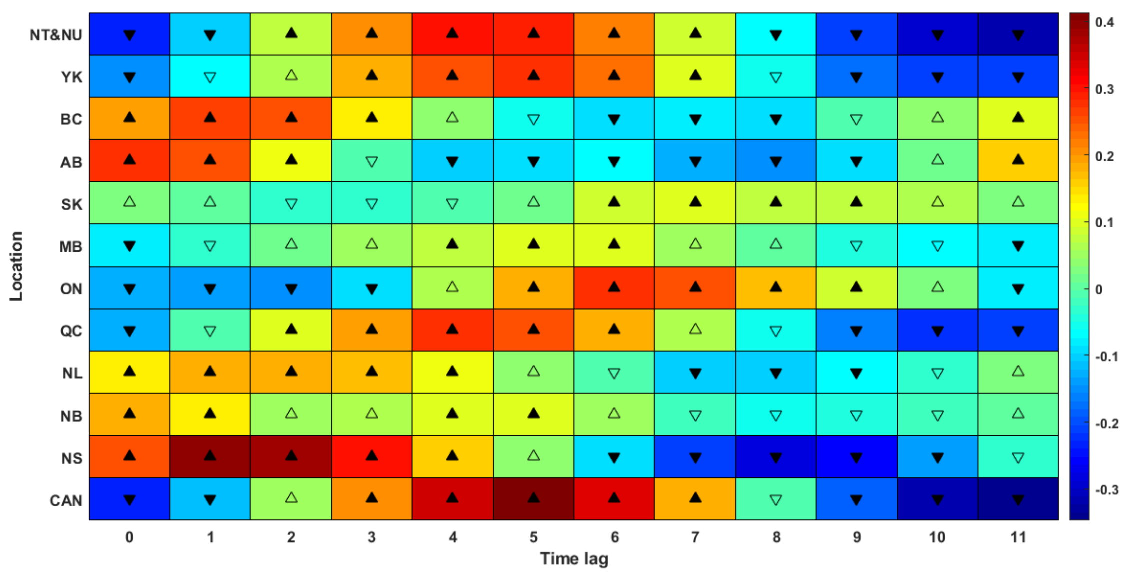

Figure 5.18 *Results of the Kendall tau test for identifying lagged dependency between precipitation and hydropower production at provincial, territorial and country-wide scales. For each case, the direction and significance of dependency is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of dependency is shaded by the color code in the side bar. Significant level is considered at 95% confidence limit.*

Few patterns can be seen in the dependency between precipitation and hydropower production, which can reveal some important high level knowledge on the large-scale mechanism of hydropower generation across Canadian regions. In the first few lags, there are two distinct patterns showing different effects of total precipitation on hydropower generation in AB, BC as well as Atlantic provinces (i.e. positive effect) vs. what is observed northern and eastern regions as well MB (i.e. negative effect). First it should be noted that the mechanism of runoff generation in mountainous BC and AB is largely different from those in Quebec and Ontario, in which negative dependence within the first time lags explain unproductive spillage. It has been shown that immediate precipitation and an increase in streamflow could be released as an unproductive spill [172]. A historical example in Quebec includes additional release ordered by Hydro-Quebec in 1996 to preserve the integrity of storage system against heavy rainfall, which did not added to power generation due to the turbine capacity [173]. The negative dependency, however, change to positive after few months lags except in mountainous provinces. Saskatchewan resembles an exception as the hydropower generation in this province is not significantly dependent on its own precipitation. Manitoba also has a negligible dependency in comparison with other provinces, meaning that the power generation in Manitoba and Saskatchewan is not significantly dependent on local precipitation in those provinces. This finding is intuitively appealing considering the hydrography of the Canadian Prairies as water in SK and MB is mainly contributed from upstream province of AB.

5.1.3.3 Snowfall and hydropower production

Figure 5.19 shows the results of the Kendall tau test for identifying lagged dependency between snowfall and hydropower production at provincial, territorial, and country-wide scales. All provinces except for Alberta and New Brunswick show a positive dependency between snowfall and hydropower production in the first months. These dependencies are statistically significant in a majority of regions, excluding Manitoba. The lack of significant dependency between snowfall and hydropower production in MB can be traced back to the fact that majority of water availability for hydropower production in Manitoba is contributed from the mountainous headwaters in the upstream province of Alberta. As the lag between snowfall and hydropower production increases, positive dependencies turn to negative.

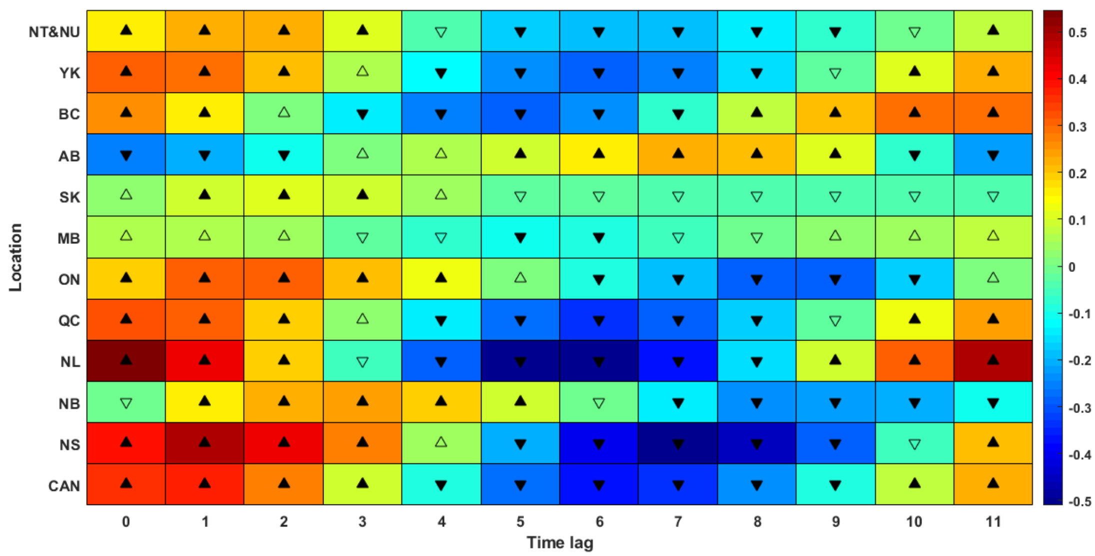

Figure 5.19 *Results of the Kendall tau test for identifying lagged dependency between snowfall and hydropower production at provincial, territorial and country-wide scales. For each case, the direction and significance of dependency is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of dependency is shaded by the color code in the side bar. Significant level is considered at 95% confidence limit.*

5.1.3.4 Rainfall and hydropower production

Figure 5.20 shows the results of the Kendall tau test for identifying lagged dependency between rainfall and hydropower production at provincial, territorial, and country-wide scales. Hydropower generation in all provinces has a negative dependency with rainfall in the first time lags except in Alberta, New Brunswick, and Nova Scotia. This negative pattern is longer and more significant in Ontario. Similar to total precipitation and hydropower dependency, this relation is weaker in Manitoba and Saskatchewan. The pattern of this relation is also significantly negative in Canada for the first three months, and then changes to significantly positive. Similar to the hydropower and precipitation dependency, one of the possible reasons which could explain the negative dependency at the first-time steps and then evolution into positive dependency after more lag time is the impact of storage and the fact that immediate rainfall can go to unproductive spillage if the reservoir storage is already full.

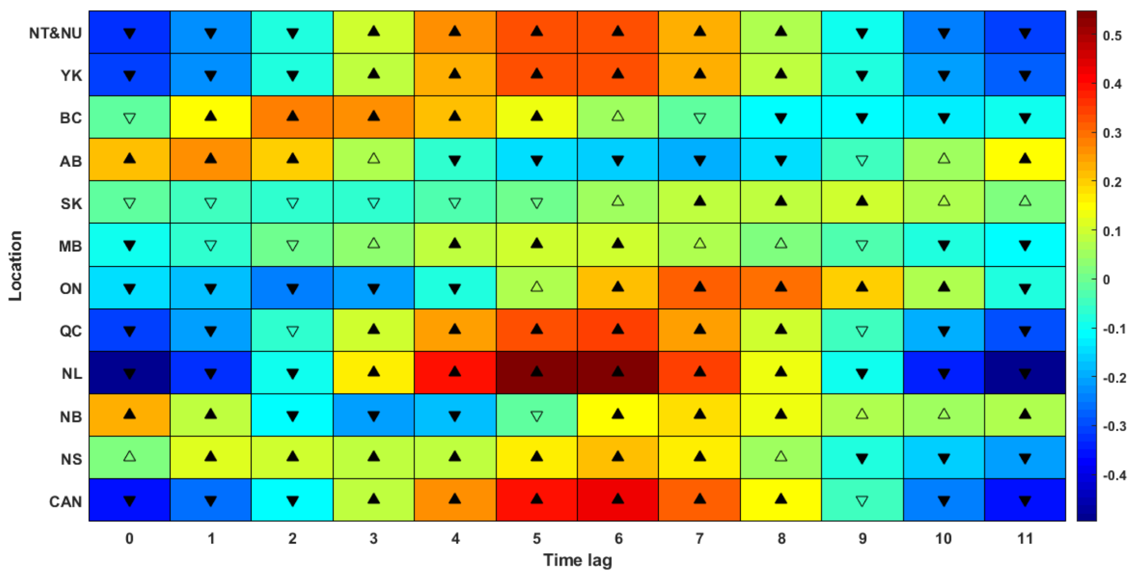

Figure 5.20 *Results of the Kendall tau test for identifying lagged dependency between rainfall and hydropower production at provincial, territorial and country-wide scales. For each case, the direction and significance of dependency is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of dependency is shaded by the color code in the side bar. Significant level is considered at 95% confidence limit.*

The above analyses were also repeated using the other two dependency measures, i.e. Spearman and Pearson correlation coefficients. It was realized that the observed patterns of dependence based on these two measures are very much similar to those reported in Figures 5.17 to 5.20 and therefore, it can be concluded that the dependencies captured between hydropower and climate variables are strong enough that are not altered by changing the dependency measure.

5.1.4 Climatic causes of hydropower generation across Canadian regions

Here the casualty analyses, as suggested by Granger and outlined in Chapter 4, is used to identify climate causes of hydropower generation across Canadian jurisdictions. This is based on intercomparing a wide range AR and corresponding ARX models for modeling monthly hydropower generation across provincial and territorial regions in Canada as well as the county as a whole. Below, we present and discuss the result of this analysis, starting from analyzing the autocorrelation structure within monthly hydropower series, to identifying critical lag times between climate drivers and hydropower production, to highlighting key climate drivers of monthly hydropower production across Canadian regions.

5.1.4.1 Analysis of autocorrelation in hydropower generation

The first step for development of AR models is the analyses of autocorrelation within the data, here monthly hydropower generation across Canadian regions. This is due to the fact that in AR models, all significantly autocorrelated lags – up to the first break in the significance of autocorrelation – can be potentially considered in the model structure. Identifying the break requires assigning a threshold for significance of autocorrelation, which is 95% (i.e. p-value $\leq$ 0.05) in this study. The analyses of autocorrelation reveal how much hydropower generation is dependent to its previous values, which turned out to be quite different across Canadian regions. Figure 5.21 summarizes the result of this analyses. In general, it seems that there are three different autocorrelation patterns within Canadian hydropower generation. First, patterns related to sharp yet short memory in monthly hydropower generation are observed in AB, ON, NL, NB and NS, in which the first break in significance of autocorrelation takes place before one full annual cycle. Second, from related to low interannual memory was observed in NT&NU, YK and BC, in which the autocorrelation in hydropower generation goes beyond annual hydrologic cycle but it does not last more than 2 or 3 years. Finally, the third form of autocorrelation patterns related to high interannual memory was observed in QC, SK, MB and Canada as a whole, in which the autocorrelation in hydropower generation goes beyond three years. These three different forms of autocorrelations can refer to systematic differences in hydropower generation across Canadian regions.

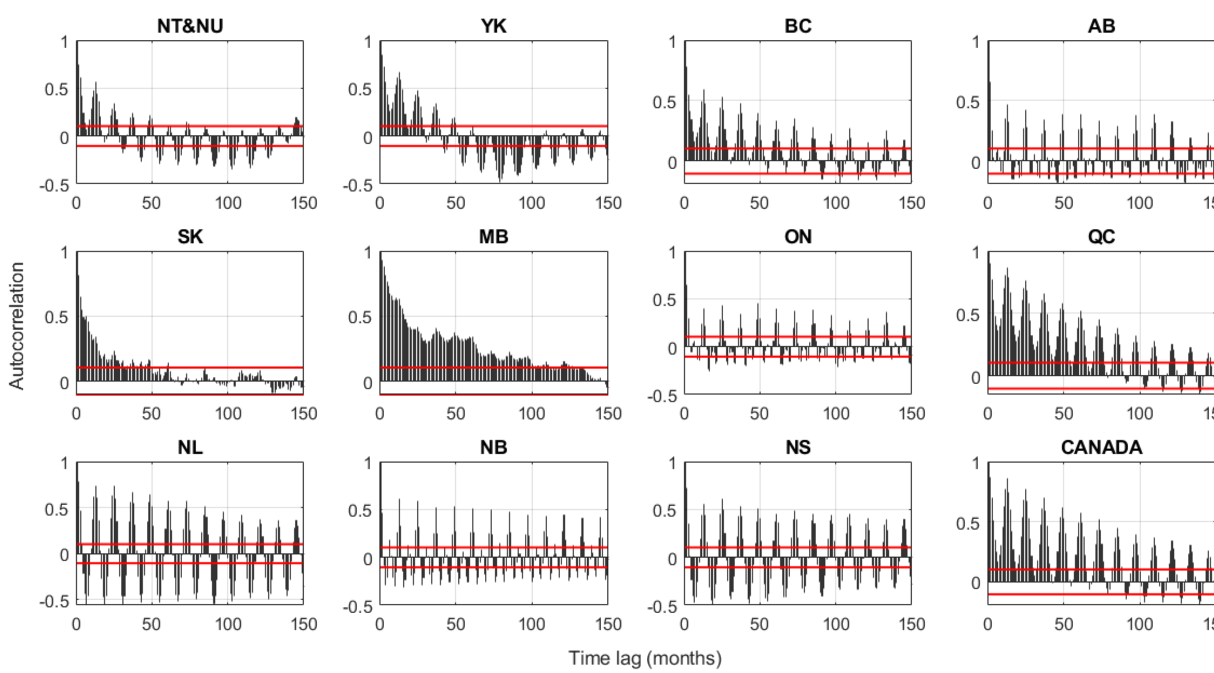

Figure 5.21 *Autocorrelation in monthly hydropower generation time series across Canadian provinces and territories; red lines are identifying the 95% significance threshold for the autocorrelation estimate.*

5.1.4.2 Tracing climate causes of hydropower generation

Apart from the AR model, Granger casualty test builds on the use of ARX models, in which monthly hydropower generation is simulated using both hydropower and one climate variable. If the ARX model performs better than AR, then it can be argued that the considered climate variable is a cause of hydropower generation. This can provide a framework to systematically trace the climatic causes of hydropower generation within each region. The results of this analysis are summarized in Figure 5.22 in which the BIC values are used to characterize the performance of AR and ARX models. The lower the BIC value, the higher the performance of the model. Within this framework, after a particular time lag in each region, adding new climate variables do not add any benefit to the prediction. This lag time can be quite short, i.e. in the case of SK, MB, due to low impact of provincial climate variables in forming the provincial runoff. In the majority of considered regions, i.e. NT&NU, YK, BC, AB, ON, QC, NL and Canada as a whole the effect of regional climate on regional hydropower generation last up to a year; however there are other regions, i.e. NB and NS, in which the effect of climate on hydropower generation can be traced beyond a year lag time. Having said that, the improvements made by adding new climate variables beyond a year lag are extremely marginal compared with the contributions made by climate variable within a year lag.

5.1.4.3 Dominant climate drivers of hydropower generation

Based on the Granger casualty test, the role of each regional climate variable in improving the regional hydropower prediction can be quantified across relevant lag times by comparing the BIC of AR and ARX models. This can provide an objective look at the role of each climate variable in the formation of hydropower generation and how this contribution can evolve in time. Figure 5.23 summarizes the finding in terms of the percentage of relative improvement in prediction of monthly hydropower generation, if a particular climate variable is considered at a particular time lag. In each panel, x-axis identified the number of lags in month and the y-axis show the percentage relative improvement in prediction, which is calculated at each time lag p as $\frac{BIC_{ARX(p,p)}-BIC_{AR(p)}}{BIC_{AR(p)}} \times 100$. Black dashed line indicates no improvement in the AR prediction. For each region and time lag, the climatic variable that causes the maximum improvement in the BIC can be identified as the dominant climate variable in the considered time step and/or region. Based on the analyses made, dominant climatic causes of hydropower generation can differ based on the region and the time lag considered.

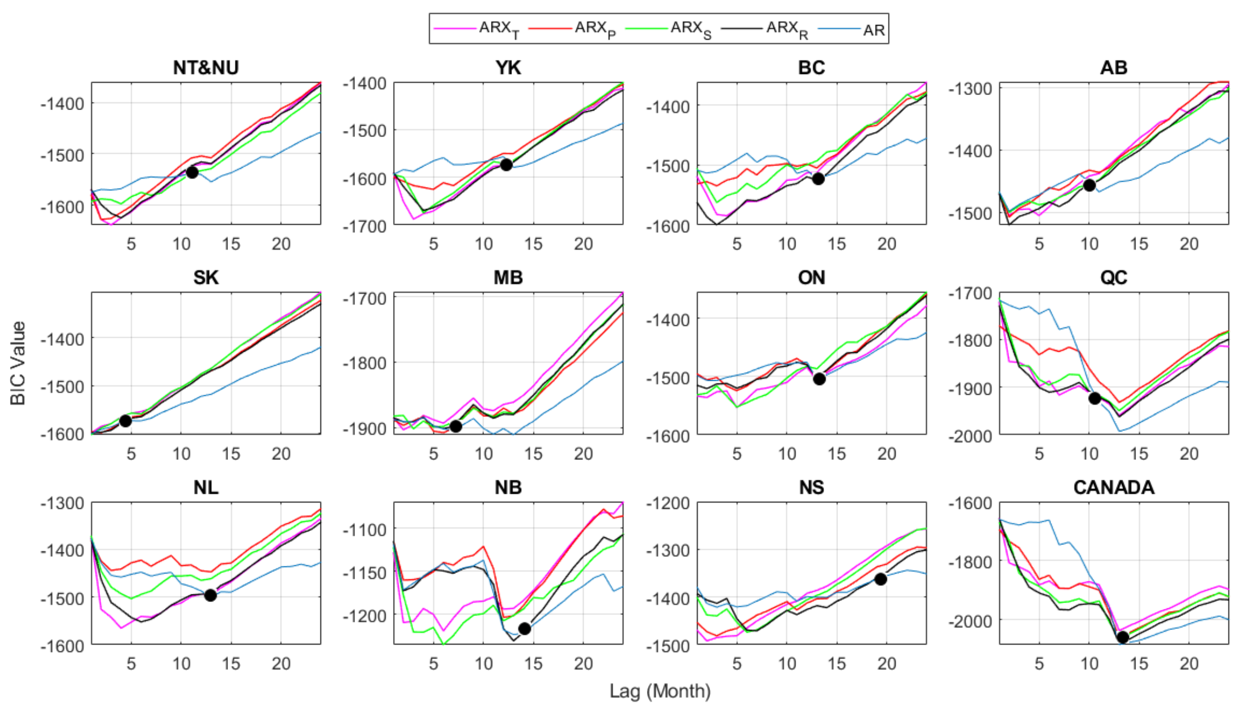

Figure 5.22 *BIC values for AR and ARX models of monthly hydropower production. In ARX model each climate variable is considered separately. Dots are identifying time lag beyond which the impact of climate variables cannot be traced.*

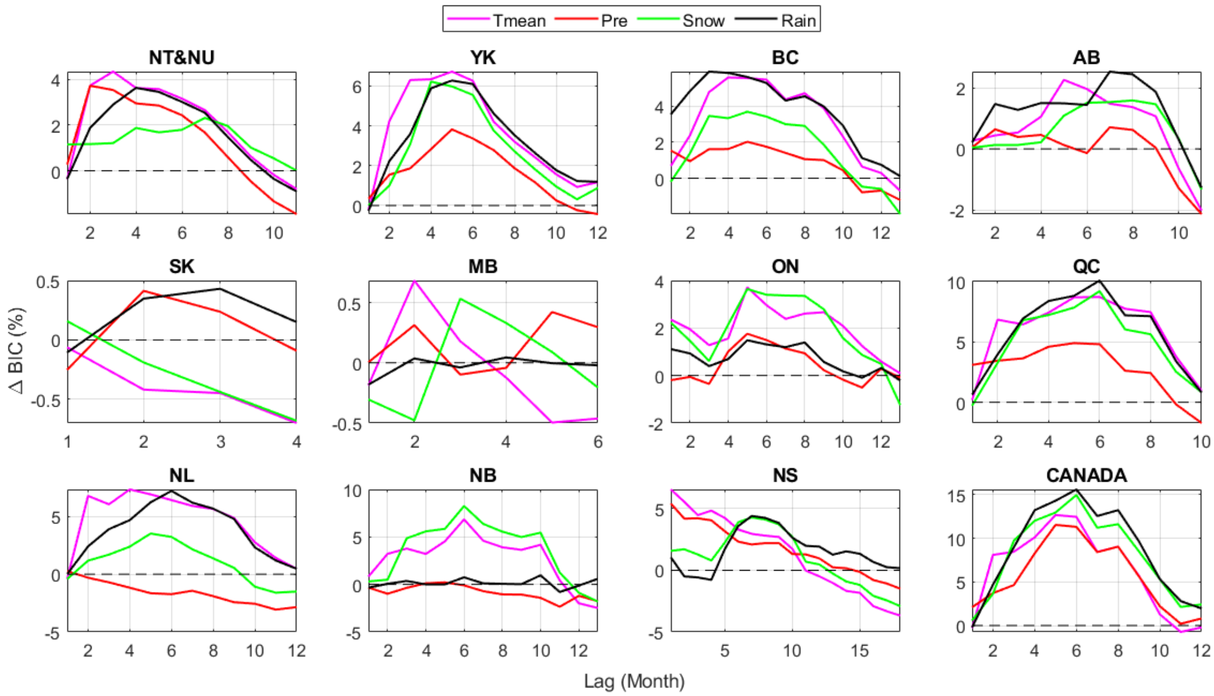

Figure 5.23 *Percentage of BIC improvement in AR model as a result of considering each climate variable as an exogenous variable. The dashed black line in each panel identifies no improvement.*

In NT&NU, temperature seems to the dominant driver in majority of time lags from 1 to 8 months, although precipitation and rainfall mark similar improvements during earlier and later months respectively. Also snow becomes the dominate driver in this region after the 8 months lag, which indicates the buffering effects of snow accumulation that causes delay between snowfall and hydropower generation. In YK, again temperature is the key driver of hydropower generation across a yearly timespan; however, snow and rain make almost the same improvement in prediction as temperature after four months lag. In BC rain stands as the dominant climate drivers, particularly within the first four months lag. After that, temperature also plays an almost similar role in predictability of hydropower generation. In Alberta also rainfall stands as the dominant climate driver, although temperature become stronger driver for 5 and 6 months lag. Saskatchewan and Manitoba show rather marginal effects of regional climate drivers on predicting the hydropower generation. In Ontario, temperature and snow stand as dominant climate causes of hydropower production, pointing on how snow accumulation and melt drive hydropower generation in this province. Similar process can be witnessed as well in New Brunswick. In Quebec, the hydropower is driven by an interplay between rain, snow and temperature within a 10 month time span. In Newfoundland and Labrador, hydropower generation is mainly driven by temperature, although rain plays an almost similar role after 6 months lag. Nova Scotia displays rather a complex hydropower generation process in which temperature and total precipitation are the main causes of hydropower production up to 5 months lag and then rainfall and snowfall takeover up to 10 months lag but only rainfall can be considered as a cause beyond 10 months lag and up to 15 months. In Canada as a whole, total precipitation is the immediate cause of hydropower generation, which is substituted by temperature for 2 and 3 months lag. After month 4 and up to 1 year lag, rainfall and snow become dominant drivers of hydropower production in Canada, although rainfall has a marginally more important role in the predictability of hydropower generation.

5.1.5 Predictive models for monthly hydropower production

By knowing the autocorrelation structure as well as climate drivers of monthly hydropower generation, it would be possible to form different predictive models for simulating hydropower generation in the current time based on past hydropower generations and climatic causes. To avoid dimensional inconsistencies and scale mismatch, regional hydropower and climate time series were normalized within 0.1 and 0.9 before applying the four schemes introduced in Chapter 4. For each region, several competing hypotheses for modeling hydropower generation were formed using each scheme by considering all possible time lags from 1 month to the critical number of time lag, after which there is no trace of climatic causes in the hydropower time series. The performance of developed models were inspected using three performance measures, i.e. BIC, coefficient of determination (R^2) as well as RMSE in offline and online simulation modes during both training and testing periods. Offline simulation mode refers to the simulation condition, in which current hydropower generation is simulated using observed hydropower production as well as climate causes in the previous time step. In the online mode, in contrast, past hydropower productions are obtained from past simulations and therefore simulation errors can transcend from one time step to the next simulation time steps. The result of analyses is summarized in Figures 5.24 to 5.26 for BIC, R^2 and RMSE for offline simulations as well as Figures 5.27 to 5.29 for corresponding online simulation. For each region, the modeling alternative that had the best online performance based on R^2 in the testing period was chosen as the non-falsified predictive model, which can be further used for impact assessment.

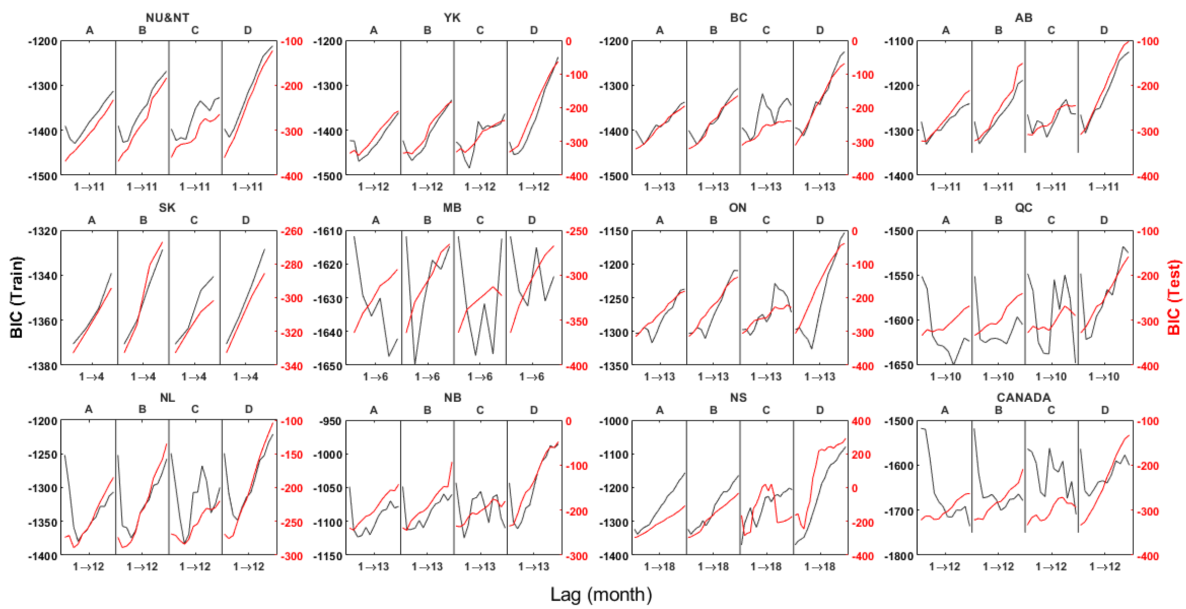

Figure 5.24 *BIC values for offline hydropower simulation at the monthly scale in both train and test phases across Canadian provinces and territories.*

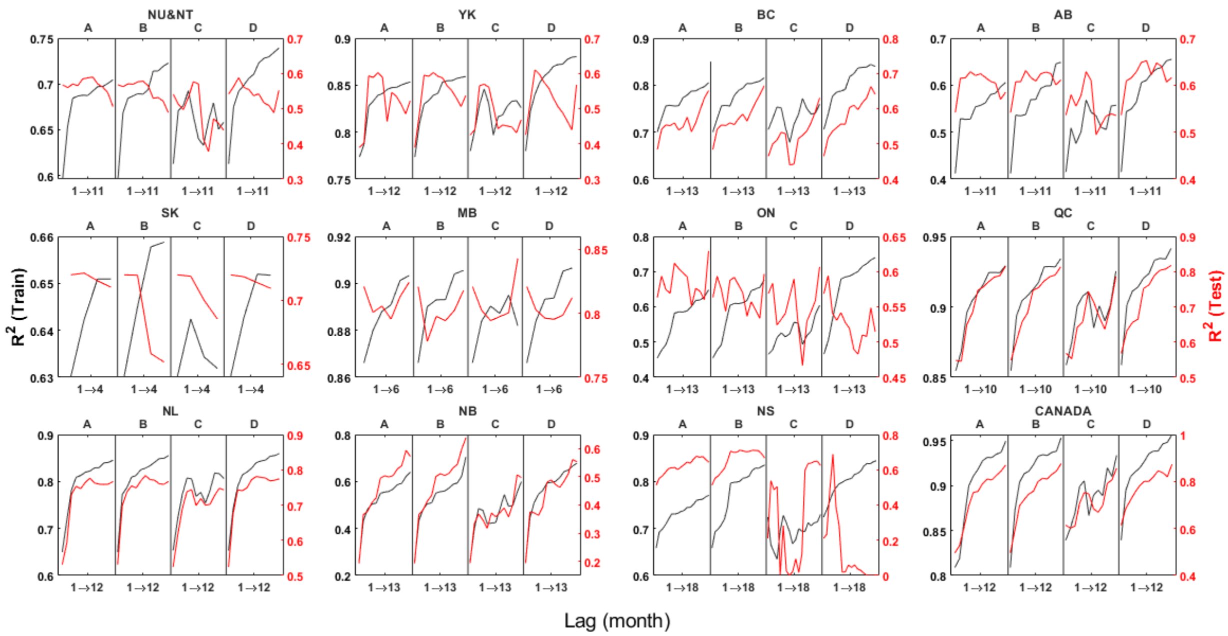

Figure 5.25 *R^2 values for offline hydropower simulation at the monthly scale in both train and test phases across Canadian provinces and territories.*

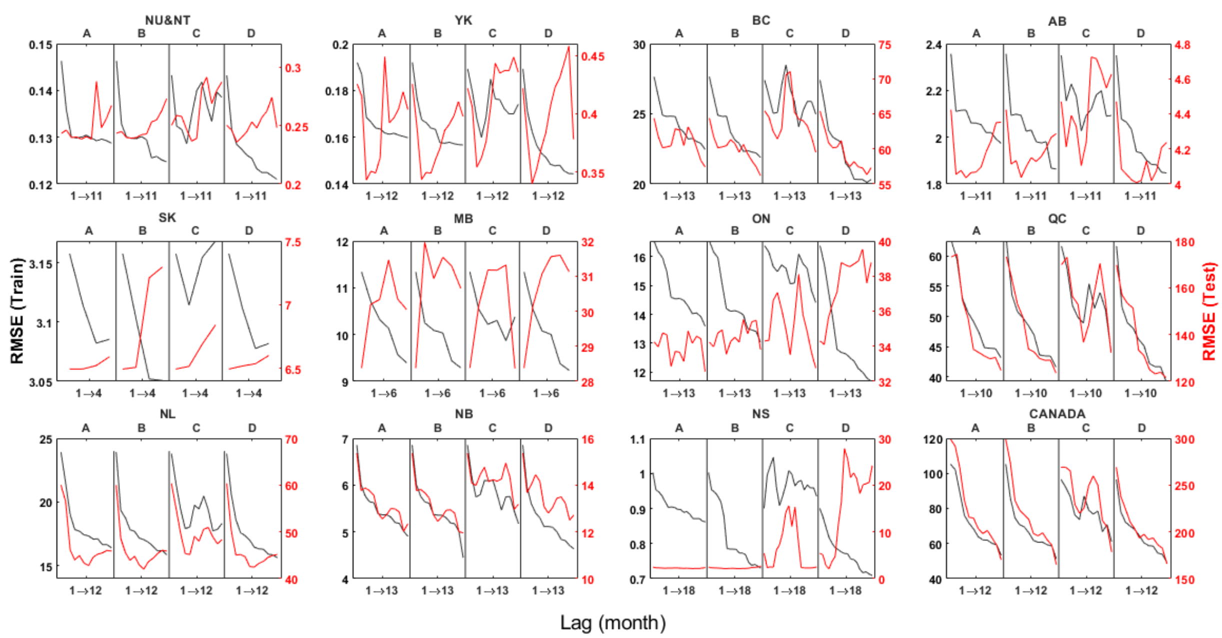

Figure 5.26 *RMSE values for offline hydropower simulation at the monthly scale in both train and test phases across Canadian provinces and territories.*

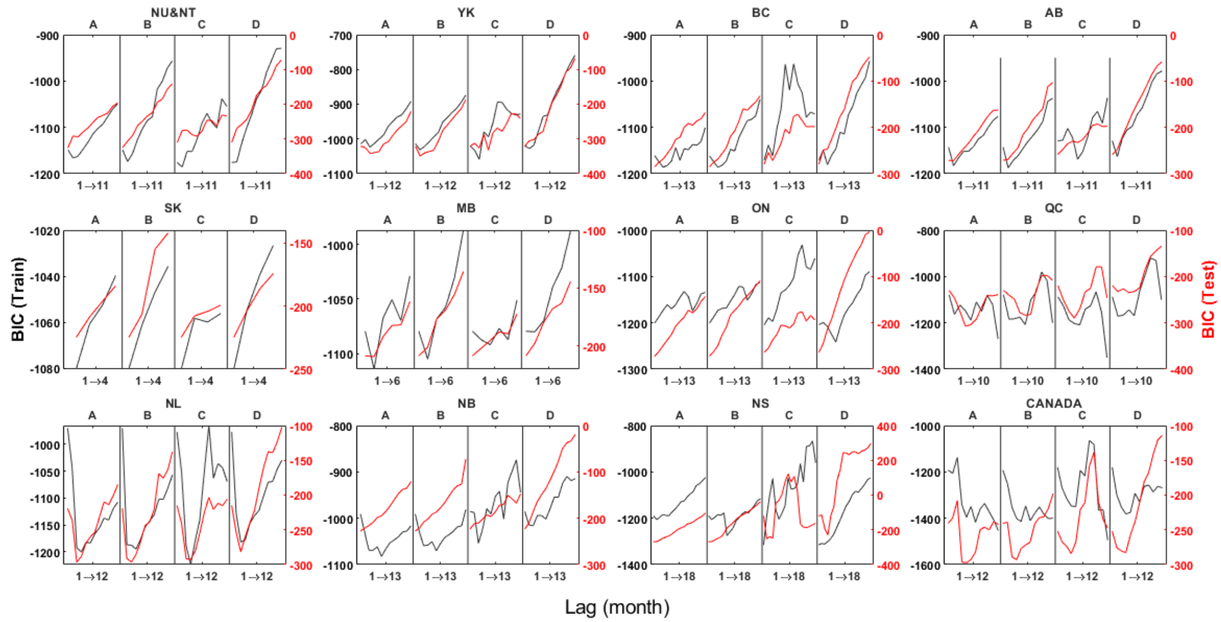

Figure 5.27 *BIC values for online hydropower simulation at the monthly scale in both train and test phases across Canadian provinces and territories.*

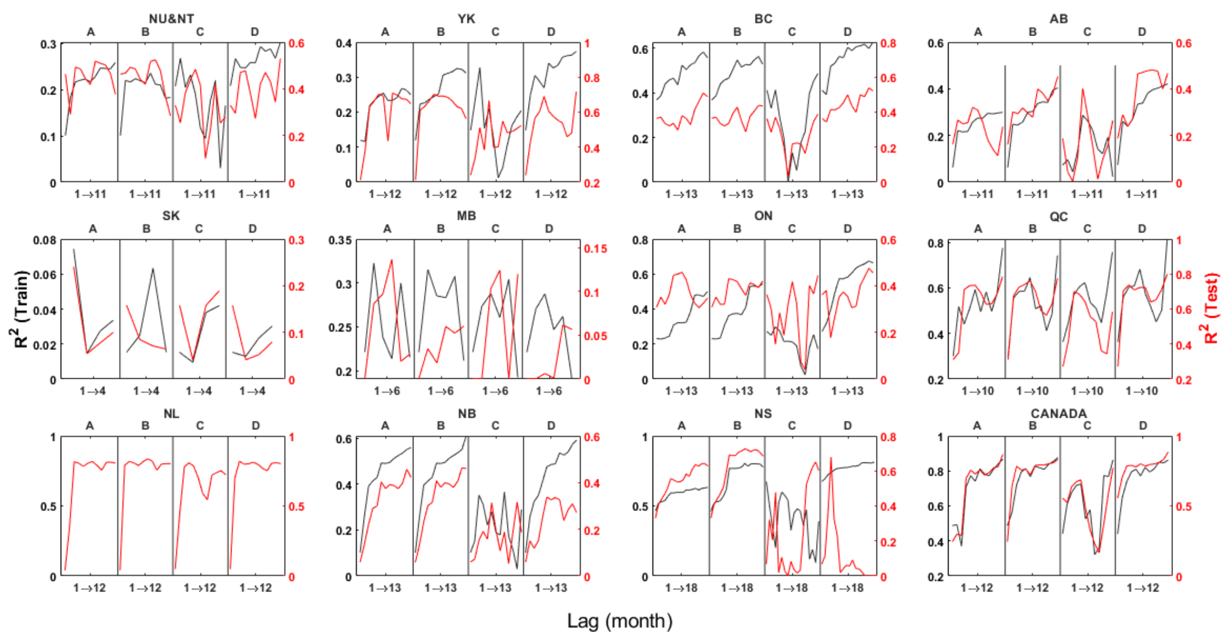

Figure 5.28 *R^2 values for online hydropower simulation at the monthly scale in both train and test phases across Canadian provinces and territories.*

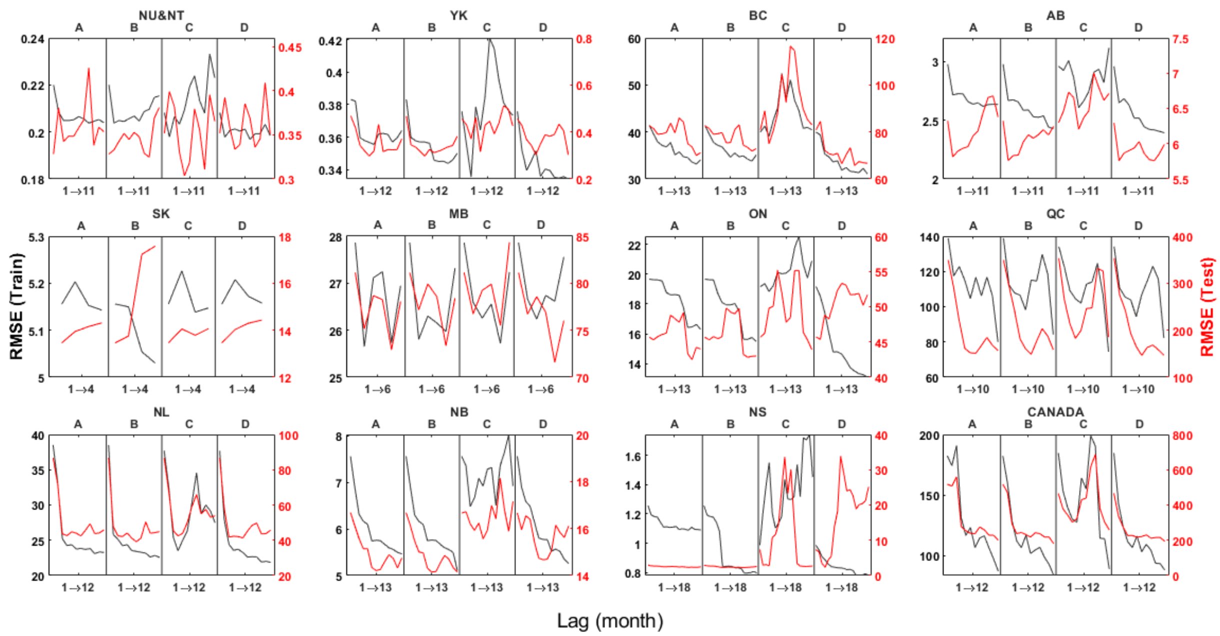

Figure 5.29 *RMSE values for online hydropower simulation at the monthly scale in both train and test phases across Canadian provinces and territories.*

The results of standardized equation for hydropower generation can be scaled back to the actual domain using the inverse transformation, considering minimum and maximum monthly hydropower production during the training period. Figure 5.30 shows the observed vs. online and offline simulations of hydropower production across Canadian regions. As it is obvious, in offline simulation modes, the non-falsified models are able to track the monthly time series of hydropower production very well. However by moving to online simulation the model, the performance of the predictive models declines substantially particularly in Saskatchewan, where regional climate variables have marginal effect in the formation of hydropower production. Despite some discrepancies particularly in New Brunswick, Manitoba, Ontario and Yukon, the predictive model simulation can capture the dynamic of production. In Canada as a whole, the non-falsified predictive model can describe more than 75% of the variance within the observed data. More details on the performance of the non-falsified predictive models are provided in Table 5.1.

Table 5.1 *Settings and performance of non-falsified predictive models for hydropower generation across Canadian Regions.*

Region	Scheme	Number of considered lag months	BIC (online simulations)	BIC (offline simulations)	R^2 (online simulation)	R^2 (offline simulation)	RMSE (online simulation)	RMSE (offline simulation)
NT&NU	D	11	6126.72	5787.89	0.28	0.71	175.24	109.60
YK	D	12	6520.39	6004.94	0.32	0.84	285.79	139.68
BC	D	12	9816.36	9564.69	0.61	0.81	28033.49	19763.72
AB	D	8	7978.56	7778.86	0.40	0.65	2197.48	1670.28
SK	A	1	8515.76	8105.06	0.02	0.67	4928.14	2833.34
MB	A	2	9717.99	9057.81	0.30	0.88	25430.31	10420.95
ON	D	12	9329.26	9191.53	0.54	0.69	14368.55	11866.80
QC	D	10	10496.78	10052.97	0.79	0.94	70971.05	38446.83
NL	B	7	9507.62	9333.78	0.71	0.82	20182.00	15905.36
NB	B	12	8419.53	8333.38	0.52	0.61	5147.99	4567.41
NS	B	12	7153.24	7100.78	0.75	0.78	790.90	735.32
CANADA	D	12	10595.57	10241.35	0.87	0.95	82060.82	50173.36

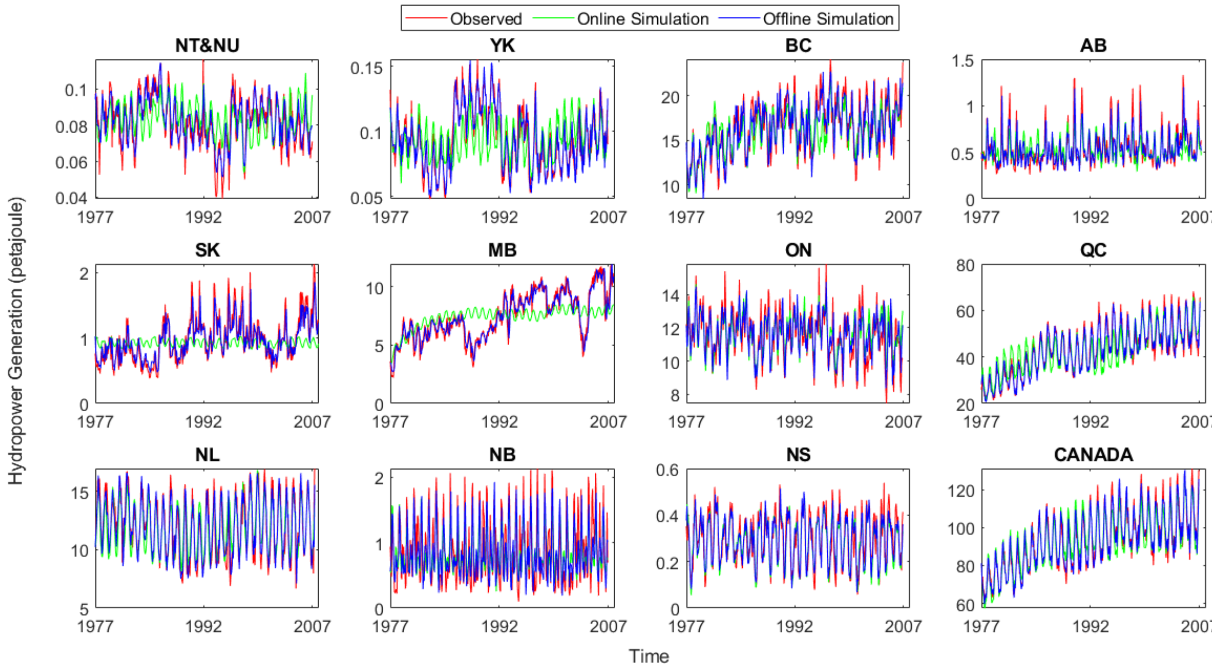

Figure 5.30 *Comparison between observed (red) and simulated monthly hydropower production across Canadian provinces and territories. Simulated results are provided in online (green) and offline (blue) modes.*

5.1.6 Future hydropower production in light of existing climate trends

To investigate the impact of climate change on hydropower generation, the magnitude of the trends captured in trend analysis is added to the observed climate data. Hydropower generation is then simulated based on the non-falsified predictive models, with and without consideration of the trends. As a result, the difference between expected monthly generation under current and future climate can reveal the expected gain/loss of hydropower production in light of the existing trends in climate data. However before implementing the analysis, the reliability of non-falsified models are quantified based on the how simulated time series can track the expected monthly hydropower production during the observed period. Figure 5.31 shows the expected monthly hydropower generation for both observed and simulated hydropower under current condition.

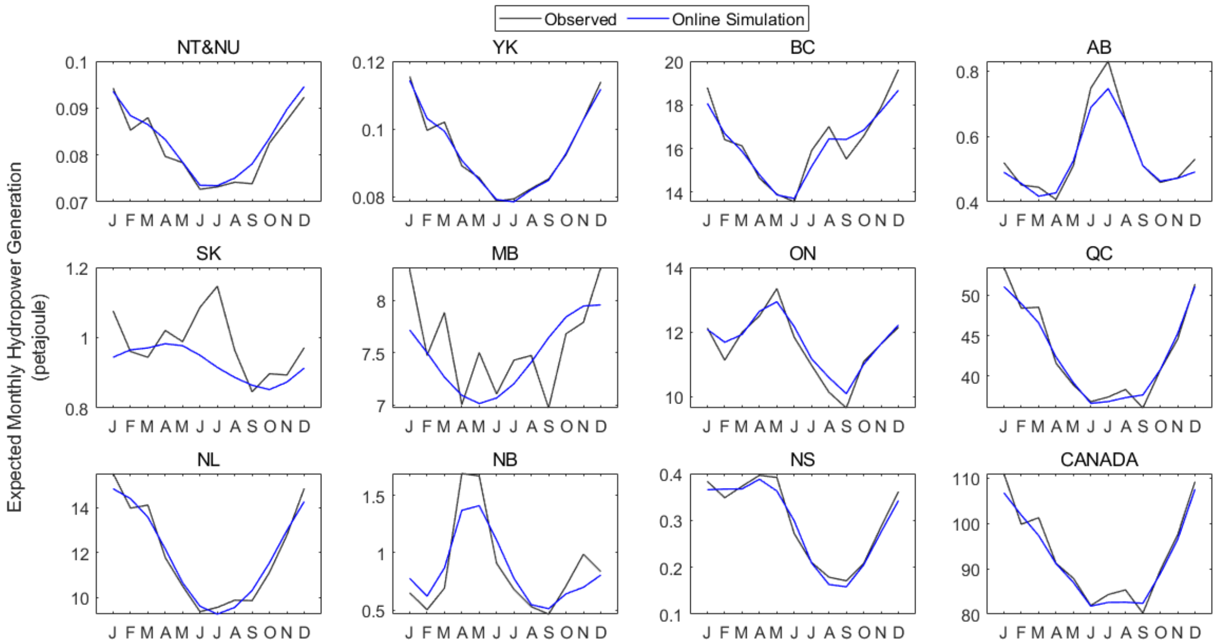

Figure 5.31 *Expected monthly hydropower production historical (black) and the simulation (blue) under current condition. Consider future condition is portrayed based on continuation of existing trends in climate variables.*

The results show that the expected values of hydropower generation gathered from simulations are close to the observed values in most of the Canadian provinces and territories. Having said that, the simulation values were completely inconsistent in Saskatchewan and Manitoba. Furthermore, the confidence level of the models to simulate the expected monthly hydropower generation is categorized based on the correlation coefficient, R^2, RMSE, and percentage of relative error between observed and simulations – see Table 5.2. The confidence of the models to capture the expected monthly hydropower generation are "very good" in eight out of twelve jurisdictions considered. By confirming the reliability of non-falsified models in reconstructing the expected monthly hydropower production, expected monthly hydropower generation under current climate trends is calculated. Figure 5.32 illustrates the results.

Table 5.2 *Confidence of the models to simulate expected monthly hydropower generation in Canadian provinces*

Province	*R*	R^2	*RMSE*	*ΔE %*	*Confidence*
NT&NU	0.97	0.95	379.23	-1.67	Very good
YK	0.99	0.98	52.72	0.20	Very good
BC	0.96	0.93	38493.89	0.85	Very good
AB	0.98	0.97	4604.66	3.04	Weak
SK	0.50	0.25	16179.04	5.93	Very weak
MB	0.59	0.34	29174.36	1.39	Very weak
ON	0.97	0.95	37291.95	-1.16	Very good
QC	0.98	0.97	56077.14	0.47	Very good
NL	0.98	0.96	2953.25	0.09	Very good
NB	0.92	0.84	4248.82	1.78	Weak
NS	0.98	0.97	1820.03	2.20	Very good
CANADA	0.98	0.97	301752.18	1.16	Very good

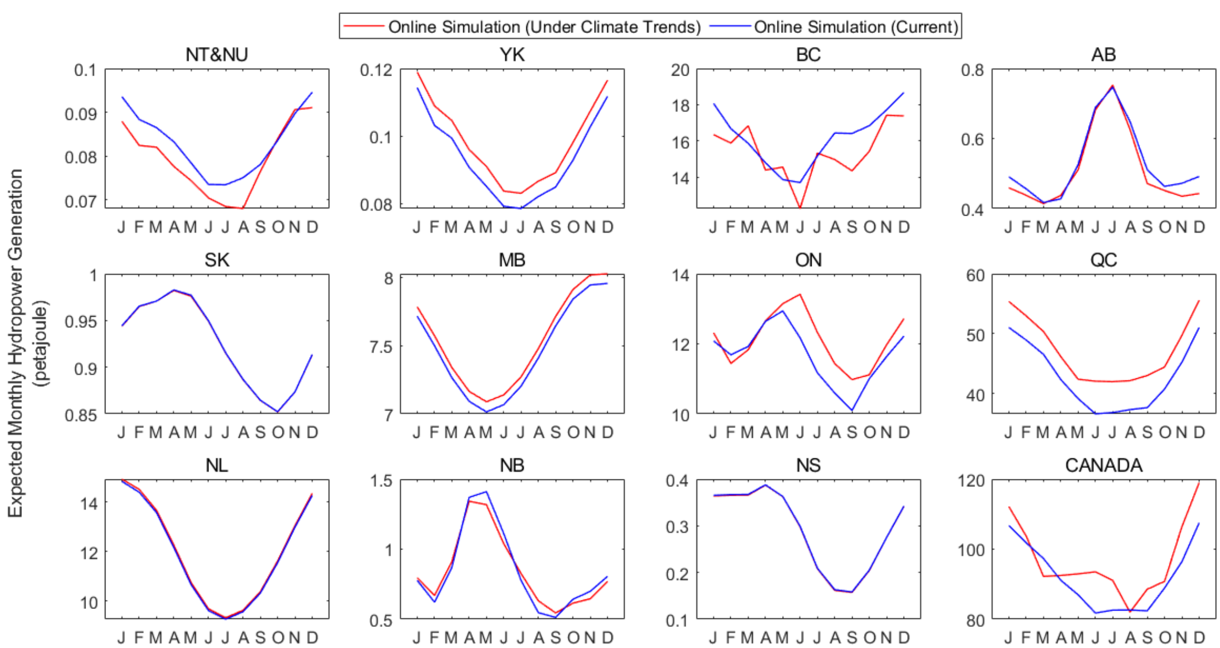

Figure 5.32 *Comparison between expected monthly hydropower production under current condition (blue) and the considered future condition (red). Consider future condition is portrayed based on continuation of existing trends in climate variables.*

The future hydropower shows a lower expected value in NT&NU in most of the months. On the other hand, hydropower will increase in all months in YK. In BC, generation will fluctuates over the time, but it decreases during summer and fall in general. The simulation were not robust in SK and MB but the results show that hydropower is not sensitive in local climate condition in these provinces. Also, in ON, hydropower increases in spring, summer, and fall but decreases in winter. Higher hydropower can be expected in all of the months under climate change in QC. NL and NS will not experience too much change in their production while, hydropower generation increases during the winter summer but decreases in spring and fall in NB. However, looking at all of Canada, hydropower increase in most of the months, and this increment is more obvious in the spring. It seems that hydropower would be more sensitive to change in local climate for most provinces. Furthermore, the percentage of net gain and loss is calculated for hydropower generation for the future with climate change – see Figure 5.33 below.

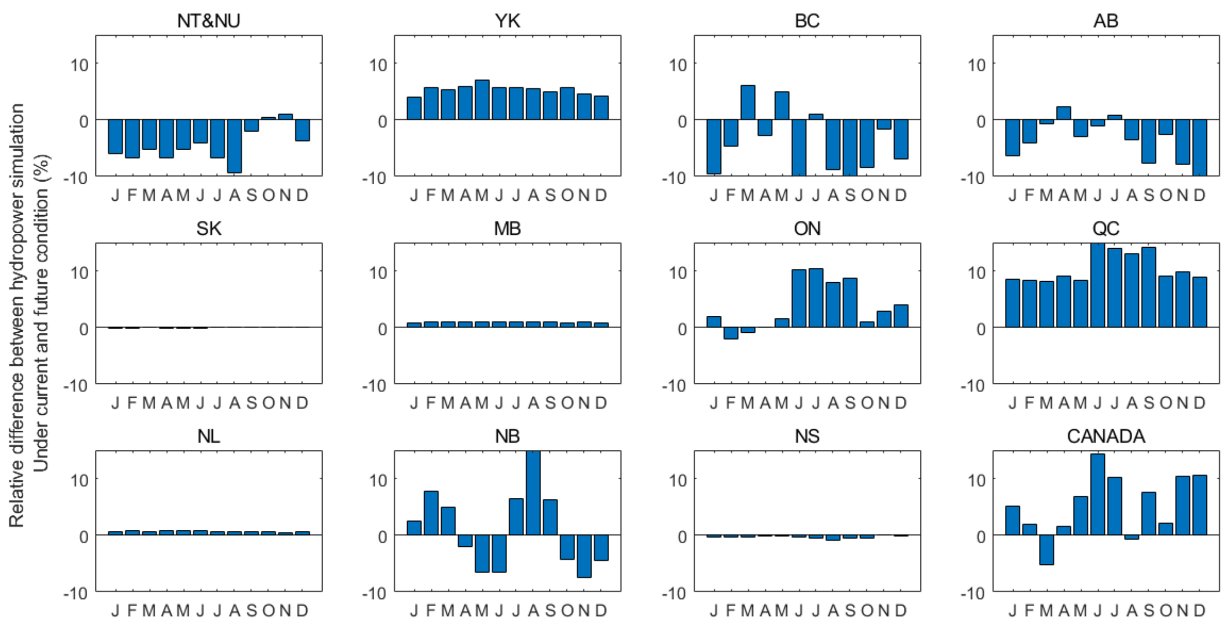

Figure 5.33 *Relative difference in % in hydropower generation between current and future conditions.*

Net hydropower generation for NT&NU will decrease to around 10% in August and around 5% in January to July. In YK, the maximum gain will occur in March (8%) and other months will experience increase in generation around 5%. In BC, the maximum gain will be 8% captured in March, while hydropower will decrease by about 12% in September. In AB, operations will experience a maximum increase of 3% in April and experience a maximum loss captured in December (10%). In SK and MB, the percentage of change is negligible. In ON, hydropower will increase during the summer and fall and maximum gain will occur in Jun and July (10%). In QC, Hydropower will increase in all months, and the maximum gain captured will be in June (6%). The amount of generation in NL will increase in every month but the amount of change is negligible in general. In NB, the winter and summer months will experience higher amounts of generation, between 10 to 20%. Hydropower generation will decrease in all the months but the percentage of changes are negligible in general. Furthermore, hydropower will increase in all the months except in March and August across Canada. The maximum gain is allocated to June (15%) and the maximum loss will occur during March (5%).

5.2 Sensitivity of local wind power production to changes in local temperature

This section is dedicated to summarizing the findings of this thesis in terms of the dependency between local wind production and local temperature. As discussed in Chapter 2, local wind speed has a direct relationship with the local wind production and therefore the local wind speed can be effectively taken as the proxy for wind power production throughout this section. Firstly, the analyses of monthly, seasonal and annual concurrence of trends in wind speed and temperature are presented across a range of temporal scales. Then the results of dependency analyses between local wind speed and local temperature are provided and discussed. Finally, a regional analyses on how local wind speed can be altered by changes in local temperature are given.

5.2.1 Concurrence trends in local wind speed and local temperature across Canada

Here, the non-parametric Mann-Kendall trend test is used to detect changes in local wind speed and mean temperature at annual, seasonal and monthly scales. The results are summarized in a set of maps, in which the magnitude, direction and the significance of the trends are shown. The magnitude is displayed by color, the direction of slope with upward (positive) and downward (negative) triangles and the significance of the trends by dots inside the triangles.

5.2.1.1 Annual scale

Figure 5.34 shows the results of the Mann-Kendall trend test for annual mean temperature in the considered stations. As it can be seen, the majority of stations has experienced an increase in the mean annual temperature. The magnitude and significance of the trend is clearly higher in western parts of the country. Moving toward east, the trends become less sharp and rathe insignificant. Moving more toward east and Atlantic regions, the direction of trend changes and become negative. Figure 5.35 summarizes the results of the Mann-Kendall trend test for annual wind speed in the same stations and during the same data period as Figure 5.35. It is clear that the majority of stations experience a decrease in wind speed in the annual scale while undergoing a positive change in the temperature. In addition, the trends are mainly significant particularly in southern parts of Atlantic Canada, Ontario and Saskatchewan. The decreasing trend in annual wind speed however is dampened and can even become positive by moving towards the north particularly in north eastern parts of the country.

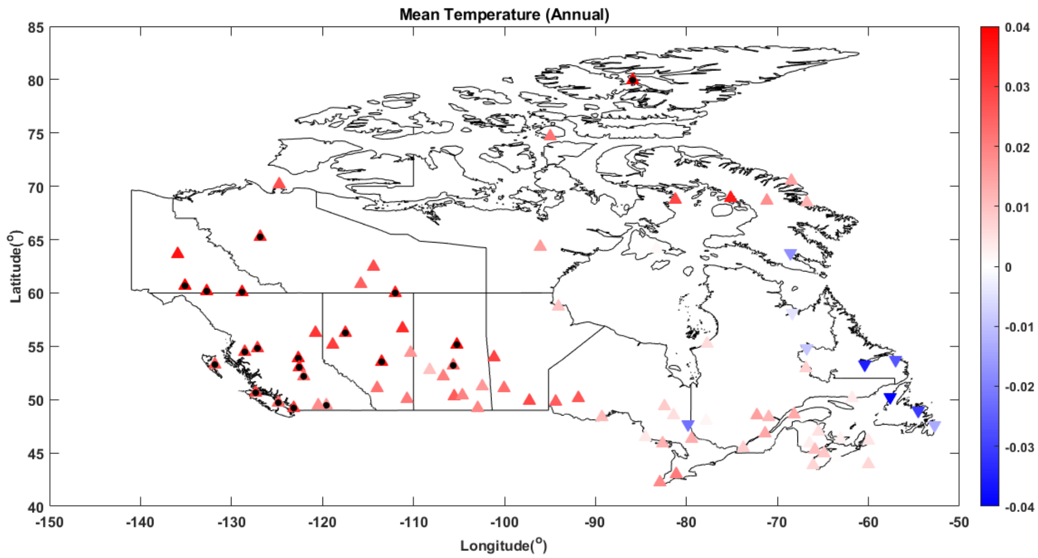

Figure 5.34 *Results of the Mann-Kendall trend test for annual mean temperature in the considered stations. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence.*

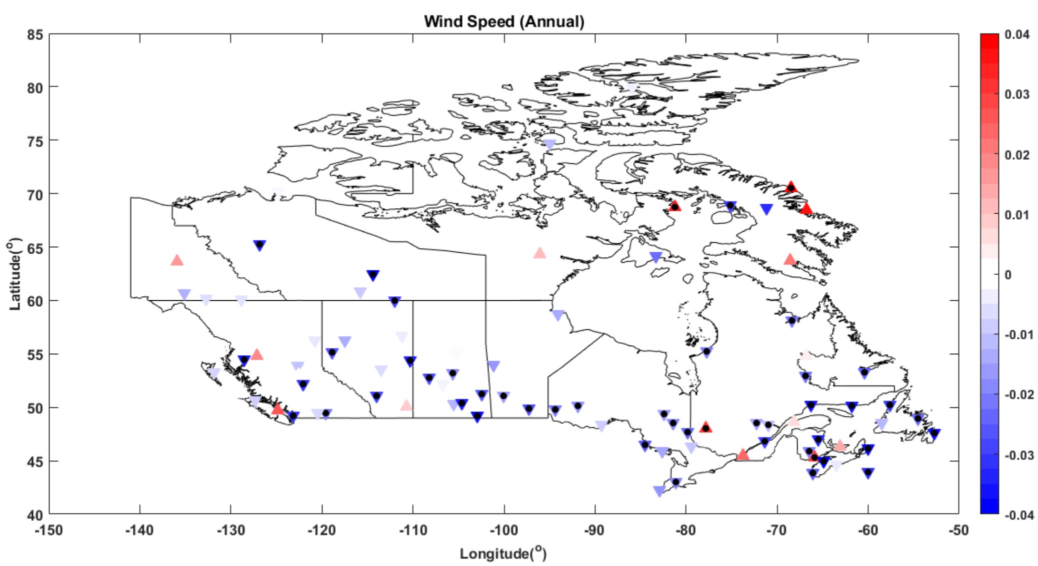

Figure 5.35 *Results of the Mann-Kendall trend test for annual wind speed in the considered stations. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence.*

5.2.1.2 Winter months and season

Figure 5.36 shows the results of the Mann-Kendall test for assessing monthly and seasonal mean temperature during winter months and season as a whole. During January and Feburary, most of the stations within northwestern, western, centeral and eastern Canada experience increases in mean temperature. The most significant increases are seen in west coast in the month of January. The significance of positive trends is decreases from west to east. In northern and Atlantic Canada, there are negative trends in January and February that can be even statistically significant. In March, northern stations also show increase in annual temperature, while Atlantic regions still experience decrease in temperature. On the other hand, in the month of March, the stations across the Atlantic regions experience decreases in temperature; meanwhile, the trend captured in other parts of the country are positive. There are more positive trends during the month of March in comparison with the other two months. Considering winter as a whole, increasing trends are captured in western, central and eastern Canada, in which the increase in temperature is significant across west coast, central Saskatchewan and southeastern Ontario. Figure 5.37 shows the results of the Mann-Kendall trend test for monthly and seasonal wind speed during the winter at the same stations in which the local temperature change are inspected. Similar to the annual scale, wind speed consistantly decreases in the majority of the stations durig the winter months and season. The significant negative trends are captured mainly in the Atlantic and western Canada. At the seasonal scale, the majority of the stations also experienced a decrease in wind speed and significant decreases are more vivid in Atlantic comparing to western Canada.

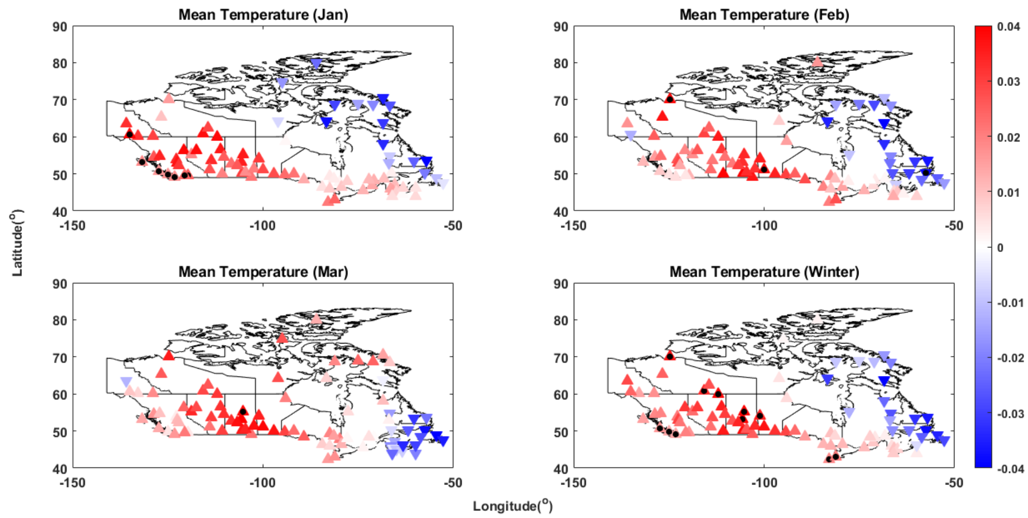

Figure 5.36 *Results of the Mann-Kendall trend test for monthly and seasonal mean temperature in the considered stations during winter. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence.*

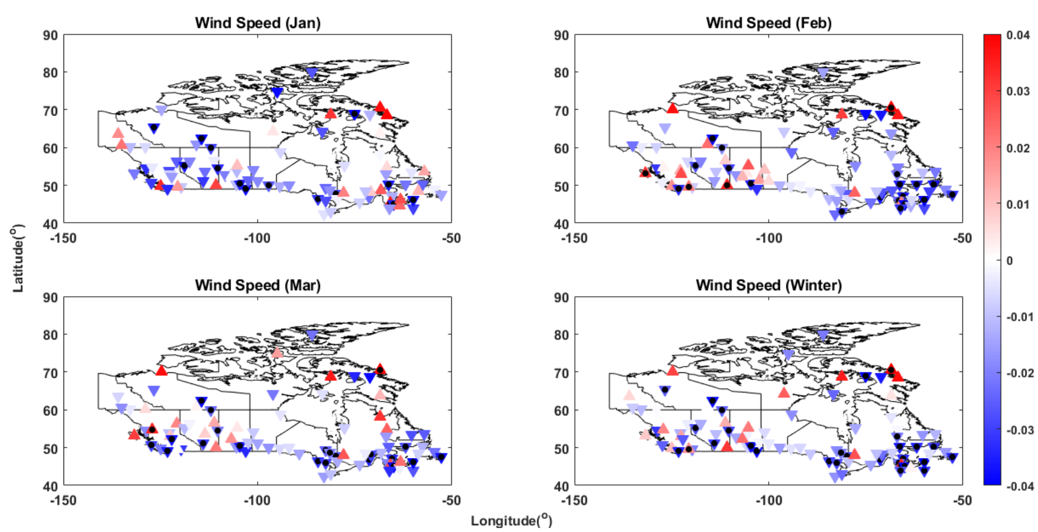

Figure 5.37 *Results of the Mann-Kendall trend test for monthly and seasonal wind speed in the considered stations during winter. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence.*

5.2.1.3 Spring months and season

Figure 5.38 demonstrates the results of the Mann-Kendall test for analyzing monthly and seasonal mean temperature in the considered stations during spring. In the month of April, the trends are consistantly positive across Canada, with more significant increases in the west coast. During May, again majority of stations considered are experiencing warming, expect eastern Alberta, Saskatchewan and north eastern Ontario. Again majority of significant cases are concentrated in the west coast. In month June, the exent of significant trends extend and they become more visiable also in southern Ontario and Quebec and north east coasts. Considering Spring as a whole, Canada is mainly warming up except in south eastern Alberta. It is interesting to mention that the majority of warming trends take place close to the coastal region, particularly in the west as well as the Hudson Bay.

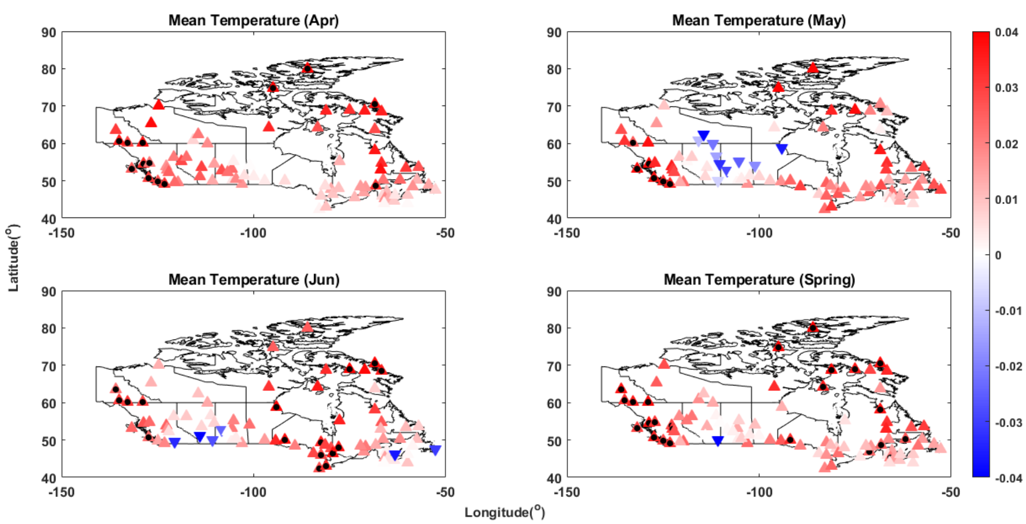

Figure 5.38 *Results of the Mann-Kendall trend test for monthly and seasonal mean temperature in the considered stations during spring. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence.*

Figure 5.39 demonstrates the results of the Mann-Kendall test for analyzing monthly and seasonal trends in wind speed across the same climate stations during spring. As it can be vividly seen the wind speed decreases in the majority of considered stations during spring months and season, particularly in the southern parts of the country. Having said that, there are regions in south eastern Quebec that experience a significant increase in the wind speed during May.

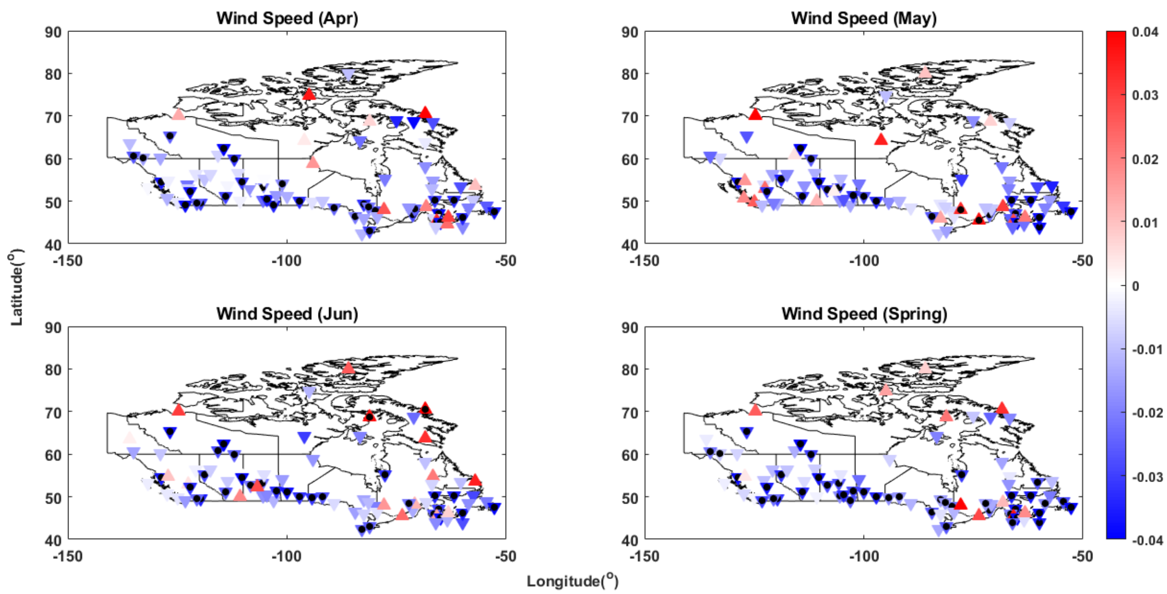

Figure 5.39 *Results of the Mann-Kendall trend test for monthly and seasonal wind speed in the considered stations during spring. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence.*

5.2.1.4 Summer months and season

Figure 5.40 shows the results of the Mann-Kendall test for monthly and seasonal mean temperature accorss considerd stations in Canada during summer. Most stations experience an increase in mean temperature in July, particularly along the west coast; although there are signs of decrease in southern Saskatchewan, easten Quebec as well as Newofoundland and Labrador that stay insignificant. Temperature increases in majority of stations across the country during August, although there are signs of decrease in north and south east regions, which stay insignificant. During September, all stations expect a couple of stations in southern Ontario show positive trend, with more concentration of significant trends in the eastern parts of the country. During the summer as whole, Canada is consistantly warming, except in an outlier station in southern Quebec that shows an insignificant decline in seasonal temperature. Significant positive trends are mainly concentrated in western Canada particularly along the west coast as well as central Alberta and Saskatchewan.

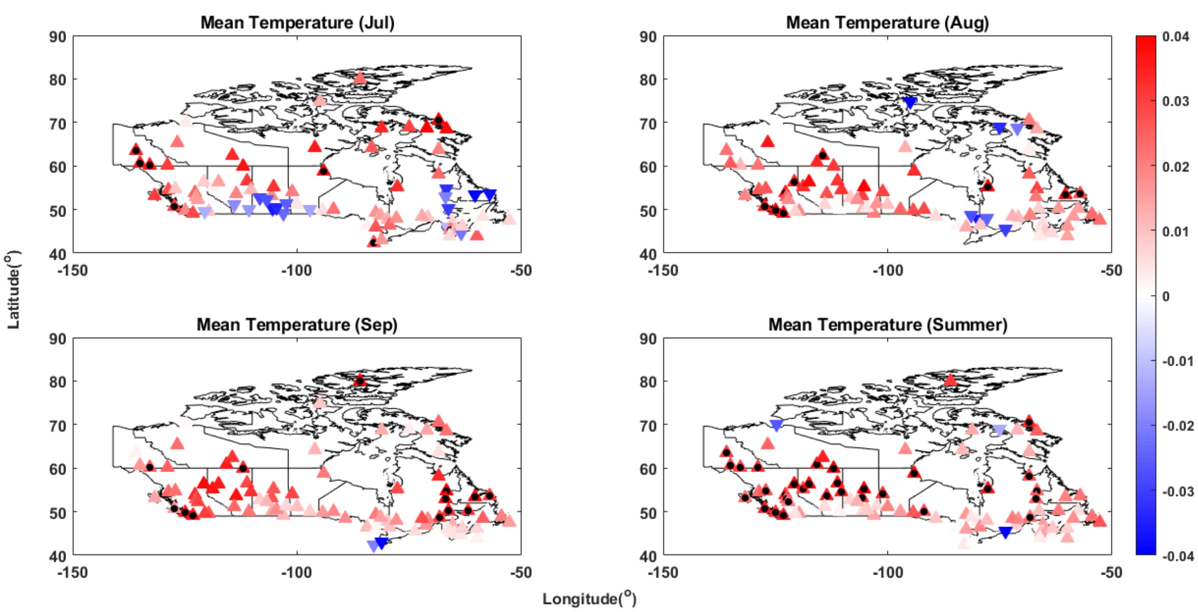

Figure 5.40 *Results of the Mann-Kendall trend test for monthly and seasonal mean temperature in the considered stations during summer. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence.*

Figure 5.41 shows the results of the Mann-Kendall test for analyzing monthly and seasonal wind speed in the considered stations during the summer. As it can be seen, wind speed generally decreases in northern Canada, northern Alberta, Saskatchewan, Manitoba and south western Ontario as well as Atlantic Canada during the month of July. The majority of significantly decreasing trends takes place across a north-west/south-east transect as well as Atlantic Canada. More-or-less similar pattern can be seen during August and September as well as Summer as a whole. Having said that the wind trend is subject to massive gradients of spatial change as for instance in Atlantic Canada. Nearby stations can show significant contradictions in the direction of trend despite being spatially close.

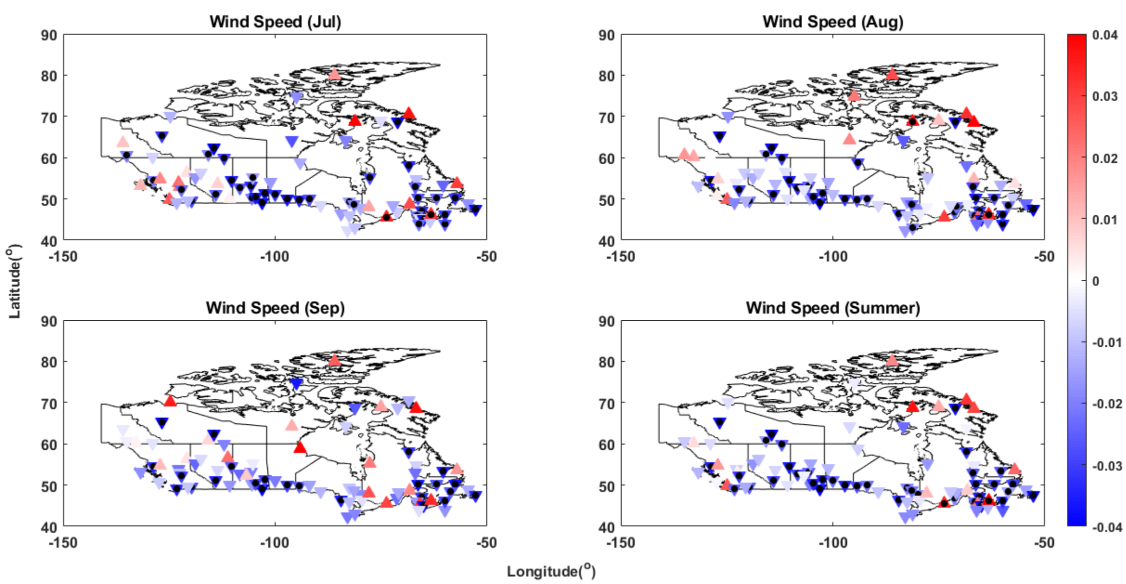

Figure 5.41 *Results of the Mann-Kendall trend test for monthly and seasonal wind speed in the considered stations during summer. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence*

5.2.1.5 Fall months and season

Figure 5.42 demonstrates the results of the Mann-Kendall test for analyzing trends in monthly and seasonal mean temperatures in the considered stations during the fall. An interesting pattern can be seen for the October temperature, in which temperature is decreasing within central northern and central Canada, yet it is increasing in the west and Atlantic coasts. During November, however, trends in northern stations are positive, yet Atlantic stations become decreasing but not significant. During December, all considered stations in Canada are showing increasing trends, except in Halifax that shows a decreasing trend, which is not significant. Considering winter as a whole, the majority of stations show an increasing trend but not significant except in the far north.

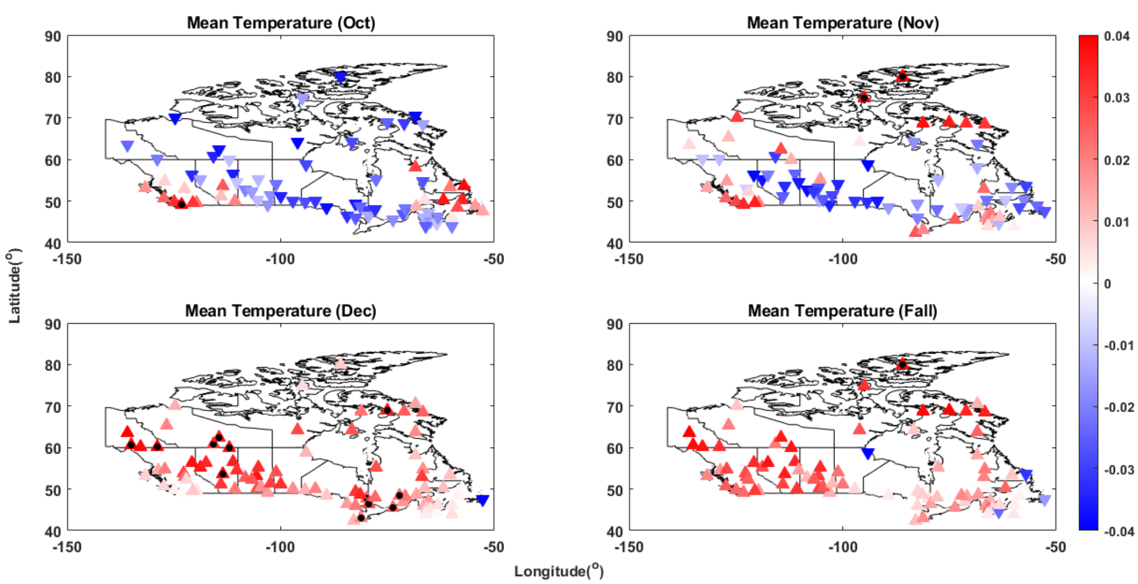

Figure 5.42 *Results of the Mann-Kendall trend test for monthly and seasonal mean temperature in the considered stations during fall. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence.*

Figure 5.43 shows the results of the Mann-Kendall test for analayzing the trend in monthly and seasonal wind speeds in the same stations during the fall. In the month of October, the majority of stations show decreasing trends in wind speed, in which Atlantic stations as well as stations along a transect from southern Ontario to the west of northwestern territories. Simular patterns are observed in the month of November, yet the number of decreasing stations are declining in Atlantic Canada. In December, a positive trend in wind speed can be seen along a transect from western Manitoba to eastern Nanuvet. Considering Fall as a whole, the general trend is decreasing although there are positive trends in northen Canada. It should be mentioned that two adgencent stations in southern BC show opposite trends, highlighting the heterogeneity in the variations in the wind speed.

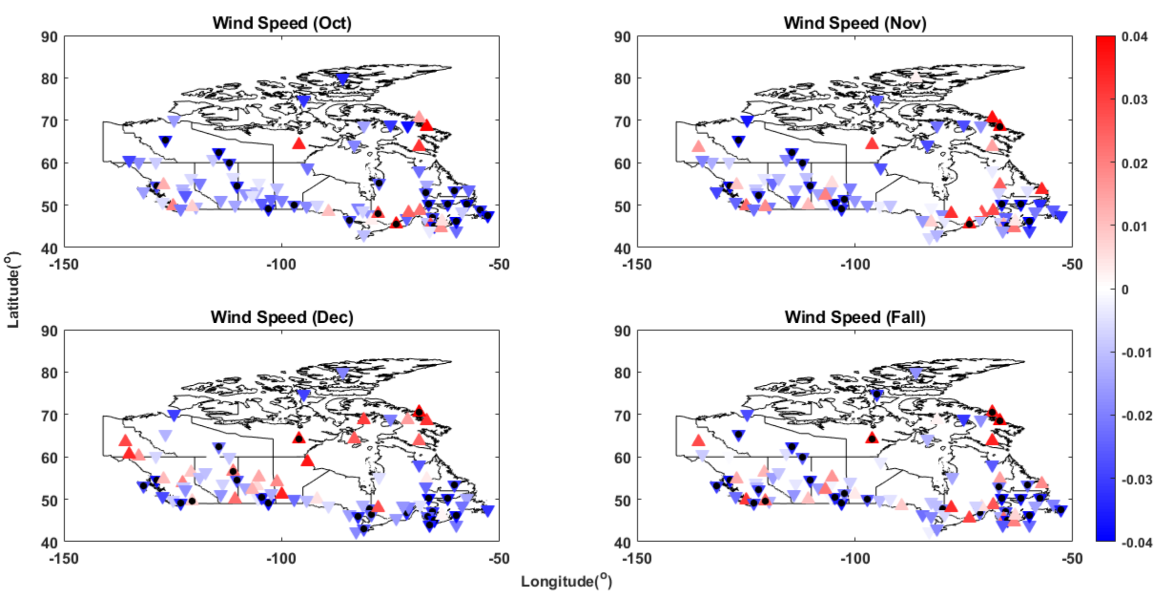

Figure 5.43 *Results of the Mann-Kendall trend test for monthly and seasonal wind speed in the considered stations during fall. For each case, the direction and significance of Sen's slope is shown with the triangular (upward positive, downward negative) and dots (dotted triangular significant; un-dotted triangular not significant); the magnitude of Sen's slope is shaded by the color code in the side bar. Significant level is considered at 95% confidence*

5.2.2 Analyzing dependence between temperature and wind speed across Canadian regions

It seems that increasing trends in local temperature across Canada coincide with decreasing trends in the local wind speed in annual, seasonal and monthly time scales. Here, the existance of the dependence between local temperature and wind speed is formally inspected based on the Kendall's tau. To do so stations are categorized in to four regions, namely western Canada (i.e. BC, AB, SK, MB), northern Canada (i.e. YK, NWT, NU) eastern Canada (i.e. ON, QC) as well as Atlantic Canada (i.e. NB, PEI, NS, NL). The results are again communicated using heatmaps, in which magnitiude, direction and significance of dependence is communicated using colors, upward or downward triangles that may be filled (significant) or unfillwd (insignifiant) as well as dots respectively. In the following heatmaps the significance of trend is considered at 95% confidence level, however the impact of altering the significance level on the number of stations with significant dependence will be discussed.

5.2.2.1 Western Canada

Figure 5.44 demonstrates the results of the Kendall's test for identifying dependency between local temperature and wind speed at monthly, seasonal, and annual scales, across stations located in western Canada. In general, the direction of dependence in one particular month can be divergent, except in the month of September in which all stations consistantly showed negative dependency between wind speed and mean temperature. The direction of dependency can also change in one station across different temporal scales. The number of significant events is marginal compared to insignificant cases in all time scales considered; yet more concentration of significant dependencies can be seen in the cold season. Within all stations only four stations show significant dependence between wind speed and local temperature at the annual scale, in which three suggesting negative and one positive dependencies.

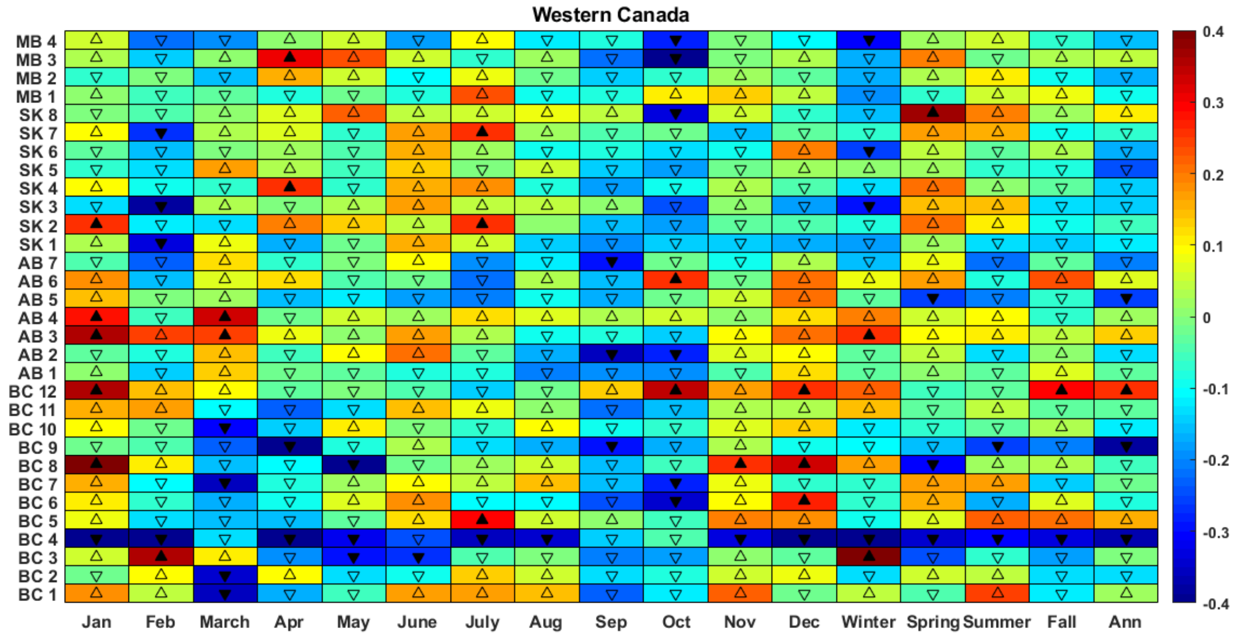

Figure 5.44 *Results of the Kendall tau test for identifying dependency between mean temperature and wind speed across western Canada at monthly, seasonal and annual scales. For each case, the direction and significance of dependency is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of dependency is shaded by the color code in the side bar. Significant level is considered at 95% confidence limit.*

Figure 5.45 shows the effect of altering the significance level on the percentage of cases with significant dependence between temperature and wind speed in western Canada. By decreasing the confidence level, the number of significant positive events increases in June. In addition, significant negative dependencies increase in the months of March, April, September, and October, but there is not a considerable change in other months. At the seasonal scale, the positive significant dependencies increase in the spring and summer while negative significant dependencies increase in winter. Reducing the significance level does not considerably add to the number of significant dependencies in the fall as well as in the annual scale.

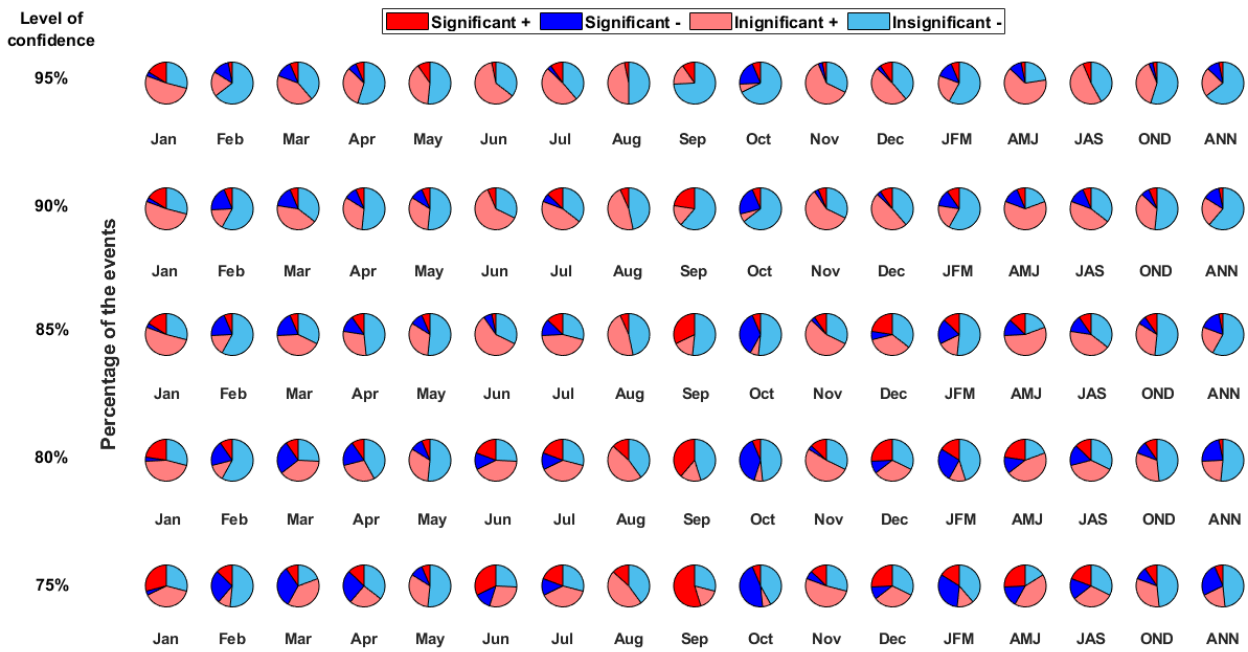

Figure 5.45 *Effect of altering the significance level on the number of cases with significant dependence between temperature and wind speed in western Canada. The significance and direction of the dependence is shown by different color.*

5.2.2.2 Northern Canada

Figure 5.46 shows the results of the Kendall test for identifying the dependency between mean temperature and wind speed across stations located in northern Canada at monthly, seasonal, and annual scales. The dependencies between mean temperature and wind speed are mainly positive in winter and spring months, particularly in NU in which number of significant depenedencies are considerable. Positive dependencies decline in Spring and turn to negative during summer months particularly in NWT. At the seasonal scale, positive dependency between wind speed and temperature are stronger and more significant in Fall and Winter. Negative dependencies are mainly in Summer, in which a number of significant cases remain low compared to the cold months.

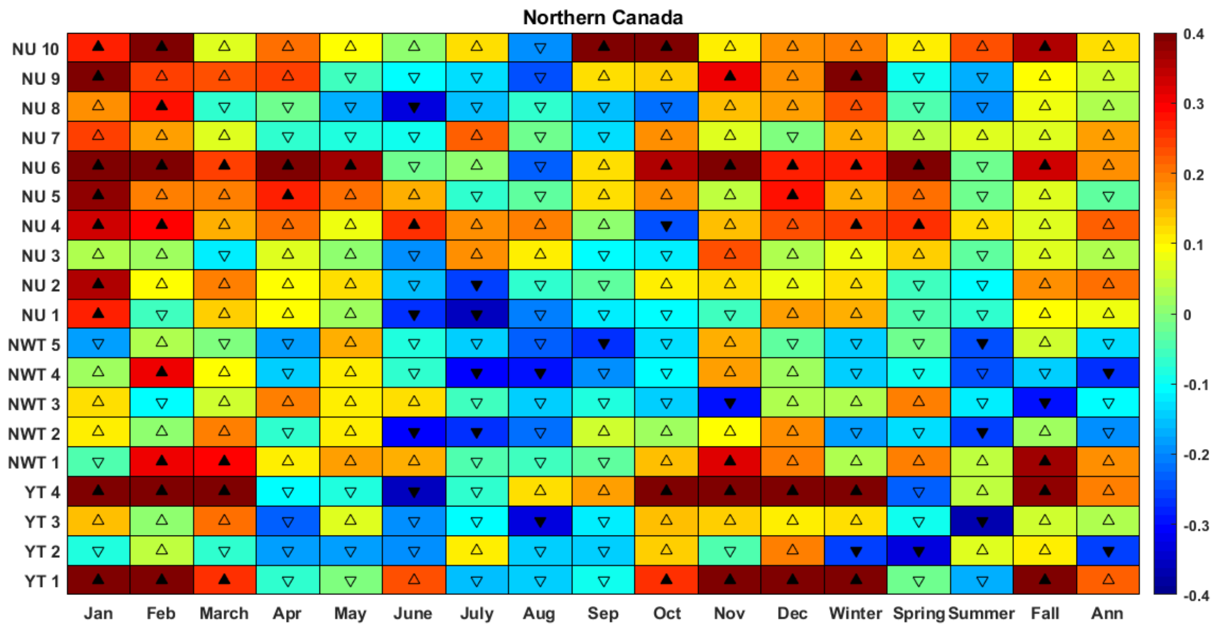

Figure 5.46 *Results of the Kendall tau test for identifying dependency between mean temperature and wind speed across northern Canada at monthly, seasonal and annual scales. For each case, the direction and significance of dependency is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of dependency is shaded by the color code in the side bar. Significant level is considered at 95% confidence limit.*

Figure 5.47 shows the effect of altering the significance level on the percentage cases with significant dependence between temperature and wind speed in northern Canada. By decreasing the confidence level, the percentage of positive significant events increases in March, April, November, and December. Furthermore, the percentage of the significant negative dependencies increases in June and August. At the seasonal scale, the percentage of positive and negative dependency increases in the winter and summer, respectively. At the annual scale, the percentage of positive dependence also increases, while the percentage of negative dependencies does not change considerably.

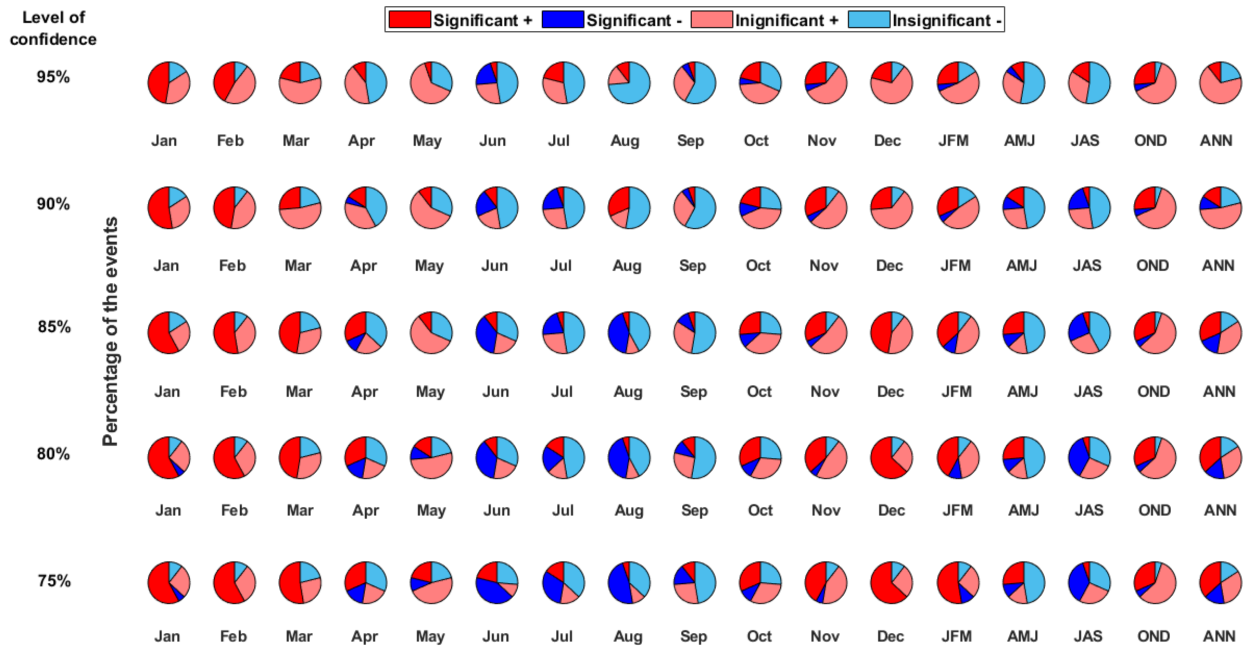

Figure 5.47 *Effect of altering the significance level on the number of cases with significant dependence between temperature and wind speed in northern Canada. The significance and direction of the dependence is shown by different color.*

5.2.2.3 Eastern Canada

Figure 5.48 shows the results of the Kendall test for assessing the dependency between local temperature and wind speed across Eastern Canada at monthly, seasonal, and annual scales. In the monthly time scale, the dominent pattern is the negative dependency between temperature and wind speed accorss May to October. There are some significant positive dependencies in cold month. Across seasonal scales, again the dominent pattern is insignificant negative dependency, which becomes significant at the annual scale for the case of two stations in Quebec.

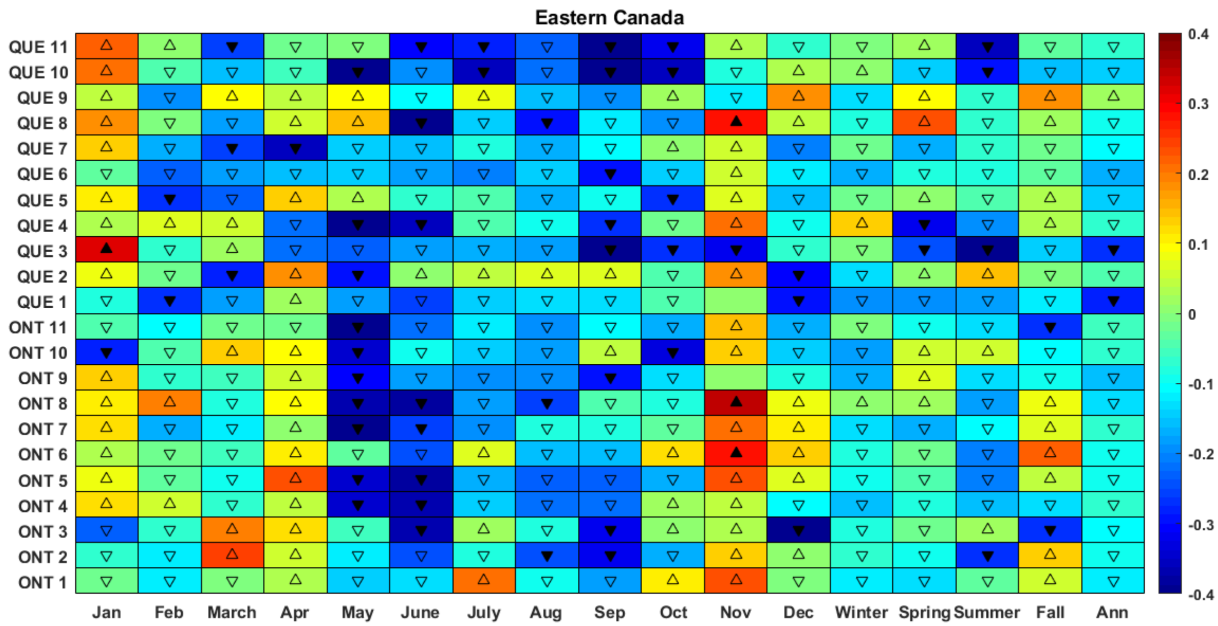

Figure 5.48 *Results of the Kendall tau test for identifying dependency between mean temperature and wind speed across eastern Canada at monthly, seasonal and annual scales. For each case, the direction and significance of dependency is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of dependency is shaded by the color code in the side bar. Significant level is considered at 95% confidence limit.*

Figure 5.49 shows the effect of altering the significance level on the number of cases with significant dependence between local temperature and wind speed across various temporal scales in Eastern Canada. By decreasing the confidence level, the percentage of significant negative events increases in May, June, July, August, September, and October. On the other hand, the percentage of significant positive dependency increases in November only and the changes are negligible in other months. At the seasonal scale, the number of significant negative relations increases during winter and summer, while the number of positive events does not change much. At the annual scale, the effect of altering the significance level on the number of cases with significant positive and negative dependence is rather negligible.

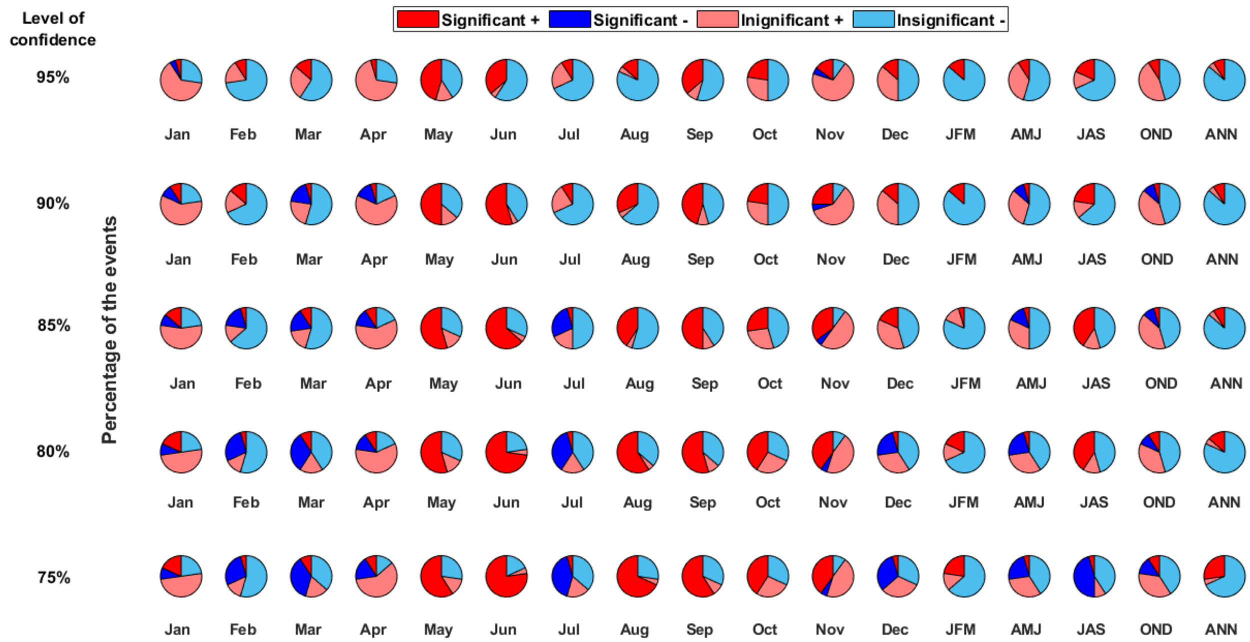

Figure 5.49 *Effect of altering the significance level on the number of cases with significant dependence between temperature and wind speed in eastern Canada. The significance and direction of the dependence is shown by different color.*

5.2.2.4 Atlantic Canada

Figure 5.50 shows the results of the Kendall tau test for identifying dependency between mean temperature and wind speed across Atlantic Canada at monthly, seasonal, and annual scales. In comparing to other regions, mean temperature and wind speed in Atlantic Canada are less significantly dependent across monthly scales. The majority of significant cases across monthly scales are negative. Across seasonal and annual scales, there are a limited number of stations with significant negative dependence. In the annual scales, none of the considered stations show significant dependency between local temperature and wind speed.

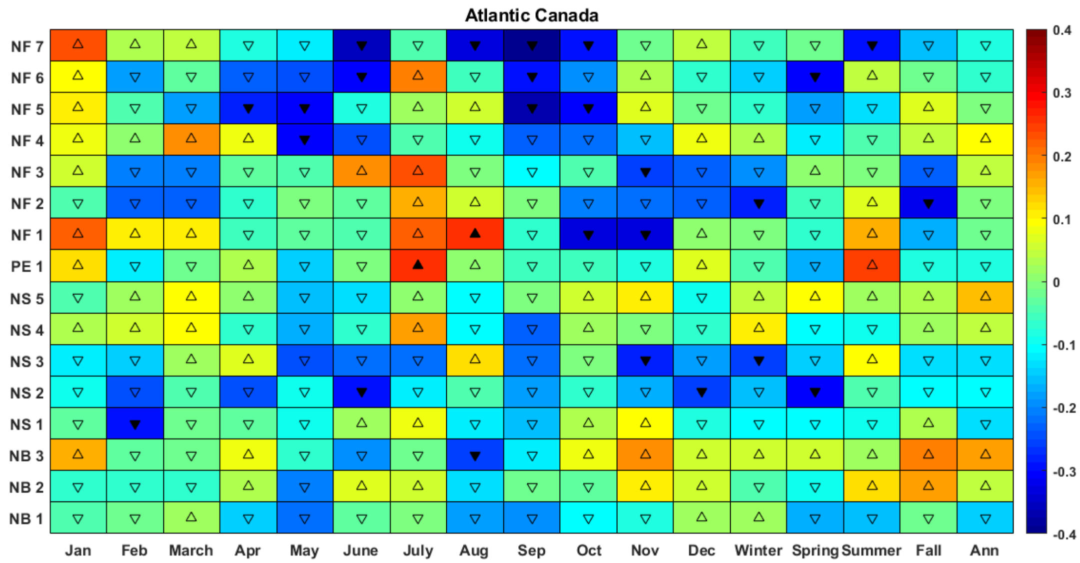

Figure 5.50 *Results of the Kendall tau test for identifying dependency between mean temperature and wind speed across Atlantic Canada at monthly, seasonal and annual scales. For each case, the direction and significance of dependency is shown with the triangular (upward positive, downward negative; filled significant, unfilled not significant); the magnitude of dependency is shaded by the color code in the side bar. Significant level is considered at 95% confidence limit.*

Figure 5.51 shows the effect of altering the significance level on the percentage of cases with significant dependence between local temperature and wind speed across Atlantic Canada. By reducing the level of significance gradually from 0.95 to 0.75, the percentage of the significant negative dependencies increases in all months, except in January and July, in which a number of cases with significant positive dependencies increases. At the seasonal scale, the number of significant negative dependencies increases in all seasons except in the summer, while the significant positive dependencies do not considerably change. At the annual scale, again dependence is very weak even by reducing the level of significance. At the 0.75 significance level, there are only two stations with significant postive dependence and one station with significant negative dependence.

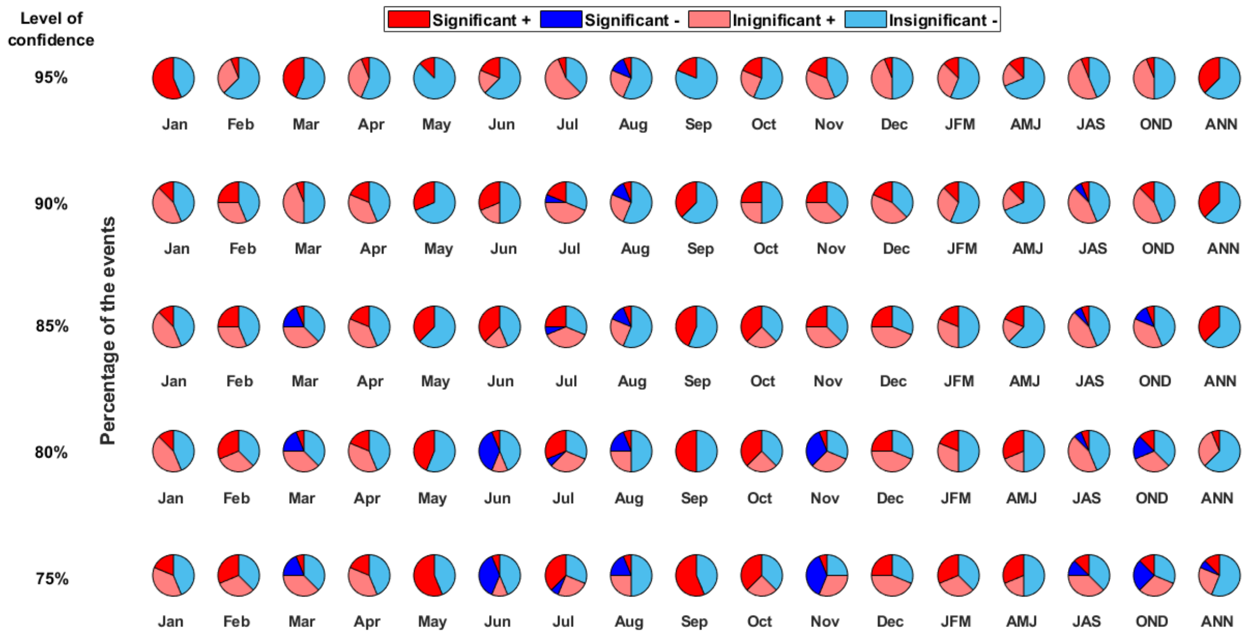

Figure 5.51 *Effect of altering the significance level on the number of cases with significant dependence between temperature and wind speed in Atlantic Canada. The significance and direction of the dependence is shown by different color.*

5.2.3 Regional analysis of wind speed response to changing temperature

The purpose of this analysis is to find how changes in local temperature can reflect in changes in local wind speed across western, northern, eastern and Atlantic Canada and in annual, seasonal and monthly time scales. To address this, only those stations in each region are considered, where significant dependence were observed between local temperature and wind speed and try to address the relationship between trend in temperature and trend in wind speed using first order simple linear regression in the form of $y = ax$, in which y is the sen slope in wind speed, x is the sen slope in temperature and a is the slope coefficient which shows how the trend in wind speed would change based on the trend in temperature. The relationships for annual, seasonal and monthly scales in the four Canadian regions are shown for two boundary significance levels, i.e. 0.95 and 0.75 and discuss how altering the significance level from 0.75 to 0.95 would change the slope coefficient. In Figures 5.52- 5.57, the x-axis indicates Sen's slope for temperature, and the y-axis indicates Sen's Slope for wind speed.

5.2.2.5 Annual scale

Figure 5.52 shows the effect of annual trend in the local temperature on the annual trend in the local wind speed across western Canada, when dependent stations are identified based on 95% significance level. It should be noted that in the annual scale and on the considered significant level of 95%, there is not enough stations to support this analysis in northern, eastern and Atlantic Canada. In western Canada, in which four stations show significant dependency, it can be concluded that increasing trend in annual local temperature has resulted in decreasing trend in the annual local wind speed.

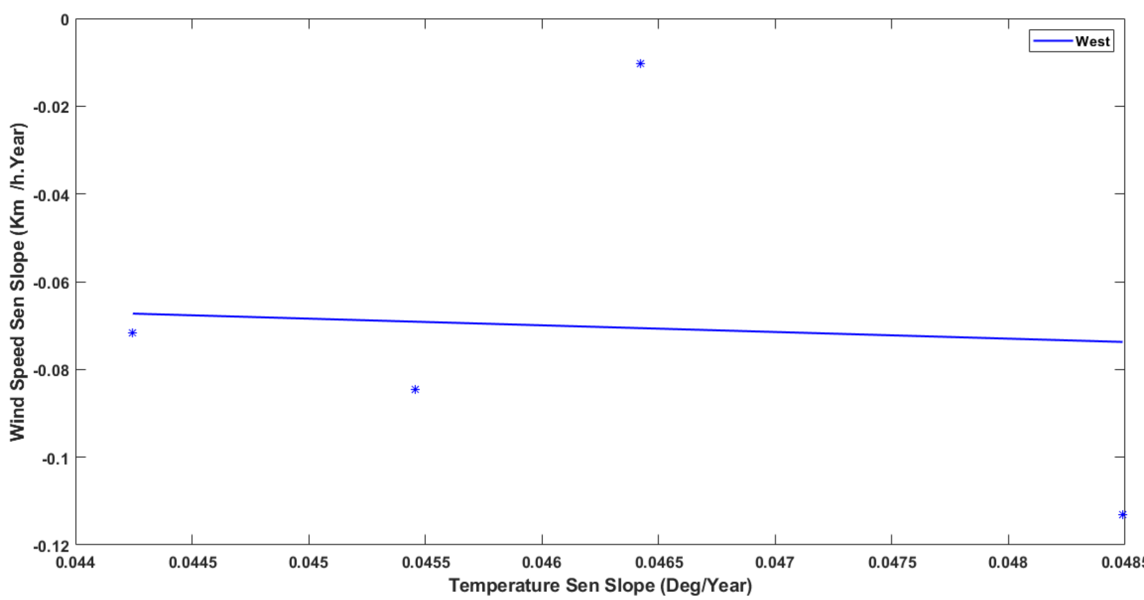

Figure 5.52 *Relationship between trends of temperature and wind speed in western Canadian stations that show significant dependence between temperature and wind speed at the annual scale. The significance level is chosen at 95% confidence.*

Figure 5.53 shows the same analysis when the level of significance is considered at 0.75. In all four Canadian regions, increasing trend in the local temperature causes decreasng trend in the local wind speed at the annual scale, although there are clear regional differences between the response of local wind speed to increasing trends in local temperature. In brief, increasing local temperature in northern Canada has the least impact on altering the local wind speed. The negative response of annual local wind speed to increasing trend in local temperature is almost identical in western and Atlantic Canada. The impact of increasing annual trend in local temperature on the annual trend in local wind speed in observed in eastern Canada, in which a degree increase in annual local temperature can cause more than 2 km decrease in annual local wind speed.

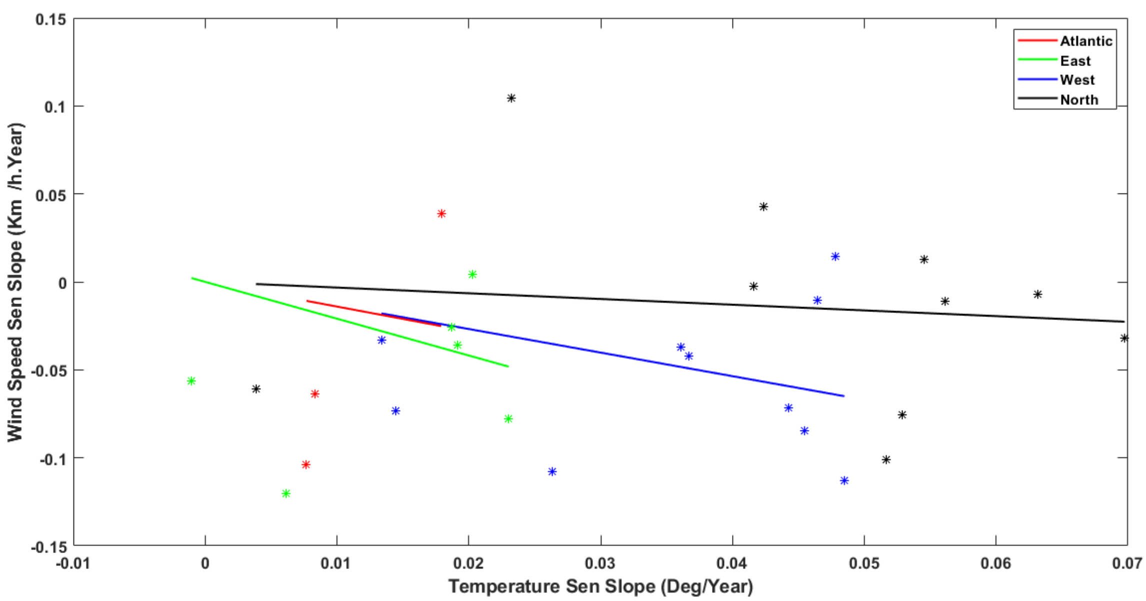

Figure 5.53 *Relationship between trends of temperature and wind speed in western, northern, eastern and Atlantic Canadian stations that show significant dependence between temperature and wind speed at the annual scale. The significance level is chosen at 75% confidence.*

Table 5.3 shows how the estimate of slope coefficient alters when the significance level gradually decreases from 0.95 to 0.75. In northern Canada an estimate for slope coefficient can be obtained when the significance level is decreased to 0.9. In eastern and Atlantic Canada, this threshold is even lower and reaches to 0.8 and 0.75, respectively. This shows the certainty about the slope coefficient is the most in the western Canada and the least in Atlantic Canada.

Table 5.3 *Effect of trends in annual local temperature on gradual changes in annual local wind speed across northern, western, eastern and Atlantic Canada. The significance level is chosen at 75%, 80%, 85%, 90% and 95%.*

Significance level	Northern Canada	Western Canada	Eastern Canada	Atlantic Canada
0.95	N/A	-1.52	N/A	N/A
0.90	-0.32	-1.61	N/A	N/A
0.85	-0.43	-1.79	N/A	N/A
0.80	-0.32	-1.63	-3.28	N/A
0.75	-0.32	-1.34	-2.09	-1.40

5.2.2.6 Seasonal scale

Figure 5.54 shows the effect of seasonal trend in the local temperature on the seasonal trend in the local wind speed across the four Canadian regions, when dependent stations are identified based on 95% significance level. During the winter and spring seasons, only in northern and western Canada an estimation of slope coefficient can be obtained, which is quite identical in both regions during winter, and suggests negative impact of increasing trend in local temperature on the local wind speed. During spring, the two regions represent two different responses, where increasing trend in local temperature has positive and negative impacts in northern and western Canada, respectively. During summer, slope coefficients can be estimated in northern and eastern Canada, suggesting negative impact. During fall, slope coefficients can be estimated only in northern Canada, which suggests a negative impact.

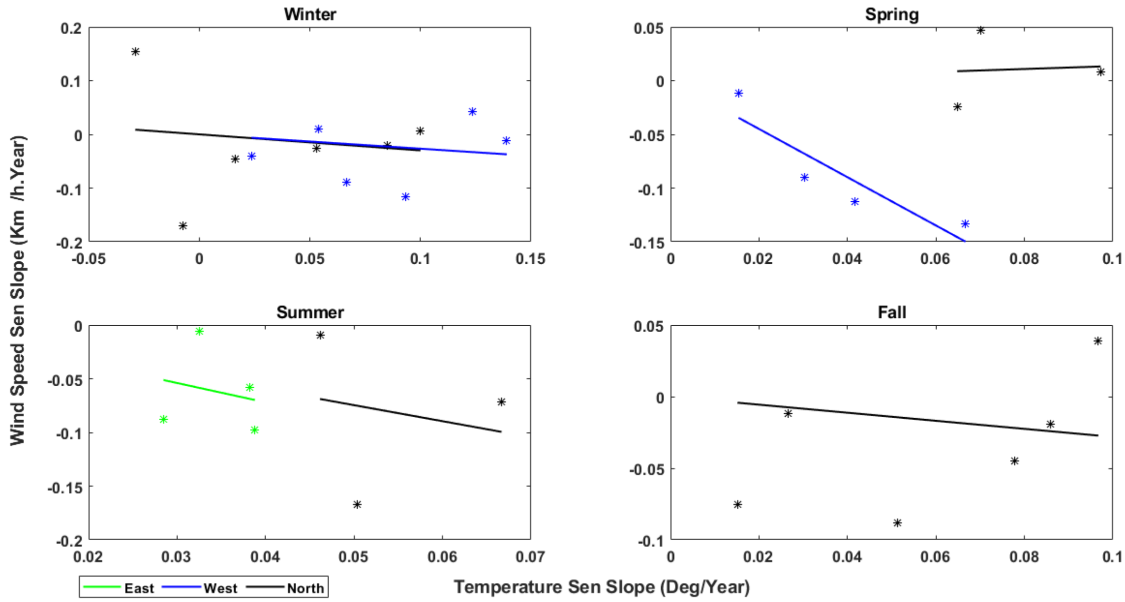

Figure 5.54 *Relationship between trends of temperature and wind speed in western, northern, eastern and Atlantic Canadian stations that show significant dependence between temperature and wind speed at the seasonal scale. The significance level is chosen at 95% confidence.*

Figure 5.55 shows the same analysis when the level of significance is considered at 0.75. In this significance level, the slope coeffieicent can be obtained in all seasons and regions. During the winter season, estimates of slope coefficient show the negative impact of increasing trend in temperature on the wind speed, except in the Atlantic Canada in which increasing trend in local temperature has postive impact on local wind speed. During Spring and Fall, estimates of slope coefficient in all regions suggest negative impacts of increasing trends in temperature on wind speed, although estimates of slope coefficient are quite divergent among the four regions. Among the four regions, the slope coefficient is the least significant in northern Canada and the most significant in the east. Negative impacts of increasonal seasonal temperature on wind speed can be confirmed during Summer as well, although the least impact is seen in western Canada and the most significant impact is observed in Atlantic Canada.

It is worthwhile to mention that by changing the significance level, the sign of slope coefficient may change, e.g. during spring in northern Canada, which highlights two forms of contradictory responses of wind speed to increasing trends in temperature. To explore this issue further, the changes in the sign and magnitudes of the slope coefficient were inspected across various seasons and/or regions under gradual changes in significance level from 0.75 to 0.95. The results, summarized in Table 5.4, show that this is only the case for northen Canada during the spring and the sign of slope coefficient remains stable across various significance levels. For the case of northern Canada during Spring, it should be noted that the sign of slope coefficient is negative across all significant levels except 0.95. This shows that the effect is most likely negative in this region and the positive impact diagnosed at the 0.95 is due to the limited number of stations, with which the estimate of the slope coefficient can be made.

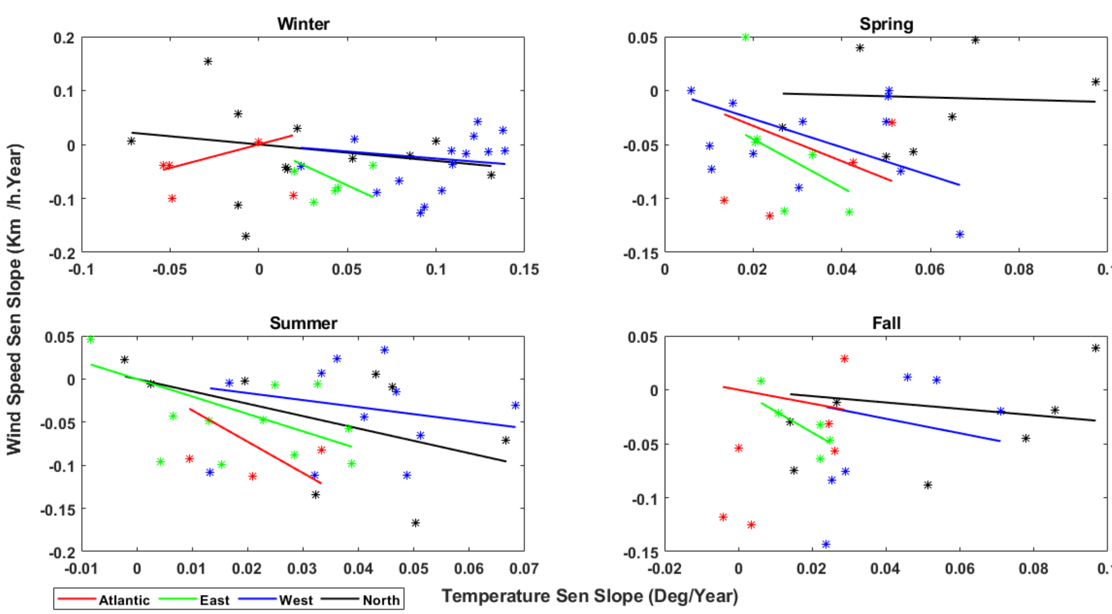

Figure 5.55 *Relationship between trends of temperature and wind speed in western, northern, eastern and Atlantic Canadian stations that show significant dependence between temperature and wind speed at the seasonal scale. The significance level is chosen at 75% confidence.*

From the results summarized in Table 5.4, it is also clear that there is more certainty about the negative impact of increasing seasonal temperature on wind speed across northern Canada as the slope coefficient can be estimated at all season and in all significance levels. In western Canada, such level of certainty can be obtained for winter and spring, while in eastern Canada it would be only for summer. For Atlantic Canada, there would be no estimation of slope coefficient until the significance level is reduced to 0.85, which shows higher uncertainty in the analyses made in this region.

Table 5.4 *Effect of trends in seasonal local temperature on the trend in seasonal local wind speed across northern, western, eastern and Atlantic Canada. The significance level is chosen at 75%, 80%, 85%, 90% and 95%.*

Region	Significance level	Winter	Spring	Summer	Fall
Northern Canada	**0.95**	-0.30	0.14	-1.49	-0.28
	0.90	-0.26	-0.15	-1.77	-0.28
	0.85	-0.34	-0.11	-1.71	-0.30
	0.80	-0.31	-0.11	-1.43	-0.30
	0.75	-0.30	-0.11	-1.43	-0.30
Western Canada	**0.95**	-0.27	-2.25	N/A	N/A
	0.90	-0.24	-1.73	-1.07	-0.70
	0.85	-0.29	-1.83	-0.89	-0.53
	0.80	-0.28	-1.43	-0.76	-0.67
	0.75	-0.26	-1.32	-0.82	-0.67
Eastern Canada	**0.95**	N/A	N/A	-1.80	N/A
	0.90	N/A	-2.43	-1.83	-1.74
	0.85	N/A	-2.25	-1.93	-1.74
	0.80	-1.39	-2.25	-1.93	-1.63
	0.75	-1.52	-2.25	-2.02	-1.98
Atlantic Canada	**0.95**	N/A	N/A	N/A	N/A
	0.90	N/A	N/A	N/A	N/A
	0.85	1.32	-1.24	N/A	1.57
	0.80	1.32	-1.64	N/A	0.08
	0.75	0.87	-1.64	-3.64	-0.64

5.2.2.7 Monthly scale

Figure 5.56 shows the effect of monthly trends in the local temperature on the monthly trend in the local wind speed across the four Canadian regions, when dependent stations are identified based on 95% significance level. At this level, it is clear that in none of the regions, the estimate of slope coefficient can be obtained across all months. In the north, increasing trend in monthly temperature has negative impacts on wind speed in June, July and November, but positive impacts in January, February, March, October and December. In western Canada, the increasing trend in monthly temperature has negative impacts on monthly wind speed in January to May, July, September and December; but it shows positive impact in month October. In eastern Canada, slope coefficients can be only estimated in March, May, June, August, September, October, November and December, in which they consistently reveal negative impact of increasing trends in the monthly temperature on local wind speed. In Atlantic Canada, slope coefficients cannot be estimated in the months of January to May as well as July and December. Estimates of slope coefficients in other months suggest negative impacts of increasing trend in monthly temperature on monthly local wind speed, except in November, in which the slope coefficient is positive. It should be mentioned that the magnitude of slope coefficients can be widely variant across different months; and in many of the cases, the slope coefficient can be very low or there might be a different understanding with respect to sign of change, when compared with seasonal results, e.g. in the case of northern Canada in winter months. This requires analyses of relationships between Sen slope in monthly temperature and Sen slope in wind speed across other significance levels.

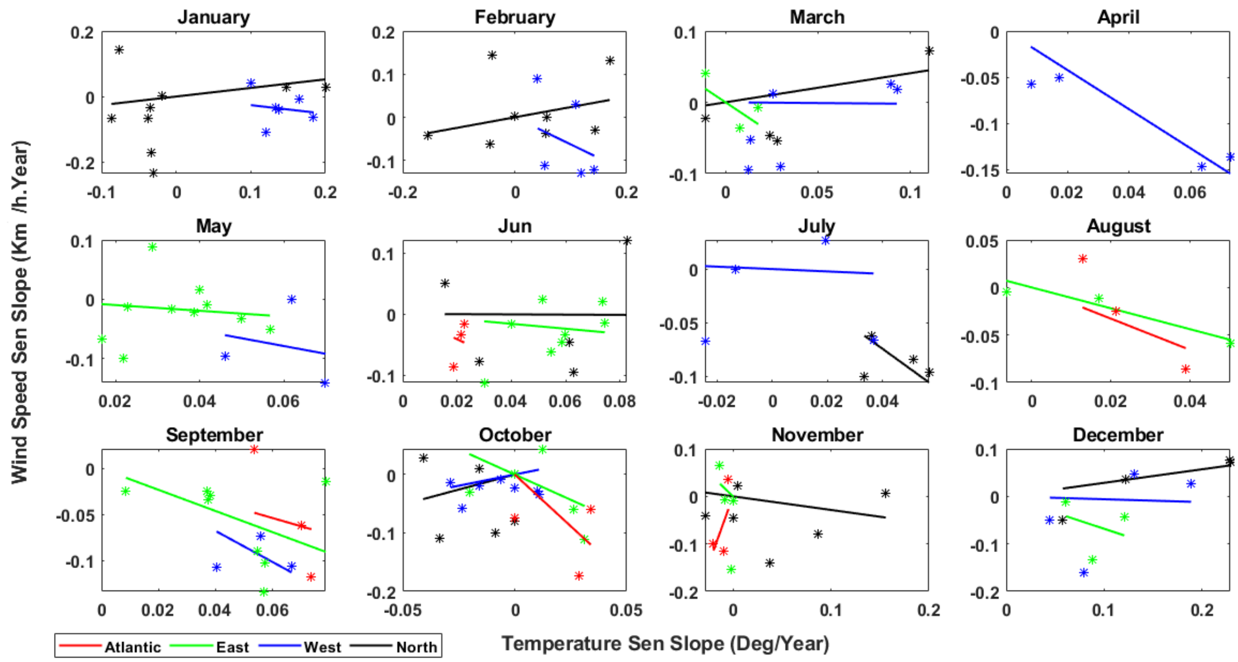

Figure 5.56 *Relationship between trends of temperature and wind speed in western, northern, eastern and Atlantic Canadian stations that show significant dependence between temperature and wind speed at the monthlty scale. The significance level is chosen at 95% confidence.*

Figure 5.57 shows the same analysis when the level of significance is considered at 0.75. In this significance level, slope coefficient can be obtained for all months and across all regions. Considering the northern region, the increasing trend in temperature has negative impacts on wind speed in January, March, April, June, July, August and November, but positive impact in February, May, October and December. In western Canada, the increasing trend in monthly local temperature can consistantly linked to the decreasing trend in wind speed in all months, except in October, in which increasing trends in local temperature has positive impact on the wind speed. A very similar argument can be made for eastern Canada, with the exception that the positive impact of increasing trend in local temperature on wind speed can be witnessed in November.

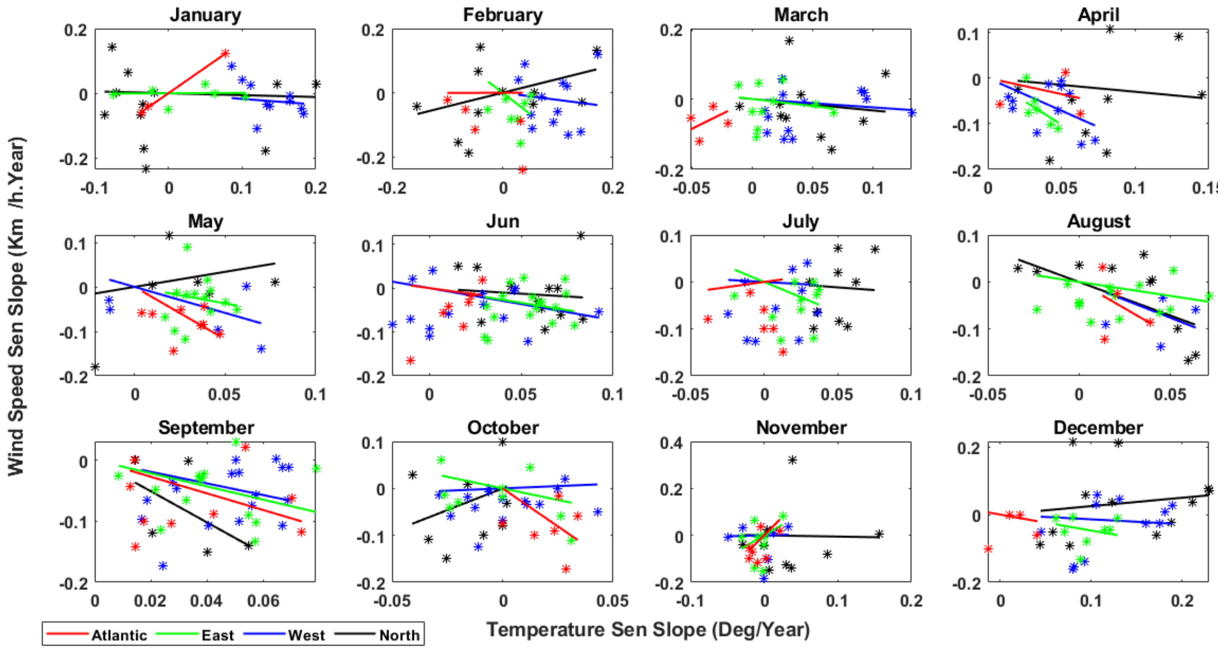

Figure 5.57 *Relationship between trends of temperature and wind speed in western, northern, eastern and Atlantic Canadian stations that show significant dependence between temperature and wind speed at the monthlty scale. The significance level is chosen at 75% confidence.*

In order to address the certainty of the analysis made across different regions and months, the alteration in the slope coefficient were observed across different significant levels – see Table 5.5. In northern Canada, the signs of slope coefficients remain consistant in February, October and December (positive) as well as in June and July (negative). In western Canada, the slope coefficient remain negative in winter months as well as April, May and July, September and December. In eastern Canada, the negative impact remains consistent in March, May, June, August to October, as well as in December. In Atlantic Canada, a positive slope coefficient remains consistent only in November, yet a negative slope coeffienct remains consistent in June as well as August to October.

Table 5.5 *Effect of trends in monthly local temperature on the trend in monthly local wind speed across northern, western, eastern and Atlantic Canada. The significance level is chosen at 75%, 80%, 85%, 90% and 95%.*

Region	Significance level	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Northern Canada	**0.95**	0.26	0.24	0.41	NA	NA	-0.02	-1.86	NA	NA	1.03	-0.29	0.28
	0.90	0.21	0.36	-0.04	-0.78	NA	-0.01	-1.09	-2.03	NA	1.03	0.08	0.40
	0.85	0.20	0.47	-0.50	-0.27	NA	-0.06	-1.09	-1.57	-3.21	1.01	0.08	0.18
	0.80	-0.06	0.43	-0.50	-0.30	0.30	-0.06	-0.32	-1.57	-2.64	1.85	0.05	0.25
	0.75	-0.06	0.43	-0.33	-0.30	0.68	-0.25	-0.23	-1.43	-2.55	1.85	-0.05	0.25
Western Canada	**0.95**	-0.26	-0.63	-0.02	-2.12	-1.31	NA	-0.11	NA	-1.69	0.77	NA	-0.06
	0.90	-0.26	-0.26	-0.21	-2.00	-1.17	NA	0.00	NA	-0.91	0.77	0.61	-0.06
	0.85	-0.26	-0.26	-0.21	-1.72	-1.17	-0.95	-0.90	NA	-0.94	0.47	0.64	-0.10
	0.80	-0.21	-0.24	-0.25	-1.65	-1.17	-0.66	-0.18	-1.53	-0.98	-0.16	0.36	-0.14
	0.75	-0.17	-0.22	-0.24	-1.43	-1.17	-0.73	-0.18	-1.53	-0.96	0.20	0.08	-0.14
Eastern Canada	**0.95**	NA	NA	-1.73	NA	-0.48	-0.41	NA	-1.10	-1.15	-1.73	-1.98	-0.68
	0.90	-0.10	-4.35	-0.51	-2.27	-0.68	-0.64	NA	-0.51	-1.27	-1.73	-0.19	-0.68
	0.85	-0.05	-1.47	-0.54	-2.03	-0.75	-0.70	-1.43	-0.55	-1.07	-1.84	1.13	-0.58
	0.80	0.01	-1.33	-0.61	-2.03	-0.75	-0.64	-1.51	-0.68	-1.11	-0.98	1.82	-0.49
	0.75	0.01	-1.33	-0.40	-2.04	-0.74	-0.67	-1.31	-0.59	-1.08	-0.98	1.82	-0.47
Atlantic Canada	**0.95**	NA	NA	NA	NA	NA	-2.07	NA	-1.65	-0.89	-3.54	5.72	NA
	0.90	NA	-0.24	NA	-0.70	-2.00	-2.42	-6.80	-1.65	-1.11	-2.82	5.19	-0.60
	0.85	NA	-0.24	1.70	-0.70	-2.05	-1.34	0.81	-1.65	-1.24	-3.24	5.19	-0.48
	0.80	NA	0.00	1.70	-0.70	-2.33	-0.58	0.44	-2.25	-1.26	-3.24	3.40	-0.48
	0.75	1.59	0.00	1.70	-0.70	-2.36	-0.58	0.44	-2.25	-1.36	-3.24	3.17	-0.48

6 Conclusions and future work

6.1 Summary of key findings on climate-hydropower dependency

The analysis of trends showed changes occurred in climate variables, namely temperature, total precipitation, rainfall and snowfall across Canada and concluded that the mean temperature increased consistently across Canada. The most significant positive trends can be seen during the summer and fall months. Also the trends in precipitation show increments in some months but decreases in some others, which can be further subject to change across different regions. Based on the results captured for snow and rain, it can be concluded that the amount of snowfall mainly decreased in most of the cases while rainfall increased. These results can prove that changes in temperature affected the form of precipitation from snow to rain.

Furthermore, the results of dependency presented a strong association between upscaled climate variables and hydropower generation in most of the provinces. The dependency analyses showed that there are strong dependencies between precipitation and hydropower in Canadian provinces except in Saskatchewan and Manitoba, in which the water is coming from upstream province of Alberta. In general, the dependency between precipitation and hydropower is positive in British Columbia, Alberta, and Atlantic provinces. In addition, it is negative in northern and eastern provinces within the first months, but it changes to positive after some lags. This points to the fact that spontaneous precipitation can goes to unproductive spill; and also the existence of few months lag between snow precipitation and runoff generation. Also hydropower is dependent on snowfall in most of the provinces, and the relation between them is positive when there is no lag in generation until four or five months lag. A robust set of dependencies between rainfall and hydropower generation can be seen across the country. The relation between these variables is negative in the first time steps in northern and eastern provinces, but become positive after some lags. This highlights that storage and turbine capacity are other factors that affect the relation between amount of rainfall and generation. The relation between mean temperature and hydropower is negative in first time steps, but becomes positive after some lag.

The analysis of causality proves that considered climate variables drive hydropower generation and the respond of hydropower to them is can be different spatially and temporally. For instance, all four climate variables considered contribute to the hydropower generation in NT&NU till 8 months lag. The dominant driver of generation is precipitation in early lags but it changes to temperature after 3 months. In YK also all the climatic variables would be cause of generation up to 12 months lag. Temperature and rainfall were the dominant driver for first and second six months lag respectively. Furthermore, the results showed that, all climate variables considered as a cause of hydro production in BC up to 10 months lag. Rainfall was the dominant driver in the majority of the time lags in this province. The pattern captured in AB showed that all the climate variables would be driver of generation till eight month lag. The dominant driver was identified as rainfall in most of the time lags. In SK and MB, the signal of all climate variables were negligible in comparison with other provinces. Hence, it could be concluded that hydropower production is not dependent on local climate in either of these provinces. All of the climate variables considered as a cause of hydropower production in both ON and QC. The dominant driver would be temperature in the first lags in both provinces. However, these drivers changed to snowfall in ON and rainfall in QC in higher lag times. All climate variables were the cause of hydropower generation, except for total precipitation across NL, where the dominant driver is the temperature in most of the time lags. In NB, only temperature and snowfall had a significant causal relation with hydropower. In the first time lag, temperature was dominant driver but it changed to snowfall after 3 months lag in this province. Also, all climate variables are causes of hydro production till 10 months lag except total precipitation in NL. The contribution of precipitation increased by considering more lags and got to the dominant driver of generation after 6 month lag. Considering Canada as a whole, all climate variables would be the cause of hydropower generation till 11 months lag. The dominant driver varies in the first time lags but rainfall becomes consistently the dominant cause of generation after 4 months lag.

A set of statistical models were developed to predict monthly hydropower production in each province based on past values of hydropower production as well as past monthly climate variables. The proposed models were success to predict hydropower generation in all provinces in offline mode. The efficiency of predictive models declined in online mode, yet they were able to effectively simulate hydropower production in most of the provinces and in Canada. The proposed models could not capture the extreme high and low productions of AB and NB; although in general they were successful to generate the general signal very well. The models, however, fully failed in predicting hydropower generation in SK and MB as the water availability in these two provinces were not dependent on local climate and is more related to the upstream province of Alberta. Based on the impact assessment results, hydropower production will be altered if the observed trends in climate variables continues. For instance, hydropower generation will decrease during winter and spring in NT&NU but the changes are negligible during the fall. The net hydropower generation will decrease around 10% in August. In YK, generation will increase in all months and the maximum gain would occur in March (8%). In BC, hydro production will fluctuate but it will decrease in most of the months. The maximum gain will be 6% which were captured in March and maximum loss of 12% will occur in September. In AB, hydropower does not change during spring and summer but it will decrease during cold months. April will experience the maximum increase of 2.5% and the maximum loss of 10% would happen in December. In ON, hydropower will increase during spring, summer, and fall months but decrease in winter. The maximum increment is captured in June and July (10%). The results show that generation will increase in all months in QC and the maximum gain will occur in June, July, and September. In NL, the amount of generation will increase in all months; although the amount of gain is negligible. In NB hydropower production will increase during winter and summer months, while it will decrease in spring and fall. In general, the summer months will experience high amounts of generation (10-15%) in this province on the other hand, maximum loss will happen in November (8%). Moreover, the generation will decrease in all the months in NS but in general the amount of change is negligible. In Canada, hydropower production will increase in most of the months. For instance, the maximum increment will happen in June (15%) and maximum loss will occur during March (5%).

6.2 Summary and key findings on climate-wind power dependency

The trend analysis shows that the mean temperature increased in most of the stations during all months except in October and November. In these two months, most of the stations show negative trends. Stations located in the eastern part of country also experienced decrement in mean temperature in the months of January to March. The positive trends are stronger in terms of magnitude and number of significant events mostly in western and central parts of Canada and the largest proportion of positive trends occurred from May to September. Furthermore, temperature increased in most of the stations on the seasonal scale, except for some decreasing trends in the eastern stations during winter and some stations in the south-central part. Summer and fall show the largest proportion of positive trends. In the annual scale, about 90% of the stations experienced an increase in temperature. On the other hand, wind speed decreased in most of the cases. These negative trends were obvious across all regions except for the north in terms of magnitude and number of significant events. In terms of the monthly scale, negative trend in wind speed generally observed across Canada from April to September. In terms of seasonal and annual scales, wind speed mostly decreased as well, which is most obvious in spring and summer.

Based on the dependency test between mean temperature and wind speed, it was shown that in the majority of cases there is no significant dependence between local temperature and wind speed. Having said that, by reducing the level of statistical significance, the number of significant dependencies increase. Within the stations that show significant dependence between temperature and wind speed, it can be concluded a positive trend in temperature has generally caused a negative impact in wind speed. By decreasing confidence level to 75%, the pattern would be similar for this region. The eastern stations have significant dependency between temperature and wind speed in all the months except, January, February, April, and July which the relation between trends is negative in all of them as well as in the summer season. By decreasing the confidence level, the dependencies for all months remain negative, except for November in which the dependence turns positive. On the other hand, the dependency between wind speed and temperature trends show a positive dependence during cold months in north region. By decreasing the confidence level the dependence become negative, except in Febuary, May, October, and December in which the dependence is positive. The results for Atlantic stations reveal that the relationship between trends is negative in June, August, September, and October and positive in November. By decreasing confidence level these relations would be negative in all of the months except in January, March, July, and November. In general, the magnitude of negative effects of temperature change on wind speed is stronger in summer and fall months. By decreasing the significance level, the number of stations increases but the direction of the fitted line of wind speed and temperature sen slopes remains constant in most of the cases, although the magnitude of slope, which manifest how much a degree change per year in temperature affects the trend in wind speed.

6.3 Contributions, limitations and future work

This research was a chance to apply statistical methods to explore the dependency between climate and two strategic renewable energy sources in Canada. In terms of climate-hydropower dependency, it was shown that hydropower is dependent on local climate pattern in most of the provinces. A set of statistical models was developed to predict hydropower generation under climatic trends. The results confirmed that the amount of hydropower generation will alter, if the captured trend in climate variables continues. Although the overall Canadian gain would be positive, there are places such as BC and AB that are significantly lose their hydropower production potential. On the other hand, the obtained investigation on climate-wind power dependency showed that local wind speed is not significantly dependent on local temperature. However, the effect of changing temperature was negative on wind speed across the stations which had significant dependency between wind speed and temperature. The holistic approach of this study presents an executive and effective information for resource managers to be able to quantify the vulnerability or resilience of production potential under different climate conditions. This information can help decision makers to developing effective strategies to offset losses or invest on the potential gain. Also, the proposed straightforward methodology would be practical for corporations to create new economic opportunities not only at the local but also across provincial scale. The information gathered from wind power show that the potential of new wind plants is more in the regions which had positive impact of warming on the wind speed. On the other hand, the regions which showed negative effects of warming on wind speed would be vulnerable for new plan investments.

Indeed, this thesis is not complete and can be improved in a number of ways:

- The proposed predictive models for monthly hydropower simulation failed in SK and MB. Future work can be done for diagnosing the spatial dependency between provincial hydropower and the climate variables in AB to find the regional climatic driver of hydropower, which are beyond the jurisdictions' territories.
- Non-falsified predictive models for hydropower simulation were selected based on the R^2. The suggestion for future work can be identifying other non-falsified models based on different goodness-of-fit measures. Accordingly, the impact assessment can be redone by an ensemble of models to account for potential uncertainty in impact assessment as a result of lack of identifiability in predictive models.
- From a broader perspective, the predictive models are developed based on deterministic statistical regression models. Future work can be proposed to use other methodologies, in particular stochastic approaches, to formally address the uncertainty in predictions.
- The considered future climate data is reconstructed by using historical trends. For future work, the projections of climate variables under different scenarios can be obtained from

GCMs, to address the impact of climate change on hydropower in light of the current available climate projections.

- The dependency analysis show that local wind speed is not significantly dependent on local temperature. Future plans can be diagnosing the dependency between wind speed and temperature in a wider spatial scale. It is suggested that analysis of dependence between temperature and wind speed is pursued along the atmospheric rivers that determine the large scale pattern of wind speed across various Canadian regions.

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