Implications of Future Climatic Data for Transportation Infrastructure Design

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Abstract

The design and evaluation of infrastructure, including transportation systems, is based on climatic loads, such as wind, snow, rain, ice accretion and temperature. Currently, the climatic parameters in the codes and guidelines that are used for design, operation, and maintenance of transportation infrastructure, such as highway bridges and pavements are based on historical observations of climatic parameters. These climatic design data, thus, do not represent the future climatic conditions under climate change. This can lead to higher risks of failure and service disruption, and higher costs of rehabilitation and replacement of infrastructure assets. Therefore, there is a need to generate future projections of climatic data taking into account climate change and implement them in the design and management of transportation systems to ensure their safety, serviceability, functionality, and durability and to avoid costly rehabilitation and strengthening, and to minimize the disruption of services. The selection and implementation of future climatic data in the design and management of transportation infrastructure is a challenging task. As a preliminary step, it is of essential importance to understand the implications of climate change for different types of transportation infrastructure systems to identify the potential risks that climate change can impose on them. In addition, it should be noted that changes in the future climatic data depend on several factors such as the climatic region, climate variable, climatic design value statistics, planning horizon, etc. Moreover, the future climatic conditions largely depend on the human-induced greenhouse gas emissions scenarios that are described by representative concentration pathways (RCPs), which yield different levels of changes in the climatic design data. The selection of an appropriate RCP emission scenario is also a challenging task. This study provides insights into the implications of climate change for transportation infrastructure systems performance, and challenges for implementation of future climatic data in the design and management of infrastructure systems. The future projections for a number of climatic design parameters at various locations across Canada are presented in order to illustrate the implications of climate change for transportation infrastructure systems.

1. Introduction

Transportation infrastructure such as roads, railways, airports, bridges and tunnels provide essential services that are critical for the wellbeing of Canadians and sustainability of Canadian communities. These infrastructure systems are subject to extreme climatic conditions due to the changing climate (Meyer, 2008; Wilbanks et al., 2012; Tonn et al., 2021). Climatic Design values in the design codes and guidelines such as the Canadian Highway Bridge Design Code (CHBDC 2019) and AASHTO LRFD Bridge Design Specifications (AASHTO 2020) are based on historical data and therefore ignoring climate change impacts. However, the Intergovernmental Panel on Climate Change Report (IPCC, 2014; IPCC, 2018), the US Fourth National Climate Assessment Report (USGCRP, 2018), and the Canada's Changing Climate Report (Bush and Lemmen, 2019) clearly indicated that the future climate is changing due to the emissions of human-induced greenhouse gases (GHGs). Climate change can lead to increased climatic loads, such as extreme temperatures, wind, ice accretion, and rain, which in turn can lead to an increased risk of infrastructure failure and service disruption or interruption for various transportation infrastructure systems (Bloetscher et al., 2014; Pedrozo-Acuña et al., 2017). The climate change risks for transportation infrastructure can vary based on their current condition due to the ageing and demand. In addition, the climate change risk levels may vary based on the location of the infrastructure and the climatic parameters that govern the design of different infrastructure systems. Previous researchers studied the impacts of climate change on various types of transportation infrastructure such as rails, roads and bridges (Lambert et al., 2013; Camp et al., 2013; Nasr et al., 2020).

Therefore, there is a need to develop design guidelines based on future climatic loads to build climate-resilient transportation infrastructure. There are existing climate resiliency studies in the literature including climate change resilience adaptation (Lounis and Daigle 2008; Asam et al., 2015; Lounis and McAllister, 2016; Jacobs et al., 2018; Bowyer et al., 2020; Knott et al., 2019). However, using future climatic design values based on climate change projections remains a challenge. In support of the Pan-Canadian Framework on Clean Growth and Climate Change and Green Infrastructure objectives of Canadian government, recently, the National Research Council Canada (NRC) led an initiative to develop decision support tools, including codes, guides and models for the design of resilient new and rehabilitation of existing buildings and core public infrastructure to ensure that the impacts of climate change and extreme weather events are considered (CRBCPI, 2020). As part of this initiative, Environment and Climate Change Canada (ECCC) in partnership with NRC and Pacific Climate Impact Consortium (PCIC) developed future climatic data for design of buildings and core public infrastructure (Cannon et al., 2020).

The selection of the projected climatic design data is a challenging task due to the high level of uncertainty associated with climate projections as well as the time variation of climatic design values and their statistics – known as non-stationarity. Previous studies observed a high level of non-stationarity in climatic data (Madsen 2013; Rootzen and Katz 2013; Cheng and AghaKouchak 2014; Lee and Ellingwood 2017). The future emission of greenhouse gasses (GHGs), which is the main driver of climate change, is highly uncertain as it depends on several socio-economic factors. The Intergovernmental Panel on Climate Change (IPCC) developed four Representative Concentration Pathway (RCP) scenarios, RCP2.6, RCP4.5, RCP6.0 and RCP8.5, to predict the GHGs concentration trajectory (Van Vuuren, 2011). Previous studies investigated these uncertainties for various engineering applications (Shirkhani et al., 2020; Shirkhani et al., 2015; Stott et al., 2002). Selection of an appropriate RCP scenario to obtain future climatic design values is a non-trivial delicate task.

In this paper, we provide insights into the challenges for selection of future climatic data required for the design and management of climate-resilient transportation infrastructure systems. The future-looking climatic design data from Cannon et al., (2020) that are obtained from the output of the Canadian Regional Climate Model (CanRCM4) under RCP8.5 emission scenario is used. The future projections of selected temperature, precipitation and wind related parameters are presented and discussed. The projected changes in 50-year wind pressure, annual precipitation as well as the maximum and minimum mean daily air temperatures are investigated. These climatic design data are of essential importance for many transportation infrastructure such as roads and bridges. The projected changes of selected climatic design data are presented for various locations across Canada in order to illustrate the impact of climate change across various climatic regions over Canada and to identify the spatial patterns of changes. In addition, to shed some lights on the challenges for selection of an appropriate RCP emission scenario, the future climatic design parameters are presented under various emission scenarios. The role of the infrastructure design life in the time horizon of climatic projections and selection of RCP emission scenarios are discussed for short (25 years) and long (75 years) life assets. The non-stationarity issue of projected climatic design data are discussed through assessing the time variation of selected climatic design parameters under various emission scenarios.

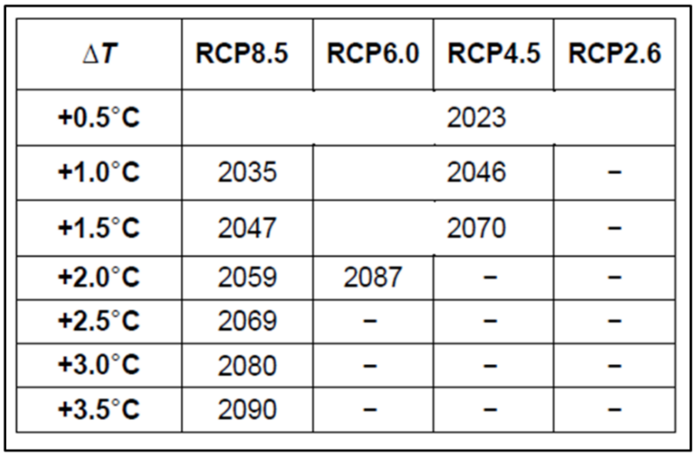
2. Climate Change Modelling and Emission Scenarios

Climate models are computer simulations of the global climate system that can be used to make projections of future climate driven by future GHG emission scenarios. Climate models, indeed, represent the components of the climate system such as atmosphere, ocean, ice and snow, and land surface as well as the biogeochemical cycles. The physical processes corresponding to each component (and interactions between them) are simulated using a numerical mathematical framework. The ability of climate models to simulate these physical processes is limited by the temporal and spatial resolution, and the knowledge gap in understanding of the governing physical processes. Therefore, the GHG emission scenario and the climate model are sources of uncertainty for the future projections of climatic design data.

In this paper, the output of the Canadian Regional Climate Model-CanRCM4 is used to estimate the projected changes in the selected climatic design data (Cannon et al., 2020). CanRCM4 dynamically downscales Canadian Earth System Model (CanESM2) to a grid with 0.44° (~50km) resolution over North America (Scinocca et al., 2016). Fifty (50) runs of CanRCM4 under RCP 8.5 high emission scenario are used to form a Large Ensemble (LE) of projected climatic data. The projected changes in climatic design data are obtained from CanRCM4 LE results.

As the CanRCM4 simulations are conducted under RCP8.5, in order to obtain the projected climatic data under other emission scenarios, a global warming level approach is implemented by Cannon et al., (2020). Based on this approach, projected changes in climatic design data are related to levels of global warming, which are in turn coupled with the RCP emission scenarios through the timing when such warming levels are reached by different RCP scenarios (see Cannon et al., 2020). The warming levels are measured relative to the baseline period of 1986-2016 (Table 1). Years that are presented in Table 1, indeed, indicate the centre year of the 31-year period for which the average change in global mean temperature is reached by the corresponding RCP emission scenario. For example, the future time horizon of 2070 corresponds to the time period of 2055-2085. For the end of the century time horizons, however, the time period might be shorter due to the data availability up to the end of century (year 2100). For instance, the warming level of $\Delta T = 3.5^{o}C$ is projected to be reached under RCP8.5 scenario by 2090 time horizon, which corresponds to the 2080-2100 period. It should be noted some ΔT warming levels do not occur before 2100 under specific emission scenarios (shown as dash in Table 1).

Table 1 – Year at which indicated global warming is exceeded for different emission scenarios (Cannon et al., 2020)



ΔT	RCP8.5	RCP6.0	RCP4.5	RCP2.6
+0.5°C	2023			
+1.0°C	2035	2046		–
+1.5°C	2047	2070		–
+2.0°C	2059	2087	–	–
+2.5°C	2069	–	–	–
+3.0°C	2080	–	–	–
+3.5°C	2090	–	–	–

3. Method and Data

The projected changes in selected climatic design data, which are of interest for design and evaluation of transportation infrastructure, are presented. Namely, we discuss projected changes in the 50-year wind pressure, annual precipitation as well as the maximum and minimum mean daily air temperatures. These climatic design data are of essential importance for many transportation infrastructure such as bridges and roads. Cannon et al., (2020) estimated the projected changes for each global warming level in Table 1 using the output of CanRCM4 LE. The climatic design parameters are estimated for the time period in which the global warming levels are reached. It should be noted that the timing of global warming levels in Table 1 are based on the center year of the 31-year period.

In general, the confidence in temperature projections are higher that other climatic variables such as precipitation and wind because temperature change is a direct consequence of the radiative imbalance associated with changing GHG and aerosol emissions (Bush and Lemmen, 2019; Cannon et al., 2020). The maximum and minimum mean daily temperatures are related to summer and winter temperatures, respectively. For each global warming level, the maximum and minimum daily mean temperatures indicate the maximum and minimum daily mean temperatures within the corresponding 31-year period. The projected changes are estimated relative to the baseline period of 1986-2016, and by taking the ensemble mean across all CanRCM4 LE members.

Projection results for regional precipitation have lower confidence than temperature (Cannon et al., 2020) mainly due to the complex physical processes and limited climate model resolution. In order to estimate the projected changes in the annual total precipitation, future projections of annual precipitation based on the CanRCM4 LE ensemble (by taking the ensemble mean over the ensemble members) are calculated for different global warming levels relative to the baseline period.

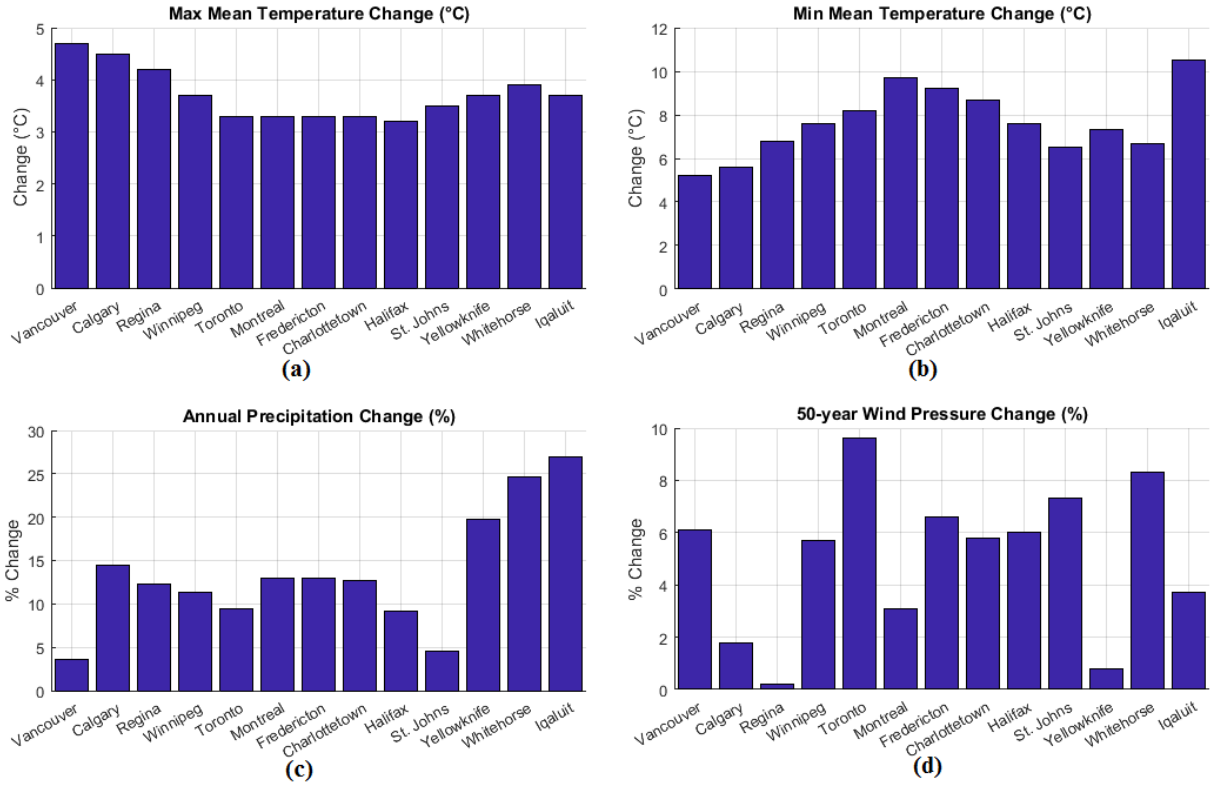
The wind projections are subject to a very high uncertainty due to the inability of conventional climate models to adequately represent many of the physical processes that drive extreme winds. The 50-year win pressure is estimated based on the design wind speed with the same return period. The design wind speeds are estimated by pooling all of the annual maxima of the daily maximum wind speed variable from all CanRCM4 LE members. The Gumbel distribution is then used for each 31-year period associated with each level of global warming, in order to obtain the corresponding 50-year wind pressure.

In order to show the regional variations, the climatic design parameters are presented for 13 locations across Canada i.e. one location from each province and territory. In order to illustrate the challenge of selection of the RCP scenario, the future climatic design parameters are presented under various emission scenarios. The results for various emission scenarios are not directly obtained from climate models forced by RCP emission scenarios, but by using the global warming level approach presented in Table 1 (Cannon et. al., 2020). The issue of climate non-stationarity is discussed through presentation of time variation of climatic design data over the design life of infrastructure. Two planning horizons or design lives of 25 and 75 years are presented in order to show the impact of climate non-stationarity for short life (e.g. road pavement) and long life (e.g. bridges) transportation infrastructures. The role of infrastructure design life in selection of RCP emission scenario is also discussed.

4. Future Climatic Design Data

4.1. Regional Changes of Climatic Design Data

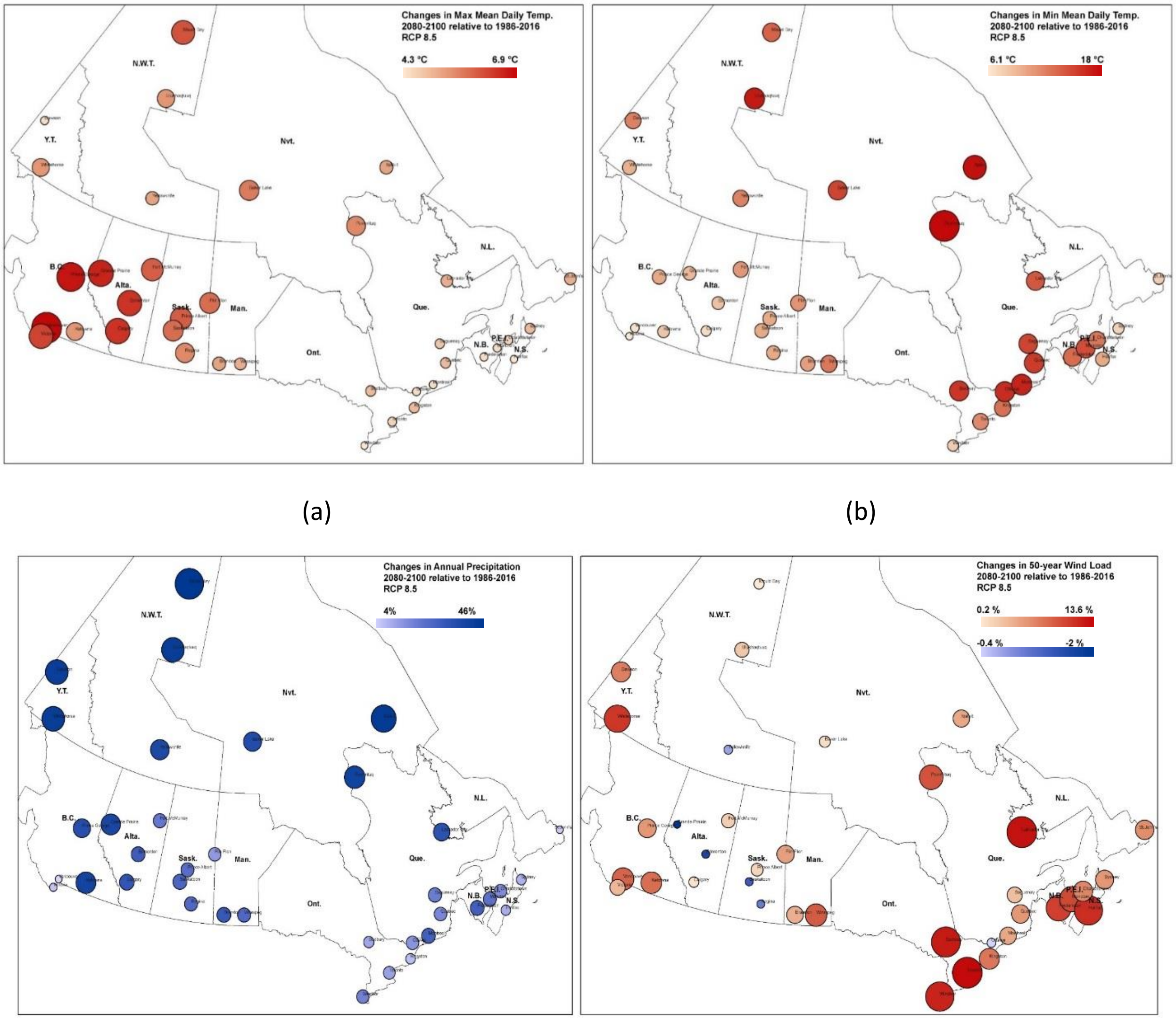
The climate change risk for infrastructure depends on the location of the infrastructure and the climate variable. That is, the change in climatic design parameters depends on both the climate variables and the climatic region. Given the diverse climatic regions across Canada, we present the projected changes in selected climatic design data for various locations across Canada. Figure 1 shows the changes for 13 locations across Canada for a warming level of $\Delta T = 2.5^o C$ (equivalent to 2069 time horizon under RCP8.5).



(a) (b) (c) (d)

Figure 1 – Projected changes in (a) maximum mean daily temperature, (b) minimum mean daily temperature, (c) annual precipitation, and (d) 50-year wind pressure for the $\Delta T = 2.5^o C$ relative to the 1986-2016 baseline period.

The map of changes (with more locations) are also shown in Figure 2 for warming level of $\Delta T = 3.5^o C$ which corresponds to the 2090 time horizon under RCP8.5. As it can be seen from Figures 1 and 2, both hot and cold extremes are projected to become warmer across Canada, with a larger warming for the clod extremes. The increase in maximum mean daily temperature is higher in the West and North of Canada. The minimum mean daily temperature is projected to increase higher in the North. The annual precipitation is projected to increase everywhere in Canada, with larger percentage changes in northern Canada. The projected changes in 50-year wind pressure, however, does not follow a specific pattern.



(a) (b)

(c) (d)

Figure 2 – Map of projected changes in (a) maximum mean daily temperature, (b) minimum mean daily temperature, (c) annual precipitation, and (d) 50-year wind pressure for the $\Delta T = 3.5^{o}C$ relative to the 1986-2016 baseline period.

There are some locations where the wind pressure is increasing, while it is decreasing in other locations. The magnitude of these changes, however remains relatively small with the maximum of 13.6% increase in Toronto under the $\Delta T = 3.5^{o}C$ warming level.

4.2. Selection of RCP Emission Scenario

The selection of RCP emission scenario for projection of future climatic data is a challenging task that requires input from engineering communities, climate scientists, code developers and decision makers. The climate change is driven by the RCP emission scenario, therefore, the projected climatic data will vary under various emission scenarios. A key information for the selection of RCP scenario can be the level of differences between future climatic design data under various emission scenarios. The differences of GHG emissions under RCP scenarios remain smaller for short term future, while these differences become larger toward the end of the century. Therefore, the time horizon of interest for the estimation of climatic design data can have implications for the selection of the appropriate RCP emission scenarios. In this section, we consider two design service lives of 25 and 75 years, and compare the projected changes in climatic design data for these time horizons under different RCP scenarios.

For the design life of 25 years, assuming the commission year of 2021, we consider the future time horizon of 2046, which corresponds to the warming level of $\Delta T = 1.0^{o}C$ under RCP 6.0 and RCP 4.5 scenarios. To obtain the projected changes in climatic design values under RCP 8.5, we approximately consider the time horizon of 2047 corresponding to the warming level of $\Delta T = 1.5^{o}C$ (Table 1).

The projected changes in selected climatic design parameters for the design life of 25 years under RCP8.5, RCP6.0 and RCP4.5 emission scenarios are compared in Figure 3. As the results show, the projected changes in maximum mean daily temperature under RCP8.5 and RCP6.0/RCP4.5 have differences that are lower than $1^{o}C$ for the selected locations. These differences for the minimum mean daily temperature are between $1^{o}C$ to $2^{o}C$. The larger differences observed in the minimum mean daily temperature is pertinent to the larger rate of warmings of the cold extremes under climate change. The largest difference between the projected changes in annual precipitation under various RCP emission scenarios are about 5% in the northern locations, where larger percentage changes are expected. The projected changes in 50-year wind pressure in some locations (e.g. Vancouver and Yellowknife) show opposite direction of change (increasing vs. decreasing) under RCP8.5 and RCP6.0/RCP4.5 scenarios. This indicates the high uncertainties associated with the projections of wind pressures. The differences of projected changes under various emission scenarios are not significant for most of the locations with maximum change of 5%. In addition, the projected changes in wind pressure under all RCP emission scenarios for the selected locations remain relatively small for this time horizon. As it can be seen, for the short-term future time horizon of 25 years, which is pertinent to transportation infrastructures with 25 years of design life, the differences between projected changes in selected climatic design data under various RCP emission scenario are relatively small. This can provide an insight for selection of RCP emission scenario for the infrastructure systems with shorter design life.

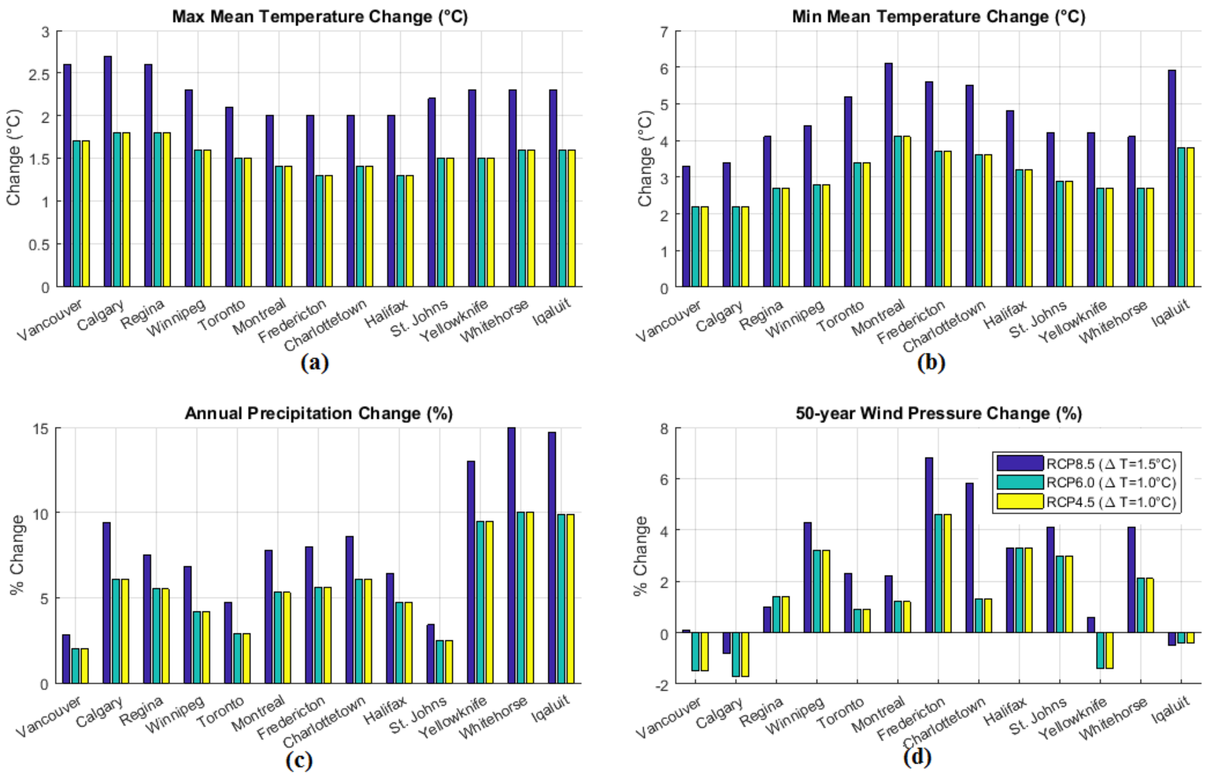


Figure 3 – Projected changes in (a) maximum mean daily temperature, (b) minimum mean daily temperature, (c) annual precipitation, and (d) 50-year wind pressure for the design life of 25 years under RCP8.5, RCP6.0 and RCP4.5 emission scenarios.

We consider infrastructure with longer design life of 75 years that is pertinent to the time horizon at the end of the century with larger differences between the emission scenarios. We consider the future time horizon of 2087, which corresponds to the warming level of $\Delta T = 2.0^o C$ under RCP6.0 emission scenario, and the time horizon of 2090 with $\Delta T = 3.5^o C$ under RCP8.5 (Table 1). The comparison of the projected changes in selected climatic design parameters for the end of century time horizon (long life infrastructure) under RCP8.5 and RCP6.0 emission scenarios are presented in Figure 4.

Figure 4a shows a difference of $2^o C$ to $3^o C$ between the projected changes in maximum mean daily temperature under RCP8.5 and RCP6.0 for locations in the West and North. These differences between RCP8.5 and RCP6.0 projections for the minimum mean daily temperature are larger and remain above $3^o C$ for all selected locations (with maximum of $7^o C$ in locations in the North). Larger differences between the projected changes in annual precipitation under various RCP emission scenarios are observed in Figure 4c (end of century) compared to those in Figure 3c (for 25 years). The differences in northern locations are between10% to 20% and lower than 10% in other selected locations. The direction of change (increasing vs. decreasing) in the 50-year wind pressure in Regina and Yellowknife is not similar under RCP 8.5 and RCP 6.0 scenarios, which indicates the presence of high uncertainties in wind projections. A maximum difference of about 8% is observed in Toronto and Halifax, while differences remain relatively small for other locations. As the results indicated, the selection of RCP scenario for the end of century time horizon, that is pertinent to long life infrastructure, is more complex since difference between various scenarios can be quite large for some parameters and locations.

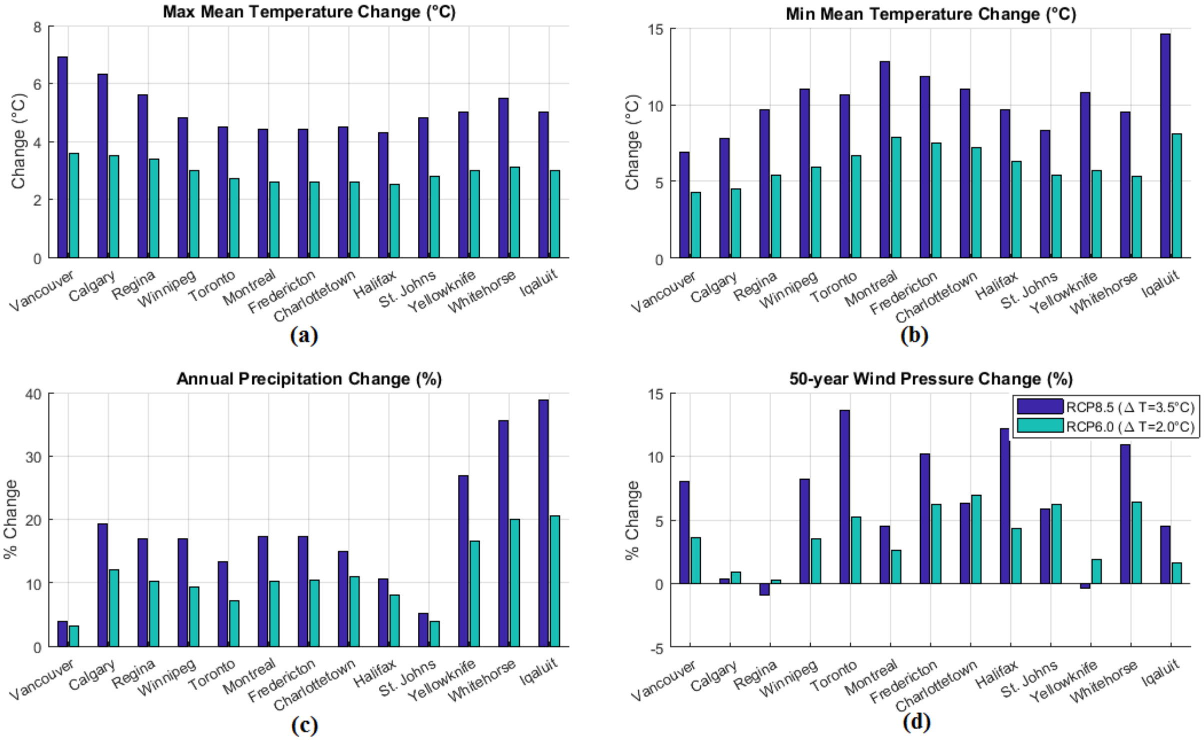


Figure 4 – Projected changes in (a) maximum mean daily temperature, (b) minimum mean daily temperature, (c) annual precipitation, and (d) 50-year wind pressure for end of century time horizon under RCP8.5, RCP6.0/RCP4.5emission scenarios.

4.3. Time Variation of Projected Climatic Design Data

The current codes and guidelines for design of transportation infrastructure are based on the assumption of the stationarity of the climate. However, this assumption may not be valid under the changing climate. In a non-stationary climate, the climatic design value can change over the design life of the infrastructure. The projected value of climatic design data at the end of the design life will then be different, and depends on the infrastructure design life and the choice of the emission scenario. As it was shown in Section 4.2, the projected changes in climatic design data for some climatic parameters will be more significant toward the end of the century. This indicates that the climate non-stationarity may become more critical for infrastructure with longer design life since it may result in larger time variation of climatic design data.

We present the time variation of selected climatic design parameters under various emission scenarios. We assumed that the projected changes in climatic design data for warming levels that cannot be reached under a specific emission scenario (See Table 1) will remain constant. Figure 5-8 shows the time variation of projected changes of selected climatic design parameters for various locations under RCP8.5, RCP6.0

and RCP4.5 emission scenarios. The time variation of climatic design parameters, known as non-stationarity, presents a challenge for the selection of the climatic design data. As it can be seen, the time variation is more significant for the longer time horizon. That is, the selection of climatic design data is more challenging for infrastructure with a longe design life.

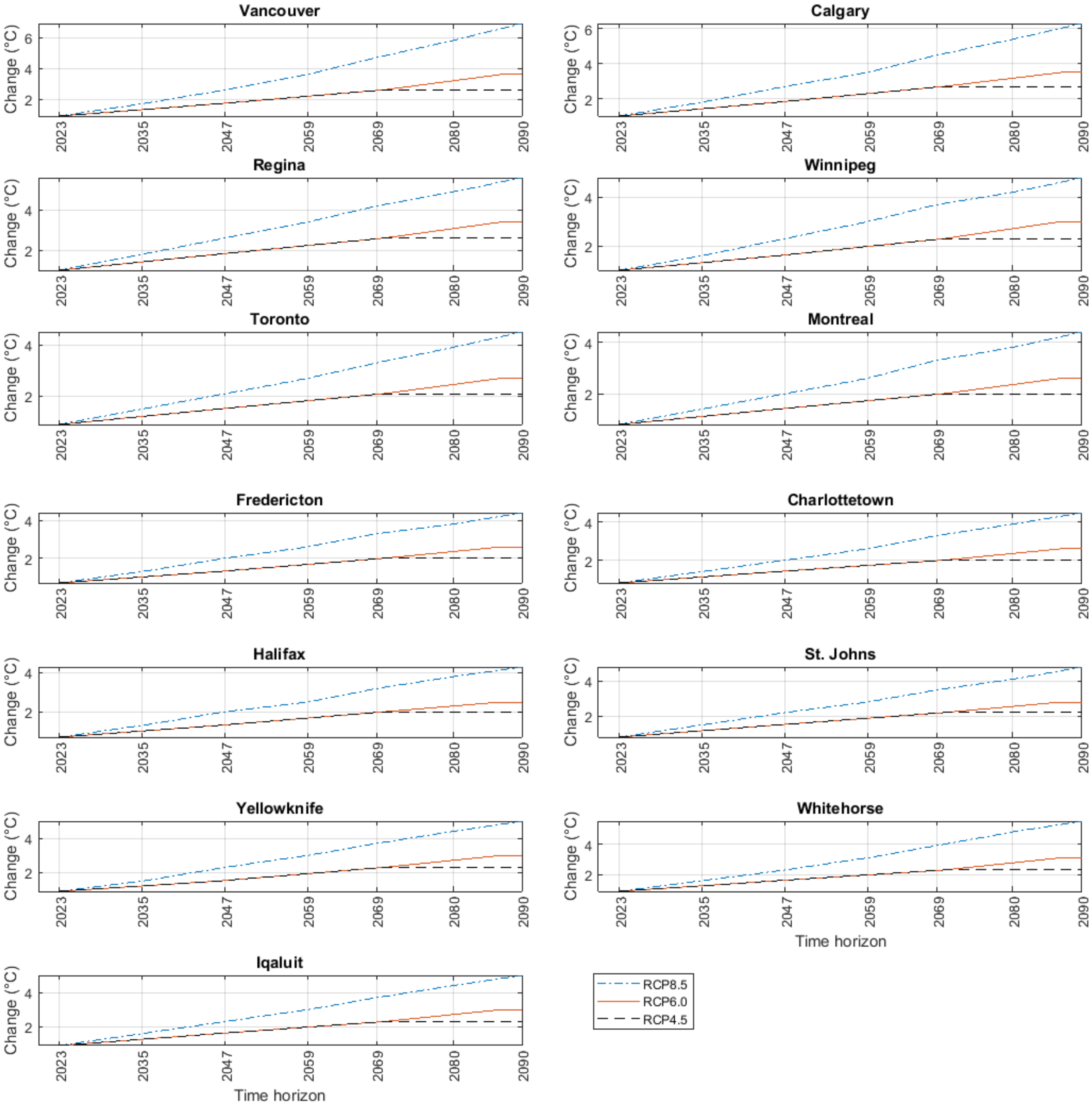


Figure 5 – Time variation of projected changes in maximum mean daily temperature for various locations under RCP8.5, RCP6.0 and RCP4.5 emission scenarios. Changes are relative to 1986-2016 baseline period.

As Figure 5 and 6 show, the maximum and minimum mean daily temperatures are increasing (warming) with time. The rate of the changes are higher for the minimum mean daily temperatures, which is pertinent to larger changes in cold weather under climate change. The projected changes under RCP6.0 and 4.5 are close except for the end of the century time horizon where larger changes are projected under RCP6.0. The projected changes in maximum and minimum mean daily temperatures under various emission scenarios remain closer to each other up to the mid-century time horizon (2050), but the differences become larger toward the end of the century.

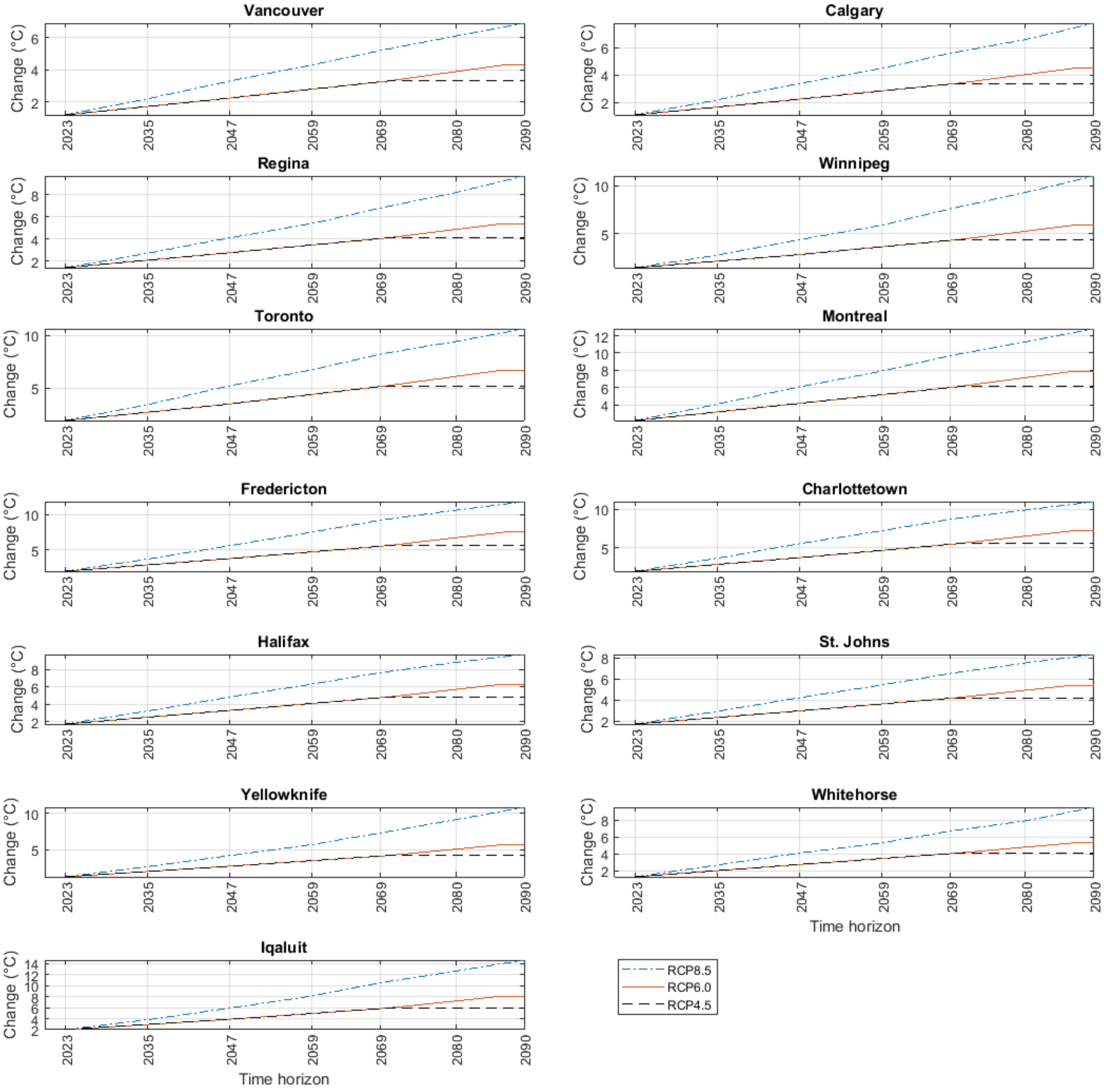


Figure 6 – Time variation of projected changes in minimum mean daily temperature for various locations under RCP8.5, RCP6.0 and RCP4.5 emission scenarios. Changes are relative to 1986-2016 baseline period.

Figure 7 shows that the trends in time variation of projected changes in annual precipitation are similar to those in the temperature-related parameters. This is mainly because of the fact that the total precipitations are affected by increases in the water-holding capacity of a warming atmosphere. Larger differences between projected changes under RCP8.5 and RCP6.0 emission scenarios are observed in the North, with a maximum of about 15%. In some locations such as St. John's, the differences remain low, even at the end of the century time horizon.

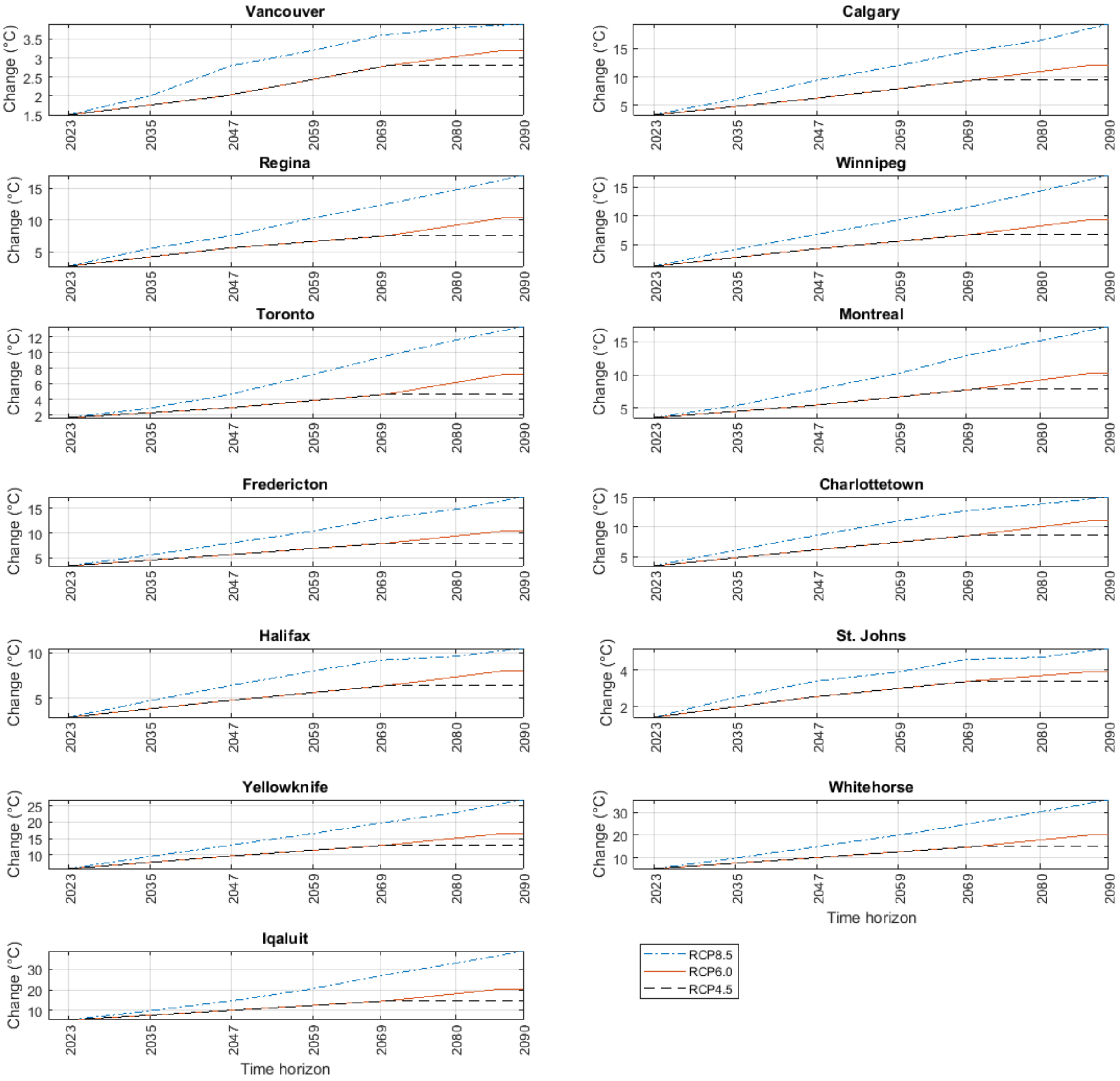


Figure 7 – Time variation of projected changes in annual precipitation for various locations under RCP8.5, RCP6.0 and RCP4.5 emission scenarios. Changes are relative to 1986-2016 baseline period.

The time variation of projected changes in 50-year wind pressure under various emission scenarios are shown in Figure 8. The trends in time variation are not monotonic in most locations and the direction of changes in wind pressure (increasing vs decreasing) varies with time. In some locations, the projected changes under RCP8.5 scenario are lower than those under lower emission scenarios. In Toronto, Halifax and Whitehorse, the changes are projected to be above 10% at the end of the century with a monotonic increase in time. For some locations such as Calgary, Regina, Montreal, Yellowknife and Iqaluit the projected changes remain below 5% under all emission scenarios. As it can be seen, the projected changes in wind pressure show a variety of patterns and trends with time and emission scenarios, which can be attributed to the high uncertainty in wind projections.

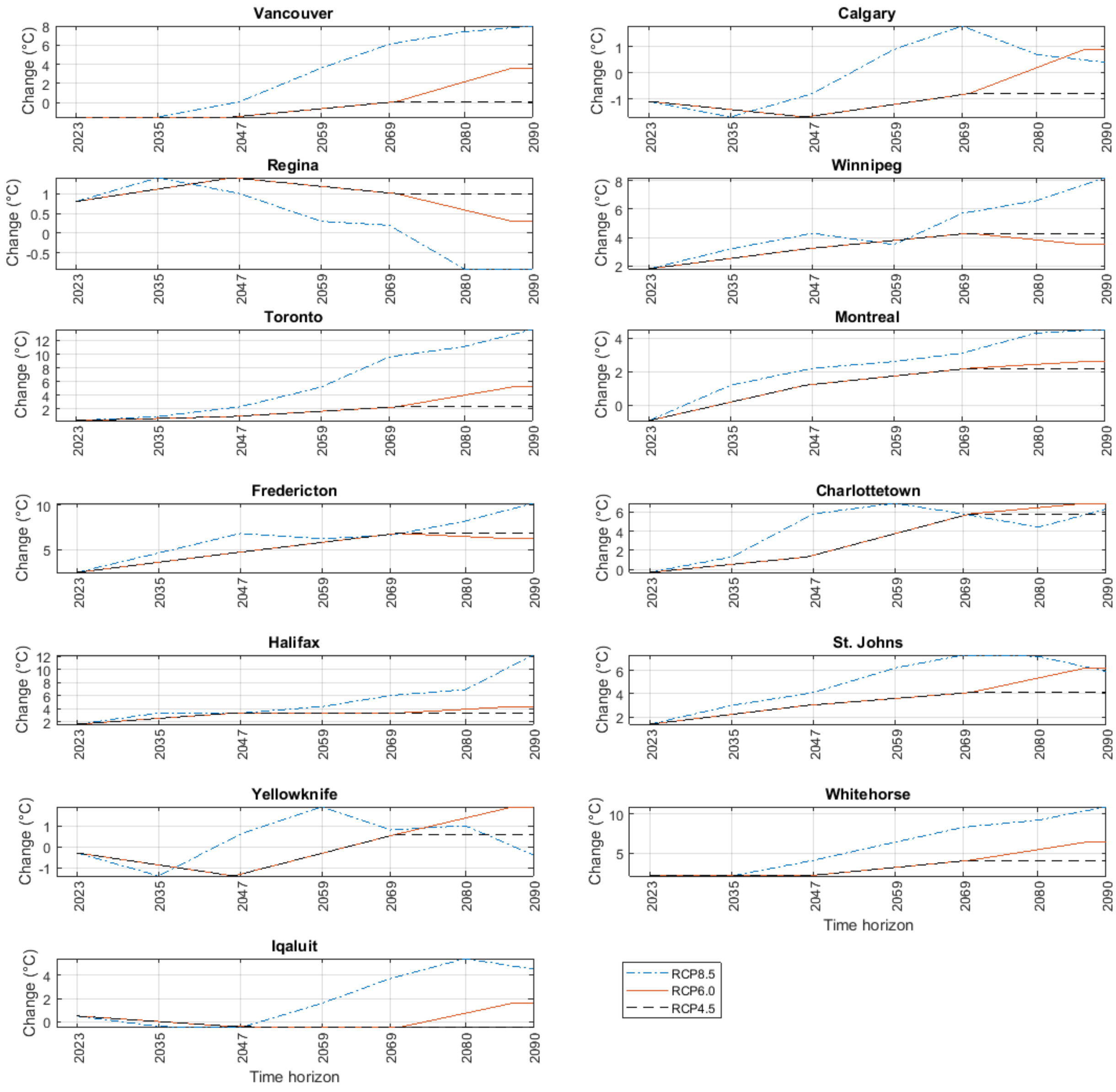


Figure 8– Time variation of projected changes in 50-year wind pressure for various locations under RCP8.5, RCP6.0 and RCP4.5 emission scenarios. Changes are relative to 1986-2016 baseline period.

5. Summary and conclusions

Climate change can lead to higher climatic loads and potentially higher risks of failure for civil engineering infrastructure systems, which are designed based on historical climatic data ignoring climate change. It was shown that the projection of climatic design values is associated with high level of uncertainty and non-stationarity that presents challenges for the selection of future climatic design data. Environment and Climate Change Canada developed future climatic data for design of buildings and core public infrastructure (Cannon et al., 2020) as part of the NRC-led initiative to develop decision support tools for the design of climate-resilient buildings and core public infrastructure (CRBCPI).

In this paper, we provided insights into the challenges for implementation of future climatic data in the design and management of transportation infrastructure systems. We used the future-looking climatic design data provided by ECCC (Cannon et al., 2020) for the CRBCPI initiative in order to provide insights into the issues with implementing projected climatic design data for engineering applications. The projected changes in the 50-year wind pressure, the annual precipitation as well as the maximum and minimum mean daily temperatures are investigated. We showed regional variation of various climatic design data in order to illustrate the impact of climate change across various climatic regions of Canada. The maximum and minimum mean daily temperature and the annual precipitation are shown to increase everywhere in Canada. The maximum mean daily temperature increases more in the West while the minimum mean daily temperature and the annual precipitation increase more in the North. The projected changes in 50-year wind pressure do not show a specific pattern and the wind pressures increase in some locations and decrease in other locations.

It was shown that the design life of the transportation infrastructure, which determines the time horizon for the projected climatic design data, can have direct implications for the selection of RCP emission scenarios. We investigated future climatic design data for two design lives or planning horizons of 25 years and 75 years with the future time horizon of 2046 and 2090 (end of century), respectively. As for the design life of 25 years, the results showed that the projected changes in maximum mean daily temperature have a difference that is lower than 1^oC under RCP8.5 and RCP6.0/RCP4.5, while it was between 1^oC to 2^oC for the minimum mean daily temperature. The differences between the projected changes in annual precipitation under various RCP emission scenarios are less than 5%, with the maximum changes in the North. Under the different RCP scenarios, the projected changes in 50-year wind pressure showed opposite direction of change in some locations, and overall, the differences are not significant for most of the locations (maximum of 5%).

We also considered the end of century time horizon that can represent the infrastructure with longer design life, e.g. 75 years for bridges. The results showed the difference of 2^oC to 3^oC under different emission scenarios for the maximum mean daily temperature in locations in the West and North. The differences for the minimum mean daily temperature were larger and above 3^oC for all selected locations (maximum difference of 7^oC in locations in the North). Larger differences between the projected changes in annual precipitation under various RCP emission scenarios were observed. As for the projected changes in 50-year wind pressure, the direction of change in some locations is not the same under RCP8.5 and RCP6.0. The maximum difference of about 8% is observed in Toronto and Halifax, while differences remain relatively small for other locations. As the results indicated, the selection of RCP scenario for the end of century time horizon is more complex since difference between various RCP scenarios can be quite large for some parameters and locations.

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