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Alberta's Climate Future

FINAL REPORT 2019

Photo Attribution: (1) Riverfront Ave in Calgary during the 2013 Alberta Floods by Ryan Quan; (2) An autumn afternoon at a farm north of Highway 37 and west of St. Albert by WinterforceMedia. Both images released under Creative Commons licence via Wikimedia Commons.

SUMMARY

Alberta's climate is already changing and many of these changes are projected to continue and even increase over the rest of this century. This report summarizes observed and projected changes in temperature and precipitation for the province and 21 of its cities and towns. It compares historical observations and trends to projected changes through 2100, and quantifies expected changes as the world warms by +1, +1.5, +2, +3 and +4°C.

Since 1950, almost every part of the province has experienced significant increases in winter temperature (from +0.5 to +1°C per decade) and decreases in the frequency of cold days, heating degree-days, and the proportion of winter precipitation falling as snow. Over half of the province has also experienced significant increases in summer temperature (from +0.1 to +0.3°C per decade), and some parts have also seen significant increases in warm days over 25 and 30°C.

Many climate indicators for Alberta are projected to increase nearly linearly as global average temperature increases, though at a greater rate of change than the global average. **Per degree of global mean temperature increase**, projected changes for Alberta include:

- A 2°C increase in average winter and 1.5°C increase in average summer temperature.
- An increase of about 3°C in the temperature of the coldest day of the year and an increase of about 2°C in the temperature of the warmest day of the year.
- A two-week lengthening of the frost-free season, and between a two to four-week lengthening of the growing season, with greater changes for more southern locations.
- A 5-10% increase in Sept-Apr precipitation, with between 5-10% more falling as rain compared to snow.
- A 50% increase in the number of very wet days (more than 25mm in 24 hours) and a 20% increase the amount of precipitation on the wettest day of the year.
- Proportional decreases in heating degree-days and increases in growing degree-days and other cumulative heating indices.

Changes in the actual number of days per year experiencing extreme high and low temperatures are projected to increase exponentially, rather than linearly, as global mean temperature increases. For many Alberta locations, the number of days per year above 30°C, for example, could double per degree of global warming.

Little change is expected in average precipitation and in the number of dry days during the growing season (May-Aug). However, temperature during the growing season is projected to increase and soil moisture is projected to decrease, increasing the risk of dry conditions as global temperature increases.

Projected changes will profoundly impact Alberta's natural environment, and have the potential to affect the province's agriculture, infrastructure, and natural resources, as well as the health and welfare of its inhabitants. For both temperature and precipitation, the changes reported here are consistent with those projected to occur throughout north-central North America in response to human-induced climate change. They are appropriate for use in scientific analyses to quantify the impacts of a warming planet on both human and natural systems, and to inform long-term planning, education, and outreach.

About This Report

Climate is the statistics of weather averaged over a relatively long period of time. The World Meteorological Organization (WMO) uses a 30-year period to define *climate normals*. Climate normals are "reference points used by climatologists to compare current climatological trends to that of the past or what is considered 'normal'." Thirty years is typically used because this period has historically been "long enough to filter out any interannual variation or anomalies, but also short enough to be able to show longer climatic trends." (WMO, 2014)

Over the course of the Earth's history, climate has varied due to natural causes. As a result, there have been periods of time in the distant past that were significantly warmer and cooler than today (Masson-Delmotte et al. 2013). Over the last two thousand years, however, with the exception of the last century, climate has changed relatively little at the global scale; global temperature has varied by less than ±0.5°C relative to the long-term average (Masson-Delmotte et al. 2013). As a result, many human systems, including infrastructure, agriculture, and the allocation and use of natural resources, are based on the assumption of a relatively stable climate: namely, that past conditions experienced over long-term, climatic time scales provide a reliable guide for planning for the future. This assumption underlies building codes, urban plans, infrastructure design and maintenance, agricultural methods, long-term water plans, flood zone delineation, and more.

Today, however, global climate is changing at a rate that is unprecedented over the last two thousand years. As the *Climate Science Special Report* concludes, "global climate continues to change rapidly compared to the pace of the natural variations in climate that have occurred throughout Earth's history," and "global annual averaged temperatures for 1986–2015 are likely much higher, and appear to have risen at a more rapid rate during the last 3 decades, than any similar period possibly over the past 2,000 years or longer" (Wuebbles et al. 2017). In addition, sea level is rising, Arctic sea ice is decreasing, ice loss from Greenland is accelerating, permafrost is thawing, and heavy rainfall and extreme heat is becoming more frequent in many locations around the world (Hartmann et al. 2013; Knutson et al. 2017; Vose et al. 2017; Easterling et al. 2017; Sweet et al. 2017; Taylor et al. 2017).

These changes have important and, in some cases, unique implications for human systems and our society. "Over the last few centuries we have been conducting an unprecedented experiment with the Earth's climate system. [But] human society is built on the implicit assumption that climate is largely stationary: that historical records can be used with confidence to determine the energy loads of our buildings, the hundred-year floodplains of our cities, and the growing zones for the crops that power our economy and feed our world. What happens when that assumption is no longer valid?" ask Hayhoe and Kopp (2016).

The **Introduction** to this report summarizes observed changes across Canada and Alberta. It briefly discusses the causes of climate change, both human-caused and natural, and cites references that provide more information regarding the detection and attribution of observed long-term trends and extreme events.

Focusing on the province of Alberta, the **Observed Trends and Future Projections** section presents and analyzes historical trends in more than 30 different climate indicators, from the temperature of the coldest day of the year to average precipitation during the growing season. Future simulations generated by an ensemble of global climate models from the Coupled Model Intercomparison Project version 5 (CMIP5), based on a higher (RCP8.5) and lower (RCP4.5) future scenario and statistically downscaled to (a) a high-resolution grid covering the entire province, and (b) 21 Alberta weather stations, are used to calculate projected changes in those same climate indicators as global mean temperature increases by +1, +1.5, and +2°C. These changes are then compared to observed trends and projected future changes under higher amounts of global temperature change such as +3 and +4°C.

The **Data, Models and Methods** section that follows describes the observational data used, how the climate indicators were defined, how historical trends were calculated, and how the future projections generated. It also describes the global climate models, scenarios, and empirical-statistical downscaling models used. It concludes by discussing the sources of uncertainty in future projections and how these were addressed in this report.

The **Products** section describes the outputs that are available for use in scientific analyses, impact modeling, long-term planning, education, and outreach. They include data files, maps, bar charts, and time series.

Sample maps and figures are included in this report to illustrate projected changes. However, the **Appendices** contain more figures and data. Specifically, the complete set of maps for the province of Alberta is available in powerpoint format as *Appendix A: Climate Indicator Maps for Alberta*. The complete set of bar charts for each of the 21 individual weather stations is available in Excel format in *Appendix B: Climate Indicator Bar Charts for Weather Stations*, and the complete set of observed and projected future indicator values for individual weather stations by year is available in Excel format in *Appendix C: Climate Indicator Time Series for Weather Stations.*

Introduction

ONE. Observed Changes in Canada

Across Canada, average annual and seasonal temperatures are increasing, and are expected to continue to increase, by approximately twice the global average (Bush and Lemmen, 2019). The greatest warming has occurred in the winter, and in the northern and western latitudes relative to more southern and eastern latitudes (Figure 1a; Bush and Lemmen, 2019). Extreme heat is also becoming more frequent; in the 2000s, approximately 80% more heat temperature records were broken at weather stations across Canada than cold records; in the 2010s, this has increased to 150% more extreme heat records to date (Figure 1b). In the western United States, the area burned by wildfire has doubled since the 1980s as a result of climate change (Gonzalez et al. 2018) and, although consistent trends in heavy precipitation events are not significant across Canada as a whole (Bush and Lemmen, 2019), across the U.S., which has a denser station network, heavy precipitation events have increased significantly, particularly in the Midwest and Northeast regions that border Canada (Easterling et al. 2017).

Damages from extreme events is a function of exposure (the people, infrastructure, and other resources exposed to the event), vulnerability (the extent to which people and systems are prepared to cope with such an event), and the event itself. As Canada's Changing Climate Report (CCCR 2019) states, "much of this rise [in costly extreme weather events worldwide] is due to greater exposure to the effects of such extreme events, as Canada's population and the value of its supporting infrastructure have both increased considerably." (Bush and Lemmen, 2019) However, as climate change alters the frequency and/or intensity of many of these extreme events, risks are also increasing. Specifically, CCCR2019 concludes that human-induced climate change "has increased the likelihood of some types of extreme events, such as the 2016 Fort McMurray wildfire (medium confidence) and the extreme precipitation that produced the 2013 southern Alberta flood (low confidence)." (Bush and Lemmen, 2019)

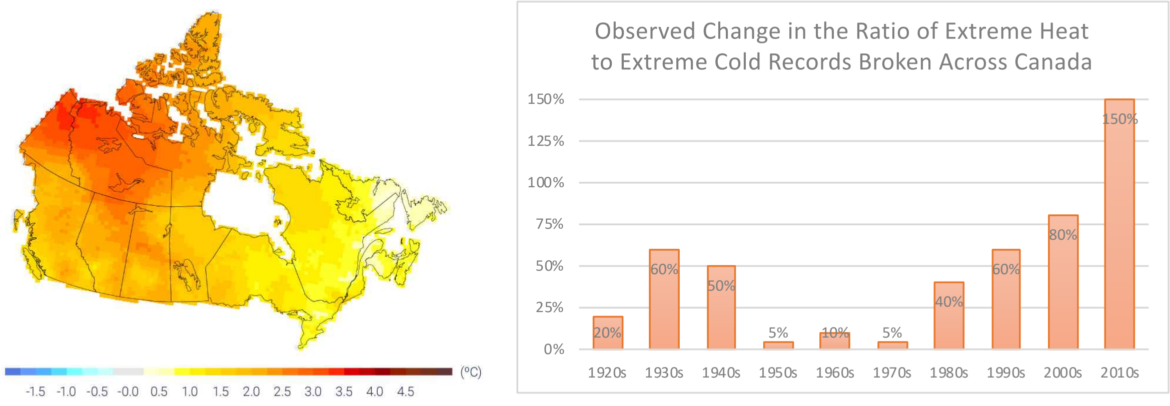
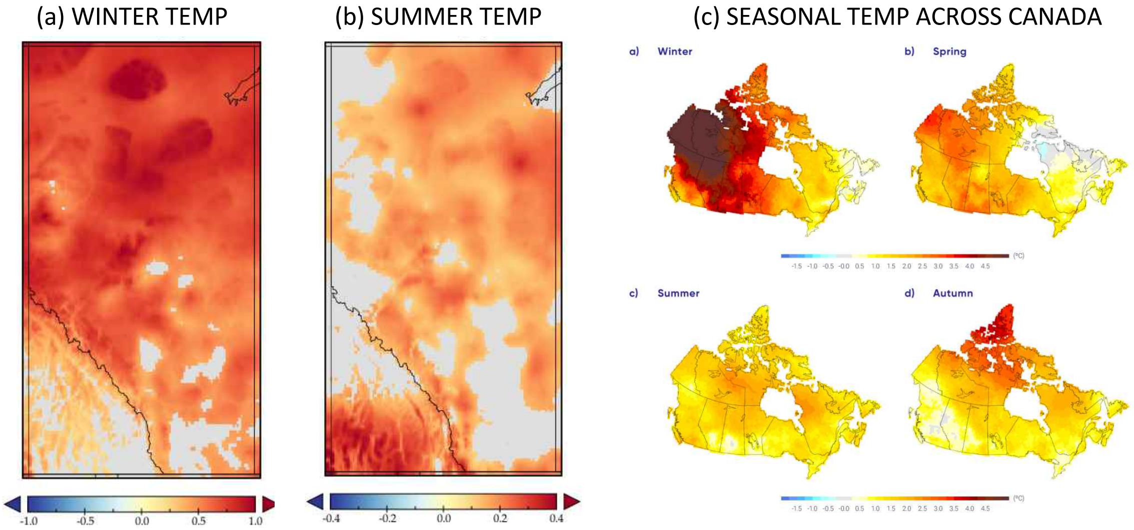


Figure 1. (a) Observed trends in annual average temperature across Canada, in degrees Celsius, from 1948 to 2016. Source: Bush and Lemmen, 2019. (b) Observed trends in the ratio of extreme heat records to extreme cold records broken each year at weather stations across Canada. A value of zero indicates that the same number of extreme heat and cold records were broken that decade; a value greater than zero indicates the percentage of more extreme heat records that were broken than extreme cold records during that decade. Source: pers. comm. From Walton, 2019 based on the methodology of Meehl et al. 2009.

TWO. Observed Changes in Alberta

In Alberta, average temperatures are increasing across all seasons, with greater increases in winter (between +0.5 and +1°C per decade; Figure 2a) as compared to summer (between +0.1 and +0.3°C per decade; Figure 2b). This is consistent with observed changes across Canada as a whole (Figure 2c), which show significantly greater increases in winter as compared to summer.


(a) WINTER TEMP

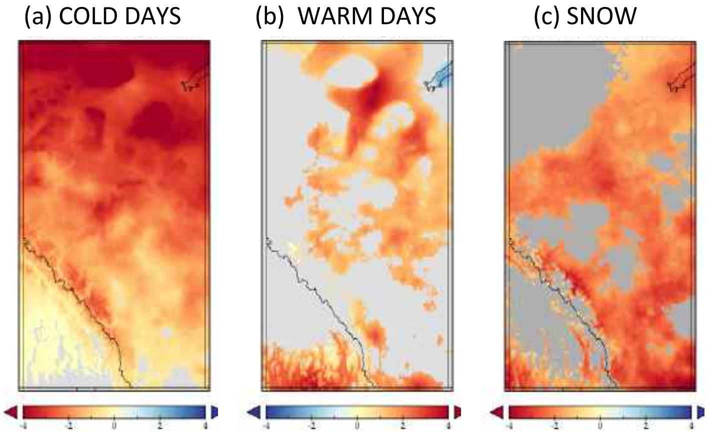
(b) SUMMER TEMP

(c) SEASONAL TEMP ACROSS CANADA

Figure 2. Observed trends in: (a) winter (DJF) and (b) summer (JJA) average temperature in Alberta from 1950 to 2013, in degrees Celsius, where coloured areas indicate locations where trends are significant at the 95% confidence interval and gray areas indicate locations where the trends are not significant at the 95% confidence interval; and (c) winter, spring, summer and fall average temperature across Canada from 1948 to 2016. Sources: (a-b) This analysis; see **Data, Models and Methods** for more detail; (c) Bush and Lemmen, 2019.

The frequency of cold days below -30°C is decreasing across the province (Figure 3a), while the frequency of warm days above 25°C is increasing, although trends not yet significant across all of the province (Figure 3b). The percentage of Sept-Apr precipitation that falls as snow versus rain is also decreasing, at a rate of -2 to -4% per decade (Figure 3c) and in a few locations in northern and central Alberta, the amount of precipitation falling on the wettest day of the year has increased, but trends are not significant across most of the province (Figure 3d). Trends in other climate indicators listed in Table 2 are available in Appendix A.

Figure 3. Observed trends in: (a) the frequency of cold days with minimum temperature below -30°C, (b) warm days with maximum temperature above 25°C per year, and (c) the percentage of Sept-Apr precipitation falling as snow versus rain from 1950 to 2013. Coloured areas indicate locations where trends are significant at the 95% confidence interval and gray areas indicate locations where the trends are not significant at the 95% confidence interval. Source: This analysis; see **Data, Models and Methods** for more detail.


(a) COLD DAYS

(b) WARM DAYS

(c) SNOW

THREE. Attribution of Recent Observed and Future Changes

In the past, the Earth's climate was controlled entirely by natural factors, including the internal natural variability of the climate system, changes in solar output, volcanic eruptions and other geologic activity, and orbital cycles. These natural factors still influence climate. However, as can be clearly seen in Figure 4, human emissions of greenhouse gases from combustion of fossil fuels and land use change now overwhelm the influence of the sun, volcanoes, natural cycles, and other natural drivers on Earth's climate.

In reference to observed warming since 1900, the *Climate Science Special Report* concludes, "there are no convincing alternative explanations [other than human agency] supported by the extent of the observational evidence" (Wuebbles et al. 2017) and the Second Volume of the U.S. National Climate Assessment expands on this, stating, "observational evidence does not support any credible natural explanations for this amount of warming [referring to the observed 1°C increase in global mean temperature from 1901 to 2016]; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause" (Hayhoe et al. 2018).

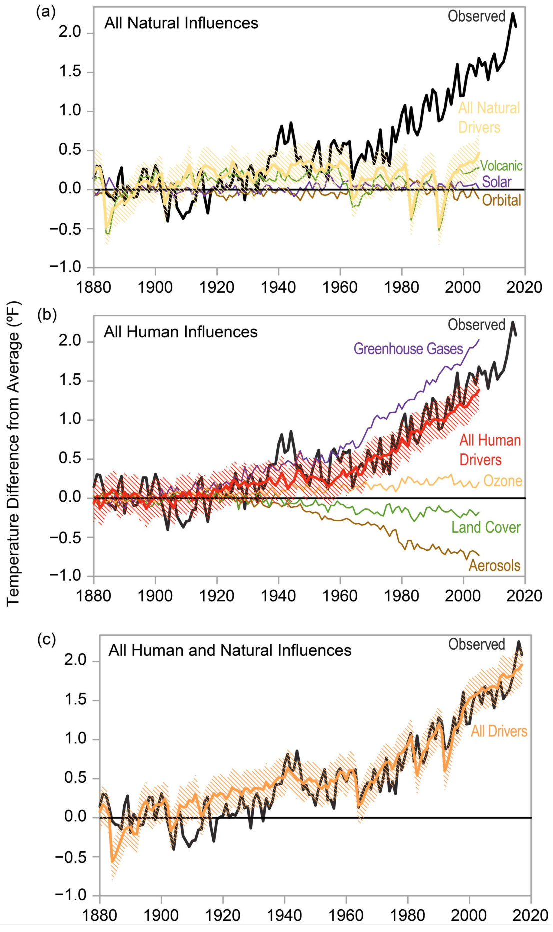


Figure 4. Both human and natural factors influence Earth's climate, but the long-term global warming trend observed over the past century can only be explained by the effect that human activities have had on the climate.

(a) The temperature changes simulated by a climate model when only natural factors (yellow) are considered. The other lines show the individual contributions to the overall effect from observed changes in Earth's orbit (brown), the amount of incoming energy from the sun (purple), and changes in emissions from volcanic eruptions (green). Note that no long-term trend in globally averaged surface temperature over this time period would be expected from natural factors alone.

(b) The simulated changes in global temperature when considering only human influences (dark red), including the contributions from emissions of greenhouse gases (purple) and small particles (referred to as aerosols, brown) as well as changes in ozone levels (orange) and changes in land cover, including deforestation (green). Changes in aerosols and land cover have had a net cooling effect in recent decades, while changes in near-surface ozone levels have had a small warming effect. These smaller effects are dominated by the large warming influence of greenhouse gases such as carbon dioxide and methane. Note that the net effect of human factors (dark red line) explains most of the long-term warming trend.

(c) The temperature change (orange) simulated by a climate model when both human and natural influences are included. The result matches the observed temperature record closely, particularly since 1950, making the dominant role of human drivers plainly visible.

Researchers do not expect climate models to exactly reproduce the specific timing of actual weather events or short-term climate variations, but they do expect the models to capture how the whole climate system behaves over long periods of time. The simulated temperature lines represent the average values from a large number of simulation runs. The orange hatching represents uncertainty bands based on those simulations. For any given year, 95% of the simulations will lie inside the orange bands. Source: NASA GISS for Hayhoe et al. 2018

Regarding specific natural factors responsible for climate change, the *Climate Science Special Report* states: "We find no convincing evidence that natural variability can account for the amount of global warming observed over the industrial era. Solar output changes and internal variability can only contribute marginally to the observed changes in climate over the last century, and we find no convincing evidence for natural cycles in the observational record that could explain the observed changes in climate (very high confidence)" (Wuebbles et al. 2017). Similarly, *Canada's Changing Climate Report* states, "the heat-trapping effect of atmospheric greenhouse gases is well-established. It is extremely likely that human activities, especially emissions of greenhouse gases, are the main cause of observed warming since the mid-20th century. Natural factors cannot explain this observed warming." (Bush and Lennen, 2019)

Other observed changes in the atmosphere, ocean and cryosphere have also been formally attributed to human-induced change, which is the result of human emissions of carbon dioxide and other heat-trapping gases released during fossil fuel combustion, deforestation, agriculture and other activities. These range from observed decreases in Arctic sea ice to global-scale increases in heavy precipitation (see Knutson et al. 2017 for a review).

Some additional amount of future change is inevitable, due to human choices that have already been made and human emissions that have already occurred. This is the result of inertia in the physical climate system in responding to human emissions of carbon dioxide, methane, and other heat-trapping gases that have already occurred, and inertia in the energy sector in transitioning from traditional fossil-based energy to low or zero-carbon energy. A significant amount of future change, however, can be avoided by reducing and eventually eliminating carbon emissions from human activities, compared to the changes that are likely to occur if the world continues to rely on fossil fuels for the majority of its energy. It is estimated that, "with significant reductions in emissions, global temperature increase could be limited to 2°C or less compared to preindustrial temperatures [but] without significant reductions, annual average temperatures could increase by 5°C or more by the end of this century compared to preindustrial temperatures." (Hayhoe et al. 2018) Natural factors are unlikely to offset this warming by a significant amount. The eruption of Mt. Pinatubo in 1991 temporarily lowered global temperature by 0.6°C for only 15 months (NASA, 2001); and even if a prolonged solar minimum such as occurred in the late 17th century were to return over this coming century, it is estimated that it would offset no more than 0.3°C of the projected warming due to human activities by 2100 (Feulner and Rahmstorf, 2010).

Regarding climate over the coming century, the *Climate Science Special Report* emphasizes the importance of human choices in determining the magnitude of future change, stating, "beyond the next few decades, the magnitude of climate change depends primarily on cumulative emissions of greenhouse gases and aerosols and the sensitivity of the climate system to those emissions (high confidence)." (Hayhoe et al. 2017) Similarly, *Canada's Changing Climate Report* states, "emissions of greenhouse gases from human activity, particularly carbon dioxide, will largely determine the magnitude of climate change over the next century. Therefore, reducing human emissions will reduce future climate change." (Bush and Lennen, 2019)

More information on the future scenarios used in this report, which are also used in the *Climate Science Special Report*, the *Fourth U.S. National Climate Assessment*, *Canada's Changing Climate Report*, and the Intergovernmental Panel on Climate Change's *Fourth* and *Fifth Assessment Reports*, is provided in the **Data, Models, and Methods** section.

Observed Trends and Future Projections

The observed trends described in this section are based on long-term observations of daily maximum and minimum temperature at: (a) 21 individual long-term weather stations across the province, and (b) daily temperature and precipitation for a high-resolution grid covering the entire province from Natural Resources Canada's Daily 10km Gridded Climate Dataset for Canada. Both datasets are described in more detail in the **Data, Models and Methods** section of this report.

The future changes described in this section are based on climate projections generated by the latest global climate models, for two possible futures: a higher scenario (RCP8.5), where carbon emissions continue to grow as the world continues to depend primarily on fossil fuels, and a lower scenario (RCP4.5), where carbon emissions peak and then begin to decline as the world transitions to non-carbon energy sources. Daily maximum and minimum temperature and precipitation projections have been statistically downscaled to a high-resolution grid covering the entire province, at the resolution of Natural Resources Canada's Daily 10km Gridded Climate Dataset for Canada. Projections have also been downscaled to the 21 individual long-term weather stations across the province. These models and scenarios are also described in more detail in the **Data, Models and Methods** section of this report.

Future projections are plotted for global mean temperature thresholds, which is defined as the 20-year time period when global mean temperature averages +1, +1.5, +2 etc. above the historical average for each future simulation. Projected changes under these thresholds can be used quantify the potential changes that would be expected across Alberta if the world meets the 1.5 or 2°C targets set by the Paris Agreement. These changes can be compared with the much greater changes that would be expected if these targets are passed, and the world warms by 3 or 4°C. How the global mean temperature thresholds are calculated and applied is also described in more detail in the **Data, Models and Methods** section of this report.

ONE. Changes in Average Temperatures

Temperatures across Canada, including Alberta, have already increased (Figures 1, 2) and are expected to continue to increase over the remainder of this century and beyond. Figure 5 shows projected changes in annual average temperature across Canada, based on a multi-model ensemble from the *Canada's Changing Climate Report 2019*. Changes in annual mean temperature are projected to be greater under a higher as compared to a lower future scenario, by end-of-century compared to mid-century, and for more northern areas as compared to more southern.

In Alberta, average temperature has increased since 1950. Winter temperature increases are significant across nearly the entire province, and are greater than observed increases in summer temperatures (Figure 2). These trends are expected to continue in the future. The number of cold days per year is expected to continue to decrease, while the number of warm and hot days is projected to continue to increase. This increase, particularly for warm and hot days, is projected to be proportionally larger than the increase in seasonal mean temperatures.

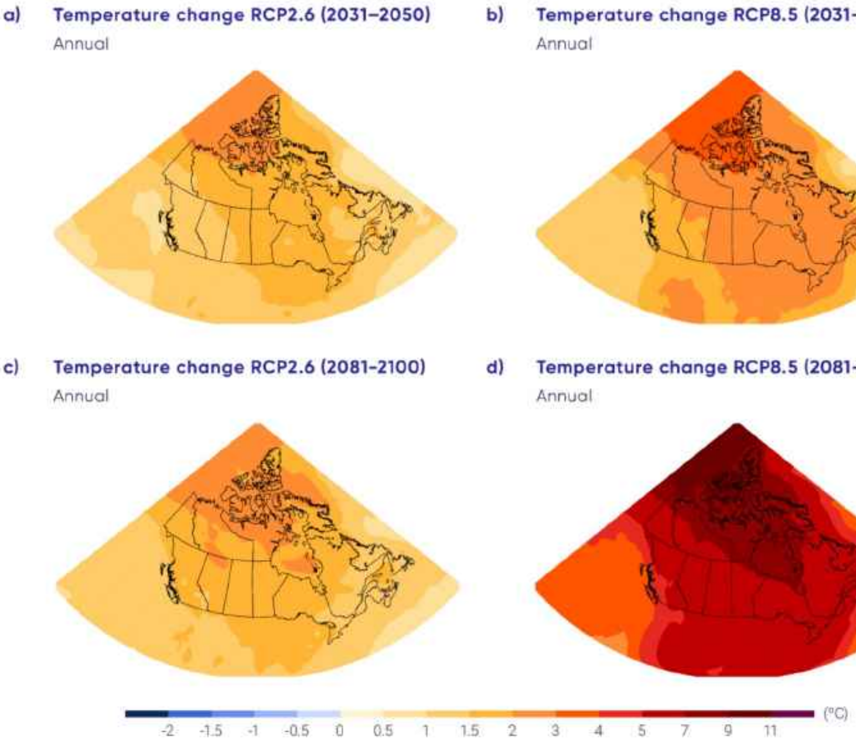


Figure 5. Projected changes in annual average temperatures, in degrees Celsius, over the near-term (2031-2050, top) and by end of century (2081-2100, bottom) for a very low scenario (RCP2.6, left), and a higher scenario (RCP8.5, right). This report is based on the same higher scenario, RCP8.5, and RCP4.5, a lower scenario that does not require negative carbon emissions before end-of-century as RCP2.6 does. For further discussion of these scenarios, please see the **Data, Models and Methods** section of this report. Source: Canada's Changing Climate Report, Bush and Lennen 2019.

In terms of **winter temperatures**,

- Average winter (Dec-Feb) temperatures across Alberta have already warmed at a rate of +0.5 to +1.0°C per decade from 1950 to 2013 (Figure 2). These trends are significant at the 95% confidence interval across nearly the entire province.
- Temperatures for January, typically the coldest month of the year, have warmed even more: by +1.0 to +1.5°C per decade from 1950 to 2013 (Figure 9a).
- Average winter temperatures across Alberta are projected to continue to increase, by about 2°C per degree of global mean temperature increase. Projected changes are about 2°C if the world warms by +1-1.5°C and up to 6-8°C if the world warms by +4°C.
- In terms of their geographic distribution, proportionally greater changes in winter temperatures are expected in the northeastern part of the province as compared to the southeastern part (Figure 6).
- Changes for January are similar to those projected for winter (see figures in Appendix A).

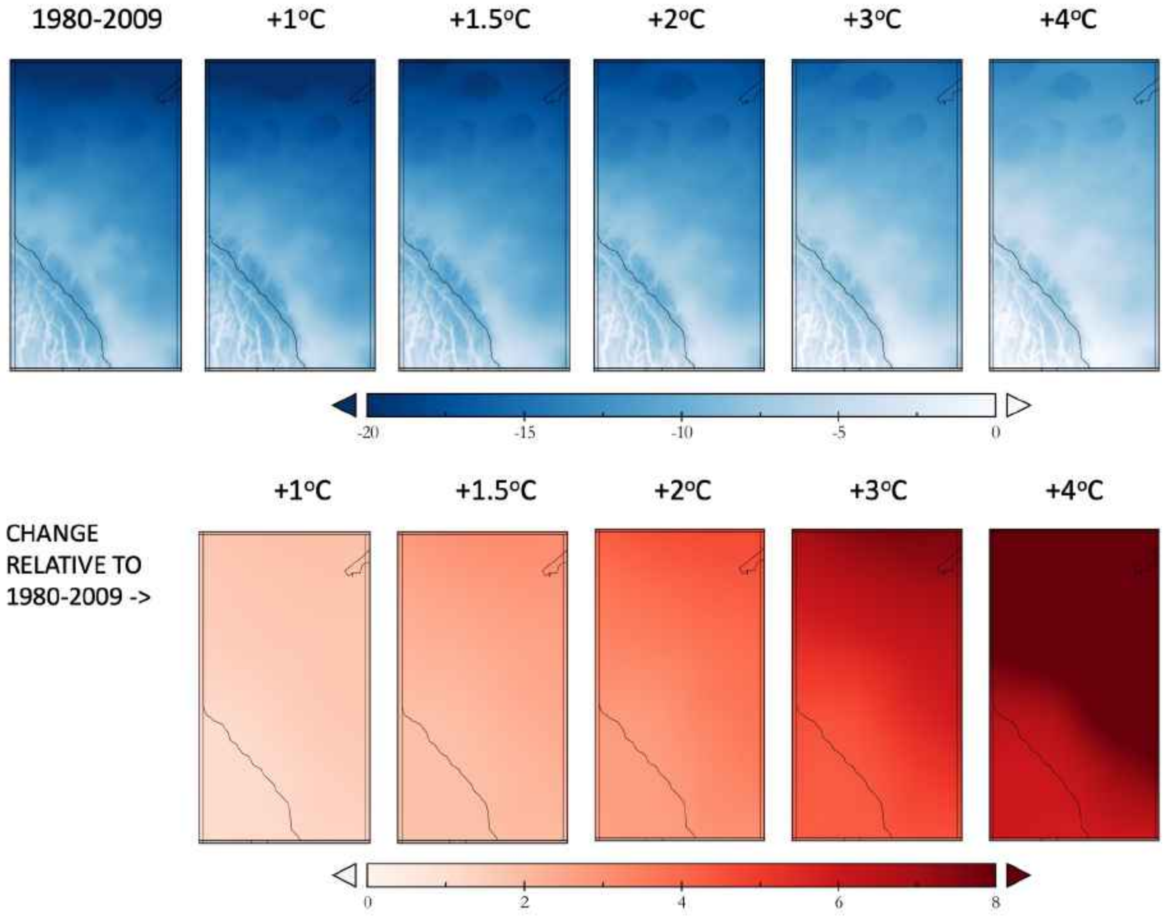


Figure 6. Winter (Dec-Feb) average temperature: historical average for 1980-2009 (left), projected future values as global mean temperature increases by +1 to +4°C (top), and the projected *change* or delta relative to 1980-2009 for those same future periods (bottom), in degrees C. Values are for observations for the historical period and a multi-model average for the future periods. For more detail regarding models and global temperature thresholds, see the **Data, Models and Methods** section.

- Both observed and projected future changes in winter temperature are greater in the northern as compared to the southern part of the province.
- Regional differences are evident by comparing Fort Chipewyan in the north with Calgary in the central and Carway in the south part of the province (Figure 7). Projected increases in average winter temperature under a lower global warming threshold of +1.5°C range from 2 for Carway up to 3°C for Fort Chipewyan, while under higher global warming threshold of +4°C, projected changes range from less than 6°C for Carway up to nearly 10°C for Fort Chipewyan (Figure 7).

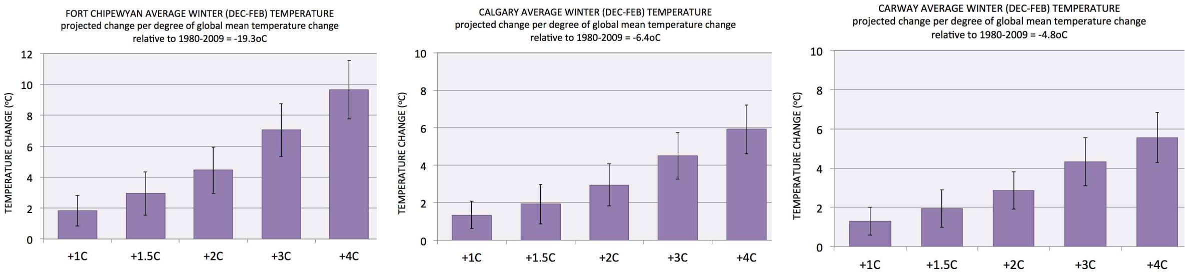


Figure 7. Projected changes in average winter temperature for three locations: Fort Chipewyan (left, north); Calgary (centre); and Carway (right, south), in degrees C for a global mean temperature change of +1, 1.5, 2, 3, and 4°C relative to the 1980-2009 average. The solid bar represents the multi-model average, while the thin lines represent the multi-model range. Greater changes are expected for the north as compared to the south.

In terms of **average summer temperatures**,

- Since 1950, average summer (Jun-Aug; Figure 2) and growing season (May-Aug, see Appendix A) temperatures warmed at a rate of +0.1 to +0.3°C per decade, with trends significant at the 95% confidence interval across much of the province.
- Average summer (Jun-Aug, Figure 8) and growing season (May-Aug, see Appendix A) temperatures are also projected to continue to increase, though not as rapidly as winter: by approximately 1.5 °C per degree of global warming, up to 5-7°C under a +4°C warming.
- In terms of their geographic distribution, projected increases in summer and growing season temperatures are slightly greater (by about 1°C under a +4°C warming) towards the south and eastern part of the province compared to the north (Figure 8).
- Changes for July, typically the warmest or second-warmest month of the year, are similar to projected changes for summer (see Appendix A).

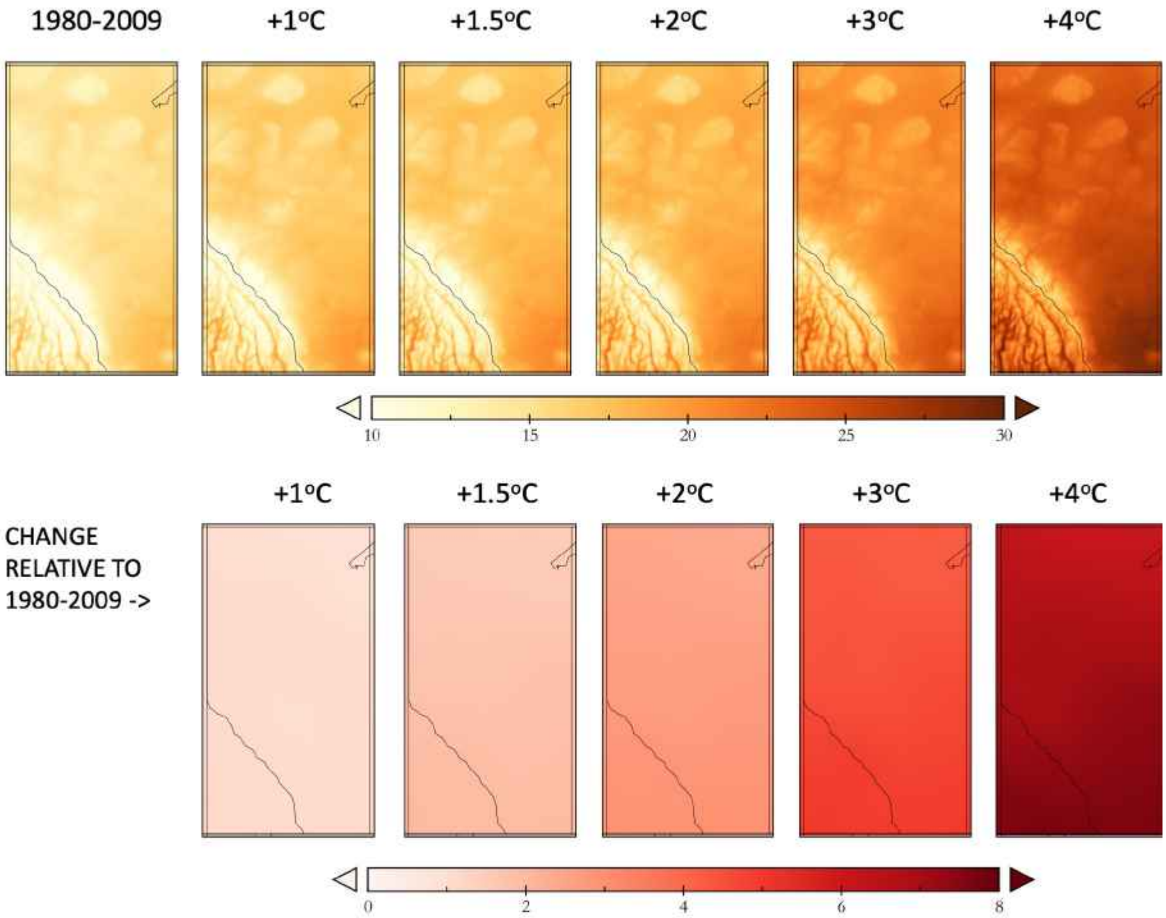


Figure 8. Summer (Jun-Aug) average temperature: historical average for 1980-2009 (left), projected future values as global mean temperature increases by +1 to +4°C (top), and the projected *change* or delta relative to 1980-2009 for those same future periods (bottom), in degrees C. Values are for observations for the historical period and a multi-model average for the future periods. For more detail regarding models and global temperature thresholds, see the **Data, Models and Methods** section.

TWO. Changes in Extreme Temperatures

Temperature extremes are also changing, with cold temperature extremes becoming less frequent and high temperature extremes more frequent.

In terms of observed trends from 1950 to 2013 in **cold temperature extremes** (Figure 9),

- The average monthly temperature of January, typically the coldest month of the year, increased by +1 to +1.5°C per decade across the entire province.
- The temperature of the coldest day of the year warmed by about 1°C per decade.
- The number of “cold” days per year below -30°C decreased, by up to 4 days per decade in the northern part of the province.
- The number of “cool” days below 5°C each year decreased by an average of 5 days per decade across most of the province.

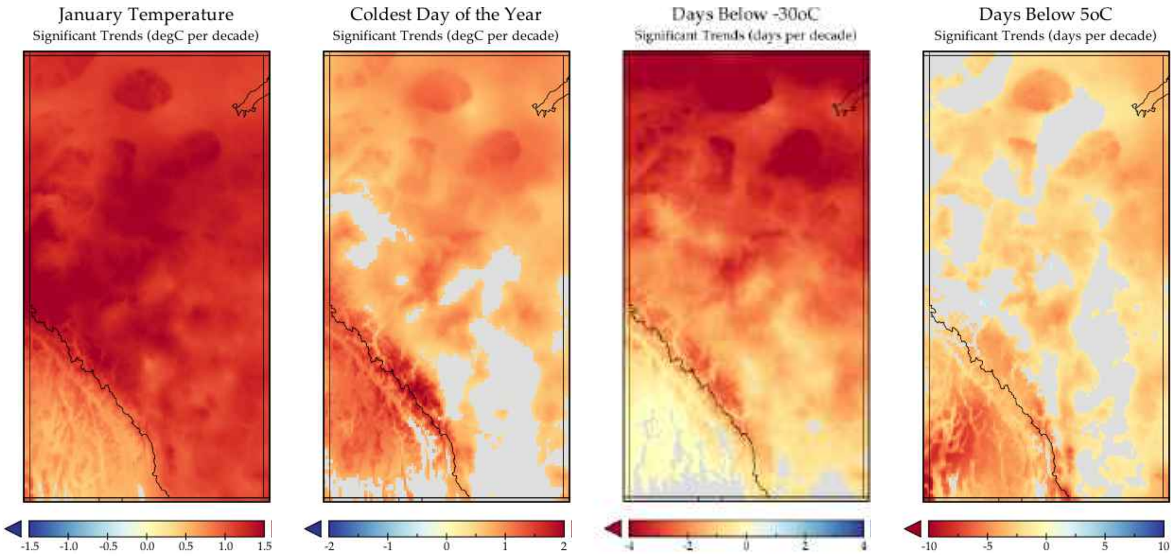


Figure 9. Observed trend from 1950 to 2013 in (left) the temperature for January, typically the coldest month of the year, and (centre left) the coldest day of the year, both in degrees C and number of (centre right) cold and (right) cool days per year with minimum temperature below -30°C and 5°C, respectively. Gray areas indicate where observed trends are not significant at the 95th confidence interval.

For cold events in the the future:

- The temperature of the coldest day of the year is projected to warm by about 3°C per degree of global warming, up to 11-13°C for a global mean temperature threshold of 4°C. If the coldest day is typically -30°C, this means that the coldest day would now average about -27°C under a 1°C global warming and -19 to -17°C under a 4°C global warming(see example for Calgary in Figure 10, left)
- Very cold days below -30°C currently occur anywhere from a few days to a few weeks a year, depending on location. These could become rare and even eventually not occur in most locations around the province. Only the most northern locations would still see a few days below -30°C if the world warmed to 4°C (see figures in Appendix A, B, and C).

- The number of cool days below 5°C, a threshold associated with stress on crops, are relatively common and are projected to decrease across the province, averaging approximately two weeks' fewer cool days per year per degree of global warming (see Appendix A, B and C).

In terms of observed trends from 1950 to 2013 in **warm and hot temperature extremes,** the frequency and magnitude of warm temperature extremes has increased across most of the province, although trends are only significant at the 95th confidence interval at some locations (Appendix A). Observed changes in the number of warm days (above 25°C) per year vary across the province, from little change in the mountains to increases of 4 days per decade across the northeastern part of the province.

For warm events in the future:

- Since 1950, the temperature of the warmest day of the year has increased by about 0.25°C per decade. In the future, it is projected to increase by about 1.5 to 2°C per degree of warming, increasing by a total of +6 to +8°C if global mean temperature increases by +4°C (see Appendix A).
- In the future, the number of warm days above 25°C could increase dramatically. For example, Calgary experienced an average of 34 days per year above 25°C during the period 1980-2009. It could experience 10 more days if the world warms by +1°C; 20 more days if it warms by +1.5°C; 35 more days, or double the historical number of days, if the world warms by +2°C, and over 60 more, almost triple the historical number of days, if the world warms by +4°C (Figure 10, centre)
- Very warm days (above 30°C) are currently very rare. However, these could increase even more sharply than warm days (Figure 10, right; and Figure 11): doubling for a global mean temperature increase of +1°C; increasing by a factor of 4 if the world warms by +2°C; and increasing nearly 10 times if the world warms by +4°C, to where the southern half of the province could see between 60-80 days per year over 30°C.

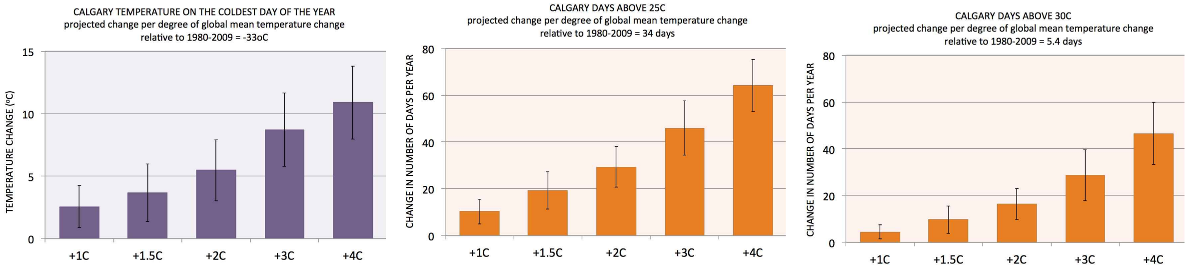


Figure 10. Projected changes in the temperature on the coldest day of the year in degrees C (left), in number of warm days per year with maximum temperature above 25°C (middle), and the number of very warm days per year with maximum temperature above 30°C (right) for Calgary. Solid bars represent multi-model average; thin lines represent multi-model range. See Appendix B for other locations.

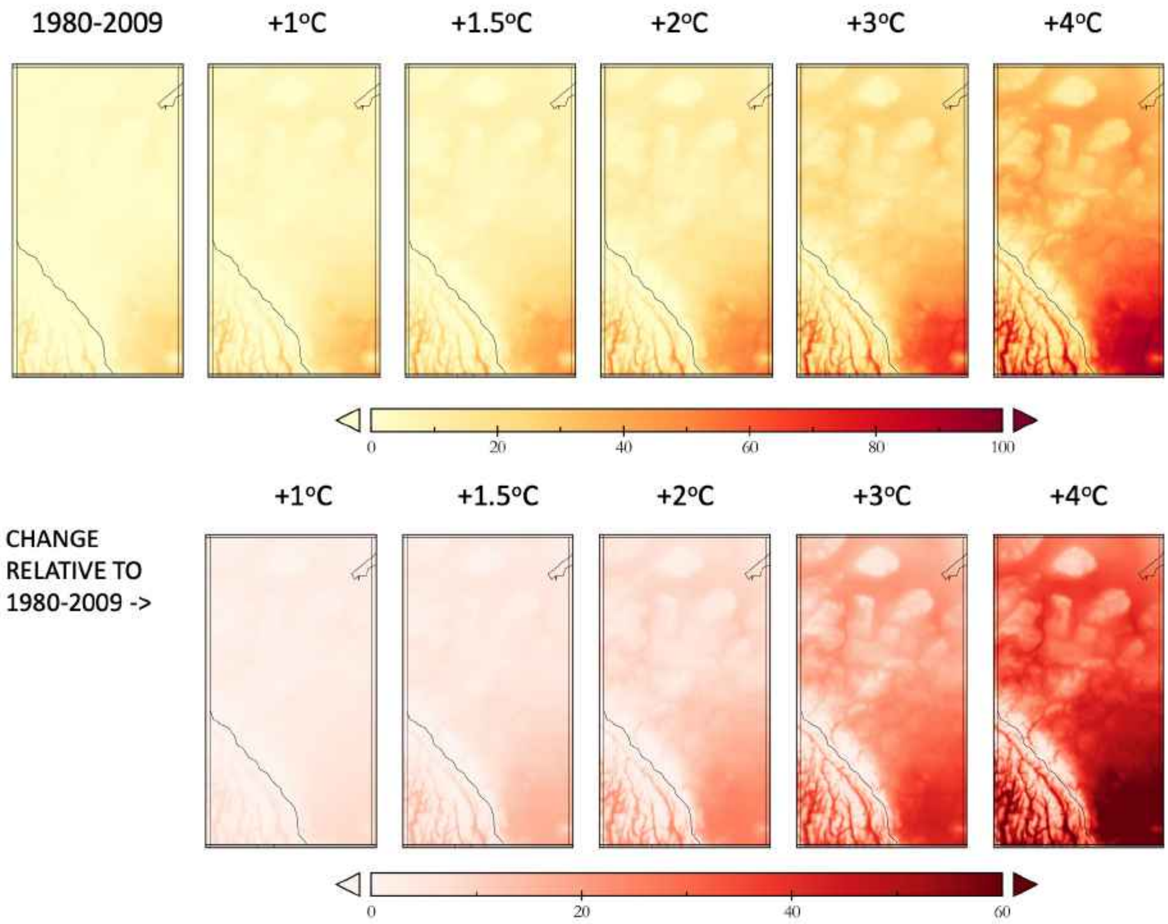


Figure 11. Hot days with maximum temperature over 30°C: historical average for 1980-2009 (left), projected future values as global mean temperature increases by +1 to +4°C (top), and the projected *change* or delta relative to 1980-2009 for those same future periods (bottom), in number of days per year. Values are for observations for the historical period and a multi-model average for the future periods. For more detail regarding models and global temperature thresholds, see the **Data, Models and Methods** section.

THREE. Changes in Growing Season, Degree-Days, and Heat Moisture Index

As seasonal temperatures increase, the frost-free and the growing seasons are getting longer.

The **frost-free season** is defined as the length of time between the last or latest freeze in spring and the first freeze in fall. A freeze is defined as a 24-hour period with minimum temperature below 0°C.

- Since 1950, the frost-free season has lengthened by about 2 days per decade, although trends are not yet significant at the 95th confidence interval in many locations (Figure 12, left panels).
- In the future, date of the *last frost* in spring is expected to move earlier in the year by about one week per degree of global mean temperature change. The *first frost* in fall is expected to move later in the year by about a week and a half per degree of global temperature change (Figure 13).

In the future, the frost-free season is expected to continue to lengthen. The number of hours over degree-day thresholds that affect chilling hours and growing hours for crops, plants, and even pest species – which show significant trends across much of the province (Figure 12, right panels) -- are expected to continue to increase as well.

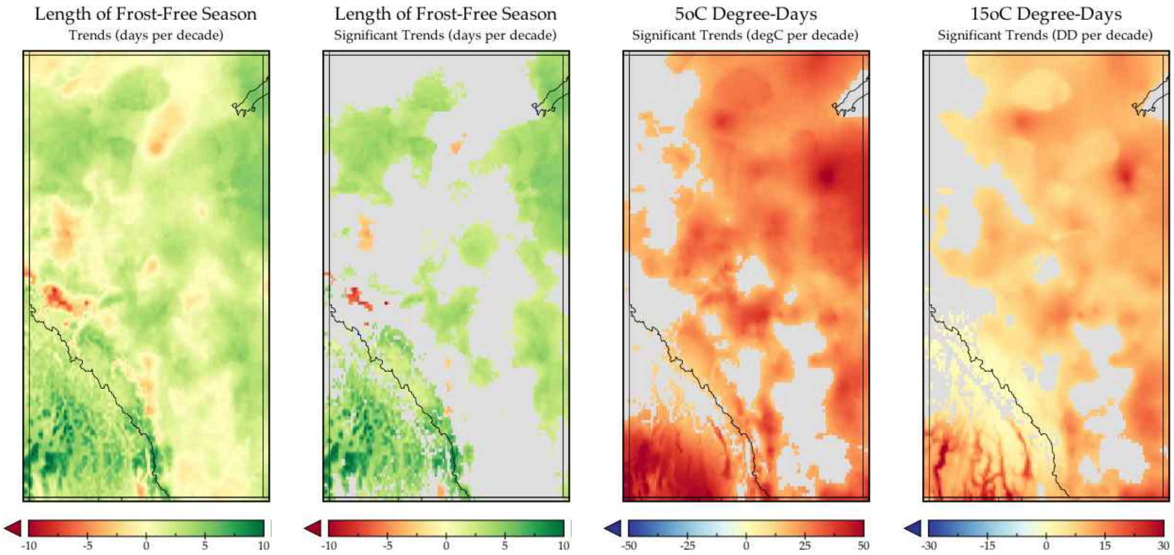


Figure 12. Observed trend from 1950 to 2013 in (left) the length of the frost-free season, and (right) degree-days over 5 and 15°C, respectively. Gray areas indicate where trends are not significant at the 95th confidence interval.

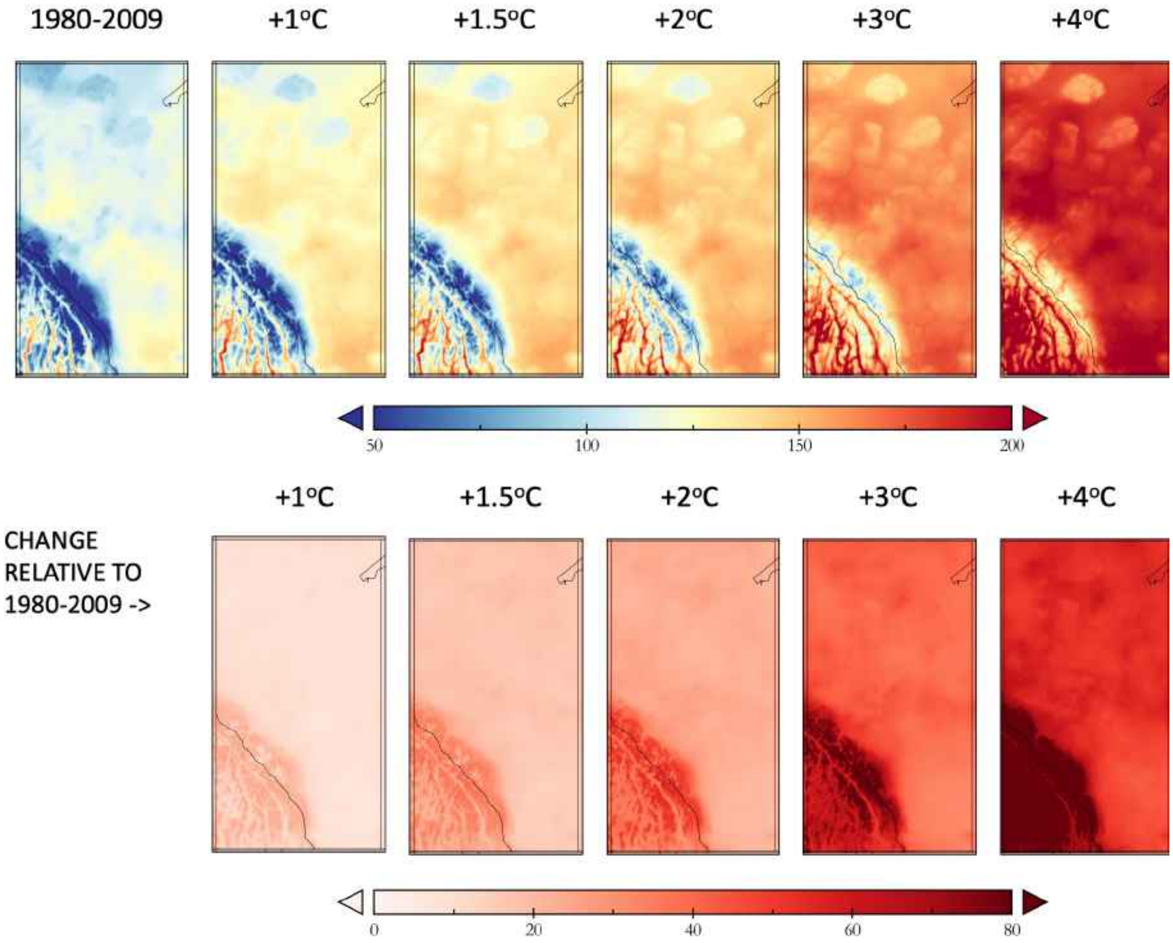


Figure 13. Changes in the length of the frost-free season: historical average for 1980-2009 (left), projected future values as global mean temperature increases by +1 to +4°C (top), and the projected *change* or delta relative to 1980-2009 for those same future periods (bottom), in number of days per year. Values are for observations for the historical period and a multi-model average for the future periods. For more detail regarding models and global temperature thresholds, see the **Data, Models and Methods** section.

The **growing season** is defined after the Agroclimatic Atlas of Alberta as the period between the first and last consecutive 5 days with average temperature over 5°C.

- The beginning of the growing season in spring is expected to change at half the rate of change of the last frost in spring in northern Alberta, about half a week per degree of global mean temperature change, and twice the rate of the projected change in the last frost in spring in southern Alberta, about two weeks per degree of global mean temperature change (Figure 14 and Appendix A).
- The end of the growing season is projected to change at the same rate throughout the province, about one week per degree of global warming (see Appendix B).
- In northern locations where the growing season is typically about four months long, it could increase by almost a half a month per degree of global warming, lengthening by over a month and a half if the world warms by +4°C. In southern locations where the growing season is currently about four and a half months long, it could increase by almost a month per degree of global warming, lengthening by an additional two and a half months to a total of seven months if the world warms by +4°C.

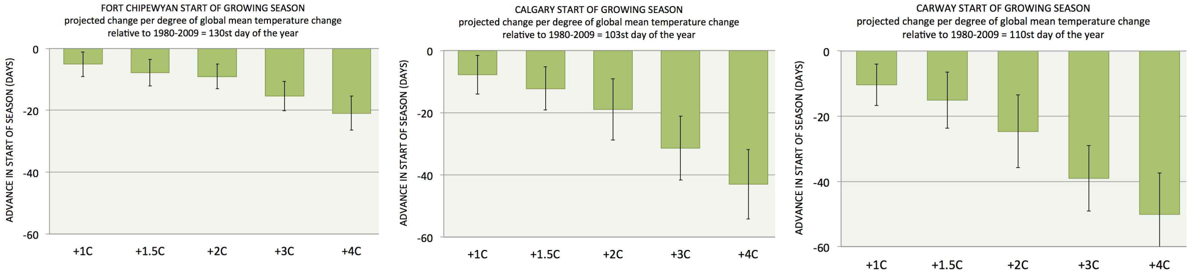


Figure 14. Projected changes in the beginning of the growing season in spring for three locations: Fort Chipewyan (left, north); Calgary (centre); and Carway (right, south), in Julian Days or day of the year. The solid bar represents the multi-model average, while the thin lines represent the multi-model range. Projected changes in the south are four times faster than projected changes in the north. Plots for the other locations are available in Appendix B.

Degree-days are calculated as the cumulative hours above a given temperature threshold each year. Degree-day thresholds ranging from 0°C to 15°C are relevant to a broad range of pests, crops, and plants, from bounding the range of pests like the corn borer, to defining the northward extent of the boreal forest.

As shown previously in Figure 12 (right), degree-days are already increasing, with significant trends across much of the province.

Appendices A, B and C contain maps and plots of observed trends and projected changes in degree-days for thresholds that the AgroClimatic Atlas of Alberta identifies as relevant to wheat and barley (0°C), canola, forages, and general plant growth (5°C), the cabbage maggot (6°C), potatoes and cutworm (7°C), corn, beans, grasshoppers, corn borers (10°C) and general insect development (15°C).

In general, as average temperature increases, so do degree-days, which will in turn shift the types of crops that can be grown where and when, as well as affecting the composition of ecosystems and the types of diseases and pests that may occur. In addition to climate, crop production depends on many other factors, including soil characteristics and water availability. For that reason, changes in degree-days cannot be taken alone as an indicator of productivity; instead, they must be incorporated into a framework that accounts for other factors in order to determine the net impact on productivity over time.

Corn Heat Units (CHUs) are another agriculturally-relevant climate indicator. CHUs are a measurement originally developed for field corn in Ontario, now used by the AgroClimatic Atlas of Alberta, that are intended to help farmers select the most appropriate varieties for their climate conditions. Since 1950, CHUs have increased across nearly the entire province, with significant trends across about a third of the province (Figure 15, left). In the future, CHUs are projected to continue to change, by about 300 CHUs per degree of global temperature increase (see Appendix A).

The **heat moisture index** (HMI) is a measure that combines temperature and precipitation in a single metric that is often used to characterize the climate of a region. Since 1950, there have been small increases in the summer and much larger increases in the annual heat moisture index (Figure 15, right). Both annual and summer heat moisture indices are projected to continue to increase as temperature increases. Annual HMI, which currently ranges from near zero to over 60 across Alberta, is projected to increase by about 10% per degree of global warming. Summer HMI, which currently ranges from about 20 to 120 across the province, is projected to increase by about 20% or more per degree of warming (see Appendix A).

Heating degree-days (HDDs), calculated as cumulative hours below a given temperature threshold where people generally turn on their furnaces, can also be used as a measure of energy used to heat buildings over the year. Using a threshold of 18°C, HDD values since 1950 have already decreased by about 100 - 150 hours per decade. Observed trends across the entire province are significant at the 95% confidence interval. In the future, the average number of heating hours per year is projected to decrease by about 500 hours per degree of global warming (Fig. 16).

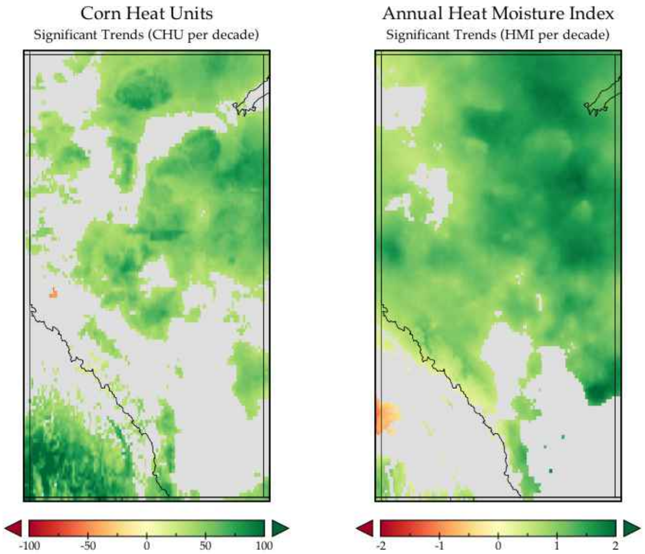


Figure 15. Observed trend from 1950 to 2013 in (left) corn heat units, and (right) the annual heat moisture index, respectively. Gray areas indicate where trends are not significant at the 95th confidence interval.

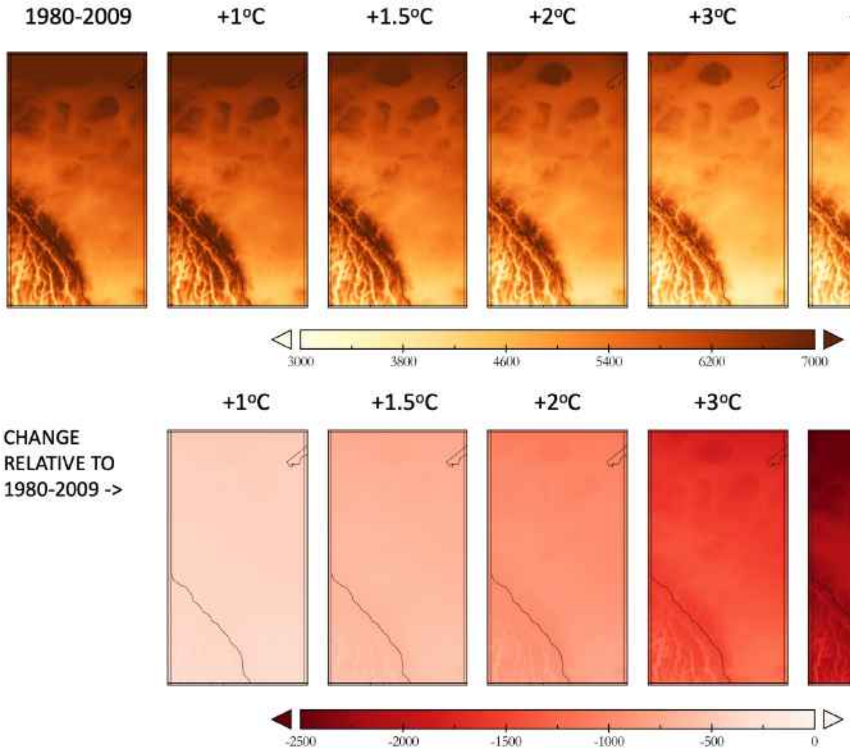


Figure 16. Heating degree-days using a threshold temperature of 18°C currently range from about 4,000 to more than 8,000 hours per year across the province (historical 1980-2009 values, top left). HDDs are projected to decrease by about 500 hours per degree of global warming: projected future values as global mean temperature increases by +1 to +4°C (top), and the projected *change* or delta relative to 1980-2009 for those same future periods (bottom), in average HDD units per year. Values are for observations for the historical period and a multi-model average for the future periods. For more detail regarding models and global temperature thresholds, see the **Data, Models and Methods** section.

THREE. Changes in Precipitation, Snow, and Dry Days

As climate changes, precipitation patterns are also expected to shift. In general, wetter areas (including Alberta and most higher latitudes) are projected to become wetter during winter and spring (Figure 17, left). The timing of precipitation is also expected to change, as the intensity of precipitation increases in a warmer world, by about 6% to 7% for each degree Celsius of temperature increase, according to the Clausius–Clapeyron relationship (Easterling et al. 2017).

As temperature increases, evaporation is also projected to increase, driving net decreases in soil moisture particularly during summer months (Figure 17, right). In turn, this could increase the risk of dry conditions during the growing season for much of North America, including Alberta, even if precipitation during the growing season is not projected to change significantly.

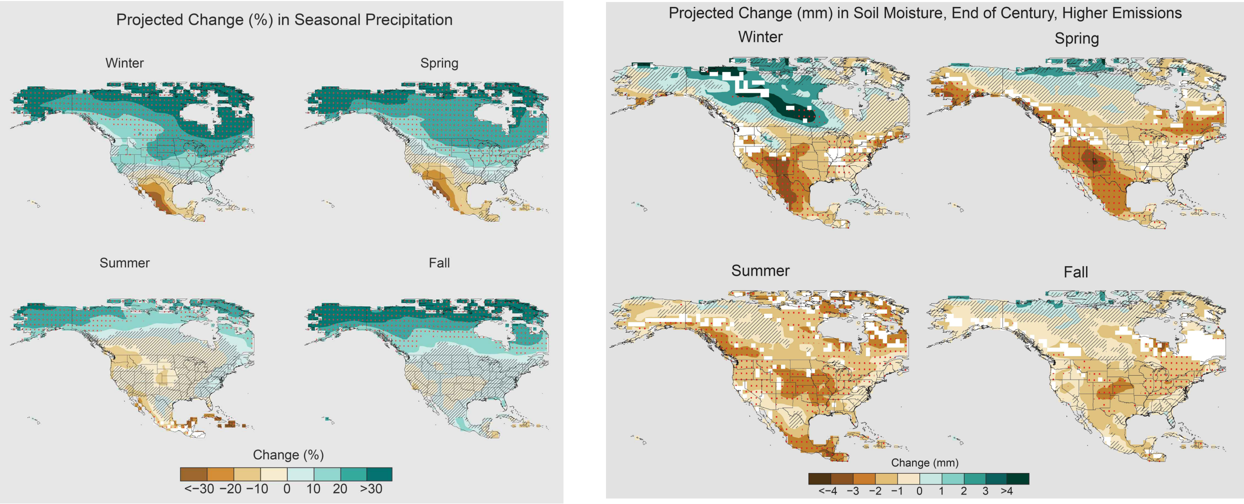


Figure 17. Projected change in (left) total seasonal precipitation from CMIP5 simulations for 2070–2099, in percent, and (right) near surface seasonal soil moisture. The values are weighted multimodel means and expressed as the percent (for precipitation) and mm (for soil moisture) change relative to the 1976–2005 average. These are results for the higher scenario (RCP8.5). Stippling indicates that changes are assessed to be large compared to natural variations. Hatching indicates that changes are assessed to be small compared to natural variations. Blank regions (if any) are where projections are assessed to be inconclusive. Source: Climate Science Special Report, Easterling et al. 2017.

Since 1950, there has been a slight increase in growing season (May-Aug) precipitation and a slight decrease in fall-winter-spring (Sep-Apr) precipitation, though these trends are not statistically significant across much of the province (see Appendix A). In the future, consistent with the seasonal trends shown in Figure 17 above, projected **seasonal average precipitation** across Alberta is expected to increase in all seasons, including:

- A projected consistent increase in fall-winter-spring (Sep-Apr) precipitation, of about 5-10% per degree of global mean temperature increase.
- A slight decline in the number of fall-winter-spring dry days across much of the province, by a day or two per degree of global mean temperature increase (projected trends for Red Deer are shown in Figure 18, top left; see Appendix A for province-wide maps, and Appendix B for other locations).

- Little change in growing season and summer precipitation. The results shown in Appendix A indicate a smaller and less consistent increase in growing season and summer precipitation, but in Figure 17 (which uses a larger sub-set of global climate models than this analysis), a small decrease is projected, overlaid by hatching which indicates that projected changes are small relative to natural variations. From the global climate models used in this report, projections show a large range that encompasses both increases and decreases in summer precipitation (see for example the projections for Red Deer in Figure 19 below).
- A slight increase in the number of dry days during the growing season, by a day or two per degree of global mean temperature increase (Figure 18, bottom left; see also Appendix A).

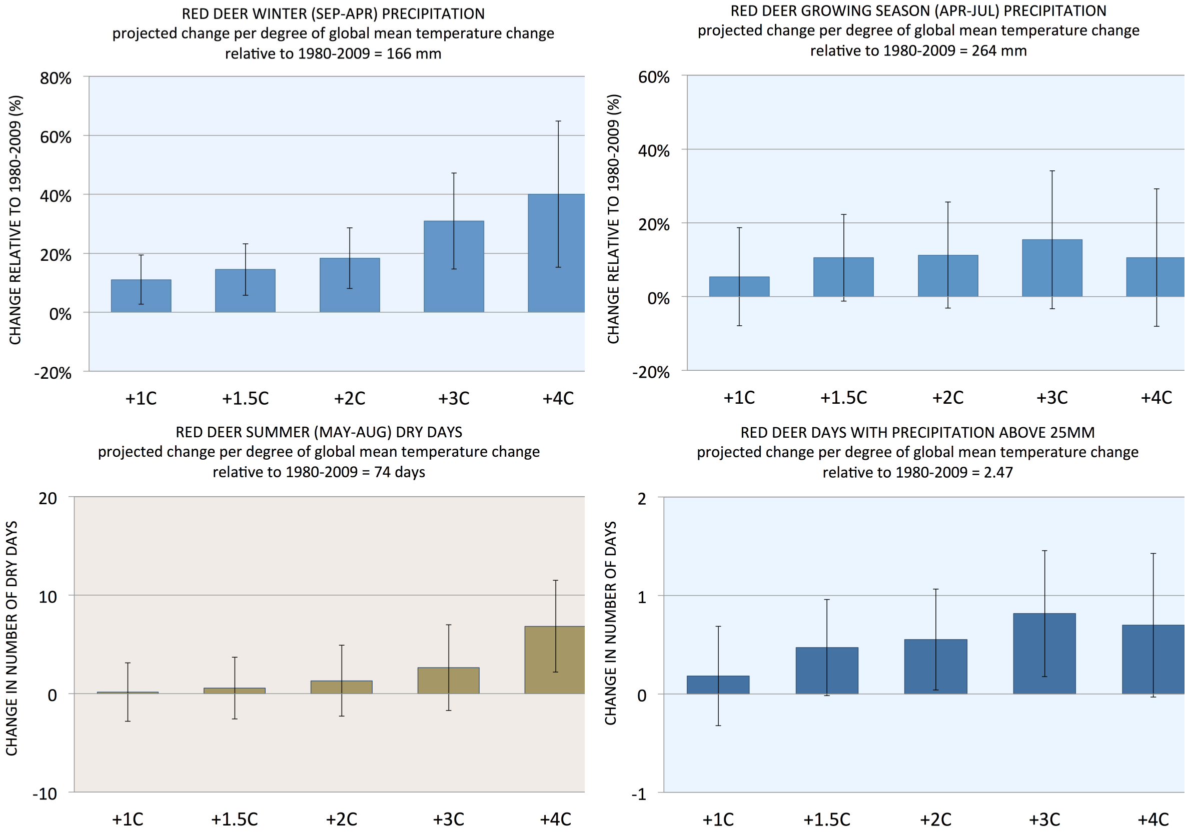


Figure 18. Projected changes in fall-winter-spring (Sep-Apr) cumulative precipitation in mm (top left), early growing season (Apr-Jul) cumulative precipitation in mm (top right), dry days during the regular growing season (May-Aug, bottom left) and the number of days per year with more than 25mm of rain in 24 hours (bottom right) for Red Deer. Similar plot for the other 20 locations are available in Appendix C.

In Alberta, observed increases in the amount of precipitation falling on the wettest day of the year are statistically significant at the 95th confidence interval only in the northern part of the province, where they have increased by 1 to 2 mm per decade. In most locations, there is no trend in the number of days per year over 25mm.

As the world warms, extreme precipitation is projected to become more frequent across the mid-latitudes in general. In Alberta, the amount of precipitation falling on the wettest day of the year is projected to increase by about 20% per degree of global warming. The number of days per year with more than 25mm of rain, currently relatively rare, is also expected to increase, by about 50% per degree of global warming (Figure 19; see also Appendix A).

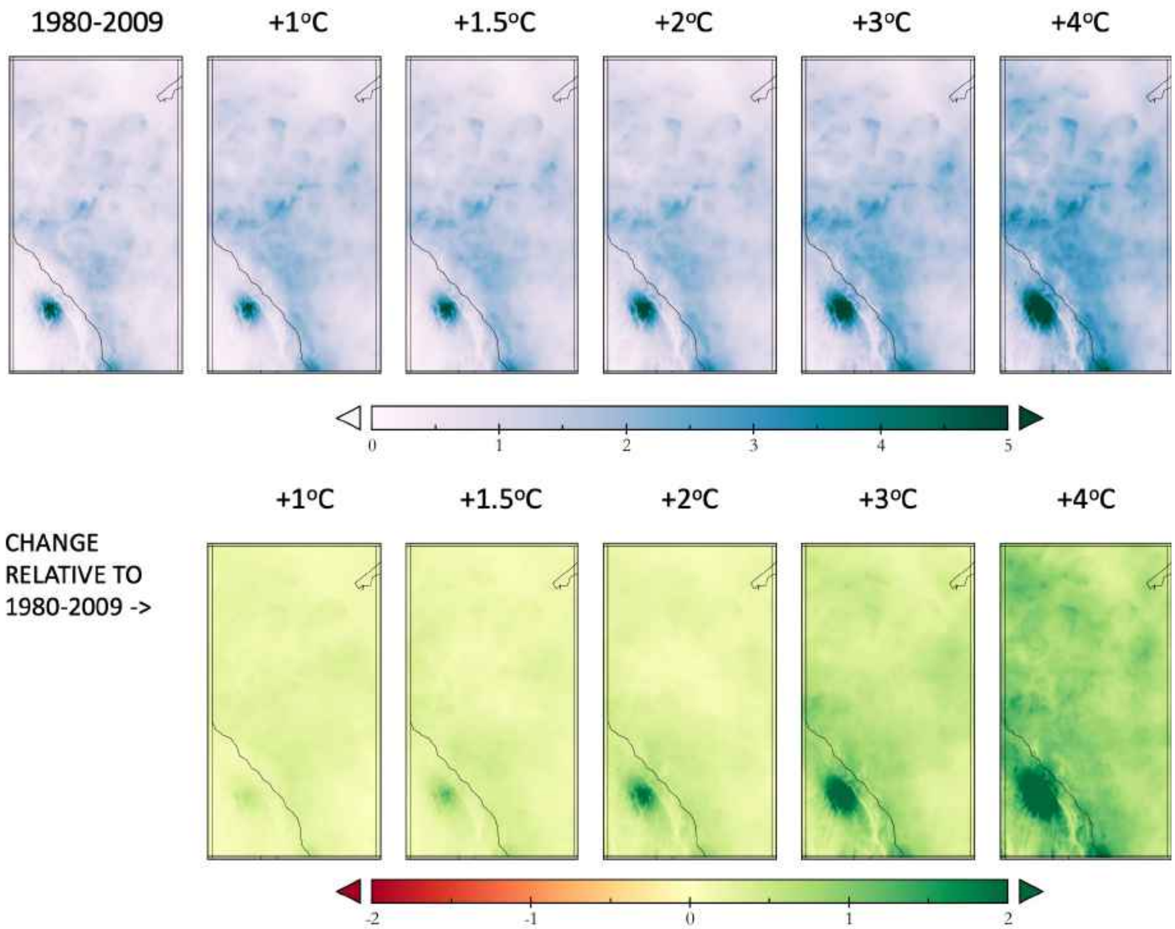


Figure 19. Number of days per year with more than 25mm of precipitation in 24hrs: historical (1980-2009) and projected future values as global mean temperature increases by +1 to +4°C (top), and the projected *change* or delta relative to 1980-2009 for those same future periods (bottom), in units of number of days per year. Values are for observations for the historical period and a multi-model average for the future periods. For more detail regarding models and global temperature thresholds, see the **Data, Models and Methods** section.

The proportion of winter (Sep-Apr) precipitation that falls as snow is also expected to change significantly. Currently, more than 50% of precipitation falls as snow across nearly all of Alberta (Figure 20). Since 1950, that percentage has increased by about 2-4% per decade, with more than half of the province experiencing trends that are significant above the 95% confidence interval (Figure 3).

As the world warms, the amount of winter precipitation falling as rain is projected to increase by about 5% per degree of global warming across much of the province, but more than 10% per degree of warming over the mountains. If the world were to warm by +4°C, only the most northern and highest-elevation locations would see more snow than rain, as indicated by the purple areas on the map (Figure 20) and for much of south-central Alberta, between 60-80% of winter precipitation would fall as rain, as indicated by the green areas on the map.

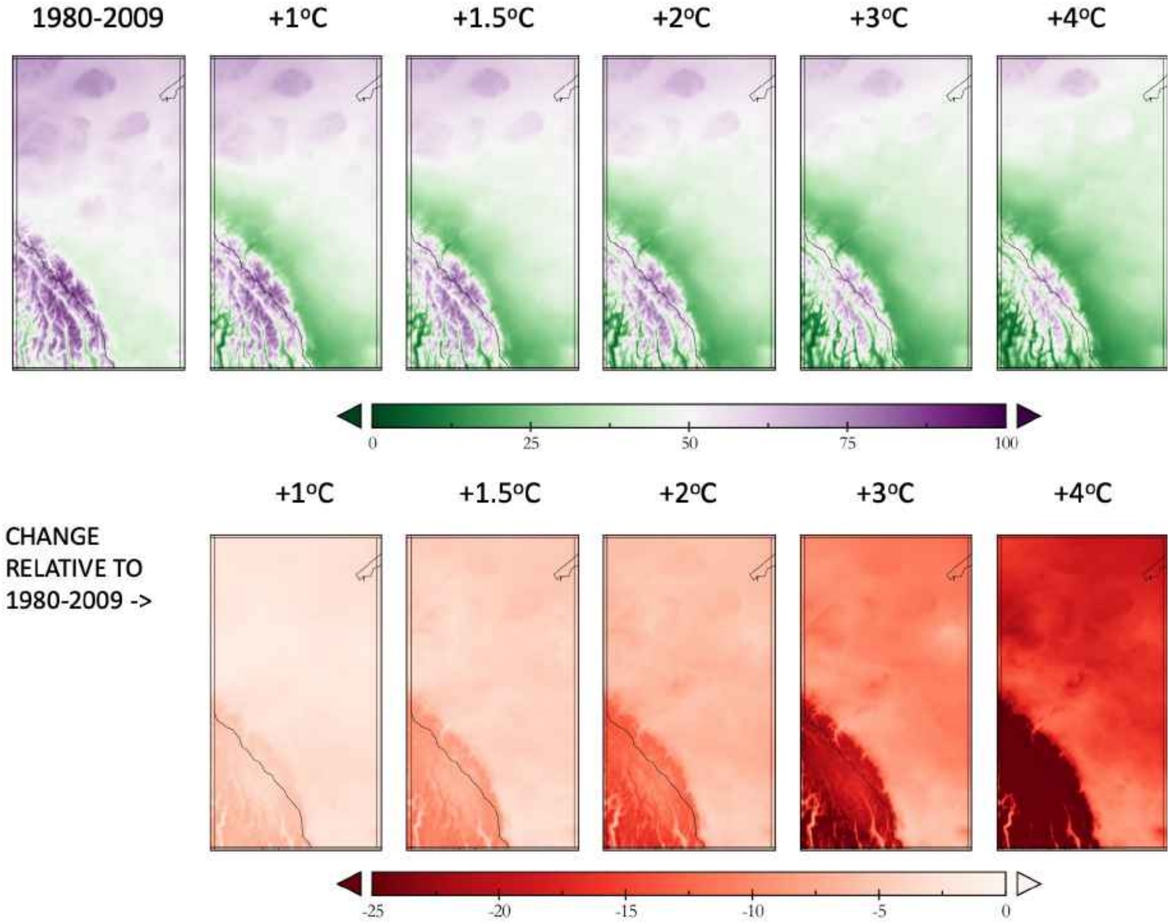


Figure 20. Percentage of Sept-Apr precipitation that falls as snow: historical 1980-2009 (left) and projected future values as global mean temperature increases by +1 to +4°C (top), and the projected *change* or delta relative to 1980-2009 for those same future periods (bottom), in percentage per year. Green shading indicates where more precipitation falls as rain than snow, and brown areas indicate where more falls as snow, less as rain. Values are for observations for the historical period and a multi-model average for the future periods. For more detail regarding models and global temperature thresholds, see the **Data, Models and Methods** section.

FOUR. Conclusions and Summary

Climate in Alberta is already changing: both winter and summer are warming, “cold” days below -30°C are becoming less frequent, the frost-free season is lengthening, and more winter precipitation is falling as rain and less as snow. These and many other observed changes are consistent with larger-scale trends observed across Canada and the world.

In the future, climate is expected to continue to change. While natural factors continue to affect the Earth’s climate, the main driver of climate change over the remainder of this century is expected to be human emissions of carbon dioxide and other heat-trapping gases.

This report shows that many of the projected changes that may be experienced across Alberta are proportional to global mean temperature. In other words, the more the world warms, the greater changes Alberta will experience. In addition, as is also the case for Canada as a whole (Bush and Lennen, 2019), projected changes for Alberta are greater than the global average: for example, winter temperature in Alberta is projected to increase by approximately +2°C for each +1°C that the world warms.

Per degree of global warming, projected changes in Alberta’s climate include:

- Increases in seasonal average temperatures, with greater increases in winter and for the month of January (about 2°C per degree of global warming) as compared to summer and the month of July (about 1.5°C per degree of global warming).
- Increases in the average temperature of the coldest day of the year by about 3°C per degree of global warming. If a global mean temperature increase of +4°C were to occur, the coldest day of the year in Alberta is projected to be 11-13°C warmer than the 1980-2009 average.
- Decreases in the number of very cold days (below -30°C) that range from a few less days per year, on average, per degree of global warming in the southern part of the province to over a week less cold days per year, on average, per degree of global warming in the northern part of the province.
- Increases in the temperature of the warmest day of the year, by about 2°C per degree of global warming. If a global mean temperature increase of +4°C were to occur, the warmest day of the year in Alberta is projected to be 5-8°C warmer than the 1980-2009 average.
- A rapid increase in the number of very warm days (above 30°C): by 2x for a global mean temperature increase of +1°C; by 4x if the world were to warm by +2°C; and by 8 to 10x if the world were to warm by +4°C.
- A lengthening of the frost free season, by about two weeks per degree of global warming.
- A lengthening of the growing season, ranging from about two weeks per degree of global warming in the northern part of the province to nearly a month per degree of global warming in the southern part of the province.
- Increases in the 0, 5, 6, 7, 10 and 15°C degree-day thresholds identified by the AgroClimatic Atlas of Alberta as being relevant to a broad range of crops and plants, as well as pests and insects.
- A decrease of about 500 heating degree-day hours per degree of global warming, a measure of how many hours homes and buildings must be heated each year.

- A consistent increase in fall-winter-spring (Sept-Apr) precipitation of about 5-10% per degree of global mean temperature increase.
- An increase in the number of days per year with more than 25mm of rain, currently occurring less than once a year in most locations across the province, by about 50% per degree of global warming.
- An increase in the average amount of precipitation falling on the wettest day of the year, by about 20% per degree of global warming.
- A consistent and continued decrease in the amount of fall-winter-spring (Sept-Apr) precipitation that falls as snow, by about 5% per degree of global warming across much of the province, but more than 10% per degree of warming over the mountains.

Growing season precipitation may increase slightly or not change at all, but temperatures are projected to increase and soil moisture during the growing season is projected to decrease, increasing the risk of drier conditions.

There is greatest certainty in projected increases in seasonal and monthly temperatures, decreases in the relative proportion of snow to rain, and decreased frequency of extreme cold days. In most locations, these trends are already occurring (see Appendix C), and are projected to continue over the remainder of the century.

Since winter has been warming faster than summer (Figure 2), many locations have not yet seen significant increases in warm days or the temperature of the warmest day of the year. As average temperature continues to increase, however, there is relatively high certainty that warm and very warm days will become more frequent, as they are already in more southern locations. Projected changes in these indicators are greater under the higher as compared to lower scenario, and under higher thresholds of global temperature change.

There is moderate certainty in projected increases in winter precipitation and increases in heavy precipitation and very wet days. Observed trends and projected future increases in heavy precipitation events are consistent across North America and have formally been attributed to the impacts of human-induced climate change. There is also moderate certainty in projected changes in drier conditions during the growing season, as a result of increased temperatures rather than changes in precipitation.

There is less certainty in projected changes in precipitation for the growing season and in changes in dry days across Alberta. Little change is expected, and model projections regarding the direction of change are inconsistent.

The observed and projected future changes documented in this report have the potential to affect Alberta's agriculture, economy, ecosystems, energy demand, infrastructure, and more. For example, as temperatures increase, the optimal growing zones for specific crops, as well as for entire ecosystems, such as the coniferous forest, will shift poleward. The geographic range of pests and diseases limited by cold winter temperatures will also expand northward. Decreasing risks of extreme cold and increased risk of extreme heat and heavy precipitation have the potential to affect both public and private infrastructure, with implications for a broad range of sectors, from insurance to energy demand for heating and cooling residential and commercial buildings.

The projections described in this report are intended to enable assessment of these impacts and inform efforts to build resilience to future change. The sections that follow provide detailed information regarding the data, models, and methods used in developing these projections, as well as the products and outputs available from this analysis.

Data, Models, and Methods

ONE. Observed Data

Observed daily maximum and minimum temperature and precipitation were obtained from two different datasets:

1. ***Gridded observations*** from the NRCan Daily 10km Gridded Climate Dataset for Canada, which contains daily temperature and precipitation from 1950 to 2013 for a uniform 1/12th degree resolution grid covering all of Canada except for the Yukon, the Northwest Territories, and Nunavut. This dataset was originally produced by Hopkinson et al. (2011) and McKenney et al. (2011) for the Canadian Forest Service, and updated in 2013. Quality-controlled, unadjusted station data from the National Climate Data Archive of Environment and Climate Change Canada data (Hutchinson et al., 2009) were interpolated onto the high-resolution grid using the Australian National University Spline (ANUSPLIN) implementation of the trivariate thin plate splines interpolation method (Hutchinson et al., 2009) with latitude, longitude and elevation as predictors. Precipitation occurrence and square-root transformed precipitation amounts were interpolated separately on each day, then combined. The number of stations across Canada used in this analysis ranged from 2000 to 3000 for precipitation, depending on the year, and 1500 to 3000 for air temperature (Hopkinson et al., 2011). Source: https://cfs.nrcan.gc.ca/projects/3/4
2. ***Long-term weather stations*** across Alberta with at least 30 years' worth of daily temperature and precipitation recorded between 1950 and 2018 from the Global Historical Climatology Network (GHCN) maintained by the U.S. National Centers for Environmental Information. GHCN is an integrated database of daily climate summaries from over 100,000 land surface stations across 180 countries that includes daily climate records from numerous sources that have been integrated and subjected to a common suite of quality assurance reviews. The stations used in this report consist of: Athabasca, Banff, Brownfield, Calgary, Calmar, Campsie, Camrose, Carway, Cold Lake, Craigmyle, Edmonton and Edmonton Stony Plain, Fort Chipewyan, Fort McMurray, Grande Prairie, High Level, Lethbridge, Lloydminster, Medicine Hat, Queenstown, and Red Deer (Table 1). Source: https://www.ncdc.noaa.gov/ghcn-daily-description

Location	GHCN ID	Latitude	Longitude
Athabasca	CA003060321	54.8167	-113.5333
Banff	CA003050520	51.1833	-115.5667
Brownfield	CA003010890	52.3167	-111.4667
Calgary	CA003031093	51.1167	-114.0167
Calmar	CA003011120	53.2833	-113.8667
Campsie	CA003061200	54.1333	-114.6833
Camrose	CA003011240	53.0333	-112.8167
Carway	CA003031400	49	-113.3833

Cold Lake	CA003081680	54.4167	-110.2833
Craigmyle	CA003021940	51.7667	-112.2833
Edmonton	CA003012208	53.5667	-113.5167
Edmonton Stony Plain	CA00301222F	53.55	-114.1167
Fort Chipewyan	CA003072658	58.7667	-111.1167
Fort McMurray	CA003062693	56.65	-111.2167
Grande Prairie	CA003072920	55.1833	-118.8833
High Level	CA003073146	58.6167	-117.1667
Lethbridge	CA003033890	49.7	-112.7667
Lloydminster	CA003013961	53.3167	-110.0667
Medicine Hat	CA003034480	50.0167	-110.7167
Queenstown	CA003035340	50.6	-112.9833
Red Deer	CA003025480	52.1833	-113.9

Table 1. City or location names, GHCN ID numbers, latitude and longitude for the 21 long-term weather stations used in this analysis.

TWO. Climate Indicators

Daily temperature and precipitation observations for both the gridded and the station-based data were then used to calculate a set of ***climate indicators*** relevant to potential impacts on the province of Alberta. Definitions for the majority of these climate indicators were derived from the Agroclimatic Atlas of Alberta. Additional indicators were derived from ClimateBC and from the primary scientific literature that quantifies relationships between climate and a host of impacts including pests, crops, trees, infrastructure, health, livestock, and more.

This analysis includes 25 temperature-based indicators, 8 precipitation-based indicators, and 3 hybrid temperature-precipitation indicators. The climate indicators are defined and listed in Tables 2A (temperature), 2B (precipitation), and 2C (hybrid variables).

Indicator	**Definition**	**Units**
Winter Temperature	Average temperature for December, January and February	Degrees C
Summer Temperature	Average temperature for June, July and August	Degrees C
Growing Season Temperature	Average temperature for May through August	Degrees C
January Temperature	Average temperature for January, typically the coldest month of the year	Degrees C
July Temperature	Average temperature for July, typically the warmest or second warmest month of the year. The isotherms of 13-18°C average temperature during July define the extent of the coniferous boreal forest.	Degrees C
Coldest Day of the Year	Minimum temperature on the coldest day of the year	Degrees C
Warmest Day of the Year	Maximum temperature on the warmest day of the year	Degrees C

Days Above 30°C	Number of days per year with maximum temperature above 30°C. Related to crop stress.	Days per Year
Days Below 5°C	Number of days per year with minimum temperature below 5°C. Related to crop stress.	Days per Year
Days Above 25°C	Number of days per year with maximum temperature above 25°C. Related to livestock stress; above this threshold, cattle need twice the water.	Days per Year
Days Below -30°C	Number of days per year with minimum temperature below -30°C. Used to represent a "very cold day" that typically occurs anywhere from a few times each year in southern Alberta to more than 20 times per year in northern Alberta.	Days per Year
Last Spring Frost	Last day in spring with minimum temperature below 0°C	Day of Year (Julian Date)
First Fall Frost	First day in fall with minimum temperature below 0°C	Day of Year (Julian Date)
Length of Frost-Free Season	Number of days between the last freeze in spring and the first freeze in fall	Days
Start of Growing Season	Earliest consecutive string of five days with average temperature above 5°C	Day of Year (Julian Date)
End of Growing Season	Latest consecutive string of five days with average temperature above 5°C	Day of Year (Julian Date)
Growing Season Length	Number of days between the start and end of the growing season as defined by at least 5 consecutive days with average temperature above 5°C	Days
0°C Degree-Days	Cumulative hours per year over 0°C, relevant for chilling hours for wheat and barley.	Degree-Days
5°C Degree-Days	Cumulative hours per year over 5°C, relevant to canola and general plant growth.	Degree-Days
6°C Degree-Days	Cumulative hours per year over 6°C, relevant to spruce budworm (needs at least 200-350 hours).	Degree-Days
7°C Degree-Days	Cumulative hours per year over 7°C, relevant to potatoes.	Degree-Days
10°C Degree-Days	Cumulative hours per year over 10°C, relevant to corn and beans, as well as grasshoppers and corn borers.	Degree-Days
15°C Degree-Days	Cumulative hours per year over 15°C, relevant to insects.	Degree-Days
Corn Heat Units	Start date = last of 3 consecutive days with average temperature greater than or equal to 12.8°C. End date = first fall frost with minimum temperature below -2°C. CHUs between the start and end date are calculated as (X + Y)/2 where X = 1.8(Tmin-4.4) if X>0 and Y = 3.33(Tmax-10)-0.084(Tmax-10)^2 if Y>0.	CHU
Heating Degree-Days	Cumulative hours per year below 18°C, relevant to energy demand for residential and commercial heating.	Degree-Days

Table 2A. These climate indicators have been calculated from daily **temperature** observations and model simulations, for a grid covering the province of Alberta and for 21 weather stations.

Precipitation-Related Indicator	Definition	Units
Fall-Winter-Spring Precipitation	Cumulative precipitation for September through April	mm
Early Growing Season Precipitation	Cumulative precipitation for April through July	mm
Growing Season Precipitation	Cumulative precipitation for May through August	mm
Wettest Day	Cumulative precipitation on the wettest day of the year	mm
Winter Dry Days	Number of days between September and April with less than 0.2mm of precipitation	Days per Year
Summer Dry Days	Number of days between May and August with less than 0.2mm of precipitation	Days per Year
Wet Days	Number of days per year with precipitation above 0.2mm.	Days per Year
Very Wet Days	Number of days per year with precipitation above 25mm.	Days per Year

Table 2B. These climate indicators have been calculated from daily **precipitation** observations and model simulations, for a grid covering the province of Alberta and for 21 weather stations.

Precipitation-Related Indicator	Definition	Units
Winter Precipitation as Snow	Percentage of precipitation for Sept through April falling as snow versus rain, defined as precipitation on a day when maximum temperature is below 2°C and minimum temperature below 0°C	%
Annual Heat Moisture Index	(Average annual temperature + 10) / (Average annual precipitation/1000)	HMI
Summer Heat Moisture Index	(Average temperature of warmest month)/(Average May to Sept precipitation/1000)	HMI

Table 2C. These climate indicators have been calculated from daily **temperature** and **precipitation** observations and model simulations, for a grid covering the province of Alberta and for 21 weather stations.

THREE. Observed Trends

Observed trends in the climate indicators listed in Table 2 (calculated for the period 1950-2013 for the gridded data, and for the period of record for each individual weather station) were calculated using Sen's Slope, an efficient algorithm that is relatively insensitive to outliers. The significance of these trends was determined using the Kendall rank correlation coefficient (also known as the Mann-Kendall tau), with $p<0.05$ to identify trends that are significant to the 95th confidence interval.

For the gridded data, the observed trends shown in Appendix A and highlighted in Figure 21 below are plotted in three different ways:

- The difference between the 1990-2009 and the 1950-1969 average (left).

- The linear trend per decade, as calculated using Sen's Slope (centre).
- The linear trend per decade, calculated using Sen's Slope, that is significant above the 95th confidence interval according to the Kendall rank correlation coefficient (right).

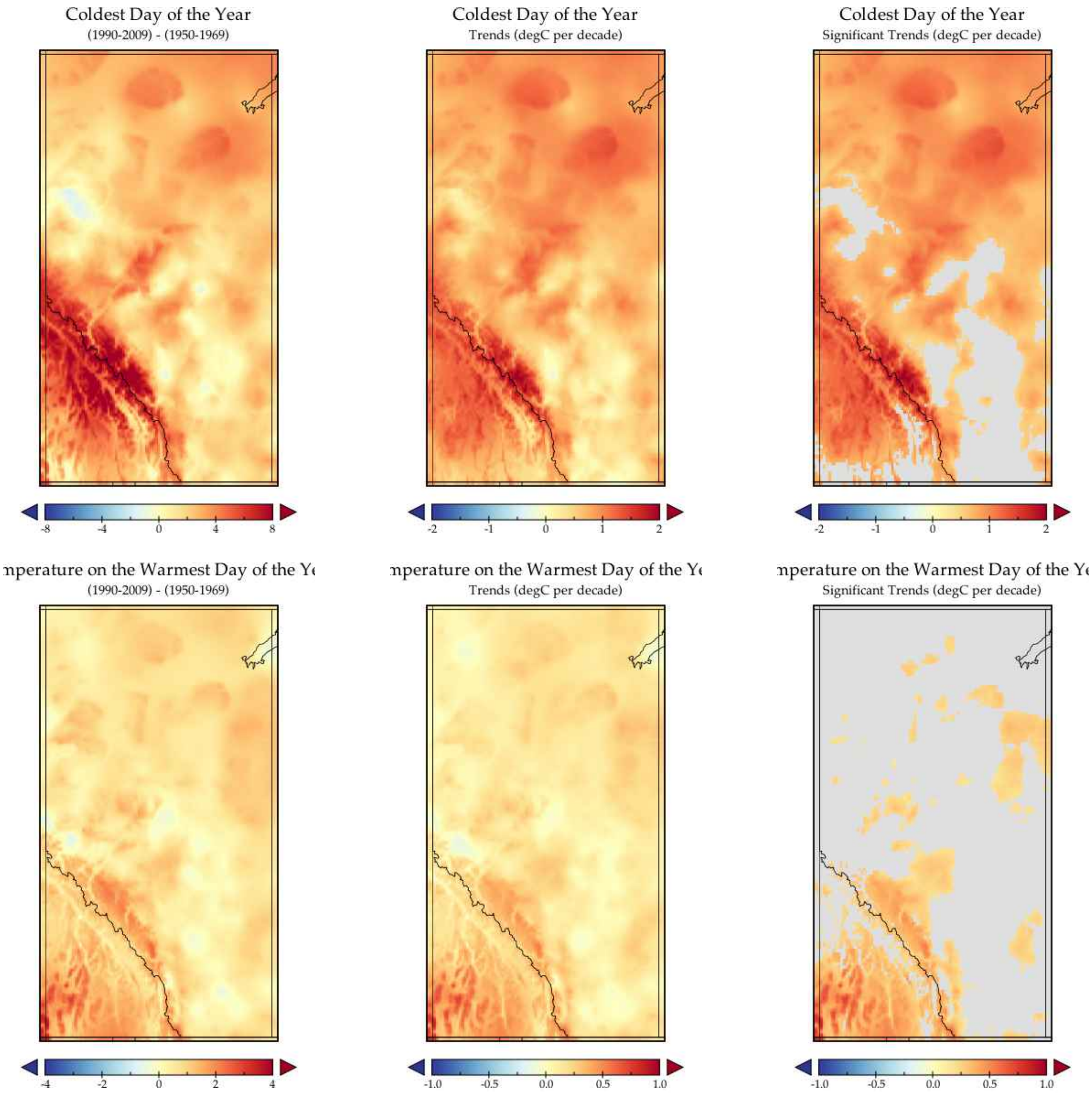


Figure 21. This figure shows the observed trends in the temperature of the coldest day of the year (top) and the warmest day of the year (bottom) from 1950 to 2013. On the right, the change (in degrees C) from 1950-1969 to 1990-2009 is plotted. In the centre, the linear trend calculated using Sen's Slope is plotted in degrees C per decade. On the left, the same linear trend is shown as in the centre, but with the Kendall rank correlation coefficient applied to remove all locations (indicated by gray shading) where the observed trend is not significant at the 95% confidence interval.

For variables with large and consistent trends across the entire province, including winter temperatures and cold days, there is little difference between these three criteria (Figure 21, top). For other variables with small and/or inconsistent trends, including summer heat and extreme precipitation, the significance test is very important, as it reveals that the observed trends are not yet significant across much of the province.

FOUR. Future Scenarios

At the local scale, how much and how fast climate will change in the future is uncertain due to multiple factors that are described in detail in Section 7 below. At the regional to global scale, however, given that human emissions of carbon dioxide and other heat-trapping gases are the primary driver of climate change today, one of the most important sources of uncertainty in future projections is the choices humans will make that determine future emissions. This uncertainty is particularly relevant to quantifying the magnitude of projected changes in average annual and seasonal temperature, and many extreme temperature and precipitation indicators, for mid-century and beyond.

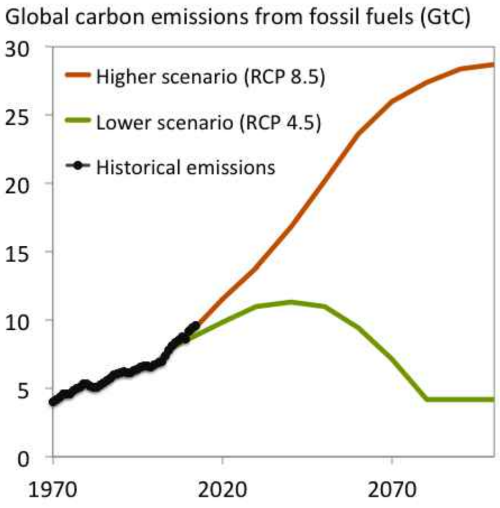


Figure 22. Historical carbon emissions (black) continue to increase from one decade to the next. This report examines how Alberta's climate might change if the world follows Representative Concentration Pathway (RCP) 8.5, a higher scenario with continued dependence on carbon-intensive fossil fuels (orange) or RCP 4.5, a lower scenario where replacing fossil fuels with zero-carbon alternatives reduces and ultimately stabilizes global carbon emissions (green). Data: CDIAC, IIASA

To account for scenario uncertainty, future projections were developed for two very different scenarios, or Representative Concentration Pathways (RCPs), that span a broad range of possible changes over the coming century (Moss et al. 2010; Figure 22). The ***lower scenario*** used here (RCP 4.5) represents a future in which the world shifts to clean energy sources in the coming decades, reducing carbon emissions from human activities to 1970 levels by around 2080. (This report does not include projections for the lowest scenario, RCP2.6, as only a few years' worth of emissions at present-day rates remain to be emitted before the carbon budget required to meet RCP2.6 is exceeded. See Hayhoe et al. 2017 for more details.) The ***higher scenario*** used here (RCP 8.5) represents a future in which people continue to depend heavily on fossil fuels, and emissions of heat-trapping gases continue to grow. The numbers in the scenario labels (RCP4.5 and RCP8.5) refer to the projected change in radiative forcing (+4.5 and +8.5) in units of watts per square meter. Radiative forcing is a measure of the extent to which humans have artificially enhanced the magnitude of the naturally-occurring greenhouse effect that already maintains the temperature of the planet at an average temperature of more than 30°C above what it would be without an atmosphere.

Each scenario is treated equivalently in this analysis, with no likelihood assigned to either. Results from the higher and a lower future scenario are used equally. However, given that the RCP scenarios begin in 2006, the *Climate Science Special Report* analyzed emissions from 2006 through 2016 and concluded that, currently, "the observed increase in global carbon emissions over the past 15–20 years has been consistent with higher scenarios (very high confidence)." (Hayhoe et al. 2017)

FIVE. Global Mean Temperature Thresholds

Future projections, such as those provided in the *Climate Science Special Report*, *Canada's Climate Future Report*, or the Intergovernmental Panel on Climate Change's *Assessment Reports*, are traditionally summarized for a given future scenario (for example, RCP8.5 or 4.5) over a range of future climatological time periods (for example, temperature change in 2040–2079 or 2070–2099 relative to 1980–2009). This approach has the advantage of developing projections for a specific time horizon. However, uncertainty in future projections for a given time horizon can be relatively high, as it includes the uncertainty due to multiple scenarios as well as the uncertainty regarding the response of the climate system to human emissions (see Sections 6 and 7 below). In addition, the RCP scenarios bear no relationship to the 1.5 and 2ºC targets of the Paris Agreement to which Canada, and every other country in the world except the U.S., is currently a party.

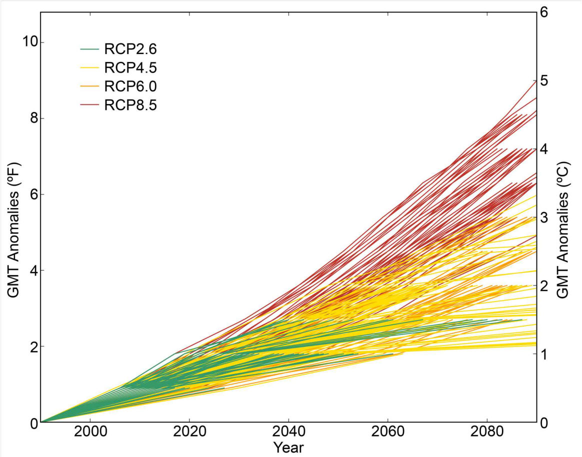


Figure 23. Global mean temperature anomalies (in degrees C on the right-hand axis) relative to 1976–2005 for four RCP scenarios, 2.6 (green), 4.5 (yellow), 6.0 (orange), and 8.5 (red). Each line represents an individual simulation from the CMIP5 archive. Every RCP-based simulation with annual or monthly temperature outputs available was used here. The values shown here were calculated in 0.5°C increments; since not every simulation reaches the next 0.5°C increment before end of century, many lines terminate before 2100. Source: Climate Science Special Report, Hayhoe et al. 2017

For that reason, in addition to the RCP scenarios, future projections were also analyzed in terms of five ***global mean temperature (GMT) thresholds***: +1, +1.5, +2, +3 and +4ºC relative to pre-industrial levels (1850-1899, as this is the oldest period available from most global climate model simulations). For each RCP4.5 and RCP8.5 simulation, a time slice of 20 years centered around the point in time at which each GMT threshold was reached was extracted from each individual global climate model simulation. Those years were then combined to quantify projected change at that GMT threshold. The methodology is described in more detail in the *Climate Science Special Report*, which includes Figure 23 to illustrate how each individual RCP simulation can be analyzed for information on the time period where that simulation reaches each GMT threshold.

GMT scenarios do not correspond to any specific time frame. However, it is possible to say that, for a given amount of emissions, a given threshold would be reached on average by a certain time period. Specifically, the greater annual emissions, the faster each GMT threshold will be reached and/or exceeded.

The utility of this approach lies in the fact that it can be used to quantify how the growing season in northern Alberta, for example, or extreme precipitation days in Calgary are likely to change as the world warms by 1.5 or 2ºC. This in turn informs the magnitude and scopeof the adaptation measures that may be required, even if the world meets the temperature targets set by the Paris Agreement (whenever that may happen). This approach can also be used to quantify the impacts that would be avoided compared to a 3 or 4ºC future. However, it is important to note that this approach is less useful for those impacts that vary based on rate of change, such as species migrations, or where equilibrium changes are very different from transient effects, such as sea level rise.

SIX. Global Climate Models and Empirical-Statistical Downscaling

As described in the Climate Science Special Report, "global climate models [or GCMs] are mathematical frameworks that were originally built on fundamental equations of physics. They account for the conservation of energy, mass, and momentum and how these are exchanged among different components of the climate system. Using these fundamental relationships, GCMs are able to simulate many important aspects of Earth's climate: large-scale patterns of temperature and precipitation, general characteristics of storm tracks and extratropical cyclones, and observed changes in global mean temperature and ocean heat content as a result of human emissions. The complexity of climate models has grown over time, as they incorporate additional components of Earth's climate system. For example, GCMs were previously referred to as "general circulation models" when they included only the physics needed to simulate the general circulation of the atmosphere. Today, global climate models simulate many more aspects of the climate system: atmospheric chemistry and aerosols, land surface interactions including soil and vegetation, land and sea ice, and increasingly even an interactive carbon cycle and/or biogeochemistry." (Hayhoe et al. 2017)

Regarding the use of these models for future projections, it states that "confidence in the usefulness of the future projections generated by global climate models is based on multiple factors. These include the fundamental nature of the physical processes they represent, such as radiative transfer or geophysical fluid dynamics, which can be tested directly against measurements or theoretical calculations to demonstrate that model approximations are valid (e.g., IPCC 1990). They also include the vast body of literature dedicated to evaluating and assessing model abilities to simulate observed features of the earth system, including large-scale modes of natural variability, and to reproduce their net response to external forcing that captures the interaction of many processes which produce observable climate system feedbacks (e.g., Flato et al. 2013)." And it concludes, "**there is no better framework for integrating our knowledge of the physical processes in a complex coupled system like Earth's climate.**" (Hayhoe et al. 2017)

This is not intended to imply that GCMs are perfect. They are not, and the differences between them represent the limitations of scientific ability to simulate the climate system. These differences are an important source of uncertainty in determining the magnitude and sometimes even the direction of projected changes in average and seasonal precipitation, as well as the magnitude of the more extreme indicators of temperature and precipitation. In most cases, it is not possible to identify a single "best" model or small subset of such models; rather, research has shown that the ensemble or average of multiple models is typically better able to simulate long-term climate than any individual model, though the multi-model mean can be optimized by a weighting scheme that takes into account the extent to which various models are related and thereby should not be treated as independent sources (Knutti, 2017).

For that reason, future projections for this report were based on simulations from 20 different GCMs from phase 5 of the Coupled Model Intercomparison Project (CMIP5). The global climate models used to generate future projections, and their country of origin, are: ACCESS1-0 (Australia), BCC-CSM-1-1 and BCC-CSM1-1-M (China), BNU-ESM (China), CCSM4 (USA), CNRM-CM5 (France), CSIRO-Mk3-6-0 (Australia), GFDL-ESM2G and GFDL-ESM2M (USA), HadGEM2-ES and HadGEM2-CC (UK), INMCM4 (Russia), IPSL-CM5A-LR, IPSL-CM5A-MR, and IPSL-CM5B-LR (France), MIROC5 (Japan), MPI-ESM-LR and MPI-ESM-MR (Germany), MRI-CGCM3 (Japan) and NorESM1-M (Norway). Results from the CanESM2 model were not used as global mean temperature thresholds were not available; if these become available, they can be added. Results from other GCMs were not included if required daily outputs were not available, they had not been downscaled, and/or known issues precluded their use in this application.

Global climate model output is typically too coarse to be applied at the scale of a province, let alone an individual weather station. For that reason, GCM outputs are typically downscaled using a statistical or dynamical method (Figure 24; for more information, see Section 7 and Kotamarthi et al. 2016). This report used projections that had been downscaled using an **empirical statistical downscaling model** that combines global climate model simulations with historical records of daily observations (using at least 30 years if not more, to cover a range of weather conditions) to produce locally relevant projections of temperature and precipitation. The downscaling models are "trained" using these observational datasets to increase the spatial resolution of the future projections and to remove or correct the bias in GCM simulations relative to observations, producing high-resolution projections at the same temporal and spatial scale of the original observations.

This report used daily maximum and minimum temperature and precipitation projections for the lower RCP4.5 and higher RCP8.5 scenarios that were statistically downscaled using the Asynchronous Regional Regression Model, a nonparametric empirical statistical downscaling method that uses a kernal density estimator to map observed distributions to those simulated by the global climate models for that region. The first version of the ARRM is described in Stoner et al. (2012); an updated description of this downscaling model that includes the newer nonparametric method and improved treatment of extremes that was applied to the temperature projections used in this report is currently in preparation.

Temperature and precipitation were downscaled to the same two observational datasets described in Section 1: (1) ***gridded observations*** from the NRCan Daily 10km Gridded Climate Dataset for Canada, which produced daily temperature and precipitation projections from 1950 to 2100 for a uniform grid; and (2) data from 21 long-term ***weather stations*** across Alberta with at least 30 years' worth of daily data recorded between 1950 and 2016 listed in Table 1. Before being used to downscale GCM simulations, all GHCN station data undergoes a quality control process that uses a nearest neighbour approach to remove any anomalously extreme temperature and/or precipitation values that are not verified by data recorded by a neighbouring station within twenty four hours of the day of the anomalous observation.

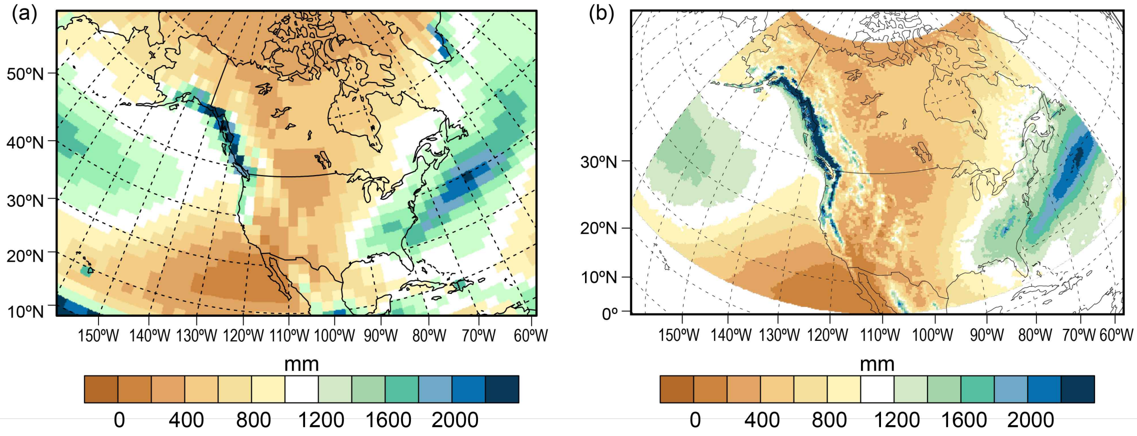


Figure 24. CMIP5 global climate models typically operate at coarser horizontal spatial scales on the order of 30 to 200 miles (50 to 300 km). This figure compares annual average precipitation (in millimeters) for the historical period 1979–2008 using (a) a resolution of 250 km or 150 miles with (b) a resolution of 15 miles or 25 km to illustrate the importance of spatial scale in resolving key topographical features, particularly along the coasts and in mountainous areas. Source: Climate Science Special Report, Hayhoe et al. 2017

SEVEN. Sources of Uncertainty in Future Projections

There are four main sources of uncertainty in future climate projections:

1. **Natural variability, which causes temperature, precipitation, and other aspects of climate to vary from year to year and even decade to decade.**

The Earth's climate is extremely complex. Interactions between the various components of the system can be non-linear, making it difficult to determine direct cause-and-effect. The response of the climate system to internal variability can be chaotic, meaning that predictions of day-to-day and even year-to-year variations in temperature and precipitation can be extremely sensitive to the initial conditions.

This source of uncertainty is particularly important over *shorter time frames.* As the *Climate Science Special Report* states, "over the next two decades, global temperature increase is projected to be between 0.5˚F and 1.3˚F (0.3˚–0.7˚C) (medium confidence). *This range is primarily due to uncertainties in natural sources of variability that affect short-term trends. In some regions, this means that the trend may not be distinguishable from natural variability* (high confidence)." (Hayhoe et al. 2017)

However, although the internal variability of the climate system is highly non-linear, *the response of the climate system to a given external forcing* (e.g., from changes in energy from the Sun, or from increasing heat-trapping gases due to human activities) *is predictable over longer timescales.* So even though it is not possible to predict the weather beyond two weeks, it is very possible to reliably simulate the long-term, large-scale response of the climate system to changes in energy from the Sun, volcanic eruptions, natural cycles, and increasing emissions of heat-trapping gases from human activities.

To address the first source of uncertainty, **natural variability**, simulations from 20 different climate models, each with a different pattern of natural variability based on different initial conditions, are used to provide a total of 365 days x 20 years x 20 models x 2 scenarios = 292,000 data points that can be used to calculate the statistics of climate and weather for each global mean temperature threshold.

Natural variability is an important source of uncertainty over shorter time scales. However, averaged over longer time scales of multiple decades, the contribution of natural variability to overall uncertainty decreases significantly for most variables, including those related to temperature and extreme precipitation.

Note 1: The WMO traditionally uses 30-year time periods to define climate normals; however, as climate changes these longer periods may smooth over changes that are occurring over shorter time scales. For that reason, this report uses 30 year periods to quantify historical climate normals, and 20 year periods for future projections corresponding to GMT thresholds.

Note 2: The number of data points decreases for global mean temperature thresholds of 3 and 4ºC as not every RCP4.5 simulation reaches those thresholds before 2080. Thus, for GMT thresholds of 3ºC and 4ºC, the total number of daily data points available to quantify the statistics of climate and weather for each period is typically between 146,000 and 292,000.

2. **Scientific and model uncertainty, including exactly how much the Earth will warm in response to human emissions and whether global climate models accurately represent important and relevant aspects of Earth's climate.**

Climate sensitivity is defined as the increase in global temperature when carbon dioxide doubles relative to pre-industrial times. Its value likely lies between 2 to 4.5ºC, but it is impossible to determine it exactly as it depends on the initial conditions of the planet and the rate, magnitude, and the type of forcing that is driving the change. As Kopp et al. (2017) indicates, the current initial conditions + forcing of the planet are unprecedented in at least the last 50 million years. This is the first source of scientific uncertainty in future projections.

The second source of uncertainty is *structural*. Are the climate models correctly representing every part of the Earth system? What if there are processes important to regional or global change, such as the radiative effects of black carbon, or possible changes in the circulation and carbon uptake of the Southern Ocean due to global warming, which are not yet included in the models?

The third source of uncertainty arises due to the fact that global climate models have limited resolution in time and space. Many processes, including cloud formation, precipitation, and the effects of dust on the atmosphere, occur at scales smaller than the model can resolved. Scientists use lab experiments, observations, and high-resolution modeling to try and understand how these processes appear in aggregate, at the scale of a global model. Using these empirical relationships, or parameterizations, introduces *parametric* uncertainty.

Although scientific uncertainty is usually distributed evenly relative to the mean or best guess value, it is important to note that the uncertainty in model structure and climate sensitivity is asymmetric. Certain aspects of the climate system and lower bounds to climate sensitivity tend to be better-understood and therefore smaller than higher bounds. As a result, by using mid-range values, global climate models are more at risk of under-estimating than over-estimating scientific uncertainty. As the *Climate Science Special Report* concludes, "while climate models incorporate important climate processes that can be well quantified, they do not include all of the processes that can contribute to feedbacks, compound extreme events, and abrupt and/or irreversible changes. For this reason, future changes outside the range projected by climate models cannot be ruled out (very high confidence). [This is referring to structural uncertainty.] Moreover, *the systematic tendency of climate models to underestimate temperature change during warm paleoclimates suggests that climate models are more likely to underestimate than to overestimate the amount of long-term future change* (medium confidence). [This is referring to climate sensitivity.]" (Hayhoe et al. 2017)

To address the second source of uncertainty, **scientific and model uncertainty**, the future projections used in this report are based on simulations from multiple global climate models and the range of projections resulting from these simulations are presented. Scientific or model uncertainty tends to be an important source of uncertainty in determining the magnitude and sometimes even the direction of projected changes in average precipitation.

3. Scenario or human uncertainty, as future climate change will occur largely in response to emissions from human activities that have not yet occurred.

Scenarios are intended to cover a wide range of plausible futures. Their purpose is to illustrate differences in the extent and severity of the global warming that would result from different choices, depending on factors such as:

- how human societies and economies evolve;
- how quickly technological advances occur;
- how new energy sources are developed; and
- how policies are enacted that affect heat-trapping gas emissions.

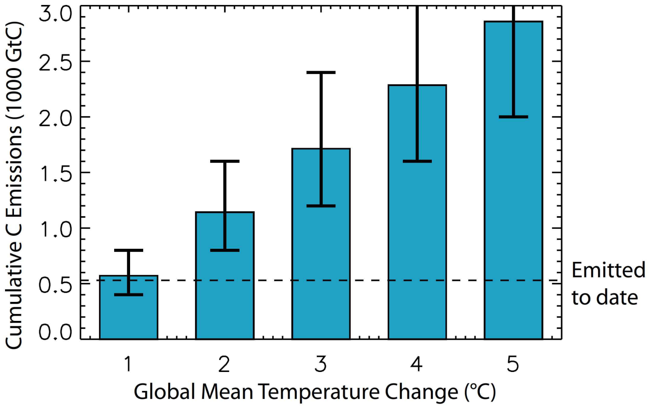


Figure 25. Allowable range of cumulative carbon emissions corresponding to global mean temperature targets from +1 to +5ºC. (Source: Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia. Source: National Research Council, 2012

Note that humans have already emitted approximately 560 gigatons of carbon (GtC) since the beginning of the Industrial Era and are currently producing about 10 GtC per year. Source: Climate Science Special Report, Kopp et al. 2017

Factors not under human control, such as the response of natural emissions of greenhouse gases to a warming Arctic, for example, or the response of clouds to a warming planet, are not explicitly included in these scenarios. Natural factors such as these contribute to the uncertainty in climate sensitivity described above.

The further into the future projections extend, the more important the role of scenario or human uncertainty becomes in quantifying the rate and magnitude of future change. The *Climate Science Special Report* concludes that, "beyond the next few decades, the magnitude of climate change depends primarily on cumulative emissions of greenhouse gases and aerosols and the sensitivity of the climate system to those emissions (high confidence)." (Hayhoe et al. 2017).

To address the third source of uncertainty, that of **human activities** and heat-trapping gas emissions, future projections in this report are based on two very different plausible pathways for the future, a higher and a lower scenario, which are then translated into global mean temperature thresholds. Each of these GMT thresholds is associated with a given amount of cumulative carbon emissions from human activities (Figure 25). In other words, to limit warming to a certain threshold, there is a specific amount of carbon emissions that can be produced, with an uncertainty range (indicated by the thin black line) due to the range of uncertainty in the ability of the ocean and biosphere to absorb the carbon produced by human activities, as well as the sensitivity of the climate system to human emissions.

While these bars do not have a specific time frame associated with them, the more carbon we humans produce, and the faster we produce it, the faster we will reach and/or surpass each global temperature threshold. On the other hand, if we are able to rapidly reduce net carbon emissions from human activities and eventually bring to zero, we will reach each threshold much more slowly, and it will still be possible to limit global temperature increase to 2ºC or less.

No attempt is made to ascertain or judge the likelihood of a given GMT threshold being reached or exceeded, or a given RCP scenario being followed. Results are presented equally for each scenario and GMT threshold. However, the *Climate Science Special Report* analyzed emissions from 2006 through 2016 and concluded that, currently, "the observed increase in global carbon emissions over the past 15–20 years has been consistent with higher scenarios (very high confidence)." (Hayhoe et al. 2017)

4. **Local uncertainty, which results from the many factors that interact to determine how the climate of one specific location, such as individual sites or weather stations in Alberta, will respond to global-scale change over the coming century.**

The *Climate Science Special Report* states that, "combining output from global climate models and dynamical and statistical downscaling models using advanced averaging, weighting, and pattern scaling approaches can result in more relevant and robust future projections. For some regions, sectors, and impacts, these techniques are increasing the ability of the scientific community to provide guidance on the use of climate projections for quantifying regional-scale changes and impacts (*medium to high confidence*)." (Hayhoe et al,. 2017) However, the application of a downscaling model adds an additional layer of uncertainty as well.

An empirical-statistical model, such as used in this report, develops a statistical relationship between GCM output and observations assuming that the conditions experienced in a given city or location tend to be part of a larger pattern of weather systems and air masses affecting the entire region. Statistical methods don't resolve the physical processes responsible for this relationship (although some of these relationships may be implied by the predictors chosen from the global model). For this reason, statistical methods are based on the fundamental assumption that the relationship between large-scale climate and local climate remains stationary over decades. If climate change alters local feedback processes that affect the relationship between local and large-scale climate, statistical methods will not be able to simulate these changes.

Statistical methods are limited by observations. It is only possible to develop projections for variables that have already been observed for a number of years, and for the scale at which they were observed. Statistical downscaling also assumes the observations provide a perfectly accurate representation of actual conditions. In reality, all kinds of factors, from observer error to long-term trends in the data due to equipment decay, can bias data. Therefore, a statistical model may end up incorporating observational error into future projections, if that error was unintentionally built into the statistical relationship between observed local variables and large-scale climate.

To address the fourth source of uncertainty, that of **local change**, global climate model simulations were statistically downscaled to individual long-term weather stations and a grid of long-term observations covering the province, to incorporate observed records of variability and change. The assumptions of stationarity that underlie the specific statistical method used in this report have been evaluated using the perfect model approach and shown to provide reliable information, compared to that of a fully dynamic global model, through 2100 under a higher RCP8.5 scenario for daily wet day precipitation out to the 99.9th percentile of the distribution and maximum and minimum temperature out to the 99.9th percentile *except in coastal areas* (which is not relevant to Alberta) (Dixon et al. 2016). They are furthermore only as precise as the observational data, which in the case of the gridded data is a resolution of approximately 10km. Over mountainous areas this is likely to preclude the resolution of significant spatial features. If higher-resolution datasets become available, this analysis could be re-done to increase the spatial resolution of the output.

Products

This analysis has produced a range of outputs and products that are appropriate for scientific analysis, future planning, and public outreach. They are described here in order, from most technical to least technical.

ONE. Daily High-Resolution Gridded and Station-Based Climate Projections - Data

1. Gridded statistically-downscaled maximum and minimum temperature and precipitation from 1950 to 2100, for 20 global climate models and 2 future scenarios. These gridded projections are daily, with the same spatial resolution as the NRCan Daily 10km Gridded Climate Dataset for Canada. They cover a rectangle that encompasses the entire province of Alberta and southeastern British Columbia.
2. Station-based statistically-downscaled maximum and minimum temperature and precipitation for 21 long-term weather stations from 1950 to 2100, for the same 20 global climate models and 2 future scenarios. These station-based projections are also daily, and are available for the long-term weather stations listed in Table 1.

Both gridded and station downcaled projections are available in netCDF format and are appropriate for use in scientific analysis by researchers and practitioners who are familiar with climate data and projections and capable of working with netCDF files using technical programs and software packages such as ArcGIS, IDL, MatLAB, NCL, R, or programming languages with netCDF libraries.

The archive consists of 120 gridded files (20 global climate models *x* 2 scenarios *x* 3 variables) and 2520 individual station files (21 stations *x* 20 global climate models *x* 2 scenarios *x* 3 variables). The archive of daily temperature and precipitation projections is available as a compressed file that, when expanded, requires ~600 GB of storage.

TWO. Annual High-Resolution Gridded and Station-Based Climate Indicators - Data

The primary daily temperature and precipitation outputs from Product One have been used to calculate a set of ***climate indicators*** from the observations and from each individual model simulations that are relevant to potential impacts on the province of Alberta. The climate indicators are listed in Tables 2A (temperature), 2B (precipitation), and 2C (hybrid variables).

Indicators were calculated using both observed and model-simulated data for the historical period, so that it is possible to compare observations with model simulations over the historical period. They were also calculated using model projections for the period 1950 to 2100, for both gridded and station-based data.

Annual gridded and station-based indicators, both observed and model-simulated, are available in netCDF format and are appropriate for use in scientific analysis by researchers and practitioners who are familiar with climate data and projections and capable of working with netCDF files using technical programs and software packages such as ArcGIS, IDL, MatLAB, NCL, R, or programming languages with netCDF libraries.

The archive consists of 36 gridded files (one for each of the climate indicators that contains annual values for observations and each of the 20 global climate models and 2 scenarios, as well as a multi-model mean and range) and 36 station files (one for each of the 36 climate indicators that contains annual values for each of the 21 weather stations, observations and simulations corresponding to each of the 20 global climate models and 2 scenarios, as well as a multi-model mean and range).

The archive of annual climate indicators is available as a compressed file that, when expanded, requires ~25 GB of storage. Each file covers the period 1950 to 2100. Since observations are only available for the historical period, their values are set to "NA" for the future.

THREE. Multi-Model Averages of Gridded Climate Indicators for Global Mean Temperature Thresholds – Data and Maps

The gridded ***climate indicators*** calculated from the observations and from each individual model simulations in Product Two have been averaged to create a historical average for 1980-2009 (observations and multi-model average) and future projections (multi-model average only) corresponding to the 20-year period when global mean temperature reaches +1, +1.5, +2,+3 and +4°C relative to pre-industrial levels.

The data is in netCDF format and is available in a compressed file that, when expanded, requires less than 1 GB of storage. Each file contains 1980-2009 and five future global mean temperature thresholds. Files can be accessed using the technical programs and software packages such as ArcGIS, IDL, MatLAB, NCL, R, or programming languages with netCDF libraries described above. However, these files can also be accessed and plotted using a user-friendly point-and-click software program called Panoply, available free of charge for PC, Mac, and Linux from NASA. To run Panoply, it may be necessary to update your Java Runtime Environment. You can do that here (click on "Free Java Download"). Further instructions on how to use Panoply are provided in Table 3.

A Brief Guide to Using Panoply to Make Maps

1. Open Panoply and from the "Open..." popup dialog box, choose one of the netCDF files you downloaded. It will be in the directory where you unzipped the archive. If you want to plot the change per degree of global warming (e.g. how much will winter temperature change when the world warms by X°C), open one of the files called "alberta.**change**.[name of climate indicator].by.global.mean.temperature.increments.nc". If you want to plot the absolute value of the variable per degree of global warming (e.g. the actual winter temperature when the world warms by X°C), open one of the files called "alberta.**abs.value**.[name of climate indicator].by.global.mean.temperature.increments.nc".

2. Once it opens, you will see the variables list in the left pane and the file header in the right pane. There will be four variables: latitude, longitude, global mean temperature, and the variable you want to plot, which will be the name of the climate indicator.

3. In the left pane, click on the climate indicator. Now, the right pane now shows the variable attributes. With the climate indicator highlighted, click on "Create Plot" icon in the upper left. The "Create Plot" popup dialog box gives three options. To make a map, choose the default option "Create georeferenced Longitude-Latitude plot" and then click "Create".

4. A plot should come up, covering the entire planet, with only the grid cells with values (those over Alberta) colored in. Before modifying the map, note that at very top of plotting window, you can see the variable name. At the bottom of the plot there is a color scale bar. If you click on the "Array 1" tab in upper left, you will see the actual values being plotted.

5. Click on the "Map" tab below the plot and make the following changes. One, change "Projection" to "Equirectangular (Regional)". Two, change the "Center on:" to -115E for longitude and 54.5N for latitude to centre the plot over Alberta. Three, change the "Height" to 11.2 degrees – but now the plot is a bit stretched. Lastly, to fix this, click on the "Fix Proportions" button. This will cause the plot to zoom in on Alberta. Note that you can zoom the map in even further, if you'd like to plot a smaller region. Use the "Height" and "Width" options to zoom and the "Center on" options to re-center.

6. Next, click on the "Scale" tab. Here, you can change the colour table, tick format, and scale bar caption, among other things. If the scale bar looks strange – the bottom number is too low or the top number is too high – enter whatever scale

range you want in the Min and Max windows at the top left, or click the "Fit to Data" button. You can also choose a colour scheme that you like here, too. There are about a hundred to choose from.

7. Now open the "Array" tab. Here, you can choose which time step or global mean temperature threshold to plot. Choose different time steps and see how the numbers change.

8. Explore the "Overlay" tab, where you can choose from various overlays for your plot, and then the "Contours" tab, where you can add contours to your plot. These variables don't need Vectors, so you can just ignore that tab. Click on the "Labels" tab to change the labels on the plot if you want to.

9. Once you have the plot looking exactly how you like it, click on the "Plot" menu item at the top of the page, then select "Save Plot Settings to Preferences". Now, every new plot you make will use these settings as a default – although of course you can change them any time you want.

10. Last step – save it. Click on the "File" menu item at the top of the page, and select "Save Image As". Note the different file formats available, and choose the one that makes the most sense for your use. Rename the file as necessary, making sure to include the time frame in the title, then click "Save". If you want to plot a different time period or global mean temperature threshold, go back to the Array tab and select it, then save under a different name.

Table 3. Instructions for making maps using the Panoply software program.

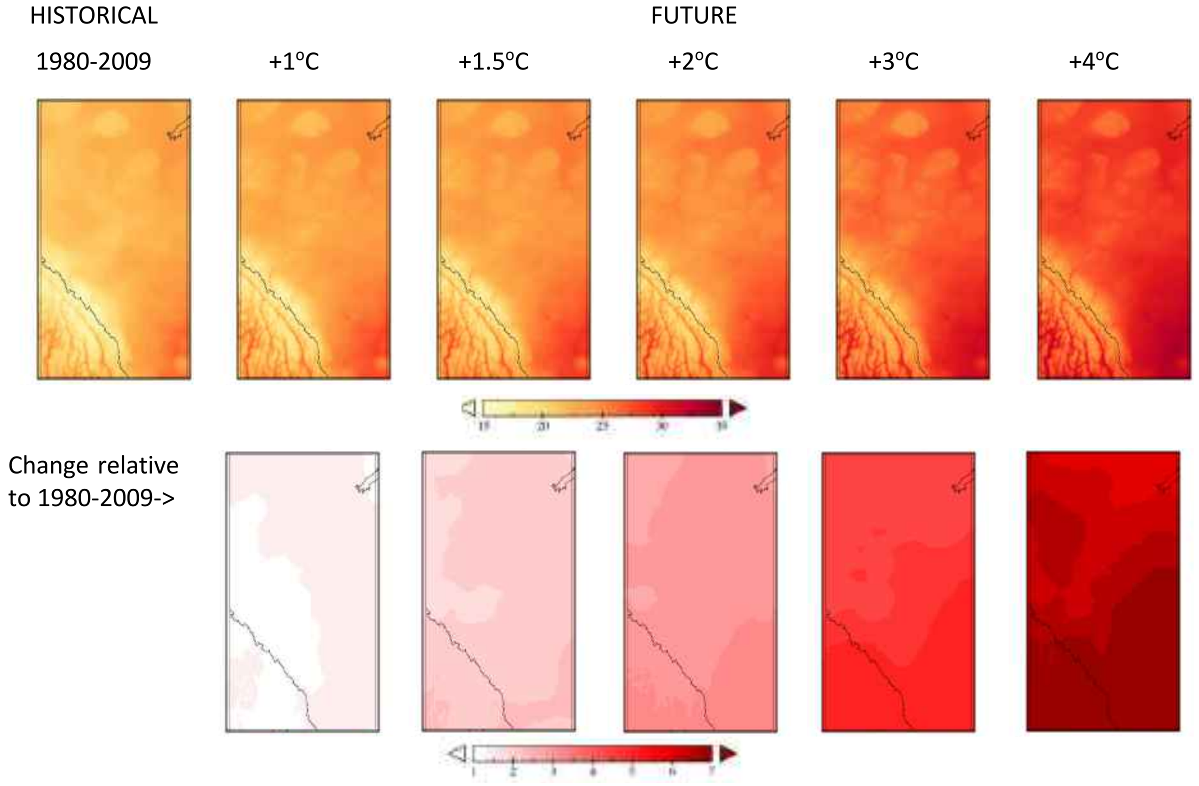


Figure 26. Historical 1980-2009 (left), projected future temperature (top), and change in temperature (bottom) of the warmest day of the year, in degrees C. Values are for observations for the historical period and a multi-model average for the future periods. Each panel for each climate indicator is available as a separate PNG image file, and a figure for each climate indicator is available in Appendix A.

Each climate indicator has been plotted, showing observed values for 1980-2009, model-simulated values for each future global mean temperature threshold, and change values relative to 1980-2009 for each future period as well. These maps are available as individual PDF images in an archive that can be downloaded. The complete set of maps for the province of Alberta is also available in powerpoint format as *Appendix A: Climate Indicator Maps for Alberta*. Each slide in the powerpoint file shows projected changes for a different climate indicator, plotted as shown in Figure 26.

FOUR. Multi-Model Averages of Station-Based Climate Indicators for Global Mean Temperature Thresholds – Data and Bar Charts

The station-based ***climate indicators*** calculated from the observations for each of the 21 long-term weather stations listed in Table 1, and from each individual model simulation in Product Two, have been averaged to create a historical average for 1980-2009 (observations and multi-model average) and future projections (multi-model average and the range, defined by the standard deviation of the multi-model ensemble) corresponding to the 20-year period when global mean temperature reaches +1, +1.5, +2,+3 and +4°C relative to pre-industrial levels. These values have been archived in a single comma-separated file for each weather station that can be opened in Excel. The format of a sample file is shown in Table 4.

	VAR1 -1SD	VAR1 MEAN	VAR1 +1SD	VAR2 -1SD	VAR2 MEAN	VAR2 +1SD
1980-2009	NA	-10.43	NA	NA	14.82	NA
+1C	0.74	1.44	2.14	0.67	1.15	1.63
+1.5C	0.96	2.00	3.04	1.37	1.99	2.61
+2C	1.90	3.05	4.19	2.35	2.96	3.57
+3C	3.51	4.72	5.93	3.56	4.58	5.60
+4C	4.99	6.32	7.66	5.27	6.54	7.80

Table 4. Sample output file format for station-based projections of changes per degree of global mean temperature. The first column contains the date/global mean temperature period. Subsequent columns are grouped in threes, where the first column gives the low end of the multi-model range, the second column gives the mean of the multi-model range, and the third column gives the high end of the multi-model range for the first climate indicator (VAR1). The next three columns give the values for the second climate indicator (VAR2), and so on. In the actual files, the indicators are labelled by name; they are condensed here for clarity.

The data has already been inserted into an Excel file for each station, and 36 bar charts have been created for each station – one for each of the 36 climate indicators listed in Tables 2A, B and C. The complete set of bar charts for individual weather stations is available as a zipped archive in excel format in *Appendix B: Climate Indicator Bar Charts for Weather Stations*.

Six sample plots are shown in Figure 27. Each plot is labelled with the city and the variable (e.g. "Calgary Winter (Sep-Apr) Precipitation") and gives the 1980-2009 value for that variable (e.g. "1980-2009 = 142 mm"). The plots contain 5 bars, one for each global mean temperature threshold from +1 to +4°C, showing the projected change relative to the 1980-2009 value. The coloured bar indicates the multi-model mean, while the thin black lines or "whiskers" indicate the multi-model range, as defined by one standard deviation above and below the mean.

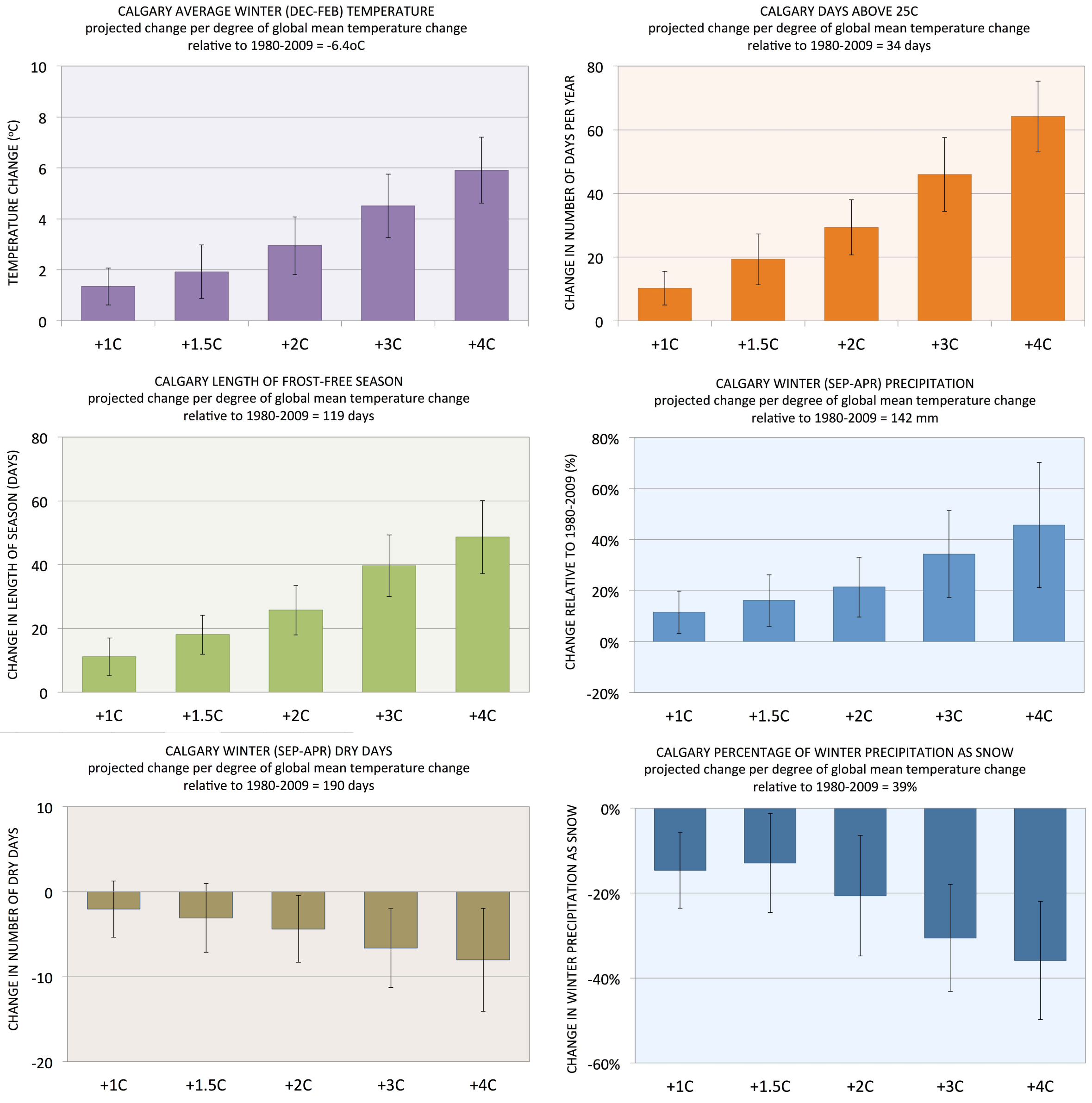


Figure 27. Projected changes in six different climate indicators for the Calgary weather station, for the variables listed at the top of each bar chart. Values shown are the projected multi-model mean (bar) and multi-model range (thin black line) for a given global mean temperature threshold, compared to the historical value shown at the top of each bar chart. 36 figures, one for each of the climate indicators listed in Tables 2A, B and C, are available in an Excel file for each of the 21 long-term weather stations listed in Table 1.

Bars above zero (Figure 27, top and middle lines) indicate that climate indicator is increasing as the world warms, while bars below zero (Figure 27, bottom line) indicate that climate indicator is decreasing as the world warms. For some variables, such as growing season precipitation in some locations, the multi-model range indicated by the thin black line may cross zero, particular for smaller amounts of global mean temperature change; this indicates that the models are uncertain regarding the direction of change, with some predicting an increase and others predicting a decrease.

The bar charts are colour-coded, with orange refering to warm temperature (light orange for mean temperature and darker orange for extremes), purple to cold temperatures (light purple for mean and darker purple for extremes), green to degree-day or growing season variables, including the frost-free season, blue to precipitation (light blue for mean and darker blue for extremes), and brown for dry days.

FIVE. Multi-Model Mean and Ranges of Station-Based Climate Indicators for the Higher and Lower Future Scenarios – Data and Time Series Plots

The station-based ***climate indicators*** calculated from the observations for each of the 21 long-term weather stations listed in Table 1, and from each individual model simulation in Product Two, have also been summarized as annual values from 1950-2100 for the higher and lower scenarios described in the Data, Models, and Methods section, as well as for the length of the observed historical record. These values have been archived in a single comma-separated file for each weather station that can be opened in Excel. The format of a sample file is shown in Table 5.

Years	OBS	RCP4.5 mean	RCP8.5 mean	RCP4.5 min	RCP4.5 max	RCP8.5 max
1950	-13.83	-10.45	-10.44	-16.71	-5.74	-5.72
1951	-14.09	-10.81	-10.79	-16.79	-5.87	-5.88
1952	-9.48	-11.57	-11.54	-16.49	-5.77	-5.73
…	…	…	…	…	…	…
2099	NA	-6.97	-4.63	-13.92	-1.33	1.17
2100	NA	-7.44	-3.33	-13.90	-1.97	0.66

Table 5. Sample output file format for station-based projections of changes by year. The first column contains the year. Subsequent columns are grouped in sixes, one set of six for each climate indicator listed in Table 2. The first column gives the observed value. Values are set to NA if observations are not available for that year. The second and third columns give the multi-model mean value for the lower scenario (RCP4.5) and the higher scenario (RCP8.5) for that year. The fourth and fifth columns give the multi-model maximum and minimum value, defined as the extremes of the multi-model ensemble for that year smoothed by a 5-year running mean, for the lower scenario. The final column gives the multi-model maximum value for the higher scenario, since only the maximum is used to make the time series plots. There is one output file for each of the 21 weather stations. In the actual files, the indicators' name also appears in the header of each column; they have been removed here for clarity.

The data has already been inserted into an Excel file for each station, and 36 time series charts from 1950 to 2100 have been created for each station – one for each of the 36 climate indicators listed in Tables 2A, B and C. The complete set of time series for individual weather stations is available as a zipped archive in excel format in *Appendix C: Climate Indicator Time Series for Weather Stations*.

Six sample plots are shown in Figure 28. Each plot is labelled with the city, the variable, and the units (e.g. "Edmonton Winter (Dec-Feb) Temperature (degC)"). Each plot contains three lines: a gray line with dots indicating observations for that location; a darker line indicating the multi-model mean for the higher scenario; and a lighter line indicating the multi-model mean for the lower scenario. The length of the observed data will vary from one station to the next, based on the years available in the historical record. The multi-model averages extend from 1950 to 2100. Each plot also contains two shaded areas: a lighter area indicating the multi-model range for the lower scenario, and a darker area indicating the top (for a variable that is increasing over time) or bottom (for a variable that is decreasing) end of the range for the higher scenario.

The time series plots are colour-coded, with orange refering to warm temperatures (e.g. average summer temperature or warmest day of the year or degree-days), purple to cold temperatures (e.g. average winter temperature or days per year below -30°C), blue to precipitation (e.g. number of wet days per year), and brown for dry days.

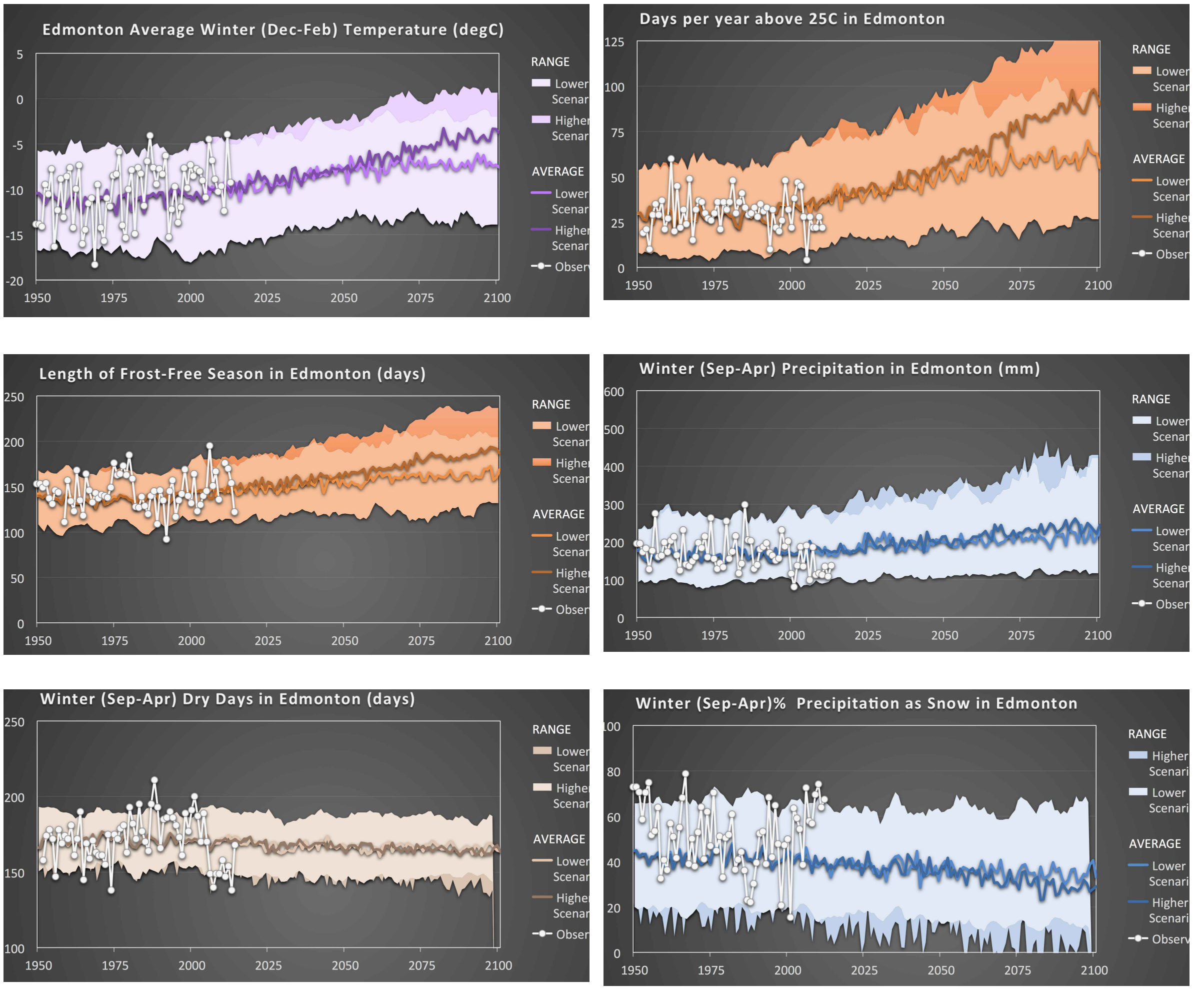


Figure 28. Projected changes in six different climate indicators for the Edmonton weather station, for the variables listed at the top of each chart. Values shown are the projected multi-model mean for the higher (darker line) and lower (lighter line) future scenarios as well as the observations (white line and dots). The multi-model range for the higher (dark) and lower (light) future scenarios is indicated by the shaded areas. 36 figures, one for each of the climate indicators listed in Tables 2A, B and C, are available in an Excel file for each of the 21 long-term weather stations listed in Table 1.

Appendices

Appendix A: Climate Indicator Maps for Alberta

This appendix consists of one Powerpoint file that contains complete set of maps for the province of Alberta.

There are 11 maps for each climate indicator: one showing the observed values for 1980-2009, five showing the future values of that indicator for each global mean temperature threshold from +1 to +4°C, and five showing the *change* relative to 1980-2009 for each global mean temperature threshold from +1 to +4°C.

For more information on the individual maps, see Products Section Three above.

Appendix B: Climate Indicator Bar Charts for Weather Stations

This appendix consists of 21 Excel files, one for each of the weather stations listed in Table 1. Each Excel files contains 36 bar charts, one for each climate indicator listed in Table 2. Each bar chart shows the observed value for 1980-2009, and projected *change* relative to 1980-2009 for each global mean temperature threshold from +1 to +4°C.

For more information on the bar charts, see Products Section Four above.

Appendix C: Climate Indicator Time Series for Weather Stations

This appendix consists of 21 Excel files, one for each of the weather stations listed in Table 1. Each Excel files contains 36 time series plots, one for each climate indicator listed in Table 2. Each time series shows the observed values for the duration of the historical record, and projected *change* corresponding to the higher and lower future scenarios, from 1950 to 2100.

For more information on the time series plots, see Products Section Five above.

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