Climate Projections for Calgary

January 2022

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Overview

1.1 Purpose

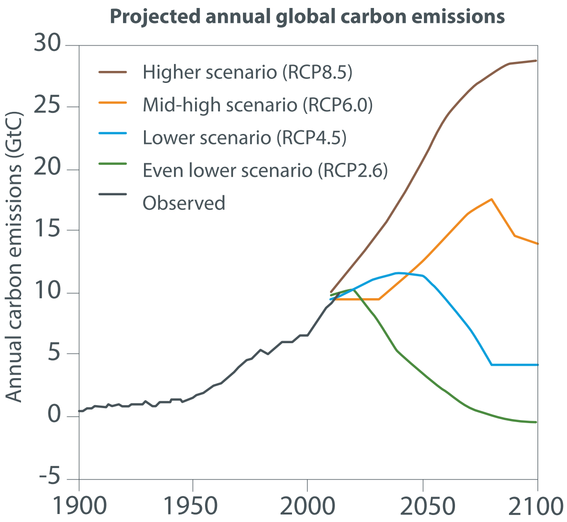
Climate change is a risk multiplier with broad reaching impacts on environmental, social and economic systems. The City of Calgary has a responsibility to be resilient by responding, preparing and adapting to the impacts of climate change. In order to prepare for climate change we need to understand what those changes will mean for our local region. This document details key climate indicators that describe how Calgary is likely to experience climate change. Many of the effects of climate change are already being experienced, both locally, in western Canada and around the world. From record-breaking heat, to extreme wildfires and smoky conditions, to catastrophic flooding, we are witnessing the impacts of climate change.

Climate impacts are included throughout this document to provide context for the selection of climate indices, as well as to assist with the interpretation of climate projections. Impacts are included as examples only, and not as a full description of the types of climate risk that we may experience in the coming years.

1.2 What is climate change?

Greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4), and ozone (O_3) are naturally occurring and necessary components of the earth's atmosphere. GHGs accumulate in the atmosphere trapping solar and surface radiation, resulting in the "greenhouse effect' that creates Earth's livable climate. As changes in climate proceed over long timeframes, so do changes in the frequency, duration, timing and extent of climate events and extreme weather.

While GHGs are natural elements, the concentration of GHGs in the atmosphere has significantly increased due to a dramatic increase of anthropogenic emissions since the end of the 19th century. Human activities that release GHG emissions are the main cause of observed warming since the mid-20th century. Increasing warming and erratic climate patterns will continue due to the high concentration of GHG emissions in the atmosphere, and will be amplified with further additions of GHG emissions, as shown in **Figure 1** (Wuebbles, 2017).



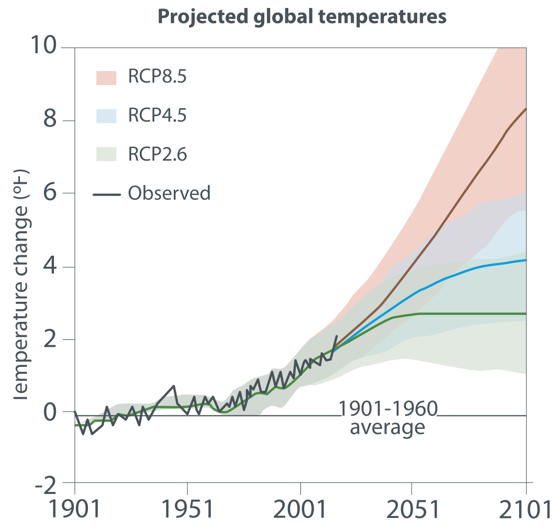


Figure 1. Global GHG emission trends
2017 Climate Science Special Report

1.3 How is the climate changing?

The global annual average temperature has increased by about 1°C since 1880, with the greatest warming occurring since the 1970s (IPCC, 2018). On average, warming in Canada is about double the magnitude of global warming. Canada's mean annual temperature has risen about 1.7ºC (range 1.1ºC –2.3ºC) over the 1948–2016 period. Temperatures have increased more in northern Canada than in southern Canada, and more in winter than in summer. Alberta has warmed by approximately 1.4°C since 1880. Globally, warming of 4°C above pre-industrial levels (1880) is expected by 2100 unless there are dramatic and sustained reductions in GHG emissions (Bush, E. and Lemmen, D.S., editors, 2019).

There are a number of hazards that accompany an increase in temperature, including shifts and changes to precipitation, an increase in the frequency and severity of storm events, and increasing severity of wildfires, smoke, and poor air quality. A summary of the climate hazards, projections and feedback loops that are directly or indirectly influenced by increasing air temperatures is provided in **Figure 3**. The City of Calgary is experiencing an increase in mean, as well as an increase in the variance associated with our climate, as shown in **Figure 2**.

1.3.1 Future climate scenarios

Future climate projections are based on the output of climate models, which use mathematical equations and the laws of physics to characterize how energy and matter interact in different parts of the ocean, atmosphere, and land. Climate projections are often shown as either a range or a median value based on outputs from an ensemble of global climate models (GCMs). For this report, the 10th, 50th and 90th percentiles of the ensemble models will be presented as the low, median and high range respectively.

1.3.2 Climate change reporting time frames

Climatological practice uses 30-year averaging periods when reporting climate statistics. The rate of change of climate parameters (e.g. precipitation, air temperature, wind, etc.) due to climate change may not be linear; therefore climate change is often assessed at the mid-term and long-term horizons. For this analysis, the 2050s indicate the average of the 2041-2070 period and the 2080s are the average of the 2071-2100 period. A baseline period of 1981-2010 is used in these analyses where possible as it provides a 30-year record of current climate to compare with modelled data.

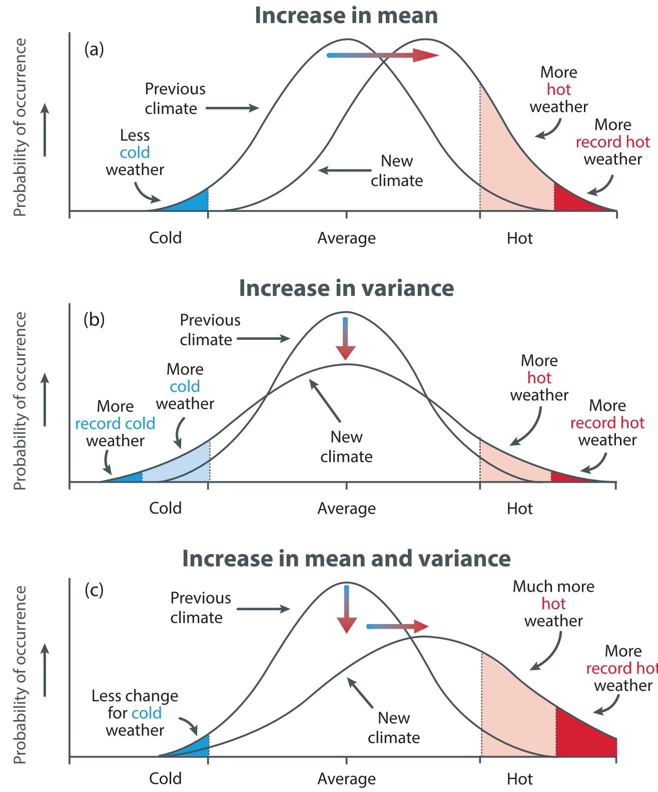


Figure 2. Increase in mean and variance of temperature with climate change

1.3.3 Climate modelling and representative concentration pathways

Global climate models (GCMs) run on a large spatial scale (>100 km grid squares) to simulate atmospheric, oceanic and other processes and provide output for daily timescales. GCMs produce climate projections of possible future climate according to different GHG emission scenarios, known as Representative Concentration Pathways (RCP).

The four RCP scenarios are described below and shown in **Figure 1**:

- **RCP2.6** is a low emissions scenario, which assumes that strict controls are placed on GHG emissions so that they peak in the 2020s. Global warming mean and likely range (1.0°C, 0.3 to 1.7° C) (IPCC, 2014).
- **RCP4.5** and **RCP6.0** scenarios are stabilization without overshoot scenarios where a range of strategies for GHG emissions are implemented and total radiative forcing stabilizes before 2100. GHG emissions peak in the 2040s for the RCP4.5 scenario and in the 2080s for the RCP6.0 scenario. (1.8°C, 1.1 to 2.6°C) and (2.2°C, 1.4 to 3.1°C) (IPCC, 2014).
- **RCP8.5** is a high emissions scenario with few or no controls placed on GHG emissions. Total radiative forcing increases over the entire 21st century. (3.7°C, 2.6 to 4.8°C) (IPCC, 2014).

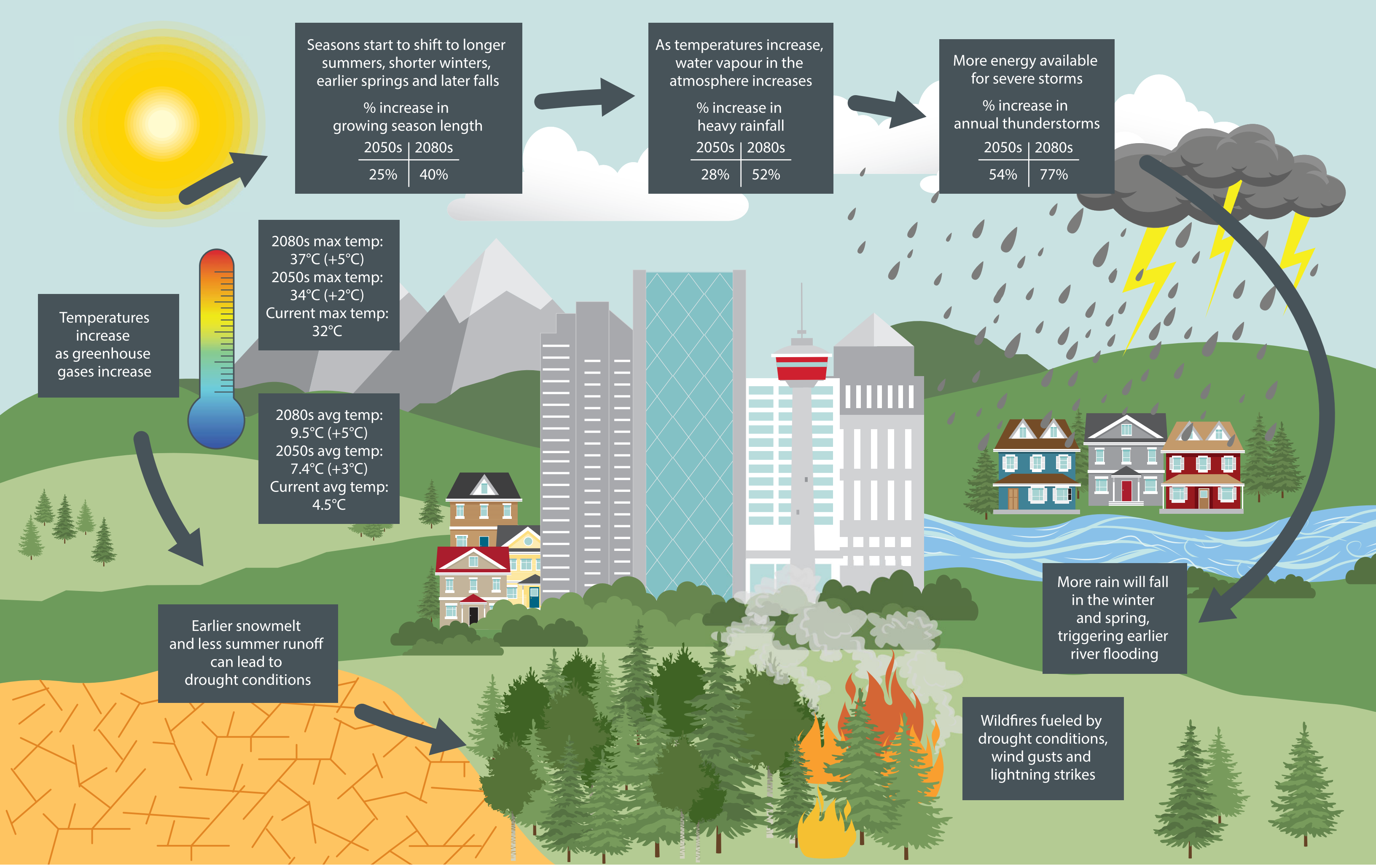


Figure 3. Projected climate changes for Calgary

The RCP8.5 scenario was chosen as the focus of this document as it closely matches current cumulative emissions and trend forecasts into the 2030s. Additionally, research finds that there is a 35% chance that emissions will exceed those assumed by RCP8.5 by the end of the century, particularly as land use change related emissions and positive climate feedback mechanisms are considered (Christensen, 2018). Many experts continue to reiterate that current atmospheric carbon dioxide concentrations match closely to the RCP8.5 scenario, and that this remains the best choice for risk assessment through the mid-century (PCIC, 2021); therefore, this review has taken a risk informed approach by using the RCP8.5 scenario so that the full breadth of changes, and the risks that they pose, can be considered.

1.4 What does climate change mean for Calgary?

Calgary is not immune from the forces of a changing environment. Changes in longer-range regional climatic trends and more severe and frequent extreme weather events are happening now and will increase due to climate change. Adapting to climate change risks requires targeted interventions and strategies to make infrastructure, services, the environment and the economy more resilient.

As such, The City and the Calgary Airport Authority (The Authority) collaboratively developed a regionally specific set of climate data suitable for a range of planning, design and engineering applications including hydrologic and hydraulic analysis and climate risk assessments; The Climate Data for Hydrologic and Hydraulic Analysis Project (GHD, 2020). The analysis was completed by climatological and water resource specialists at the engineering consultancy GHD, with extensive peer review provided by the Pacific Climate Impacts Consortium (PCIC) and Dr. Donald Burn, PhD, Civil Engineering, University of Waterloo. The methodology, results and analysis were reviewed and critiqued through every phase of the project by the peer reviewers, as well as by subject matter experts at The City and The Authority. Climate projections have been summarized here by The City of Calgary.

Using climate projections to predict changes in temperature, precipitation, wind and extreme events provides the first phase of information necessary to support climate adaptation. Projections can then be used in targeted climate risk assessments across multiple sectors and scales. Climate projections can help decision makers, asset owners, and the public to understand impacts on the people in our community, built infrastructure, the natural environment and the economy. This report builds on earlier climate change vulnerability work completed in 2017 for The City of Calgary (WaterSMART, 2017) and is more comprehensive in its extent. Through producing this report on regional climate projections, The City of Calgary intends to provide current and accurate climate information publicly. Stakeholders are encouraged to use the results of this study to complete their own climate risk assessments, support adaptation planning and improve our climate resilience.

1.4.1 Historical period data

Historical weather data was sourced from the Environment and Climate Change Canada (ECCC) station at the Calgary International Airport, with quality assurance/quality control conducted by The City of Calgary for the period 1960-2014. The historical data period refers to the 1960-2014 Calgary Airport data, and the baseline to 1981-2010 Calgary Airport data.

1.4.2 Technical methodology

Downscaling of climate models

PCIC downscaled the daily air temperature and precipitation data using statistical downscaling methodology (e.g. the Bias Corrected Constructed Analog with Quantile mapping, version 2 [BCCAQv2]) to a grid of approximately 6 by 10 km. The PCIC data include 27 GCMs, and three GCMs have two runs each, for a total of 30 data sets at this grid size. The grid size was selected based on the availability of gridded historical climate observations.

The wind, solar radiation, and relative humidity data were dynamically downscaled with Regional Climate Models (RCMs) to a grid that is approximately 15 by 25 km through the North America Coordinate Regional Downscaling Experiment (NA-CORDEX). The grid size was selected based on the availability and resolution of RCMs. Data for up to 16 GCM pairs is available through this data source. The available high-resolution datasets described are currently the highest-resolution data available and provide a clear climate change signal for Calgary within the level of certainty available in current climate modelling. Climate models use approximations to describe the complexity of the climate system while not being able to precisely define phenomena at a scale smaller than their grid cell.

The GCM output data was compared to historical observations and bias-corrected to the ECCC Calgary airport weather station. Bias-correction methods assume that GCMs may not be able to simulate the absolute values of a climate variable but that they are able to model the relative change in a climate variable with reasonable accuracy. The bias-correction process accounts for differences in how the GCMs and GCM-RCMs model local climate. The Delta-Mapping with Percentiles method of bias-correction used was to correct the historical data (1960-2014) based on the differences between the GCM baseline (1981-2010). The bias correction methods quantify the change (e.g. the "delta") between the GCM future time period and the GCM baseline period, and then apply the delta to the observed historical data.

Calgary's climate projections are determined using both global and regional models as presented in **Table 1**.

Table 1. Climate projection models

Climate parameter	GCM	RCM
Daily temperature and precipitation	X	
Daily snow, wind, solar radiation		X
Hourly precipitation and wind		X
Combine climate parameters	X	X

1.4.3 Quality assurance/quality control

The precipitation and air temperature data from the Calgary International Airport were subjected to quality assurance/quality control (QA/QC) by the City of Calgary. The reviewed data are available for the period 1960-2014 at an hourly and daily time step. The QA/QC process involved corrections to account for daylight savings time, overlapping data records (e.g. when the station equipment was being upgraded and two climate stations were active at the same time), and the interpolation of missing values. Statistical tests were used to determine if the historical air temperature data was homogeneous and if there were outliers, change points, and/or trends present in the data.

2

Calgary's future climate

This section describes various climate hazards relevant to Calgary and how they are projected to change in the future (**Table 2**). The certainty of projections for certain parameters (for example, temperature) is greater than that for other parameters (for example, precipitation).

There are certain climate hazards that are not well projected by climate models, including thunderstorms, tornadoes, lightning, hail, freezing rain, heavy snow fall, extreme winds, drought, wildfire and evapotranspiration. These hazards are based on complex and spatially defined weather patterns and are not as closely linked to current climate modelling methodologies. For these hazards, a literature review and a historical trend analysis was conducted, to better understand how the factors that affect these phenomena are changing and how this may impact their frequency under future climate conditions.

Table 2. Summary of climate hazard trends for Calgary

Climate related hazard	Project climate hazard trend	References
Extreme heat	⇧	(GHD, 2020)
Higher average temperatures	⇧	(GHD, 2020)
Wildfire	⇧	(Flannigan, 2016), (Wotton, 2017), (Wang, 2017), (WSP, 2021)
Drought	Likely ⇧	(GHD, 2020)
Short duration high intensity (SDHI) storms	⇧	(GHD, 2020), (Trenberth, 2011)
Severe storms (i.e. hail, tornadoes, high winds)	Likely ⇧	(GHD, 2020), (Etkin, 2018), (Brimelow, 2017), (Romps, D. M., Seeley, J. T., Vollaro, D., & Molinari, J., 2014), (GHD, 2020), (ECCC, 2021)
High winds	Likely stable	(GHD, 2020), (Zeng, 2019), (Vautard, 2010) (Greene, 2010)
River flooding	Likely ⇧	(Rajulapati, Tesemma, Shook, Paplexiou, & Pomeroy , 2020), (Tesemma, et. al., 2020), (Pomeroy, 2015)
Heavy snowfall	⇩	(GHD, 2020), (DeBeer, 2016)

2.1 Climate indices

The City investigated a number of climate parameters and their respective indices for this report. Climate parameters are a model output (for example, temperature), while indices are metrics used to measure the trend in parameters (for example, number of hot days). A full list of indices is provided in **Table 3**. There are several types of indices which were employed in this report, including, averages, maximums, minimums, and thresholds.

Table 3. Climate parameters and indices for Calgary

	Type of index	Index name	Unit	Section	Figures and tables
TEMPERATURE	Averages, timings and seasons	Annual average daily temperature	°C	2.2.1	Table 4
		Monthly average daily temperature	°C	2.2.1	Figure 4
	Maxima and minima	Annual average coldest daily air temperature	°C	2.2.2	Table 5
		Average coldest daily air temperature by month	°C	2.2.2	Figure 5
		Average warmest daily air temperature by month	°C	2.2.2	Figure 6
	Threshold temperatures	Cold days: number of daily maximum air temperatures below threshold (0°c, -10°c, -20°c, -30°c)	# days/year	2.2.3	Table 6
		Cold nights: number of daily minimum air temperatures below threshold (0°c, -10°c, -25°c)	# days/year	2.2.3	Table 7
		Average number of cold spells (max temp < -10°c for 5 days)	# spells/year	2.2.3	Table 8
		Number of daily maximum air temperatures above threshold (0°c, 10°c, 20°c, 30°c)	# days/year	2.2.3	Table 9
		Number of tropical nights above threshold (20°c)	# days/year	2.2.3	Table 10
		Number of hot days (daily maximum air temperature ≥ 29°c)	# days/year	2.2.3	Table 11
		Number of heat waves (daily maximum air temperature ≥ 29°c and daily minimum air temperature ≥ 14°c for two or more days)	# heat waves/ year	2.2.3	Table 12
		Average length of heatwaves	days	2.2.3	Table 13
	Seasonal	Growing season length	# days/year	2.2.4	Figure 7
		Frost free season length	# days/year	2.2.4	Table 14
		Timing of first fall frost	date	2.2.4	Table 15
		Timing of last spring frost	date	2.2.4	Table 16
		Average number of freeze-thaw cycles	# of cycles/winter	2.2.4	Table 17
	Design	Heating degree days (average annual sum of the number of degrees that each day's mean air temperature is below 18°c)	# degrees/year	2.5.4	Figure 18 Table 29
		Above freezing degree days (average annual sum of the number of degrees that each day's mean air temperature is above 0°c)	# degrees/year	2.5.4	Figure 19 Table 30
		Winter melting degree days (average winter sum of the number of degrees that each day's mean air temperature is above 0°c)	# degrees/winter	2.5.4	Figure 20 Table 31
		Freezing degree days (average winter sum of the number of degrees that each day's mean air temperature is less than 0°c)	# degrees/year	2.5.4	Figure 21 Table 32
		January 2.5% Design temperature approximation	°C	2.5.4	Table 33
		Cooling degree days (average annual sum of the number of degrees that each day's mean air temperature is above 18°c)	# degrees/year	2.5.4	Table 34
		July 2.5% Design temperature approximation	°C	2.5.4	Table 35

	Type of index	Index name	Unit	Section	Figures and tables
PRECIPITATION	Totals	Average annual precipitation totals	mm	2.3.2	Table 18
		Average monthly precipitation totals	mm	2.3.2	Figure 8
		Monthly and total annual precipitation for the historical period, modified wet, average and dry typical years	mm	2.3.3	Table 22
	Return periods	1 In 100 year, 1-day precipitation	mm	2.3.2	Table 20, Table 21
		1 In 2, 5, 20, 50, 200 year 1-day precipitation	mm	2.3.2	Table 20, Table 21
		1 In 100, 200 year (2-day, 5-day) precipitation	mm	2.3.2	Table 20, Table 21
		1 In 50 hourly precipitation	mm	2.3.2	Table 20, Table 21
		1 In 2, 5, 10, 20, 50 year (1, 3, 6, 12-hourly) precipitation	mm	2.3.2	Table 20, Table 21
	Drought	Average number of dry days (daily average precipitation less than 1 mm)	# days/year	2.3.4	Table 23
		Average number of dry spells (daily average precipitation less than 1 mm for a minimum of 14 days)	# dry spells/year	2.3.4	Table 23
		Longest dry spell	days	2.3.4	Table 23
		Return period of 2-week drought	years	2.3.4	Table 23
	Heavy snowfall	Average annual snowfall totals	cm	2.3.6	Table 24
		Average monthly snowfall totals	cm	2.3.6	Figure 11
EXTREME EVENTS	Severe storms	Average annual convective events/conditions	#days/year	2.3.7	Figure 12
		Average monthly convective events/conditions	#days/month	2.3.7	Table 25
	High winds	Average number of days with maximum wind gusts ≥ 90 km/hr	# days/year	2.4	Figure 14 Table 26
OTHER	Solar radiation	Average annual solar radiation	W/m^2	2.5.1	Table 27
		Average daily solar radiation per month	W/m^2	2.5.1	Figure 15
	Evapotranspiration	Average annual total evapotranspiration	mm/year	2.5.2	Table 28
		Average monthly total evapotranspiration	mm	2.5.2	Figure 16

2.2 Temperature projections

2.2.1 Average temperatures

The projected monthly average daily temperatures for the historical, 2050s and 2080s periods (along with the P10 and P90 ranges, as noted by the error bars) are presented in **Figure 4**.

The annual average air temperature for the same time periods are summarized in **Table 4**. Average air temperatures show an increasing trend across the future time periods.

Table 4. Annual average daily air temperature during historical, 2050s and 2080s time periods

		2050s			2080s		
Time period	**Historical**	**Low[1]**	**Median[1]**	**High[1]**	**Low[1]**	**Median[1]**	**High[1]**
Annual	4.3	6.3	7.4	8.7	8.2	9.5	11.1

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

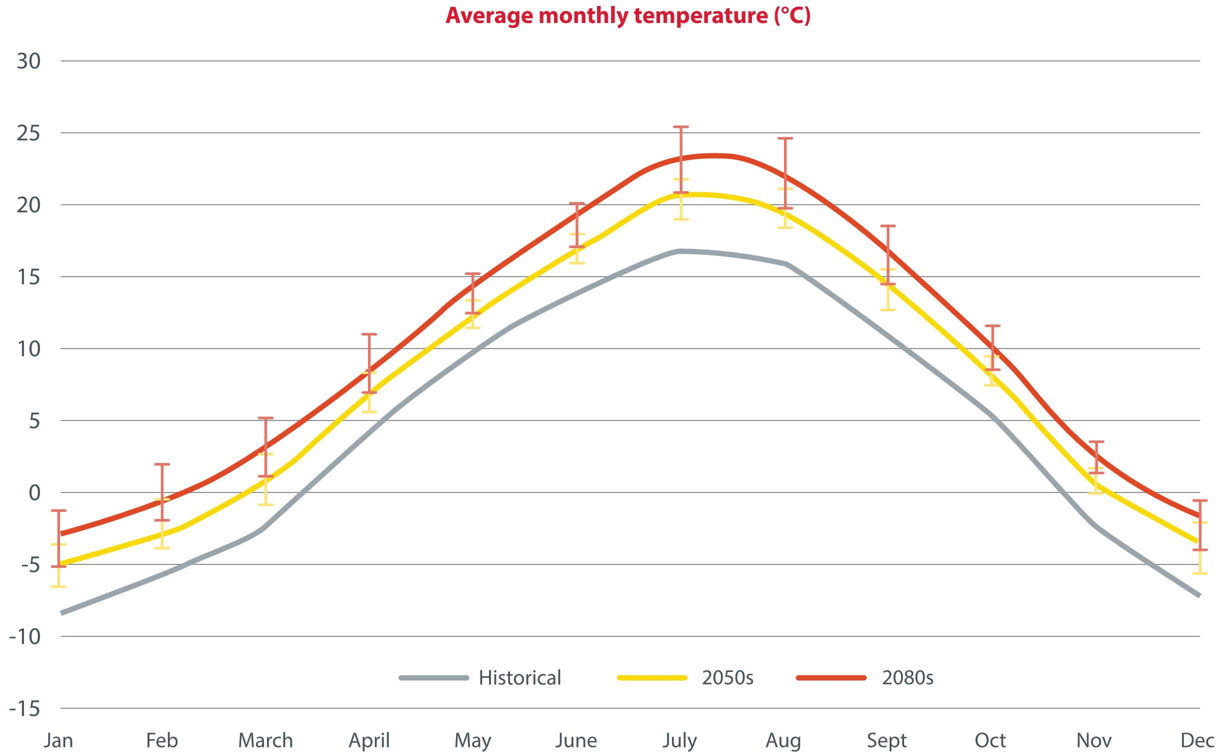


Figure 4. Monthly average daily air temperature during historical, 2050s and 2080s time periods

2.2.2 Minimum and maximum temperatures

The projected average coldest and warmest daily temperatures per month for the historical, 2050s and 2080s periods (along with the P10 and P90 ranges) are presented in **Figure 5** and **Figure 6**, respectively. The annual average coldest daily air temperature for the same time periods are summarized in **Table 5**. Projections show that average coldest and warmest daily air temperatures for Calgary are expected to increase for all future time periods.

The projected average coldest daily temperatures do not reflect the lowest recorded air temperatures for each month, rather show the overall warming trend in average cold days that will be experienced as the climate changes. Cold days and extreme cold events are expected to decrease, while warm days and extreme heat events are expected to increase. An increasing trend in the average coldest daily air temperature by month and by year (both minimum and maximum) is presented in **Figure 5**.

The same trend can be observed for warm days in Calgary. With temperatures projected to increase, summers will be warmer and this positive trend is exhibited by the average and minimum of the warmest daily air temperature which are shown in **Figure 6**.

Table 5. Average coldest daily air temperature during historical, 2050s and 2080s time periods (all values in °C)

Time period	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Annual	-32.5	-30.4	-27.7	-25.1	-26.1	-23.7	-21.6

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

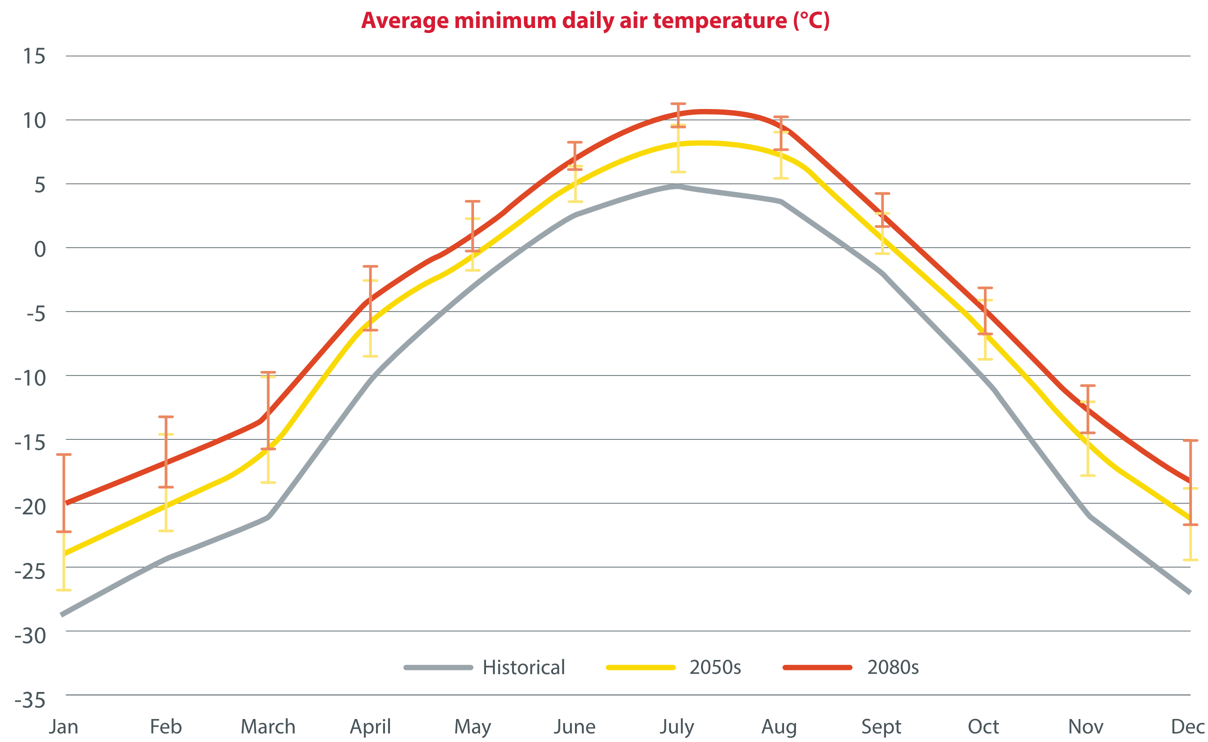


Figure 5. Average coldest daily air temperature by month during historical, 2050s and 2080s time periods (including P_{10} and P_{90} ranges)

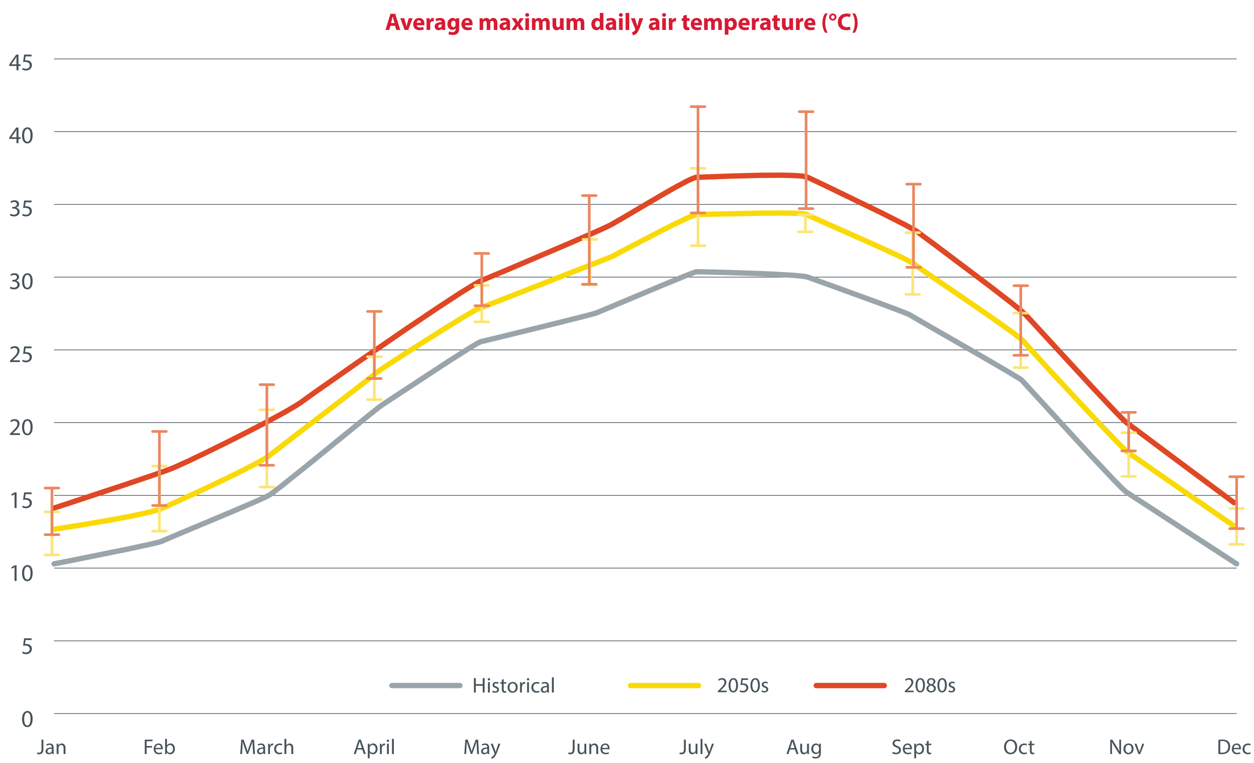


Figure 6. Average warmest daily air temperature by month during historical, 2050s and 2080s time periods (all values in °C)

2.2.3 Threshold temperatures

Threshold temperature indices illustrate the frequency of exceedance of various temperatures. In the context of climate change, cold temperature thresholds are expected to be exceeded less frequently. As well, cold temperature extremes are projected to be less severe (Bush, E. and Lemmen, D.S., editors, 2019). For example, it is possible that Calgary will not experience daily minimum temperatures below -30°C in an average year in the 2050s or the 2080s time horizon (see **Table 6**); however, it is still possible to see daily minimum temperatures below -30°C, albeit less frequently than before. The same trends are exhibited for daily minimum temperatures below -25°C occurring less frequently (see **Table 7**) as is the case for cold spells (see **Table 8**).

Similarly, temperatures are projected to increase with a changing climate and the number of days each year where the maximum temperatures exceeds 30°C are increasing (**Table 9**). Currently, Calgary does not experience many tropical nights (when the minimum daily temperature is ≥ 20°C), however the number of tropical nights are expected to increase with a changing climate as exhibited in **Table 10**. The number of hot days (days with maximum temperatures ≥ 29°C) is also projected to increase, as indicated in **Table 11**, below.

ECCC issues heat warnings in Alberta (excluding the southern portion) when two or more consecutive days of daytime maximum temperatures are expected to reach 29°C or higher and overnight minimum temperatures are expected to remain equal to or above 14°C (ECCC, 2021). Because heat warnings are typically used interchangeably with heat wave, heat waves in this discussion are defined to be the same as the criteria for heat warnings in Alberta. The number and length of heat waves are expected to increase in the future, as shown in **Table 12** and **Table 13**.

Table 6. Cold days: Number of daily maximum air temperatures below threshold during historical, 2050s and 2080s time periods (days per year)

Air temperature threshold (°C)	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
-30	0.2	0	0	0.1	0	0	0
-20	6	1	2	4	0	1	2
-10	24	12	17	21	8	11	16
0	67	42	49	55	36	39	49

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

Table 7. Cold nights: Number of daily minimum air temperatures below threshold during historical, 2050s and 2080s time periods (days per year)

Air temperature threshold (°C)	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
-25	11	1	4	8	0	1	2
-10	70	38	46	51	25	33	40
0	783	134	147	163	103	120	138

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

Table 8. Average number of cold spells (< -10°C for 5 days) per year during historical, 2050s and 2080s time periods (days per year)

Air temperature threshold (°C)	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
≤ -10°C for 5 days	4.5	2.0	3.1	5.0	1.0	2.3	4.0

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

Table 9. Number of daily maximum air temperatures above threshold during historical, 2050s, and 2080s time periods (days per year)

Air temperature threshold (°C)	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
0	297	311	316	323	317	326	330
10	192	212	224	238	225	239	257
20	80	102	117	128	119	143	152
30	3	14	20	31	23	39	60

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

Table 10. Number of tropical nights (≥20°C) during historical, 2050s and 2080s time periods (days per year)

Time period	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Annual	0.0	0.0	0.5	1.9	1.0	4.7	9.0

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

Table 11. Number of hot days (≥29°C) during baseline, 2050s and 2080s time periods (days per year)

Time period	Baseline (1981-2010)	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Annual	6.8	14.2	26.5	37.7	32.4	48.1	63.0

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

Table 12. Number of heat waves during baseline, 2050s and 2080s time periods (all values in °C)

Time period	Baseline (1981-2010)	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Annual	0.2	0.1	3.0	5.0	5.0	7.1	9.0

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

Table 13. Length of heatwave (days) during baseline, 2050s and 2080s time periods

Time period	Baseline (1981-2010)	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Annual	0.5	0.2	4.8	7.9	4.0	10.6	19.9

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

2.2.4 Seasonal temperatures

As annual average temperatures increase, seasonal temperatures will increase, resulting in a shift in seasons. For example, the growing season (number of days from the first fall frost to the last spring frost) is expected to lengthen (for the shortest, average and longest possible scenarios, **Figure 7**) and the frost season expected to shorten (**Table 14 – Table 16**) which will have significant effects on agriculture and vegetation. The months of July and January are still expected to be the warmest and coldest months of the year, respectively, in any given time period.

The shifts in seasonality also affect freeze –thaw cycles, which have significant effects on construction and road design. As shown in **Table 17**, there is a slight projected increase in the number of freeze-thaw cycles for Calgary in the 2050s during the winter, and then a slight decrease in the 2080s from the 2050s levels. The increase in initial freeze-thaw cycles in the 2050s and then decrease in the 2080s could be attributed to gradual warming processes. A significant driver of Calgary's freeze-thaw cycles are chinooks, which will continue to affect the region. Chinooks are generated by large scale pressure systems and mountain interactions and are not expected to change.

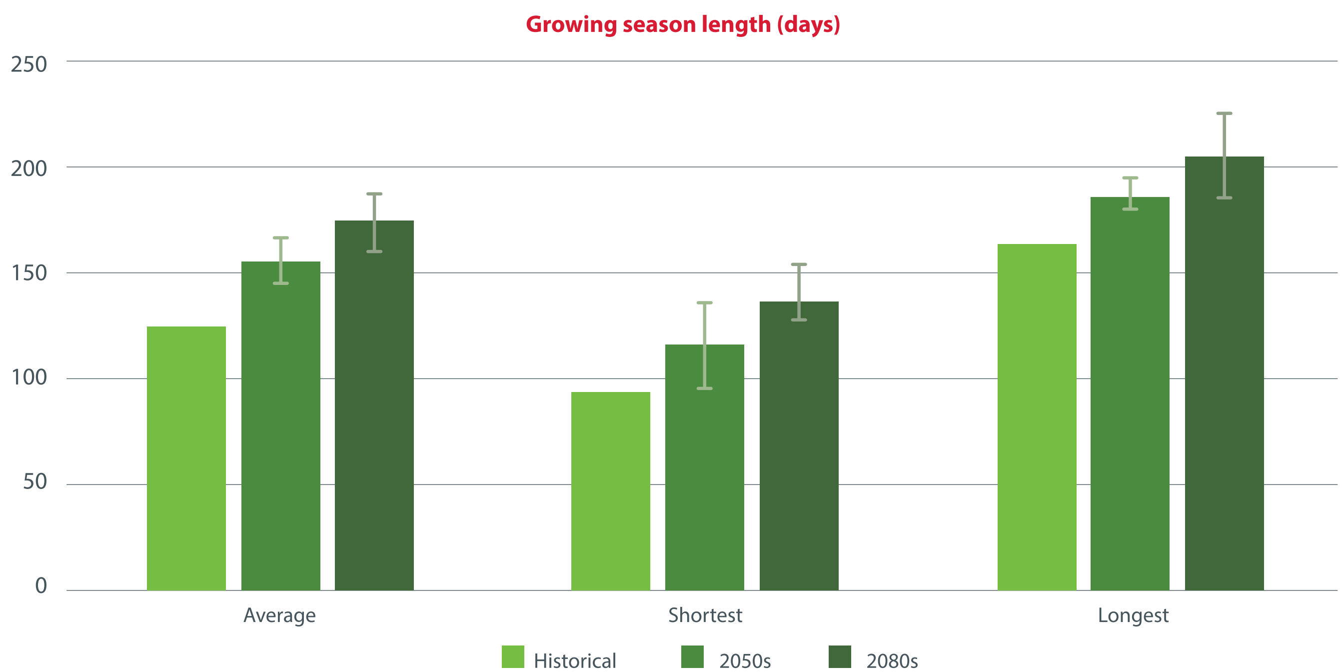


Figure 7. Growing season length during historical, 2050s and 2080s time periods (days per year)

Table 14. Frost season length[2] during historical, 2050s and 2080s time periods (days per year)

Length	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Average	241	199	211	219	179	192	205
Shortest	202	164	176	186	128	157	176
Longest	277	227	252	255	215	226	244

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

[2] Frost season length is calculated as the number of days from the first fall frost to the last spring frost, inclusive.

Table 15. Timing of first fall frost[2] during historical, 2050s and 2080s time periods (date)

Timing	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Average	Sept 17	Sep 29	Oct 3	Oct 9	Oct 5	Oct 12	Oct 16
Earliest	Aug 23	Aug 24	Sept 10	Sept 13	Sept 10	Sept 13	Sept 22
Latest	Oct 19	Oct 19	Oct 19	Oct 30	Oct 28	Oct 30	Nov 11

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

[2] First fall frost is calculated as the first day in a year, from July 15 onward, that the minimum daily air temperature (Tmin) ≤ 0°C.

Table 16. Timing of last spring frost[2] during historical, 2050s and 2080s time periods (date)

Timing	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Average	May 15	April 21	May 1	May 6	April 9	April 22	April 28
Earliest	April 21	March 28	April 3	April 12	March 5	March 28	April 3
Latest	June 16	May 11	May 23	June 13	May 10	May 20	May 23

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

[2] Last spring frost is calculated as the last day in a year, up to July 15, that the minimum daily air temperature (Tmin) ≤ 0°C.

Table 17. Average number of freeze-thaw cycles[3] in winter during historical, 2050s and 2080s time periods

Time period	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Winter[2]	16.2	17.7	18.5	19.1	16.4	17.6	18.4

[1] Indicates the 10th and 90th percentiles across the regionally downscaled modelled projections (GHD, 2020).

[2] Winter = December, January, February.

[3] A freeze period is defined as any number of consecutive days where the daily mean air temperature (Tmean) ≤ 0°C while a thaw period is defined as any number of consecutive days where Tmean > 0°C. One freeze-thaw cycle is defined as one period of freeze followed by one period of thaw (and vice versa).

2.3 Precipitation projections

2.3.1 Methodology

Historical precipitation data was sourced from the ECCC weather station at the Calgary Airport. For the regional Intensity, Duration, Frequency (IDF) curve analysis, the approach incorporated data from 102 ECCC weather stations. Extensive data quality assurance and QA/QC and supplementation of missing data points was completed as necessary. A full description of methods for QA/QC, data supplementation, and statistical analysis can be provided upon request.

Analysis was completed at hourly and daily timesteps using 27 GCMs, with three of the GCMs having two runs, for a total of 30 GCM model runs, and 16 regionally downscaled climate models from the North American Coordinated Experiment (NA-CORDEX). Regional grid scales of 6 x 10 km in size were used, and the analysis compared both RCP 4.5 and RCP8.5. Bias correction of the GCM output data was completed through the delta mapping by percentiles methods. The delta mapping method applies the relative changes between the GCM baseline data and the GCM 2050s or 2080s to the historical data record.

2.3.2 Rainfall projections

Annual total precipitation is anticipated to increase approximately 7% and 9% by the 2050s and 2080s, respectively, as shown in **Table 18**. Monthly precipitation is expected to increase for all months of the year, with higher monthly totals in the 2080s than the 2050s (except September); these results are presented in **Figure 8** (the bars represent the 10th and 90th percentile ranges of all models).

As shown in **Table 19**, rainfall is expected to increase across all durations (i.e., during short duration events < 24 hours, and longer duration events > 1 day). Short duration high intensity (SDHI) rainfall is projected to increase more quickly, and more substantially than longer duration rainfall. At higher return periods (i.e., larger storms with a lower frequency of occurrence, e.g., a 1:100 year event) there is a greater degree of increase than at lower return periods (i.e., more frequent storms, e.g., a 1:5 year event). Projections indicate the degree of change will be greater by the 2080s than it will be in the 2050s.

The projected increase in short duration rainfall totals can be described by employing the Clausius-Clapeyron (CC) relationship, which predicts an increase in the saturation vapour pressure of air by 7% for every 1°C increase in surface temperature (Trenberth, 2011). The increase in precipitation associated with longer duration storms trends more towards average precipitation increases and is not associated with the underlying assumptions of the CC relationship but supported by GCM analysis. Rainfall projections from regionally downscaled climate models are more suited for longer duration events as they demonstrate the influence of climate change on overall precipitation patterns.

The projected shift in precipitation is addressed through the development of an IDF curve that displays a 'bend' in the middle for the 2050s and 2080s time frames (**Figure 9** and **Figure 10**). IDF of rainfall estimates have been projected out to the 2050s and 2080s, to include extreme event scenarios, up to a 1:1000 year storm event (**Table 20**, **Table 21**). The uncertainty in more extreme events is greater than that for more frequent events. The 1:200, 1:500 and 1:1000-year precipitation were also compared to estimates of the Probable Maximum Precipitation (PMP) for the region and are within the PMP estimates (GHD, 2020).

The City is currently evaluating how to incorporate the information below into design practice. It is to be included in the upcoming update of the 2011 Stormwater Management & Design Manual (COC, 2011). The City is also currently evaluating how climate change should be accounted for as part of future design practice.

Table 18. Average annual precipitation totals (mm) during historical, 2050s and 2080s time periods

Time period	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Annual	416.6	392.8	439.5	502.0	388.0	452.7	526.1

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

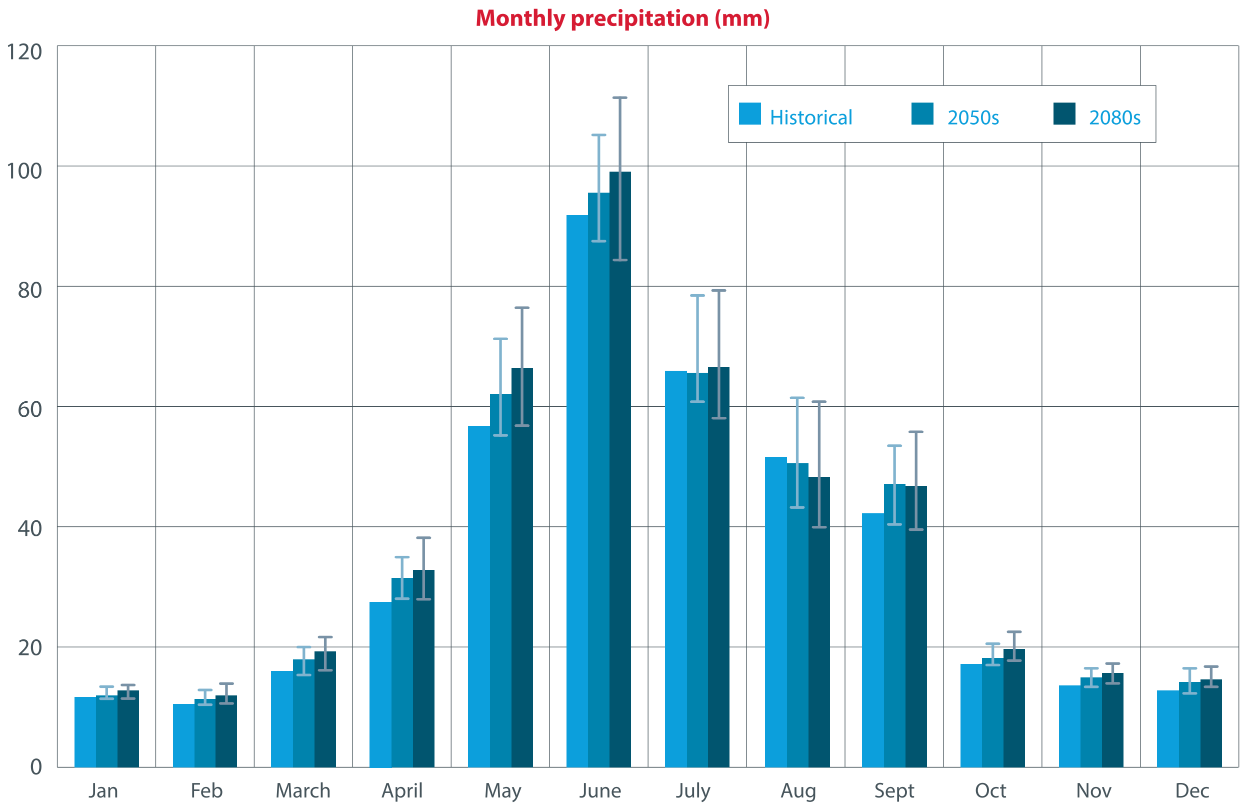


Figure 8. Average monthly precipitation for the historic, median 2050s and 2080s at the Calgary International Airport

Table 19. Summary of climate projected increase in rainfall IDF for Calgary

Precipitation event	2050s	2080s
Short duration (< 24 hours)	28% increase[1]	52% increase[1]
Long duration (2-30 days)	1-15% increase[1]	10-20% increase[1]

[1] Averaged over all return periods.

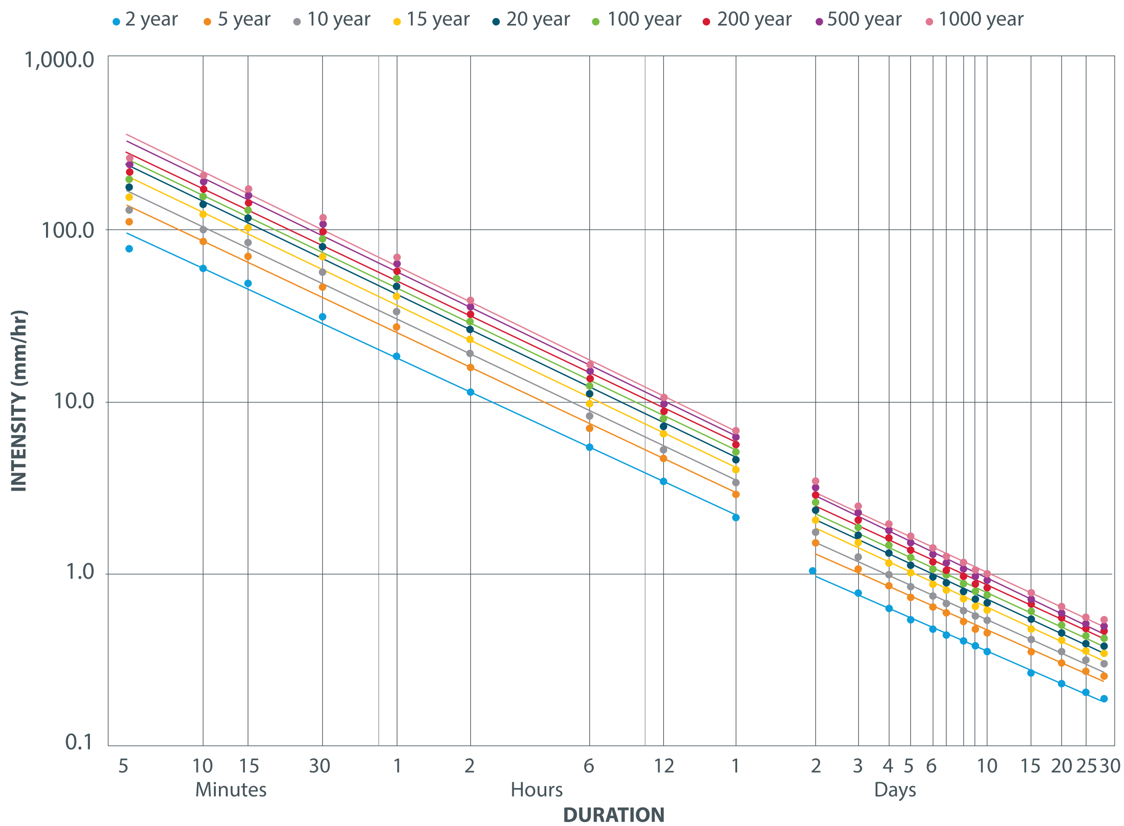


Figure 9. Single-station (Calgary International Airport) IDF curve for the 2050s using Clausius-Clapeyron rainfall deltas (up to 24 hours) and GCM median deltas (2 day to 30 day)

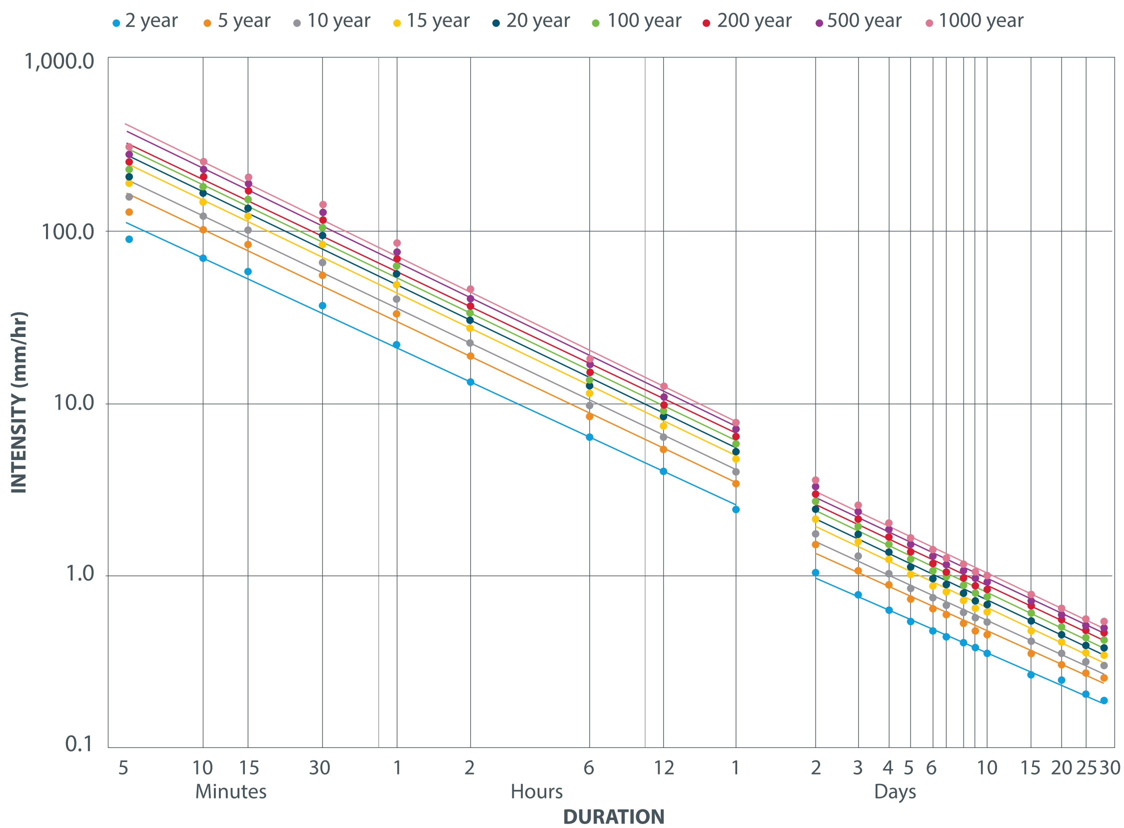


Figure 10. Single-station (Calgary International Airport) IDF curve for the 2080s using Clausius-Clapeyron rainfall deltas (up to 24 hours) and GCM median deltas (2 day to 30 day)

Table 20. 2050s climate adjusted IDF of rainfall estimates (mm) for the Calgary International Airport using Clausius-Clapeyron rainfall deltas (up to 24-hr) and GCM median deltas (2-day to 30-day)

Time	2 yrs	5 yrs	10 yrs	25 yrs	50 yrs	100 yrs	200 yrs	500 yrs	1:1000 yrs
5 min	6.5	9.2	11	13.3	15	16.7	18.4	20.6	22.3
10 min	9.9	14.3	17.2	20.9	23.6	26.3	29.0	32.5	35.2
15 min	12.2	17.8	21.5	26.2	29.6	33.1	36.5	41.0	44.4
30 min	15.7	23.5	28.7	35.3	40.2	45.1	49.9	56.3	61.1
1 hr	18.7	27.9	34.1	41.8	47.5	53.2	58.9	66.4	72.0
2 hr	22.5	31.9	38.2	46.1	51.9	57.8	63.6	71.2	77.0
6 hr	31.5	42.1	49.1	58	64.6	71.1	77.6	86.2	92.7
12 hr	39.8	53.9	63.2	74.9	83.7	92.3	101.0	112.4	121.0
24 hr	50.6	69.2	81.4	97	108.5	119.9	131.3	146.3	157.6
2-d	51.2	70.9	82.9	98.9	110.5	121.8	133.0	147.5	158.9
3-d	56.4	76.7	90.0	106.4	119.0	131.0	143.3	158.8	170.6
4-d	60.1	81.4	96.1	113.6	126.8	139.7	152.8	170.3	183.5
5-d	63.9	85.7	101.6	120.7	135.1	149.1	162.8	180.8	194.0
6-d	68.2	90.5	106.2	126.6	140.6	154.7	168.9	187.4	201.0
7-d	73.4	96.2	111.5	132.5	147.8	162.0	176.1	195.6	209.8
8-d	77.7	99.5	116.3	137.1	151.0	165.1	179.5	198.2	212.2
9-d	80.2	104.4	120.7	142.7	157.2	172.3	188.1	208.1	222.9
10-d	83.6	108.5	126.4	148.1	164.8	181.1	197.9	219.5	235.4
15-d	95.5	127.5	146.6	173.6	193.7	214.0	232.3	257.6	277.1
20-d	112.2	146.9	171.8	201.4	221.1	240.1	260.0	286.8	306.9
25-d	121.6	161.8	186.8	216.0	237.5	259.8	281.5	310.7	331.6
30-d	135.0	181.4	211.0	248.3	273.8	298.4	322.9	355.3	380.0

Table 21. 2080s climate adjusted IDF of rainfall estimates (mm) for the Calgary International Airport Using Clausius-Clapeyron rainfall deltas (up to 24-hr) and GCM median deltas (2-day to 30-day)

Time	2 yrs	5 yrs	10 yrs	25 yrs	50 yrs	100 yrs	200 yrs	500 yrs	1000 yrs
5 min	7.7	10.9	13.1	15.8	17.8	19.8	21.8	24.4	26.4
10 min	11.7	17.0	20.4	24.8	28.0	31.2	34.4	38.6	41.8
15 min	14.5	21.2	25.5	31.1	35.2	39.3	43.3	48.7	52.7
30 min	18.6	28.0	34.1	42.0	47.8	53.5	59.3	66.8	72.5
1 hr	22.2	33.2	40.5	49.6	56.4	63.2	69.9	78.8	85.5
2 hr	26.7	37.9	45.3	54.7	61.7	68.6	75.5	84.6	91.5
6 hr	37.4	50.0	58.4	68.9	76.7	84.4	92.2	102.3	110.0
12 hr	47.3	64.0	75.0	89.0	99.4	109.7	119.9	133.4	143.6
24 hr	60.1	82.1	96.7	115.1	128.8	142.4	155.9	173.7	187.2
2-d	51.9	71.4	84.3	100.7	113.3	126.2	139.1	155.0	167.3
3-d	56.1	77.3	92.9	112.2	126.5	139.8	153.0	170.4	183.2
4-d	60.7	83.2	99.6	118.2	132.9	147.8	161.3	178.2	191.3
5-d	64.6	86.6	102.1	121.8	137.0	150.6	164.5	183.5	197.4
6-d	67.2	91.4	107.5	127.6	141.3	155.8	107.5	189.8	204.1
7-d	72.6	96.5	114.0	133.3	147.6	161.7	175.8	194.4	208.9
8-d	76.2	100.7	116.0	136.7	152.6	168.3	183.9	204.5	220.0
9-d	81.3	104.5	121.9	144.8	161.7	178.2	194.7	216.1	232.1
10-d	84.8	109.6	127.7	151.4	169.5	187.1	204.6	227.8	245.3
15-d	98.0	127.5	150.7	176.9	196.8	217.9	238.8	266.4	287.3
20-d	116.5	145.4	170.6	198.1	220.5	243.6	266.7	296.8	319.5
25-d	124.9	158.7	183.9	213.4	235.8	258.5	282.7	313.0	336.3
30-d	136.7	181.9	211.7	247.9	273.3	299.7	328.9	366.8	394.1

2.3.3 Typical precipitation year analysis

The Calgary region has highly variable precipitation from year to year. The three typical precipitation years were identified from the historical dataset (1960-2014), representing each of the average, wet and dry precipitation years. A typical year provides the City with suitable year(s) for continuous modelling so that results are representative of typical conditions. An event-based analysis was performed using the historical precipitation record considering both the number of storm events in the year and the precipitation volumes associated with each event. The wet, dry and average years were modified to ensure the monthly precipitation totals corresponded to the historical monthly means (GHD, 2020). For the average typical year, the number and severity of the storms and the total precipitation were both in the mid-range. Similarly, for the wet typical year, the number and severity of storms and total precipitation were both in the high range, and the opposite for the dry typical year. Future climate projected versions of the typical years were developed using the delta mapping by percentiles method.

Applying climate models to the typical years resulted in increased precipitation in every month of the year except for August. The highest increases occurred in the spring (March, April, and May) and in the fall (September to December). The overall percent increase in monthly precipitation is relatively constant for the wet, average, and typical years, at a 5-6% increase for the 2050s and a 9-10% increase for the 2080s.

Table 22. Observed monthly and total annual precipitation during the historical period, modified wet, average and dry typical years

Month	Historical average (mm)	Wet typical year (1965) (mm)	Average typical year (1980) mm	Dry typical year (1967) (mm)
January	11.6	11.8	9.7	4.1
February	10.4	16.2	10.6	9.7
March	15.8	16.2	14.0	11.0
April	27.4	35.4	22.2	22.6
May	56.7	87.5	52.8	46.2
June	91.8	132.8	103.6	63.2
July	66.0	86.6	62.8	21.8
August	51.5	70.2	47.4	37.4
September	42.2	73.1	41.0	15.6
October	17.0	20.7	18.8	10.3
November	13.5	22.4	16.2	5.3
December	12.8	17.6	14.8	11.2
Total	**416.4**	**590.5**	**413.9**	**258.4**
2050s	–	**625.3**	**435.1**	**272.1**
2080s	–	**650.9**	**452.3**	**283.6**

2.3.4 Drought projections

As shown in Section 2.3.2 and 2.3.3, precipitation is projected to increase with a warming climate. However, this highlights the need to consider the weight of evidence for meteorological drought-related indicators (e.g., the standardized precipitation index, increasing temperatures, and increasing evapotranspiration) as the higher probability of seasonal drought is likely. Relying on one factor such as the median modelled response to climate change does not predict extreme conditions. Drought falls towards the outlier end of the precipitation spectrum, rather than the median. When multiple methods and indices are considered it suggests a slight increasing potential for drought conditions to occur, as evident in **Table 23**.

Table 23. Indicators of meteorological drought during baseline, 2050s and 2080s time periods

Indicators	Baseline (1981-2010)	2050s	2080s
		Median[1]	Median[1]
Number of dry days[2]	296.2	296.7	296.8
Number of dry spells[2,3]	5.9	6.0	6.0
Return period of 2-week drought (years)[4]	55	27.5	18.3

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

[2] Dry day is defined as daily precipitation below 1 mm.

[3] Dry spell is defined as a daily precipitation below 1 mm for a minimum of 14 days.

[4] Considers only the median of the model ensemble.

2.3.5 Long-term drought

The above meteorological drought-related indicators focus specifically on precipitation. From a broader climate hazard perspective, droughts also include considerations of temperature, river flows and shifts in seasonality. Future droughts are expected to be more frequent and intense over the southern prairies during summer, when evaporation and transpiration due to increased temperatures exceed precipitation (Bush, E. and Lemmen, D.S., editors, 2019). Additionally, lower river flows and shifts in seasonality are likely to occur, increasing the risk of multi-year drought conditions.

Calgary's water supply, which comes from the Bow and Elbow river source watersheds, is reliant on mountain snowpack, precipitation and glacial runoff. River flows are usually high during the spring run-off period, which typically starts in May and ends in mid-July; followed by a steady decrease in flows occurring in summer and early fall (COC, 2020). With climate change bringing shorter, warmer winters, earlier spring, longer summers and later fall, the Bow and Elbow rivers will experience a shift in runoff seasonality (COC, 2021). The mountain snowpack will be smaller and will melt earlier in the year and summer base flows may be less enhanced by glacial runoff. These conditions will result in lower flows and decreased water quality for the Bow and Elbow rivers amidst drier, longer and hotter summers.

Multi-year droughts and the accompanying impacts will be intensified by population growth and high-water consumption during the hotter summers and fall seasons (COC, 2020). Impacts may also accumulate in severity when other compounding climate risks such as heatwave and wildfire coincide with drought occurrences.

2.3.6 Snowfall projections

The future daily snowfall time series was created by applying the threshold air temperature of 1.5°C to the precipitation and temperature data. Any precipitation hour where the air temperature was below the threshold of 1.5°C was classified as snow, while any precipitation hour with an air temperature equal to or above 1.5°C was classified as rain. The hourly data were then aggregated to the daily timescale. The snowfall is measured in cm, which is approximately equivalent to one mm of rainfall. **Figure 11** shows the average total monthly snowfall amounts for the historic, median 2050s and median 2080s time periods (the bars represent the 10th and 90th percentile ranges of all models).

In the future climate, Calgary will see a decrease in the amount of snow falling monthly and annually. The heaviest snow is expected to occur in the winter and early spring season (November to March) with very little falling between April and October. As temperatures continue to increase, more spring and fall precipitation will fall as rain, suggesting less snowfall year-round will occur (**Table 24**). The relative reductions from historical snowfall values are largest in the shoulder months (September to November, March to May), and smallest in the coldest months (December to February). As evident in **Figure 11**, the months that receive the most snowfall will shift from April (16 cm) to March in the 2050s (12.5 cm) and December/January by the 2080s (11.5 cm).

The climate models show a range of a decrease in snowfall during the winter (December, January, February) of about 2% (using the median of the 30 GCMs) in the 2050s. By the 2080s this ranges from a decrease from 0.3% to 8.5% across the 30 GCMs. During the springtime (March, April, May), the models show a decrease in snowfall ranging from 15% (March) to 81% (May) by the 2050s, and 33% (March) to 86% (May) by the 2080s. The larger reductions in snowfall amounts in late spring are exhibited in **Figure 11**. These results agree with previous seasonal temperature projections, suggesting a shift in seasons – earlier springs, longer summers and shorter winters. The increase in air temperature in the 2080s accounts for the decrease in snowfall in this time horizon compared to the 2050s.

Table 24. Average annual snowfall totals (cm) during historical, 2050s and 2080s time periods

		2050s			2080s		
Time period	**Historical**	**Low[1]**	**Median[1]**	**High[1]**	**Low[1]**	**Median[1]**	**High[1]**
Annual	100.2	58.4	71.9	87.8	46.5	59.8	74.4

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

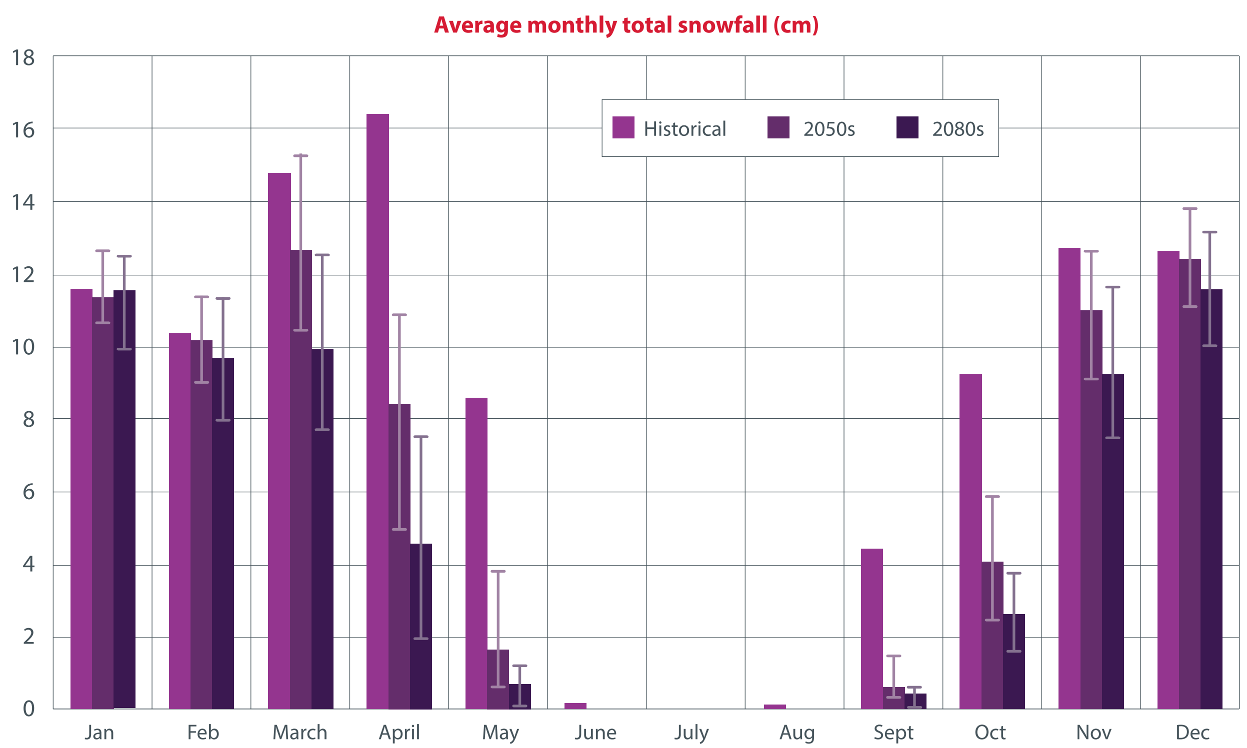


Figure 11. Average monthly snowfall during historical, 2050s, and 2080s time periods

2.3.7 Severe storms

The Calgary region sees a high number of convective storms in a year, earning its place within 'hail alley' in southern Alberta (Brimelow, 2017). Convective storms are often characterized by intense precipitation, thunder, lighting, hail, strong winds and sometimes the potential for tornadic development. Although some GCMs calculate convective precipitation, the uncertainties are considerable due to the inability to resolve and parameterize small scale and convective processes, respectively. Alternatively, weather typing can be used to project convective precipitation by correlating historical convective precipitation to other climatic variables. Weather typing was used to determine the number of likely convective events which were compared with the number of days in which the conditions were suitable to support convective precipitation. Climate projections were incorporated with both datasets in order to estimate the increasing potential for severe storm events (GHD, 2020).

As presented in **Figure 12** and **Table 25**, as the climate continues to change, the conditions favourable for the development of convective precipitation will occur over more months of the year. Historically, potential convective precipitation at the Calgary International Airport occurs from May to September. However, in the 2050s the possibility of convective precipitation expands to cover the period from April through October. In the 2080s, the possibility extends from March through October, due to the temperature increase. All months from April through October (2050s) and March through October (2080s) may see an increase in potential convective precipitation days.

Similarly, the conditions favourable for the occurrence of convective precipitation are expected to become more common as climate change progresses. Annually, the occurrence of potential convective precipitation days in Calgary is projected to increase by approximately 55% in the 2050s and 77% in the 2080s (considering the median of the 30 GCMs). The range in average annual change from historic to the future time horizons is presented in **Table 25**.

Table 25. Average annual convective events/conditions[2] during historical, 2050s and 2080s time periods

Time period	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Annual	22/44	28/52	34/73	38/89	28/44	39/89	45/111

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

[2] Convective events/conditions designation was determined by specific GHD methodology and a weather typing model to identify potential convective precipitation events based on historical data (GHD, 2020).

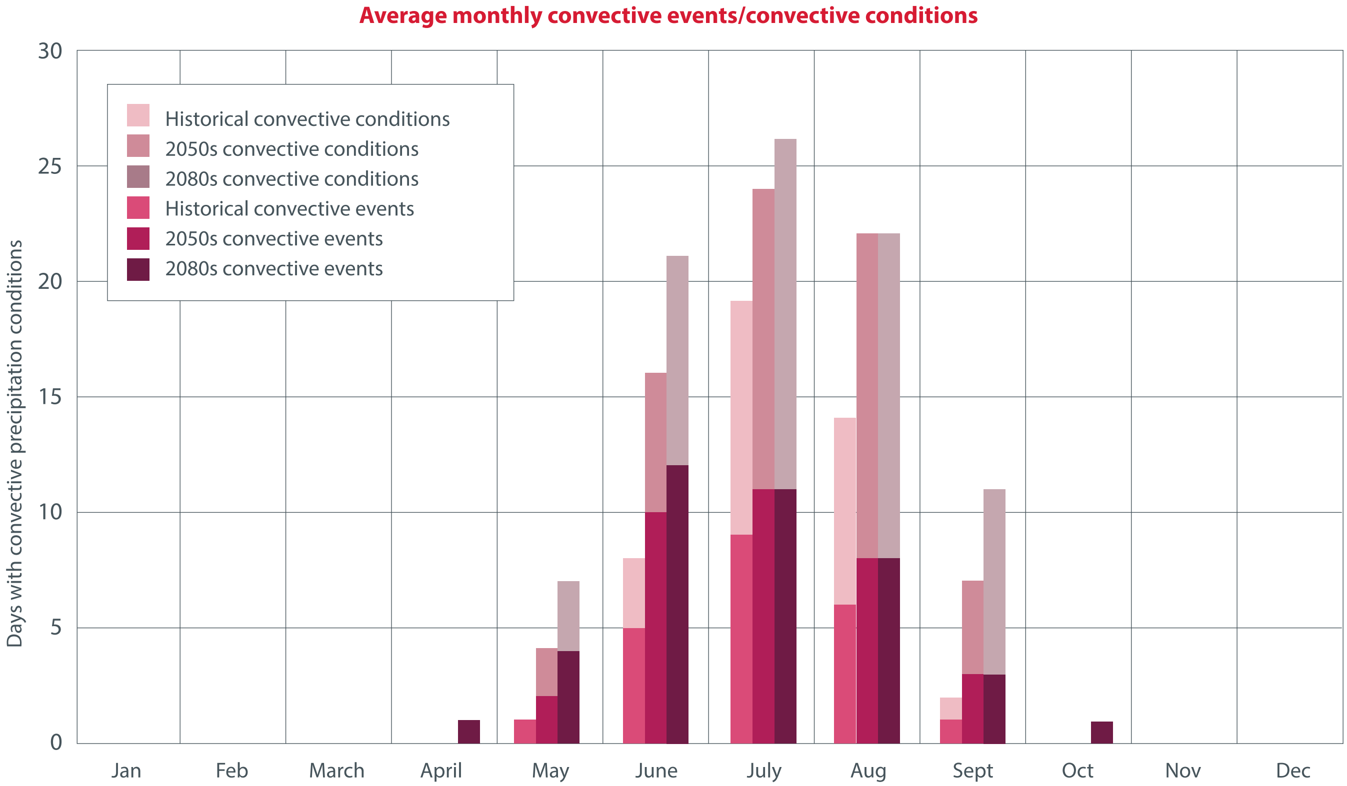


Figure 12. Average monthly convective precipitation events and convective conditions during historical, 2050s and 2080s time periods

Hail

One of the identifiers used for the analysis of convective precipitation events at the Calgary International Airport is hail. Based on the report *Hail Climatology for Canada: An Update by the Institute for Catastrophic Loss Reduction 2018* (Etkin, 2018), there was an increasing trend in hail in Alberta through the years 1975-2010 (**Figure 12**). Although hail cannot be explicitly modelled by global and regional climate model due to limitations in resolution, large hail events are projected to increase with the hail stones increasing in size, due to increasing atmospheric energy. Conversely, smaller hail events are expected to decrease due to a rising melting level in a warming atmosphere (Brimelow, 2017). Further, the longer convective storm season (**Figure 11**) will likely contribute to Calgary experiencing more hail events (Etkin, 2018).

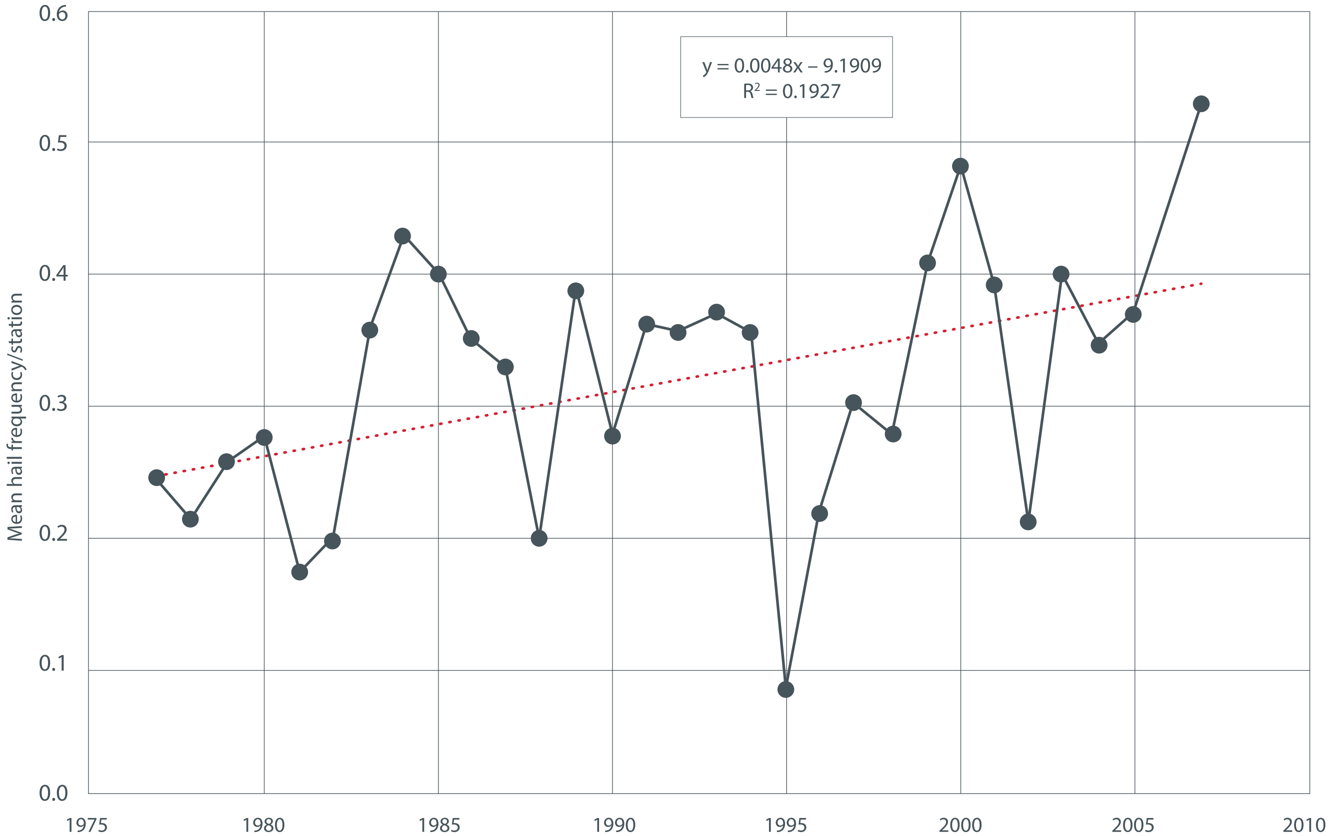


Figure 13. Trends in Alberta hail frequency (May-September) Source: Etkin, 2018

Lightning

Lightning strikes are being recognized as closely linked to climate change, although the scarcity of lightning monitoring, shifting technology, and inter-annual variability has made overall trend tracking challenging. As with convective storms, it is not a climate variable that is modelled with GCM projections; however, given the links between atmospheric energy, convective storms, and lightning, it is reasonable to anticipate an increase in the annual amount of lightning in a given year by the 2050s, and a larger increase by the 2080s (Romps, D. M., Seeley, J. T., Vollaro, D., & Molinari, J., 2014).

2.4 Wind projections

The future climate analysis of wind data is difficult to predict, as wind data are highly variable in both space and time and are based on a multitude of factors, including (but not limited to) surface roughness, topography, pressure gradients and daytime heating. The GCM-RCMs are focused on bulk movement of the atmosphere and therefore cannot model small scale variability and/or local turbulence, both of which impact local site anemometer readings. Therefore, differences in wind direction and/or speed between the station and the GCM-RCM grid do not necessarily represent model deficiencies but may instead represent the different scales between a 25 km grid to a single station.

An analysis of wind projections was performed with the 12 GCM-RCMs in the NA-CORDEX database that had output for the RCP8.5 scenario with the following outcomes:

- Wind direction on land is mainly controlled by the local topography. Prevailing westerly winds are most common in Calgary and are not anticipated to change due to climate change. The future climate analysis did not show a consistent change in wind direction.
- Wind speed is projected to remain constant or decrease throughout the year, with small increases in low wind speeds in the winter. Some GCMs project that wind speeds will increase, but the majority of GCMs project that wind speed will decrease overall for Calgary.

Wind speed observations from the Calgary International Airport indicate a statistically significant decreasing trend for the mean wind speed, daily maximum wind speed, and wind gust speed in all seasons of the year from 1960-2014 (**Figure 14**) (GHD, 2020). Multiple authors have noted that global wind speeds have been decreasing since the 1980s, but the trend began to reverse in approximately 2010 (Zeng, 2019; Vautard, 2010), which is supported by data from the Calgary International Airport whereby data since 2010 shows an increase in windspeed. As discussed previously, convective storms are likely to be increasing in frequency, and often strong wind gusts are associated with severe storms; therefore, it is possible that Calgary will experience an increase in strong wind gusts associated with convective storms, but could experience a decrease in wind speed otherwise. **Table 26** includes a summary of baseline and projected wind gust days for the City.

Table 26. Average wind gust days for Calgary during historical, 2050s and 2080s time periods

Climate indicator	Season	Historical	2050s			2080s		
			Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Average number of days with maximum wind gusts ≥ 90 km/hr[2]	Annual	4.1	4.6	3.3	6.0	4.0	2.6	5.5

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

[2] Data provided by GHD (GHD, 2020). The wind threshold of 90km/hr was chosen based on ECCC's warning criteria for wind warnings (ECCC, 2021).

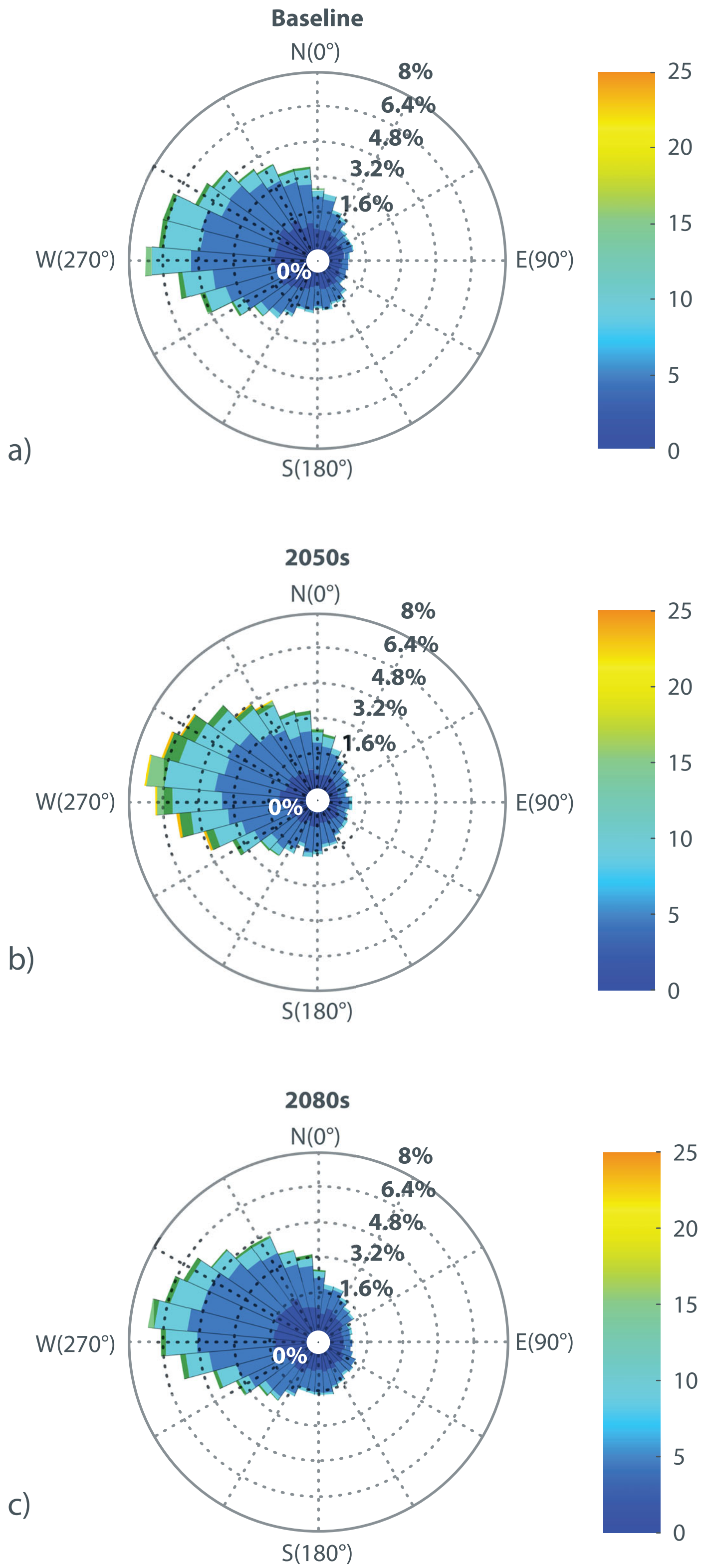


Figure 14. Comparison of annual wind rose patterns during baseline (1981-2010), 2050s and 2080s time periods

2.5 Combined and design parameter projections

2.5.1 Solar radiation

Solar radiation is a function of location, elevation, time of year and the amount of cloud cover. Of these, climate change will only impact cloud cover, and therefore climate projected changes in solar radiation are small. The historical hourly solar radiation data was accessed by GHD from the Canadian Weather Energy and Engineering Datasets (CWEEDS). The GCM-RCM projections were then used to perturb the historical solar radiation data to determine the 2050s and 2080s climate using the RCP8.5 scenario. A median projection time series dataset was developed and represents the median of the ensemble GCM-RCM datasets.

As presented in **Figure 15** and **Table 27**, solar radiation is expected to increase slightly in the summer months and decrease slightly during the remainder of the year with a warming climate.

Table 27. Average annual solar radiation (w/m²) during historical, 2050s and 2080s time periods

Time period	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Annual	13,395	12,629	13,002	13,404	12,360	12,860	13,375

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

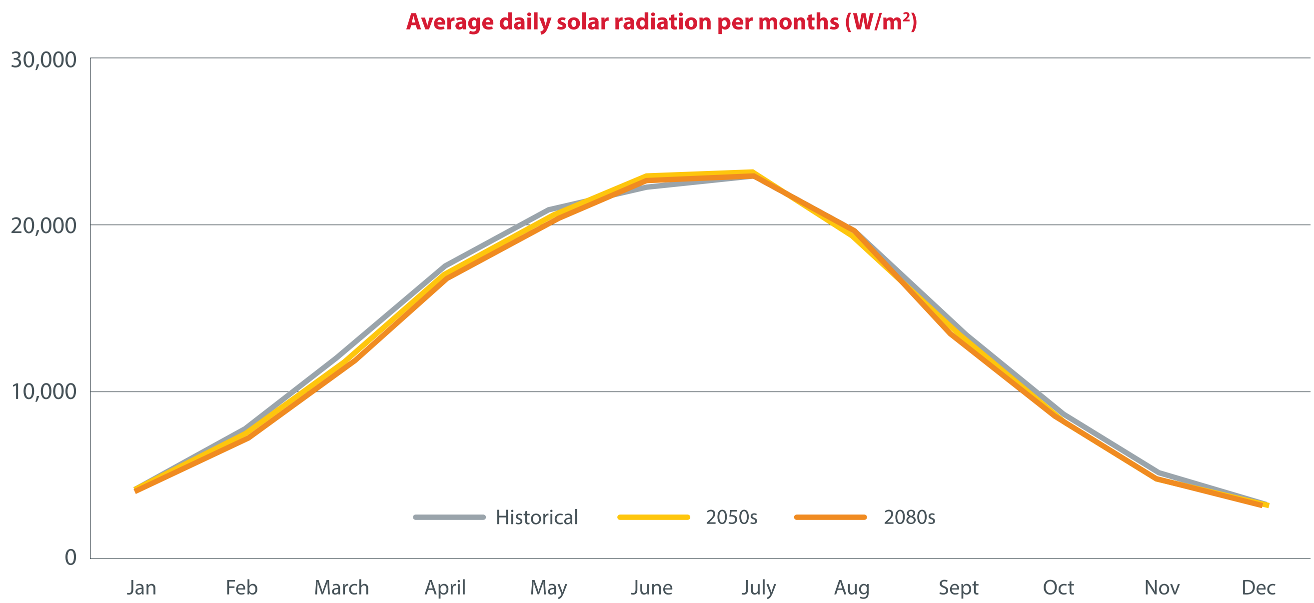


Figure 15. Trends in solar radiation during historical, 2050s, and 2080s time periods

2.5.2 Evapotranspiration

Evapotranspiration is the water that is lost to the atmosphere from the surface of the earth, including soil and vegetation transpiration. The Penman–Monteith equation was used to calculate evapotranspiration, requiring the input of air temperature, relative humidity, wind speed, and solar radiation. These climate parameters are all measured at the Calgary airport, and therefore evapotranspiration was calculated for the historical and future time periods using this information.

As presented in **Table 28** and **Figure 16**, there is a strong agreement between the 2050s and 2080s time periods that evapotranspiration will increase particularly from June through October and remain relatively similar (with a slight increase) through the winter and early spring. Previous studies have found that evaporation and evapotranspiration are strongly influenced by wind speed and the vapour pressure deficit (which is a function of water and air temperature).The increase in evapotranspiration may have an effect on vegetation health and survival, as well as contribute to the continuing increased risk due to wildfire. Similarly, this is one of the factors that points to an increasing potential for drought conditions, whereby increasing evapotranspiration can be used to infer increasing drought conditions.

Table 28. Annual evapotranspiration (mm/year) during historical, 2050s and 2080s time periods

		2050s			2080s		
Time period	**Historical**	**Low[1]**	**Median[1]**	**High[1]**	**Low[1]**	**Median[1]**	**High[1]**
Annual	872	898	956	1024	926	10,07	1,103

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the regionally downscaled modelled projections (GHD, 2020).

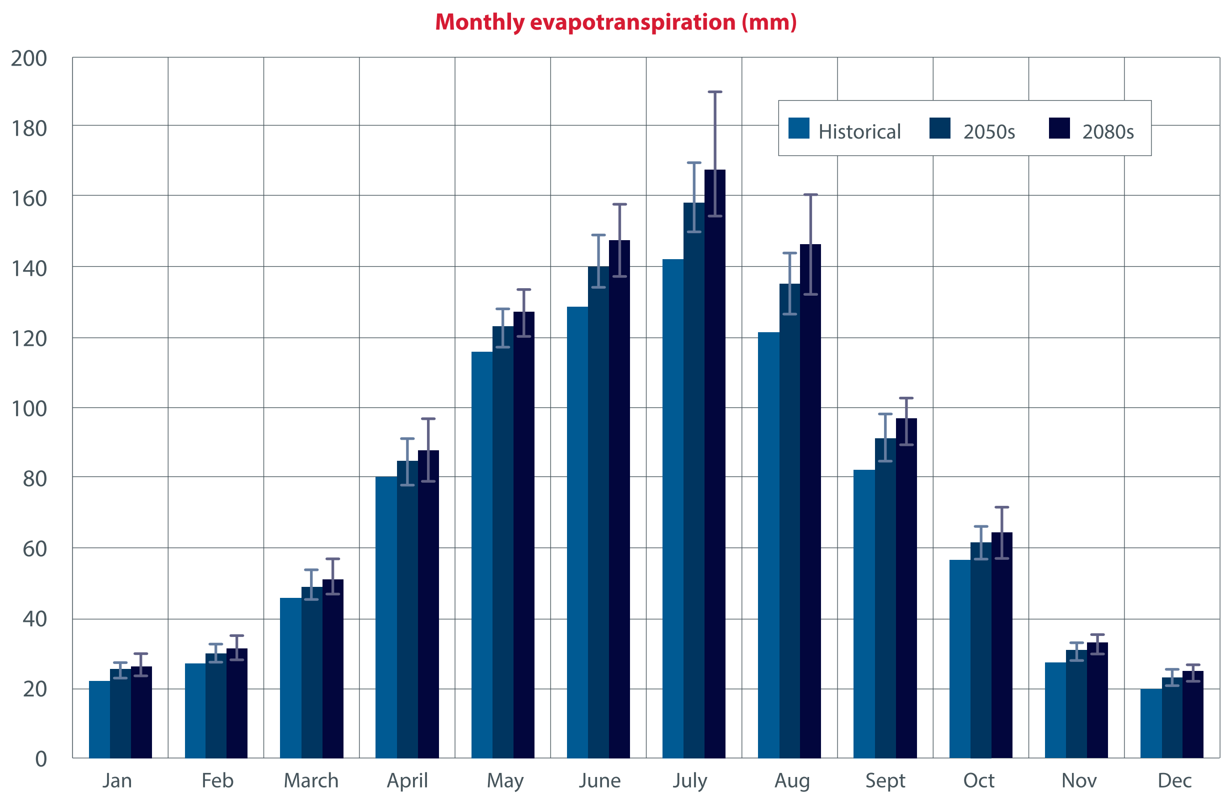


Figure 16. Average monthly evapotranspiration during historical, 2050s and 2080s time periods

2.5.3 Relative humidity

The relative humidity of air can be defined as the measure of how much water vapour is in the air compared to the maximum water vapour possible at the current temperature (Aguado, 2010). Historical relative humidity data was available at the Calgary Airport for the historical period, and 16 GCM-RCM pairs with projections of relative humidity were available from the NA-CORDEX database; the historical data was perturbed to the 2050s and 2080s climate utilizing the RCP8.5 scenario.

Although a commonly used metric, relative humidity has limitations in its use and should not be used as the only metric to measure water vapour in a changing climate (Aguado, 2010). The main limitation of relative humidity is that it depends not only on the amount of water vapour present, but the temperature as well. Because more water vapour can exist in warmer air than cooler air, if the temperature of the air increases, the maximum possible water vapour increases, and the relative humidity decreases even if the moisture content remains unchanged. For example, relative humidity will change throughout the day as the temperature changes, regardless of the amount of moisture in the air. In the morning when the temperature is lower, the relative humidity is at its highest and will decrease throughout the day as the temperature increases. As shown previously in this document, with a changing climate, we can expect higher temperatures and increasing precipitation for the Calgary region; however, the 2050 projections shown in the figure below exhibit little to no change in relative humidity: as relative humidity is the ratio of water vapour content to saturation value, and both quantities are expected to increase with temperature, relative humidity is not expected to change in a warming climate.

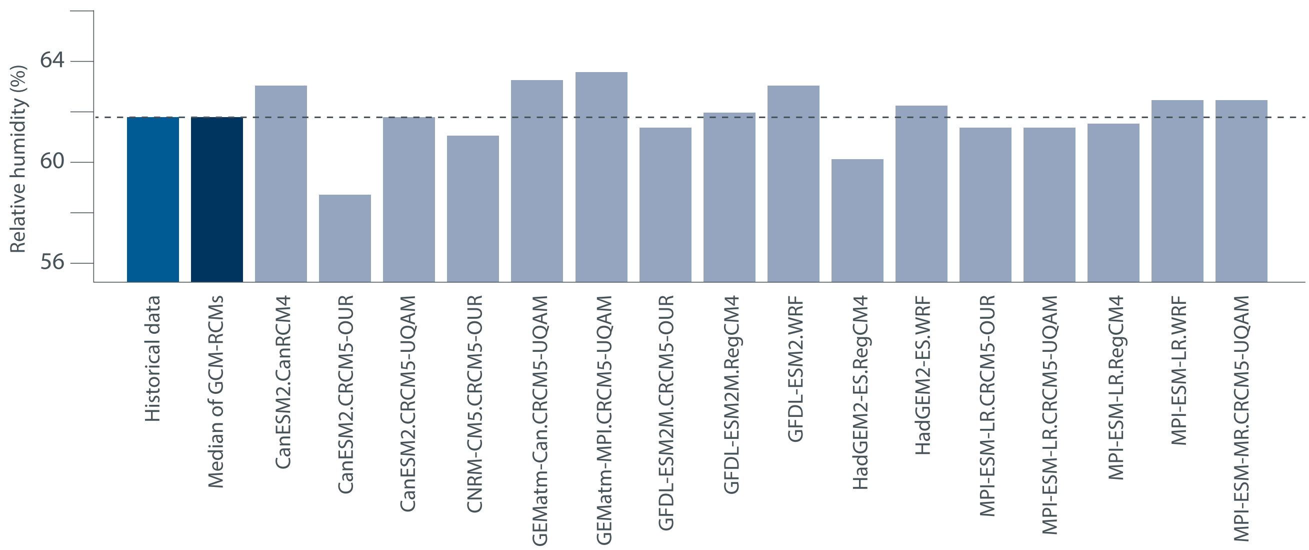


Figure 17. Comparison of relative humidity for current and 2050s future climate time series for the Calgary International Airport

2.5.4 Temperature design metrics

Several temperature indicators can be used to inform winter and summer conditions for building heating and cooling design. For winter, these metrics include heating degree days (HDD), above freezing degree days (AFDD), melting degree days (MDD), freezing degree days (FDD) and the January 1% and 2.5% design temperatures. For summer, cooling degree days (CDD) and July 2.5% design temperature were considered as design metrics.

Degree days are the average annual sum of the number of degrees Celsius that each day's mean air temperature is below or above a defined threshold (<18°C for HDD, ≥ 0°C for AFDD and MDD, ≤ 0°C for FDD). These metrics can be used to compare to design thresholds (e.g., HDD, FDD), or compared to historical averages to show warming or cooling trends. The degree days were calculated from historical and projected temperatures.

Design temperatures are typically the extreme temperatures that a certain piece of equipment or infrastructure will be exposed to and designed for, in a typical year. Design temperatures are important metrics used to design a building's heating or cooling system using the most extreme conditions under which the building is expected to operate normally. According to the National Building Code, "Failure to maintain the inside temperature at the pre-determined level will not usually be serious for small temperature discrepancies or short durations of time. The outside conditions used for design should, therefore, not be the most severe in many years, but should be the somewhat less severe conditions that are occasionally but not greatly exceeded (NRC, 2019)." Design temperatures for winter and summer are different, whereby winter (January design temperature) and summer (July design temperature and humidity), defines the heating and cooling requirements, respectively; therefore, there are different considerations required for both winter and summertime design.

As average temperatures are expected to shift, so are extreme temperatures. Extreme cold temperatures are expected to become less frequent and more moderate, while extreme hot temperatures are expected to increase, both in frequency of occurrence and to higher extremes. As average temperatures and seasonal shifts occur this will mean a lower heating demand in buildings (i.e. decrease in HDDs, **Table 29**). Additionally, the increasing intensity and frequency of heat events will increase cooling needs in the future (i.e. increase in CDD, **Table 34**). Much of the data presented below includes the average, warmest or coldest projections, as well as the 50th (median), 10th (low) and 90th (high) projections, to display the range.

Winter design considerations

Heating Degree Days (HDD) are the average annual sum of the number of degrees Celsius that each day's mean air temperature is below 18°C. When the mean air temperature is ≥18°C the degree day is 0 (Climate Atlas, 2021). HDD gives an indicator of the amount of energy required to keep the internal temperature of a small building at 21°C and the fuel required to do so; therefore, HDD can be a useful metric for assessing the severity of climate and can give a basis of climate-related codes (NRC, 2019). If climate projections show a decrease in HDD, then a facility operator can expect to spend fewer days of the year heating the facility.

Freezing Degree Days (FDD) are the average annual sum of the number of degrees Celsius that each day's mean air temperature is below 0°C. They can be used in similar fashion to HDD but are more appropriate for road and pavement design as it can be used to approximate frost depth (Soliman, H., Kass, S., & Fleury, N., 2008). If projections show a decrease in FDD, a less severe winter is expected, whereas higher FDD imply greater snow and ice accumulation and have an impact on City roads.

Another indicator, Melting Degree Days MDD (MDD), are the average annual sum of the number of degrees Celsius that each day's air temperature is above 0°C for the winter season only, where an increase in MDD suggests a milder winter season and more mid-winter thaws. Above Freezing Degree Days are like MDD (days above 0°C) but are calculated over the entire year.

The 1% and 2.5% January design temperature is defined as "the lowest temperature at or below which only 1% or 2.5% of the hourly outside air temperatures in January occur (NRC, 2019)", which corresponds to 8 or 19 hours out of 40,920 hours total (55 years), respectively. However, even as temperatures increase with climate change, the potential for extreme cold will continue to exist and therefore the 2.5% (instead of the 1%) January design temperature should be used to inform building heating design.

As shown in **Table 29** and **Figure 18**, the HDD are expected to decrease as temperatures increase. Modelled projections of AFDD and winter MDD indicate that winter days (December, January, February) with a mean temperature 0°C will increase, as shown in **Figure 19** and **Figure 20**, respectively. FDD will continue to decrease by about 30% to the 2050s and over 50% by the 2080s as is evident in **Figure 21**. These results are supported by the decrease in the 1 and 2.5% January design temperatures (**Table 33**), suggesting an overall increase in temperatures during the winter season.

Table 29. Heating degree days during historical, 2050s and 2080s time periods

Indicator	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Average	5064	3728	4093	4408	3112	3505	3830

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

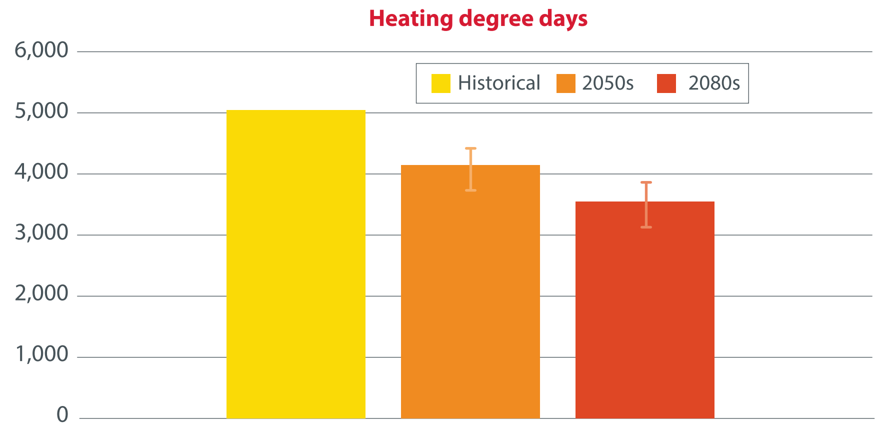


Figure 18. Trends in heating degree days during the historical, 2050s and 2080s time periods

Table 30. Above freezing degree days during historical, 2050s and 2080s time periods

Indicator	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Average	2564	3019	3378	3725	3326	3969	4473

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

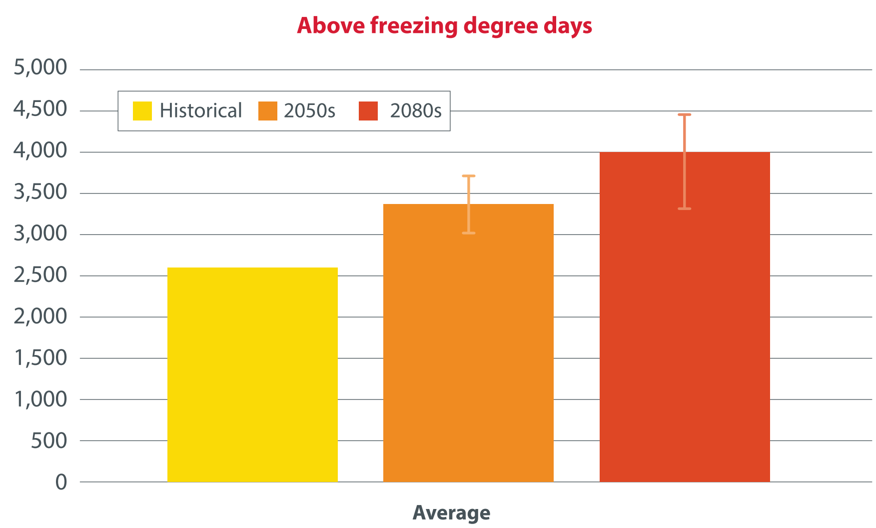


Figure 19. Trends in above freezing degree days during the historical, 2050s and 2080s time periods

Table 31. Winter melting degree days during historical, 2050s and 2080s time periods

Indicator	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Average	70	114	133	186	161	194	272

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

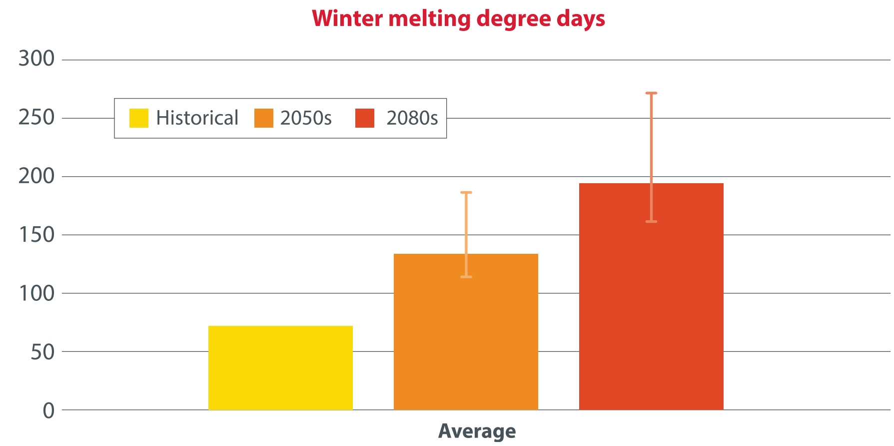


Figure 20. Trends in winter melting days during the historical, 2050s and 2080s time periods

Table 32. Freezing degree days during historical, 2050s and 2080s time periods

Indicator	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Average	1,000	535	661	794	374	460	577

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

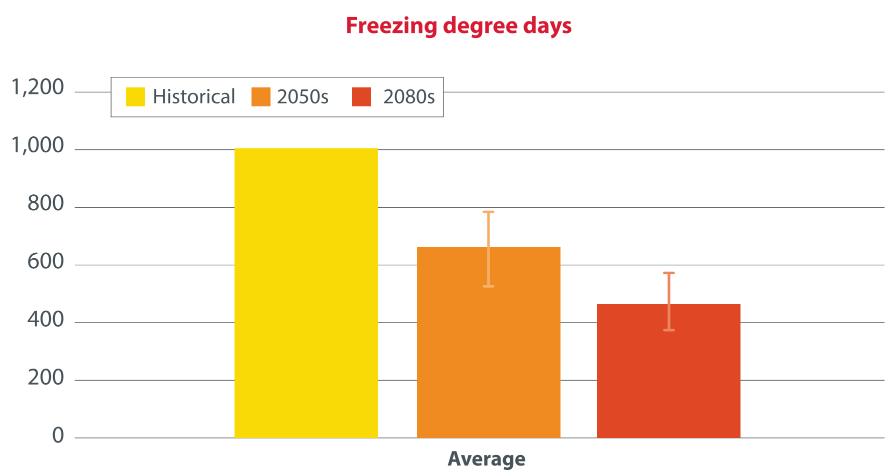


Figure 21. Trends in freezing degree days during the historical, 2050s, and 2080s time periods

Table 33. January 1% and 2.5% design air temperatures during historical, 2050s and 2080s time periods (values in °C)

Indicator	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
1%	-31.7	-29.9	-26.9	-22.6	-25.7	-23.3	-18.7
2.5%	-29.4	-27.7	-24.9	-20.5	-23.6	-21.1	-17.0

[1] Indicates the 10th (low), 50th (median) and 90th (high) percentiles across the downscaled modelled projections (GHD, 2020).

Summer design considerations

Cooling degree days (CDD) are equal to the average annual sum of the number of degrees Celsius a given day's mean temperature is above 18°C. For example, if the daily mean temperature is 21°C, the CDD value for that day is equal to 3°C. If the daily mean temperature is below 18°C, the CDD value for that day is set to zero. CDD can be used to estimate how much air conditioning is required in a year to maintain indoor comfort and safe living conditions for occupants. 18°C is the temperature at which air conditioning becomes necessary to maintain a comfortable indoor temperature, particularly within large buildings and multi-family housing. As the number of days that are above 18°C increase, so too will the need for air conditioning to maintain safe, comfortable and productive indoor conditions. This will have an increased energy demand, and increased cost.

The 2.5% July design temperature is calculated based on July air temperatures and humidity, whereby using "the 2.5% values used for the dry- and wet-bulb design conditions represent percentiles of the cumulative frequency distribution of hourly dry- and wet-bulb temperatures and correspond to July temperatures that are higher than 19°C on average over the long term (BCBC, 2018)." The upper 2.5th percentile of hourly air temperature in July was calculated from 40,920 (55 years) July hourly air temperatures per series.

As shown in **Table 34**, the cooling degree days increase with a changing climate. As overall temperatures increase, the change can be reflected in design temperatures to support climate adapted facilities for comfort and energy efficiency into the 2050s and the 2080s, as evident in **Table 35**.

Table 34. Cooling degree days during historical, 2050s and 2080s time periods (degree-days)

Indicator	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
Average	46.1	136.6	209.6	278.5	238.5	415.3	601.1

[1] Indicates the 10th and 90th percentiles across the downscaled modelled projections (GHD, 2020).

Table 35. July 2.5% design air temperatures during historical, 2050s and 2080s time periods (values in °C)

Frequency	Historical	2050s			2080s		
		Low[1]	Median[1]	High[1]	Low[1]	Median[1]	High[1]
2.5%	28.0	30.4	32.2	34.5	32.5	34.8	39.0

[1] Indicates the 10th and 90th percentiles across the downscaled modelled projections (GHD, 2020).

2.6 Closing

The City of Calgary has a responsibility to be resilient by responding, preparing and adapting to the impacts of climate change. In order to prepare, we need to understand how climate hazards will evolve and what this will mean for our local region. The City experiences a multitude of climate hazards, including: extreme heat, higher average air temperatures, wildfires, drought, short duration high intensity rainfall, severe storms, high winds, river flooding, and snowfall, most of which are expected to increase in frequency, intensity or duration in a changing climate. For the purposes of this document, these hazards are categorized more broadly (temperature, precipitation related) and then broken down and assessed using climate indices which helps communicate relevant climate hazards in a variety of ways. The information presented above is not exhaustive but is intended to be illustrative of the type and breadth of information available to track climate hazard trends in a changing climate. Please contact the City for further information, to connect with other subject matter experts, and for assistance in understanding the information presented within this document.

3

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