MANITOBA-MINNESOTA TRANSMISSION PROJECT
HISTORIC AND FUTURE CLIMATE STUDY

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DATE: JULY 17, 2015

REPORT: PPD-14/16 (REV1)

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INTEROFFICE MEMORANDUM

FROM		TO	
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DATE July 17, 2015

FILE **PPD-14/16**

SUBJECT **Manitoba-Minnesota Transmission Project Historic and Future Climate Study (REV1)**

Enclosed is the "Manitoba-Minnesota Transmission Project Historic and Future Climate Study (REV1)". This study characterizes the historic climate and presents a series of future climate scenarios for the Manitoba-Minnesota Transmission Project study area. Data used in this study was primarily obtained from Environment Canada meteorological stations and an ensemble of Global Climate Models (GCMs), originating from international modeling agencies. This report presents historic climate for the period of 1981-2010 and climate scenarios for three future time periods: the 2020s, 2050s, and 2080s.

This technical memorandum is to be used in the support of the Manitoba-Minnesota Transmission Project Environmental Impact Statement. In order to provide appropriate interpretation and guidance, please consult the Water Resources Engineering Department prior to external distribution.

If you have any questions regarding this report, please feel free to contact me at (204) 360-6318 or at kkoenig@hydro.mb.ca.

Best regards,

Kristina Koenig

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EXECUTIVE SUMMARY

This study characterizes historic climate and presents future climate projections of temperature, precipitation, and wind speed for the Manitoba-Minnesota Transmission Project (MMTP) study area. MMTP's transmission line extends from the Dorsey Converter Station located northwest of Winnipeg, to the Manitoba-Minnesota border near Piney, MB and includes upgrades to associated stations at Dorsey, Riel, and Glenboro South, all in Manitoba.

For the historic climate analysis, six Environment Canada meteorological stations were used to capture the extent of the transmission line and the project infrastructure located to the west of Winnipeg. The most recent 30-year normal period published by Environment Canada extends from 1981-2010 and is used to represent the baseline climate in this study. In Winnipeg, the mean annual temperature is 3.0 °C, the mean annual precipitation is 521 mm/year, and the mean annual wind speed is 17.1 km/h. Historical trends observed in the analysis indicate statistically significant increases in temperature and decreases in wind speed within the study area.

An ensemble of 15 Global Climate Models (GCMs) was used to project the future climate. GCMs simulate the climate system and are used to project the climate based on future scenarios of atmospheric greenhouse gas concentrations. Regional Climate Models (RCMs) use GCM data as boundary conditions to simulate the climate with finer resolution but over a limited region of the globe. RCMs represent more detailed topography and smaller scale climate processes but require large computing resources. This study supplements GCM results with finer resolution Canadian Regional Climate Model projections (CRCM4.2.3 was used). The GCM and CRCM grid point nearest to Winnipeg Richardson International Airport was selected and three future horizons were used: 2010-2039 (2020s), 2040-2069 (2050s), and 2070-2099 (2080s).

The ensemble mean projection, developed from 69 GCM simulations, showed that annual temperatures and precipitation are generally projected to increase while wind speed is projected to decrease. The GCM ensemble average projects mean temperature to increase by 1.5°C for the 2020s, 2.9°C for the 2050s, and 4.1°C for the 2080s. Annual total precipitation is projected to increase by 3.5% for the 2020s, 4.2% for the 2050s and 6.7% for the 2080s. Mean wind speeds are projected to show little or no decrease in the future. Seasonal analysis shows that winter is projected to experience the greatest change in temperature and the greatest relative change in precipitation. Summer months are projected to experience the greatest reduction in surface wind speed.

Extreme temperature events are projected to occur more frequently, with minimum temperatures projected to increase by a greater magnitude than maximum temperatures. Some evidence suggests that extreme precipitation and wind speed events are also projected to increase. Trends for freezing precipitation, wind gust speeds, tornado occurrence, lightning, drought, and forest fires were examined primarily through literature reviews, which showed that freezing precipitation, wind gust speeds, forest fire conditions, and conditions leading to lightning strikes and tornadoes are expected to increase.

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1.0 INTRODUCTION

Climate information is generally derived from historic observations; however, historic observations may no longer be a valid representation of the future climate due to greenhouse gas (GHG) induced climate change (IPCC, 2013). This report characterizes historical and future climate conditions for the planned Manitoba-Minnesota Transmission Project. The intention of this document is to help practitioners meet the requirements outlined by the National Energy Board (National Energy Board, 2014; National Energy Board, 1985) and CEA Act 2012 (Canadian Environmental Assessment Agency, 2012) for addressing climate change in an Environmental Assessment. Requirements generally fall into two broad categories:

(1) Outlining how the project will contribute to climate change, primarily through the emission of greenhouse gases;

(2) Determining and describing the impact that climate change will have on the project.

This report addresses the second requirement and is structured into two main parts: Historic Climate Analysis and Future Climate Scenarios. The historic climate analysis is based on climate observation and establishes baseline conditions for temperature, precipitation, wind and trends. Future climate scenarios supplement the historic climate analysis with data from Global Climate Models (GCMs) and a Regional Climate Model (RCM), forced by a range of GHG concentration scenarios, to project future climate with respect to temperature, precipitation, and wind speed.

Quantitative projections of future climate are required to assess future impacts of climate change. The scientific community is virtually certain that human influence has warmed the global climate system (IPCC, 2013); however, there is less confidence in how the climate will change at the regional or local scale. Levels of confidence in projections for future climate vary from one region to another and between climate variables. Due to uncertainties, the Intergovernmental Panel on Climate Change's (IPCC) Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA) recommends that climate impact assessments should follow an approach that uses a number of plausible future climate scenarios (IPCC-TGICA, 2007).

Climate scenarios are plausible representations of the future that are consistent with assumptions of future GHG concentrations and the understood effects of GHG's on the climate (IPCC-TGICA, 2007). The climate scenarios produced for this report were developed according to the guidance of the IPCC's TGICA "General Guidelines on the Use of Scenario Data for Climate Impact Adaptation Assessment (2007)".

1.1 OBJECTIVES

The objective of this technical memorandum is to characterize the historic climate and analyze an ensemble of future climate scenarios that can be used to examine the impacts of future climate (climate change) on the proposed Manitoba-Minnesota Transmission Project (MMTP).

1.2 STUDY AREA

The MMTP extends from the Dorsey Converter Station located northwest of Winnipeg, to the Manitoba-Minnesota border near Piney, MB. This project also includes upgrades to associated stations at Dorsey, Riel and Glenboro South, all in Manitoba. Project infrastructure, the Ecozones of the region (Marshall et al., 1999) and the locations of six Environment Canada climate stations used to study the region are illustrated in Figure 1. The study area falls primarily within the Prairie, Boreal Plain, and Boreal Shield Ecozones.

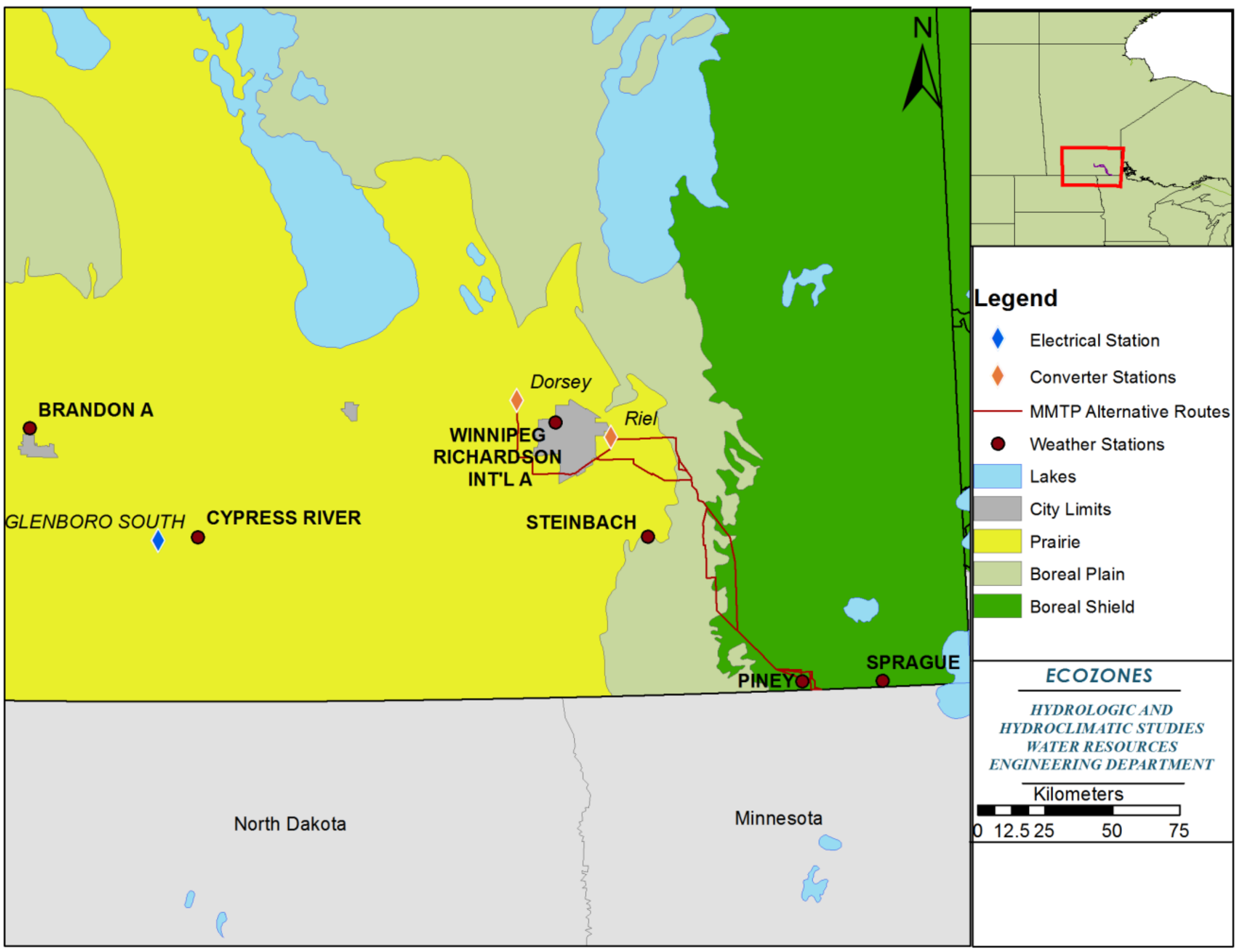


Figure 1 - Project Infrastructure, Climate Stations, and Ecozones

2.0 HISTORIC CLIMATE ANALYSIS

This section characterizes the current climate in the study area including normals and trends. Monthly, seasonal and annual time scales are considered. Seasons are divided as follows: Winter represents the months of December, January, and February. Spring represents the months of March, April and May. Summer represents the months of June, July and August. Autumn represents the months of September, October and November.

General climate characteristics coincide with ecozones shown in Figure 1. The MMTP spans the Boreal Shield, Boreal Plain, and Prairies ecozones. The Boreal Shield ecozone has a strong continental climate and is characterized by long, cold winters and short, cool summers (Smith, 1998). The Boreal Plain ecozone is characterized by cold winters and moderately warm summers while the Prairies ecozones climate is described as sub-humid to semiarid and has short, warm summers, long, cold winters, low levels of precipitation, and high evaporation (Smith, 1998). Winds are frequent and often strong in the Prairies ecozone, and precipitation in summer time is often localized, heavy storms (Smith, 1998).

The climate across the study area is characterised by regional influences that include relatively large diurnal temperature fluctuations, localized storms, large scale weather systems, specifically Alberta Clippers and Colorado Lows, and the occurrence of tornadoes in the summer. Data from climate stations in the three described ecozones are used in this study.

2.1 APPROACHES AND METHODOLOGY

The methodology for the data analysis is broken into three components: the climate normals analysis, the climate trends analysis, and the trends in extremes analysis.

2.1.1 CLIMATE NORMALS

Climate normals published by Environment Canada (EC) are used to describe the climatic characteristics of the study area. Climate normals are arithmetic calculations based on weather observations at a given location over a specified time period. The World Meteorological Organization (WMO) describes normals as averages of meteorological data computed over periods of thirty consecutive years. The WMO considers thirty years as a sufficient amount of time to eliminate year-to-year variations (i.e. natural climate variability). In order to capture the most recent data, Environment Canada has set the current thirty year period to 1981-2010, and is also used as the baseline period for the development of future climate scenarios described in Section 3.0.

Climate normals representing averages (temperature and wind) are calculated by applying the '3-and-5' rule which states that if more than 3 consecutive daily values are missing or more than 5 daily values in total in a given month are missing, the monthly mean should not be computed and the year-month mean should be considered missing (Environment Canada, 2014). For normals representing totals (precipitation), individual months must be 100% complete (Environment Canada, 2014).

Due to missing data, not all climate stations cover the complete 1981-2010 period. To distinguish the quality of a station's climate record, EC has assigned each climate station with a quality code ranging from A to D. Quality codes are established through length and completeness of the meteorological record at each station.

In the context of normals, EC reports the occurrence of extreme temperature, precipitation, and wind events. It is important to note the limitations of reporting on recorded extreme events. EC's database is periodically updated to include the latest measurements. However, analyses must be performed on a finite amount of data which is limited by the date of extraction. As such, the extreme values presented in this report are subject to change with time and should be checked to ensure the values used are the most current. In addition, the extreme events reported by EC are not restricted to the 1981-2010 normal period but rather based on the entire period of record for the given station.

2.1.2 CLIMATE TRENDS

A trend analysis of historic climate data was performed on mean temperature, total precipitation and mean wind speed to determine the statistical significance and magnitude of trend. Trend analysis uses homogenized data, which is designed for climate change studies and was also performed for the extreme indices discussed in Section 2.1.3. Trends are analyzed seasonally and annually.

Statistical significance of trends were analyzed using a computer program that implements the Mann-Kendall test for trend against randomness with the addition of an iterative pre-whitening and de-trending algorithm to compensate for autocorrelation effects (Zhang, 2000). Compensating for autocorrelation helps isolate the climate change signal by reducing noise due to the influence of one year's climate onto the following year. The Mann-Kendall test is a non-parametric method of evaluating the statistical significance of a trend against the null hypothesis that there is no trend, and is robust against non-normality and outliers. A statistical significance level of 5% is used, corresponding to a standard normal two-sided Z-statistic of 1.96. Positive Z-statistics correspond to positive correlations, and negative Z-statistics correspond to negative correlations.

Trend magnitudes are estimated based on Kendall's rank correlation tau statistic. Conceptually, this approach is equivalent to taking the median slope of all lines that can be drawn between all possible pairs of data points in the time series, rather than a weighted average as in the least squares process (Sen, 1968). Generally, this approach is less sensitive to outliers. Trend magnitudes are reported on a per-decade basis: °C/decade, (mm/year)/decade, (km/h)/decade. Seasonal and annual trends in temperature, precipitation, and wind speed for each station were evaluated.

The longest available record period was used in trend analyses. Date ranges are identified in Table 2 but were not always consistent for seasonal and annual records due to missing records for individual months. The date range represents the longest record available from the seasonal analysis. Note that trend analysis results are particularly sensitive to the time period in consideration and years with missing data.

2.1.3 TRENDS IN EXTREMES

A suite of extreme indices was used in order to identify and quantify the occurrence of extreme events (Table 1). Twelve temperature and ten precipitation based indices were selected from the Expert Team on Climate Change Detection and Indices (ETCCDI) publication (Klein Tank et al., 2009). These indices are based primarily on thresholds that have been defined as extreme climatic events in all climates, while some thresholds are percentile-based. Three additional indices were included in this report to account for extreme wind events: maximum daily mean wind speed (WDx), count of days with wind gusts that are greater than 70km/h (Wgx70), and count of days with wind gusts that are greater than 90km/h (Wgx90) (Cheng et al., 2014).

Table 1 - Extreme Event Indices

Identifier		Variable	Description
Temperature	**TNn**	Minimum of minimum temperature	Annual minimum value of the daily minimum temperatures
	TNx	Maximum of minimum temperature	Annual maximum value of the daily minimum temperatures
	TXn	Minimum of maximum temperature	Annual minimum value of the daily maximum temperatures
	TXx	Maximum of maximum temperature	Annual maximum value of the daily maximum temperatures
	DTR	Diurnal temperature range	Annual mean difference between maximum and minimum temperature
	GSL	Growing season length	Annual count between first span of at least 6 days with daily mean temperature TG>5^{o}C and first span after July 1st of 6 days with TG<5^{o}C.
	FD	Number of frost days	Annual count of days when TN (daily minimum temperature) < 0^{o}C.
	ID	Number of icing days	Annual count of days when TX (daily maximum temperature) < 0^{o}C.
	SU	Number of summer days	Annual count of days when TX (daily maximum temperature) > 25^{o}C.
	TR	Number of tropical nights	Annual count of days when TN (daily minimum temperature) > 20^{o}C.
	WSDI	Warm spell duration index	Annual count of days in a span of at least 6 days where TX > 90th percentile
	CSDI	Cold spell duration index	Annual count of days in a span of at least 6 days where TN > 10th percentile
Precipitation	**PRCPTOT**	Ann. total precipitation in wet days	Total precipitation in wet days (> 1 mm)
	SDII	Simple precipitation intensity index	Mean precipitation amount on a wet day
	R10mm	Heavy precipitation days	Annual count of days when precipitation ≥ 10mm
	R20mm	Very heavy precipitation days	Annual count of days when precipitation ≥ 20mm
	R95pTOT	Precipitation due to very wet days	Annual total precipitation when daily precipitation > 95p
	R99pTOT	Precipitation due to extremely wet days	Annual total precipitation when daily precipitation > 99p
	Rx1day	Max. one-day precipitation	Annual maximum 1-day precipitation
	Rx5day	Max. five-day precipitation	Annual maximum consecutive 5-day precipitation
	CDD	Consecutive dry days	Maximum number of consecutive days with daily precipitation < 1mm
	CWD	Consecutive wet days	Maximum number of consecutive days when daily precipitation ≥ 1mm
Wind	**WDx**	Max. daily mean wind speed	Annual maximum daily mean wind speed
	Wgx70	70km/hr wind gust days	Annual count of days when maximum wind gust speed ≥ 70 km/hr.
	Wgx90	90 km/hr wind gust days	Annual count of days when maximum wind gust speed ≥ 90 km/hr.

Prior to analysis, the datasets were screened for missing data in order to ensure that extreme indices were not being calculated on time series data that contained considerable amounts of missing values. Incomplete time series data sets were identified based on the description found in Donat et al. (2013), which was chosen because of its specific design for a climate extreme index dataset. This method required that any month with three or more missing daily observations was assigned a missing value, and that any year with one month with a missing value or 15 or more missing daily observations was assigned a missing value. Additionally, any day with three or more hours of missing data was assigned a missing value for the daily average calculations. After this screening process, each weather station was re-evaluated based on completeness of record.

Extreme indices are analyzed and reported on annual time frames. For the indices which use percentiles for extreme thresholds, the percentiles are calculated at a specific location for the entire period of record. As a result the percentile-based thresholds are unique to each location.

2.2 DATA SOURCES

The 1981-2010 climate normals used in this study were derived by EC and can be found online at: http://climate.weather.gc.ca/climate_normals/index_e.html (accessed September, 2014). Due to the limited availability of quality controlled data, not all stations or variables consider the same time frame for the calculation of normals (Table 2). Temperature and Precipitation normals are based on available data at Winnipeg, Steinbach, Piney, Sprague and Cypress River. Brandon data is used to supplement wind normals at Winnipeg. Currently, EC's quality checked database only extends to 2007 for most stations, despite the current nominal normal period end date of 2010. Data used in the calculation of normals may be subject to further quality assurance checks by EC.

Homogenized and adjusted datasets were used for climate and extreme event trend analysis where available. This dataset is produced by EC and referred to as the Adjusted and Homogenized Canadian Climate Data (AHCCD; Vincent et al., 2012; Mekis and Vincent, 2011; Wan et al., 2009). AHCCD accounts for changes in instrumentation, station relocations, and changes to observing practices during this period. AHCCD were not available for all climate variables at all stations. The Winnipeg station has the three parameters of interest (temperature, precipitation, and wind). The Steinbach weather station has AHCCD data for precipitation only. Piney had no AHCCD data. Sprague was added as a supplemental station with temperature and precipitation data to provide a north-south gradient for trend analysis. Trends analysis near Glenboro, used Cypress River data for temperature and precipitation and Brandon data for wind.

Table 2 - Climate Stations and Available Data

Station	EC ID	Latitude (°N)	Longitude (°E)	Elevation (m)	Dataset Properties			
					Parameter	Trend Time Period	Normals Time Period	Normals Code**
Winnipeg Richardson Int'l A	5023227	49.91	-97.24	238.7	Temperature	1872-2012	1981-2007	A
					Precipitation	1872-2007	1981-2007	A
					Wind	1953-2011	1981-2010	A
Steinbach	5022780	49.53	-96.77	253.6	Temperature	N/A	1981-2005	C
					Precipitation	1956-2012	1981-2005	C
					Wind	N/A	N/A	N/A
Piney	5022171	49.03	-96.01	325.5	Temperature	N/A	1981-2007	A
					Precipitation	N/A	1981-2007	A
					Wind	N/A	N/A	N/A
Sprague	5022760	49.02	-95.60	329.2	Temperature	1916-2012	1981-1998	D
					Precipitation	1916-2012	1981-1998	D
					Wind	N/A	N/A	N/A
Cypress River	5010640	49.55	-95.08	374.3	Temperature	1948-2012	1981-2010	A
					Precipitation	1949-2012	1981-2010	A
					Wind	N/A	N/A	N/A
Brandon	5010480	49.91	-99.95	409.4	Temperature	1890-2010	1981-2010	A
					Precipitation	1890-2012	1981-2010	A
					Wind	1958-2011	1981-2010	A

N/A: data for the climate parameter are unavailable.

**Normal Codes: A = World Meteorological Organization "3 and 5 rule" (i.e. no more than 3 consecutive and no more than 5 total missing for either temperature or precipitation), B = At least 25 years of data, C = At least 20 years of data, D = At least 15 year of data.

2.3 Results

2.3.1 Climate Normals

Temperature Normals (1981-2010) and Extremes

The average annual temperature in the study area ranges from 2.7°C at Sprague to 3.2°C at Piney. Figure 2 shows the average monthly temperatures across the project area. Table 3 shows the average annual temperature, temperature climate normals, and extreme maximum and minimum temperature recorded for each month for the meteorological stations used in this analysis. Little variability in mean monthly temperature was evident across the study area. Bolded values in each row represent the extreme temperatures recorded. Extreme minima fall below -40°C at all locations. Extreme maxima are above 35°C.

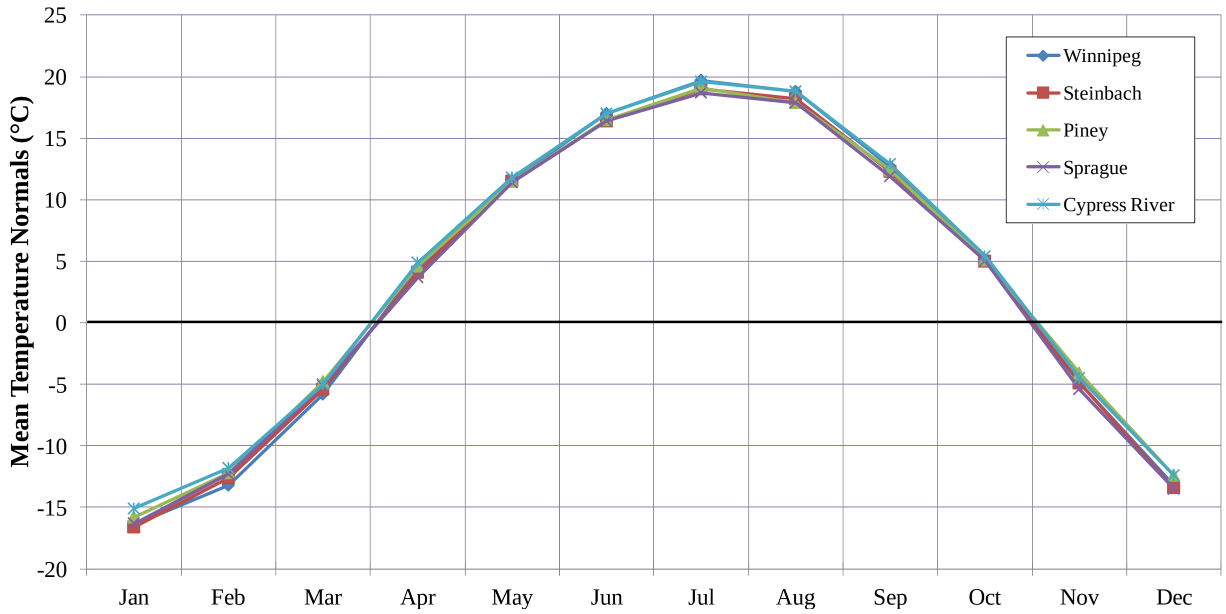


Figure 2 - Monthly Mean Temperature Normals (1981-2010)

Table 3 - Temperature Normals (1981-2010) and Extremes

	Parameter (°C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr
Winnipeg	**Daily Mean**	-16.4	-13.2	-5.8	4.4	11.6	17.0	19.7	18.8	12.7	5.0	-4.9	-13.2	3.0
	Extreme Maximum (1938-2007)	7.8	11.7	23.3	34.3	37.0	37.8	37.8	**40.6**	38.8	30.5	23.9	11.7	-
	Extreme Minimum (1938-2007)	-42.2	**-45.0**	-37.8	-26.3	-11.1	-3.3	1.1	0.0	-7.2	-17.2	-34.0	-37.8	-
Steinbach	**Daily Mean**	-16.6	-12.6	-5.4	4.1	11.5	16.4	19.0	18.2	12.3	5.0	-4.9	-13.4	2.8
	Extreme Maximum (1956-2005)	7.2	12.8	21.1	33.5	36.0	36.0	35.6	**37.5**	35.5	31.5	23.3	10.5	-
	Extreme Minimum (1956-2005)	-42.2	**-44**	-37.2	-27.5	-11.7	-3.3	1.0	-2.0	-7.8	-21.0	-36.0	-40.0	-
Piney	**Daily Mean**	-15.8	-12.2	-4.8	4.6	11.5	16.5	19.1	17.9	12.4	5.1	-4.1	-12.4	3.2
	Extreme Maximum (1980-2007)	9.5	11.5	18.0	31.0	33.0	35.0	**38.0**	36.5	35.0	29.0	19.0	9.5	-
	Extreme Minimum (1980-2007)	-46	**-48.5**	-38.5	-22.0	-9.0	-3.0	1.5	-3.0	-9.0	-20.0	-40.5	-43.5	-
Sprague	**Daily Mean**	-16.3	-12.3	-5.1	3.7	11.4	16.4	18.7	17.9	11.9	5.0	-5.4	-13.5	2.7
	Extreme Maximum (1915-1998)	11.1	12.8	23.9	33.3	35.0	36.7	**38.9**	36.0	35.0	30.0	22.2	9.4	-
	Extreme Minimum (1915-1998)	**-48**	-47.2	-45.6	-30.0	-13.3	-6.7	-1.7	-5.6	-11.1	-27.2	-40.0	-46.7	-
Cypress River	**Daily Mean**	-15.1	-11.8	-5.0	4.9	11.8	17.0	19.6	18.8	12.9	5.4	-4.5	-12.4	3.5
	Extreme Maximum (1904-2007)	7.2	12.0	19.4	37.0	38.0	40.5	**42.2**	39.4	37.2	33.0	23.3	13.3	-
	Extreme Minimum (1904-2007)	**-43.9**	-43.5	-38.9	-30.0	-12.2	-3.3	-1.1	-3.9	-10.6	-21.5	-36.7	-39.5	-

*Bolded values in each row represent the annual extreme temperatures recorded.

PRECIPITATION NORMALS (1981-2010) AND EXTREMES

Total precipitation accumulation varies throughout the study area from an annual average total annual precipitation of 521mm at Winnipeg to 637mm at Sprague. Total precipitation normals are presented in Figure 3 and Table 4. Table 4 also includes the sum of rainfall, snowfall in snow water equivalents, extreme maximum daily events of precipitation and bolded values represent the extreme daily precipitation on record for each station. Precipitation falling in the summer represents 47% of annual precipitation in Winnipeg.

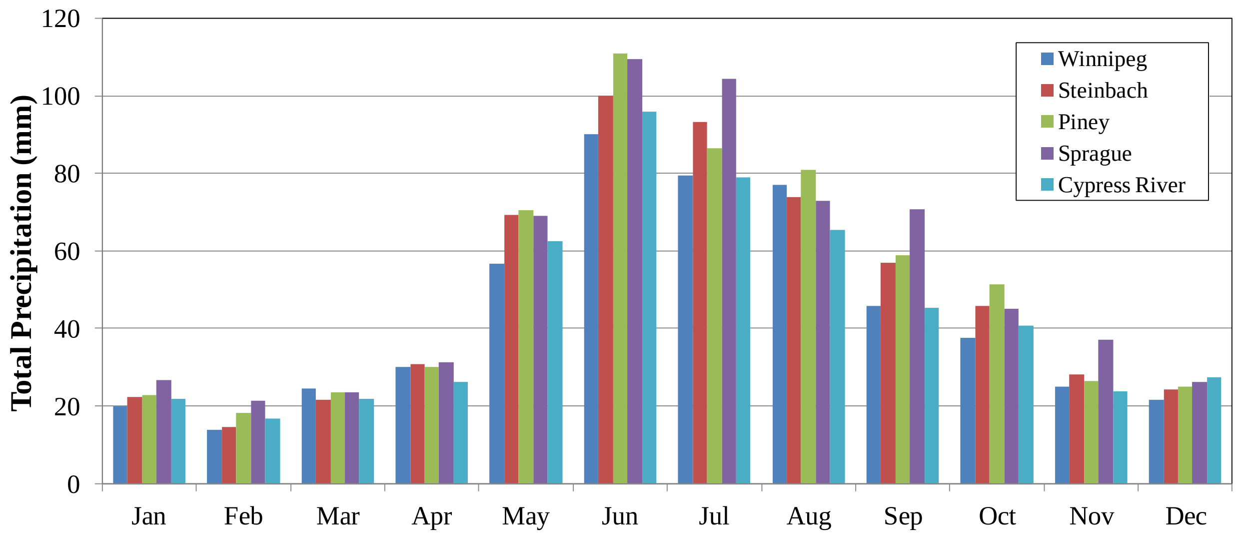


Figure 3 - Monthly Total Precipitation Normals (1981-2010)

Table 4 - Precipitation Normals (1981-2010) and Extremes

	Parameter (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr.
Winnipeg	**Precipitation**	19.9	13.8	24.5	30.0	56.7	90.0	79.5	77.0	45.8	37.5	25.0	21.5	521.1
	Extreme Daily Precipitation (1938-2007)	22.5	23.6	35.6	44.1	60.2	69.8	83.6	**83.8**	65	74.4	27.7	21.8	-
Steinbach	**Precipitation**	22.2	14.5	21.5	30.9	69.2	100.1	93.2	73.8	57.0	45.9	28.1	24.2	580.5
	Extreme Daily Precipitation (1956-2005)	17.8	18.8	43.8	60.5	68.1	57.0	**132.8**	81.4	96.5	59.2	30.4	17.0	-
Piney	**Precipitation**	22.9	18.2	23.5	30.1	70.4	111.0	86.6	81.0	59.0	51.4	26.5	25.0	605.6
	Extreme Daily Precipitation (1980-2007)	17.0	25.0	22.0	36.0	48.5	**149.0**	72.2	79.0	57.0	68.6	31.0	22.0	-
Sprague	**Precipitation**	26.6	21.3	23.5	31.3	69.1	109.4	104.5	73.0	70.7	45.0	37.1	26.1	637.5
	Extreme Daily Precipitation (1915-1998)	24.0	35.4	33.0	60.5	70.6	81.0	78.0	**109.0**	84.8	84.8	50.0	30.5	-
Cypress River	**Precipitation**	21.9	16.7	21.8	26.3	62.5	96	78.9	65.3	45.4	40.7	23.8	27.5	526.8
	Extreme Daily Precipitation (1904-2007)	21.0	41.6	30.5	41.9	51.3	101.6	78.0	**107.6**	71.1	57.9	36.2	30.0	-

*Bolded values in each row represent the annual extreme daily precipitation recorded

WIND NORMALS (1981-2010) AND EXTREMES

The mean annual wind speed (measured at 10 metres) in the study area ranges from 14.9 km/h at Brandon to 17.1 km/h at Winnipeg. Wind at Winnipeg most frequently blows from the south while wind at Brandon most frequently blows from the west or north east. Both stations have experienced extreme gust speeds exceeding 90 km/h in all months. The maximum observed gust speed ranges from 129 km/h at Winnipeg to 139 km/h at Brandon. Wind normals, maximum gust speeds and wind roses for Winnipeg and Brandon are presented in Table 5, Figure 4, Figure 5, and Figure 6.

Mean wind speed and direction varies across the study area. In addition to Winnipeg and Brandon, limited wind data for Sprague (not presented) were considered as supplementary information. It was found that Winnipeg recorded the greatest mean wind speed from the three stations. At an annual scale, the most frequent wind direction varies from South at Winnipeg to West at Brandon and North at Sprague.

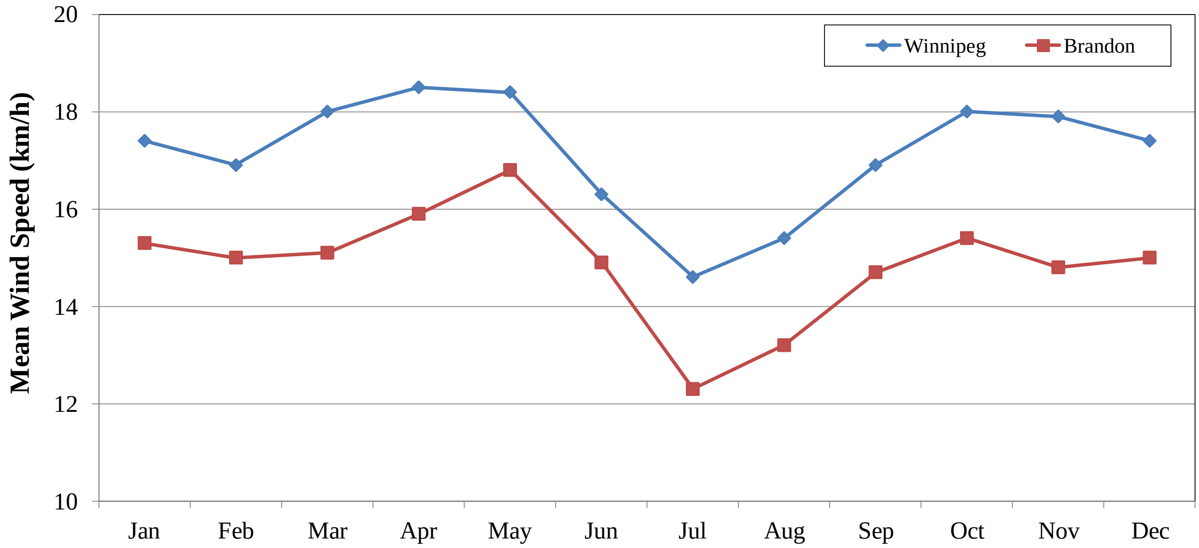


Figure 4 - Monthly Mean Wind Speed (1981-2010)

Table 5 - Wind Normals (1981-2010) and Extremes

	Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr.
Winnipeg	**Mean Wind Speed (km/h)**	17.4	16.9	18.0	18.5	18.4	16.3	14.6	15.4	16.9	18.0	17.9	17.4	17.1
	Most Frequent Direction	S	S	S	S	S	S	S	S	S	S	S	S	S
	Maximum Gust Speed (km/h) (1955-1994)	106	**129**	113	106	109	127	127	122	98	119	124	98	-
Brandon	**Mean Wind Speed (km/h)**	15.3	15.0	15.1	15.9	16.8	14.9	12.3	13.2	14.7	15.4	14.8	15.0	14.9
	Most Frequent Direction	W	W	W	NE	NE	W	W	W	W	W	W	W	W
	Maximum Gust Speed (km/h) (1961-2010)	117	121	95	115	109	130	**139**	119	111	107	115	98	-

*Bolded values in each row represent the annual extreme wind speed recorded.

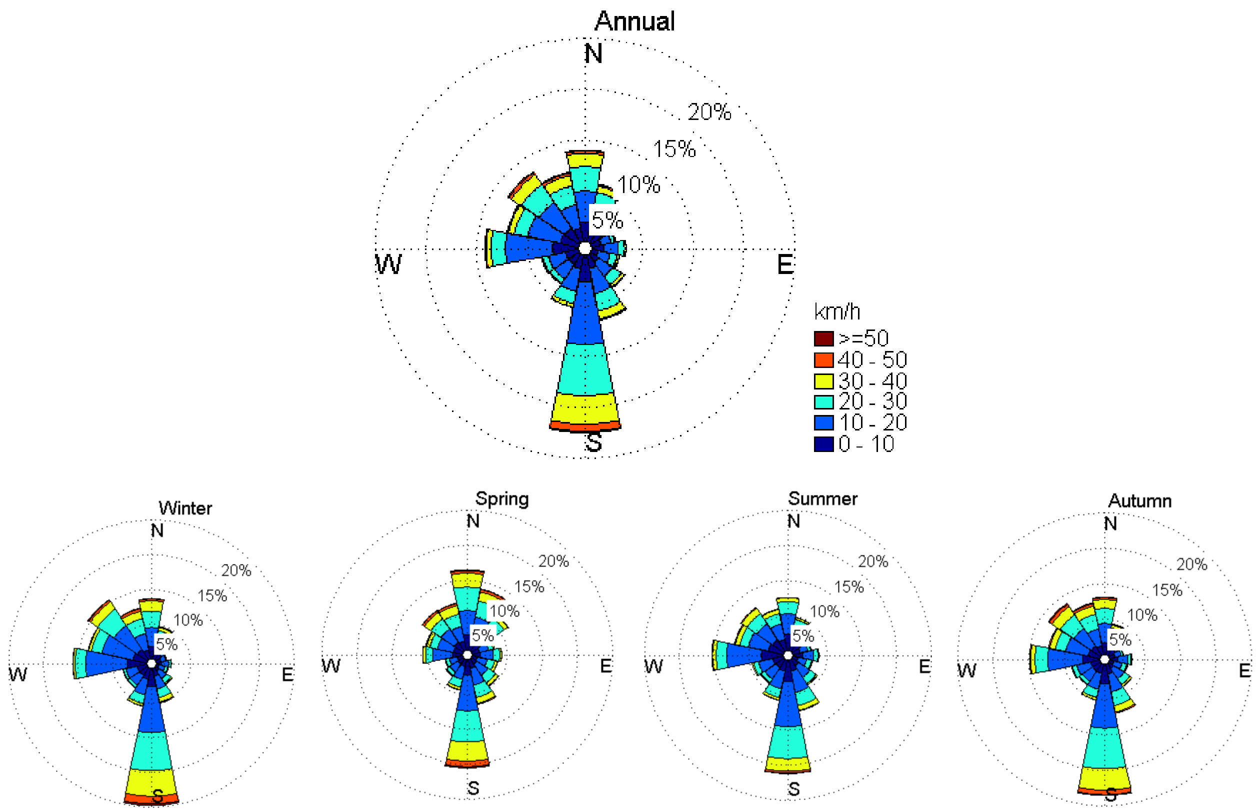


Figure 5 - Winnipeg Wind Roses for Hourly Wind Normals (1981-2010)

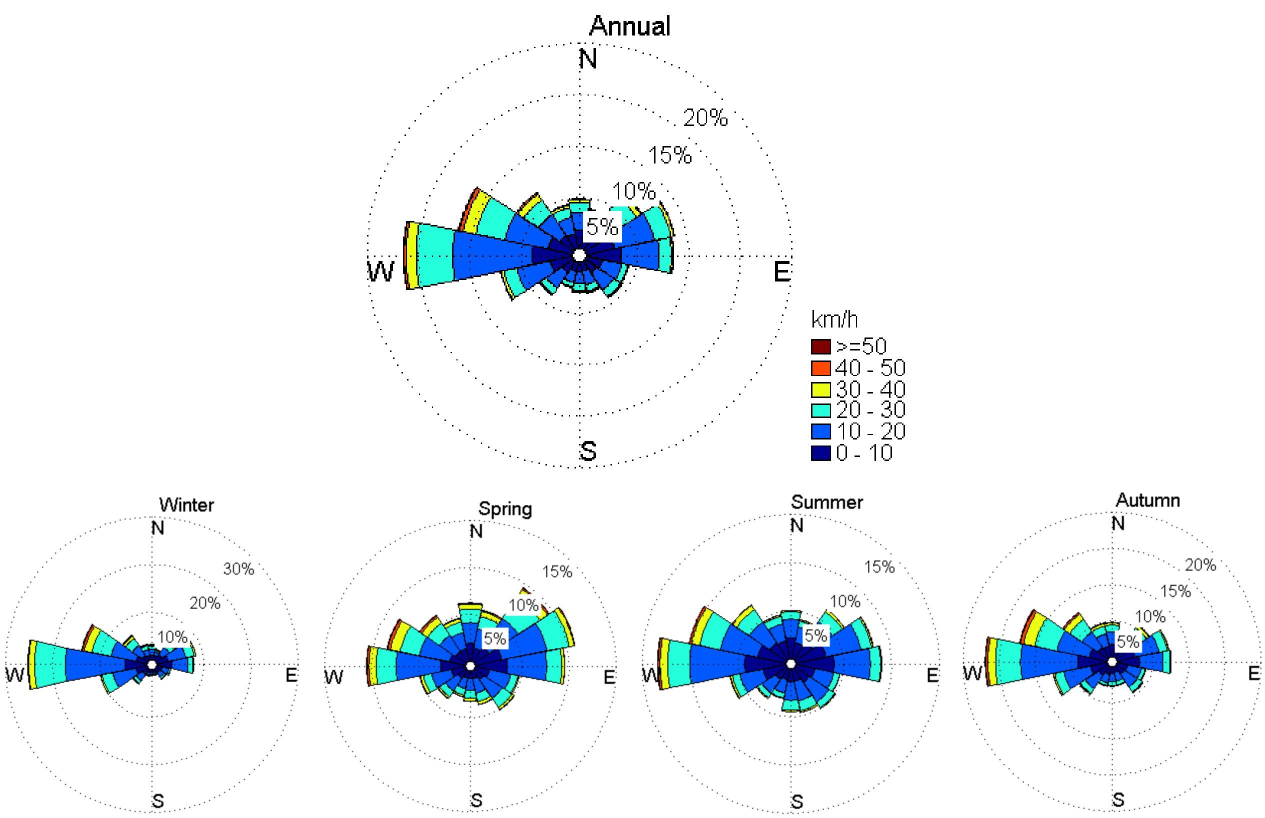


Figure 6 - Brandon Wind Roses for Hourly Wind Normals (1981-2010)

2.3.2 Climate Trends

The sections below characterize climate trends by temperature, precipitation, and wind speed. Results (statistical significance and magnitude) are shown in tables and summarized in the text.

Mean Temperature Trends

Mean temperature trends are shown in Table 6 for Winnipeg, Sprague, and Cypress River. Trends are reported in degrees Celsius per decade (ºC/dec.).

Annually: Statistically significant upward trends were detected at Winnipeg, Sprague, and Cypress River.

Seasonally: Statistically significant upward trends were detected for all seasons at Winnipeg and Sprague. Statistically significant upward trends were detected for winter, spring, and summer at Cypress River. Of the three seasons, winter showed the largest trends.

Table 6 - Summary of Mean Temperature Trends

Station	Maximum Period	Annual		Winter		Spring		Summer		Autumn	
		ºC/dec.	Zstat	ºC/ dec.	Zstat	ºC/ dec.	Zstat	ºC/ dec.	Zstat	ºC/ dec.	Zstat
Winnipeg	1872-2012	**0.19**	4.92	**0.30**	4.17	**0.21**	4.19	**0.10**	3.49	**0.16**	3.69
Sprague	1915-2012	**0.18**	3.70	**0.37**	3.29	**0.26**	3.69	**0.11**	2.34	**0.14**	2.13
Cypress River	1949-2012	**0.31**	2.68	**0.58**	2.62	**0.45**	2.71	**0.20**	2.21	0.25	1.70

* Bold values indicate statistically significant trends (ie. Zstat < -1.96 or Zstat > 1.96).

Total Precipitation Trends

Precipitation trends are shown in Table 7 for Winnipeg, Steinbach, Sprague, and Cypress River. Trends are reported in millimeters per year per decade ((mm/yr)/dec) which represents the rate of change in precipitation totals (per season or annum) per decade.

Annually: Statistically significant upward trends were only detected at Sprague.

Seasonally: Statistically significant upward trends were detected at Steinbach in winter and at Sprague in summer.

Table 7 - Summary of Total Precipitation Trends

Station	Maximum Period	Annual		Winter		Spring		Summer		Autumn	
		(mm/yr) / dec.	Zstat	(mm/yr) / dec.	Zstat	(mm/yr) / dec.	Zstat	(mm/yr) / dec.	Zstat	(mm/yr) / dec.	Zstat
Winnipeg	1872-2007	2.28	0.85	0.66	0.93	0.82	0.67	1.55	0.95	-1.02	-0.91
Steinbach	1956-2005	30.67	1.80	**6.38**	1.97	4.43	0.50	6.58	0.81	5.49	0.98
Sprague	1916-2007	**16.98**	3.11	0.22	0.19	2.75	1.38	**11.50**	3.44	4.08	1.71
Cypress R.	1949-2012	5.95	0.53	4.01	1.11	3.39	0.66	1.04	0.11	6.27	1.48

* Bold values indicate statistically significant trends (ie. Zstat < -1.96 or Zstat > 1.96).

MEAN WIND SPEED TRENDS

Mean wind speed trends are shown in Table 8 for Winnipeg and Brandon. Trends are reported in kilometers per hour per decade ((km/h)/dec).

Annually: Statistically significant downward trends were detected at both Winnipeg and Brandon.

Seasonally: Statistically significant downward trends were detected at Winnipeg and Brandon in all seasons.

Table 8 - Summary of Mean Wind Speed Trends

Station	Maximum Period	Annual		Winter		Spring		Summer		Autumn	
		(km/h)/ dec.	Zstat	(km/h)/ dec.	Zstat	(km/h)/ dec.	Zstat	(km/h)/ dec.	Zstat	(km/h)/ dec.	Zstat
Winnipeg	1953-2011	**-0.65**	-5.98	**-0.58**	-5.21	**-0.83**	-5.96	**-0.47**	-4.99	**-0.70**	-5.91
Brandon	1953-2011	**-0.55**	-5.74	**-0.48**	-4.13	**-0.57**	-4.05	**-0.54**	-5.97	**-0.51**	-4.57

* Bold values indicate statistically significant trends (ie. Zstat < -1.96 or Zstat > 1.96).

CLIMATE TREND SUMMARY

While trend significance and magnitude vary in space and time, there is general agreement that mean temperatures have historically increased (IPCC, 2013) and mean wind speeds have historically decreased (Wan et al., 2010). There is less agreement among stations and seasons for total precipitation, which are generally noisier. The two stations with statistically significant precipitation trends both showed increases. As a result of climate change, extrapolation of historic climate trends into the future is not recommended as the future will not necessarily be a simple continuation of past climate trends (IPCC, 2013).

Climate trends using the longest available record were compared to trends for 1958-2005 which is common among all stations and parameters. Both time periods generally agree on the direction of trends but some differences exist for certain variables and seasons. Despite differences, both time periods show strong evidence that winter mean temperature, winter minimum temperature and spring minimum temperature have increased, regionally. Both time periods also show evidence that mean wind speed has decreased and very few significant precipitation trends were detected. Generally, a larger number of statistically significant temperature trends were detected using the longer record compared to the common period but common period trends were of larger magnitude.

2.3.3 TRENDS IN EXTREME EVENTS

Trend analyses of 25 historic extreme indices were conducted at Winnipeg, Sprague, Steinbach, Cypress River, and Brandon and are presented in Table 9. AHCCD data from Environment Canada were used for the analysis, but not all stations had data for all the variables of interest.

For temperature based indices, statistically significant upwards trends were detected for minimum and maximum temperature, growing season length, and number of tropical nights. Statistically significant downward trends were detected for diurnal temperature range, number of frost days, number of ice days and cold spells. Long-term temperature data were unavailable for Steinbach.

For precipitation based indices, statistically significant upward trends were detected for total precipitation on wet days, very heavy precipitation days, and consecutive wet days. Statistically significant downward trends were detected for the simple precipitation intensity index and consecutive dry days.

For wind speed based indices, data were only available for Winnipeg and Brandon. Statistically significant decreasing trends were detected at Winnipeg for maximum wind gusts above 90km/h and at Brandon for annual maximum mean daily wind speed. These results are in agreement with findings in Wan et al. (2010), showing decreasing wind speed trends across the prairies.

While not all locations agreed on trend significance, the direction of statistically significant trends are in agreement.

Table 9 - Historical Direction of Annual Trends in Extreme Indices

Extreme Index		Location and Observed Trend				
		Winnipeg (1872-2012)	Sprague (1916-2012)	Steinbach (1956-2012)	Cypress River (1948-2012)	Brandon (1890-2012)
Temperature	TNn	▲	◎	-	◎	▲
	TNx	▲	◎	-	◎	◎
	TXn	▲	◎	-	◎	▲
	TXx	◎	◎	-	◎	◎
	DTR	▼	▼	-	◎	◎
	GSL	▲	◎	-	◎	◎
	FD	▼	▼	-	◎	▼
	ID	◎	▼	-	◎	◎
	SU	◎	◎	-	◎	◎
	TR	▲	◎	-	◎	◎
	WSDI	◎	◎	-	▲	◎
	CSDI	▼	◎	-	◎	◎
Precipitation	PRCPTOT	◎	▲	▲	◎	◎
	SDII	◎	▼	◎	▼	▼
	R10mm	◎	◎	◎	◎	◎
	R20mm	◎	▲	◎	◎	◎
	R95p	◎	◎	◎	◎	◎
	R99p	◎	◎	◎	◎	◎
	Rx1day	◎	◎	◎	◎	◎
	Rx5day	◎	◎	◎	◎	◎
	CWD	◎	▲	◎	◎	◎
	CDD	◎	▼	▼	▼	▼
Wind	WDx	◎	-	-	-	▼
	Wgx70	◎	-	-	-	◎
	Wgx90	▼	-	-	-	◎

Legend

Temperature, Precipitation, and Wind Extremes:

- ▲ (green) Winnipeg (1872-2012)
- ▲ (black) Sprague (1916-2012)
- ▲ (orange) Steinbach (1956-2012)
- ▲ (red) Cypress River (1948-2012)
- ▲ (blue) Brandon (1890-2012)

The direction of each triangle corresponds to the direction of the trend.

◎ indicates no significant trend at statistical significance level of 5%.

- indicates that data were unavailable for the station.

Refer to Figure 1 for definitions and descriptions of the extreme indices.

3.0 FUTURE CLIMATE SCENARIOS

This section presents projected future climate scenarios for the study area for temperature, precipitation, and wind speed. Seasons are divided as in Section 2.0: Historic Climate Analysis.

3.1 APPROACH AND METHODOLOGY

Climate scenarios provide views of how the future might unfold under various conditions including radiative forcing scenarios (described in Section 3.1.2.1). An understanding of the climate system, climate change, and scenario development is important in the development of future climate scenarios.

3.1.1 THE CLIMATE SYSTEM AND CLIMATE CHANGE

When studying climate change, it is important to distinguish between weather and climate. Weather refers to the day-to-day state of the atmosphere while climate refers to the weather statistics (means, variability, extremes, etc.) over a certain time-span and certain area (IPCC, 2013). Climate can vary by location depending on the latitude, vegetation cover, distance to a large body of water, topography, and other geographic features and processes (such as volcanoes and ocean currents).

Probability distributions can be useful in distinguishing between weather, which occurs day-to-day, and climate which is a more general characterization. An illustrative example in Figure 7 shows the maximum daily temperature events during 1981-2010 at Winnipeg, represented as a time series plot and as an empirical Cumulative Distribution Function (CDF). The CDF illustrates statistical characteristics including the minimum, median, and maximum values as well as information about variability and shape of the distribution. F(x) denotes the cumulative probability density between zero and one.

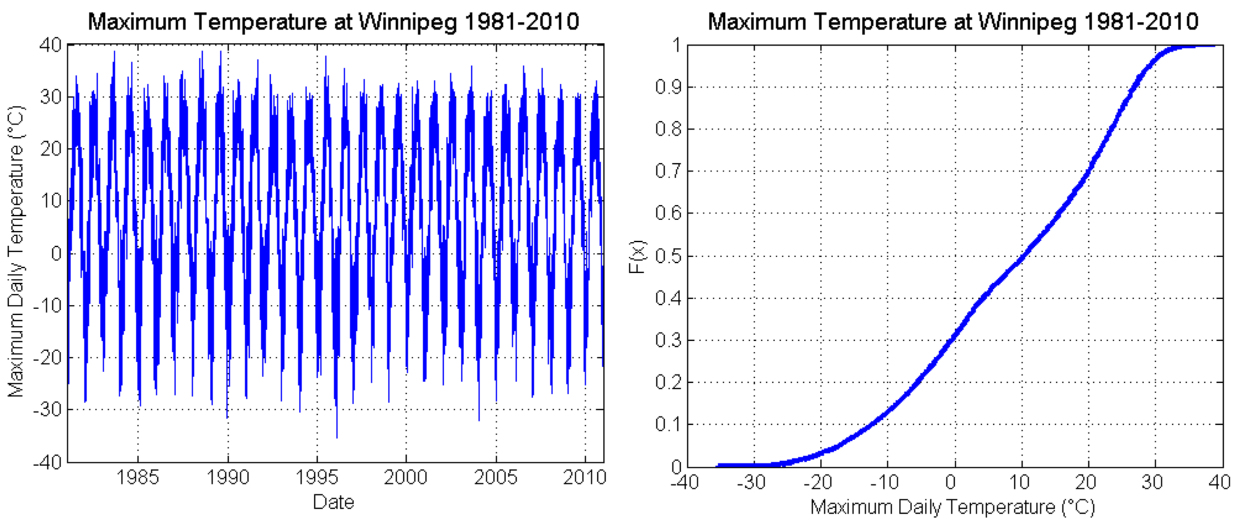


Figure 7 - Winnipeg Maximum Temperature (1981-2010) Time Series and Empirical CDF

The IPCC refers to climate change when there is a statistically significant variation to the mean state of the climate that usually persists for decades or longer and which includes shifts in the frequency and magnitude of sporadic weather events as well as the slow continuous rise in global mean surface temperature (IPCC, 2013). The climate system is extremely complex and is linked by physical processes including fluxes of mass, heat, and momentum. The IPCC has stated that observed warming of the climate system is unequivocal and that human influence on the climate system is clear (IPCC, 2013).

Climate varies naturally and change can occur through external and internal factors (IPCC, 2013). Natural climate variability can be related to external processes such as shifts in radiative forcing (e.g. volcanic eruptions) or internal processes such as the El Niño Southern Oscillation (ENSO). The climate may respond slowly or rapidly and can lead to periods of colder or warmer temperatures. According to IPCC, the last 10,000 years have seen global surface temperature fluctuations of less than 1°C, with some fluctuations lasting centuries (IPCC, 2013).

3.1.2 Climate Scenarios Derived from Global Climate Models

GCMs are the most advanced tools for simulating the response of the global climate system to changes in external forcing such as atmospheric GHG concentrations. GCMs simulate past and present climate and are used to project future climatic change by simulating the interaction of the atmosphere, ocean, and land surface. They solve physical equations that describe the movement of energy, momentum, conservation of mass, and other large scale processes. GCMs are used to simulate a wide range of periods but the simulations designed for climate change assessments cover the period between 1850 and 2100. The models typically operate with a horizontal grid resolution on the order of hundreds of kilometers and 18 to 95 vertical levels (Sillmann et al, 2013). Despite challenges in climate modeling, including those related to coarse resolutions, GCMs are able to reproduce historic warming patterns quite well (Knutti, 2008).

3.1.2.1 Radiative Forcing Scenarios

In order to project future climate, radiative forcing scenarios called Representative Concentration Pathways (RCPs) are used to prescribe the levels of GHGs and aerosols in the atmosphere. To do so, a number of assumptions are made about how society will evolve and the scenarios represent different demographic, social, economic, regulatory, technological, and environmental developments. Radiative forcing scenarios are used in GCMs to simulate the evolution of climate over time in response to changes in atmospheric forcing agents.

RCPs were developed by the independent research community and are accepted for use in future climate modeling. RCPs are named according to their radiative forcing in 2100 based on GHGs and other sources. An overview of the four RCPs and their development can be found in van Vuuren (2011) and are summarized in Table 10. Figure 8 illustrates the RCP's projections of carbon dioxide

(CO_2) concentrations and modeled global surface warming. Radiative forcing energy is measured in W/m^2 (watts per square metre).

Table 10 - Representative Concentration Pathways, adapted from van Vuuren (2011)

RCP	Description and Radiative Forcing	CO_2 eq (ppm)
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 by 2100	~1370 ppm
RCP6.0	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100	~850 ppm
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100	~650 ppm
RCP2.6	Peak in radiative forcing at ~3 W/m^2 before 2100 and then a decline to 2.6 W/m2 by 2100	~490 ppm

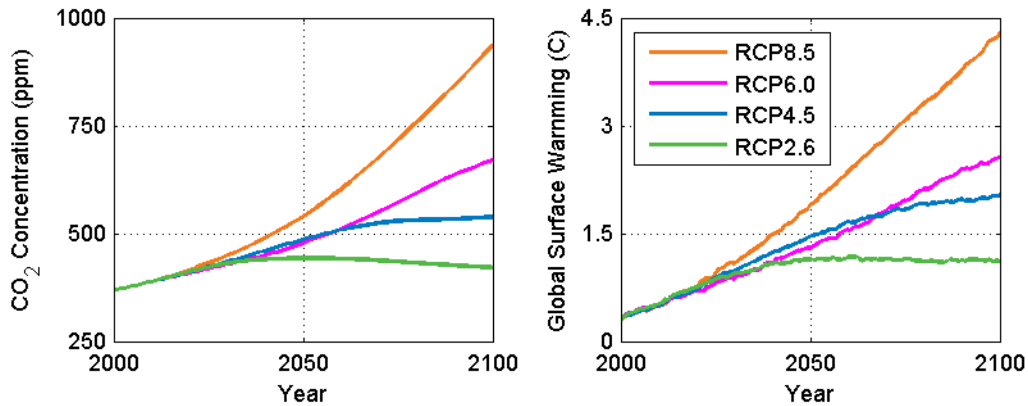


Figure 8 - RCP CO_2 Concentrations (left) and Projected Global Surface Warming (right)

RCP8.5 is associated with the greatest warming effect by year 2100, followed by RCP6.0, RCP4.5 and RCP2.6. Le Quéré et al. (2009) and Raupach and Canadell (2010) indicate that recent CO_2 concentrations and emission growth rates have exceeded IPCC's previous emissions scenarios (Nakicinovic et al., 2000) and they are currently tracking just above RCP8.5 (Sanford et al., 2014). However, since it is not possible to know how the future will unfold, all four RCPs are currently considered to be equally probable and as suggested by van Vuuren (2011), the four scenarios must be considered in future climate analysis in order to capture the range of variability in climate change projections. The range in GHG emissions between RCPs helps to illustrate an important part of the uncertainty inherent in modeling of future climate.

3.1.2.2 Temporal and Spatial Domain

The temporal domain of this study consists of one baseline period and three future periods, taken from climate model simulations. The baseline period represents the historic climate with which future climate information is combined to quantify climate change. Thus, the baseline period serves as the reference point from which changes in future climate are calculated (IPCC-WG1, 2001). Consistent with Section 2.0 of this report, 1981-2010 is used as the baseline period. The three future horizons are: 2010-2039 (referred to as the 2020s), 2040-2069 (the 2050s), and 2070-2099 (the 2080s). In general, climate change signals in short-term projections (i.e.: pre-2050s) are often masked by natural climate variability and longer term projections show a more prominent climate change signal.

Climate models use grids and grid points for computations. Grids represent spatial areas and points are used to store the grid data. Spatial resolution varies among models. The primary spatial domain for this study consists of the climate model grid point nearest to Winnipeg (49.91°N and 97.24°W). A single point is selected for GCM analysis due to relatively large grids with respect to the study area and the intent to capture extremes, which can otherwise be smoothed when spatial averages are computed over multiple grids. Multiple grid points near the study area were considered for supplementary analysis using finer resolution RCM data. All selected climate model grids are classified as land.

3.1.2.3 Quantile Mapping

Quantifying projections of climate change and developing future climate scenarios requires that systematic biases present in GCMs be accounted for. In this report, quantile mapping (Mpelasoka and Chiew, 2009; Watanabe et al., 2012; Chen et al., 2013; Wilke et al., 2013) of empirical distribution functions is used to account for bias in GCM data. Quantile mapping (e.g.: "daily scaling" and "daily translation" methods in Mpelasoka and Chiew, 2009) is a rank-based statistical method which enables assessment of projected climate change impacts on the mean climate as well as the tail ends (upper and lower quantiles; extremes) of the climatic CDFs.

The fundamental process underlying quantile mapping is the development of adjustment factors which represent differences between the baseline climate and future climate CDFs. Figure 9 illustrates this calculation. Depending on available data, adjustment factors are developed annually or monthly and for different sized bins of quantiles. The bin size refers to the number of quantiles that are grouped together to calculate an adjustment factor.

For temperature and precipitation, daily GCM data is used to produce monthly adjustment factors that are then combined with daily historic data to develop future climate scenarios. For wind speed, monthly GCM data are used to develop annual adjustment factors.

To aid understanding, the methodology is described separately for quantile mapping of daily GCM temperature and precipitation and quantile mapping of monthly GCM wind speed data. Adjustment factors are reported for three bins and also reported as per the traditional Delta method which represents the change in mean climate (see "constant scaling method" in Mpelasoka and Chiew, 2009).

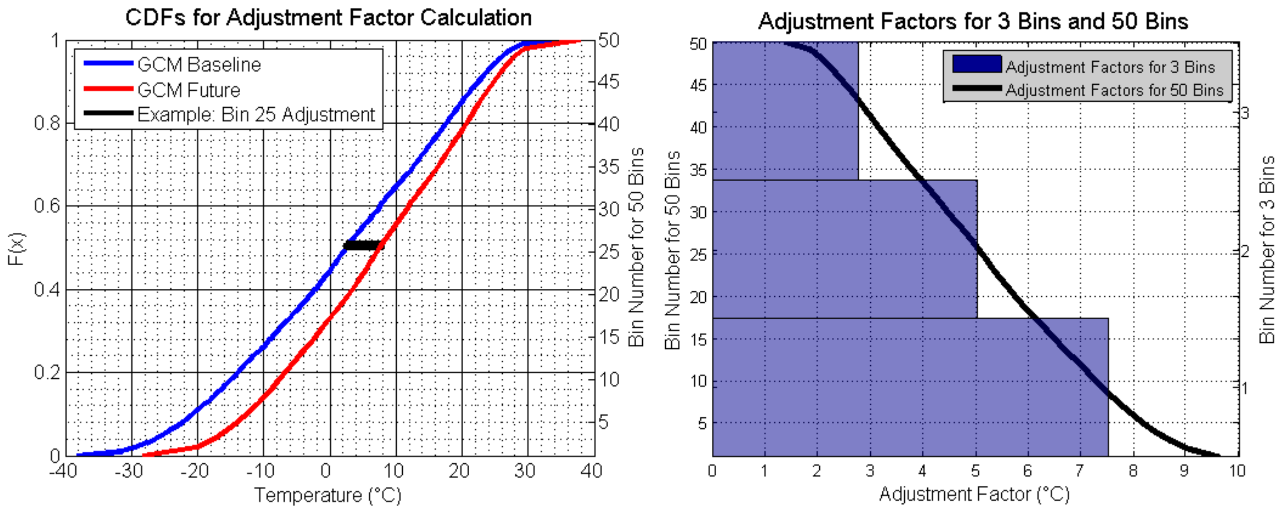


Figure 9 - Quantile Mapping Example (CDFs Left; Adjustment Factors Right)

3.1.2.4 Temperature and Precipitation

As in Mpelasoka and Chiew (2009), the daily scaling quantile mapping method is applied in two steps: Step 1 calculates adjustment factors for 50 bins by comparing CDFs of GCM future climate and GCM baseline climate. Step 2 applies these adjustment factors to the baseline historic climate to develop daily time series of future climate scenarios. This method accounts for changes in extreme events followed by an additional adjustment to preserve the GCM's climate change signal in the monthly mean climate. Adjustment factors are calculated as absolute values for minimum temperature, maximum temperature, and as percent changes for precipitation.

In rare instances a further adjustment is required to correct the Diurnal Temperature Range (DTR, difference between daily minimum and maximum temperatures). This adjustment is required when a future day exhibits a minimum temperature that exceeds the maximum temperature and can occur because minimum temperature and maximum temperature are quantile mapped individually. This adjustment preserves historic diurnal temperature range normals for a given month plus the GCM projected climate signal on the mean future diurnal temperature range for the same month.

Step 1 Examples: Calculation of adjustment factors ($\Delta_{m,b}$) for maximum temperature and precipitation bins (b) for a specific month (m)

$$\Delta\, Tmax_{m,b} = Tmax_{m,b}^{GCM\ Future} - Tmax_{m,b}^{GCM\ Baseline}$$

$$\Delta\, P_{m,b} = \frac{P_{m,b}^{GCM\ Future} - P_{m,b}^{GCM\ Baseline}}{P_{m,b}^{GCM\ Baseline}}\ x\ 100$$

Step 2 Examples: Application of adjustment factors to historic record to develop future climate projections for maximum temperature and precipitation.

$$Tmax^{Future\ Scenario} = Tmax_{m,b}^{Observed} + \Delta\, Tmax_{m,b}$$

$$P^{Future\ Scenario} = P_{m,b}^{Observed} * \left(\frac{\Delta\, P_{m,b}}{100}\right)$$

To aid in comparison with other variables and to condense the presentation of information, adjustment factors for temperature and precipitation are calculated annually and averaged for three bins. This process is described in further detail in the section below.

3.1.2.5 Wind Speed

Given the novel nature of future wind speed studies, projections are developed using a simplified approach. The approach reflects limited scientific understanding, experience and support available for studying climate change impacts on wind speed. Monthly GCM data is used to produce annual adjustment factors, thereby increasing the sample size which forms the CDFs.

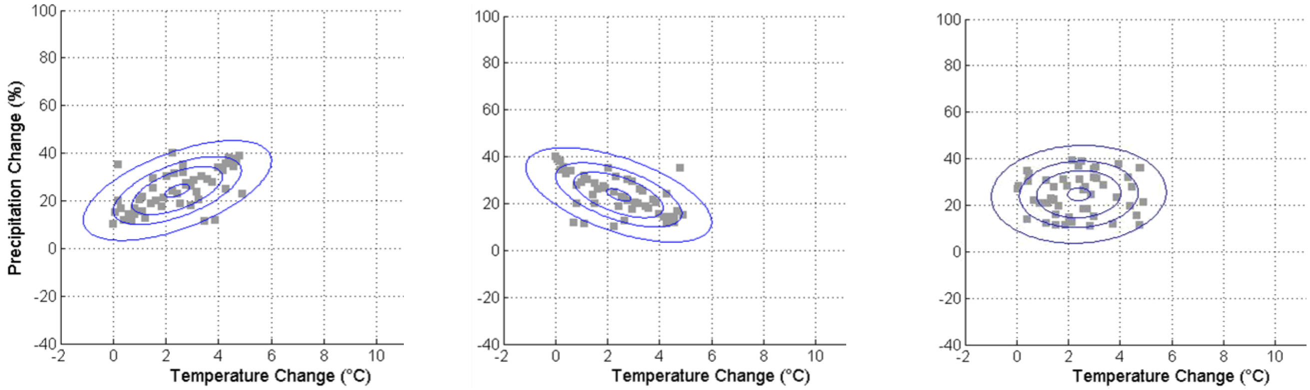
Results are presented for annual adjustment factors aggregated into three bins. The first bin (1-33rd percentile) represents changes to the occurrence of months with lower average wind speed. The second bin (33-66th percentile) represents the changes to the occurrence of months with typical average wind speed. The third bin (66-99th percentile) represents changes to the occurrence of months with higher average wind speeds. The 0th and 100th percentile change are omitted to smooth the calculation by avoiding large spikes in the tail ends of the empirical distribution function.

3.1.2.6 Specialized Graphics Used to Present Climate Change Projections

Scatter plots, CDFs, and box plots are used to illustrate the future climate projections.

Annual and seasonal scatter plots illustrate the correlation between precipitation and mean temperature changes (Figure 16). Each point represents temperature changes and the corresponding precipitation change projected by one GCM simulation, calculated using the Delta method (see “constant scaling method” in Mpelasoka and Chiew, 2009).

To analyze the range of projections, distribution ellipses are superimposed on the plots. Distribution ellipses encompass the specified percentage of adjustment factors (50%, 75%, and 95%) assuming a bivariate normal distribution. Ellipse geometry reflects the degree of correlation between the variables. Ellipses collapse diagonally as the correlation approaches +1 (positive covariance) or -1 (negative covariance). Figure 10 illustrates example ellipses showing positive covariance, negative covariance and no correlation. This analysis does not represent the probability of occurrence, as the projections are considered equally probable.



Positive Covariance **Negative Covariance** **No Correlation**

Figure 10 - Example Ellipses Showing Different Types of Covariance

Box plots and CDFs are also used to illustrate projected climate change. Similar to CDFs (see Figure 12), box plots represent multiple probability density functions in a single figure (see Figure 11 as an example). Box plots are used to illustrate the entire ensemble of GCM projections. The median projection is marked by a red line; the blue boxes represent the inter-quartile range (25th percentile to 75th percentile; IQR). Whiskers represent the distribution tails up to 1.5 times the IQR and red "+" markers illustrate outliers.

3.1.3 Projection of Trends in Extreme Indices

Several types of extreme events originate from the interactions between mechanisms of very different spatial and temporal scales. Because GCMs operate at rather coarse spatial resolution, they are able to represent large scale processes but those smaller than the grid size need to be parameterized. As a result, many small-scale processes that are key drivers in the development of some extreme events are not well simulated by these GCMs. Unfortunately, scientific knowledge of some of those processes is not sufficient to develop a parameterization. Of particular importance for extreme events are the processes that involve feedback mechanisms. For instance, some of the land-atmosphere interactions, ocean-atmosphere interactions, stratospheric processes, and blocking dynamics, are often poorly understood or represented in climate models (IPCC SREX, 2012).

The Canadian Regional Climate Model (CRCM) was selected for the analysis of future extreme events because its finer resolution allows for an improved representation of some of the feedback mechanisms compared to the coarse resolution GCMs

Daily CRCM minimum temperature, maximum temperature, total precipitation and mean wind speed data is bias corrected using quantile mapping. The daily translation method (Mpelasoka and Chiew, 2009) is used in this application to correct and analyze the entire 1961-2100 time series. Two CRCM grid points nearest to Winnipeg and Cypress River were used to analyze future trends in extreme temperature, precipitation, and wind speed indices. Trend directions for each location are reported separately, as a qualitative indicator of changes in extremes within the study area.

Due to the small number of CRCM projections used is this study, it is not possible to establish a confidence level for the projection of extreme events. Furthermore, it is important to reiterate the novel nature of future wind speed studies. The approach followed in this study only shows how one model (CRCM4.2.3) projects future extreme events to change and results should be interpreted with caution. To supplement CRCM results, this study presents findings the IPCC's assessment on extreme events (IPCC SREX, 2012). However, the IPCC's assessment is conducted on larger spatial scales and is not necessarily a direct representation of the study area.

The IPCC's Fifth Assessment Report (AR5) discusses extreme events, outlines issues associated with extreme event analysis, and provides summaries of the findings (IPCC 2013). The results are characterized by phenomenon type, expected changes, region affected, time period examined and confidence in the expected change. Relevant findings are presented in Section 3.3.2. Other weather events including freezing precipitation, tornadoes, lightning strikes, drought, and forest fires are also explored. However, due to difficulties in defining these events, uncertainties in measuring them and limitations in climate model output, the analysis is qualitative and relies on a review of published literature.

3.2 Data Sources

A primary ensemble of 69 GCM simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) that was supplied by Ouranos Consortium was used in this report. These simulations originate from 15 GCMs that were presented in the IPCC's Fifth Assessment Report (AR5) and include simulations driven by all four RCP scenarios (IPCC, 2013). The 69 simulations were selected such that each simulation had daily output for minimum temperature, maximum temperature and precipitation for the required future time periods. A subset of 60 common simulations with monthly wind speed data were also used in the analysis of future wind speed. While simulation availability is expected to grow, as modeling agencies make their output available, this report uses available GCM data as of May 2014. Not every GCM has output from all four RCPs. Several GCM and RCP combinations include multiple runs (members) where the same GCM and RCP is used, but the initial conditions of the simulation is slightly changed such that natural climate variability can be explored. Each simulation is considered equally plausible, and all must be given consideration in future climate analysis (IPCC 2013). Details of the GCMs used in this study can be found in Table 11.

Quantile Mapping of GCM and CRCM data also uses observed data from Environment Canada climate stations, which are gap filled where possible, using gridded Natural Resources Canada (NRCan) data. NRCan data is spatially interpolated using the Australian National University ANUSPLINE method (Hutchinson et al., 2009) at a 10km by 10km grid. Daily NRCan data is based on observed data, and as expected, the data at the grid point nearest to the weather stations correlate well with observations. Due to the absence of observed wind speed data at Cypress River, Brandon wind speed data was used to bias correct CRCM data. Brandon and Cypress River are located in adjacent CRCM grid cells.

Output from the Canadian Regional Climate Model 4.2.3 (CRCM) (de Elía and Côté, 2010; Music and Caya, 2007; Caya and Laprise, 1999) is used to supplement GCM analysis and analyze trends in future climate extremes. CRCM4.2.3 data were generated and supplied by Ouranos (http://www.ouranos.ca/) where the model was run over the North-American domain with a 45 km horizontally spaced grid. CRCM simulations “aet”, “aev”, and “agx” were chosen for an analysis of the time series of extreme indices as these runs offer the longest continuous period of simulation (1961-2100). Details on the CRCM runs can be found in Table 12. CRCM simulations were driven by atmospheric fields taken from older CMIP3 GCMs and the previous vintage of emission scenarios (Nakicenovic et al., 2000). Currently, three CRCM simulations are available for the time periods assessed in this study. These simulations are driven by two different GCMs (Table 12) and the A2 emission scenario (Nakicenovic et al., 2000), which is most comparable to RCP8.5. RCP8.5 produces warmer future conditions than the A2 emission scenario (Knutti and Sedlacek, 2012).

Table 11 - Global Climate Model Simulation Information

Institution Abbrev.	Model	Institution Full Name
BCC	BCC-CSM1.1 BCC-CSM1.1(m)	Beijing Climate Center, China Meteorological Administration
GCESS	BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University
CCCma	CanESM2	Canadian Centre for Climate Modelling and Analysis
CMCC	CMCC-CESM CMCC-CM CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici
INM	INM-CM4	Russian Institute for Numerical Mathematics
MIROC	MIROC-ESM-CHEM MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC	MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MPI-M	MPI-ESM-LR MPI-ESM-MR	Max Planck Institute for Meteorology (MPI-M)
MRI	MRI-CGCM3	Meteorological Research Institute
NCC	NorESM1-M	Norwegian Climate Centre

Table 12 - Canadian Regional Climate Model 4.2.3 Simulation Information

Driving GCM	Emission Scenario	Simulation ID	Simulation Years
CGCM3.1 T47 (run #4)	A2	aet	1961-2100
CGCM3.1 T47 (run #5)	A2	aev	1961-2100
ECHAM5 (run #1)	A2	agx	1961-2100

3.3 Results

Results are separated by variable and by time period and are presented in a manner that addresses projected changes to the mean climate and projected changes to extremes. Figures focus on the 2050s, where figures for the 2020s and 2080s can be found in Appendix B.

3.3.1 Global Climate Model Projections

This section summarizes results from available GCM simulations. Statistics for 69 simulations are presented for temperature and precipitation while statistics for a subset of 60 simulations are presented for wind speed. Data at grid points near Winnipeg and Cypress River were extracted and analyzed. A comparison of the results from Winnipeg and Cypress River showed that the GCM projections for both locations are similar. Therefore, results for Winnipeg alone are presented.

3.3.1.1 Future Temperature

The 69 GCM simulation ensemble average projects:

- The maximum temperature to change by an annual average of +1.5°C in the 2020s, +2.8°C in the 2050s and +4.0°C in the 2080s. All simulations are in agreement that maximum temperatures will increase in all three time periods. The variability in the change to temperature among simulations ranges from +0.2°C to +2.7°C in the 2020s, from 0.9°C to +5.7°C in the 2050s, and from +1.1°C to +8.7°C in the 2080s.
- The average temperature to change by an annual average of +1.5°C in the 2020s, +2.9°C in the 2050s and +4.1°C in the 2080s. All simulations are in agreement that average temperature will increase in all three time periods. The variability in the change to temperature among simulations ranges from +0.2°C to +2.7°C in the 2020s, from +1.1°C to +5.6°C in the 2050s, and from +1.3°C to +8.7°C in the 2080s.
- The minimum temperature to change by an annual average of +1.5°C in the 2020s, +3.0°C in the 2050s and +4.2°C in the 2080s. All simulations are in agreement that minimum temperature will increase in all three time periods. The variability in the change to temperature among simulations ranges from +0.2°C to +2.6°C in the 2020s, from +1.3°C to +5.5°C in the 2050s, and from +1.4°C to +8.7°C in the 2080s.

Winter months are generally projected to experience greater changes in temperature than summer months, however there is variability on the magnitude of monthly temperature changes among GCM simulations. Monthly and annual ensemble average projections are summarized in Table 13. Lineplots and Boxplots in Figure 11 illustrate the projected changes from the ensemble of 69 GCM simulations and the future climate normal projections.

Table 13 - GCM Ensemble Average Projected Temperature Changes at Winnipeg (°C)

Variable		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
2020	Maximum Temperature	1.8	1.5	2.0	1.4	1.2	1.2	1.4	1.5	1.3	1.2	1.3	1.6	1.5
	Mean Temperature	2.0	1.8	2.1	1.5	1.2	1.2	1.3	1.4	1.3	1.1	1.4	1.8	1.5
	Minimum Temperature	2.3	2.0	2.2	1.4	1.1	1.1	1.2	1.3	1.3	1.1	1.4	2.0	1.5
2050	Maximum Temperature	3.4	3.2	3.6	2.9	2.2	2.4	2.8	2.9	2.7	2.3	2.5	3.2	2.8
	Mean Temperature	3.9	3.7	3.8	2.8	2.2	2.3	2.6	2.7	2.6	2.2	2.6	3.7	2.9
	Minimum Temperature	4.4	4.1	4.0	2.6	2.2	2.2	2.5	2.6	2.5	2.2	2.7	4.1	3.0
2080	Maximum Temperature	4.6	4.5	4.8	4.0	3.1	3.4	3.9	3.7	3.7	3.2	3.7	4.3	4.0
	Mean Temperature	5.4	5.2	5.0	3.8	3.1	3.3	3.7	3.9	3.6	3.2	3.8	1.9	4.1
	Minimum Temperature	6.1	5.8	5.2	3.7	3.1	3.2	3.5	3.8	3.6	3.2	3.9	5.4	4.2

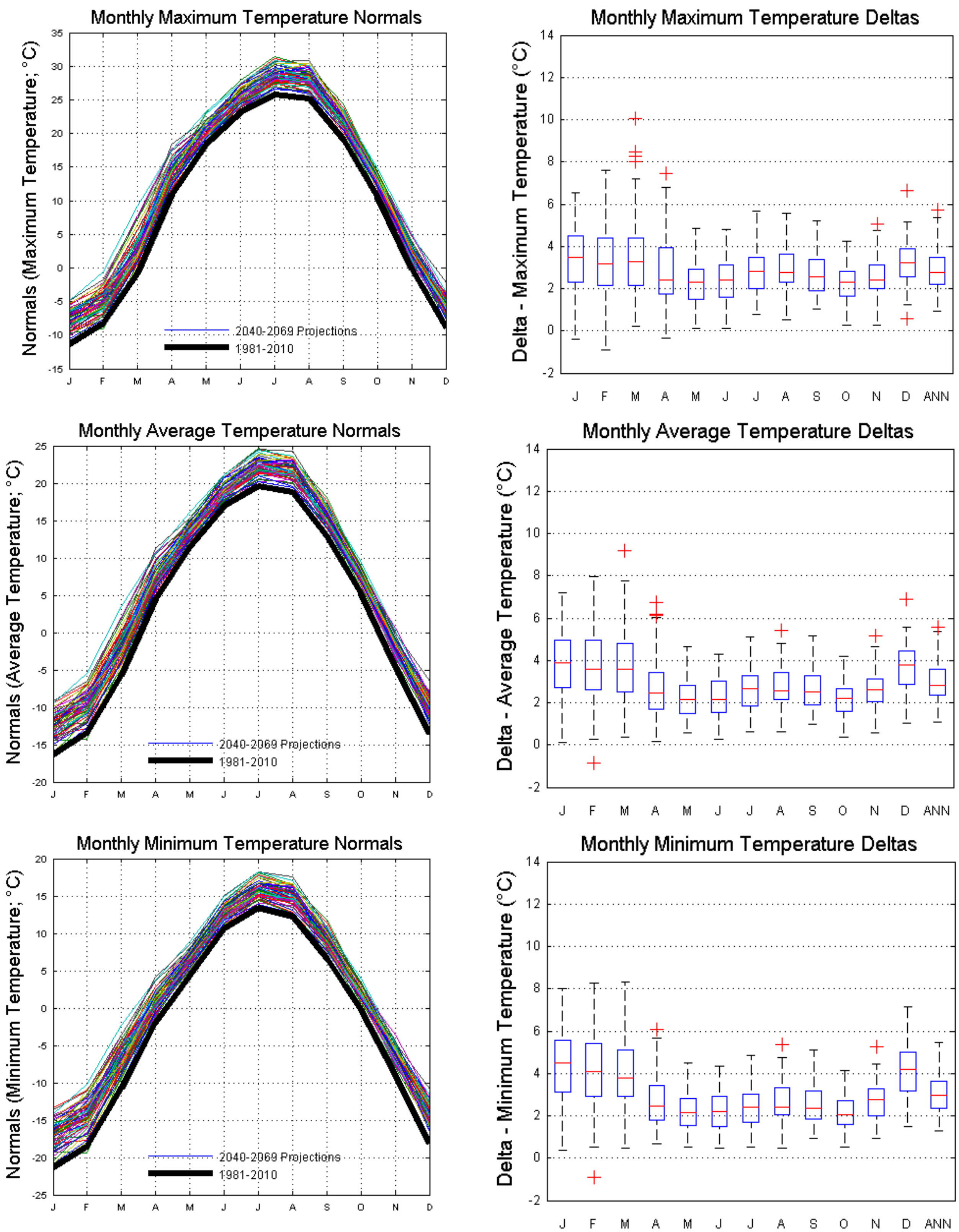


Figure 11 - Future Temperature Normals and Projected Changes at Winnipeg (2050s)

Comparison of temperature CDFs show non-uniform changes with a tendency for greater changes to the low percentile bin (colder temperatures) in comparison to the medium percentile and high percentile bins. Changes to the CDFs can be generalized by computing ensemble average changes for three bins; a low percentile bin (cold extremes) a medium percentile bin (medium temperatures) and a high percentile bin (warm extremes). These ensemble averaged changes to the temperature distribution function are included below in Table 14.

Table 14 - GCM Ensemble Average Projected Changes (°C) to Temperature CDF at Winnipeg

Bin	Minimum Percentile	Maximum Percentile	Minimum Temperature			Maximum Temperature		
			2020s	2050s	2080s	2020s	2050s	2080s
3 (warm)	66	99	1.3	2.4	3.5	1.4	2.7	3.6
2 (median)	33	66	1.2	2.4	3.4	1.4	2.7	3.7
1 (cold)	1	33	2.1	4.2	5.7	1.7	3.2	4.4

This non-uniform change in projections suggests that extreme cold temperatures are projected to become less extreme. However, despite the GCM ensemble average projection, analysis of individual simulations shows potential for increased variability. The differences between the results from the 69 simulations are evident in the CDFs shown in Figure 12.

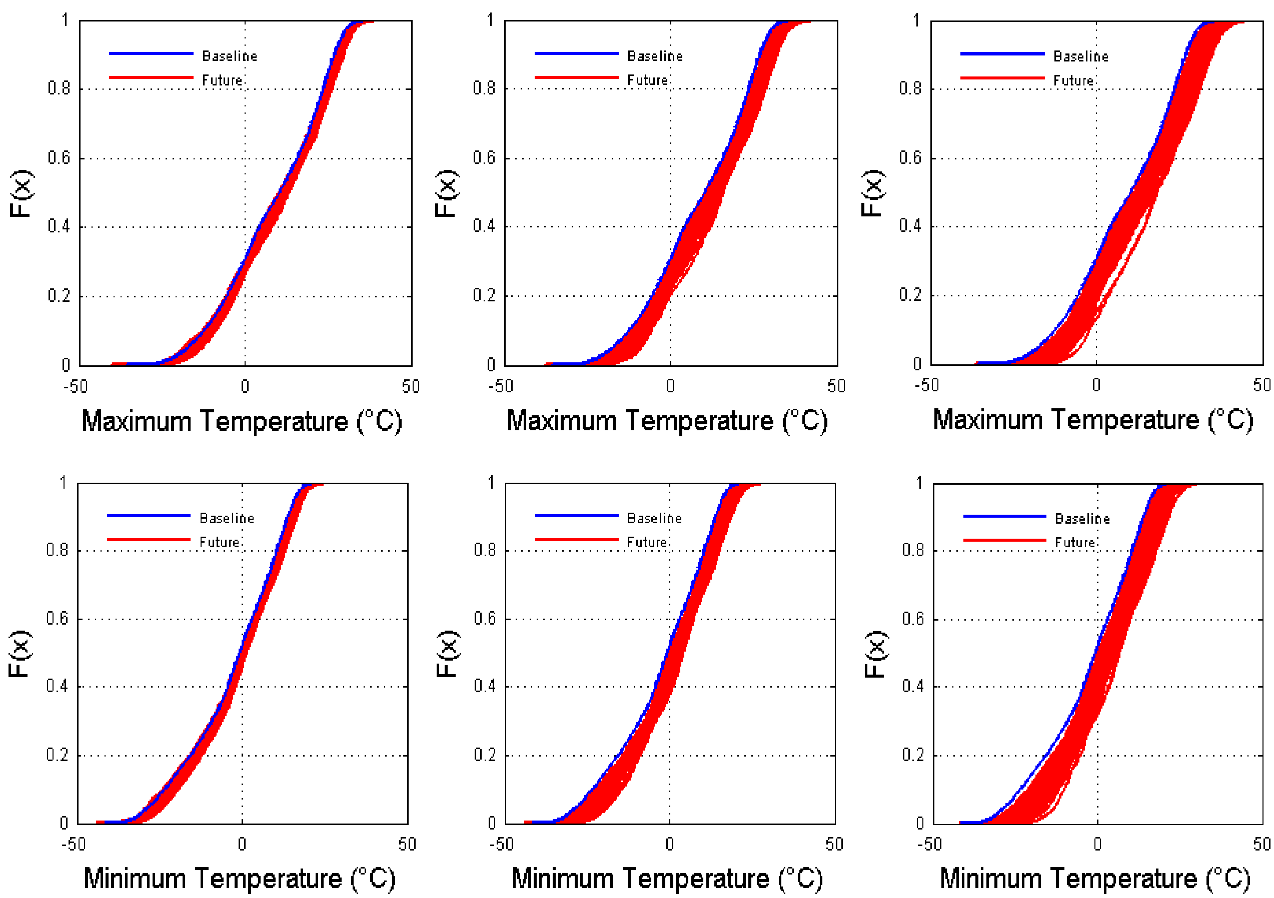


Figure 12 - Max (top) and Min (bottom) Temperature at Winnipeg (2020s left; 2050s center; 2080s right).

3.3.1.2 Future Precipitation

The 69 GCM simulation ensemble average projects:

- Total annual precipitation to change by +3.5% in the 2020s, +4.2% in the 2050s and +6.7% in the 2080s. Most simulations are in agreement that total annual precipitation will increase in all three time periods. The variability among simulations for the changes in precipitation range from -6.0% to +11.6% for the 2020s, from -4.8% to +17.7% for the 2050s, and from -3.2% to +23.6% for the 2080s.

Analysis at the monthly scale shows that winter months are generally projected to experience greater relative changes in precipitation than summer months, with some summer projections centered near zero (that is, projections of little change in precipitation). Figure 13 illustrates the projected changes from the ensemble of 69 GCM simulations and the future climate normal projections. Monthly and annual ensemble average projections are summarized in Table 15.

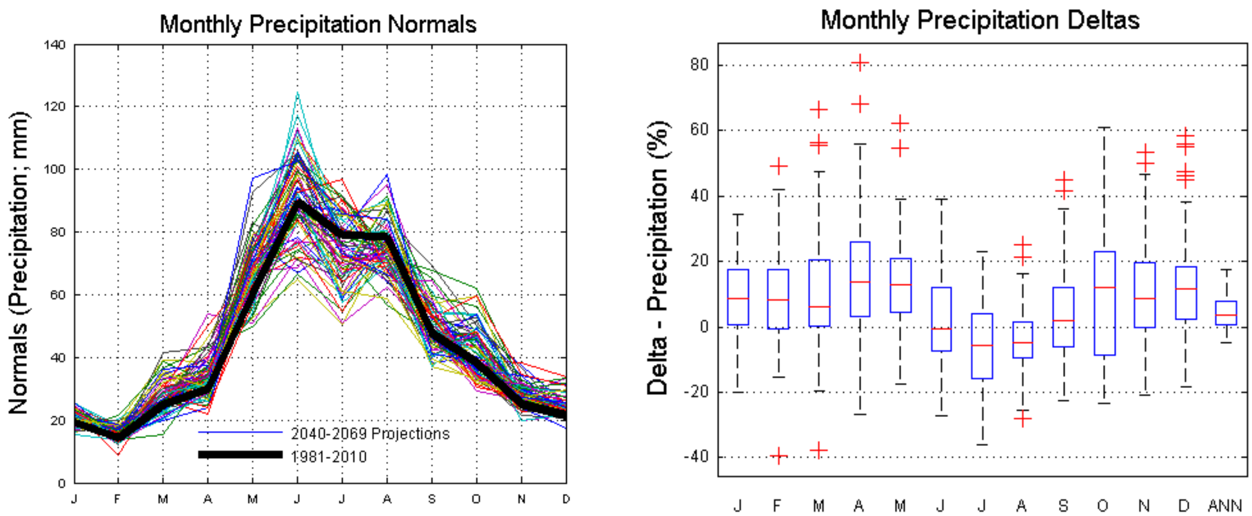


Figure 13 - Future Precipitation Normals and Projected Changes at Winnipeg (2050s)

Table 15 - GCM Ensemble Average Projected Precipitation Changes at Winnipeg (%)

	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
2020s	**Total Precipitation**	6.2	7.5	3.5	6.5	8.0	3.8	0.3	-1.9	2.1	7.3	5.3	6.3	3.5
2050s	**Total Precipitation**	8.6	9.3	10.6	15.7	12.6	1.2	-6.0	-3.9	3.5	10.1	10.7	13.9	4.2
2080s	**Total Precipitation**	13.1	15.7	15.5	23.2	15.5	4.0	-5.3	-5.1	5.1	16.3	11.8	15.5	6.7

Since the most frequently occurring value in the daily precipitation record is zero, the probability distribution is skewed. In order to better assess changes to the precipitation CDFs, the precipitation time series are further divided into two categories; days with precipitation (wet days) and days without precipitation. Days with 0.2mm or more precipitation characterize a wet day which is the smallest non-zero value in the observed record. Wet days are then separated into three bins representing days with low precipitation (<0.8mm) days with medium amounts of precipitation (0.8mm to 3.0mm) and days with larger amounts of precipitation (>3.0mm). Note that the 0.8mm and 3.0mm thresholds approximately correspond to the 33rd and 66th percentile in the historic record.

Projected changes to the CDFs for daily wet day precipitation generally show a uniform percent change among the three bins (Table 16). However, this relative change corresponds to different absolute changes depending on the bin. For example, in the 2050s, the ensemble average +4.2% change in the high bin (days with >3.0mm) corresponds to a larger total volume change (i.e.: more water) than the ensemble average +8.9% change in the low bin (days with <0.8mm). Table 16 contains the ensemble average changes calculated for each bin. The CDFs are shown in Figure 14.

Table 16 - GCM Ensemble Average Projected Changes to Precipitation CDF at Winnipeg

Bin	Minimum Percentile	Maximum Percentile	Precipitation Change in Occurrence		
			2020s	2050s	2080s
3 (high)	66	99	3.4%	4.2%	12.5%
2 (medium)	33	66	3.2%	4.3%	12.7%
1 (low)	1	33	1.3%	8.9%	11.8%

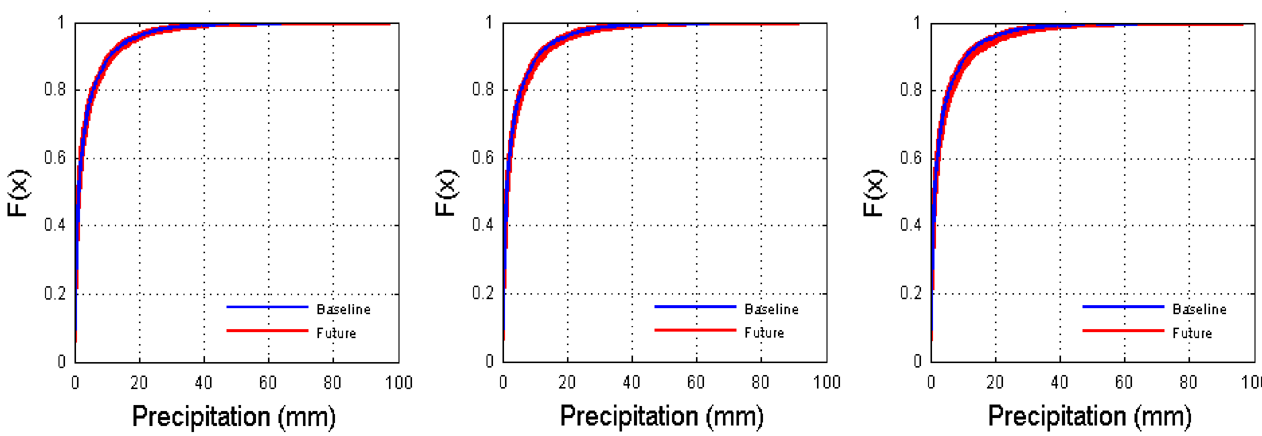


Figure 14 - Daily Precipitation on Wet Days at Winnipeg (2020s left; 2050s center; 2080s right).

3.3.1.3 PROJECTED WIND SPEED

The 60 GCM simulation ensemble average projects:

- Average annual wind speed to change by -0.7% in the 2020s, -1.4% in the 2050s and -2.1% in the 2080s. There is considerable disagreement on the direction of change (increase or decrease) in average annual surface wind speed. The variability among projections ranges from wind speed changes of -4.0% to +2.5% in the 2020s, -9.7% to +3.9% in the 2050s, and -12.6% to +3.2% in the 2080s.

Analysis at the monthly scale shows that the largest projected changes occur in summer and are projected to decrease. The projected changes in wind speed in non-summer months are close to zero. However, there is little agreement on the projected direction of change in monthly wind speed among GCM simulations, suggesting that there is considerable uncertainty in future wind speed projections. The boxplot in Figure 15 illustrates the projected changes from the ensemble of 60 GCM simulations. Monthly and annual ensemble average projections are summarized in Table 17.

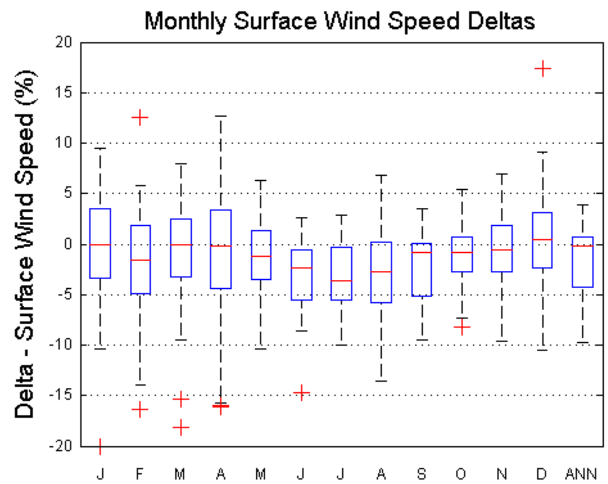


Figure 15 - Projected Changes (2050s) in Average Monthly Surface Wind Speed at Winnipeg

Table 17 - GCM Ensemble Average Projected Wind Speed Changes at Winnipeg (%)

	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
2020s	**Mean Surface Wind Speed**	-0.2	-0.7	-0.2	-0.2	-0.6	-1.2	-1.5	-1.8	-1.4	-0.5	-0.7	0.6	-0.7
2050s	**Mean Surface Wind Speed**	-0.4	-1.8	-0.7	-0.7	-1.3	-3.0	-3.0	-2.9	-2.1	-0.9	-0.6	0.5	-1.4
2080s	**Mean Surface Wind Speed**	-0.7	-2.0	-1.1	-1.1	-1.9	-4.7	-4.3	-4.1	-3.7	-1.4	-0.9	0.3	-2.1

Generally, the ensemble average projects small changes in wind speed among the three bins. Similar to monthly average wind speed projections, there is little agreement among GCM simulations regarding the direction of change. As such, these results should be interpreted with caution and supplemented with additional information as the science matures. One note of interest is that the GCM ensemble average shows months with lower baseline wind speed projecting larger relative decreases compared to months with higher baseline wind speeds. Ensemble average bin changes are reported in Table 18.

Table 18 - GCM Ensemble Average Projected Changes to Surface Wind Speed CDF at Winnipeg

Bin	**Minimum Percentile**	**Maximum Percentile**	**Wind Speed Change**		
			2020s	**2050s**	**2080s**
3 (high)	66	99	-0.5%	-1.0%	-1.5%
2 (medium)	33	66	-0.7%	-1.4%	-2.0%
1 (low)	1	33	-1.0%	-2.0%	-3.0%

3.3.1.4 Future Temperature and Precipitation Covariance

Annual and seasonal scatter plots for the 2050s are shown in Figure 16. Individual GCM simulations are shown with blue markers and the ensemble averages are shown as larger red markers. Ensemble average changes (deltas) are reported within the figure for easy reference.

Annually, very little correlation exists between projected changes in mean temperature and precipitation. Slight positive correlation is seen in winter and autumn (increasing temperature and precipitation) while summer shows negative correlation (increasing temperature and decreasing precipitation). In spring, projected changes in mean temperature and precipitation are not well correlated. Those seasonal correlations are consistent with the various mechanisms responsible for the precipitation and temperature changes (IPCC, 2013).

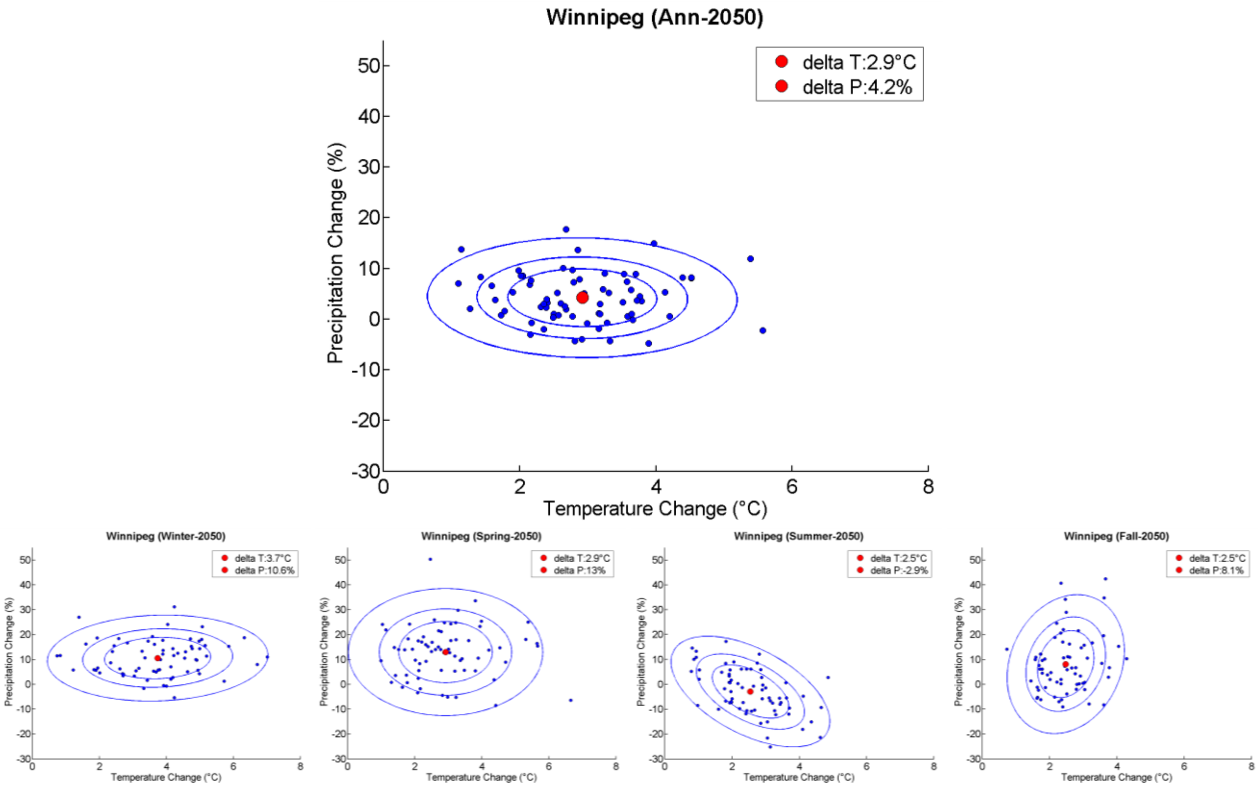


Figure 16 - Annual (top) and Seasonal (bottom) Covariance Scatter Plots (2050s)

3.3.2 PROJECTED CHANGES IN CLIMATE EXTREMES

3.3.2.1 Canadian Regional Climate Model Projections

Trends in extreme indices were projected for the period of 1961-2099 using three bias-corrected CRCM simulations. Table 19 displays the projected direction of trends for CRCM grid points near two Environmental Canada climate stations used in this analysis. Trends are only noted if they are statistically significant for two or three simulations. Somewhat more confidence is given to the trends that have all three runs of the CRCM in agreement. However, it is important to reiterate that the results are not robust and provide only a low level of confidence, since they are only based on a single RCM.

At both locations, the three CRCM simulations show agreement in trend direction and significance for 15 extreme indices. (TNn, TNx, TXn, TXx, GSL, FD, ID, SU, TR, WSDI, CSDI, PRCPTOT, SDII, R10mm, and R95pTOT). Temperature trends show increased frequency and severity of heat extremes (TNx, TXx, GSL, SU, TR, WSDI) and reduced frequency and severity of cold extremes (TNn, TXn, FD, ID, CSDI). Precipitation trends show increasing wet-day precipitation (PRCPTOT, SDII), increasing number of heavy precipitation days (R10mm) and increasing total annual precipitation due to very wet days (R95pTOT).

To test spatial variability, 1961-2099 data from five non-bias corrected CRCM points along the proposed MMTP route were further examined. All three CRCM simulations at the five grid points agreed on direction and significance of the trends for the 15 noted extreme indices.

Table 19 - Projected Trends in Annual Extreme Indices from Bias Corrected CRCM Simulations

Extreme Index	CRCM Trend (1961-2099)		Legend	
TNn	▲	▲	▲ (green)	Winnipeg
TNx	▲	▲	▲ (red)	Cypress River
TXn	▲	▲		
TXx	▲	▲	▲	3/3 CRCM simulations agree on direction and significance of trend
DTR	▽	▼		
GSL	▲	▲		
FD	▼	▼		
ID	▼	▼		
SU	▲	▲		
TR	▲	▲	△	2/3 CRCM simulations agree on direction and significance of trend
WSDI	▲	▲		
CSDI	▼	▼		
PRCPTOT	▲	▲		
SDII	▲	▲		
R10mm	▲	▲		
R20mm	△	▲		
R95pTOT	▲	▲	◎ indicates no significant trends or a significant trend for only one simulation	
R99pTOT	◎	△		
Rx1day	◎	◎		
Rx5day	◎	◎		
CWD	◎	◎	Refer to Figure 1 for definitions and descriptions of the extreme indices.	
CDD	◎	◎		
WDx	◎	◎		

CRCM projections are generally consistent with projections for North America published by the IPCC. The IPCC's SREX (2012) and Fifth Assessment Report (IPCC, 2013) indicate warmer and fewer cold days and nights, warmer and more frequent hot days and nights, increased frequency of warm spells/heat waves and increased frequency or proportion of total rainfall from heavy precipitation events.

A review of the scientific literature was conducted for parameters that are not easily analysed using climate model data. The literature review was intended to find the range of possible future scenarios related to extreme climate indices, such as freezing precipitation, wind gusts, tornado occurrence, lightning strikes, drought, and forest fires.

3.3.2.2 Freezing Precipitation

The term freezing precipitation encompasses both freezing rain (>0.5mm droplets) and freezing drizzle (<0.5mm droplets). Freezing rain or drizzle generally occurs when frozen precipitation falls through a layer of the atmosphere that is above freezing. The frozen precipitation melts and subsequently falls into another layer that is below-freezing where it becomes supercooled. The supercooled droplets then freeze upon contact with solid objects creating a layer of ice (Lambert and Hansen, 2011).

Due to the high frequency of freezing precipitation events on the east coast of North America, most studies focus on this region. There are relatively few studies of historic or future freezing precipitation events for southern Manitoba. In addition, indentifying freezing precipitation events within a climate model is challenging and very few have attempted to address this topic as a result, there currently is not a consensus on methodology.

Historically, southern Manitoba experiences on average less than 10 hours of freezing rain and 20-30 hours of freezing drizzle per year compared to up to 50 hours freezing rain and 80-100 hours of freezing drizzle per year in eastern Newfoundland (Cortinas et al., 2004; Stuart and Isaac, 2010). Using different methodology and sub-sets of GCMs and emissions scenarios from IPCC's Fourth Assessment Report, Cheng et al. (2011), and Lambert and Hansen (2011) project changes to freezing rain over Eastern and Central Canada. Cheng et al. (2011) projects an increase for southern Manitoba with the greatest increase in frequency to occur during December, January and February, a moderate/small increase in November, March and April and potentially no change or a slight decrease in October and May. The greatest increase is projected for the end of the 21st century. On an annual basis Lambert and Hansen (2011) also projected an increase in freezing rain by the end of the century. It is important to note that the studies are not focused on Manitoba, and that they are based on relatively few GCMs. Therefore, robust conclusions on freezing precipitation should not be drawn.

3.3.2.3 Wind Gusts

Temperature and precipitation changes due to climate change have been extensively studied, but changes to wind regimes have not been as widely examined (McInnes et al., 2011). Issues also exist with wind observations which are sensitive to anemometer height, location of measurements, and exposure of the observations site (Wan et al., 2010), and therefore wind measurements are highly variable (Cheng et al., 2014).

One approach to establishing climate change projections for wind gusts is to use historical data. Historic wind gust speeds were shown by Cheng (2014) to have increased in the past five decades. Temperature anomalies were found to have a positive correlation with wind gusts; for every 1˚C increase in daily temperature anomaly, there is a 0.2 km/h speed increase in wind gusts over 50 km/h. Similarly, pressure was found to be correlated, where for every 1 hPa drop in daily pressure anomaly, wind gust speed increased by 0.2 km/h for gusts over 50 km/h (Cheng, 2014). Historical records show that wind gust speeds have increased as daily temperature anomalies increase and daily pressure anomalies decrease. Climate change simulation project increasing temperature and decreasing pressure, which suggests that frequency and intensity of future wind gusts can be anticipated to increase based on evidence from the historical records (Cheng, 2014).

Cheng et al. (2014) used downscaled daily future wind speeds from GCMs to make projections for future wind gusts regimes over Canada. Southern Manitoba is projected to experience increases in annual mean frequency of gusts of 20-40% for 70 km/h gusts and increases of 100-200% in 90 km/h gusts by the end of the century (Cheng et al., 2014). The large percentage of increase in the highest speed wind gusts is because of the relative rarity of these events (Cheng et al., 2014). Increases in severe wind gusts of 20-40% are more likely (Cheng et al., 2014; Cheng, 2014). Seasonality analysis shows that increase in frequency of wind gusts will be greater in winter than in summer (Cheng et al., 2014). Wind direction is also projected to change. The u-component (east-west) of wind is projected to increase over central North America, with no change expected to the v-component (north-south; Kulkarni and Huang, 2014).

3.3.2.3 Tornado Occurrence

The effects of climate change on tornado occurrence are difficult to model. Poor quality of observational data means studying and predicting tornadoes is difficult based on historical data (Brooks, 2013). By combining statistical methods with lightning flash density data and population density data, Sills et al. (2012) identified southern Manitoba as a region prone to F2 to F5 tornadoes. Using data from Sills et al. (2012), Figure 17 shows general locations of all confirmed and probable tornadoes between 1980 and 2009 in Southern Manitoba."

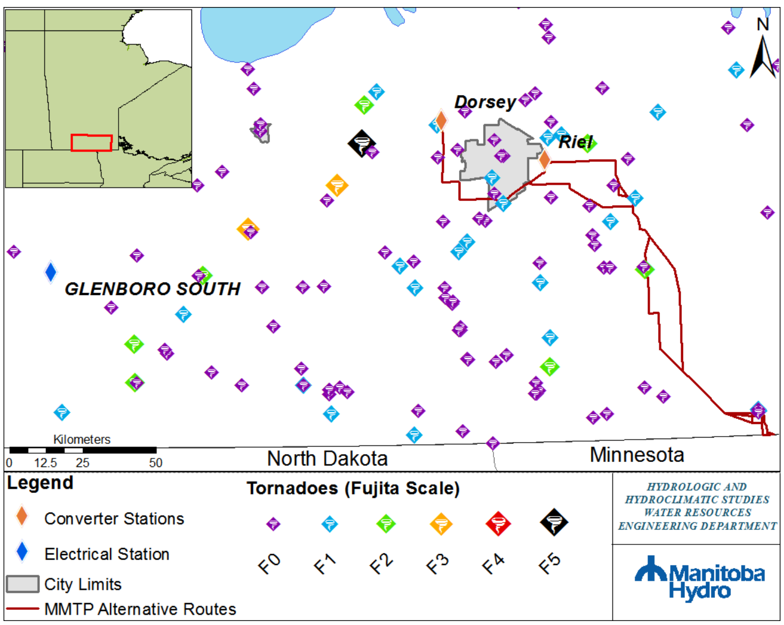


Figure 17 - Confirmed and probable tornadoes for 1980-2009 (Sills et. al., 2012)

Future tornado projections can, however, be centered on the processes which lead to formation of tornadoes. Two important parameters in formation of convective storms and tornadoes are convectively available potential energy (CAPE) and deep troposphere wind shear (SHR6). Climate change simulations suggest an increase in CAPE and a decrease in SHR6 (Brooks, 2013). While decreases in SHR6 lead to lower occurrence of tornadoes, Diffenbaugh et al (2013) found that the decreasing SHR6 occurs on days with low CAPE. Days with high CAPE were found to have also have low convective inhibition. The atmospheric conditions on these days may increase the occurrence of severe storms and tornadoes (Diffenbaugh et al, 2013). Therefore, both Brooks (2013) and Diffenbaugh et al (2013) indicate that the increase in CAPE in future climate scenarios may lead to more favourable conditions for severe thunderstorms and tornadoes, however there still remains a high degree of uncertainty in projections on conditions that favour tornado development.

Cusack (2014) found that tornadoes are 50% more frequent over metropolitan areas, after corrections for observational bias. This is because of the heat island effect of cities and increased roughness causing an increase in low-level shear (Cusack, 2014). If climate changes were to amplify the urban heat island effect, it is possible that this could result in an increased risk of tornadoes over and down-wind from metropolitan areas.

A weather-risk assessment (Teshmont, 2006) states that as summer and spring temperatures increase as a result of climate change, there may be an increase in tornado frequency in southern Manitoba. A related weather study on transmission lines states that, despite a low probability of occurrence of tornadoes in Manitoba, there is a higher probability that tornadoes will cross transmission lines because of the long tracks of both the transmission line and the tornado itself (Morris, 2014).

3.3.2.4 Lightning Strikes

Lightning is formed when updrafts in convective storms cause a sorting of particle where the largest particles remain near the bottom of clouds and smaller, lighter particles are carried upwards. As the smaller particles are carried into the mixed-phase zone of the clouds, collisions between differently-sized particles occur. This causes a build-up of charge resulting in lightning (Price, 2013).

Burrows and Kochtubajda (2010) describe lightning in Canada over 1999-2008 and show that lightning activity is influenced by season length, proximity to cold water bodies, elevation and diurnal heating and cooling cycles. Within the prairies, southeastern Manitoba experiences some characteristics similar to the Great Plains region of the United States including higher average flash densities (approximately 0.75 to 1.5 flashes per km^2 per year) and greater lightning occurrence (late March to late October). However, these characteristics are generally less extreme than in south-western Ontario. In southern Manitoba, more than 50% of the lightning typically occurs overnight as a result of dissipating thunderstorm activity drifting in from other regions. Environment Canada publishes additional location-specific lightning data online: http://www.ec.gc.ca/foudre-lightning/default.asp?lang=En&n=4871AAE6-1%20-%20Manitoba#Manitoba.

Aerosol composition, concentration, and distribution are also important factors in lightning formation (Williams, 2005). Aerosol loads change the polarity of clouds, which may alter the amount of lightning that occurs in the future. As aerosol loads and concentrations change into the future, there will be a change in the nuclei upon which clouds are condensed, which will cause a shift in the development of thunderclouds (Price, 2013). Increases in aerosol loads increase uplift of suspended nuclei up to the point where aerosol loads become high enough for water droplets to absorb solar radiation, resulting in heating of the troposphere. The heating effect chokes the development of thunderstorms (Price, 2013). Aerosol loads in the future are difficult to predict, as they relate to climate change science as well as to human and societal behaviours. It is possible that a drier future climate results in an increase in suspended aerosol and areas that experience higher drying have more lightning (Price, 2009).

Climate change projections show that there could be an increase in more explosive storms, with increasing occurrence of convective storms leading to the formation of lightning (Price, 2009). A double CO_2 scenario (projected to occur around 2050) shows a 10% increase in lightning for every 1˚C of warming, however this value is highly regionalized (Price, 2013). The majority of the increase in lightning is projected to occur in the tropics. The Great Plains region of North America is also projected to experience increasing electrification, with the expectation that intense storms that lead to electrification, and therefore to lightning, will increase (Price, 2009). Lightning interactions with climate change have not been specifically studied in Manitoba.

3.3.2.5 Droughts and Floods

Droughts and floods can generally be described as periods (days to years) of low or high water availability. Droughts can be characterized into three categories: hydrological drought (below normal streamflow, lake and groundwater levels), agricultural drought (lack of growing season precipitation), and meteorological drought (prolonged precipitation deficit) (Trenberth et al., 2014). IPCC SREX (2012) defines a flood as the overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged.

Challenges in determining the frequency, duration, and severity of historic and future droughts and floods have been documented in scientific literature (Trenberth et al., 2014; Sheffield et al., 2012; Dai, 2013; IPCC SREX, 2012; IPCC, 2013). For drought, challenges arise due to differences in event characterization, methodologies for drought detection, complex and unknown atmospheric-land-ocean dynamics, natural climate variability, and regional variability. Similar challenges exist in characterizing historic and future floods due to different flood drivers (e.g.: snowmelt, precipitation, ice jamming), complex terrain (e.g.: non-contributing areas) and anthropogenic interaction (e.g.: river diversions, withdrawals and drainage improvements). Environment Canada publishes historic information related to water availability, droughts and floods online at: https://ec.gc.ca/eau-water/default.asp?lang=En&n=2DE7B40F-1.

Historically, a lack or abundance of precipitation is a root cause of droughts and floods. For droughts, Dai (2011) suggests that the rate of drying has become increasingly more important since the 1980s. In addition, changes in available energy, wind speed, and humidity all affect the rate of evapotranspiration and therefore the rate of which moisture is removed from the surface (Sheffield et al., 2014; Dai, 2011). So while precipitation is projected to increase on average within the MMTP study region, this does not rule out periods of dryness. Similarly, while winter precipitation is projected to increase on average, warmer temperatures may lead to less snow accumulation which could result in lower spring melts and lower spring flood peaks (Whitfield, 2012).

On a global scale, the IPCC has overall low confidence in observed trends and projections of droughts and floods (IPCC, 2013; IPCC SREX, 2012). For central North America, the IPCC shows that there is medium confidence that future duration and intensity of droughts will increase (IPCC SREX, 2012). IPCC SREX (2012) also shows that there is medium confidence that floods driven by heavy rainfall could increase into the future in some regions and that earlier spring peak flows are likely in snowmelt fed rivers but there is low confidence on the projected magnitude of change.

3.3.2.6 Forest Fires

Although there is lack of agreement in the literature about future forest fire regimes, historic analyses show that areas burned by forest fires in the North American boreal forest have been increasing in the past 50 years, but still falls within long-term historic variability (Bergeron et al., 2010). Predictions of forest fires and climate change are highly regionalized (Girardin and Mudelsee, 2008). It is therefore difficult to make sweeping generalizations of fire regimes across Canada because of variability in forest distribution and tree composition (Tardiff, 2004). It is possible to piece together a picture of future forest fires regimes in Manitoba through studies that have been conducted in the area.

Historical analysis of fire regimes in Manitoba shows a link between drought cycles and area burned (Tardiff, 2004). Additionally, there is correlation between soil moisture and forest fires. Fires spread rapidly when the available fuel is dry and weather conditions are warm, dry and windy (Girardin and Mudelsee 2008). The past 150 years have seen a lengthening of the fire cycle in parts of Manitoba, from 55 to 200 years which raises the risk of a large fire (Tardif, 2004; Flannigan et al., 2005a). The lengthening of the fire cycle may be related to modern fire suppression strategies, which lengthens the time between fires but can also increase the risk of large fires (Tardiff, 2004). While the definition of a large fire is subjective, de Groot et. al. (2013) classifies large fires as those covering more than 200 hectares. Additional information on historical fires including fire weather normals and fire behaviour normals are available online through Natural Resource Canada's Canadian Wildland Fire Information System (CWFIS; http://cwfis.cfs.nrcan.gc.ca/).

Fire activity is influenced by weather/climate, fuels, ignition agents, and human activity (Flannigan et al., 2005b). Weather is the most important factor influencing fires because it drives other important parameters such as fuel moisture, soil moisture, lightning ignitions, and wind (Flannigan et al., 2005b). Area burned is most directly linked to temperature (DeGroot et al., 2013; Flannigan et al., 2005a), which is expected to rise into the future across the study area. Temperature can be modeled using GCMs (Gillett et al., 2004), so links can be established between climate change and forest fire regimes.

Fire severity indices and area burned were shown by DeGroot et al (2013) to increase into the future under global climate change. Severity of fire weather is expected to increase across large portions of Canada and a lengthening of the fire season is also predicted by climate change modeling, with the fire season starting earlier in the year (DeGroot et al., 2013). In southern Manitoba, the ratio of area burned for a 3xCO_2 scenario was modeled to be in the range of 1.5 – 2 (Flannigan et al., 2005b), indicating a potential doubling of area burned. Additionally, lightning ignitions of wildfires are expected to increase by 44% because of increased occurrence of cloud-to-ground lightning (Flannigan et al., 2005a; Flannigan et al., 2005b). Higher greenhouse gas scenarios (e.g.: RCP8.5) predict more drought and more wildfires. The highest greenhouse gas scenario will lead to forest fire occurrence in the upper range of historical range (before fire suppression was commonplace). Moderate greenhouse gas scenarios result in wildfire occurrence which fall within the range of the past 240 years (Girardin, 2008).

3.3.3 Uncertainty in Future Climate Scenarios

Many sources of uncertainty exist in projecting future climate and should be considered when interpreting results. Sources of uncertainty include future atmospheric forcing scenarios, GCM structure and internal variability within the GCM. The spread of projections shown in box plots in Section 3 (Figure 13, for example) show the combined uncertainty. Sources of uncertainty can also be examined in isolation. For example, the range in GHG emissions between RCPs, shown in Figure 18, illustrates an important part of the uncertainty inherent in modelling of future climate. Figure 18 also shows how RCP uncertainties impact future global temperature projections, although, the temperature projections are also subject to GCM uncertainty.

To better understand uncertainties related to internal GCM variability (natural climate variability; Chen, 2011) a subset of simulations is considered. Five runs of CanESM2 RCP4.5 projections for the 2050s are selected for this assessment. Figure 18 illustrates projections of mean temperature and precipitation. The range of monthly temperature projections vary by as much as 3.6°C (February) but only vary by 0.5°C annually. The range of monthly precipitation projections vary by as much as 82% (February) but only vary by 18% annually.

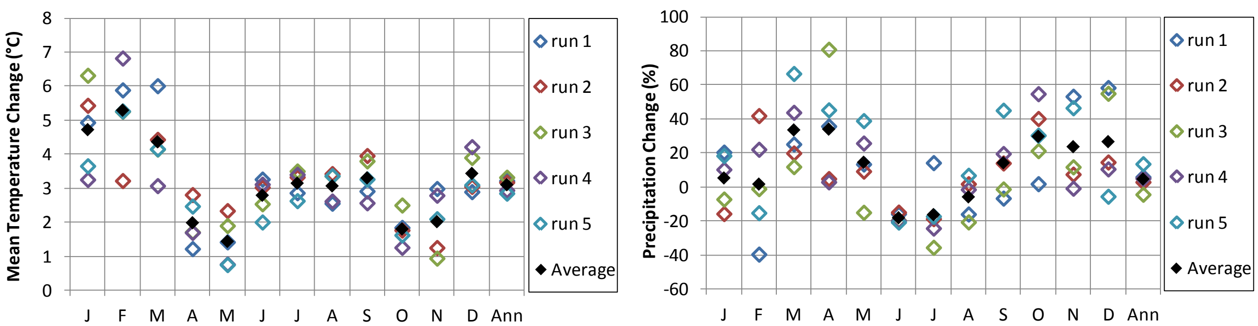


Figure 18 - CanESM2 RCP4.5 2050s Temperature and Precipitation Projections (run 1-5)

While it is important to consider uncertainty, there is no clear method to account for it. Several studies, such as those described in Knutti (2010) have found improved performance when using an ensemble average from multiple GCMs. However, the performance relates to historic climate and not the performance in projecting future climate. In this study, all simulations are considered equally probable and the ensemble average is used to summarize future projections.

4.0 CONCLUSION

This study characterizes historic climate normals, trends, and future climate projections for the MMTP study area. Data from several climate stations were used to characterize the study area that includes the transmission line and the Glenboro Electrical Station. Due to the changing climate, the historical climate may not accurately represent future conditions.

The MMTP crosses the Prairie, Boreal Plains, and Boreal Shield Ecozones, which are generally characterized by cold climate with moderate precipitation. 1981-2010 climate normals for Winnipeg indicate an average annual temperature of 3.0°C, an average total precipitation of 521mm/year and an annual average wind speed of 17.1km/h. Homogenized and adjusted data were used to analyze historic temperature, precipitation, and wind speed trends. Temperature records showed the most pronounced statistically significant increasing trends, particularly in winter. Significant increasing annual precipitation trends were detected in Sprague, but not at the other locations. Significant decreasing trends in mean wind speed were detected, but the magnitude of the trend in wind speed was weak.

An ensemble of 69 Global Climate Model (GCM) simulations from 15 GCMs was used to assess future climate projections. This study also used the Canadian Regional Climate Model (CRCM) to compare with GCM results. Three future horizons were identified: 2010-2039 (2020s), 2040-2069 (2050s), and 2070-2099 (2080s).

The GCMs generally project annual mean temperatures and total precipitation to increase with time. There is greater uncertainty for mean wind speed projections, but the ensemble average projects small decreases during summer, and little change in non-summer months. Although there was variability within the GCM ensemble, the averages show that the mean temperature will increase by +1.5°C in the 2020s, +2.9°C in the 2050s, and +4.1°C in the 2080s. Annual total precipitation is also projected to increase by +3.5% for the 2020s, +4.2% for the 2050s, and +6.7% for the 2080s. Mean surface wind speeds are projected to decrease by to decrease by -0.7% in the 2020s, -1.4% in the 2050s, and -2.1% in the 2080s. Seasonal analysis shows that winter is projected to experience the greatest change in temperature and the greatest relative changes in precipitation.

Extreme temperature events are projected to occur more frequently, with minimum temperatures projected to increase by a greater magnitude than maximum temperature events. Extreme precipitation and wind speed events are also projected to increase. Trends for freezing precipitation, wind gust speeds, tornado occurrence, lightning, drought, and forest fires were examined primarily through literature reviews, which showed that freezing precipitation, wind gust speeds, forest fire conditions, and conditions leading to lightning strikes and tornadoes could increase with climate change.

ACKNOWLEDGEMENTS:

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 11 and Table 12 of this report) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. We also thank the Ouranos Consortium for providing CRCM4.2.3 and CMIP5 data as well as technical support, methodology and report review.

5.0 GLOSSARY

Autocorrelation The correlation of a variable with itself over successive time intervals

Baseline A standard to which things are measured or compared.

Climate change Refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

Convectively Available Potential Energy Convectively available potential energy is a measure of the amount of energy available for convection and is related to instability through the atmosphere. CAPE is directly related to maximum vertical wind speeds (National Weather Service, n/d)

Cold Spells Span of at least six consecutive days where minimum daily temperature is below the historical 10^{th} percentile (Klein Tank et al, 2009).

Consecutive Dry Days Maximum number of consecutive days where daily precipitation accumulation is lower than 1 mm (Klein Tank et al, 2009).

Consecutive Wet Days Maximum number of consecutive days where daily precipitation accumulation exceeds 1 mm (Klein Tank et al, 2009).

Correlation A statistical relation between two or more variables such that systematic changes in the value of one variable are accompanied by systematic changes in the other.

Covariance A measure of the strength of the correlation between two or more sets of random variates.

Diurnal Temperature Range The mean difference between daily maximum and daily minimum temperature in a certain period. (Klein Tank et al, 2009).

Ensemble A group of Global Climate Models and/or climate simulations forced by one or more GHG emission scenarios. An ensemble is expected to address various aspects of uncertainty such as model imperfections, emission scenario uncertainty, climate sensitivity etc. (see definition of "Member").

Evapotranspiration The combination of water moving from the earth's surface into atmospheric water vapour, and includes evaporation of water and transpiration from plants (National Weather Service, n/d)

Extremes Extreme values, in the context of climate normals, refer to the absolute greatest value on record for a certain parameter and time frame (daily, monthly, seasonal, and/or annual). In the case of temperature, there is an extreme value for both the maximum and minimum temperatures observed in the record period. Extremes are also used to define events in other contexts such as the occurrence of rare events.

Frost Days Days when minimum daily temperature is below 0˚C (Klein Tank et al, 2009).

Greenhouse gas Greenhouse gases are gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol.

Heavy Precipitation Day Days when total daily precipitation accumulation is greater than 10 mm (Klein Tank et al, 2009).

Homogenized data Data that are free of variations due to non-climatic factors, such as variability in observations and changes to instrumentation.

Ice Days Days when maximum daily temperature is below 0˚C (Klein Tank et al, 2009).

Large Fire In Canada, large fires are those that cover more than 200 hectares (de Groot et al., 2013).

Mann-Kendall test A nonparametric test for randomness against trend.

Maximum Gust Speed The speed of motion of air in km/h, usually observed at 10 meters above the ground. It represents the maximum instantaneous speed.

Mean temperatures Mean near-surface air temperature for a specified time period (daily, monthly, seasonal, and/or annual). Air temperature is generally measured or modeled at 1 to 2 meters above ground.

Member The results from a climate model simulation that uses certain initial conditions is referred to as one member experiment. Global climate models are often run multiple times with varying initial conditions and the results from these models are then recognized as different member experiments.

Negative covariance Indicates that higher than average values of one variable tend to be paired with lower than average values of the other variable.

Normals The average or mean of a climatic parameter over a specific time period. A period of 30 years is commonly used.

Positive covariance Indicates that higher than average values of one variable tend to be paired with higher than average values of the other variable.

Precipitation Refers to total precipitation, or the sum of all the different precipitation types (i.e. rain, snow, ice pellets, drizzle, etc.).

Projection A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions to emphasize that projections involve assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized, and are therefore subject to substantial uncertainty.

Scenario A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline.

Simple Precipitation Intensity Index

The mean accumulation of precipitation on a wet day (daily accumulation greater than 1 mm) (Klein Tank et al, 2009).

Statistical significance A fixed probability of wrongly rejecting the null hypothesis of a statistical hypothesis test if it is in fact true.

Tropical Nights Nights when the minimum daily temperature is above 20˚C (Klein Tank et al, 2009).

Very Heavy Precipitation Day

Days when total daily precipitation accumulation is greater than 20 mm (Klein Tank et al, 2009).

Wet Days Days when total daily precipitation accumulation is greater than 1 mm (Klein Tank et al, 2009).

Wind speed The speed of motion of air, usually observed at 10m above the ground.

Wind direction The direction from which the wind is blowing with respect to north (360 degrees on the compass). For example, an easterly wind is blowing from the east, not toward the east. It represents the average direction during the two minute period ending at the time of observation and is expressed as one of the 16 points of the compass (N, NE, WNW, etc.).

Z-statistic value A quantity calculated from a sample of data, whose value is used to decide whether or not a null hypothesis should be rejected in a particular hypothesis test.

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APPENDIX A – ABBREVIATIONS

AHCCD .... Adjusted and Homogenized Canadian Climate Data
AR5........................... IPCC's Fifth Assessment Report
CAPE.......................... Convectively Available Potential Energy
CDF............................Cumulative Distribution Function
CMIP5....................... Coupled Model Intercomparison Project Phrase 5
CRCM....................... Canadian Regional Climate Model
ºC .... Degrees Celsius
ºC/dec .... Degrees Celsius per Decade
ENSO......................... El Niño Southern Oscillation
ETCCDI..................... Expert Team on Climate Change Detection and Extreme Indices
GCM .... Global Climate Model
GHG .... Greenhouse Gas
IPCC .... Intergovernmental Panel on Climate Change
km/h........................... Kilometers per Hour
km/h/dec. .... Kilometers per Hour per Decade
Max............................ Maximum
Min. .... Minimum
MMTP....................... Manitoba-Minnesota Transmission Project
mm/yr/dec.................. Millimeters per year, per decade
NEB........................... National Energy Board
NRCan...................... Natural Resources Canada
Precip .... Precipitation
RCP........................... Representative Concentration Pathways
SHR6 .... Deep Troposphere Wind Shear (6 km)
SW .... South West
TGICA .... Task Group on Scenarios for Climate and Impact Assessment
W .... West
W/m^2........................... Watts per square metre
WMO .... World Meteorological Organization
Zstat .... Z-statistic

APPENDIX B – SUPPLEMENTAL FIGURES FOR 2020S AND 2080S

B.1 2080S GCM SCATTER PLOTS AT WINNIPEG

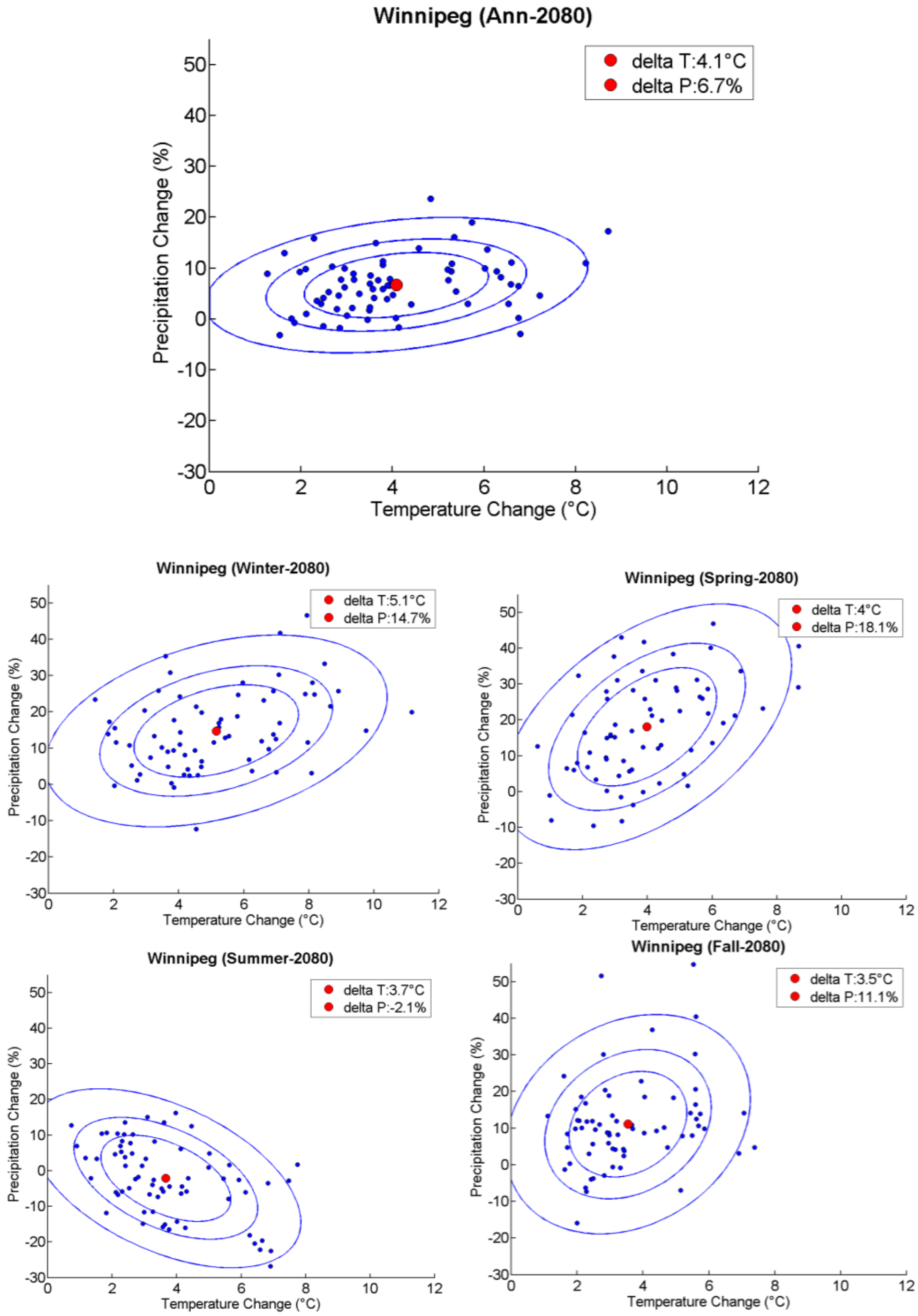

Figure B1 - Annual and seasonal scatter plots for Winnipeg International Airport (2080s). Change in temperature (delta T), change in precipitation (delta P).

B.2 FUTURE MONTHLY NORMALS AND GCM DELTAS AT WINNIPEG

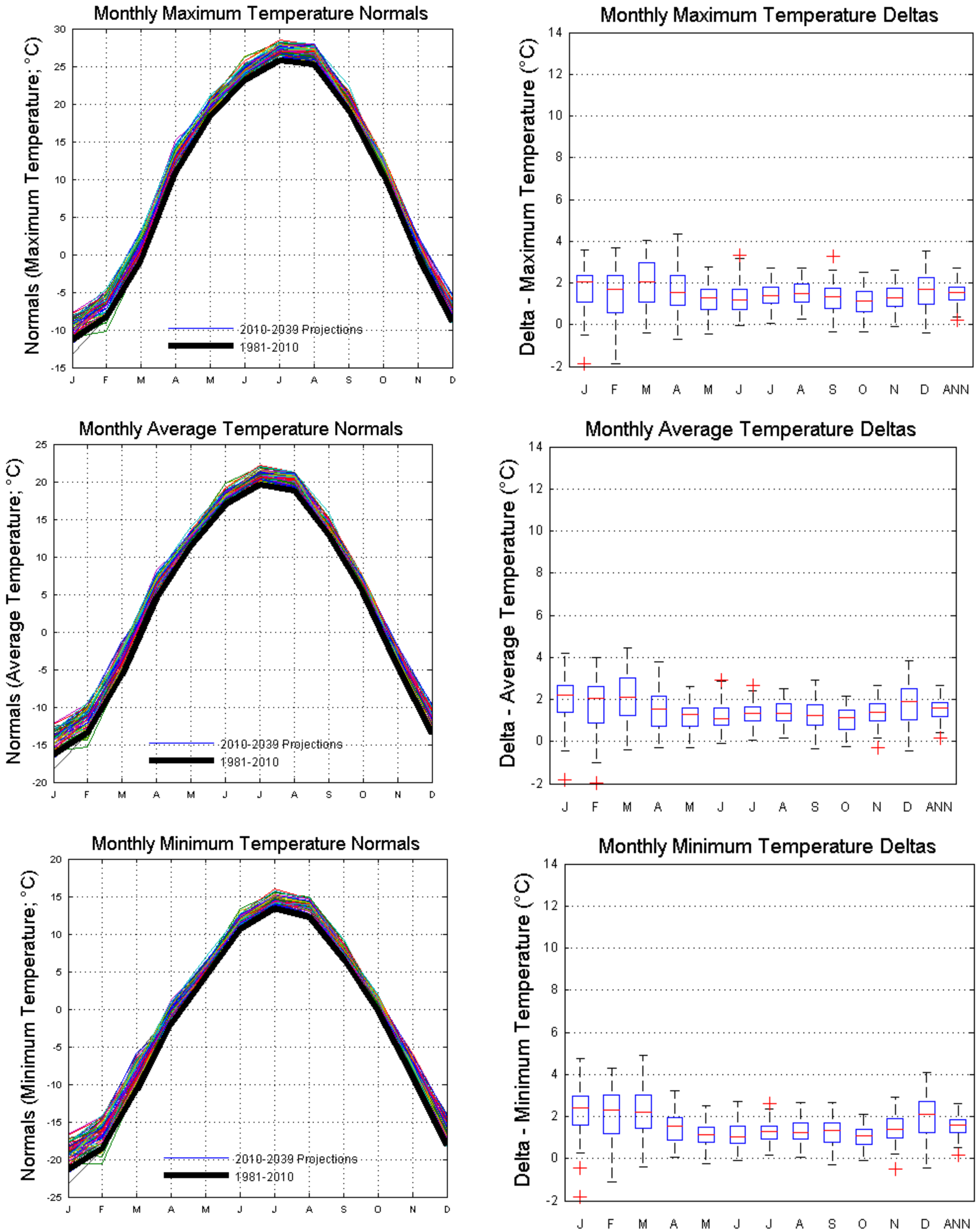

Figure B.2.1 - Future Temperature Normals and Projected Changes (2020s)

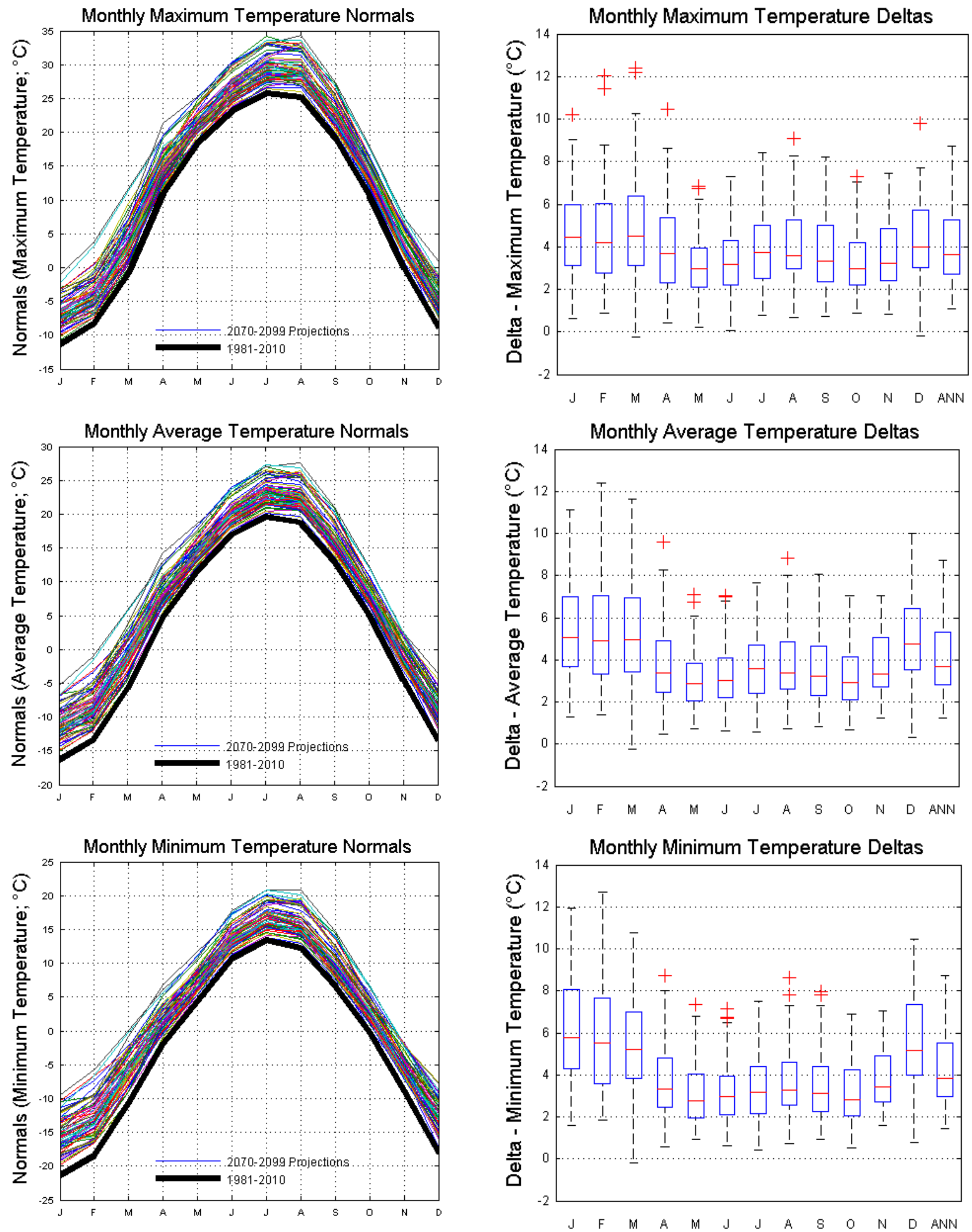

Figure B.2.2 - Future Temperature Normals and Projected Changes (2080s)

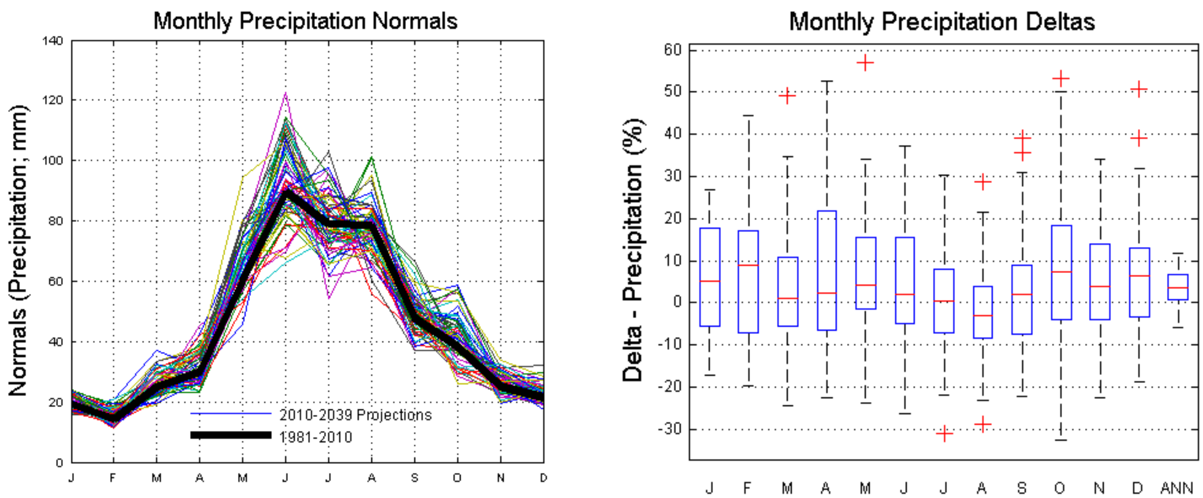

Figure B.2.3 - Future Precipitation Normals and Projected Changes (2020s)

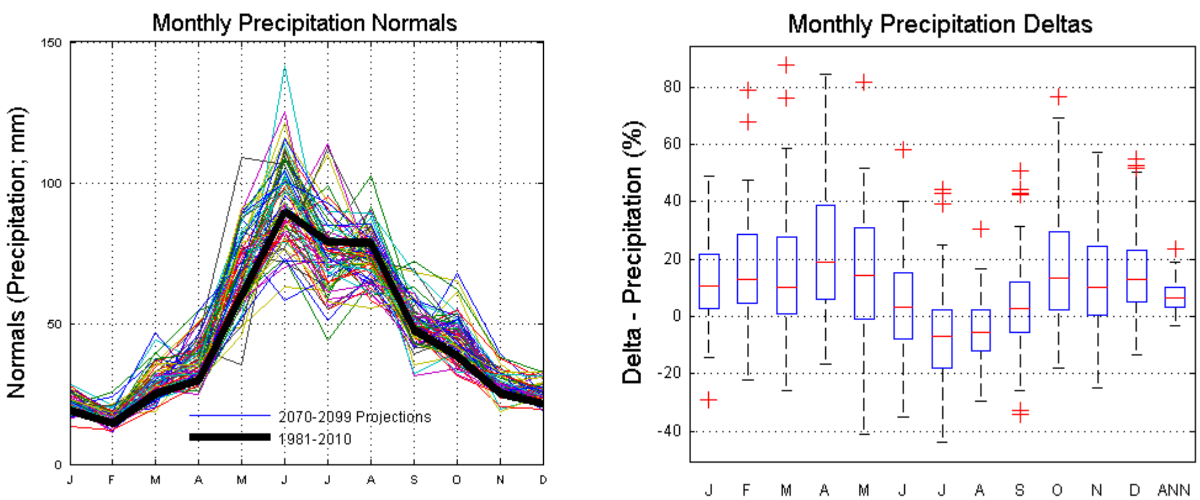

Figure B.2.4 - Future Precipitation Normals and Projected Changes (2080s)

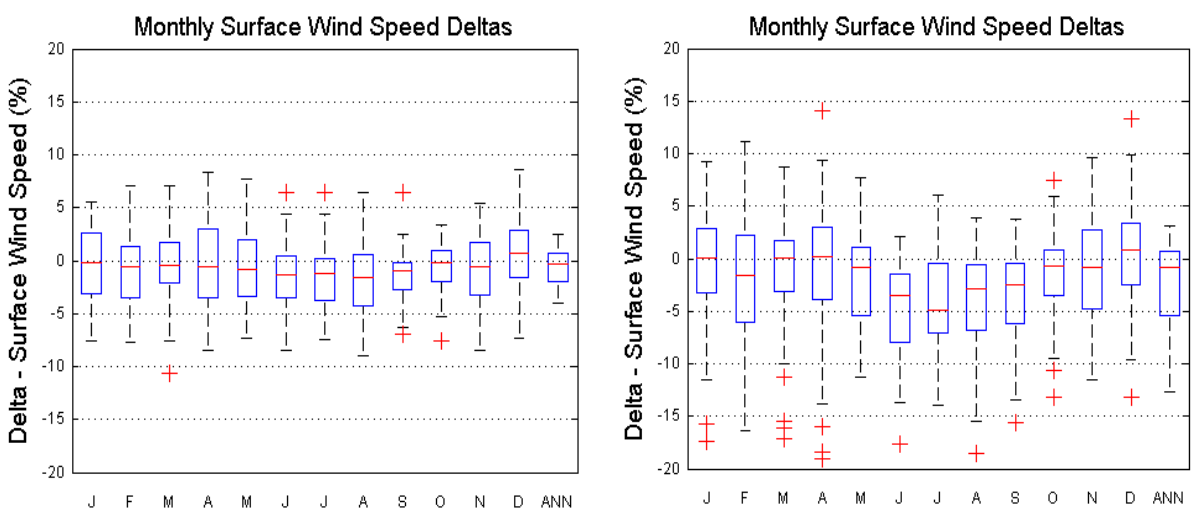

Figure B.2.5 - Future Mean Wind Speed Projected Changes (2020s Left; 2080s Right)