APPENDIX 4.2A:
HISTORIC CLIMATE STUDY

EXECUTIVE SUMMARY

Historic climate conditions for the Regional Cumulative Effects Assessment's (RCEA) Region of Interest were summarized using 1981–2010 climate normals from Environment Canada. In addition, climate trends were determined from climate records that extend as far back as 1896. Six climate stations were selected as indicator stations to provide spatial representation of the RCEA's Region of Interest. The climate stations utilized are located in Churchill, Lynn Lake, Gillam, Thompson, Flin Flon and Norway House, Manitoba. Historic climate is quantified in terms of temperature, precipitation, wind, evapotranspiration and streamflow.

The RCEA study region exhibits a south-to-north temperature cooling gradient with above zero annual average temperatures in the southern extent of the region (0.2°C at Flin Flon) to below zero in the north (-6.5°C at Churchill). Temperature extremes range from 37.4°C at Thompson to -49.4°C at Norway House. Trend analysis indicates a general increasing trend in annual, winter and spring average temperature over the study region.

On an annual basis, precipitation totals range from 452 mm at Churchill to 532 mm at Norway House. A southeast-to-northwest drying gradient exists over the study region. An extreme daily precipitation event of 78 mm occurred at Flin Flon. On an annual basis, increasing precipitation trends were detected at Churchill and Gillam while a decreasing trend was detected at Thompson.

The annual average wind speed varies from 10.6 km/h in Flin Flon to 20.7 km/h in Churchill. The highest gust speed (161.0 km/h) was recorded at Churchill. Decreasing trends in mean annual wind speed were detected at all four stations with data. Some stations also exhibited decreasing mean wind speed in spring, autumn and summer.

Fourteen rivers in northern Manitoba with minimal human impact were assessed for trend in annual average streamflow. Trend directions range from minor increases to minor decreases but no statistically significant trends were detected.

TABLE OF CONTENTS

Page

1.0 INTRODUCTION 7
1.1 Region of Interest 7
2.0 METHODS 9
2.1 Data Sources 9
2.2 Trend Analysis 11
3.0 CLIMATE NORMALS 13
3.1 Temperature 13
3.2 Precipitation 15
3.3 Wind 17
3.4 Lake Evaporation 18
4.0 REGIONAL CLIMATE SUMMARY 19
4.1 Temperature 19
4.2 Precipitation 22
4.3 Potential Evapotranspiration 24
5.0 CLIMATE TRENDS 26
5.1 Temperature Trends 26
5.2 Degree Day Trends 26
5.3 Precipitation Trends 27
5.4 Wind Speed Trends 28
5.5 Evapotranspiration Trends 28
5.6 Streamflow Trends 29
5.7 Detection and Attribution of Observed Climate Changes 30
6.0 SUMMARY 31
6.1 Acknowledgements 31
7.0 REFERENCES 33

LIST OF TABLES

Table 2.1-1: Climate Stations 10
Table 2.1-2: Streamflow Stations 11
Table 3.1-1: Daily Average Temperature (°C) 13
Table 3.1-2: Minimum Temperature (°C) 14
Table 3.1-3: Maximum Temperature (°C) 14
Table 3.1-4: Degree Days (DD/month and DD/year) 15
Table 3.2-1: Average Total Precipitation (mm/month and mm/year) 16
Table 3.2-2: Extreme Daily Precipitation (mm/day) 16
Table 3.2-3: Average Snow Depth (cm) 16
Table 3.3-1: Wind Speed and Direction (km/h) 17
Table 3.3-2: Extreme Wind Speed (km/h) 18
Table 3.4-1: Lake Evaporation (mm/month, mm/year) 18
Table 5.1-1: Trends in Daily Average Temperature (°C/decade) 26
Table 5.2-1: Trends in Annual Degree-Days (DD/decade) 27
Table 5.3-1: Trends in Total Precipitation (mm/decade) 27
Table 5.3-2: Trends in Precipitation Falling as Snow (mm/decade) 28
Table 5.4-1: Trends in Daily Average Wind Speed ([km/h]/dec.) 28

LIST OF FIGURES

Page

Figure 4.1-1: Time Series of Annual Average Temperature and Regional Extreme Temperature 20
Figure 4.2-1: Time Series of Average Annual Total Precipitation and Regional Extreme Daily Precipitation 22

LIST OF MAPS

Page

Map 1.1-1: Location of Selected Indicator Climate Stations 8
Map 4.1-1: Mean Temperature Decadal Averages 21
Map 4.2-1: Total Annual Precipitation Decadal Averages 23
Map 4.3-1: Average Total Annual Potential Evapotranspiration 25

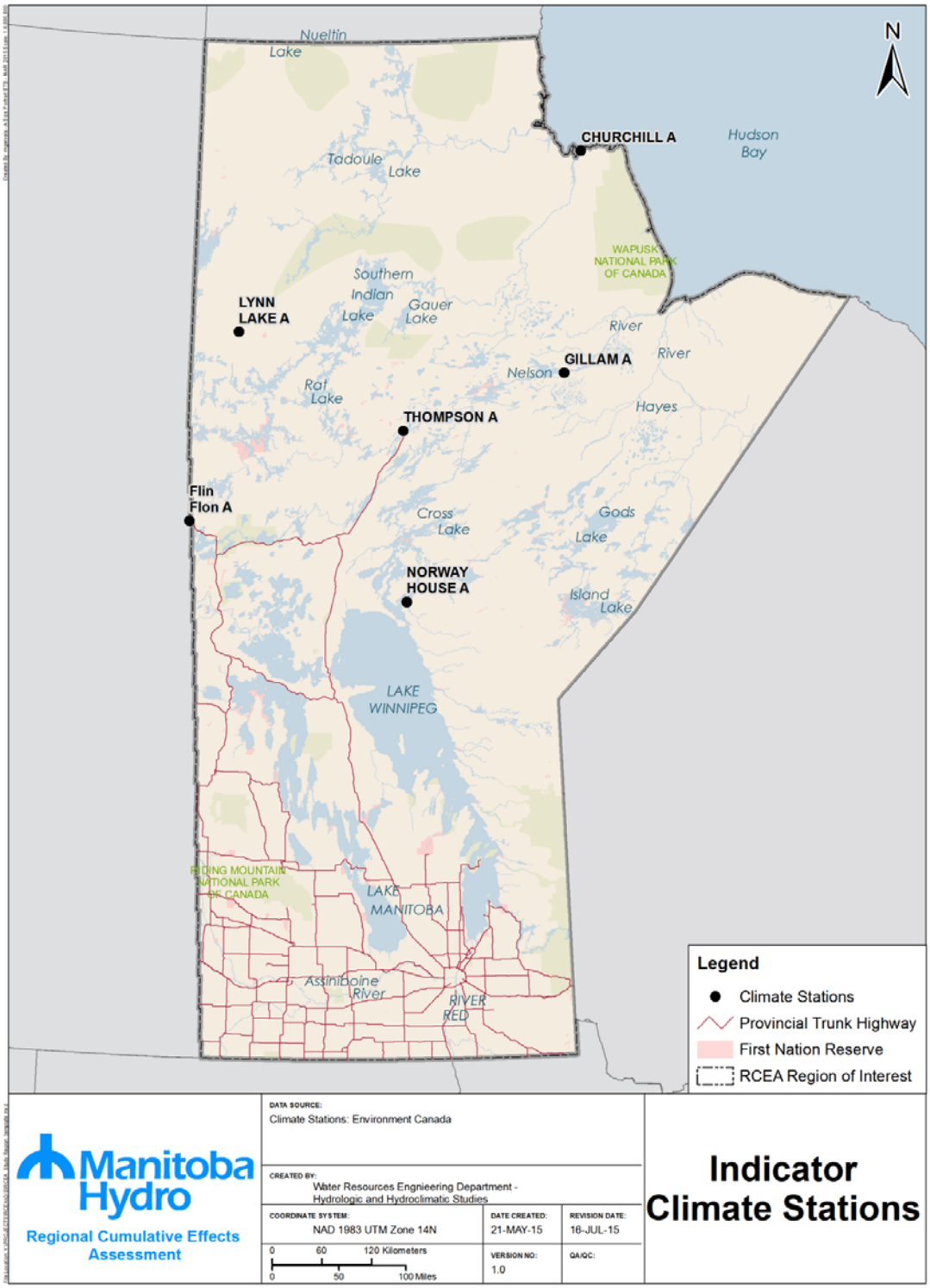
1.0 INTRODUCTION

The objective of this report is to quantify the historic climate for the Regional Cumulative Effects Assessment (RCEA) Region of Interest. Historic climate is quantified in terms of climate normals and climate trends for temperature, precipitation and wind speed. Additional information is provided for degree days, evapotranspiration and streamflow.

1.1 Region of Interest

The Region of Interest is located in northern Manitoba, encompassing the main areas directly affected by Manitoba Hydro developments associated with Lake Winnipeg Regulation, Churchill River Diversion and associated transmission projects (Manitoba Hydro 2014). Six climate stations from Environment Canada's database are shown in

Map 1.1-1 and were used to characterize the climatic conditions for the RCEA's Region of Interest. Climate stations were selected based on the length and quality of the data record. The six stations are located within Manitoba at: Churchill, Lynn Lake, Gillam, Thompson, Flin Flon and Norway House.



Map 1.1-1: Location of Selected Indicator Climate Stations

2.0 METHODS

The methods and data sources used to characterize historic climate normals and perform trend analyses are described below.

2.1 Data Sources

The 1981–2010 climate normals used in this study were derived by Environment Canada and can be accessed online at: http://climate.weather.gc.ca/climate_normals/index_e.html (accessed December, 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 2.1-1). Currently, Environment Canada's quality checked database only extends up until 2007 for several stations, despite the current normal's period nominal end date of 2010. As a result, the normals at several climate stations only consider data up until 2007. Data used in the calculation of normals may be subject to further quality assurance checks by Environment Canada. This may result in minor changes to some values presented in this document. Henceforth, the location name will be used when referring to a climate station. Refer to Table 2.1-1 for the Environment Canada name and identification (ID) number.

Homogenized and adjusted datasets were used for climate trend analysis for the parameters and locations in Table 2.1-1 where available. This dataset is produced by Environment Canada and is referred to as the Adjusted and Homogenized Canadian Climate Data (AHCCD) (Vincent *et al.* 2012; Mekis and Vincent 2011; Wan *et al.* 2009). Homogenized temperature, homogenized wind and adjusted precipitation data for the meteorological stations were used for trend analysis and account for changes in instrumentation type, station relocations and changes to observing practices during this period (Vincent *et al.* 2012; Mekis and Vincent 2011; Wan *et al.* 2009). AHCCD extends to 2011 for temperature and precipitation (Table 2.1-1). AHCCD for wind extends to 2014 but wind data is not available in AHCCD for Lynn Lake or Norway House. While the temperature and precipitation AHCCD record for Norway House begins in the 1890s, it is important to note that there is considerable missing data prior to 1973.

Monthly data from AHCCD were used for mean temperature, total precipitation, precipitation falling as snow and mean wind speed trend analyses. Daily mean temperature data from AHCCD were used for calculating degree-days and performing trend analyses.

Water Survey of Canada (WSC) data was used for streamflow trend analysis and can be accessed online at http://www.ec.gc.ca/rhc-wsc/. Fourteen stations (Table 2.1-2) in northern Manitoba, which have minimal influence from human development, were analyzed.

Two gridded data sources were utilized in Section 4 for the purpose of representing the regional climate with greater spatial detail. Decadal averaged temperature and precipitation is derived from Natural Resources Canada's 10 km by 10 km gridded dataset (Hopkinson *et al.* 2011; McKenney *et al*. 2011; Hutchinson *et al.* 2009). The 1950–2000 average total annual potential evapotranspiration is derived from the Trabucco and Zomer (2009) dataset.

Table 2.1-1: Climate Stations

Location Name	Environment Canada Name and ID Number	Dataset Properties			
		Parameter	Normals Time Frame	Trend Time Frame	Normals Code*
Churchill	Churchill Airport 5060600	Temperature	1981-2007	1932-2010	A
		Precipitation	1981-2003	1932-2011	D
		Wind	1981-2010	1953-2014	A
Lynn Lake	Lynn Lake Airport 5061646	Temperature	1981-2005	1952-2011	C
		Precipitation	1981-2005	1952-2010	C
		Wind	1981-2005	n/a	C
Gillam	Gillam Airport 5061001	Temperature	1981-2010	1943-2011	A
		Precipitation	1981-2010	1943-2011	A
		Wind	1981-2010	1953-2014	C
Thompson	Thompson Airport 5062922	Temperature	1981-2007	1967-2011	A
		Precipitation	1981-2007	1967-2011	A
		Wind	1981-2010	1967-2014	A
Flin Flon	Flin Flon Airport 5050960	Temperature	1981-2007	1927-2010	A
		Precipitation	1981-2007	1927-2010	A
		Wind	1981-2002	1954-2014	D
Norway House	Norway House Airport 506B047	Temperature	1981-2005	1897-2005	C
		Precipitation	1981-2005	1896-2005	C
		Wind	1981-2005	n/a	C

*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.
n/a = not available

Table 2.1-2: Streamflow Stations

Station Name	WSC ID	Trend Time Frame	Drainage Area (km^2)
Hayes River Below Gods River	04AB001	1974-2006	103,000
Gods River Near Shamattawa	04AD002	1970-2010	65,000
Grass River above Standing Stone Falls	05TD001	1960-2009	15,400
Burntwood River above Leaf Rapids	05TE002	1985-2009	5,810
Footprint River above Footprint Lake	05TF002	1978-2006	643
Odei River near Thompson	05TG003	1979-2009	6,110
Gunisao River at Jam Rapids	05UA003	1973-2007	4,610
Kettle River near Gillam	05UF004	1966-2009	1,090
Limestone River Near Bird	05UG001	1963-2009	3,270
Angling River near Bird	05UH001	1979-2009	1,560
Cochrane River near Brochet	06DA002	1972-2009	28,400
Little Beaver River near the mouth	06FB002	1974-2010	4,270
Deer River north of Belcher	06FD002	1978-2010	1,890
Seal River below Great Island	06GD001	1955-2009	48,100

2.2 Trend Analysis

Trend analysis was performed on homogenized mean temperature, mean wind speed, adjusted total precipitation, adjusted precipitation falling as snow, degree days at various thresholds and mean annual streamflow. Trend analysis was conducted using a computer program implementing the Mann-Kendall test for trend against randomness with an iterative pre-whitening and trend magnitude estimation algorithm to compensate for autocorrelation effects, outliers, and non-normality of the data. This algorithm was also implemented by Wang and Swail (2001) and Zhang *et al*. (2000).

A statistical significance level of 5% was used throughout, 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. Significant trends are bolded when presented in tables. Patterns in the trends of lower significance are not discussed. Trend magnitudes are estimated based on Kendall's rank correlation tau statistic. Conceptually, this approach is equivalent to taking the median slope of all possible lines between one point and all other points of measurement, rather than a weighted average as in the least squares process (Sen 1968).

Trend magnitudes are reported on a per-decade basis: °C/decade, (mm/year)/decade, (km/h)/decade, degree days (DD)/decade. Seasonal trends reflect year-to-year variation between the same seasons in successive years. Seasons are referred to as winter (December, January and February), spring (March, April and May), summer (June, July and August), and autumn (September, October and November).

Monthly data from AHCCD were used for all climate variables except for DD. In the case of DD, daily mean temperature data from AHCCD were used to compute DD which were then summed annually for trend analysis. Since DDs represent totals, if a single day of mean temperature data were missing, then the entire year is considered missing. As such, the DD trend analysis contains more missing data than the mean temperature trend analysis. Daily WSC data were used to compute mean annual streamflow based on the calendar year (January to December).

Trend analysis conducted in this report considers the entire available record period from Environment Canada's AHCCD dataset and WSC datasets. Date ranges used are identified in Table 2.1-1 and Table 2.1-2. For climate variables, date ranges 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. As a result of climate change, extrapolation of historic climate trends into the future is not recommended as the future may not necessarily be a simple continuation of the past (Intergovernmental Panel on Climate Change [IPCC] 2013).

3.0 CLIMATE NORMALS

Climate normals for 1981–2010 are presented in Table 3.1-1 to Table 3.4-1 for temperature, degree days, precipitation, wind and lake evaporation.

3.1 Temperature

The air temperature regime is summarized using normals of daily average, daily minimum and daily maximum temperatures. In addition, extreme daily minimum and maximum temperatures are presented from the entire period of record at respective stations.

Annual daily average temperatures are summarized in Table 3.1-1 and range from -6.5°C at Churchill to 0.2°C at Flin Flon. In general, a south-to-north gradient exists where the southernmost station, Norway House, is on average 5.8°C warmer then the northernmost station, Churchill. Lynn Lake, Gillam and Thompson are located at similar latitudes and as expected, have similar average temperature regimes.

Table 3.1-1: Daily Average Temperature (°C)

Station	Months												Year
	J	F	M	A	M	J	J	A	S	O	N	D	
Churchill	-26.0	-24.5	-18.9	-9.8	-1.0	7.0	12.7	12.3	6.4	-1.2	-12.7	-21.9	-6.5
Lynn Lake	-24.3	-20.3	-13.0	-3.1	5.6	12.9	16.2	14.7	7.7	-0.6	-12.5	-21.4	-3.2
Gillam	-24.4	-21.7	-14.6	-4.4	3.9	11.6	15.8	14.4	7.9	0.0	-11.6	-21.4	-3.7
Thompson	-23.9	-20.1	-12.5	-2.2	6.1	12.6	16.2	14.5	7.8	0.1	-12.0	-20.9	-2.9
Flin Flon	-19.8	-16.2	-8.9	0.8	8.4	14.9	18.2	17.0	10.4	2.6	-8.4	-17.1	0.2
Norway House	-21.5	-17.6	-10.3	-0.2	7.9	14.1	17.6	16.5	9.7	2.0	-8.8	-18.2	-0.7

Daily average minimum and maximum temperatures, as well as extreme minimum and maximum temperatures are summarized in Table 3.1-2 and Table 3.1-3. The annual average daily minimum temperature ranges from -10.7°C at Churchill to -4.8°C at Flin Flon. The extreme minimum temperature recorded in this region is -49.4°C at Norway House in January. The annual average daily maximum temperature ranges from -2.3°C at Churchill to 5.1°C at Flin Flon. The extreme maximum temperature recorded in this region is 37.4°C at Thompson in June.

Total degree days (DD) are shown in Table 3.1-4. Annual DD above 5°C ranges from 649.9 at Churchill to 1431.1 degree days at Flin Flon. Annual DD above 10°C ranges from 244.1 at Churchill to 736.2 degree days at Flin Flon. Annual DD below 0°C ranges from 2,226.1 at Flin Flon to 3,610.1 at Churchill. Greater DD above 5°C and 10°C at Flin Flon reflect the warmer conditions experienced at southern extents of the study region while greater DDs below 0°C at Churchill reflect to colder conditions experienced in the north.

Table 3.1-2: Minimum Temperature (°C)

Station	Parameter	Months												Year
		J	F	M	A	M	J	J	A	S	O	N	D	
Churchill	Daily Avg. Min	-30.1	-28.8	-23.9	-14.4	-5.0	2.0	7.3	7.7	3.2	-3.9	-16.4	-25.9	-10.7
	Extreme Min	-45.0	-45.4	-43.9	-33.3	-25.2	-9.4	-2.2	-2.2	-11.7	-24.5	-36.1	-41.8	
Lynn Lake	Daily Avg. Min	-29.3	-26.1	-19.8	-9.4	-0.8	6.6	10.3	9.0	3.0	-4.2	-16.5	-26.0	-8.6
	Extreme Min	-46.7	-46.1	-45.2	-33.0	-16.4	-5.6	0.8	-2.8	-10.7	-28.9	-37.7	-47.1	
Gillam	Daily Avg. Min	-29.0	-27.3	-21.2	-10.6	-2.2	5.1	9.7	8.7	3.3	-3.5	-15.5	-25.9	-9.0
	Extreme Min	-46.1	-45.0	-42.6	-33.0	-22.8	-6.1	-1.7	-1.7	-9.1	-26.9	-39.4	-45.1	
Thompson	Daily Avg. Min	-29.3	-26.5	-19.9	-9.1	-0.8	5.4	9.1	7.6	1.9	-4.3	-16.6	-26.2	-9.1
	Extreme Min	-48.9	-47.8	-48.3	-34.4	-18.3	-5.6	-1.1	-3.5	-11.1	-27.1	-41.2	-47.6	
Flin Flon	Daily Avg. Min	-24.5	-21.5	-15.0	-5.3	2.3	9.5	13.0	12.0	6.1	-0.9	-11.6	-21.3	-4.8
	Extreme Min	-44.5	-45.6	-41.0	-31.0	-13.0	-2.0	4.4	-1.5	-6.7	-16.5	-35.0	-44.0	
Norway House	Daily Avg. Min	-26.9	-23.7	-16.9	-6.2	1.7	8.1	11.9	10.9	4.7	-2.1	-12.9	-23.2	-6.2
	Extreme Min	-49.4	-45.6	-41.5	-32.7	-12.0	-2.0	1.8	-1.4	-7.0	-22.8	-35.9	-45.0	

Table 3.1-3: Maximum Temperature (°C)

Station	Parameter	Months												Year
		J	F	M	A	M	J	J	A	S	O	N	D	
Churchill	Daily Avg. Max	-21.9	-20.2	-13.9	-5.1	2.9	12.0	18.0	16.8	9.5	1.6	-9.0	-17.8	-2.3
	Extreme Max	1.7	1.8	9.0	28.2	28.9	32.2	34.0	36.9	29.2	20.6	7.2	3.0	
Lynn Lake	Daily Avg. Max	-19.3	-14.4	-6.2	3.2	11.9	19.1	22.1	20.3	12.4	3.1	-8.4	-16.7	2.3
	Extreme Max	7.7	7.5	12.4	27.4	31.6	35.2	33.9	35.3	29.3	24.0	11.4	5.6	
Gillam	Daily Avg. Max	-19.7	-16.0	-7.9	1.9	9.9	18.0	21.8	20.0	12.4	3.6	-7.6	-16.9	1.6
	Extreme Max	2.9	4.6	12.4	28.7	32.4	36.8	35.2	35.1	31.0	22.4	9.5	2.6	
Thompson	Daily Avg. Max	-18.3	-13.5	-5.0	4.8	13.1	19.8	23.1	21.4	13.6	4.4	-7.3	-15.7	3.4
	Extreme Max	8.1	8.2	15.9	29.4	32.6	37.4	35.9	34.6	32.2	24.6	13.4	5.0	
Flin Flon	Daily Avg. Max	-15.1	-10.8	-2.7	6.9	14.4	20.4	23.4	22.0	14.7	6.0	-5.1	-12.9	5.1
	Extreme Max	9.5	10.0	15.0	27.0	32.5	35.0	35.0	33.9	30.0	24.0	17.5	8.3	
Norway House	Daily Avg. Max	-16.1	-11.4	-3.8	5.9	14.1	20.1	23.3	22.0	14.8	6.0	-4.7	-13.2	4.7
	Extreme Max	7.7	9.0	14.0	25.9	33.0	33.8	34.7	32.2	31.1	22.9	12.8	5.4	

Table 3.1-4: Degree Days (DD/month and DD/year)

Station	Parameter	Months												Year
		J	F	M	A	M	J	J	A	S	O	N	D	
Churchill	Above 10°C	0.0	0.0	0.0	0.0	4.7	32.5	104.5	87.4	14.7	0.3	0.0	0.0	244.1
	Above 5°C	0.0	0.0	0.0	0.7	18.0	96.7	236.8	225.9	67.7	4.0	0.0	0.0	649.9
	Below 0°C	807.2	691	586.8	299.7	89.2	1.7	0.0	00.0	1.1	73.4	381.1	678.8	3610.1
Lynn Lake	Above 10°C	0.0	0.0	0.0	0.8	25.8	109.2	194.3	155.6	25.5	1.2	0.0	0.0	512.3
	Above 5°C	0.0	0.0	0.0	8.3	83.8	238.4	348.2	303.3	100.2	12.4	0.0	0.0	1094.6
	Below 0°C	751.1	573	406.8	138.4	14.1	0.00	0.0	0.0	1.4	74.4	372.7	650.3	2982.2
Gillam	Above 10°C	0.0	0.0	0.0	1.3	18.8	88.2	180.8	141.0	28.3	1.5	0.0	0.0	459.9
	Above 5°C	0.0	0.0	0.2	8.1	63.1	203.4	333.2	290.2	105.6	12.2	0.0	0.0	1016.1
	Below 0°C	752.1	611.2	454.5	165.3	30.4	0.0	0.0	0.0	0.7	58.2	342.1	664.2	3078.8
Thompson	Above 10°C	0.0	0.0	0.0	1.5	26.5	101.8	191.7	147.0	28.3	1.4	0.0	0.0	498.1
	Above 5°C	0.0	0.0	0.2	11.9	88.6	229.1	345.8	295.6	103.6	13.3	0.1	0.0	1088.2
	Below 0°C	739.3	561.1	392.1	118.6	10.8	0.0	0.0	0.0	0.8	63.5	361.4	656.1	2903.7
Flin Flon	Above 10°C	0.0	0.0	0.0	2.2	41.8	154.8	255.1	218.3	60.3	3.7	0.0	0.0	736.2
	Above 5°C	0.0	0.0	0.5	23.0	127.6	298.5	409.9	372.1	168.3	31.2	0.1	0.0	1431.1
	Below 0°C	614.4	451.6	278.8	62.6	2.3	0.0	0.0	0.0	0.0	30.7	256.3	529.5	2226.1
Norway House	Above 10°C	0.0	0.0	00.0	2.4	43.1	134.5	236.4	202.8	51.7	2.7	0.0	0.0	673.7
	Above 5°C	0.0	0.0	0.3	18.9	123.3	274.4	391.2	356.1	151.2	24.8	0.2	0.0	1340.3
	Below 0°C	660	495.5	328.9	79.5	4.3	0.0	0.0	0.0	0.2	38	262.4	564	2432.7

3.2 Precipitation

The precipitation regime is summarized using normals of total monthly and annual precipitation and snow depth. In addition, extreme daily total precipitation is presented from the entire period of record at respective stations.

Average total annual and total monthly precipitation is summarized in Table 3.2-1. On average, total annual precipitation ranges from 452.5 mm at Churchill to 532.3 mm at Norway House. Generally, the wettest months occur during the summer (June, July and August) and early autumn (September). Daily extreme precipitation totals are presented in Table 3.2-2. The most extreme daily precipitation event of 78.2 mm occurred at Flin Flon in July.

Average snow depths are summarized in Table 3.2-3 and represent the average accumulated snow depth in centimetres on the ground. The annual average (which includes months without any snow accumulation) ranges from 12 cm in Norway House to 16 cm in Gillam. The maximum value of average snow depth typically occurs in February or March, just prior to snow melt. On average, Gillam experiences the greatest monthly averaged snow depth of 47 cm in March.

Table 3.2-1: Average Total Precipitation (mm/month and mm/year)

Station	Months												Year
	J	F	M	A	M	J	J	A	S	O	N	D	
Churchill	18.7	16.6	18.1	23.6	30.0	44.2	59.8	69.4	69.9	48.4	35.5	18.4	452.5
Lynn Lake	20.3	16.3	19.8	24.1	37.3	61.8	85.4	68.8	61.0	37.6	26.8	18.8	477.9
Gillam	19.6	19.0	22.7	21.7	42.6	55.8	78.6	76.1	56.8	42.2	38.0	23.3	496.4
Thompson	19.5	16.5	22.5	29.0	47.4	67.8	80.9	70.7	62.1	37.1	32.9	22.8	509.2
Flin Flon	17.7	14.8	19.0	28.0	40.8	67.2	83.1	67.2	64.2	37.6	25.9	22.0	487.6
Norway House	20.7	23.2	23.8	24.7	50.3	70.0	80.2	75.3	61.2	47.0	29.0	27.1	532.3

Table 3.2-2: Extreme Daily Precipitation (mm/day)

Station	Months											
	J	F	M	A	M	J	J	A	S	O	N	D
Churchill	14.4	16.5	21.9	34.4	55.6	36.4	58.5	51.8	62.3	38.0	35.1	21.8
Lynn Lake	12.7	13.4	15.6	48.5	36.3	55.6	59.2	42.4	46.0	29.8	27.2	12.2
Gillam	17.5	23.8	18.6	34.3	46.0	48.7	64.4	52.1	36.8	30.6	21.6	17.2
Thompson	14.5	11.4	22.8	24.8	34.3	46.4	76.6	75.3	62.0	45.0	28.3	15.8
Flin Flon	13.2	14.2	24.0	39.4	62.6	54.0	78.2	53.8	55.6	29.6	16.9	18.6
Norway House	25.4	14.8	21.4	20.8	43.6	51.2	58.8	68.4	59.4	31.5	29.8	20.0

Table 3.2-3: Average Snow Depth (cm)

Station	Months												Year
	J	F	M	A	M	J	J	A	S	O	N	D	
Churchill	28	31	34	33	13	0	0	0	0	2	15	24	15
Lynn Lake	34	37	33	14	1	0	0	0	0	3	17	26	14
Gillam	35	44	47	22	3	0	0	0	0	2	14	26	16
Thompson	37	43	42	16	1	0	0	0	0	2	13	28	15
Flin Flon	33	40	35	8	0	0	0	0	0	1	11	24	13
Norway House	34	41	33	6	0	0	0	0	0	1	9	22	12

3.3 Wind

The wind regime is summarized using normals of monthly average wind speed and most frequent wind direction. In addition, extreme wind speeds are presented for maximum hourly wind speed and maximum gust speed from the entire period of record at respective stations.

Average annual and monthly wind speed and direction are summarized in Table 3.3-1. On average, the annual average wind speed ranges from 10.6 km/h at Flin Flon to 20.7 km/h at Churchill. The most frequent wind direction varies by month and location but tends to be from the northwest or west on an annual basis. Generally, Churchill, Gillam and Flin Flon experience higher average wind speeds in fall while Lynn Lake, Thompson and Norway House experience higher average wind speeds in spring.

Extreme hourly wind speed and maximum gust speed for the entire period of record are presented in Table 3.3-2. Extreme hourly wind speeds range from 41 km/h at Norway House to 116 km/h at Churchill. Maximum gust speeds have exceeded 90 km/h at least once for all locations with the highest gust speed of 161 km/h occurring at Churchill in September.

Table 3.3-1: Wind Speed and Direction (km/h)

Station	Parameter	Months												Year
		J	F	M	A	M	J	J	A	S	O	N	D	
Churchill	Daily Avg. Speed	22.7	21.7	20.9	21.0	20.3	18.1	16.8	17.8	21.6	23.1	22.6	21.6	20.7
	Most Frequent Direction	W	NW	NW	NW	N	N	N	N	N	NW	W	W	NW
Lynn Lake	Daily Avg. Speed	11.5	11.6	11.9	12.8	12.7	12.6	11.6	11.7	12.3	12.3	10.8	10.8	11.9
	Most Frequent Direction	NW	NW	NW	N	E	E	W	W	NW	NW	NW	NW	NW
Gillam	Daily Avg. Speed	14.4	13.5	13.8	15.0	15.2	15.2	14.1	15.2	17.1	17.5	15.8	13.9	15.1
	Most Frequent Direction	W	W	W	NE	NE	NE	NE	S	NW	NW	W	W	W
Thompson	Daily Avg. Speed	10.8	11.0	11.9	13.6	13.5	12.5	11.1	11.3	11.8	11.7	10.7	9.8	11.6
	Most Frequent Direction	W	W	W	NE	NE	NE	W	W	W	W	W	W	W
Flin Flon	Daily Avg. Speed	9.1	9.9	9.9	10.8	10.8	11.2	10.6	10.6	12.0	12.0	10.9	9.3	10.6
	Most Frequent Direction	NW	N	S	S	S	S	S	S	S	N	N	N	S
Norway House	Daily Avg. Speed	10.0	10.6	11.6	13.0	13.1	12.5	11.4	11.0	12.1	12.2	10.9	9.9	11.5
	Most Frequent Direction	NW	NW	S	S	NE	SW	SW	SW	NW	NW	NW	NW	NW

Table 3.3-2: Extreme Wind Speed (km/h)

Station	Parameter	Months											
		J	F	M	A	M	J	J	A	S	O	N	D
Churchill	Max Hourly Speed	92	93	80	74	84	77	72	95	116	96	93	106
	Max Gust Speed	126	119	105	97	108	109	109	129	161	121	122	104
Lynn Lake	Max Hourly Speed	52	59	54	56	57	56	56	56	50	56	56	70
	Max Gust Speed	80	95	85	91	120	81	100	116	80	87	93	111
Gillam	Max Hourly Speed	67	65	76	61	67	74	74	70	83	64	68	65
	Max Gust Speed	89	82	91	83	100	96	107	96	91	81	74	96
Thompson	Max Hourly Speed	48	54	48	52	59	48	50	56	61	58	52	56
	Max Gust Speed	81	74	83	87	93	130	105	93	82	80	80	95
Flin Flon	Max Hourly Speed	48	56	48	58	55	56	56	48	59	48	48	59
	Max Gust Speed	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Norway House	Max Hourly Speed	46	41	43	48	48	46	46	48	46	52	43	46
	Max Gust Speed	76	76	80	93	78	78	93	83	93	80	83	81

3.4 Lake Evaporation

Environment Canada publishes evaporation normals and defines evaporation as the calculated lake evaporation occurring from a small natural open water-body having negligible heat storage and very little heat transfer at its bottom and sides (Environment Canada 2015). In other words, it represents evaporative loss from small water bodies such as ponds and small reservoirs.

Lake evaporation normals were only available from Churchill and Thompson and are presented in Table 3.4-1. On a monthly and annual basis, Churchill experiences lower lake evaporation compared to Thompson.

Table 3.4-1: Lake Evaporation (mm/month, mm/year)

Station	Months												Year
	J	F	M	A	M	J	J	A	S	O	N	D	
Churchill	0.0	0.0	0.0	0.0	0.0	120.0	124.0	96.1	54.0	0.0	0.0	0.0	394.1
Lynn Lake	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Gillam	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Thompson	0.0	0.0	0.0	0.0	0.0	141.0	139.5	111.6	63.0	0.0	0.0	0.0	455.1
Flin Flon	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Norway House	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

4.0 REGIONAL CLIMATE SUMMARY

As an alternative to characterizing climate at discrete locations for the 1981–2010 normals, a regional climate summary is provided to describe the general climate over a larger area with respect to time. Graphics are used to summarize the regional climate, providing visuals for comparison of spatial differences, temporal differences and variability.

Several data sources are used to develop the regional summary. AHCCD data from climate stations presented in Section 3.0 are used to develop time series plots and illustrate changes to average conditions and regional extreme events over time. The Natural Resources Canada's 10 km by 10 km gridded dataset, based on Environment Canada station data (Hopkinson *et al.* 2011; McKenney *et al*. 2011; Hutchinson *et al.* 2009), is used to map average annual temperature and average annual total precipitation over time. Six periods of ten year averages are presented to illustrate how annual average conditions have changed in time and space. A gridded evapotranspiration dataset (Trabucco and Zomer 2009) is also used to map potential evapotranspiration.

Extended climate records such as those provided though anecdotal evidence and paleoclimate records can also enhance the understanding of past regional climate and how it has varied. For example, Ball (1983) used Hudson Bay Company archives and suggests that northern Manitoba experienced more extreme weather (colder with more frequent snowfall and northerly winds) in the early 1700s and large weather variability from 1780–1815. Description of river conditions from individual years can also be useful in characterizing climate within a watershed. For example, Ball (1983) presents information from 1731 at Churchill showing above average rainfall days, average wind conditions but lower river levels in October, suggesting drought in the interior.

Some studies have also used proxy data to study past climate. Using borehole temperatures, including records in northern Canada, Huang *et al*. (2000) present reconstructed Northern Hemisphere temperatures for the period of 1500-2000. The authors show that borehole temperature reconstructions are consistent with recent warming in the observed record and also suggest that warming in the twentieth century was greater than warming in the past five centuries. Using tree ring data, St. George *et al.* (2009) present reconstructed Palmer Drought Severity Index (PDSI) on the Canadian Prairies. The authors show that northern Saskatchewan experienced dry conditions in the late 1880s, early 1900s and also 1940 while also noting that there is considerable spatial heterogeneity in drought on the Canadian Prairies.

4.1 Temperature

Figure 4.1-1 illustrates the time series of average annual temperature (left axis) and the minimum and maximum values of daily mean temperature (right axis) for the AHCCD period of record. While normals presented in Section 3 represent 30 year averages, there is considerable inter-annual variability. Figure 4.1-1 confirms that the south-to-north cooling gradient is generally maintained on a yearly basis however the difference in temperatures within the same year is not consistent between all stations.

Map 4.1-1 illustrates spatial differences in decadal averaged mean temperature throughout the study region. These maps show spatial patterns such as the south-to-north cooling gradient as well as a slight east-to-west warming gradient in central Manitoba. The east-to-west gradient identifies the spatial pattern which produces slightly warmer temperatures at Flin Flon than Norway House, despite Flin Flon's more northern location. These maps also show an increasing temperature trend as warmer conditions progress northward over the decades. A more detailed analysis on temperature trends is provided in Section 5.

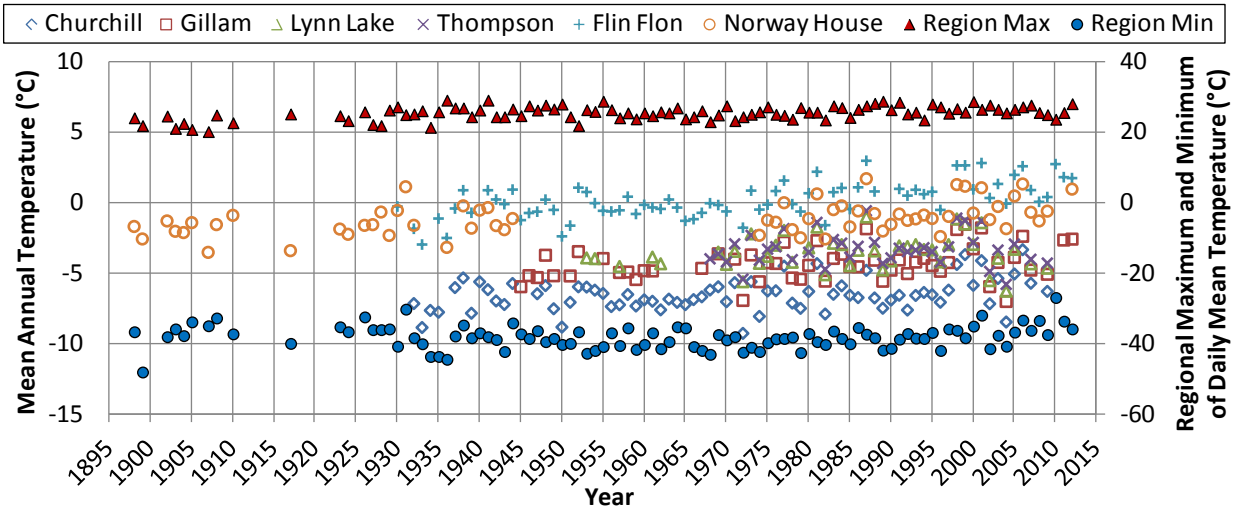
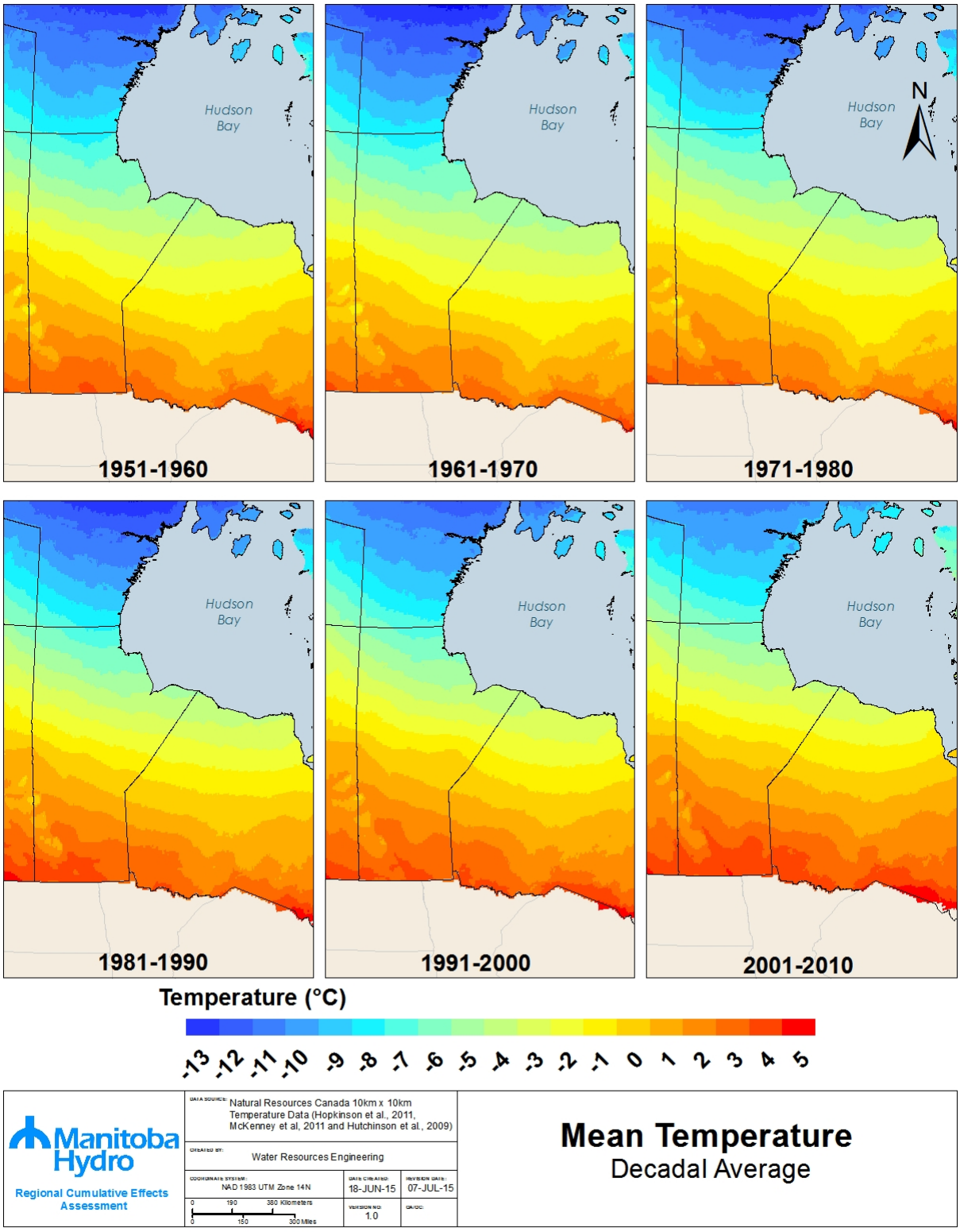


Figure 4.1-1: Time Series of Annual Average Temperature and Regional Extreme Temperature



Map 4.1-1: Mean Temperature Decadal Averages

4.2 Precipitation

Figure 4.2-1 illustrates the time series of total annual precipitation (left axis) and the maximum value of total daily precipitation (right axis) for the AHCCD period of record. While normals presented in Section 3 represent 30 year averages, there is considerable inter-annual and spatial variability. This figure provides a temporal representation showing relatively wet years (*e.g.*, 2005) and relatively dry years (*e.g.*, 1981). It is important to note that multiple stations are typically combined to create the AHCCD record. As such, the extreme precipitation shown in Figure 4.2-1 exceeds the extreme precipitation shown in Table 3.2-2. The extreme precipitation shown in Figure 4.2-1 originates from the Churchill Marine climate station (ID: 5060602) which recorded 94 mm/day on July 24, 1934.

Map 4.2-1 illustrates spatial differences in decadal averaged total annual precipitation throughout the study region. These maps show spatial patterns such as the southeast-to-northwest drying gradient with wetter conditions typically existing in southeast Manitoba and northwest Ontario. Trends in precipitation are less apparent than temperature and a more detailed analysis on precipitation trends is provided in Section 5.

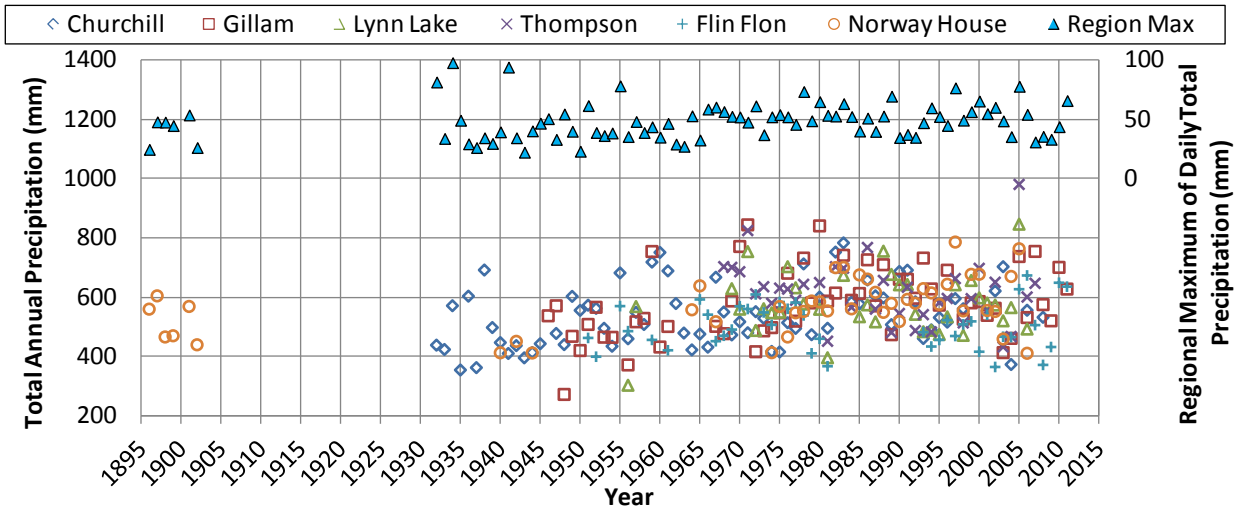
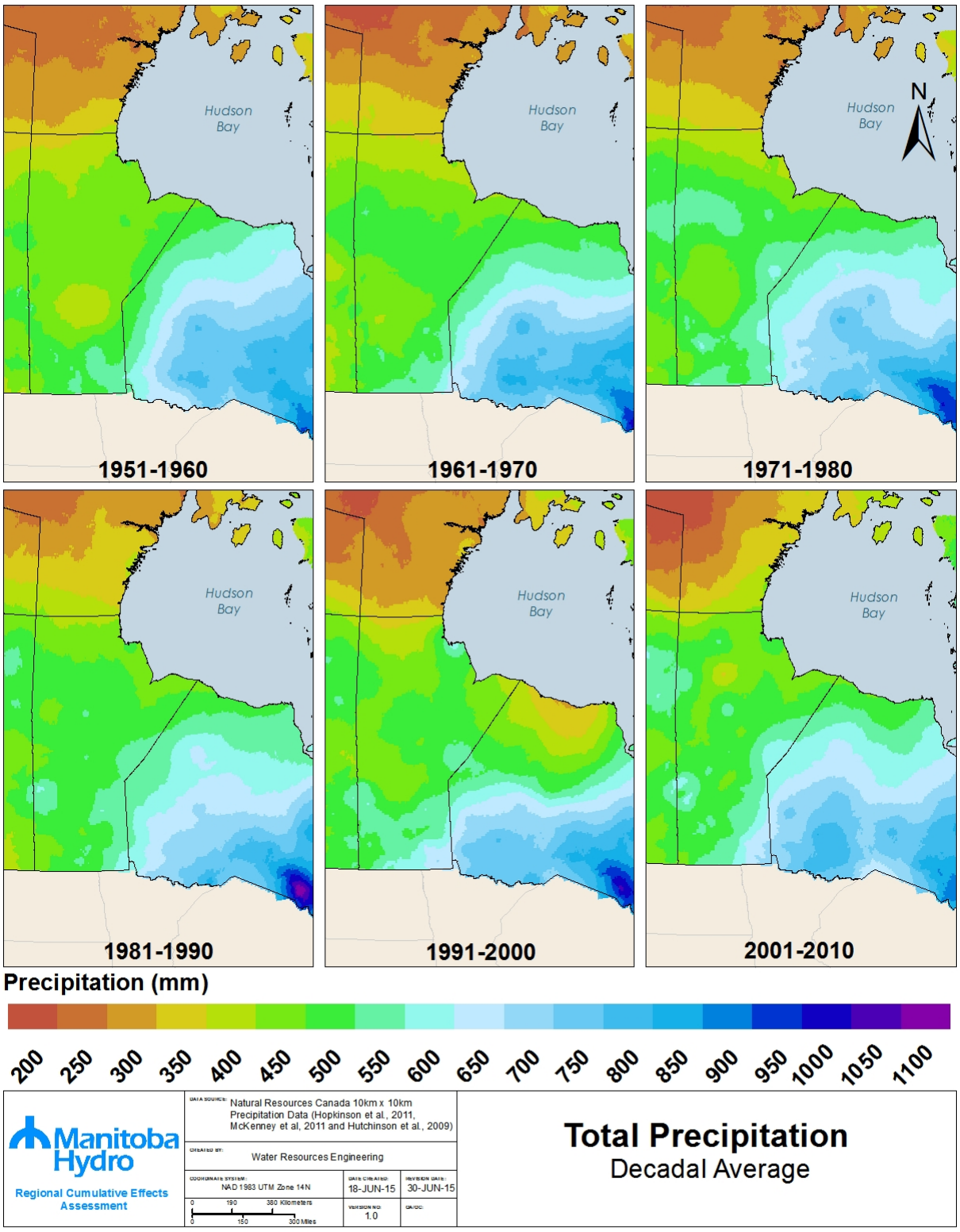


Figure 4.2-1: Time Series of Average Annual Total Precipitation and Regional Extreme Daily Precipitation

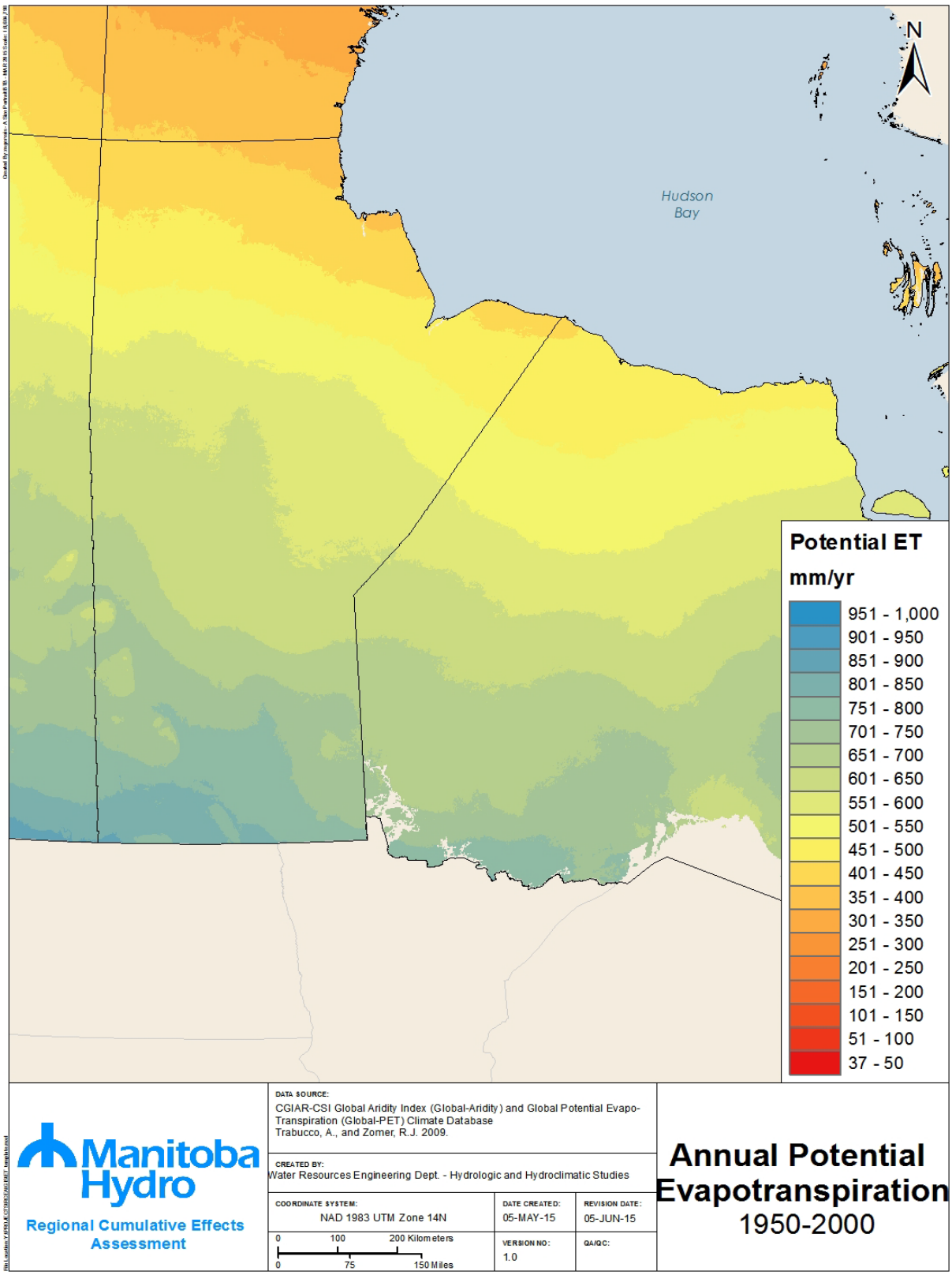


Map 4.2-1: Total Annual Precipitation Decadal Averages

4.3 Potential Evapotranspiration

Accurate measurement of Actual Evapotranspiration (AET) is challenging due to its complex nature. Evapotranspiration is the flux of water vapor from the land surface, water surface and plants into the atmosphere. Evapotranspiration is a complex process, influenced by many factors including solar radiation, wind, vapor pressure gradient, moisture availability and land cover type. As a result, actual evapotranspiration is highly variable in space, challenging to quantify and few high quality, long term, historic records of actual evapotranspiration exist. Alternatively, simplified methods for estimating Potential Evapotranspiration (PET) are readily available. PET estimates provide an indication of the maximum rate of evapotranspiration given the geographic location and climate conditions, assuming an unlimited supply of water. Therefore PET is often used to estimate AET over water surfaces while scaling factors are used to estimate AET for soil and vegetated surfaces, which is typically less than PET.

The Hargreaves method (Hargreaves *et al*. 1985) is a common approach for estimating PET over large areas. The Hargreaves method only requires location, mean daily temperature and the diurnal temperature range, which is readily available in historic datasets for many locations. Map 4.3-1 illustrates the average total annual potential evaporation during the 1950-2000 time period using data from Trabucco and Zomer (2009). Since the Hargreaves method is largely a function of temperature, similar spatial patterns, including a south to north gradient, is seen for both potential evapotranspiration and temperature. Average annual PET rates range from approximately 351 to 700 mm/yr in northern Manitoba.



Map 4.3-1: Average Total Annual Potential Evapotranspiration

5.0 CLIMATE TRENDS

Trends in temperature, degree days, precipitation, wind speed and streamflow were assessed for the entire period of record available at the climate and streamflow stations. Available literature is also used to enhance characterization of trends including trends in evapotranspiration. Results presented below focus on statistically significant trends.

5.1 Temperature Trends

Annual increasing trends in mean temperature were detected at all indicator stations (Table 5.1-1). Increases range from 0.1°C/decade at Churchill to 0.4°C/decade at Lynn Lake.

Seasonally, increasing trends were detected at all stations in winter, four stations in spring, two stations in summer and only at Flin Flon in autumn. Flin Flon was the only location where a statistically significant trend was detected annually and in all four seasons (Table 5.1-1).

Table 5.1-1: Trends in Daily Average Temperature (°C/decade)

Station	Period of Record	Winter		Spring		Summer		Autumn		Annual	
		trend	z-stat.	trend	z-stat.	trend	z-stat.	trend	z-stat.	trend	z-stat.
Churchill	1932-2010	**0.3**	**3.00**	**0.2**	**2.17**	0.1	1.80	0.2	1.54	**0.1**	**2.28**
Lynn Lake	1952-2011	**0.6**	**2.43**	0.4	1.15	0.2	1.81	0.2	1.03	**0.4**	**2.95**
Gillam	1943-2011	**0.5**	**2.78**	**0.5**	**2.58**	**0.3**	**3.23**	0.3	1.79	**0.3**	**3.41**
Thompson	1967-2011	**0.7**	**2.13**	0.2	0.63	0.3	1.79	0.3	1.61	**0.3**	**2.14**
Flin Flon	1927-2010	**0.5**	**3.76**	**0.4**	**3.44**	**0.2**	**2.84**	**0.2**	**2.58**	**0.3**	**4.31**
Norway House	1897-2005	**0.5**	**2.96**	**0.3**	**2.91**	0.1	1.86	0.0	0.41	**0.2**	**2.57**

Note: Bold type indicates statistically significant trends.

5.2 Degree Day Trends

Annual increasing trends in DD were detected at Lynn Lake, Gillam, Thompson and Flin Flon for the 5°C threshold and at Gillam and Flin Flon for the 10°C threshold. Decreasing annual trends in DD below 0°C were detected at all stations except Lynn Lake (Table 5.2-1).

For the DD above 5°C, statistically significant increases range from 34.2 DD/decade at Thompson to 50.3 DD/decade at Lynn Lake. For DD above 10°C, statistically significant increases range from 24.4 DD/decade at Gillam and 28.3 DD/decade at Flin Flon. For DD below 0°C, statistically significant decreases range from -70.2 DD/decade at Churchill to -113.0 DD/decade at Flin Flon.

Table 5.2-1: Trends in Annual Degree-Days (DD/decade)

Station	Period of Record	DD (> 5°C)		DD (>10°C)		DD (<0°C)	
		trend	z-stat.	trend	z-stat.	trend	z-stat.
Churchill	1932-2009	15.6	1.80	8.8	1.79	**-70.2**	**-2.56**
Lynn Lake	1953-2005	**50.3**	**2.26**	30.0	1.87	-20.3	-1.82
Gillam	1946-2012	**41.1**	**3.17**	**24.4**	**2.49**	**-89.4**	**-3.44**
Thompson	1968-2012	**34.2**	**2.16**	24.5	1.88	**-91.6**	**-2.24**
Flin Flon	1930-2012	**37.5**	**2.68**	**28.3**	**2.46**	**-113.0**	**-3.73**
Norway House	1898-2009	36.3	1.86	28.6	1.66	**-76.9**	**-2.74**

Note: Bold type indicates statistically significant trends.

5.3 Precipitation Trends

Increasing trends in total annual precipitation were detected at Churchill and Gillam, while a decreasing trend was detected at Thompson (Table 5.3-1). An increasing trend in annual precipitation falling as snow was also observed at Gillam (Table 5.3-2).

Seasonally, increasing total winter precipitation trends were detected at Churchill, Gillam and Norway House. An increasing trend was also present for total spring precipitation at Norway House and total autumn precipitation at Churchill and Norway House. For precipitation falling as snow, increasing trends were detected at Churchill, Gillam and Norway House in winter, a decreasing trend was detected at Thompson in summer while increasing trends were detected at Gillam and Norway House for autumn.

Table 5.3-1: Trends in Total Precipitation (mm/decade)

Station	Period of Record	Winter		Spring		Summer		Autumn		Annual	
		trend	z-stat.	trend	z-stat.	trend	z-stat.	trend	z-stat.	trend	z-stat.
Churchill	1932-2011	**5.2**	**2.80**	1.1	0.31	2.5	0.66	**7.3**	**2.45**	**19.4**	**2.61**
Lynn Lake	1952-2010	3.8	1.55	4.3	1.57	1.6	0.46	4.0	0.66	3.8	0.36
Gillam	1943-2011	**5.0**	**1.96**	4.9	1.41	2.8	0.64	6.3	1.85	**18.7**	**2.17**
Thompson	1967-2011	-2.5	-0.92	3.7	0.59	-11.6	-1.34	-5.8	-0.93	**-31.3**	**-2.14**
Flin Flon	1927-2010	1.5	0.62	-2.7	-1.15	2.1	0.63	-1.1	-0.52	8.8	0.64
Norway House	1896-2005	**5.4**	**3.07**	**8.1**	**2.09**	4.5	1.28	**4.5**	**1.96**	10.7	1.22

Note: Bold type indicates statistically significant trends.

Table 5.3-2: Trends in Precipitation Falling as Snow (mm/decade)

Station	Period of Record	Winter		Spring		Summer		Autumn		Annual	
		trend	z-stat.	trend	z-stat.	trend	z-stat.	trend	z-stat.	trend	z-stat.
Churchill	1932-2007	**4.9**	**2.76**	0.7	0.23	0.0	0.71	0.3	1.36	10.3	1.58
Lynn Lake	1952-2007	3.7	1.51	1.5	0.54	0.0	0.05	1.2	0.28	-2.1	-0.33
Gillam	1943-2010	**5.1**	**2.19**	1.8	0.77	0.0	-1.00	**5.7**	**2.44**	**13.5**	**1.96**
Thompson	1967-2007	-1.0	-0.33	-4.7	-1.28	**-0.1**	**-2.22**	-6.5	-1.80	-12.3	-1.52
Flin Flon	1927-2010	2.1	0.91	-3.2	-1.76	0.0	-0.37	-1.6	-1.38	-2.5	-0.55
Norway House	1896-2005	**4.5**	**3.07**	4.1	1.84	0.00	0.44	**5.0**	**2.68**	5.8	1.24

Note: Bold type indicates statistically significant trends.

5.4 Wind Speed Trends

Decreasing trends in mean annual wind speed were detected at all four indicator stations with homogenized wind speed data. Decreases were also detected at Churchill, Thompson and Flin Flon for mean autumn wind speed, Gillam and Thompson for mean summer wind speed, and Thompson and Flin Flon for mean spring wind speed. No statistically significant wind speed trends were detected in winter.

Table 5.4-1: Trends in Daily Average Wind Speed ([km/h]/decade)

Station	Period of Record	Winter		Spring		Summer		Autumn		Annual	
		trend	z-stat.	trend	z-stat.	trend	z-stat.	trend	z-stat.	trend	z-stat.
Churchill	1953-2014	-0.14	-0.90	-0.27	-1.73	-0.17	-1.52	**-0.41**	**-2.90**	**-0.23**	**-2.73**
Lynn Lake	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Gillam	1953-2014	0.08	0.50	-0.18	-1.30	**-0.39**	**-3.74**	0.00	0.04	**-0.13**	**-2.20**
Thompson	1967-2014	-0.16	-1.35	**-0.33**	**-3.11**	**-0.34**	**-2.80**	**-0.33**	**-2.86**	**-0.29**	**-3.39**
Flin Flon	1954-2014	-0.11	-0.93	**-0.36**	**-2.11**	-0.10	-0.54	**-0.30**	**-2.16**	**-0.30**	**-2.76**
Norway House	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Note: Bold type indicates statistically significant trends.

5.5 Evapotranspiration Trends

In the absence of high quality, long term records with good spatial coverage, a detailed assessment of evapotranspiration trends within the study region was not conducted. Several studies have aimed at computing evaporation and evapotranspiration trends based on available observed or re-analysis (modeled) data and are summarized in literature such as the IPCC Fifth Assessment Report (AR5) (IPCC 2013).

Burn and Hesch (2006, 2007) analyzed potential evaporation (PE) and pan evaporation trends across the Canadian Prairies. While Burn and Hesch (2006) did not report location-specific results,

Burn and Hesch (2007) detected statistically significant decreasing trend in warm season evaporation at Norway House for 1971-2000 and at The Pas for 1961-2000. Burn and Hesch (2006, 2007) suggest potential causes for decreasing evaporation trends which include decreasing wind speeds and decreasing vapor pressure deficit.

Fernandes *et al*. (2007) analyzed AET in Canada for the period of 1960–2000. In northern Manitoba, a statistically significant increase was detected for Churchill (classified as Arctic Tundra) but not at The Pas (Northwestern Forest).

Chapter 2 of IPCC's AR5 (IPCC 2013) reports that global evapotranspiration over land has increased from the early 1980s up to the late 1990s, but also notes that pan evaporation has decreased in many regions. Decreases in pan evaporation are generally attributed to declining wind speeds but the effect of wind speed trends on actual evapotranspiration trends is more complex due to land-atmosphere feedbacks (van Heerwaarden *et al*. 2010). Furthermore, in vegetated regions, with high transpiration rates, rising CO_2 concentrations can reduce stomatal openings and evapotranspiration.

5.6 Streamflow Trends

Trends in annual average streamflow can be indicative of overall changes in water availability within a watershed, over a specified period of time. Overall, there is low confidence that that global river streamflow trends have increased during the 20th century but some evidence suggests that mean annual flow and winter base flow have increased in higher latitudes (IPCC 2013). While precipitation is typically a major driver of streamflow trends, this is not always the case and for many large rivers, human influences must be considered in interpretation (IPCC 2013).

Annual average streamflow trends were assessed in 14 northern Manitoba rivers with minimal influence from human development (Table 2.1-2). Periods of record vary among the rivers but start as early as 1955 and end as late as 2010. Some records contain considerable amounts of missing data but only records with at least 18 years (and up to 47 years) were included. Trend directions range from minor increases to minor decreases but no statistically significant trends were detected at the 5% significance level.

Burn and Whitfield (2015) assessed trends in floods for Canadian rivers with minimal anthropogenic impact. Two locations in northern Manitoba were considered and are characterized as either having a snowmelt dominated flood regime (nival) or are larger catchments with a later flood date. While no statistically significant trends were detected in northern Manitoba, the author's provide generalized results throughout Canada: nival rivers tend to show decreasing trends in flood magnitude and timing, consistent with reduced snowpack in a warmer climate. Rivers with larger catchments, later mean flood dates that exhibit nival-like responses, show more increases than decreases in flood magnitude. These increases are likely due to increases in extreme precipitation events. The authors also suggest that rivers with rainfall dominated flood regimes (pluvial) are experiencing increased flood risk but characterizing changes in flood regimes is difficult due to the complex nature and different flood causing mechanisms.

5.7 Detection and Attribution of Observed Climate Changes

Trend detection provides evidence of change over time. For parameters such as temperature, changes are consistent throughout the region, consistent with global patterns (IPCC 2013) and agree on the direction of change thereby providing more robust indicators of past regional change. However, interpretation of trends is challenging in parameters and areas with greater natural variability such as precipitation in northern Manitoba. In many cases, changes are not regionally consistent and can disagree on the direction of change, providing a less robust indicator of past regional change.

Attribution studies aim at linking detected change to a specific cause. For some indicators, such as increased global mean temperatures from 1951–2010, the IPCC states that increases are very likely due to anthropogenic increases in greenhouse gas concentrations (IPCC 2013). For less conclusive indicators such as precipitation, where observation coverage is limited and modeling efforts are uncertain, the IPCC provides limited confidence in detection and attribution. However, the effect of anthropogenic forcing is greatest in high latitudes of the Northern Hemisphere, where precipitation increases are a robust feature of climate model simulations (IPCC 2013). The IPCC also has higher confidence that average land-based precipitation over mid-latitude areas of the Northern Hemisphere has likely increased since 1951 (IPCC 2013). This report does not attempt to assign attribution to observed trends.

6.0 SUMMARY

Six indicator climate stations were used to characterize climate in the RCEA study region. Annual average temperature ranges from -6.5°C at Churchill to +0.2°C at Flin Flon. The observed record also indicates a wide range of extreme temperatures ranging from -49.4°C at Norway House to +37.4°C at Thompson. Trend analysis generally indicates increasing annual, winter and spring temperature trends with fewer trends detected in summer and autumn. Regional analysis exhibits a south-to-north cooling gradient in mean annual temperature. Since temperature is a primary driver, DD, Evaporation and Potential Evapotranspiration (PET) generally follow similar patterns as temperature.

Annual average total precipitation ranges from 453 mm at Churchill to 532 mm at Norway House. Of the six indicator climate stations, the extreme daily total precipitation recorded was 78 mm which occurred at Flin Flon. Within the region, Gillam exhibits greatest value of average snow depth (47 cm) which typically occurs in March. Trend analysis shows mixed results with increasing annual precipitation detected at Churchill and Gillam and a decreasing trend in annual precipitation detected at Thompson. Increasing trends in total winter precipitation and winter precipitation falling as snow were detected at Churchill, Gillam and Norway House. Regional analysis exhibits more spatial and temporal variability than temperature, but generally shows a southeast-to-northwest drying gradient in annual average total precipitation.

Annual average wind speed ranges from 10.6 km/h at Flin Flon to 20.7 km/h at Churchill and most frequently blows from the northwest or west. The extreme hourly wind speed of 116 km/h and extreme gust speed of 161 km/h were both recorded at Churchill and both in the month of September. Generally, all six stations have experienced wind gusts in excess of 90 km/h. Decreasing trends in mean annual wind speed were detected at Churchill, Gillam, Thompson and Flin Flon. Decreasing trends were also detected at a few stations for spring, summer and autumn but no statistically significant trends were detected for winter.

Fourteen rivers in northern Manitoba with minimal human impact were assessed for trend in annual average streamflow. Trend directions range from minor increases to minor decreases but no statistically significant trends were detected.

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