Let's Talk about Climate Change: Great Lakes Region

Office of the Chief Ecosystem Scientist

Version 1.3 (August 28, 2017)

Parks Canada Parcs Canada

Canada

Let's Talk about Climate Change: Great Lakes Region

Scott Parker
Parks Canada, Office of the Chief Ecosystem Scientist
248 Big Tub Road, Tobermory, Ontario N0H 2R0
e. scott.parker@pc.gc.ca

Special thanks to: Gilles Seutin, Patrick Nantel, Ryan Eagleson, Yanick Laliberté Tremblay, Liz Nelson, Dan McKenney, Pia Papadopol, Jean-François Gobeil, Cavan Harpur, Leo Carbrera, Tammy Dobbie and Claire LaCroix.

This report is one in a series that provides a regional summary of observed and projected climate change trends and impacts facing all of Canada's national parks, national marine conservation areas and certain national historic sites. This is an internal document to Parks Canada and is intended to encourage and inform broader conversations and support place–based actions on climate change.

The "Let's Talk about Climate Change" series regions are defined by biogeoclimatic and operational similarities, and include: 1) Atlantic Region; 2) Quebec Region; 3) Great Lakes Region; 4) Prairie and Boreal Plains Region; 5) Mountain Region; 6) Pacific Region; 7) Northwest Region; and, 8) Arctic and Hudson Plains Region.

This report and others in the series are available at the Parks Canada Climate Change SharePoint Website: http://collaboration/sites/PD010/SitePages/Home.aspx

Contents

1. Introduction

The fifth and most recent report from the Intergovernmental Panel on Climate Change (IPCC, 2014) establishes with certainty that the Earth's climate system is warming, "and since the 1950's, many of the observed changes are unprecedented over decades to millennia". Human activity has increased atmospheric concentrations of greenhouse gas (GHG) to levels not observed in at least the last 800,000 years. Worldwide, a rapidly changing climate is having profound impact on our social-ecological systems, amplifying existing risks and creating new ones.

Canada's rate of warming is about double the global rate (even greater in the north) and the last three decades have been the warmest 30-year period in at least 1,400 years. Some of the observed changes include shifts in species distribution and abundance, glacier loss, thawing permafrost, decreasing sea ice, earlier ice break-ups, increasing wildfires, sea level rise along some coasts, changes to phenology, and an increase in extreme weather events such as heat waves, droughts, heavy rainfall and more (e.g., Lemmen *et al.*, 2016; Warren and Lemmen, 2014). The risks and impacts are felt across Parks Canada, from the ecosystems and cultural resources we protect, to the facilities and infrastructure we build and maintain, to the visitor experiences we offer - and most concerning, these impacts are projected to increase for decades to come. It is an uncertain and complex context, one which will test the adaptive capacity and effectiveness of policy, planning, and management frameworks.

To advance place-based climate response efforts, this document is one in a series of regional reports that provides accessible summary information about climate change in Canada's national parks, national marine conservation areas (NMCAs) and certain national historic sites. For some sites this will support preliminary conversations on climate change and for others the content will be eclipsed by a need for more detailed vulnerability assessments, adaptation strategies and decision support tools. Regardless, the intent is to encourage and equip individuals and sites to talk about climate change, both internally and externally, and consider the challenges in their own context.

1.1. "Natural Solution" Concept

As a lead conservation and protected area agency, and the largest federal land owner and third largest federal asset manager in the country, Parks Canada's response to climate change is a matter of importance. Part of the response will involve recognizing and positioning protected areas as a "natural solution" to climate change in regional, national and international plans and programs (e.g., Dudley *et al.*, 2010; Lopoukhine *et al.*, 2012; NAWPA, 2012).

As a "natural solution", well-designed and effectively managed protected areas:

- Mitigate climate change through the sequestration and storage of carbon in forests, coastal wetlands ("blue carbon") and other natural ecosystems.
- Protect biodiversity by providing a safe haven for species.
- Enhance connectivity and species movements within and across protected area networks.

- Provide essential ecosystem goods and services, such as clean water, erosion control, flood/storm water protection, genetic diversity, cultural opportunities, etc…
- Serve as a benchmark for climate change related research and monitoring.
- Provide a context for social learning, good governance, and adaptive management.
- Help people and communities cope by supporting sustainable and resilient economies in and around protected areas and promoting social well-being (e.g., healthy parks – healthy people).
- Demonstrate environmental stewardship through "green" design and conservation practices.
- Create and facilitate meaningful experiences that help to inspire, inform, and guide actions in response to climate change.

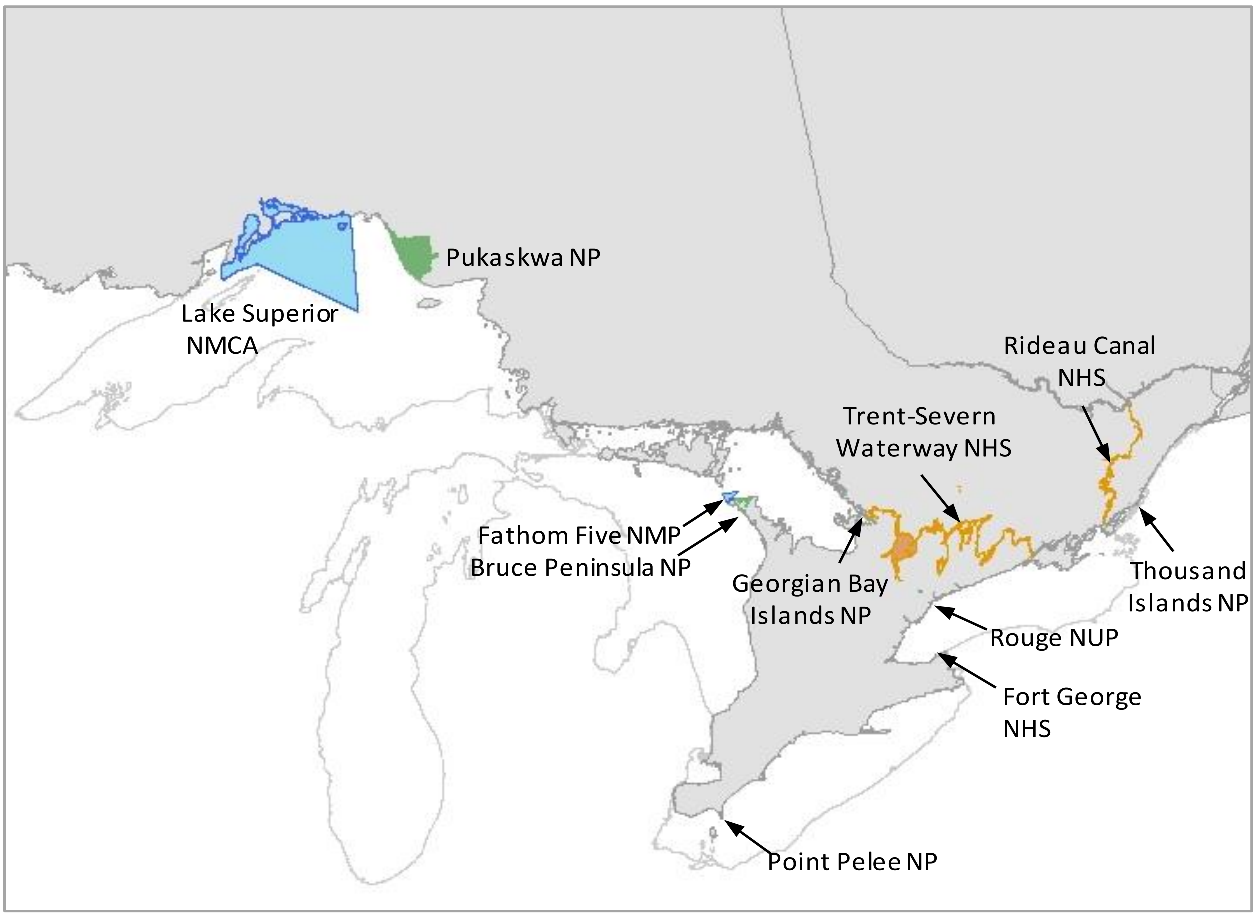


Figure 1. National Parks (NP), National Marine Conservation Areas (NMCA / NMP), National Urban Park (NUP) and National Historic Sites (NHS) included in this Great Lakes regional report.

2. Observed and Projected Climate Trends

This section provides site specific summaries of historic observed temperature and precipitation trends as well as future climate projections. These are only a subset of the climate variables available for analysis and presentation (see Appendix 1).

2.1 Methods

Historic observed mean monthly temperature and total precipitation data was accessed from the Adjusted and Homogenized Canadian Climate Data website (http://www.ec.gc.ca/dccha-ahccd) for the climatological stations within or closest to each protected area. Temperature and precipitation stations were not always in the same location and preference was given to selecting stations with the longest and most current data for a protected area. All available years were plotted and the trend was determined using a generalized linear model (R Core Team, 2014) including 95% confidence intervals. For the analysis, winter = December, January and February; spring = March, April and May; summer = June, July and August; and, autumn = September, October and November.

A table with future climate change projections was determined for the centre of each protected area. Season by season descriptions were provided to complement the earlier park-based assessments by Scott and Suffling (2000) and to help inform seasonal operations and activities. The climate projections were determined following Price *et al.* (2011) and used the average of four General Circulation Models (GCMs) and the lowest and highest Representative Concentration Pathway (RCP) GHG scenarios. The RCP 2.6 (lowest) scenario assumes that we take action and GHG emissions peak in 2010-2020 and decline thereafter. The RCP 8.5 (highest) scenario assumes we take no action and emissions continue to rise throughout the 21st century. Figures 3 and 4 also include a projection based on the RCP 4.5 scenario, where emissions peak around 2040 and then decline.

2.2 Regional Climate Change Summaries

2.2.1 Physical Effects

The Great Lakes already exhibit considerable natural variability (seasonal to decadal cycles) in temperature, evapotranspiration, water levels and other factors (Gronewold *et al.*, 2013), however, despite this variability, signals of climate change are evident.

- Since the 1950’s the average annual air temperature in the region has warmed by between 0.8-2˚C, with the greatest increase in the winter and spring (McDermid *et al.*, 2015). This warming trend is projected to continue and model results indicate a further increase of 1-8˚C, depending on the location and RCP scenario used.
- A longer frost-free period has been observed and is projected to continue, resulting in a longer growing season (e.g., advanced by 1-1.5 days/decade, McDermid *et al.*, 2015).
- Precipitation patterns have been variable, with slightly wetter conditions being observed in most areas. This trend is expected to continue with an increase in total annual precipitation of 2-7% in the next 30 years (except at Bruce/Fathom Five). The frequency

and magnitude of extreme precipitation events is expected to increase during the winter and spring, with more drought-like conditions in the summer and autumn (e.g., Cheng *et al.*, 2012a; Wuebbles *et al.*, 2010). The frequency of lake effect snow (notably around Superior and Huron) has increased and this trend is expected to continue (Kunkel *et al.*, 2009).

- Great Lakes surface water temperatures have increased by as much as 3.5˚C in the last century and are predicted to continue to warm by 3-6˚C depending on the lake/location and RCP scenario used (Trumpickas *et al.*, 2009; Zhong *et al.*, 2016). Lake Superior is warming the fastest at a rate of nearly 1°C/decade (Larouche and Galbraith, 2016).
- There has been a 71% reduction in the extent of ice cover between 1973 and 2010 (Minns *et al.*, 2014b; Wang *et al.*, 2012). The greatest warming and shortening of ice duration appears to be occurring in the northern- and eastern sectors, especially in nearshore areas (Mason *et al.*, 2016). An earlier onset and longer period of thermal stratification is expected (Zhong *et al.*, 2016).
- Great Lakes water levels are primarily driven by climatic variables (e.g., precipitation, evaporation, ice cover) (IJC, 2009). Most models suggest that future lake levels will generally fluctuate around the lower end of their historical range with annual means slightly below long term mean levels (e.g., 20-25cm lower by 2050) (IJC, 2012; MacKay and Seglenieks, 2013; Music *et al.*, 2015).
- Although maximum spring runoff is occurring earlier and with a lower amplitude, flooding from more extreme precipitation events is expected to increase (Adamowski *et al.*, 2013; Cheng *et al.*, 2012b; Cunderlik and Ouarda, 2009; Jones *et al.*, 2015; Karl *et al.*, 2009).
- The length of the wildfire season, as well as fire frequency and intensity, are all expected to increase, particularly in the boreal forest (Flannigan *et al.*, 2005; Le Goff *et al.*, 2009; Wang *et al.*, 2015).

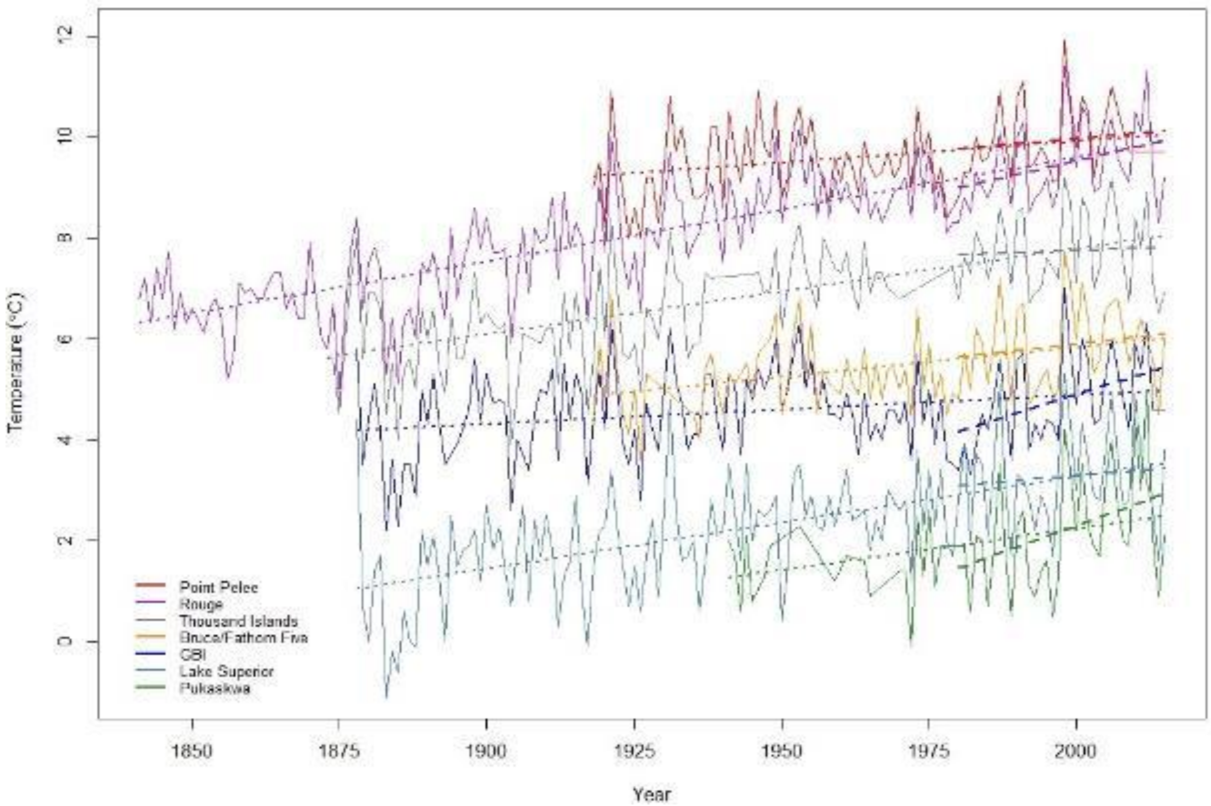


Figure 2. Mean annual temperatures for the national parks, national marine conservation areas and the national urban park in the Great Lakes region (Ontario). Two trend lines included, one for the full time series and a second for just the time period between 1980 and 2015. The trend is significant (P<0.05) for all full time series, however only the trend at the Rouge, GBI, and Pukaskwa are significant (P<0.05) for the shorter 1980 to 2015 time period.

Mean Annual Temperature

Change from 1980-2010 Baseline

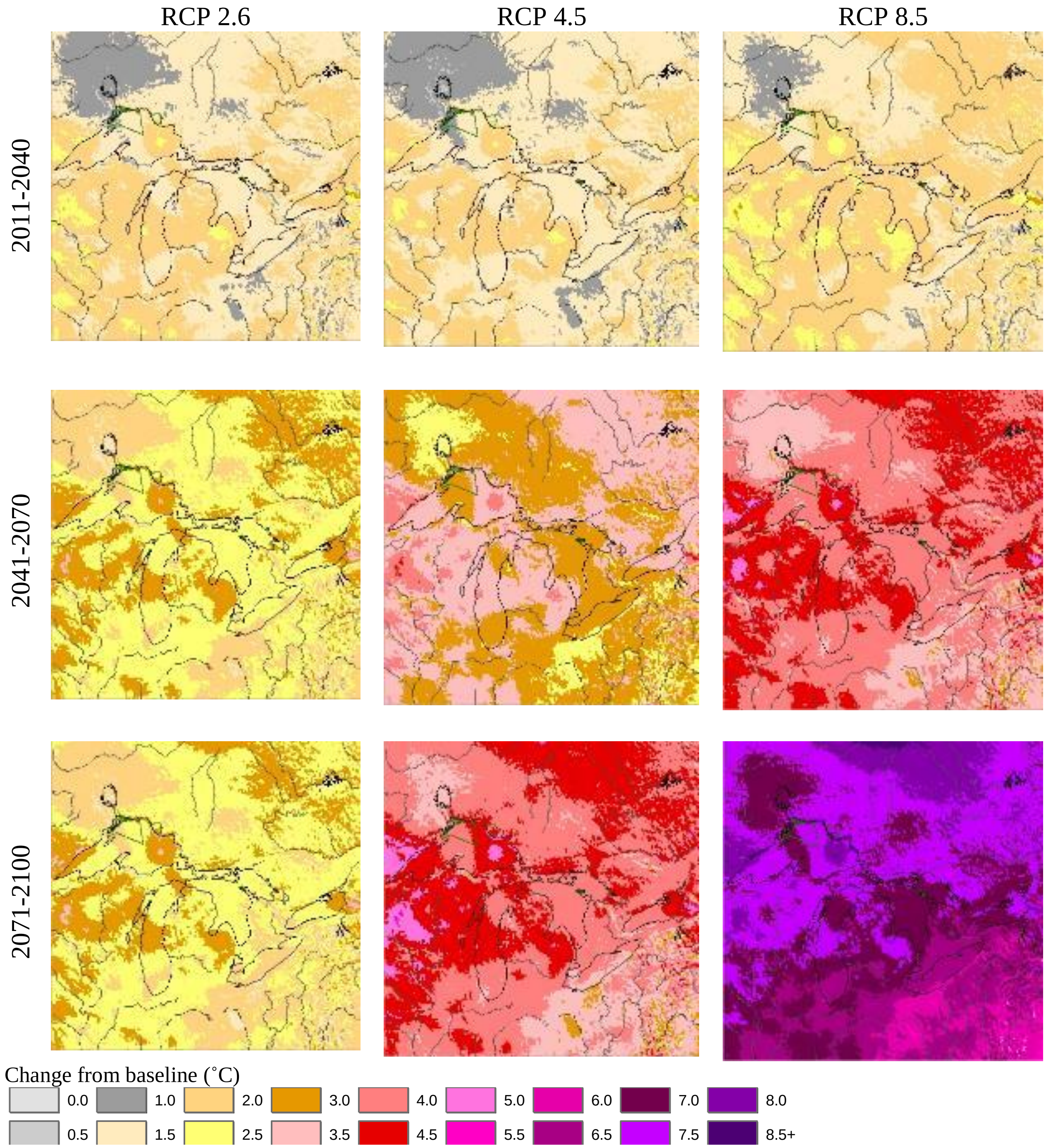


Figure 3. Temperature projections represent a composite (average) of four spatially interpolated downscaled Global Circulation Models: CanESM2, CESM1CAM5, HADGEM2ES and MIROCESM, using three greenhouse gas scenarios (RCPs) for three future time periods. Climate data provided by Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie (http://cfs.nrcan.gc.ca/projects/3).

Total Annual Precipitation

Change from 1980-2010 Baseline

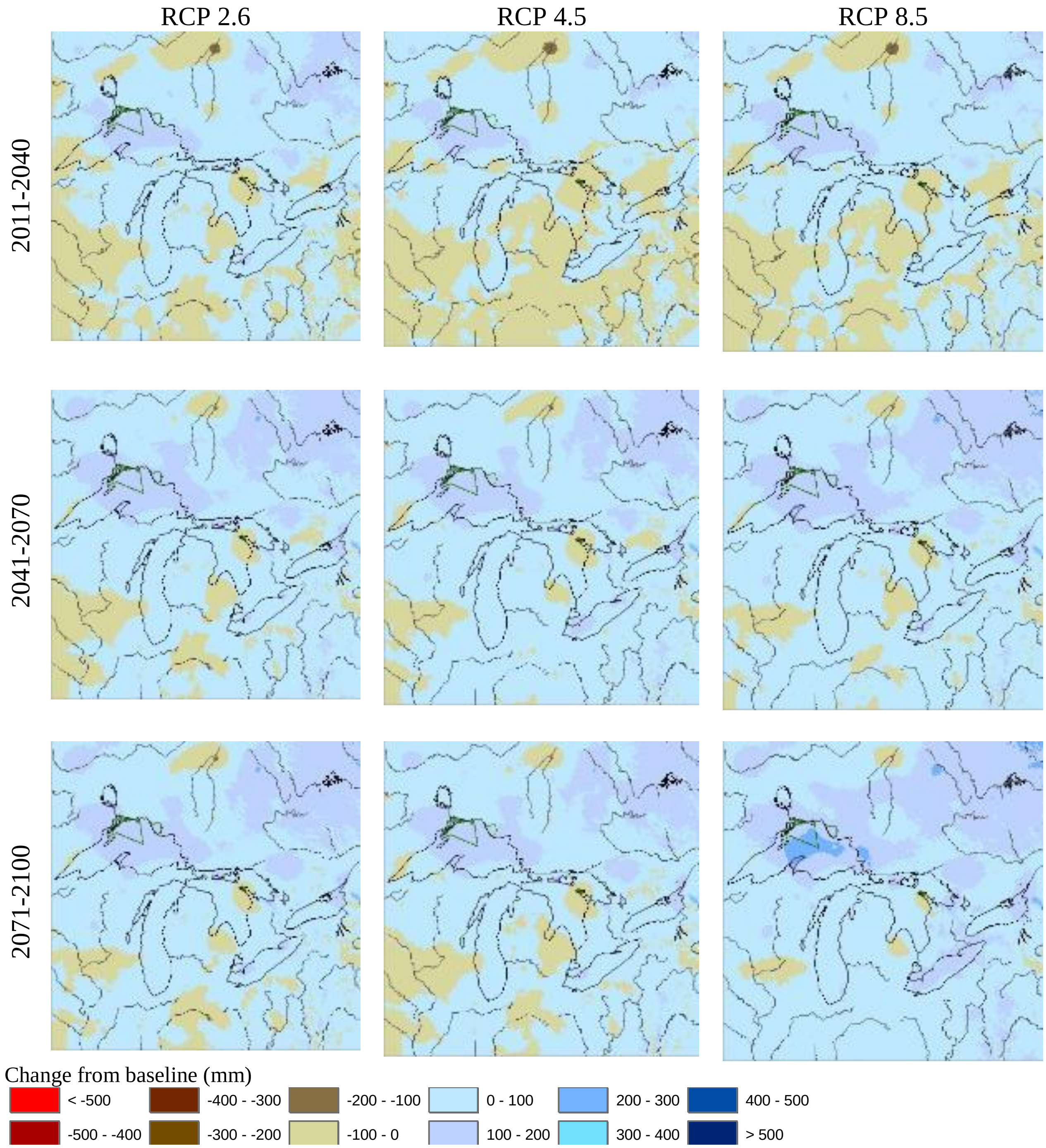
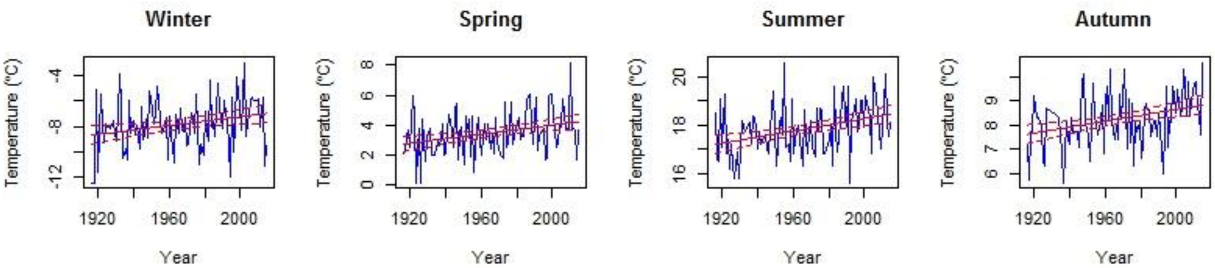


Figure 4. Precipitation projections represent a composite (average) of four spatially interpolated downscaled Global Circulation Models: CanESM2, CESM1CAM5, HADGEM2ES and MIROCESM, using three greenhouse gas scenarios (RCPs) for three future time periods. Climate data provided by Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie (http://cfs.nrcan.gc.ca/projects/3).

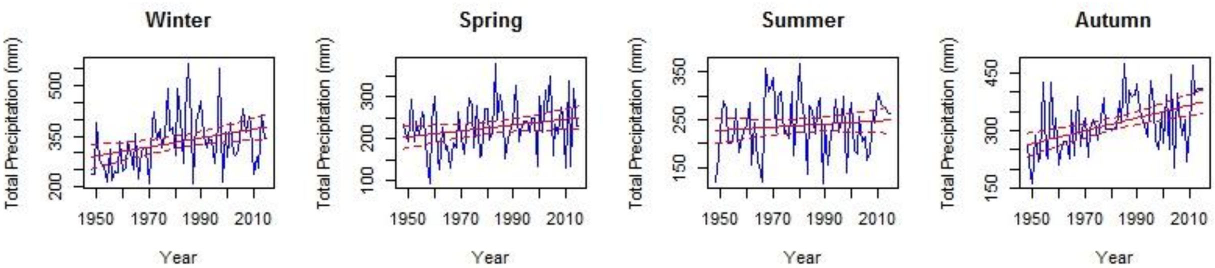
Bruce Peninsula National Park and Fathom Five National Marine Park

A. Mean Temperature



Seasonal mean temperature at Gore Bay Climatological Station (6092920) from 1916 to 2015. A significant trend ($P<0.05$) observed for winter (0.017°C/yr), spring (0.015°C/yr), summer (0.013°C/yr) and autumn (0.012°C/yr).

B. Total Precipitation



Seasonal total precipitation at Wiarton Climatological Station (6119500) from 1948 to 2014. A significant trend ($P<0.05$) observed for winter (1.3mm/yr) and autumn (1.7mm/y). No significant trend ($P<0.05$) observed for spring or summer.

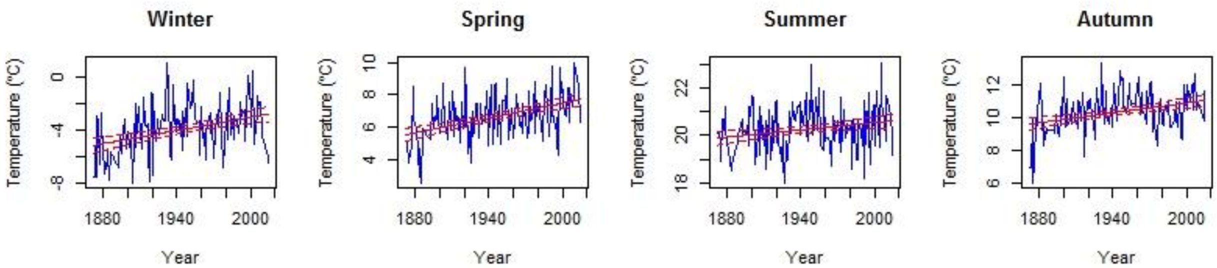
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 81° 29' 30.64" W, 45° 11' 36.25" N; elevation 211 m.

Increase / decrease in:	2011-2040			2041-2070			2071-2100		
Mean Winter Temperature (°C)	1.7	to	2.0	2.6	to	4.6	2.7	to	7.8
Mean Spring Temperature (°C)	2.0	to	2.1	3.1	to	4.3	2.6	to	7.3
Mean Summer Temperature (°C)	1.5	to	1.6	2.1	to	3.9	2.2	to	6.7
Mean Autumn Temperature (°C)	2.0	to	2.2	2.8	to	4.2	2.8	to	7.5
Precipitation in Winter	-1%	to	-2%	2%	to	7%	1%	to	17%
Precipitation in Spring	-13%	to	-15%	-6%	to	-11%	-11%	to	2%
Precipitation in Summer	0%	to	-6%	-3%	to	-9%	0%	to	-11%
Precipitation in Autumn	-9%	to	-10%	-7%	to	-11%	-6%	to	-16%
Number of days of growing season	18.0	to	19.0	26.0	to	37.0	25.0	to	83.0
Growing degree-days during growing season	22%	to	23%	32%	to	54%	32%	to	100%
Advance in start of growing season (days)	9.0	to	9.0	14.0	to	20.0	12.0	to	43.0
Climate Moisture Index (sum May-Sept)	-2.1	to	-3.7	-3.7	to	-10.2	-2.5	to	-20.6

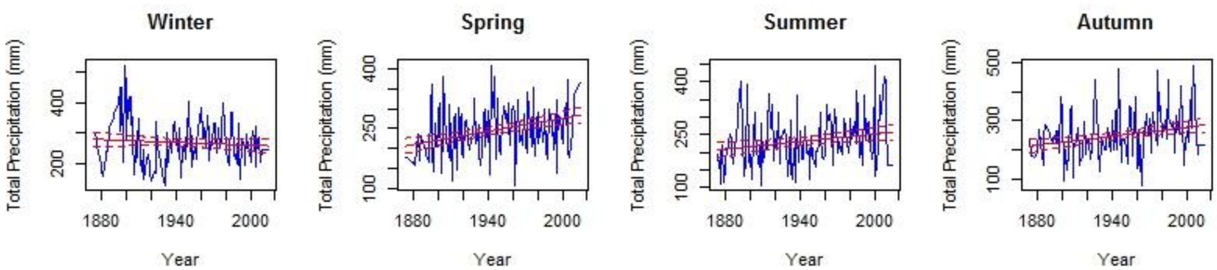
Fort George National Historic Site

A. Mean Temperature



Seasonal mean temperature at Welland Climatological Station (6139449) from 1873 to 2015. A significant trend (P<0.05) observed for winter (0.017°C/yr), spring (0.015°C/yr), summer (0.005°C/yr) and autumn (0.01°C/yr).

B. Total Precipitation



Seasonal total precipitation at Welland Climatological Station (6139445) from 1873 to 2014. A significant trend (P<0.05) observed for spring (0.5mm/yr), summer (0.4mm/yr) and autumn (0.5mm/yr). No significant trend (P<0.05) observed for winter.

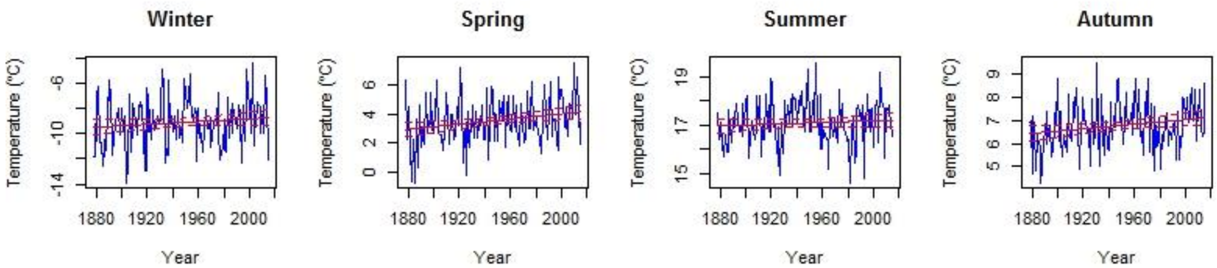
C. Climate Change Projection for Centre of Historic Site Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 79˚ 03’ 40.07” W, 43˚ 15’ 02.01” N

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Max Winter Temperature (°C)	7.1	to	7.1	7.8	to	9.3	7.8	to	12.0
Max Spring Temperature (°C)	1.9	to	2.0	2.9	to	4	2.4	to	6.4
Max Summer Temperature (°C)	2.0	to	2.2	2.7	to	4.6	2.7	to	7.6
Max Autumn Temperature (°C)	8.6	to	8.9	9.5	to	11.1	9.4	to	14.5
Min Winter Temperature (°C)	2.5	to	2.7	3.4	to	5.1	3.4	to	8.0
Min Spring Temperature (°C)	1.9	to	1.9	2.7	to	3.7	2.2	to	6.2
Min Summer Temperature (°C)	1.3	to	1.4	2.0	to	3.6	2.0	to	6.3
Min Autumn Temperature (°C)	15.5	to	15.7	16.4	to	17.7	16.3	to	20.8
Precipitation in Winter	7%	to	10%	16%	to	20%	15%	to	33%
Precipitation in Spring	6%	to	11%	-7%	to	18%	14%	to	24%
Precipitation in Summer	-1%	to	1%	-2%	to	-3%	-2%	to	2%
Precipitation in Autumn	0%	to	-9%	-5%	to	2%	-1%	to	-11%
Advance in start of growing season (# of days)	18.4	to	20.8	11.8	to	14.0	13.4	to	59.8

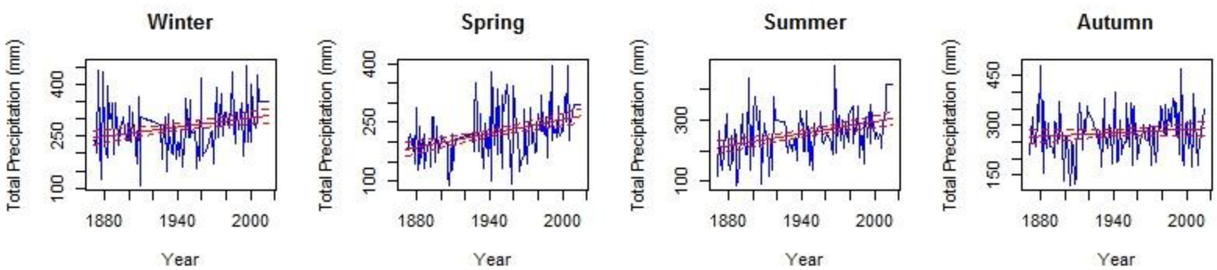
Georgian Bay Islands National Park

A. Mean Temperature



Seasonal mean temperature at Beatrice Climatological Station (6110607) from 1878 to 2015. A significant trend ($P<0.05$) observed for spring (0.009°C/yr) and autumn (0.005°C/yr). No significant trend ($P<0.05$) observed for winter or summer.

B. Total Precipitation



Seasonal total precipitation at Orillia Climatological Station (6115811) from 1871 to 2015. A significant trend ($P<0.05$) observed for winter (0.4mm/yr), spring (0.6mm/yr) and summer (0.65mm/yr). No significant trend ($P<0.05$) observed for autumn.

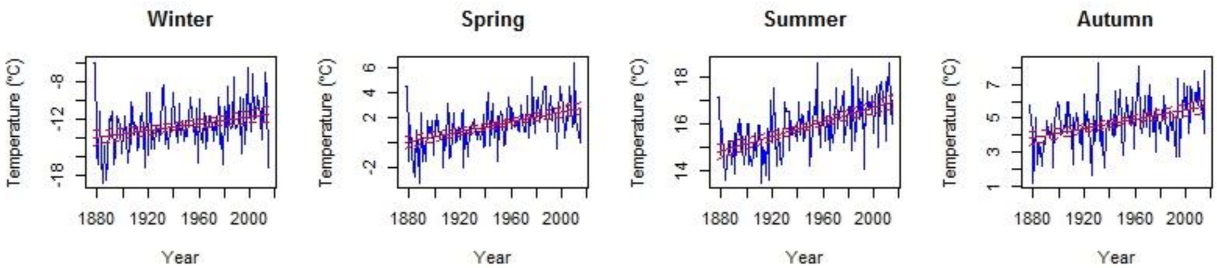
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid 79° 52’ 14.02” W, 44° 52’ 48.90” N; elevation 185 m

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	2.2	to	2.4	3.1	to	4.9	3.1	to	8.0
Mean Spring Temperature (°C)	2.3	to	2.3	3.3	to	4.5	2.8	to	7.3
Mean Summer Temperature (°C)	1.8	to	2.0	2.5	to	4.3	2.6	to	7.2
Mean Autumn Temperature (°C)	2.1	to	2.4	3.0	to	4.4	2.9	to	7.8
Precipitation in Winter	24%	to	24%	29%	to	35%	29%	to	49%
Precipitation in Spring	-1%	to	3%	4%	to	10%	6%	to	19%
Precipitation in Summer	-1%	to	2%	0%	to	-4%	-6%	to	3%
Precipitation in Autumn	4%	to	4%	1%	to	5%	-5%	to	6%
Number of days of growing season	18.0	to	19.0	25.0	to	35.0	24.0	to	65.0
Growing degree-days during growing season	21%	to	24%	32%	to	51%	31%	to	93%
Advance in start of growing season (days)	9.0	to	9.0	13.0	to	18.0	11.0	to	38.0
Climate Moisture Index (sum May-Sept)	-2.8	to	-4.2	-5.0	to	-11.8	-3.2	to	-23.9

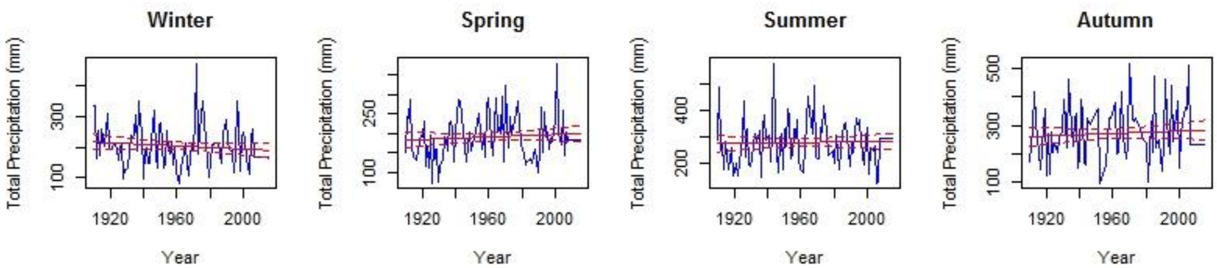
Lake Superior National Marine Conservation Area

A. Mean Temperature



Seasonal mean temperature at Thunder Bay Climatological Station (6048260) from 1877 to 2015. A significant trend ($P<0.05$) observed for winter (0.018°C/yr), spring (0.02°C/yr), summer (0.015°C/yr) and autumn (0.014°C/yr).

B. Total Precipitation



Seasonal total precipitation at Terrace Bay Climatological Station (6048231) from 1910 to 2007. No significant trend ($P<0.05$) observed for any season.

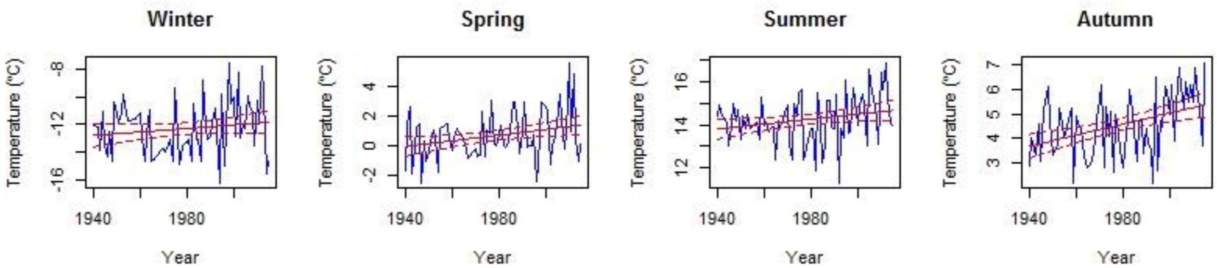
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 87° 38’ 57.64” W, 48° 24’ 08.75” N; elevation 184 m.

Increase / decrease in:		**2011-2040**			**2041-2070**			**2071-2100**	
Mean Winter Temperature (°C)	0.7	to	1.2	1.8	to	4.0	2.0	to	7.6
Mean Spring Temperature (°C)	2.1	to	2.0	3.1	to	4.6	2.9	to	8.3
Mean Summer Temperature (°C)	1.9	to	2.0	2.5	to	4.1	2.6	to	7.0
Mean Autumn Temperature (°C)	1.8	to	2.0	2.6	to	3.9	2.7	to	7.3
Precipitation in Winter	43%	to	42%	46%	to	53%	43%	to	65%
Precipitation in Spring	15%	to	19%	26%	to	33%	23%	to	51%
Precipitation in Summer	3%	to	3%	5%	to	-3%	-10%	to	4%
Precipitation in Autumn	17%	to	19%	26%	to	24%	21%	to	24%
Number of days of growing season	20.0	to	22.0	30.0	to	41.0	30.0	to	70.0
Growing degree-days during growing season	30%	to	31%	41%	to	68%	42%	to	130%
Advance in start of growing season (days)	14.0	to	14.0	19.0	to	26.0	19.0	to	41.0
Climate Moisture Index (sum May-Sept)	1.6	to	2.9	-2.6	to	2.9	-12.6	to	3.3

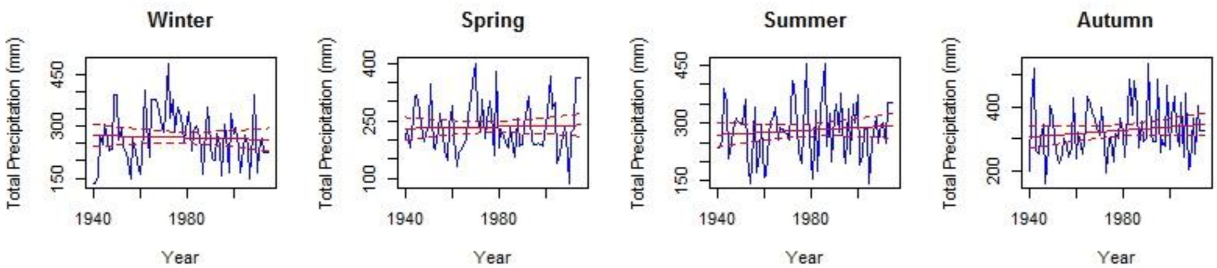
Pukaskwa National Park

A. Mean Temperature



Seasonal mean temperature at Wawa Climatological Station (6059407) from 1940 to 2015. A significant trend (P<0.05) observed for spring (0.019°C/yr), summer (0.012°C/yr) and autumn (0.022°C/yr). No significant trend (P<0.05) observed for winter.

B. Total Precipitation



Seasonal total precipitation at Wawa Climatological Station (6059D09) from 1940 to 2014. No significant trend (P<0.05) observed for any season.

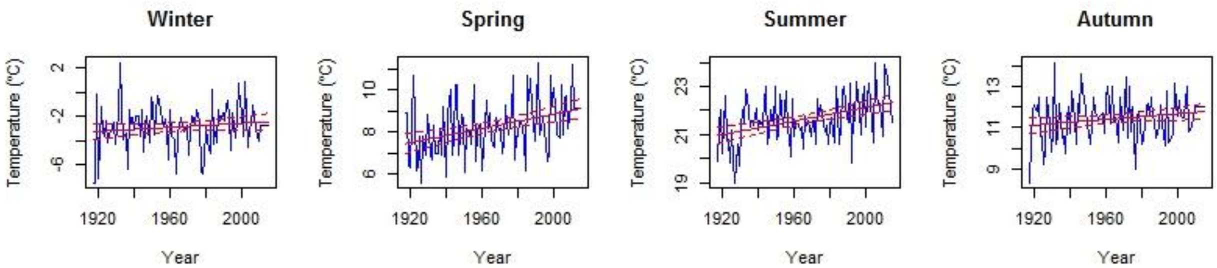
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 85° 54’ 14.68” W, 48° 17’ 21.70” N; elevation 473 m.

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	1.0	to	1.5	2.1	to	4.2	2.3	to	7.8
Mean Spring Temperature (°C)	2.3	to	2.3	3.4	to	4.8	3.1	to	8.4
Mean Summer Temperature (°C)	2.4	to	2.5	3.0	to	4.7	3.1	to	7.5
Mean Autumn Temperature (°C)	1.8	to	1.9	2.5	to	3.9	2.6	to	7.4
Precipitation in Winter	27%	to	27%	29%	to	36%	25%	to	47%
Precipitation in Spring	6%	to	9%	14%	to	22%	13%	to	37%
Precipitation in Summer	6%	to	6%	2%	to	9%	-8%	to	8%
Precipitation in Autumn	5%	to	6%	10%	to	13%	8%	to	11%
Number of days of growing season	19.0	to	21.0	29.0	to	41.0	29.0	to	66.0
Growing degree-days during growing season	41%	to	42%	54%	to	84%	55%	to	154%
Advance in start of growing season (days)	14.0	to	15.0	20.0	to	27.0	19.0	to	38.0
Climate Moisture Index (sum May-Sept)	5.1	to	6.0	0.9	to	6.6	-10.3	to	6.8

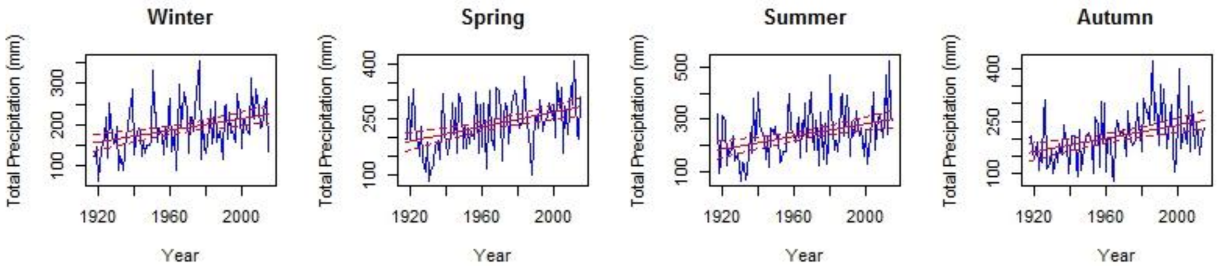
Point Pelee National Park

A. Mean Temperature



Seasonal mean temperature at Harrow Climatological Station (6130257) from 1917 to 2015. A significant trend ($P<0.05$) observed for spring (0.017°C/yr) and summer (0.014°C/yr). No significant trend ($P<0.05$) observed for winter or autumn.

B. Total Precipitation



Seasonal total precipitation at Amherstburg Climatological Station (6130257) from 1917 to 2015. A significant trend ($P<0.05$) observed for winter (0.7mm/yr), spring (1mm/yr), summer (0.7mm/yr) and autumn (0.9mm/yr).

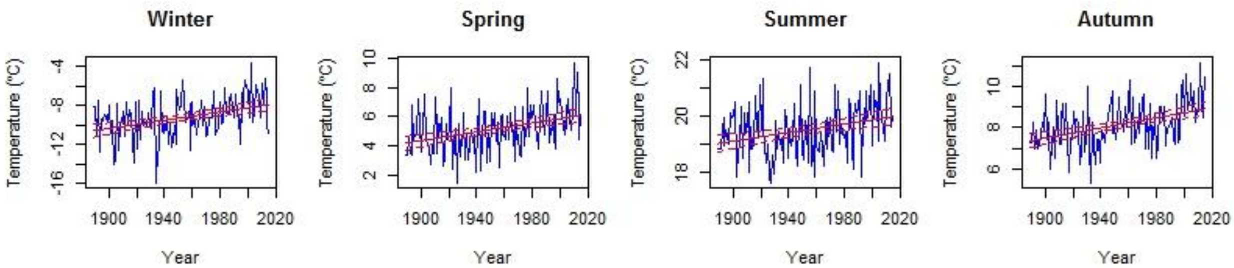
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 82° 31’06.92” W, 41° 57’ 45.67” N; elevation 175 m.

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	1.7	to	1.8	2.4	to	3.9	2.4	to	6.4
Mean Spring Temperature (°C)	2.1	to	2.1	2.8	to	3.9	2.3	to	6.2
Mean Summer Temperature (°C)	1.9	to	2.0	2.6	to	4.3	2.6	to	7.1
Mean Autumn Temperature (°C)	2.1	to	2.4	3.0	to	4.5	2.9	to	7.7
Precipitation in Winter	6%	to	12%	17%	to	19%	14%	to	31%
Precipitation in Spring	16%	to	17%	14%	to	27%	19%	to	31%
Precipitation in Summer	15%	to	17%	13%	to	14%	15%	to	17%
Precipitation in Autumn	5%	to	6%	-3%	to	6%	-5%	to	4%
Number of days of growing season	17.0	to	19.0	25.0	to	37.0	20.0	to	66.0
Growing degree-days during growing season	19%	to	21%	27%	to	43%	26%	to	75%
Advance in start of growing season (days)	12.0	to	14.0	17.0	to	21.0	12.0	to	39.0
Climate Moisture Index (sum May-Sept)	-9.3	to	-9.6	-11.5	to	-18.4	-10.3	to	-29.5

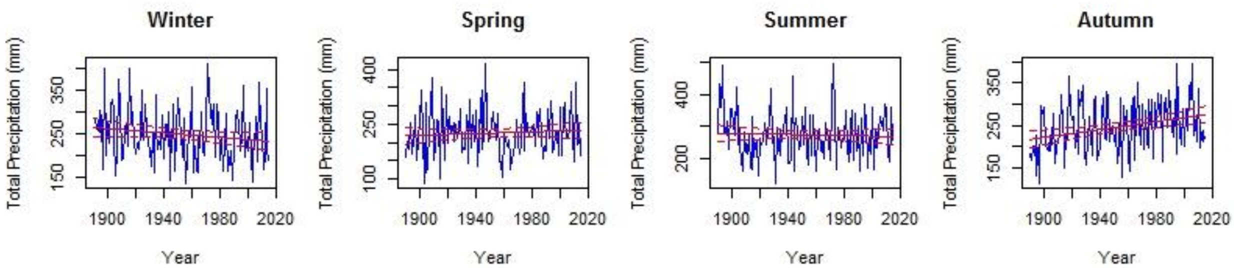
Rideau Canal National Historic Site

A. Mean Temperature



Seasonal mean temperature at Ottawa Climatological Station (6105976) from 1890 to 2015. A significant trend ($P<0.05$) observed for winter (0.021°C/yr), spring (0.012°C/yr), summer (0.008°C/yr) and autumn (0.012°C/yr).

B. Total Precipitation



Seasonal total precipitation at Ottawa Climatological Station (6105976) from 1890 to 2015. A significant trend ($P<0.05$) observed for autumn (0.5mm/yr). No significant trend ($P<0.05$) observed for winter, spring or summer.

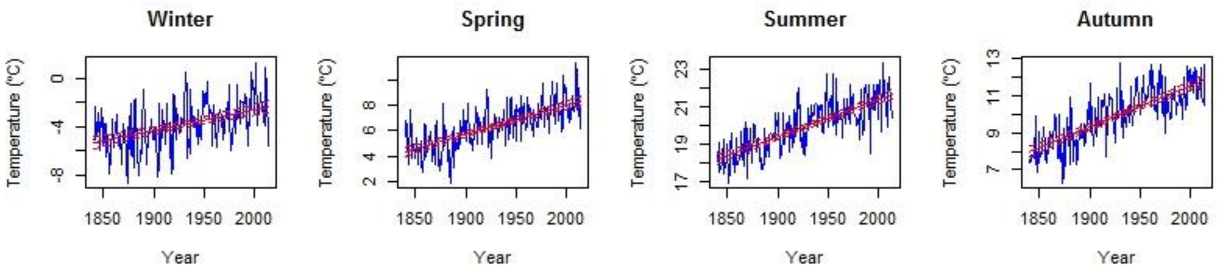
C. Climate Change Projection for Centre of Historic Site Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 76˚ 01’ 35.97”W, 44˚ 53’ 45.82 N

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Max Winter Temperature (°C)	8.9	to	9.0	9.6	to	11.1	9.6	to	13.9
Max Spring Temperature (°C)	2.4	to	2.5	3.5	to	4.7	3.1	to	7.3
Max Summer Temperature (°C)	2.0	to	2.1	2.7	to	4.6	2.7	to	7.8
Max Autumn Temperature (°C)	9.4	to	9.6	10.2	to	11.8	10.1	to	15.3
Min Winter Temperature (°C)	2.4	to	2.7	3.4	to	5.3	3.4	to	8.6
Min Spring Temperature (°C)	2.3	to	2.3	3.3	to	4.5	2.9	to	7.3
Min Summer Temperature (°C)	1.5	to	1.6	2.2	to	3.9	2.3	to	6.8
Min Autumn Temperature (°C)	8.7	to	8.9	9.6	to	10.9	9.5	to	14.2
Precipitation in Winter	12%	to	13%	19%	to	23%	18%	to	36%
Precipitation in Spring	5%	to	10%	0%	to	19%	13%	to	26%
Precipitation in Summer	-3%	to	-3%	-4%	to	-6%	-7%	to	0%
Precipitation in Autumn	-13%	to	2%	-1%	to	3%	-7%	to	2%
Advance in start of growing season (# of days)	14.8	to	18.2	9.4	to	10.6	11.8	to	32.2

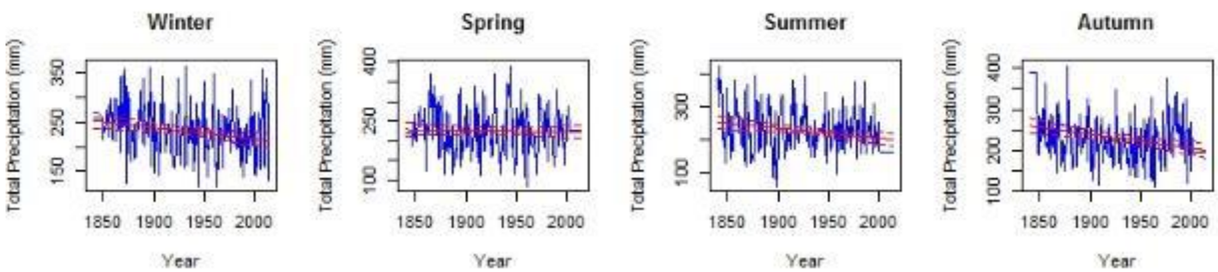
Rouge National Urban Park

A. Mean Temperature



Seasonal mean temperature at Toronto Climatological Station (6158355) from 1840 to 2015. A significant trend (P<0.05) observed for winter (0.017°C/yr), spring (0.023°C/yr), summer (0.02°C/yr), and autumn (0.022°C/yr).

B. Total Precipitation



Seasonal total precipitation at Toronto Climatological Station (6158350) from 1840 to 2015. A significant trend (P<0.05) observed for winter (-0.2mm/yr), summer (-0.3mm/yr) and autumn (-0.3mm/yr). No significant trend (P<0.05) observed for spring.

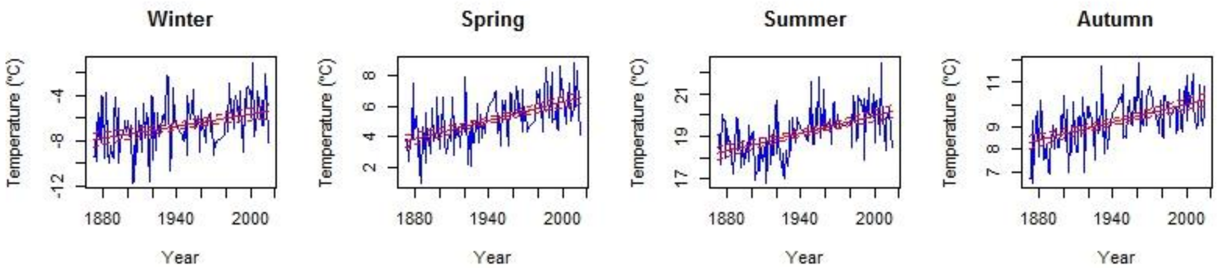
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 79° 13' 43.67" W, 43° 55' 58.42" N; elevation 211 m.

Increase / decrease in:		**2011-2040**			**2041-2070**			**2071-2100**	
Mean Winter Temperature (°C)	1.9	to	2.1	2.7	to	4.4	2.7	to	7.4
Mean Spring Temperature (°C)	1.8	to	1.9	2.8	to	3.9	2.3	to	6.5
Mean Summer Temperature (°C)	1.3	to	1.5	2.0	to	3.8	2.1	to	6.7
Mean Autumn Temperature (°C)	1.9	to	2.2	2.8	to	4.2	2.7	to	7.6
Precipitation in Winter	13%	to	14%	20%	to	24%	20%	to	38%
Precipitation in Spring	7%	to	12%	11%	to	18%	14%	to	26%
Precipitation in Summer	-1%	to	3%	-1%	to	-3%	-2%	to	3%
Precipitation in Autumn	-3%	to	-5%	-3%	to	-8%	-4%	to	-13%
Number of days of growing season	18.0	to	19.0	26.0	to	35.0	23.0	to	80.0
Growing degree-days during growing season	17%	to	19%	26%	to	44%	24%	to	82%
Advance in start of growing season (days)	9.0	to	9.0	14.0	to	18.0	10.0	to	39.0
Climate Moisture Index (sum May-Sept)	-8.7	to	-10.0	-11.5	to	-17.9	-9.9	to	-29.9

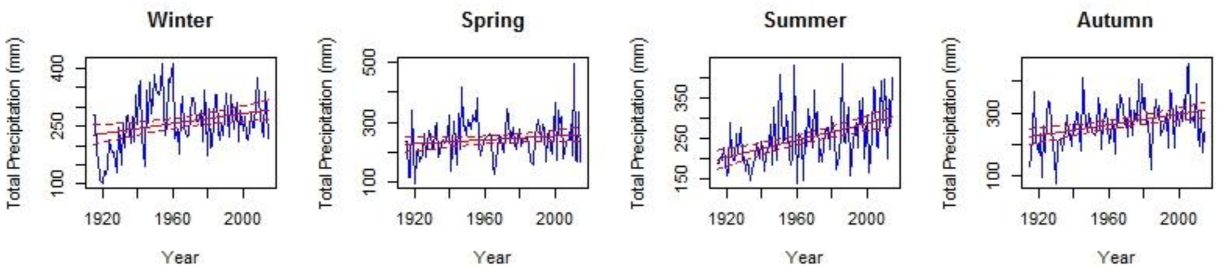
Thousand Islands National Park

A. Mean Temperature



Seasonal mean temperature at Kingston Climatological Station (6104142) from 1872 to 2015. A significant trend ($P<0.05$) observed for winter (0.018°C/yr), spring (0.02°C/yr), summer (0.014°C/yr) and autumn (0.013°C/yr).

B. Total Precipitation



Seasonal total precipitation at Brockville Climatological Station (6100971) from 1915 to 2015. A significant trend ($P<0.05$) observed for the winter (0.6mm/yr), summer (1mm/yr) and autumn (0.9mm/yr). No significant trend ($P<0.05$) observed for spring.

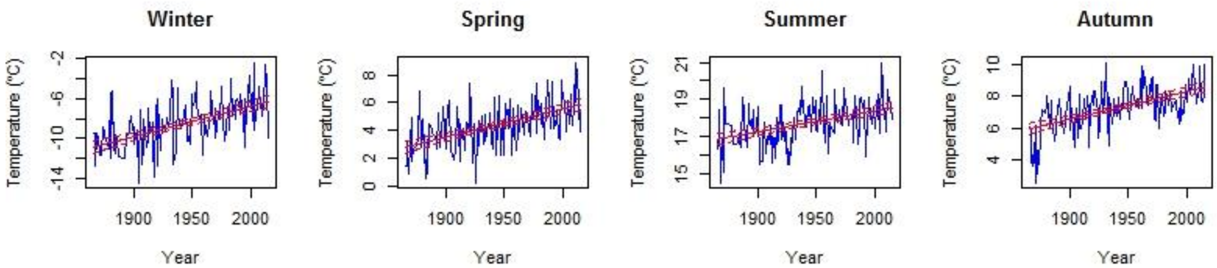
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 76° 00' 56.82" W, 44° 22' 33.09" N; elevation 90 m.

Increase / decrease in:	2011-2040			2041-2070			2071-2100		
Mean Winter Temperature (°C)	2.1	to	2.3	3.0	to	4.7	3.0	to	7.6
Mean Spring Temperature (°C)	2.4	to	2.5	3.4	to	4.6	3.0	to	7.2
Mean Summer Temperature (°C)	1.7	to	1.8	2.4	to	4.2	2.4	to	7.2
Mean Autumn Temperature (°C)	2.0	to	2.3	2.9	to	4.3	2.8	to	7.7
Precipitation in Winter	19%	to	19%	27%	to	31%	25%	to	45%
Precipitation in Spring	13%	to	19%	18%	to	28%	22%	to	35%
Precipitation in Summer	1%	to	2%	-1%	to	0%	-2%	to	4%
Precipitation in Autumn	1%	to	2%	0%	to	4%	-6%	to	2%
Number of days of growing season	19.0	to	20.0	27.0	to	34.0	24.0	to	60.0
Growing degree-days during growing season	20%	to	22%	30%	to	49%	29%	to	87%
Advance in start of growing season (days)	10.0	to	11.0	16.0	to	20.0	13.0	to	37.0
Climate Moisture Index (sum May-Sept)	-6.2	to	-6.2	-8.1	to	-13.9	-6.6	to	-26.8

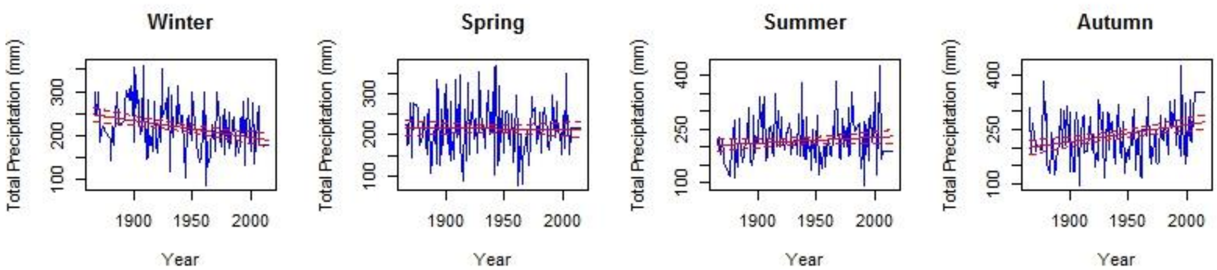
Trent-Severn Waterway National Historic Site

A. Mean Temperature



Seasonal mean temperature at Peterborough Climatological Station (6166415) from 1866 to 2015. A significant trend (P<0.05) observed for winter (0.03°C/yr), spring (0.02°C/yr), summer (0.011°C/yr) and autumn (0.017°C/yr).

B. Total Precipitation



Seasonal total precipitation at Peterborough Climatological Station (6166418) from 1866 to 2007. A significant trend (P<0.05) observed for winter (-0.4mm/yr) and autumn (0.5mm/yr). No significant trend (P<0.05) observed for spring or summer.

C. Climate Change Projection for Centre of Historic Site Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 78˚ 18’ 10.10” W, 44˚ 17’ 55.35” N

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Max Winter Temperature (°C)	8.3	to	8.5	9.1	to	10.6	9.1	to	13.4
Max Spring Temperature (°C)	2.3	to	2.3	3.3	to	4.5	2.9	to	7.1
Max Summer Temperature (°C)	1.9	to	2.0	2.6	to	4.5	2.6	to	7.6
Max Autumn Temperature (°C)	9.0	to	9.3	9.9	to	11.5	9.8	to	15.0
Min Winter Temperature (°C)	2.3	to	2.5	3.3	to	5.2	3.2	to	8.4
Min Spring Temperature (°C)	2.3	to	2.3	3.2	to	4.3	2.7	to	7.0
Min Summer Temperature (°C)	1.5	to	1.6	2.1	to	3.8	2.2	to	6.6
Min Autumn Temperature (°C)	9.4	to	9.6	10.3	to	11.6	10.2	to	14.8
Precipitation in Winter	10%	to	10%	16%	to	21%	16%	to	34%
Precipitation in Spring	2%	to	7%	-6%	to	13%	9%	to	22%
Precipitation in Summer	-3%	to	-5%	-6%	to	-7%	-2%	to	-8%
Precipitation in Autumn	-8%	to	-13%	-8%	to	-12%	-9%	to	-17%
Advance in start of growing season (# of days)	14.8	to	18.4	8.4	to	10.2	11.0	to	33.2

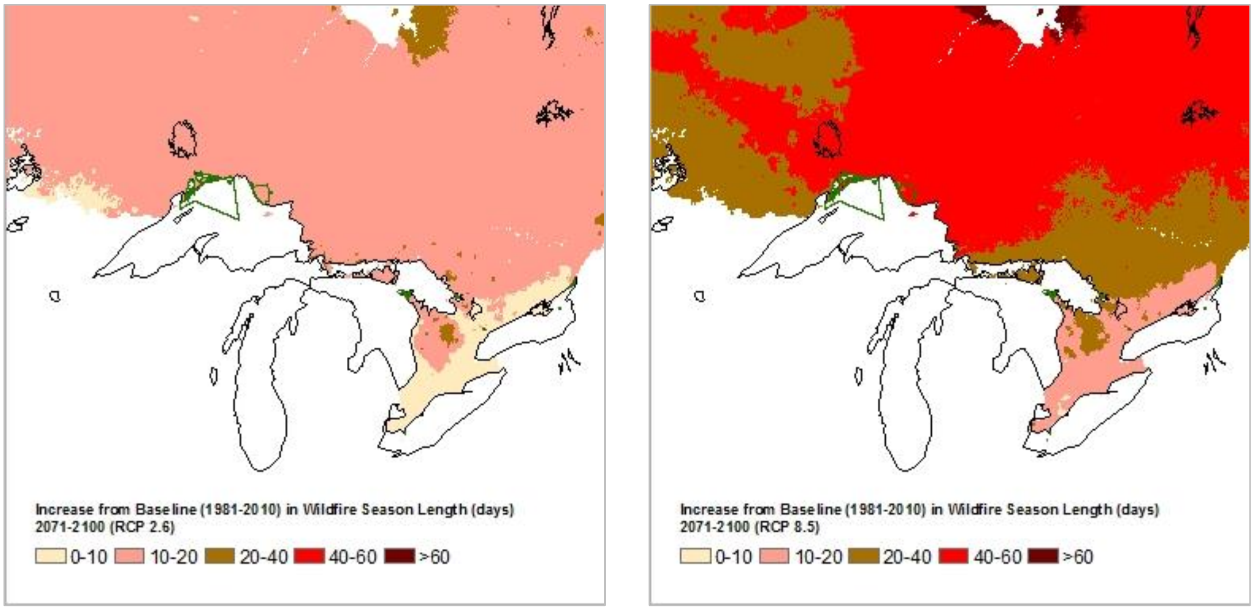


Figure 5. Increase in wildfire season length (days) under RCP 2.6 and 8.5 scenarios.

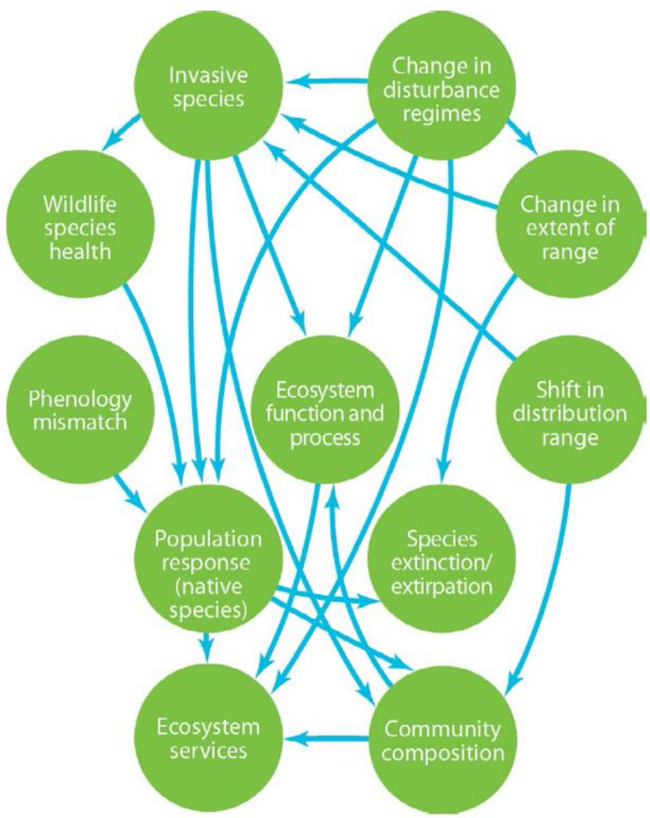
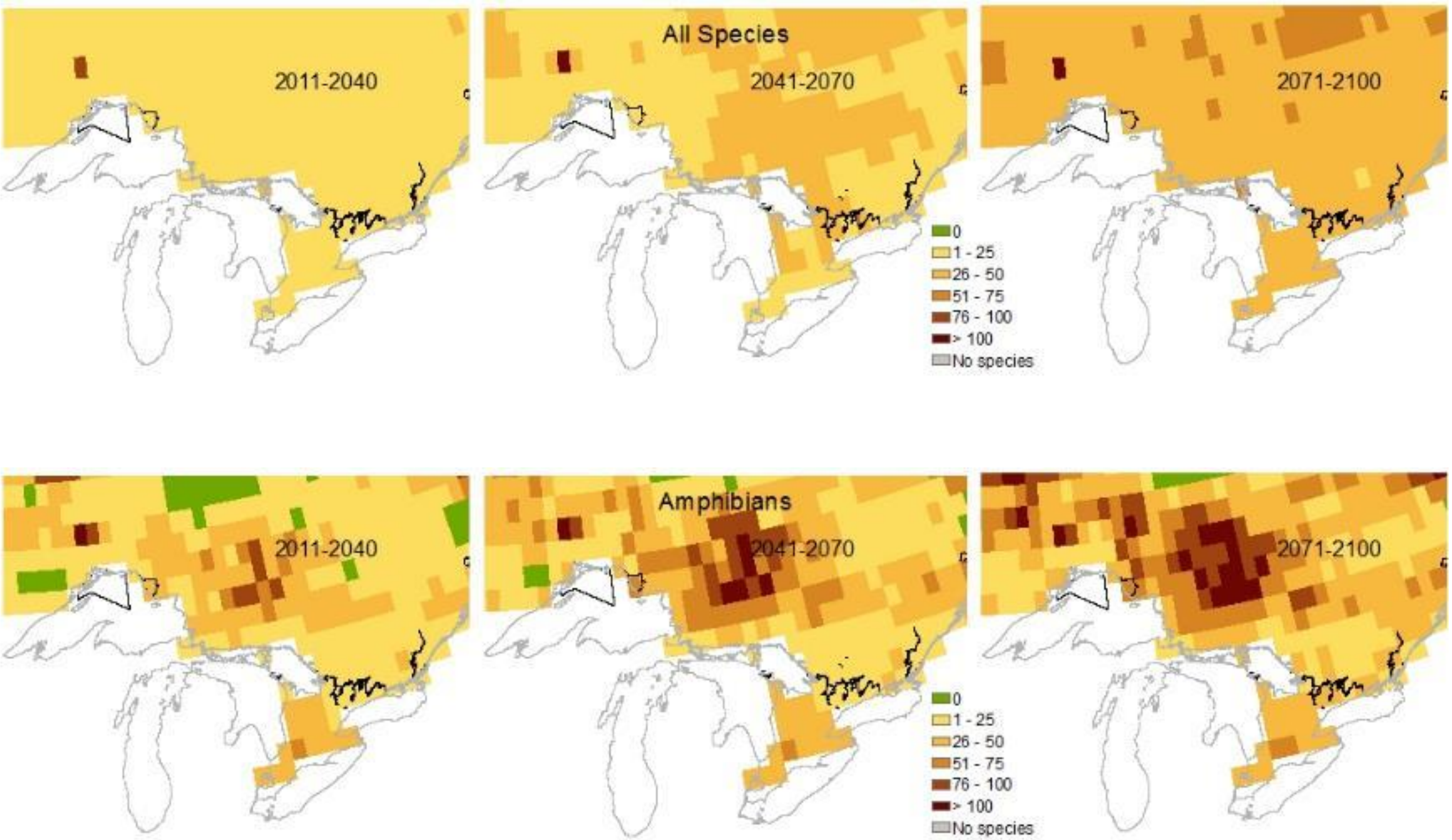


Figure 6. The complex ecosystem linkages and interactions to climate change (from Nantel *et al.*, 2014)


All Species
2011-2040
2041-2070
2071-2100
0
1 - 25
26 - 50
51 - 75
76 - 100
> 100
No species
Amphibians
2011-2040
2041-2070
2071-2100
0
1 - 25
26 - 50
51 - 75
76 - 100
> 100
No species

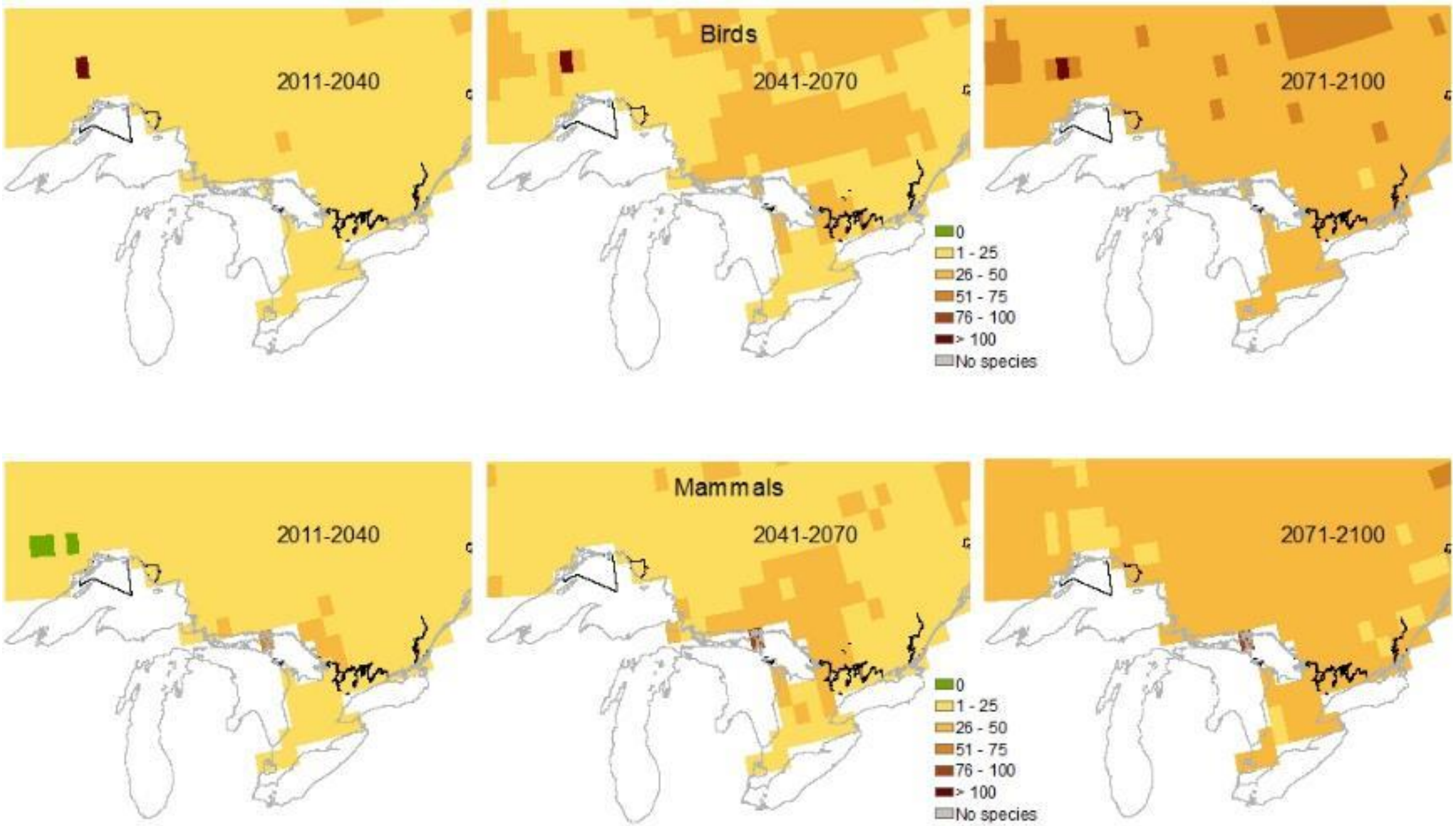


Figure 7. Percentage of projected species turnover (50 km x 50 km grid) relative to current species occurrence, assuming full dispersal (i.e., species can move into new areas) using ten coupled atmosphere-ocean general circulations models (AOGCMS) as in Lawler *et al.* (2009) and the A2 emission scenario. **Species turnover** is calculated as a composite measure of **species loss** (i.e., % of species currently in a cell whose projected future range does not include the cell) and **species gain** (i.e., % increase in species due to range expansion). Data and analysis discussed further in Lindsay *et al.* (2016).

2.2.2 Other Effects

Ecosystems and Biodiversity

- A longer period of lake stratification is altering species composition (Minns *et al.*, 2014a; Reavie *et al.*, 2016) and there are concerns it may result in more frequent episodes of anoxia (e.g., Lake Erie's central basin, Zhou *et al.*, 2015).
- Climate change will influence environmental chemistry and pollutants, including an exacerbation of the effects of acid deposition (lower pH due to higher CO_2 levels), nutrient loading (precipitation events), and mercury toxicity (released under anoxic conditions, warmer waters increase the rate of methylation)(e.g., Dove-Thompson *et al.*, 2011; Michalak *et al.*, 2013; Noyes *et al.*, 2009). Prolonged periods of low lake levels can lead to sediment and contaminant buildup (Gregg *et al.*, 2012)
- Species response to climate change will vary with abiotic (e.g., isolated by fragmented landscape or island context, thermal conditions, etc…), biotic (e.g., competition, habitat) and physiological stresses. Some species, or variant forms, will survive and adapt, while others may move or face extinction (e.g., Pecl *et al.*, 2017).
- From a global perspective, vertebrate population abundances have declined by 58% between 1970 and 2012 (WWF, 2016). Projections estimate that ~60% of plants and ~35% of animals will lose over half of their range by 2080 due to climate change (Warren *et al.*, 2013). The median rate of northward migration, for those species where migration is even attainable, is ~16.9 km/decade (Chen *et al.*, 2011).
- In Ontario, fish distribution has been observed to move northward at a rate of 12-17 km/decade. Cold-water fishes (e.g., brook trout, lake trout, lake whitefish) are seeking refuge further north and in deeper waters, while cool- and warm-water fishes (e.g., walleye, smallmouth bass) are moving into vacated habitats and warmer waters (Alofs *et al.*, 2014; Chu, 2015; Dove-Thompson *et al.*, 2011).
- As the climate envelope for boreal forest tree species (e.g., black spruce, white spruce, jack pine, balsam fir, trembling aspen) becomes less suitable along the forests southern boundary, conditions are becoming more favourable for Great Lakes-St. Lawrence forest species (e.g., white pine, red pine, sugar maple, red oak). Similarly, Carolinian species (e.g., shagbark hickory, tulip tree) are expected to increase in range (McKenney *et al.*, 2010; Walker *et al.*, 2002; Warren *et al.*, 2013). Nationally, it is suggested that vegetation distribution (biomes) will change in over half of Canada`s national park as CO_2 levels double from preindustrial (Scott *et al.*, 2002).
- Wildlife species will continue to experience range shifts and changes in abundance. For example, southern flying squirrel, white tailed deer, American woodcock, red fox, and fisher are expected to expand their range northward, while lynx, alder flycatcher, and northern flying squirrel are expected to contract their range (Nituch and Bowman, 2013; Varrin *et al.*, 2007). In addition, a loss of ~76% in summer range and ~45% in winter range for 90 climate threatened bird species is projected for the region (National Audubon Society, 2015).
- Lower lake levels and warmer waters will alter shoreline ecosystems. For example, coastal wetlands may become stranded, disconnecting potential spawning and nursery habitats, exposed lakebeds will be more vulnerable to *Phragmites australis* and other invasive plant species, and the phenology of wetland dependent species may be altered

(Mortsch *et al.*, 2006). As another example, warming along the coast of Lake Superior may create habitat conditions which are no longer suitable for disjunct coastal arctic plants (e.g., *Cerastium alpinum, Pinguicula vulgaris, Dryas dummondii*) (Lemieux *et al.*, 2008).

- A reduced window for crossing lake ice will affect wildlife diversity and predator – prey relationships, such as moose and wolves (Peterson *et al.*, 2014).
- The change in boreal forest composition to more deciduous species may offset some of the concerns associated with climate change and wildfires (Terrier *et al.*, 2013).
- Asynchrony between life history events has been observed. Although photoperiod is not changing, other ecological cues are changing, such as temperature, river flow, etc… For example, the first date of emergence for northern leopard frogs has shifted 22 days earlier due to warmer conditions (Klaus and Lougheed, 2013). As well, earlier peaks in insect and plant biomass have been observed and this may mismatch migrant bird hatchling growth and development (e.g., asynchrony between wood warbler and eastern spruce budworm) (Knudsen *et al.*, 2011; Nituch and Bowman, 2013).
- Plant productivity may increase due to increased CO_2, that is, if species are not otherwise limited by habitat conditions (e.g., soil, moisture, nutrients, light, or pollinators) or disturbances (e.g., fire, flooding, or drought) (Warren *et al.*, 2013).
- The distribution and impacts of pathogens and parasites are expected to increase with warmer temperatures and the northward migration of species (Marcogliese, 2008; 2016). For example, in some areas moose population decline has been attributed to the transmission of the deadly brain worm (*Parelaphostrongylus tenuis*) from range expanding white tailed deer (Pickles *et al.*, 2013).
- Conditions, including milder winters and drought, may be more favourable for invasive species colonization (Walther *et al.*, 2009) and for more extensive forest insect and disease outbreaks (e.g., spruce budworm, gypsy moth, mountain pine beetle) (Warren and Lemmen, 2014). As a response to warmer waters, 27 species of fish, including non-native species, may move northward into Ontario (Mandrak, 1989).

Visitor Experience

- Visitation may increase due to an earlier spring and warmer summer and autumn conditions. For Ontario's provincial parks, visitation is projected to increase system wide by the 2020s (11–27%) due to a warmer climate, and even higher (23-41%) when combined with demographic changes (Jones and Scott, 2006). When temperatures exceeded 25-30˚C, a strong decrease in visitation has been observed in some parks (Fisichelli *et al.*, 2015; Hewer *et al.*, 2016).
- It may be necessary to extend the operating season to accommodate visitor safety and demand.
- Recreational beaches may face increased closures due to water quality from warmer waters and increased nutrient and bacteria loads (stormwater runoff). Harmful algal blooms and filamentous algae growth will increase under such conditions as well (Barton *et al.*, 2013; Reavie *et al.*, 2014).
- Lower water levels will affect recreational boating access and navigational safety (Shlozberg *et al.*, 2014).

- Decreased snowpack will negatively impact recreational activities such as snowshoeing, skiing, ice fishing, ice travel and snowmobiling.
- In terms of human health, there may be heat related concerns during extreme temperature events, as well there may be concerns due to increases in disease risks. For example, Lyme disease (bacterial disease transmitted by an infected tick) which was formerly restricted to localized areas by temperature and relative humidity, is expected to expand to the entire Great Lakes region by mid-century (Eisen *et al.*, 2016; Ogden *et al.*, 2006). As well, increasing incidences of West Nile virus (mosquito vector) have been linked to climate change (Soverow *et al.*, 2009).
- A longer and more intense fire season will affect visitor safety and experience (e.g., area closures, no campfires).

Assets and Infrastructure

- Increased lake storm intensity and less ice cover increases the risk of coastal flooding and erosion (Assel, 2005; BaMasoud and Byrne, 2012).
- Within the region, climate change assessments have been undertaken following the "Public Infrastructure Engineering Vulnerability Committee" protocol (PIEVC, 2008). They include an assessment of risks and vulnerabilities to the water supply system near Point Pelee NP (Genivar, 2013) and surface drainage near Rouge NUP (Genivar, 2010; 2011). Concerns with freezing rain (e.g., transmission lines) and culvert capacity are highlighted.
- Water regulators on the canals will need to adjust to a higher probability of earlier flood onsets and earlier peak flows (Adamowski *et al.*, 2013).
- Lower water levels will restrict navigation and dock access in some locations, including (e.g., Coleman *et al.*, 2016).
- There is an increasing risks to assets and infrastructure associated with wildfire in some areas. Although fire is generally not recognized as a significant ecosystem driver in the Carolinian or Great Lakes-St. Lawrence forests as compared to the boreal forest, more severe fire weather (heat and drought) may create conditions where fire suppression is no longer feasible or effective (Colombo, 2008; Flannigan *et al.*, 2005).
- Variability in ice cover will alter operational access to island sites (Minns *et al.*, 2014b).

Cultural Resources

- Flood, storm surge, and wildfire may damage some archaeological sites.
- There is a potential for increased deterioration of facilities and collections (e.g., non-mechanically ventilated interiors, HVACs) from increased temperature, humidity, and precipitation, e.g., increased mold, rot and fungal decay; increased corrosion, etc… (Brimblecombe, 2014; Brimblecombe and Brimblecombe, 2016; Horowitz *et al.*, 2016; Marissa *et al.*, 2016).

3. Climate Change Actions

In general, most protected area agencies in Canada are only beginning to consider and develop climate change policies, planning tools, and management frameworks (Lemieux *et al.*, 2011) (note: a draft Parks Canada climate change strategy, version 4.4, was last revised in 2008). There are, however, examples of adaptation and mitigation actions already underway in individual sites and within other jurisdictions that may inspire and guide actions (e.g., Gross *et al.*, 2016; Lemieux *et al.*, 2010; US NPS, 2010).

3.1 Adaptation

Adaptation is an adjustment in natural or human systems in response to actual or expected climate change impacts. Adaptation in protected areas often involves the implementation of established ecosystem-based management practices. These actions can represent "**no regrets**" since they broadly benefit the ecological and commemorative integrity at a site, regardless of the rate of climate change. This includes working with regional partners to manage landscape level disturbances; protecting and restoring ecosystems to build resilience; preventing the spread of invasive species; protecting species at risk; conserving built heritage at historic sites; replacing storm damaged resources and infrastructure with more sustainable and resilient designs; and, responding to changing visitor interests and needs.

Other adaption examples include:

- Mainstream and exemplify the "natural solution" concept and practices in regional adaptation and mitigation strategies, such the Great Lakes Water Quality Agreements - Lakewide Action and Management Plans (http://www.ijc.org) or within the areas World Biosphere Reserves (of which BPNP/FFNMP, GBINP, and TINP are each located).
- Partially removing a barrier sill may be desirable to maintain a hydrological connection to the lake at coastal wetlands that would other otherwise be stranded and inaccessible during periods of prolonged low lake levels.
- Design or retrofit stormwater systems and hydraulic structures to accommodate new "normal" precipitation and temperature patterns. For example, replacing "like with like" culverts is ineffective if they remain undersized or continue to fill with debris. Larger structures can serve both a drainage and road "ecopassage" function, thus making landscape more permeable to water flow and species movements.
- Communicate climate change through park programs and exhibits, including the risks to biodiversity and ecosystems, and the connection between GHG reductions and park stewardship.

Regional adaptation resources:

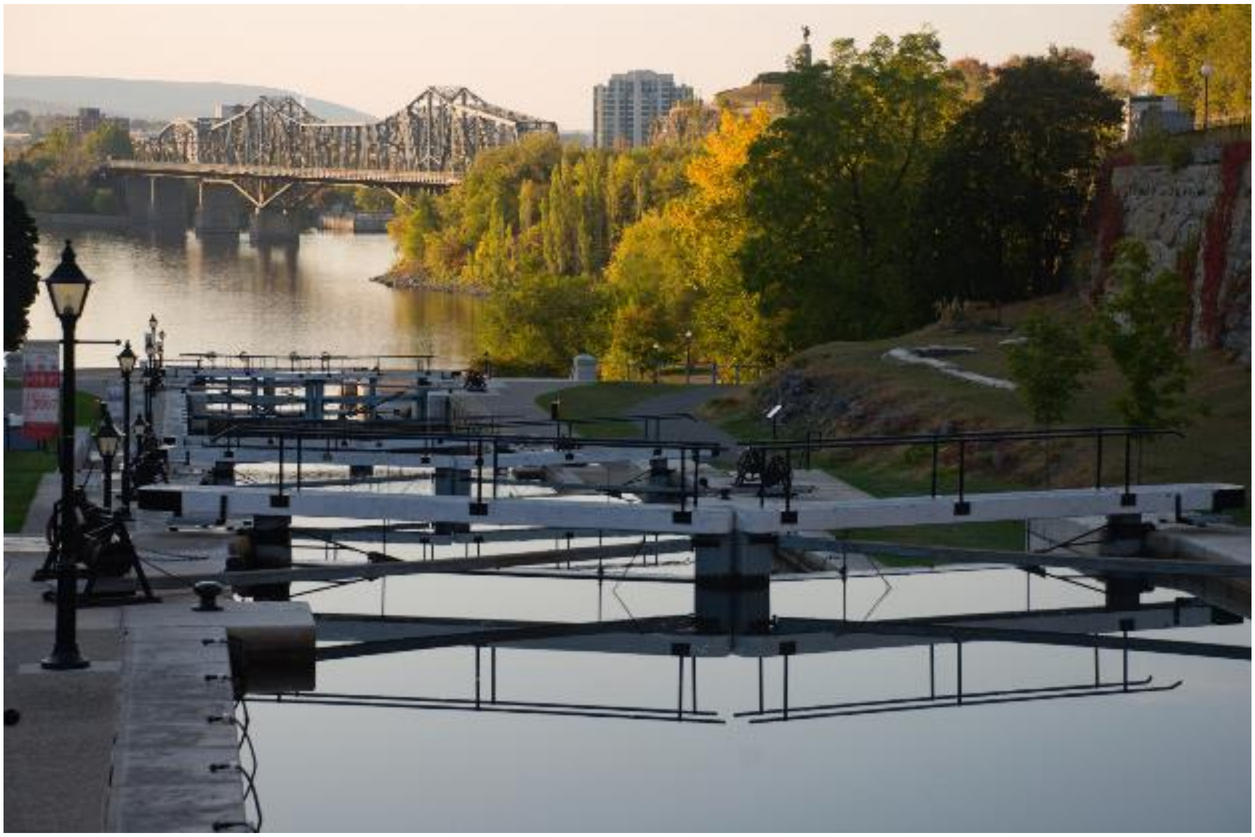
- The State of Climate Change Adaptation in the Great Lakes Region report (Gregg *et al.*, 2012).
- The Ontario Centre for Climate Impacts and Adaptation Resources (OCCIAR) website (http://www.climateontario.ca).

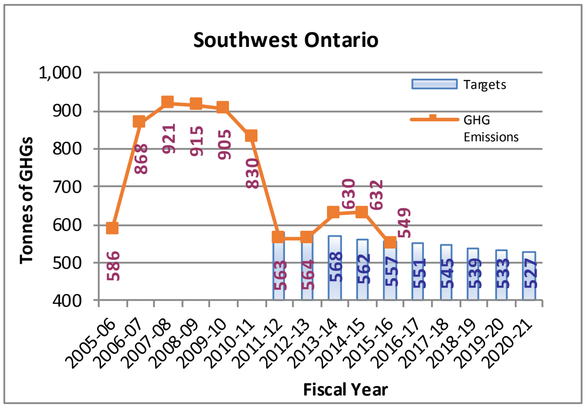
3.2 Mitigation

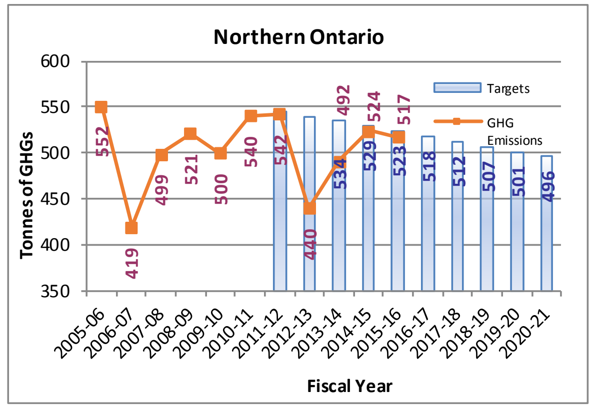
Mitigation refers to human interventions that reduce the source or enhance the sinks of greenhouse gas emissions. Carbon dioxide, methane, nitrous oxide, water vapour and ozone are the primary GHGs in the earth's atmosphere, in addition to human-made chlorine- and bromine-containing substances. Parks Canada's Asset and Environmental Management team provides national functional leadership, expertise and support related to GHG reductions. Sites interested in working on GHG reduction and more sustainable operations should confer with this team. As an example, this team annually tracks all Field Unit energy expenditures and GHG emissions and reports progress towards federal government reduction targets. The current target is 40% reduction in GHG emissions from federal buildings and fleets below the 2005 levels by 2030 (Canada, 2016); it is clear that this will require an ambitious and concerted effort on the part of all.

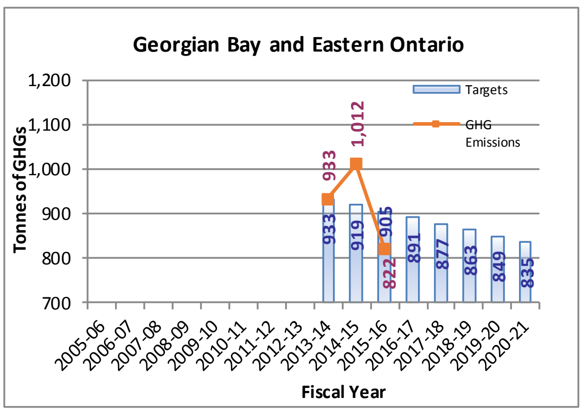
Mitigation examples include:

- Evaluate progress towards Parks Canada / Field Unit GHG reduction targets.
- Specify "green" and energy efficient designs for construction and renovation projects.
- Reduce the number and/or size of park vehicles and vessels to match need and maximize efficiency. Provide hybrid or electric where possible.
- Electric utility and lawn vehicles for campground maintenance.
- Anti-idling and cabin heat-recovery systems in trucks.
- Review Parks Canada (2015) and US NPS (2012a).









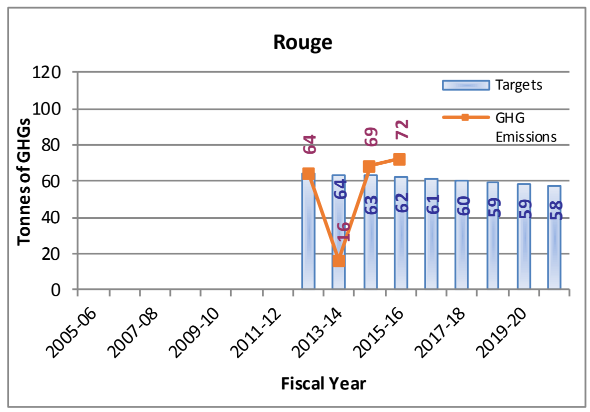
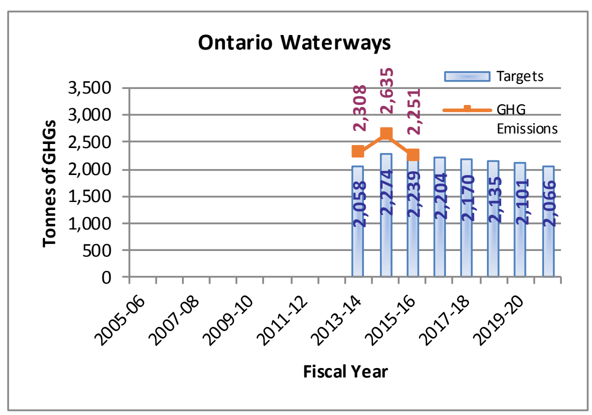


Figure 8. Greenhouse Gas Emissions per Field Unit. Emissions are calculated from energy (e.g., heating, electricity) and fuel expenditures, excluding travel, air charters, and some other sources. GHG emissions from energy cost are adjusted for source (e.g., coal, hydro, diesel, etc...). The targets in these figures are from 2015 reduction targets (Parks Canada, 2015). Revised, lower targets to be communicated in 2017 (Canada, 2016).



3.3 Possible Next Steps

This report is intended to be a stepping off point, from here individuals and sites are encourage to consider how best to advance climate change actions in their own context. Here is a checklist of ideas that others have consider that may be of particular interest or relevance.

☑ Enhance workforce climate literacy (e.g., Peterson *et al.*, 2011; US NPS, 2012b).

- ☑ Undertake more detailed analysis of climate trends, including impact models (e.g., hydrology, wildfire, infrastructure at risk) and extreme weather events (e.g., Charron, 2016).

- ☑ Conduct future scenario planning and explore operations under novel and equally plausible future conditions. Use scenarios to test ("wind tunnel") strategic decisions and inform contingency plans (e.g., Gross *et al.*, 2016; US NPS, 2013).

- ☑ Conduct vulnerability assessments of species, ecosystems or governance structures. Vulnerability is the degree to which a system is susceptible to, and unable to cope with, the impacts of climate change (e.g., Edwards *et al.*, 2015; Gleeson *et al.*, 2011; Gross *et al.*, 2016).

- ☑ Incorporate climate change impacts and adaptation strategies into management planning. Recalibrate management objectives in the face of ecosystem change, system novelty and loss of resilience (e.g., Lemieux *et al.*, 2011).

- ☑ Revise visitor management and operational plans in response to changing visitor patterns and use (e.g., Fisichelli *et al.*, 2015; Hewer *et al.*, 2016). Diversify visitor experiences to provide alternatives to weather-dependent activities.

- ☑ Understand carbon stocks and dynamics (e.g., US NPS, 2012a).

- ☑ Evaluate and communicate the value of ecological goods and services (e.g., clean water/air, provision of food, maintain biodiversity, nature-based tourism, carbon storage, etc…) and manage for the sustainability of these services (e.g., Gross *et al.*, 2016).

- ☑ Maintain a list of climate science and management actions to help inform and influence park messaging.

- ☑ Build networks and collaborate across multiple scales (e.g., Waterton Lakes NP, crownmanagers.org).

- ☑ Consider the Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol (https://pievc.ca/protocol) in climate change vulnerable infrastructure projects.

- ☑ "Explicitly recognize climate change as a management issue in state of the park reporting and monitoring frameworks". This adaption option was one of two from 165 options deemed as necessary and "definitely implementable" by senior decision-makers for the Ontario park system (Lemieux and Scott, 2011).

Please contact the Office of the Chief Ecosystem Scientist if you have any questions or would like to explore any of these next steps further. In addition, PDF copies of all references and the climate data are freely available upon request.

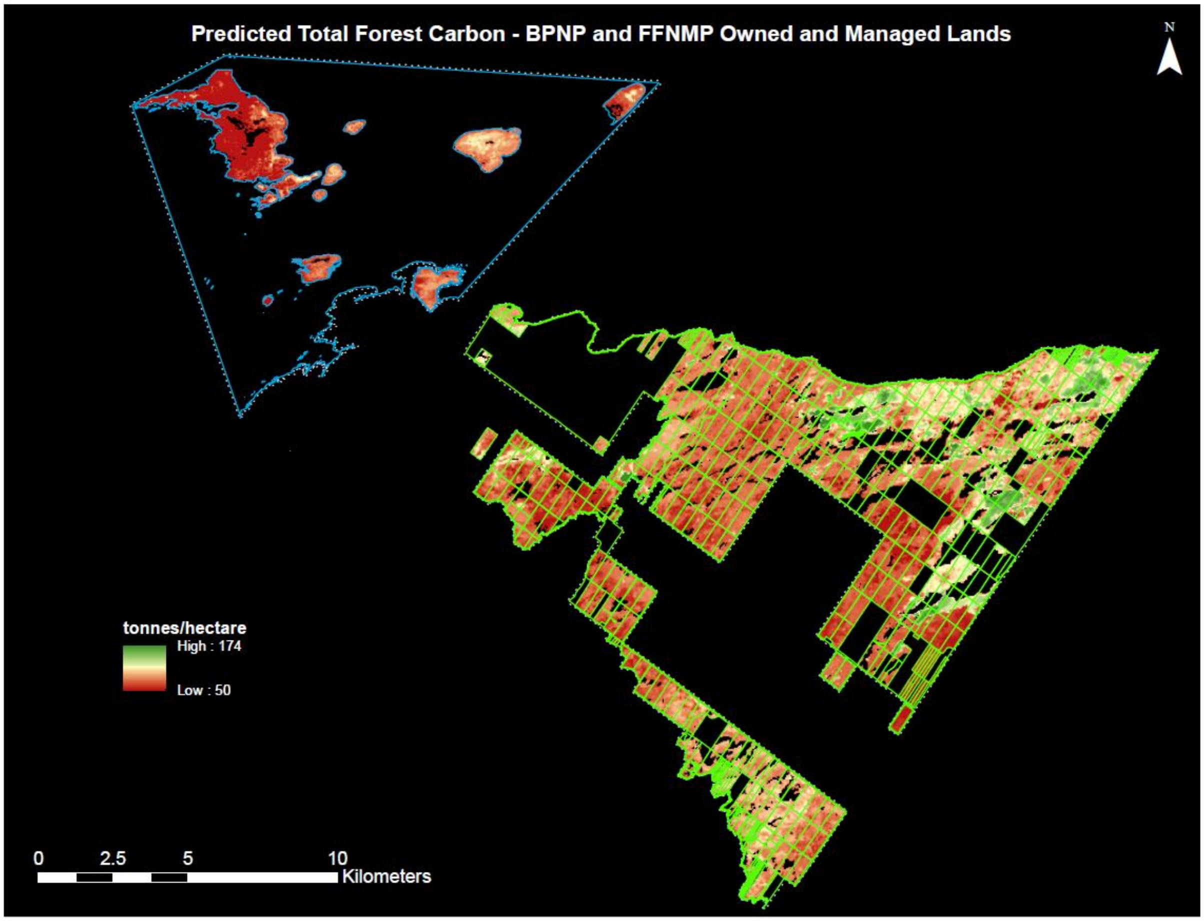


Figure 9. The predicted total forest carbon (above ground and root) for Bruce Peninsula National Park is 1,320,934 tonnes and is 130,311 tonnes for Fathom Five National Marine Park (original data source: Puric-Mladenovic and Clark, 2010). The GBOE Field Unit produced 822 tonnes of GHGs in 2015, which in this context is equivalent to the carbon offset by planting 17,718 balsam fir or 12,974 poplar or the carbon stored in ~15 ha of cedar forest or ~6 ha of maple/beech forest.

4. References

Adamowski, J., Adamowski, K., and Prokoph, A. (2013). Quantifying the spatial temporal variability of annual streamflow and meteorological changes in eastern Ontario and southwestern Quebec using wavelet analysis and GIS. *Journal of Hydrology, 499*, 27-40. doi:10.1016/j.jhydrol.2013.06.029.

Alofs, K. M., Jackson, D. A., and Lester, N. P. (2014). Ontario freshwater fishes demonstrate differing range-boundary shifts in a warming climate. *Diversity and Distributions, 20*(2), 123-136. doi:10.1111/ddi.12130.

Assel, R. A. (2005). Classification of annual Great Lakes ice cycles: Winters of 1973-2002. *Journal of Climate, 18*(22), 4895-4905. doi:10.1175/jcli3571.1.

BaMasoud, A. and Byrne, M. L. (2012). The impact of low ice cover on shoreline recession: A case study from western Point Pelee, Canada. *Geomorphology, 173*, 141-148. doi:10.1016/j.geomorph.2012.06.004.

Barton, D. R., Howell, E. T., and Fietsch, C. L. (2013). Ecosystem changes and nuisance benthic algae on the southeast shores of Lake Huron. *Journal of Great Lakes Research, 39*(4), 602-611. doi:10.1016/j.jglr.2013.09.010.

Brimblecombe, P. (2014). Refining climate change threats to heritage. *Journal of the Institute of Conservation, 37*(2), 85-93. doi:10.1080/19455224.2014.916226.

Brimblecombe, P. and Brimblecombe, C. (2016). Climate Change and Non-mechanically Ventilated Historic Interiors. *APT Bulletin, 47*(1), 31-38. http://www.jstor.org/stable/43799261

Canada. (2016). *A Federal Sustainable Development Strategy for Canada 2016–2019*. http://fsds-sfdd.ca/index.html#/en/intro/.

Charron, I. (2016). *A Guidebook on Climate Scenarios: Using Climate Information to Guide Adaptation Research and Decisions, 2016 Edition*. Ouranos. https://www.ouranos.ca/publication-scientifique/Guidebook-2016.pdf.

Chen, I. C., Hill, J. K., Ohlemuller, R., Roy, D. B., and Thomas, C. D. (2011). Rapid Range Shifts of Species Associated with High Levels of Climate Warming. *Science, 333*(6045), 1024-1026. doi:10.1126/science.1206432.

Cheng, C. S., Auld, H., Li, Q., and Li, G. L. (2012a). Possible impacts of climate change on extreme weather events at local scale in south-central Canada. *Climatic Change, 112*(3-4), 963-979. doi:10.1007/s10584-011-0252-0.

Cheng, C. S., Li, Q., Li, G., and Auld, H. (2012b). Climate Change and Heavy Rainfall-Related Water Damage Insurance Claims and Losses in Ontario, Canada. *Journal of Water Resource and Protection, 4*, 49-62. doi:http://dx.doi.org/10.4236/jwarp.2012.42007.

Chu, C. (2015). *Climate Change Vulnerability Assessment for Inland Aquatic Ecosystems in the Great Lakes Basin, Ontario*. Ontario Ministry of Natural Resources and Forestry. http://www.climateontario.ca/MNR_Publications/CCRR-43.pdf.

Coleman, J. M. A., Sosa-Rodriguez, F. S., Mortsch, L. D., and Deadman, P. J. (2016). Assessing stakeholder impacts and adaptation to low water-levels: the Trent-Severn waterway. *Climatic Change, 134*(1), 115-129. doi:10.1007/s10584-015-1524-x.

Colombo, S. J. (2008). *Ontario's Forests and Forestry in a Changing Climate*. Ontario Ministry of Natural Resources. https://www.ontario.ca/document/ontarios-forests-and-forestry-changing-climate.

Cunderlik, J. M. and Ouarda, T. (2009). Trends in the timing and magnitude of floods in Canada. *Journal of Hydrology*, *375*(3-4), 471-480. doi:10.1016/j.jhydrol.2009.06.050.

Dove-Thompson, D., Lewis, C., Gray, P. A., Chu, C., and I., D. W. (2011). *A Summary of the Effects of Climate Change on Ontario's Aquatic Ecosystems*. Ontario Ministry of Natural Resources. http://files.ontario.ca/environment-and-energy/aquatics-climate/stdprod_088243.pdf.

Dudley, N., Stolton, S., Belokurov, A., Krueger, L., Lopoukhine, N., MacKinnon, K., Sandwith, T., and Sekhran, N. (2010). *Natural Solutions: Protected areas helping people cope with climate change*. IUCN WCPA, TNC, UNDP, WCS, The World Bank and WWF, Gland, Switzerland, Washington DC and New York, USA. https://www.iucn.org/content/natural-solutions-protected-areas-helping-people-cope-climate-change.

Edwards, J. E., Pearce, C., Ogden, A. E., and Williamson, T. B. (2015). *Climate Change and Sustainable Forest Management in Canada : A Guidebook for Assessing Vulnerability and Mainstreaming Adaptation into Decision Making*. Canadian Council of Forest Ministers. http://www.ccfm.org/english/coreproducts-cc.asp.

Eisen, R. J., Eisen, L., Ogden, N. H., and Beard, C. B. (2016). Linkages of Weather and Climate with *Ixodes scapularis* and *Ixodes pacificus* (Acari: Ixodidae), Enzootic Transmission of *Borrelia burgdorferi*, and Lyme Disease in North America. *Journal of Medical Entomology*, *53*(2), 250-261. doi:10.1093/jme/tjv199.

Fisichelli, N. A., Schuurman, G. W., Monahan, W. B., and Ziesler, P. S. (2015). Protected Area Tourism in a Changing Climate: Will Visitation at US National Parks Warm Up or Overheat? *PLoS ONE*, *10*(6), 13. doi:10.1371/journal.pone.0128226.

Flannigan, M. D., Logan, K. A., Amiro, B. D., Skinner, W. R., and Stocks, B. J. (2005). Future Area Burned in Canada. *Climatic Change*, *72*(1), 1-16. doi:10.1007/s10584-005-5935-y.

Genivar. (2010). *Toronto and Region Conservation Authority Flood Control Dam Water Resources Infrastructure Assessment*. Engineers Canada. https://pievc.ca/toronto-and-region-conservation-authority-claireville-and-g-ross-water-control-dams.

Genivar. (2011). *Climate Change Vulnerability Assessment for Culverts, City of Toronto*. Engineers Canada. https://pievc.ca/city-toronto-study-three-road-culverts.

Genivar. (2013). *Union Water Supply System Climate Risk Assessment*. Engineers Canada. https://pievc.ca/sites/default/files/uwss_climate_risk_assessment_final_report_may_2013.pdf.

Gleeson, J., Gray, P., Douglas, A., Lemieux, C. J., and Nielsen, G. (2011). *A Practitioner's Guide to Climate Change Adaptation in Ontario's Ecosystems*. Ontario Centre for Climate Impacts and Adaptation Resources, Sudbury, Ontario. http://www.mnr.gov.on.ca/en/Business/ClimateChange/Publication/STDPROD_091282.html.

Gregg, R. M., Feifel, K. M., Kershner, J. M., and Hitt, J. L. (2012). *The State of Climate Change Adaptation in the Great Lakes Region*. EcoAdapt, Bainbridge Island, WA. http://ecoadapt.org/data/library-documents/EcoAdapt_GreatLakesAdaptation.pdf.

Gronewold, A. D., Fortin, V., Lofgren, B., Clites, A., Stow, C. A., and Quinn, F. (2013). Coasts, water levels, and climate change: A Great Lakes perspective. *Climatic Change*, *120*(4), 697-711. doi:10.1007/s10584-013-0840-2.

Gross, J. E., Woodley, S., Welling, L. A., and Watson, J. E. M. (Eds.). (2016). *Adapting to Climate Change: Guidance for Protected Area Managers and Planners* (Vol. No. 24). Gland, Switzerland: IUCN. https://portals.iucn.org/library/node/46685.

Hewer, M., Scott, D., and Fenech, A. (2016). Seasonal weather sensitivity, temperature thresholds, and climate change impacts for park visitation. *Tourism Geographies, 18*(3), 297-321. doi:10.1080/14616688.2016.1172662.

Horowitz, A. D., Lopez, M. F., Ross, S. M., and Sparenberg, J. A. (2016). *Climate Change and Cultural Heritage Conservation. A Literature Review*. Association for Preservation Technology (APT), Technical Committee on Sustainable Preservation's Education and Research focus group. http://www.apti.org/clientuploads/Technical%20Committees/2015-2016/APT%20TC-SP%20Literature%20Review%20Climate%20Change%20%20Cultural%20Heritage%20Conservation%202016June30.pdf.

IJC. (2009). *Impacts on Upper Great Lakes Water Levels: St. Clair River*. International Upper Great Lakes Study. http://www.ijc.org/files/publications/IUGLS%20St%20Clair%20Report.pdf.

IJC. (2012). *Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels*. International Joint Commission, Upper Great Lakes Study. http://www.ijc.org/files/publications/Lake_Superior_Regulation_Full_Report.pdf.

IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Intergovernmental Panel on Climate Change (IPCC). The Summary for Policymakers of the Working Group II contribution to the Fifth Assessment Report. http://www.ipcc.ch/index.htm.

Jones, B. and Scott, D. (2006). Implications of climate change for visitation to ontario's provincial parks. *Leisure/Loisir, 30*(1), 233-261. doi:10.1080/14927713.2006.9651350.

Jones, N. E., Petreman, I. C., and Schmidt, B. J. (2015). *High Flows and Freshet Timing in Canada: Observed Trends*. Ontario Ministry of Natural Resources and Forestry. http://www.climateontario.ca/MNR_Publications/CCRR42.pdf.

Karl, T. R., Melillo, J. M., and Peterson, T. C. (Eds.). (2009). *Global Climate Change Impacts in the United States*. New York: Cambridge University Press. https://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf.

Klaus, S. P. and Lougheed, S. C. (2013). Changes in breeding phenology of eastern Ontario frogs over four decades. *Ecology and Evolution, 3*(4), 835-845. doi:10.1002/ece3.501.

Knudsen, E., Linden, A., Both, C., Jonzen, N., Pulido, F., Saino, N., Sutherland, W. J., Bach, L. A., Coppack, T., Ergon, T., Gienapp, P., Gill, J. A., Gordo, O., Hedenstroom, A., Lehikoinen, E., Marra, P. P., Moller, A. P., Nilsson, A. L. K., Peron, G., Ranta, E., Rubolini, D., Sparks, T. H., Spina, F., Studds, C. E., Saether, S. A., Tryjanowski, P., and Stenseth, N. C. (2011). Challenging claims in the study of migratory birds and climate change. *Biological Reviews, 86*(4), 928-946. doi:10.1111/j.1469-185X.2011.00179.x.

Kunkel, K. E., Ensor, L., Palecki, M., Easterling, D., Robinson, D., Hubbard, K. G., and Redmond, K. (2009). A New Look at Lake-Effect Snowfall Trends in the Laurentian Great Lakes Using a Temporally Homogeneous Data Set. *Journal of Great Lakes Research, 35*(1), 23-29. doi:10.1016/j.jglr.2008.11.003.

Larouche, P. and Galbraith, P. S. (2016). Canadian Coastal Seas and Great Lakes Sea Surface Temperature Climatology and Recent Trends. *Canadian Journal of Remote Sensing, 42*(3), 243-258. doi:10.1080/07038992.2016.1166041.

Lawler, J. J., Shafer, S. L., White, D., Kareiva, P., Maurer, E. P., Blaustein, A. R., and Bartlein, P. J. (2009). Projected climate-induced faunal change in the Western Hemisphere. *Ecology, 90*(3), 588-597. doi:10.1890/08-0823.1.

Le Goff, H., Flannigan, M. D., and Bergeron, Y. (2009). Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change. *Canadian Journal of Forest Research, 39*(12), 2369-2380. doi:10.1139/x09-153.

Lemieux, C. J., Beechey, T. J., and Gray, P. A. (2011). Prospects for Canada's protected areas in an era of rapid climate change. *Land Use Policy, 28*, 928– 941. doi:doi:10.1016/j.landusepol.2011.03.008.

Lemieux, C. J., Beechey, T. J., Scott, D. J., and Gray, P. A. (2010). *Protected Areas and Climate Change in Canada - Challenges and Opportunities for Adaptation*. Canadian Council on Ecological Areas (CCEA). http://ccea.org/Downloads/en_papers_occasional19.pdf.

Lemieux, C. J. and Scott, D. J. (2011). Changing Climate, Challenging Choices: Identifying and Evaluating Climate Change Adaptation Options for Protected Areas Management in Ontario, Canada. *Environmental management, 48*(4), 675-690. doi:10.1007/s00267-011-9700-x.

Lemieux, C. J., Scott, D. J., Davis, R. G., and Gray, P. A. (2008). *Changing Climate, Challenging Choices: Ontario Parks and Climate Change Adaptation*. University of Waterloo, Department of Geography, Waterloo, ON

Lemmen, D. S., Warren, F. J., James, T. S., and Mercer Clarke, C. S. L. (Eds.). (2016). *Canada's Marine Coasts in a Changing Climate*. Ottawa, ON: Government of Canada. http://www.nrcan.gc.ca/environment/resources/publications/impacts-adaptation/reports/assessments/2016/18388.

Lindsay, K., Gobeil, J.-F., Lawler, J. L., Schloss, C., Beazley, K. F., and Beechey, T. J. (2016). *Wildlife Conservation, Protected Areas and Climate Change in Canada: Implications of Projected Species Range Shifts*. Canadian Council on Ecological Areas, CCEA Secretariat, Ottawa, Ontario. http://www.ccea.org/wp-content/uploads/2015/10/CCEA_WildlifeConservationProtectedAreasandClimateChangeinCanada_Digital.pdf.

Lopoukhine, N., Crawhall, N., Dudley, N., Figgis, P., Karibuhoye, C., Laffoley, D., Miranda Londoño, J., MacKinnon, K., and Sandwith, T. (2012). Protected areas: providing natural solutions to 21st Century challenges. *S.A.P.I.EN.S, 5.2*. https://sapiens.revues.org/1254

MacKay, M. and Seglenieks, F. (2013). On the simulation of Laurentian Great Lakes water levels under projections of global climate change. *Climatic Change, 117*(1), 55-67. doi:10.1007/s10584-012-0560-z.

Mandrak, N. E. (1989). Potential Invasion of the Great Lakes by Fish Species Associated with Climatic Warming. *Journal of Great Lakes Research, 15*(2), 306-316.

Marcogliese, D. J. (2008). The impact of climate change on the parasites and infectious diseases of aquatic animals. *Revue Scientifique Et Technique-Office International Des Epizooties, 27*(2), 467-484.

Marcogliese, D. J. (2016). The Distribution and Abundance of Parasites in Aquatic Ecosystems in a Changing Climate: More than Just Temperature. *Integrative and Comparative Biology, 56*(4), 611-619. doi:10.1093/icb/icw036.

Marissa, M., Rockman, M., Smith, C., and Meadow, A. (2016). *Climate Change Impacts on Cultural Resources*. Cultural Resources Partnerships and Science, United States National Park Service (US NPS), Washington, DC. https://www.nps.gov/subjects/climatechange/culturalimpactstable.htm.

Mason, L. A., Riseng, C. M., Gronewold, A. D., Rutherford, E. S., Wang, J., Clites, A., Smith, S. D. P., and McIntyre, P. B. (2016). Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. *Climatic Change, 138*(1), 71-83. doi:10.1007/s10584-016-1721-2.

McDermid, J. L., Dickin, S. K., Winsborough, C. L., Switzman, H., Barr, S., Gleason, J. A., Krantzberg, G., and Gray, P. A. (2015). *State of Climate Change Science in the Great Lakes Basin: A Focus on Climatological, Hydrological and Ecological Effects.* Ontario Climate Consortium and Ontario Ministry of Natural Resources and Forestry. http://climateconnections.ca/our-work/the-state-of-climate-change-science-in-the-great-lakes/.

McKenney, D. W., Pedlar, J. H., Lawrence, K., Gray, P. A., Colombo, S. J., and Crins, W. J. (2010). *Current and Projected Future Climatic Conditions for Ecoregions and Selected Natural Heritage Areas in Ontario*. Ontario Ministry of Natural Resources, Sault Ste. Marie, ON. http://www.climateontario.ca/MNR_Publications/stdprod_088016.pdf.

Michalak, A. M., Anderson, E. J., Beletsky, D., Boland, S., Bosch, N. S., Bridgeman, T. B., Chaffin, J. D., Cho, K., Confesor, R., Daloglu, I., DePinto, J. V., Evans, M. A., Fahnenstiel, G. L., He, L. L., Ho, J. C., Jenkins, L., Johengen, T. H., Kuo, K. C., LaPorte, E., Liu, X. J., McWilliams, M. R., Moore, M. R., Posselt, D. J., Richards, R. P., Scavia, D., Steiner, A. L., Verhamme, E., Wright, D. M., and Zagorski, M. A. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences, 110*(16), 6448-6452. doi:10.1073/pnas.1216006110.

Minns, C. K., Shuter, B. J., and Fung, S. (2014a). *Regional Projections of Climate Change Effects on Thermal Habitat Space for Fishes in Stratified Ontario Lakes*. Ontario Ministry of Natural Resources and Forestry. http://www.climateontario.ca/MNR_Publications/CCRR-41.pdf.

Minns, C. K., Shuter, B. J., and Fung, S. R. (2014b). *Regional Projections of Climate Change Effects on Ice Cover and Open-Water Duration for Ontario Lakes Using Updated Ice-Date Models*. Ontario Ministry of Natural Resources. http://www.climateontario.ca/MNR_Publications/ccrr40.pdf.

Mortsch, L., Ingram, J., Hebb, A., and Doka, S. (Eds.). (2006). *Great Lakes Coastal Wetlands Communities: Vulnerabilities to Climate Change and Response to Adaptation Strategies*: Environment Canada. http://www.publications.gc.ca/pub?id=9.689486&sl=0.

Music, B., Frigon, A., Lofgren, B., Turcotte, R., and Cyr, J.-F. (2015). Present and future Laurentian Great Lakes hydroclimatic conditions as simulated by regional climate models with an emphasis on Lake Michigan-Huron. *Climatic Change, 130*(4), 603-618. doi:10.1007/s10584-015-1348-8.

Nantel, P., Pellatt, M. G., Keenleyside, K. A., and Gray, P. A. (2014). Biodiversity and Protected Areas. In F. J. Warrenand D. S. Lemmen (Eds.), *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation* (pp. 159-190). Ottawa, ON: Government of Canada. http://www.nrcan.gc.ca/environment/resources/publications/impacts-adaptation/reports/assessments/2014/16309.

National Audubon Society. (2015). *Audubon's Birds and Climate Change Report: A Primer for Practitioners*. National Audubon Society. Contributors: Gary Langham, Justin Schuetz, Candan Soykan, Chad Wilsey, Tom Auer, Geoff LeBaron, Connie Sanchez, Trish Distler, New York. http://www.audubon.org/conservation/climate-change.

NAWPA. (2012). *North American Protected Areas as Natural Solutions for Climate Change*. North American Intergovernmental Committee on Cooperation for Wilderness and

Protected Area Conservation. http://nawpacommittee.org/wp-content/uploads/2012/08/NAWPA-CCWG-Brochure.pdf.
Nituch, L. A. and Bowman, J. (2013). *Community-Level Effects of Climate Change on Ontario's Terrestrial Biodiversity*. Ontario Ministry of Natural Resources. http://www.climateontario.ca/MNR_Publications/CCRR-36.pdf.
Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., Erwin, K. N., and Levin, E. D. (2009). The toxicology of climate change: Environmental contaminants in a warming world. *Environment International, 35*(6), 971-986. doi:10.1016/j.envint.2009.02.006.
Ogden, N. H., Maarouf, A., Barker, I. K., Bigras-Poulin, M., Lindsay, L. R., Morshed, M. G., O'Callaghan, C. J., Ramay, F., Waltner-Toews, D., and Charron, D. F. (2006). Climate change and the potential for range expansion of the Lyme disease vector Ixodes scapularis in Canada. *International Journal for Parasitology, 36*(1), 63-70. doi:10.1016/j.ijpara.2005.08.016.
Parks Canada. (2015). *Master Plan For the Reduction of Greenhouse Gas (GHG) Emissions within Parks Canada's Operations*. http://intranet2/media/2163749/master_plan_for_ghg_reduction_2015.pdf
Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., Lenoir, J., Linnetved, H. I., Martin, V. Y., McCormack, P. C., McDonald, J., Mitchell, N. J., Mustonen, T., Pandolfi, J. M., Pettorelli, N., Popova, E., Robinson, S. A., Scheffers, B. R., Shaw, J. D., Sorte, C. J. B., Strugnell, J. M., Sunday, J. M., Tuanmu, M.-N., Vergés, A., Villanueva, C., Wernberg, T., Wapstra, E., and Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science, 355*(6332). doi:10.1126/science.aai9214.
Peterson, D. L., Millar, C. I., Joyce, L. A., Furniss, M. J., Halofsky, J. E., Neilson, R. P., and Morelli, T. L. (2011). *Responding to climate change in national forests: a guidebook for developing adaptation options.* U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. https://www.treesearch.fs.fed.us/pubs/39884.
Peterson, R. O., Vucetich, J. A., Bump, J. M., and Smith, D. W. (2014). Trophic Cascades in a Multicausal World: Isle Royale and Yellowstone. In D. J. Futuyma (Ed.), *Annual Review of Ecology, Evolution and Systematics* (Vol. 45, pp. 325-+). Palo Alto: Annual Reviews
Pickles, R. S. A., Thornton, D., Feldman, R., Marques, A., and Murray, D. L. (2013). Predicting shifts in parasite distribution with climate change: a multitrophic level approach. *Global Change Biology, 19*(9), 2645-2654. doi:10.1111/gcb.12255.
PIEVC. (2008). *Adapting to Climate Change Canada's First National Engineering Vulnerability Assessment of Public Infrastructure, April 2008*. Engineers Canada, Public Infrastructure Engineering Vulnerability Committee (PIEVC). https://pievc.ca/documents.
Price, D. T., McKenney, D. W., Joyce, L. A., Siltanen, R. M., Papadopol, P., and Lawrence, K. (2011). *High-Resolution Interpolation of Climate Scenarios for Canada Derived from General Circulation Model Simulations*. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. http://cfs.nrcan.gc.ca/publications?id=32971.

Puric-Mladenovic, D. and Clark, G. (2010). *Predictive modeling and mapping of biomass and carbon for Eco-district 6e14*. Faculty of Forestry, University of Toronto. http://www.forestry.utoronto.ca/SettledLandscapes/BruceBiomassExplorer/.

R Core Team. (2014). R: A Language and Environment for Statistical Computing. http://www.R-project.org

Reavie, E. D., Barbiero, R. P., Allinger, L. E., and Warren, G. J. (2014). Phytoplankton trends in the Great Lakes, 2001-2011. *Journal of Great Lakes Research, 40*(3), 618-639. doi:10.1016/j.jglr.2014.04.013.

Reavie, E. D., Sgro, G. V., Estepp, L. R., Bramburger, A. J., Shaw Chraïbi, V. L., Pillsbury, R. W., Cai, M., Stow, C. A., and Dove, A. (2016). Climate warming and changes in *Cyclotella sensu lato* in the Laurentian Great Lakes. *Limnology and Oceanography*. doi:10.1002/lno.10459.

Scott, D., Malcolm, J. R., and Lemieux, C. (2002). Climate change and modelled biome representation in Canada's national park system: implications for system planning and park mandates. *Global Ecology and Biogeography, 11*(6), 475-484. doi:10.1046/j.1466-822X.2002.00308.x.

Scott, D. and Suffling, R. (2000). *Climate Change and Canada's National Park System: A screening level assessment*. Adaptation and Impacts Research Group, Environment Canada, and University of Waterloo. http://publications.gc.ca/site/eng/249276/publication.html.

Shlozberg, R., Dorling, R., and Spiro, P. (2014). *Low Water Blues. An Economic Impact Assessment of Future Low Water Levels in the Great Lakes and St. Lawrence River*. Council of the Great Lakes Region (CGLR) and Mowat Centre. https://mowatcentre.ca/low-water-blues/.

Soverow, J. E., Wellenius, G. A., Fisman, D. N., and Mittleman, M. A. (2009). Infectious Disease in a Warming World: How Weather Influenced West Nile Virus in the United States (2001-2005). *Environmental Health Perspectives, 117*(7), 1049-1052. doi:10.1289/ehp.0800487.

Terrier, A., Girardin, M. P., Périé, C., Legendre, P., and Bergeron, Y. (2013). Potential changes in forest composition could reduce impacts of climate change on boreal wildfires. *Ecological Applications, 23*(1), 21-35. doi:10.1890/12-0425.1.

Trumpickas, J., Shuter, B. J., and Minns, C. K. (2009). Forecasting impacts of climate change on Great Lakes surface water temperatures. *Journal of Great Lakes Research, 35*(3), 454-463. doi:10.1016/j.jgir.2009.04.005.

US NPS. (2010). *National Park Service Climate Change Response Strategy*. National Park Service Climate Change Response Program, U.S. Department of the Interior, Fort Collins, Colorado. http://www.nps.gov/subjects/climatechange/resources.htm.

US NPS. (2012a). *Green Parks Plan. Advancing Our Mission through Sustainable Operations*. https://www.nps.gov/greenparksplan/.

US NPS. (2012b). *National Park Service Climate Change Action Plan 2012-2014*. National Park Service Climate Change Response Program, U.S. Department of the Interior, Fort Collins, Colorado. http://www.nps.gov/subjects/climatechange/resources.htm.

US NPS. (2013). *Using Scenarios to Explore Climate Change: A Handbook for Practitioners*. National Park Service Climate Change Response Program. Fort Collins, Colorado. http://www.nps.gov/subjects/climatechange/upload/CCScenariosHandbookJuly2013.pdf.

Varrin, R., Bowman, J., and Gray, P. A. (2007). *The Known and Potential Effects of Climate Change on Biodiversity in Ontario's Terrestrial Ecosystems: Case Studies and Recommendations for Adaptation*. Ontario Ministry of Natural Resources. http://www.climateontario.ca/MNR_Publications/276927.pdf.

Walker, K. V., Davis, M. B., and Sugita, S. (2002). Climate change and shifts in potential tree species range limits in the Great Lakes region. *Journal of Great Lakes Research, 28*(4), 555-567.

Walther, G. R., Roques, A., Hulme, P. E., Sykes, M. T., Pysek, P., Kuhn, I., Zobel, M., Bacher, S., Botta-Dukat, Z., Bugmann, H., Czucz, B., Dauber, J., Hickler, T., Jarosik, V., Kenis, M., Klotz, S., Minchin, D., Moora, M., Nentwig, W., Ott, J., Panov, V. E., Reineking, B., Robinet, C., Semenchenko, V., Solarz, W., Thuiller, W., Vila, M., Vohland, K., and Settele, J. (2009). Alien species in a warmer world: risks and opportunities. *Trends in Ecology & Evolution, 24*(12), 686-693. doi:10.1016/j.tree.2009.06.008.

Wang, J., Bai, X. Z., Hu, H. G., Clites, A., Colton, M., and Lofgren, B. (2012). Temporal and spatial variability of Great Lakes ice cover, 1973-2010. *Journal of Climate, 25*(4), 1318-1329. doi:10.1175/2011jcli4066.1.

Wang, X. L., Thompson, D. K., Marshall, G. A., Tymstra, C., Carr, R., and Flannigan, M. D. (2015). Increasing frequency of extreme fire weather in Canada with climate change. *Climatic Change, 130*(4), 573-586. doi:10.1007/s10584-015-1375-5.

Warren, F. J. and Lemmen, D. S. (Eds.). (2014). *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation*. Ottawa, ON: Government of Canada. http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/pdf/assess/2014/pdf/Full-Report_Eng.pdf.

Warren, R., VanDerWal, J., Price, J., Welbergen, J. A., Atkinson, I., Ramirez-Villegas, J., Osborn, T. J., Jarvis, A., Shoo, L. P., Williams, S. E., and Lowe, J. (2013). Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change, 3*(7), 678-682. doi:10.1038/nclimate1887.

Wuebbles, D. J., Hayhoe, K., and Parzen, J. (2010). Introduction: Assessing the effects of climate change on Chicago and the Great Lakes. *Journal of Great Lakes Research, 36*, 1-6. doi:10.1016/j.jglr.2009.09.009.

WWF. (2016). *Living Planet Report 2016. Risk and resilience in a new era*. WWW International, Gland, Switzerland. http://wwf.panda.org/about_our_earth/all_publications/lpr_2016/.

Zhong, Y. F., Notaro, M., Vavrus, S. J., and Foster, M. J. (2016). Recent accelerated warming of the Laurentian Great Lakes: Physical drivers. *Limnology and Oceanography, 61*(5), 1762-1786. doi:10.1002/lno.10331.

Zhou, Y. T., Michalak, A. M., Beletsky, D., Rao, Y. R., and Richards, R. P. (2015). Record-Breaking Lake Erie Hypoxia during 2012 Drought. *Environmental Science & Technology, 49*(2), 800-807. doi:10.1021/es503981n.

Appendix 1. Climate Change Projections

Climate change summaries were determined for the geo-centroid[1] of each national park and national marine conservation area. The method used to prepare the map followed Price *et al.* (2011) and used greenhouse gas (GHG) concentration scenarios adopted by the IPCC (2014) and General Circulation Models (GCMs)[2].

Of the four IPCC GHG concentration scenarios, the lowest and highest Representative Concentration Pathways (RCP), RCP 2.6 and RCP 8.5 were chosen. These are named after possible radiative forcing values in the year 2100 relative to pre-industrial values (i.e., +2.6 and +8.5 watts/m^2, respectively). RCP 2.6 assumes that global annual GHG emissions (measured in CO_2-equivalents) peak in 2010-2020, with emissions declining substantially thereafter. In RCP 8.5, emissions continue to rise throughout the 21st century.

To produce a high-resolution climate map, monthly time-series data were obtained for each GCM representing both the 20th century (1981–2010) and the scenarios of GHG concentration for the 21st century. Each monthly value at each GCM grid node was normalized either by subtracting (for temperature variables) or dividing by (for other climate variables) the mean of that month's values for the 30-year baseline period 1981–2010. The GCM projected changes in temperature and precipitation were averaged over 30-year periods and then interpolated using ANUSPLIN to the locations of climate stations in Canada and the USA. These data were then combined with observed station normals for the period 1981–2010 to create projected normals for three consecutive 30-year periods: 2011–2040, 2041–2070 and 2071–2100.

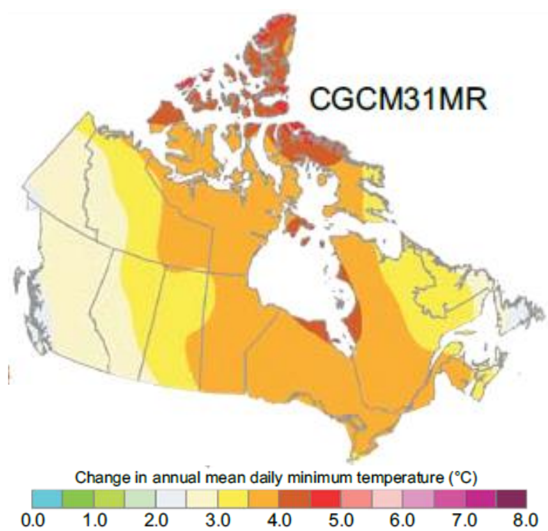


Figure A1. Projected change in annual daily minimum temperature for 2041-2070, relative to 1961-1990 (Price *et al.*, 2011).

A Bessel interpolation scheme was used to generate daily temperature and precipitation sequences that pass monotonically through the monthly values. This allowed for a suite of bioclimatic indicator variables to be estimated for these periods, including for example, mean growing season duration and precipitation during the growing season (Table A1). A set of composite maps averaging the values of the four GCMs was created and used to extract the projected climatic data for the parks and NMCAs at each geo-centroid.

No model driven by scenarios of future climate can ever provide definitive answers to questions about specific outcomes (e.g., how much change will occur at a specified location by a specified date?). However, temperature projections aligned with recent trends and there appears

[1] In the cases of parks for which the geo-centroid is located in the sea, we extracted the data for 5 sets of coordinates determined to be on the land using Google maps.
[2] CANESM2, CESM1CAM5, HADGEM2ES, and MIROCESM.

to be strong agreement on the magnitude of warming to be expected in the short term (until 2030–2040), independent of the RCP scenarios. This is because much of the warming projected for the next two to three decades is “committed warming” resulting from GHG emissions that have already occurred. It is only after ca. 2040 that the warming trajectories diverge, when early mitigation efforts (RCP 2.6 scenario) would evidently begin to have a positive effect. Further into the future, the range of possible warming increases, largely because of the divergence among the different GHG emission trajectories.

Table A1. Bioclimatic variables mapped for past and future climates[a]

No.	Variable[b]	Description
1	Annual mean temperature	Annual mean of monthly mean temperatures
2	Mean diurnal temperature range	Annual mean of monthly mean daily temperature ranges
3	Isothermality	Variable 2 ÷ variable 7
4	Temperature seasonality	Standard deviation of monthly mean temperature estimates, expressed as a percentage of their mean
5	Maximum temperature of warmest period	Highest monthly maximum temperature
6	Minimum temperature of coldest period	Lowest monthly minimum temperature
7	Annual temperature range	Variable 5 – variable 6
8	Mean temperature of wettest quarter	Mean temperature of three wettest consecutive months
9	Mean temperature of driest quarter	Mean temperature of three driest consecutive months
10	Mean temperature of warmest quarter	Mean temperature of three warmest months
11	Mean temperature of coldest quarter	Mean temperature of three coldest months
12	Annual precipitation	Sum of monthly precipitation values
13	Precipitation of wettest period	Precipitation of wettest month
14	Precipitation of driest period	Precipitation of driest month
15	Precipitation seasonality	Standard deviation of monthly precipitation estimates, expressed as a percentage of their mean
16	Precipitation of wettest quarter	Total precipitation of three wettest consecutive months
17	Precipitation of driest quarter	Total precipitation of three driest consecutive months
18	Precipitation of warmest quarter	Total precipitation of three warmest months
19	Precipitation of coldest quarter	Total precipitation of three coldest months
20	Start of growing season	Date when daily mean temperature first meets or exceeds 5°C for five consecutive days in spring
21	End of growing season	Date when daily minimum temperature first falls below –2°C after 1 August
22	Growing season length	Variable 21 – variable 20
23	Total precipitation in the three months before start of growing season	Total precipitation in the three months before variable 20
24	Total growing season precipitation	Total precipitation during variable 22
25	Growing degree-days during growing season	Total degree-days during variable 22, accumulated for all days where mean temperature exceeds 5°C
26	Annual minimum temperature	Annual mean of monthly minimum temperatures
27	Annual maximum temperature	Annual mean of monthly maximum temperatures
28	Mean temperature during growing season	Mean temperature during variable 22
29	Temperature range during growing season	Highest minus lowest temperature during variable 22
30	Climate Moisture Index (monthly)	Precipitation minus potential evapotranspiration

[a] In all cases, the descriptions should be considered estimates rather than actual values.
[b] Variables 1–19 were generated by ANUCLIM; variables 20–29 were generated by SEEDGROW. The approach used creates a daily sequence of minimum and maximum temperature and precipitation, with the values forced monotonically through the monthly values. The resulting values are intended to represent mean conditions only, as the weather in any given year would be expected to produce different results, because of interannual variability.