Let's Talk about Climate Change: Arctic and Hudson Plains Region

Office of the Chief Ecosystem Scientist

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Parks Canada Parcs Canada

Canada

Let's Talk about Climate Change: Arctic and Hudson Plains Region

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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

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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) and National Historic Sites (NHS) included in this regional assessment (labelled).

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. Of note, finding a representative station was challenged by the fact that there are fewer stations with limited distribution for this region. 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 were 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 (Vuuren *et al.*, 2011). 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 2 and 3 also include a projection based on the RCP 4.5 scenario, where emissions peak around 2040 and then decline.

Vertical allowances for each site were acquired from the Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT, http://www.bio.gc.ca/science/data-donnees/index-en.php). The vertical allowances are "recommended changes in the elevation of coastal infrastructure required to maintain the current level of flooding risk in a future scenario of sea level rise". These estimates are based on a future projection of regional sea level rise using the RCP 4.5 and RCP 8.5 scenarios and the historical water level records, including both tides and storm surge. The historical records do not incorporate predicted changes in storm tides.

2.2 Regional Climate Change Summaries

2.2.1 Physical Effects

- This region continues to experience the most pronounced climate changes anywhere in the world. Since 1948 the average annual air temperature in the Mackenzie District (western Arctic) has warmed by 2.7˚C, in the Arctic tundra (central Arctic) by 2.0˚C and in the Arctic mountains and fiords (eastern Arctic) by 1.6˚C (Environment Canada, 2016;

Lemmen *et al.*, 2016). This warming trend is projected to continue and model results indicate a further increase of 2-8˚C by 2100, depending on the location and RCP scenario used (Figure 2). Warming is projected to be greatest in winter and least in summer.

- Total annual precipitation and the ratio of snow to rain has increased throughout the region (Mekis and Vincent, 2011). This trend is expected to continue, with the greatest increase in autumn and winter precipitation amounts (e.g., in excess of 25% increase by 2080s) (Warren and Lemmen, 2014). Reductions in spring-time snow coverage have affected surface energy and hydrological processes (Brutel-Vuilmet *et al.*, 2013; Derksen and Brown, 2012).
- The extent of Arctic sea ice, especially multi-year ice, is decreasing at a rate of 10-24.9% per decade in September (i.e., the month of minimal ice coverage)(Derksen *et al.*, 2012; Howell *et al.*, 2009; Richter-Menge *et al.*, 2016). Sea ice is also thinning and average spring thickness is projected to be only 1.4 m by 2050, a meter thinner than 2008 (Stroeve *et al.*, 2012). Some projections predict an ice-free Arctic by 2050 (e.g., Tivy *et al.*, 2011).
- Regional rivers and lakes are expected to experience later freeze-up and earlier break-up dates (Brown and Duguay, 2011) with more risk of flooding due to freeze-thaw cycling (Prowse *et al.*, 2011). After at least 50 years of perennial ice, Canada's northern most lake (i.e., Ward Hunt Lake in Quttinirpaaq NP) was seasonally ice free in 2011 and 2012 (Paquette *et al.*, 2015).
- The intensity, duration and frequency of storm events is expected to increase (Akperov *et al.*, 2015; IPCC, 2013). A northward shift in storm track is expected along the Atlantic coast region (Loder *et al.*, 2013).
- There are local differences in the direction and magnitude of sea level change due to factors such as vertical land motion (e.g., glacial isostatic rebound). For example, mean annual sea levels at Tuktoyaktuk, NT have risen 2.4 mm/yr and in contrast have fallen 9.3mm/yr at Churchill, MB (data from Hydrographic Station, http://www.psmsl.org/data) Projections for the region indicate that areas where the land is currently sinking will experience a rise by more than 40 cm by 2100, while areas where the land is currently rising (rebounding) will experience a relative sea level fall of more than 80 cm by 2100 (James *et al.*, 2014; Lemmen *et al.*, 2016).
- Permafrost temperature is increasing and this trend is projected to continue (Derksen *et al.*, 2012; Ednie and Smith, 2015; IPCC, 2013). In some areas the degradation of the permafrost is leading to decreased substrate stability, surface subsidence, waterlogging, increase in water flows, thermokarst development and collapse of forested peat plateaus, as well as an associated release of GHG (e.g., Baltzer *et al.*, 2014; de Grandpre *et al.*, 2012; Segal *et al.*, 2016; Walvoord and Kurylyk, 2016; Warren *et al.*, 2013).
- Arctic ice caps and glaciers are projected to shrink by ~18% by 2100 (Lenaerts *et al.*, 2013) contributing to sea level rise and affecting ocean circulation. An ensemble of glaciers in the Torngat Mountains have already shrunk by 27% between 1950 and 2005 (Barrand *et al.*, 2017).
- Rising levels of atmospheric CO_2 also increase the amount of CO_2 absorbed by the oceans. This causes the oceans to become more acidic, affecting the ability of marine organisms to form calcareous skeletal structures and fix carbon (Doney *et al.*, 2009; Fabry *et al.*, 2008; Orr *et al.*, 2005).

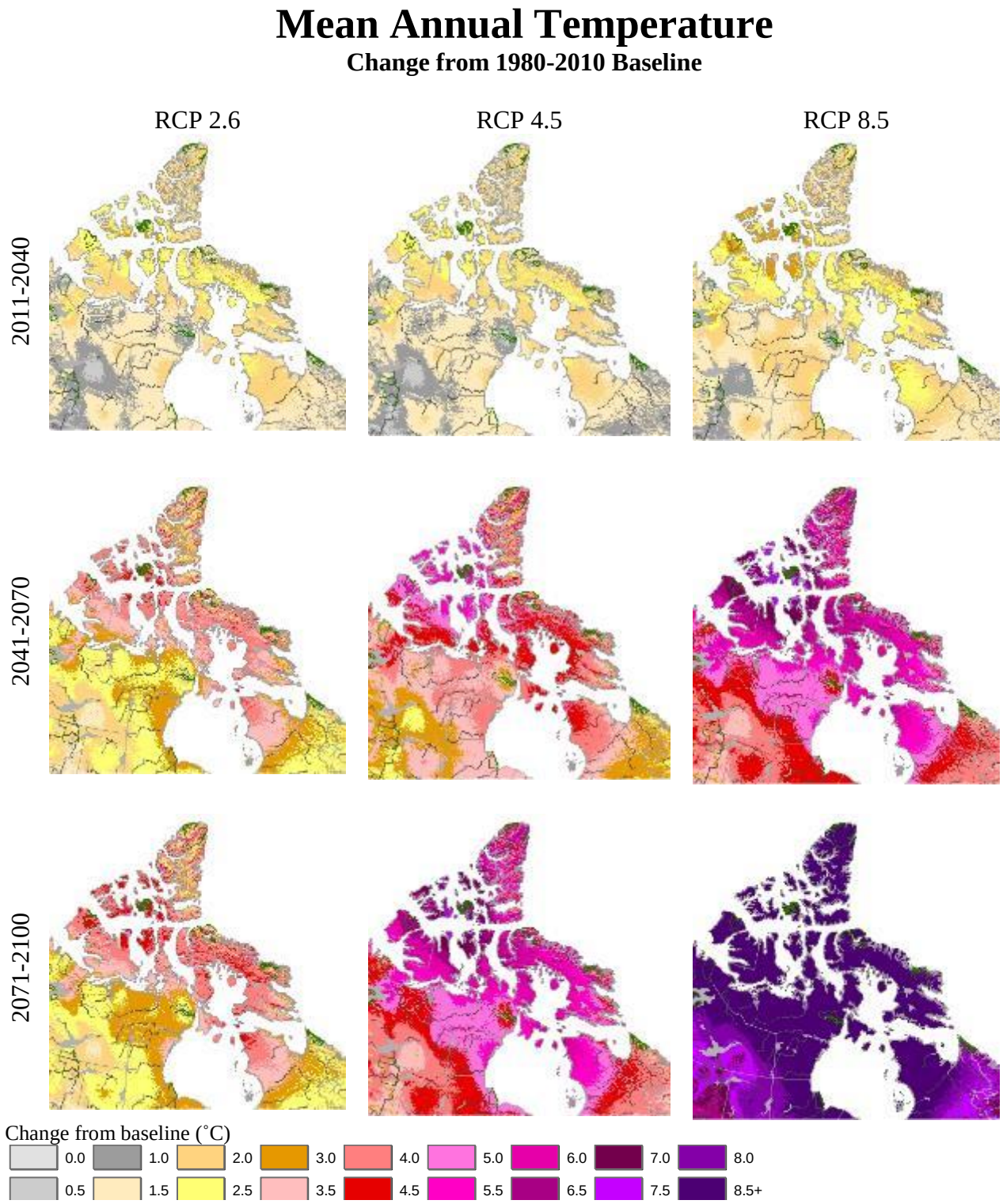


Figure 2. Temperature projections represent a composite (average) of four spatially interpolated downscaled Global Circulation Models: CanESM2, CESM1CAM5, HADGEM2ES and MIROCESM, using three greenhouse gas scenarios (RCPs) for three future time periods. Climate data provided by Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie (http://cfs.nrcan.gc.ca/projects/3).

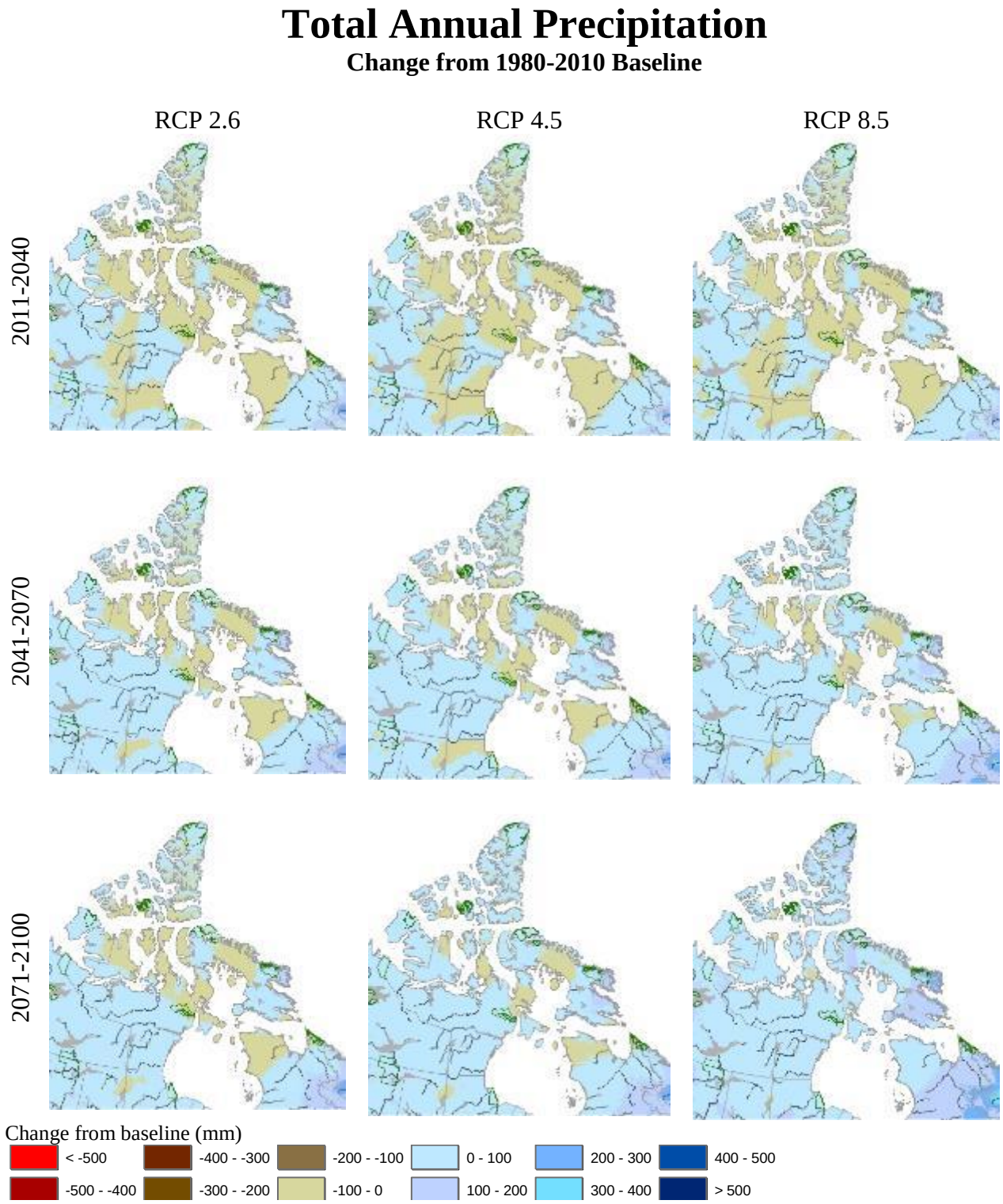
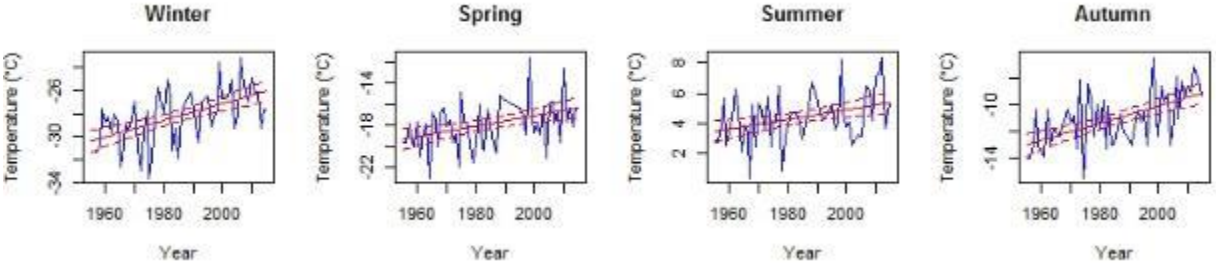


Figure 3. Precipitation projections represent a composite (average) of four spatially interpolated downscaled Global Circulation Models: CanESM2, CESM1CAM5, HADGEM2ES and MIROCESM, using three greenhouse gas scenarios (RCPs) for three future time periods. Climate data provided by Natural Resources Canada,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

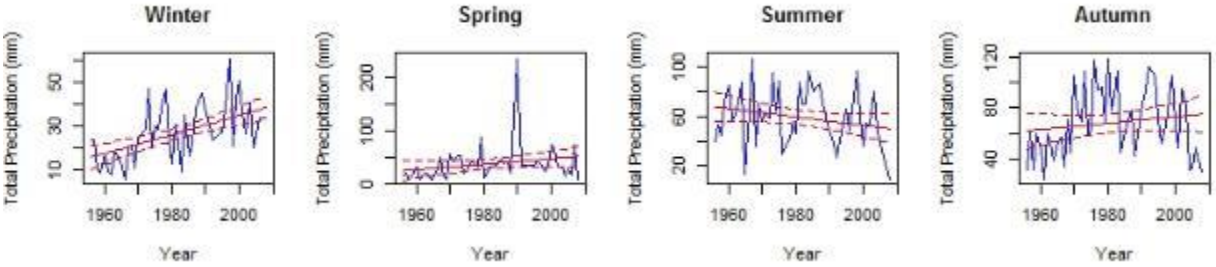
Aulavik National Park

A. Mean Temperature



Seasonal mean temperature at Sachs Harbour Climatological Station (2503648) from 1955 to 2015. A significant trend (P<0.05) observed for winter (0.072°C/yr), spring (0.049°C/yr), summer (0.032°C/yr) and autumn (0.065°C/yr).

B. Total Precipitation



Seasonal total precipitation at Sachs Harbour Climatological Station (2503650) from 1956 to 2013. A significant trend (P<0.05) observed for winter (0.4mm/yr). No significant trend (P<0.05) observed for spring, summer or autumn.

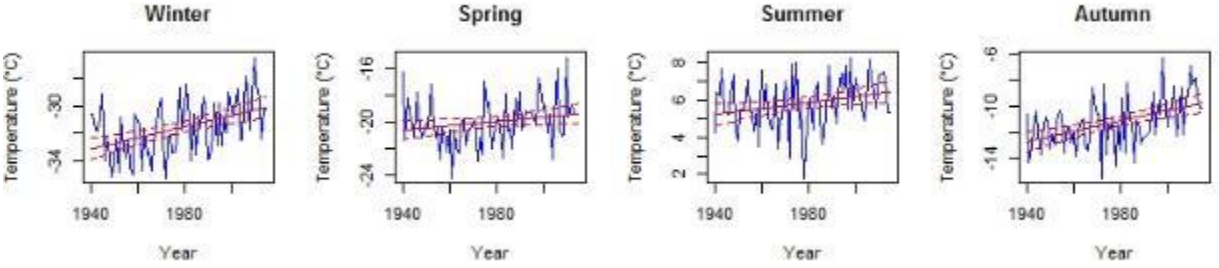
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1.)

Geo-centroid: 119° 35' 42.23" W, 73° 44' 57.86" N; elevation 59 m

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	5.1	to	5.8	7.2	to	12.0	7.3	to	20.6
Mean Spring Temperature (°C)	2.4	to	2.7	3.6	to	6.5	4.1	to	12.3
Mean Summer Temperature (°C)	0.5	to	0.7	1.4	to	2.9	1.7	to	5.8
Mean Autumn Temperature (°C)	3.7	to	3.8	5.4	to	8.0	5.5	to	12.0
Precipitation in Winter	-13%	to	-15%	-9%	to	9%	-10%	to	52%
Precipitation in Spring	-10%	to	-15%	-8%	to	1%	-6%	to	37%
Precipitation in Summer	11%	to	12%	13%	to	28%	15%	to	39%
Precipitation in Autumn	9%	to	11%	18%	to	29%	16%	to	54%
Number of days of growing season	24.0	to	26.0	35.0	to	48.0	37.0	to	68.0
Growing degree-days during growing season	-13%	to	21%	115%	to	354%	164%	to	1000%
Advance in start of growing season (days)	15.0	to	18.0	20.0	to	26.0	21.0	to	33.0
Climate Moisture Index (sum May-Sept)	3.8	to	3.9	2.5	to	3.2	-0.1	to	3

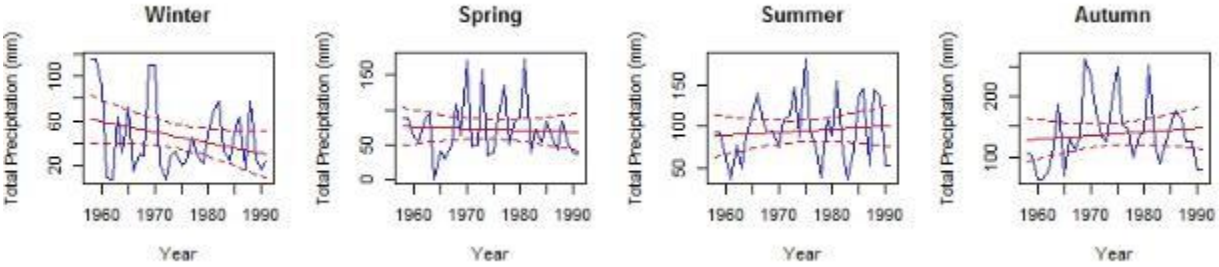
Auyuittuq National Park

A. Mean Temperature



Seasonal mean temperature at Cape Hooper Climatological Station (2400660) from 1957 to 2015. A significant trend (P<0.05) observed for winter (0.049°C/yr), summer (0.016°C/yr) and autumn (0.04°C/yr). No significant trend (P<0.05) observed for spring.

B. Total Precipitation



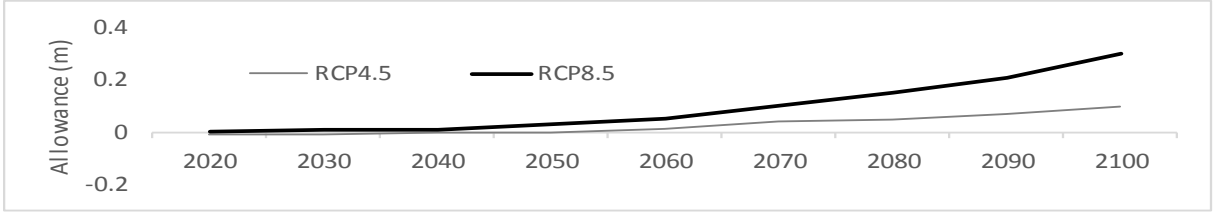
Seasonal total precipitation at Cape Hooper Climatological Station (2400660) from 1958 to 1991. No significant trend (P<0.05) observed for winter, spring, summer or autumn.

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

Geo-centroid: 66° 01' 40.10" W, 67° 21' 08.55" N; elevation 1579m

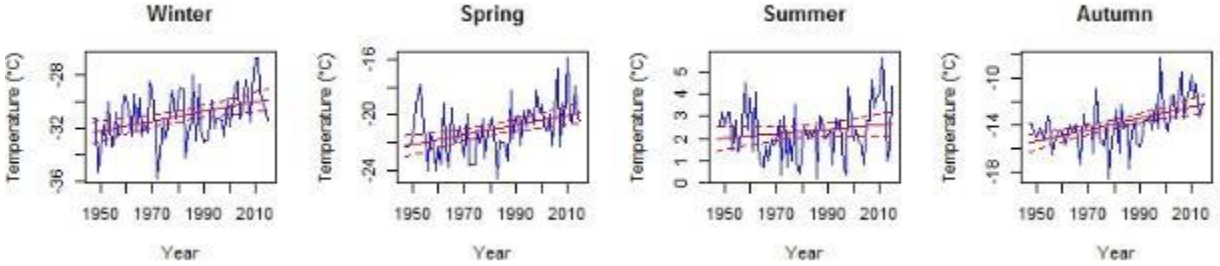
Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	4.8	to	5.4	7.2	to	10.3	7.4	to	16.3
Mean Spring Temperature (°C)	0.8	to	0.8	2.1	to	3.8	2.6	to	9.2
Mean Summer Temperature (°C)	0.4	to	0.5	1.1	to	2.5	1.4	to	5.3
Mean Autumn Temperature (°C)	1.3	to	1.3	2.3	to	3.7	2.3	to	6.8
Precipitation in Winter	-7%	to	-7%	2%	to	10%	0%	to	22%
Precipitation in Spring	-6%	to	0%	3%	to	8%	8%	to	22%
Precipitation in Summer	6%	to	7%	10%	to	12%	9%	to	29%
Precipitation in Autumn	20%	to	24%	28%	to	35%	29%	to	50%
Number of days of growing season	NA	to	NA	NA	to	NA	NA	to	NA
Growing degree-days during growing season	NA	to	NA	NA	to	NA	NA	to	NA
Advance in start of growing season (days)	NA	to	NA	NA	to	NA	NA	to	NA
Climate Moisture Index (sum May-Sept)	39.2	to	39.3	39.8	to	40.2	39.4	to	41.1

D. Sea Level Vertical Allowance, Pangnirtung NU



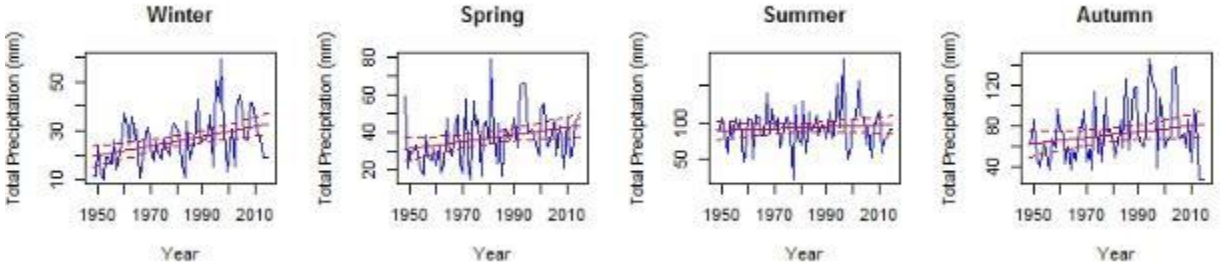
Qausuittuq National Park

A. Mean Temperature



Seasonal mean temperature at Resolute Climatological Station (2403498) from 1947 to 2015. A significant trend (P<0.05) observed for winter (0.037°C/yr), spring (0.036°C/yr) and autumn (0.049°C/yr). No significant trend (P<0.05) observed for summer.

B. Total Precipitation



Seasonal total precipitation at Resolute Climatological Station (2403500) from 1948 to 2014. A significant trend (P<0.05) observed for winter (0.2mm/yr) and spring (0.2mm/yr). No significant trend (P<0.05) observed for summer or autumn.

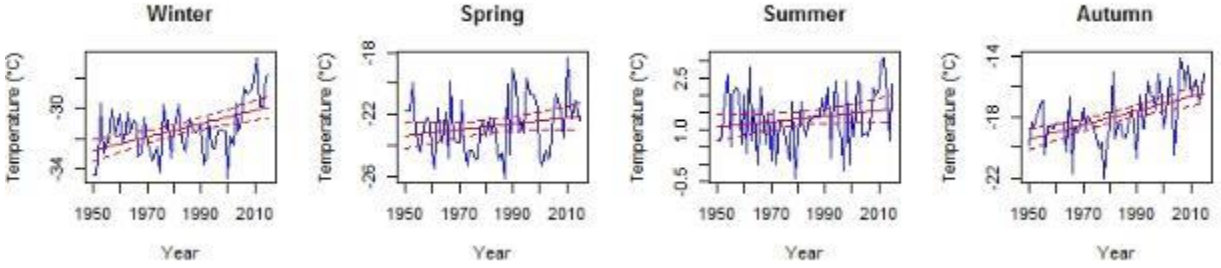
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 100° 55' 55.56" W, 76° 08' 28.56" N; elevation 121m

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	3.9	to	4.4	6.2	to	11.4	6.4	to	21.3
Mean Spring Temperature (°C)	1.8	to	2.0	3.1	to	5.9	3.5	to	12.5
Mean Summer Temperature (°C)	1.5	to	1.6	2.1	to	3.4	2.4	to	6.2
Mean Autumn Temperature (°C)	4.4	to	4.5	6.6	to	9.9	6.9	to	14.8
Precipitation in Winter	-25%	to	-28%	-20%	to	1%	-20%	to	47%
Precipitation in Spring	-3%	to	-4%	0%	to	11%	2%	to	47%
Precipitation in Summer	-2%	to	-4%	-1%	to	9%	-1%	to	24%
Precipitation in Autumn	3%	to	3%	11%	to	20%	9%	to	51%
Climate Moisture Index (May-Sept)	6.7	to	6.9	6.4	to	6.7	4.8	to	6.3

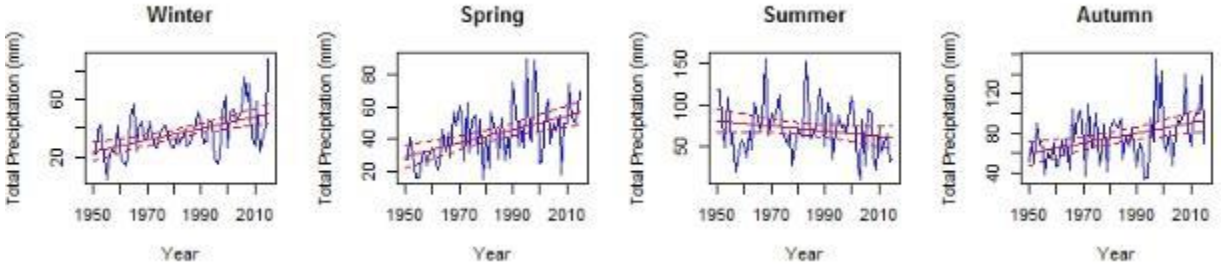
Quttinirpaaq National Park

A. Mean Temperature



Seasonal mean temperature at Alert Climatological Station (2400305) from 1950 to 2015. A significant trend (P<0.05) observed for winter (0.044°C/yr) and autumn (0.046°C/yr). No significant trend (P<0.05) observed for spring and summer.

B. Total Precipitation



Seasonal total precipitation at Alert Climatological Station (2400306) from 1950 to 2015. A significant trend (P<0.05) observed for winter (0.4mm/yr), spring (0.4mm/yr) and autumn (0.5mm/yr). No significant trend (P<0.05) observed for summer.

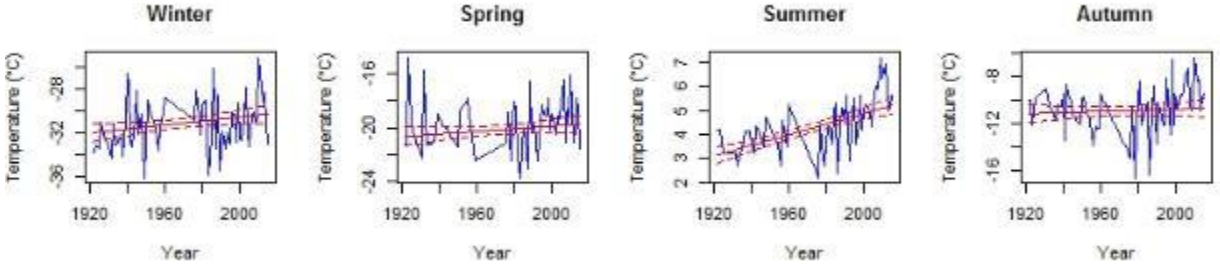
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 71° 37' 19.18" W, 82° 05' 35.31" N; elevation 1271m

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	2.7	to	3.2	4.5	to	8.2	4.7	to	16.3
Mean Spring Temperature (°C)	1.1	to	1.2	2.2	to	4.7	2.8	to	10.3
Mean Summer Temperature (°C)	1.3	to	1.3	1.9	to	3.3	2.2	to	6.0
Mean Autumn Temperature (°C)	2.3	to	2.5	4.1	to	7.4	4.2	to	12.2
Precipitation in Winter	-14%	to	-16%	-7%	to	17%	-5%	to	62%
Precipitation in Spring	-1%	to	-4%	0%	to	23%	5%	to	41%
Precipitation in Summer	5%	to	9%	14%	to	28%	16%	to	54%
Precipitation in Autumn	29%	to	28%	39%	to	54%	40%	to	94%
Climate Moisture Index (sum May-Sept)	32.0	to	32.5	33.0	to	34.4	32.8	to	36.0

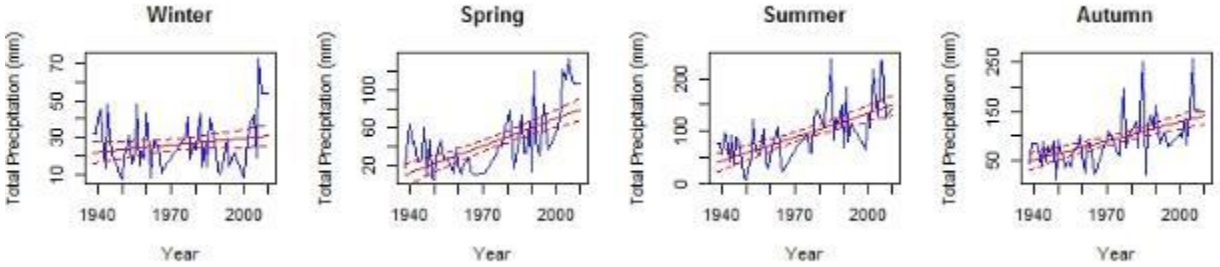
Sirmilik National Park

A. Mean Temperature



Seasonal mean temperature at Pond Inlet Climatological Station (2403206) from 1922 to 2015. A significant trend (P<0.05) observed for winter (0.018°C/yr) and summer (0.022°C/yr). No significant trend (P<0.05) observed for spring and autumn.

B. Total Precipitation



Seasonal total precipitation at Nanisivik Climatological Station (2402730) from 1938 to 2010. A significant trend (P<0.05) observed for spring (1mm/yr), summer (1.5mm/yr) and autumn (1.3mm/yr). No significant trend (P<0.05) observed for winter.

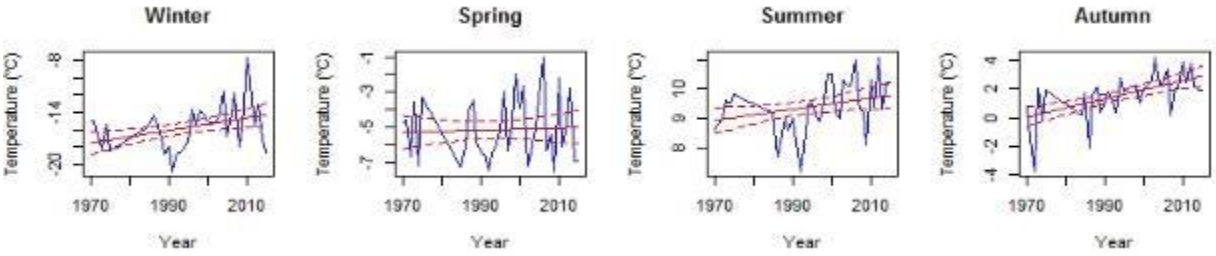
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 79° 50' 46.95" W, 73° 05' 01.80" N; elevation 190m

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	4.1	to	4.6	6.2	to	9.4	6.2	to	16.6
Mean Spring Temperature (°C)	2.0	to	2.0	3.1	to	5.1	3.6	to	10.6
Mean Summer Temperature (°C)	1.7	to	1.7	2.5	to	4.4	2.7	to	7.5
Mean Autumn Temperature (°C)	2.1	to	2.2	3.9	to	6.3	3.9	to	10.4
Precipitation in Winter	0%	to	8%	18%	to	36%	18%	to	68%
Precipitation in Spring	-18%	to	-20%	-12%	to	-13%	-12%	to	14%
Precipitation in Summer	0%	to	3%	5%	to	16%	7%	to	33%
Precipitation in Autumn	24%	to	25%	39%	to	52%	37%	to	75%
Number of days of growing season	29.0	to	29.0	39.0	to	50.0	38.0	to	71.0
Advance in start of growing season (days)	14.0	to	15.0	19.0	to	25.0	19.0	to	34.0
Climate Moisture Index (sum May-Sept)	6.7	to	7.3	5.8	to	6.8	3.4	to	6.6

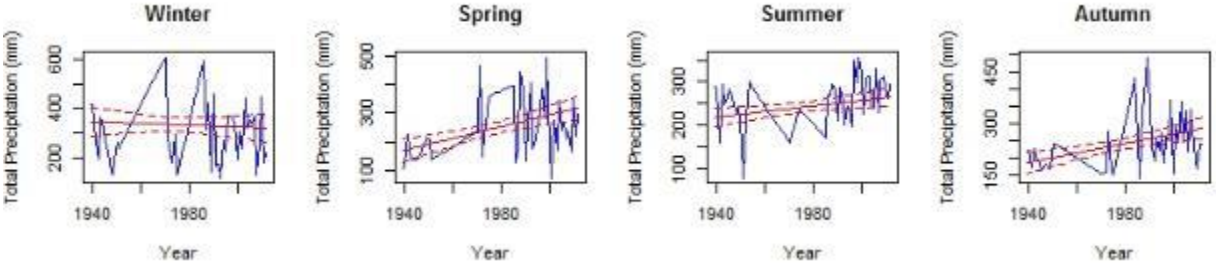
Torngat Mountains National Park

A. Mean Temperature



Seasonal mean temperature at Nain Climatological Station (8502800) from 1970 to 2015. A significant trend (P<0.05) observed for winter (0.073°C/yr), summer (0.019°C/yr) and autumn (0.064°C/yr). No significant trend (P<0.05) observed for spring.

B. Total Precipitation



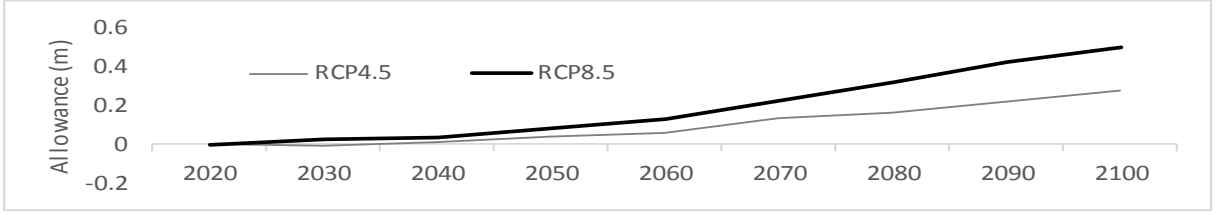
Seasonal total precipitation at Nain Climatological Station (8502800) from 1939 to 2013. A significant trend (P<0.05) observed for spring (2mm/yr), summer (0.6mm/yr) and autumn (1.4mm/yr). No significant trend (P<0.05) observed for winter.

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

Geo-centroid: 63° 59' 54.52" W, 59° 13' 46.51" N; elevation 136m

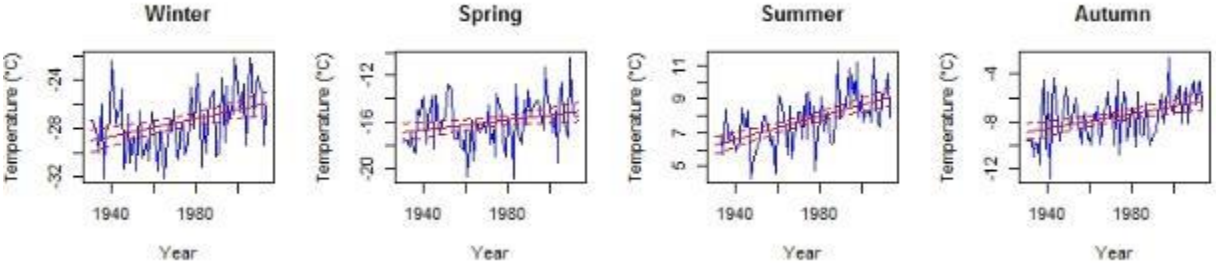
Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	4.0	to	4.3	6.2	to	8.2	6.1	to	12.1
Mean Spring Temperature (°C)	0.9	to	0.9	2.3	to	3.8	2.5	to	8.3
Mean Summer Temperature (°C)	0.8	to	0.9	1.5	to	2.6	1.6	to	5.5
Mean Autumn Temperature (°C)	0.9	to	1.0	1.7	to	2.9	1.8	to	5.9
Precipitation in Winter	0%	to	-2%	4%	to	8%	7%	to	18%
Precipitation in Spring	-29%	to	-32%	-21%	to	-26%	-13%	to	-24%
Precipitation in Summer	16%	to	19%	16%	to	20%	15%	to	24%
Precipitation in Autumn	-3%	to	-4%	-1%	to	3%	1%	to	10%
Number of days of growing season	2.0	to	4.0	13.0	to	27.0	15.0	to	66.0
Growing degree-days during growing season	33%	to	35%	62%	to	127%	69%	to	322%
Advance in start of growing season (days)	5.0	to	6.0	10.0	to	16.0	11.0	to	37.0
Climate Moisture Index (sum May-Sept)	17.1	to	17.6	15.1	to	16.5	11.1	to	15.8

D. Sea Level Vertical Allowance, Nain, NL



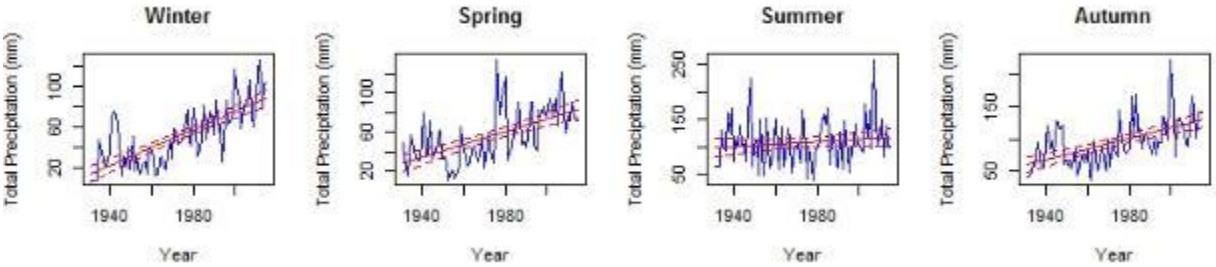
Tuktut Nogait National Park

A. Mean Temperature



Seasonal mean temperature at Kugluktuk Climatological Station (2300902) from 1930 to 2014. A significant trend (P<0.05) observed for winter (0.037°C/yr), spring (0.021°C/yr), summer (0.034°C/yr) and autumn (0.031°C/yr).

B. Total Precipitation



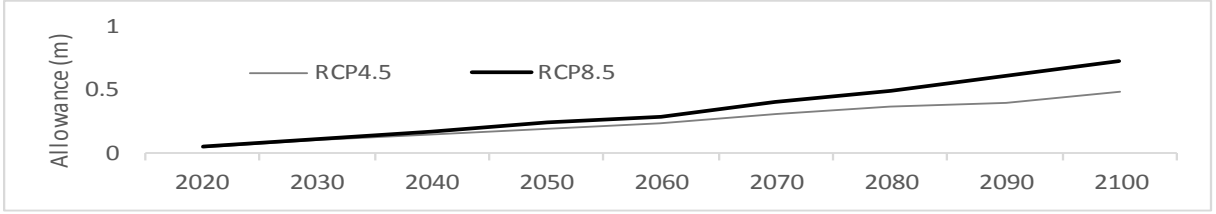
Seasonal total precipitation at Kugluktuk Climatological Station (2300902) from 1931 to 2014. A significant trend (P<0.05) observed for winter (0.8mm/yr), spring (0.7mm/yr) and autumn (0.8mm/yr). No significant trend (P<0.05) observed for summer.

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

Geo-centroid: 121° 48' 45.57" W, 68° 44' 59.27" N; elevation 623m

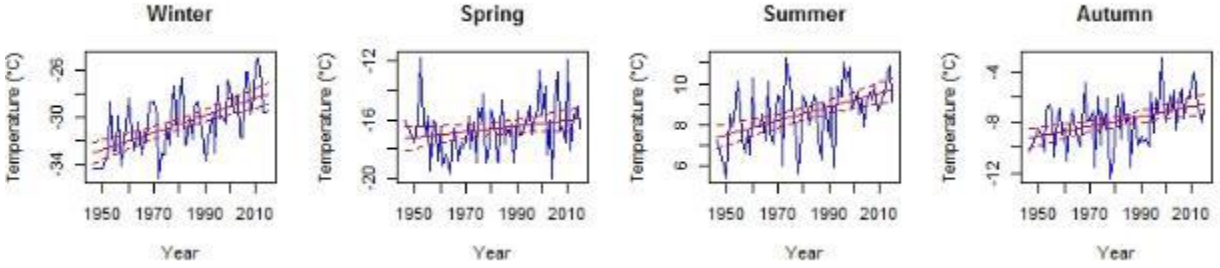
Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	0.9	to	1.7	2.9	to	6.6	3.0	to	13.0
Mean Spring Temperature (°C)	0.8	to	1.0	1.9	to	4.4	2.3	to	9.0
Mean Summer Temperature (°C)	0.6	to	0.9	1.5	to	3.2	1.7	to	5.9
Mean Autumn Temperature (°C)	2.2	to	2.2	3.3	to	5.0	3.3	to	8.2
Precipitation in Winter	-19%	to	-19%	-5%	to	-15%	-13%	to	19%
Precipitation in Spring	-10%	to	-12%	-1%	to	-8%	-7%	to	21%
Precipitation in Summer	19%	to	19%	24%	to	34%	28%	to	43%
Precipitation in Autumn	15%	to	18%	25%	to	34%	24%	to	52%
Number of days of growing season	12.0	to	13.0	18.0	to	29.0	20.0	to	55.0
Growing degree-days during growing season	10%	to	32%	68%	to	167%	79%	to	375%
Advance in start of growing season (days)	6.0	to	8.0	9.0	to	14.0	10.0	to	25.0
Climate Moisture Index (sum May-Sept)	8.9	to	9.1	7.1	to	8.4	5.0	to	8.2

D. Sea Level Vertical Allowance, Tuktoyaktuk, NT



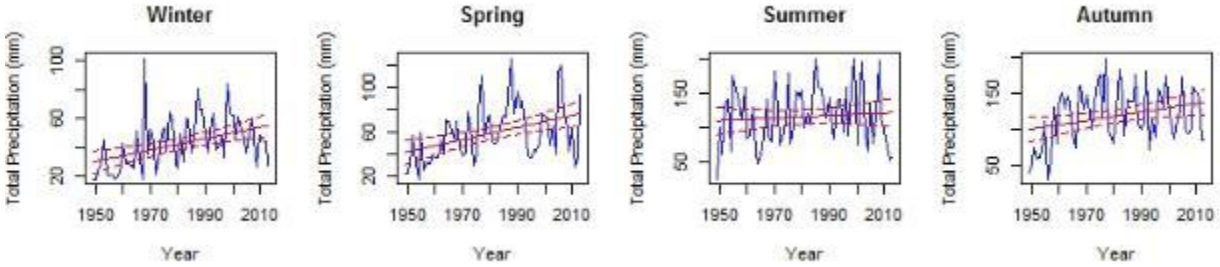
Ukkusiksalik National Park

A. Mean Temperature



Seasonal mean temperature at Baker Lake Climatological Station (2300503) from 1946 to 2015. A significant trend (P<0.05) observed for winter (0.072°C/yr), summer (0.034°C/yr) and autumn (0.04°C/yr). No significant trend (P<0.05) observed for spring.

B. Total Precipitation



Seasonal total precipitation at Baker Lake Climatological Station (2300500) from 1949 to 2013. A significant trend (P<0.05) observed for winter (0.4mm/yr), spring (0.5mm/yr) and autumn (0.6mm/yr). No significant trend (P<0.05) observed for summer.

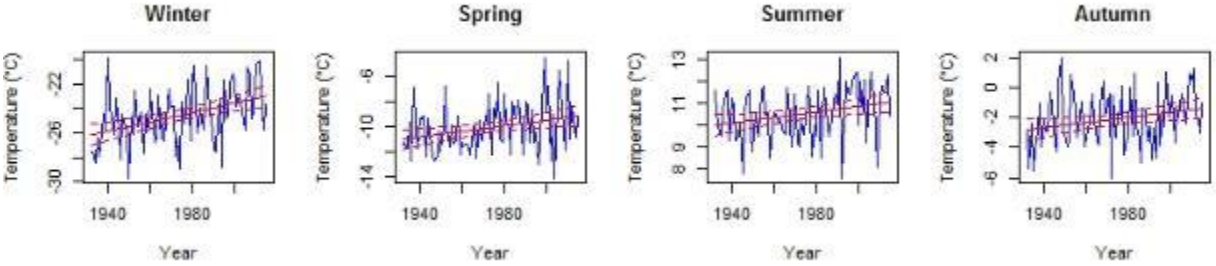
C. Climate Change Projection for Centre of Park Relative to 1981-2010 Baseline Mean (Appendix 1)

Geo-centroid: 89° 53' 47.79" W, 65° 53' 46.08" N; elevation 153m

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Mean Winter Temperature (°C)	1.3	to	2.1	3.6	to	7.0	3.7	to	13.6
Mean Spring Temperature (°C)	0.0	to	0.2	1.4	to	3.6	1.8	to	9.2
Mean Summer Temperature (°C)	0.8	to	1.0	1.6	to	3.7	2.2	to	7.2
Mean Autumn Temperature (°C)	0.8	to	0.8	1.9	to	3.7	2.0	to	7.3
Precipitation in Winter	-37%	to	-39%	-26%	to	-32%	-10%	to	-31%
Precipitation in Spring	-12%	to	-15%	-5%	to	-6%	-9%	to	16%
Precipitation in Summer	-4%	to	1%	4%	to	8%	3%	to	12%
Precipitation in Autumn	9%	to	12%	20%	to	27%	18%	to	46%
Number of days of growing season	8.0	to	9.0	14.0	to	23.0	16.0	to	42.0
Growing degree-days during growing season	18%	to	28%	50%	to	132%	70%	to	318%
Advance in start of growing season (days)	8.0	to	9.0	11.0	to	16.0	13.0	to	24.0
Climate Moisture Index (sum May-Sept)	5.7	to	6.8	3.7	to	5.9	-0.6	to	5.0

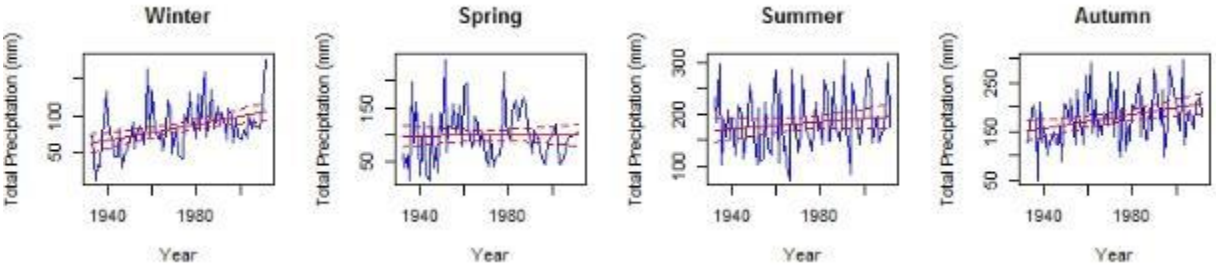
Wapusk National Park

A. Mean Temperature



Seasonal mean temperature at Churchill Climatological Station (5060595) from 1932 to 2015. A significant trend (P<0.05) observed for winter (0.039°C/yr), spring (0.023°C/yr), summer (0.013°C/yr) and autumn (0.017°C/yr).

B. Total Precipitation



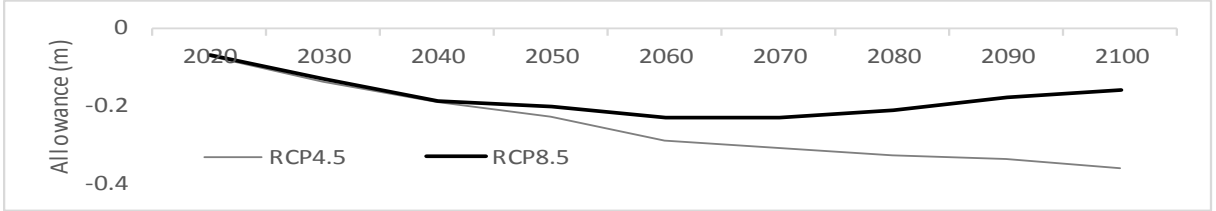
Seasonal total precipitation at Churchill Climatological Station (5060606) from 1932 to 2015. A significant trend (P<0.05) observed for winter (0.5mm/yr) and autumn (0.7mm/yr). No significant trend (P<0.05) observed for spring or summer.

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

Geo-centroid: 93° 16' 16.69" W, 57° 47' 37.01" N; elevation 40m

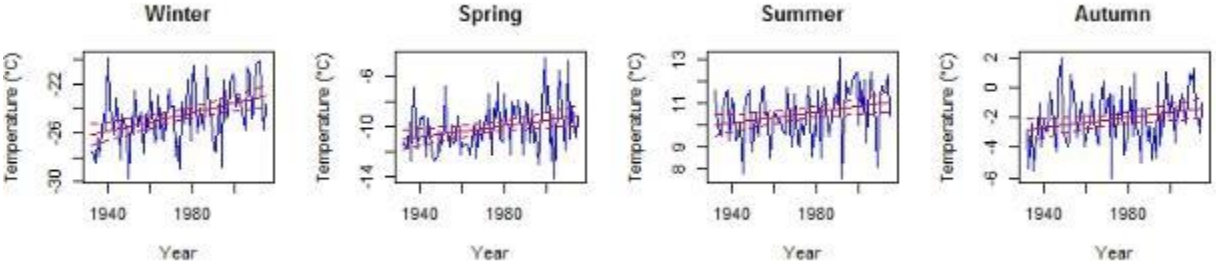
Increase / decrease in:	2011-2040			2041-2070			2071-2100		
Mean Winter Temperature (°C)	2.6	to	3.5	4.4	to	7.3	4.6	to	12.3
Mean Spring Temperature (°C)	1.9	to	2.0	3.0	to	4.4	2.9	to	9.3
Mean Summer Temperature (°C)	1.6	to	1.8	2.3	to	4.1	2.6	to	7.7
Mean Autumn Temperature (°C)	1.9	to	2.0	2.8	to	4.3	2.9	to	7.9
Precipitation in Winter	4%	to	6%	13%	to	15%	12%	to	33%
Precipitation in Spring	-17%	to	-18%	-10%	to	-13%	-14%	to	2%
Precipitation in Summer	8%	to	10%	10%	to	7%	5%	to	10%
Precipitation in Autumn	5%	to	7%	7%	to	17%	14%	to	19%
Number of days of growing season	15.0	to	15.0	21.0	to	28.0	21.0	to	54.0
Growing degree-days during growing season	28%	to	32%	44%	to	81%	47%	to	177%
Advance in start of growing season (days)	8.0	to	8.0	11.0	to	15.0	11.0	to	33.0
Climate Moisture Index (sum May-Sept)	2.0	to	2.1	-2.2	to	1.6	-10.3	to	1.3

D. Sea Level Vertical Allowance, Churchill, MB



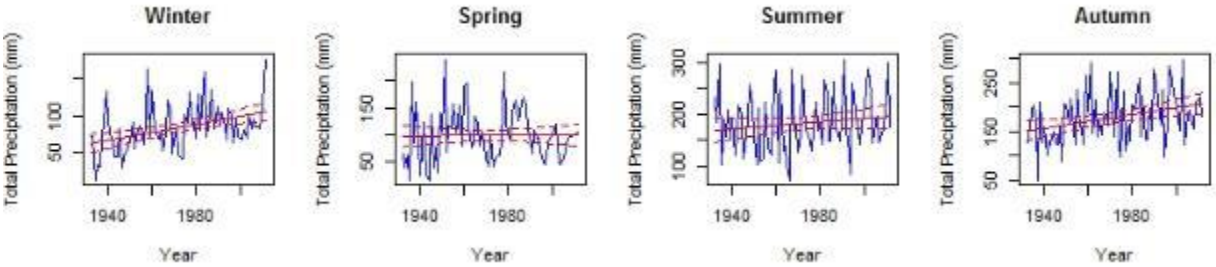
York Factory National Historic Site

A. Mean Temperature



Seasonal mean temperature at Churchill Climatological Station (5060595) from 1932 to 2015. A significant trend (P<0.05) observed for winter (0.039°C/yr), spring (0.023°C/yr), summer (0.013°C/yr) and autumn (0.017°C/yr).

B. Total Precipitation

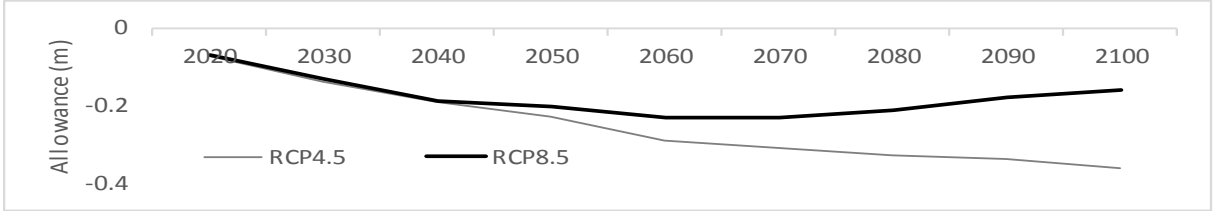


Seasonal total precipitation at Churchill Climatological Station (5060606) from 1932 to 2015. A significant trend (P<0.05) observed for winter (0.5mm/yr) and autumn (0.7mm/yr). No significant trend (P<0.05) observed for spring or summer.

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

Increase / decrease in:	**2011-2040**			**2041-2070**			**2071-2100**		
Max Winter Temperature	9.2	to	10.1	10.9	to	13.5	11.1	to	17.8
Max Spring Temperature	1.9	to	2.0	2.9	to	4.2	2.8	to	8.7
Max Summer Temperature	1.9	to	2.0	2.5	to	4.3	2.8	to	7.9
Max Autumn Temperature	11.3	to	11.4	12.2	to	13.6	12.3	to	17.4
Min Winter Temperature	2.6	to	3.6	4.6	to	7.5	4.7	to	12.9
Min Spring Temperature	1.7	to	1.7	2.8	to	4.4	2.8	to	9.6
Min Summer Temperature	1.8	to	2.0	2.6	to	4.3	2.8	to	7.8
Min Autumn Temperature	-7.1	to	-7.2	-4.8	to	-6.3	-1.3	to	-6.2
Precipitation in Winter	-1%	to	-3%	5%	to	8%	4%	to	24%
Precipitation in Spring	-12%	to	-12%	-6%	to	-36%	-9%	to	8%
Precipitation in Summer	11%	to	11%	11%	to	14%	8%	to	13%
Precipitation in Autumn	12%	to	15%	15%	to	25%	21%	to	25%
Advance in start of growing season (# of days)	10.8	to	14.6	7.8	to	8.2	10.2	to	35.6

D. Sea Level Vertical Allowance, Churchill, MB



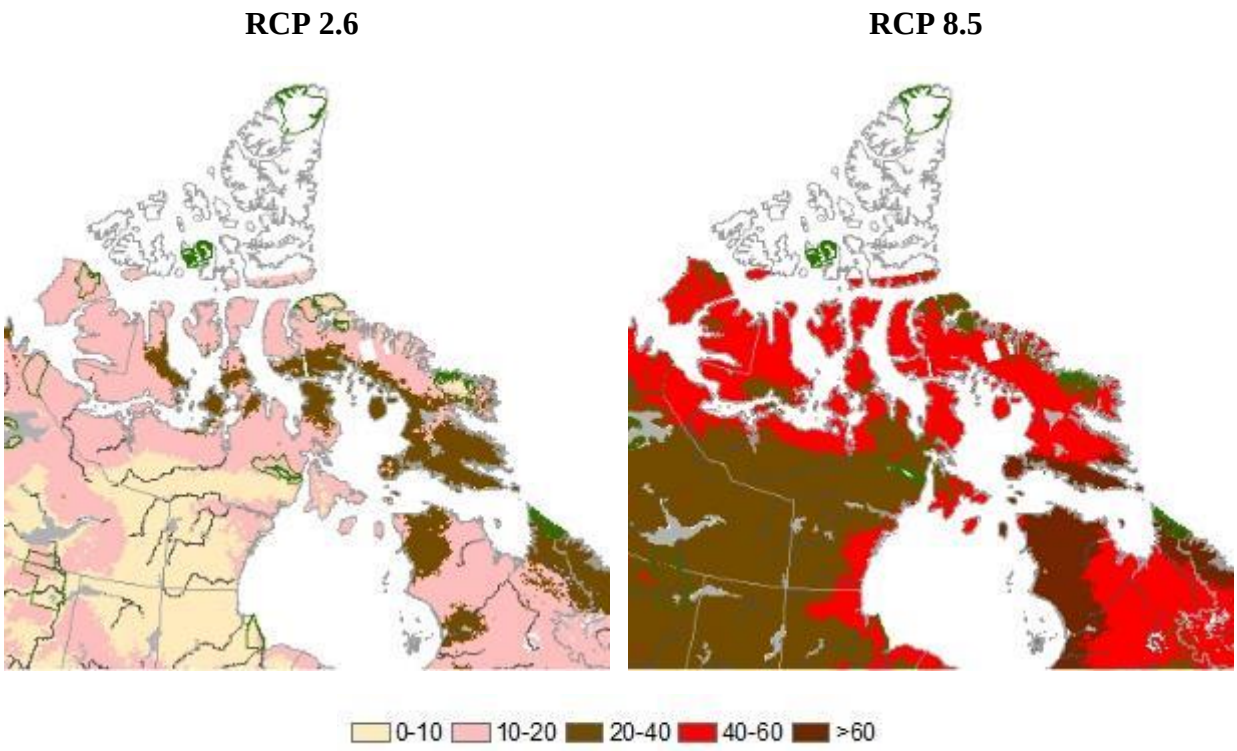


Figure 4. Projected increase in wildfire season length in days from baseline (1981-2010) by 2071-2100 under RCP 2.6 and 8.5 scenarios (data source: http://cfs.nrcan.gc.ca/fc-data-catalogue).

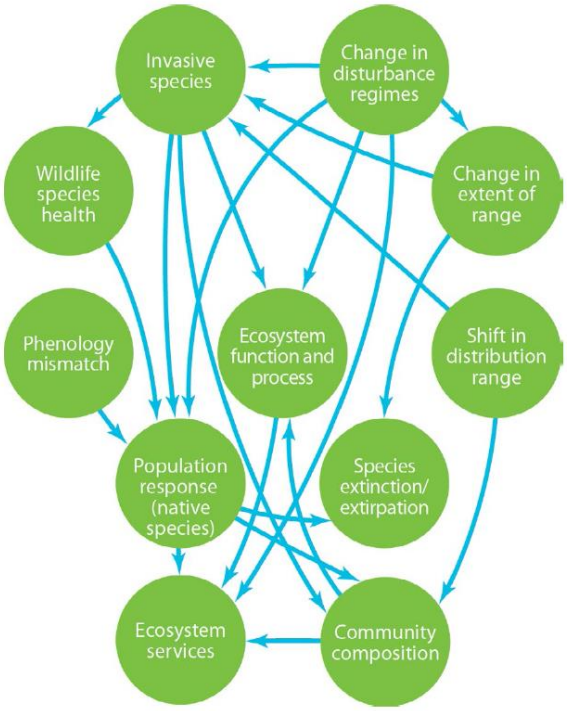
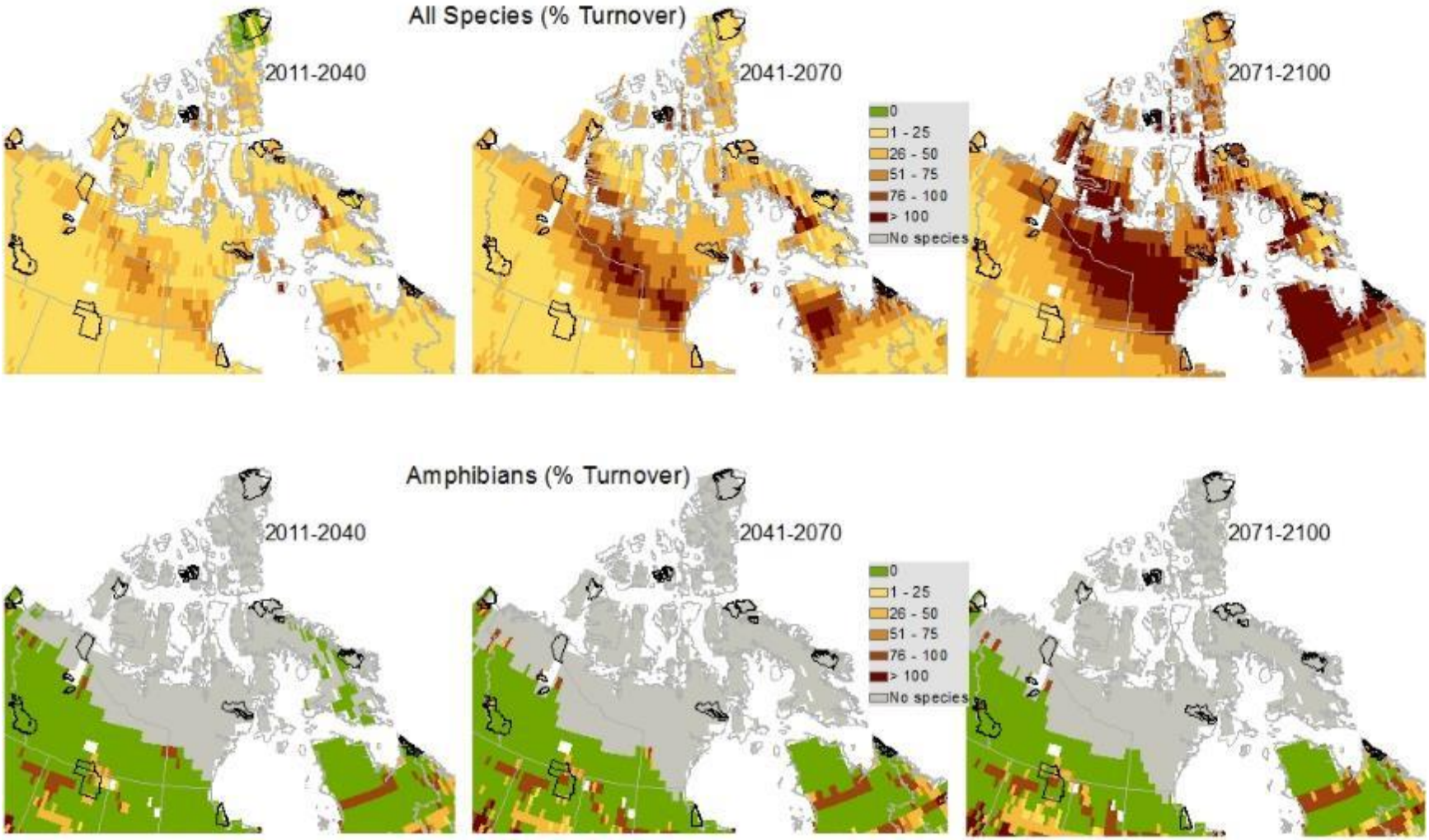


Figure 5. The complex ecosystem linkages and interactions to climate change (from Nantel *et al.*, 2014)


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

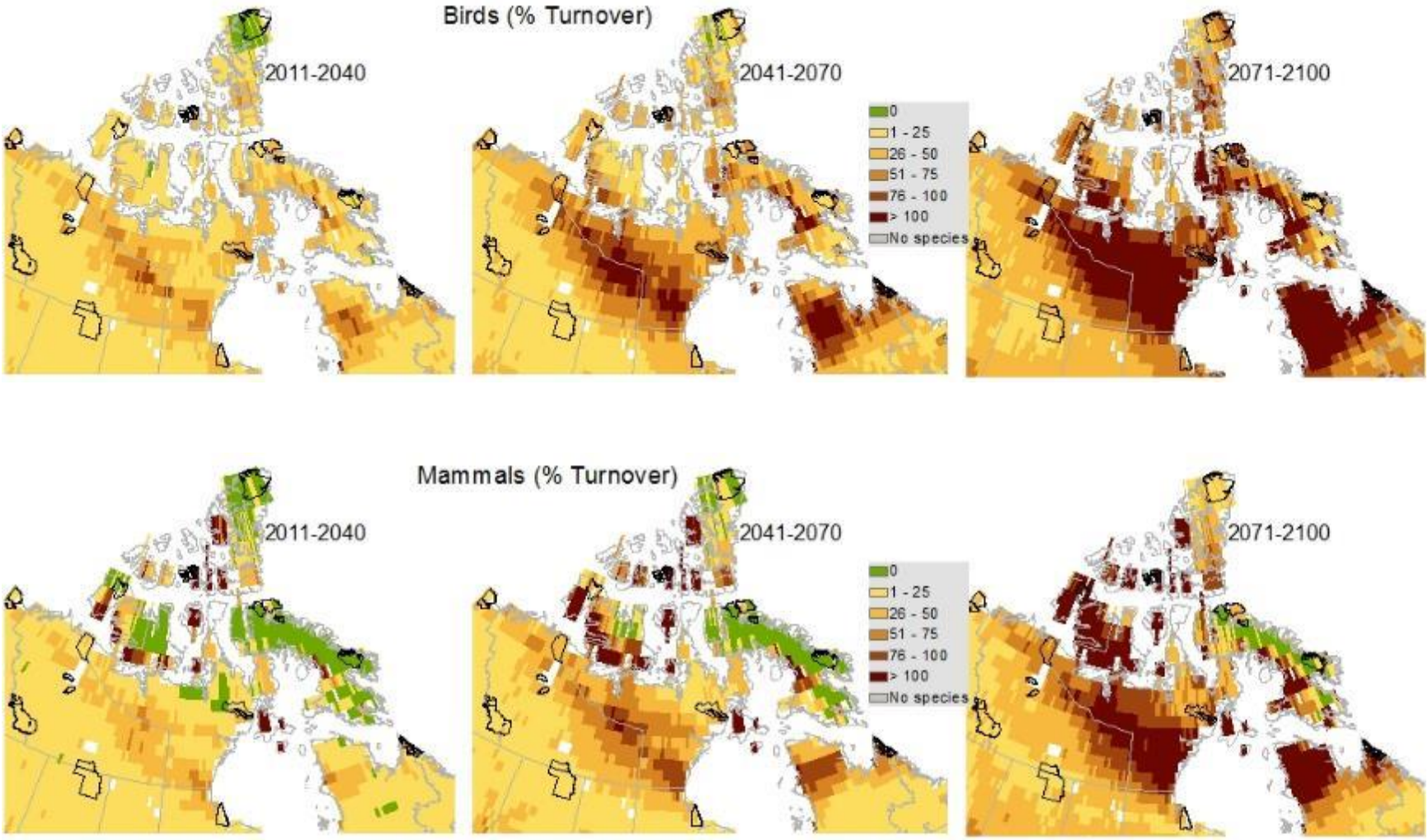


Figure 6. Percentage of projected species turnover (50 km x 50 km grid) relative to current species occurrence, assuming full dispersal (i.e., species can move into new areas) using ten coupled atmosphere-ocean general circulations models (AOGCMS) as in Lawler *et al.* (2009) and the A2 emission scenario. **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).

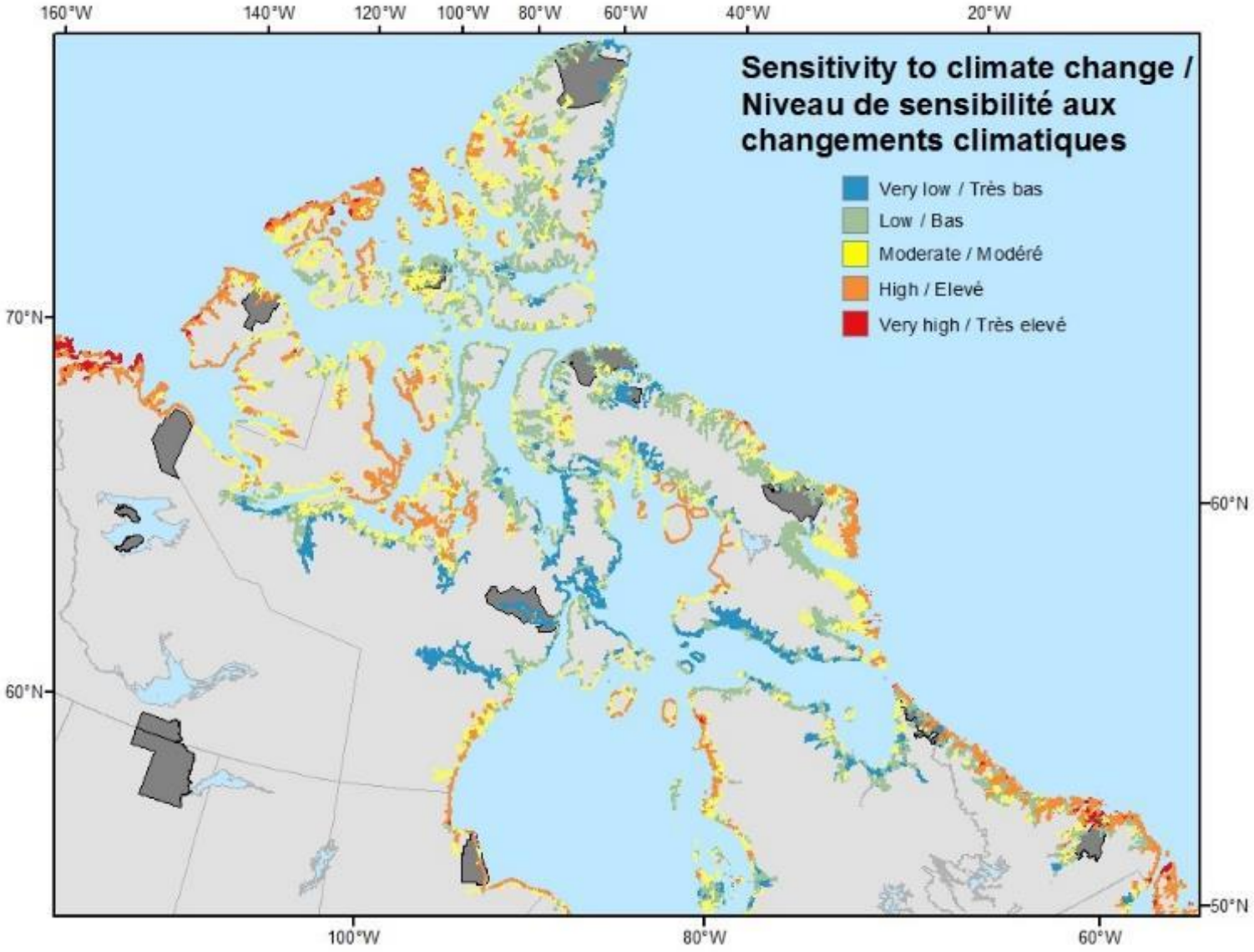
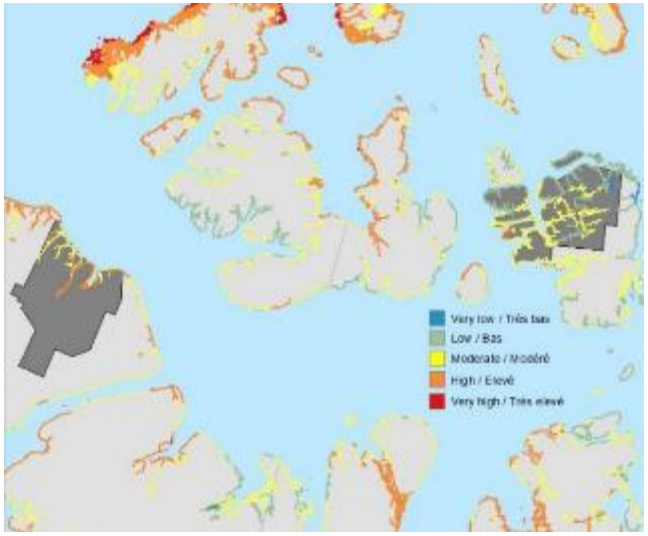
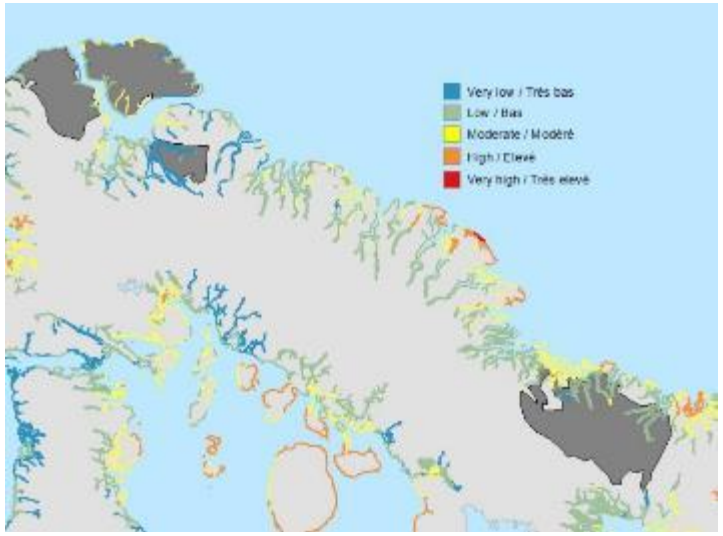


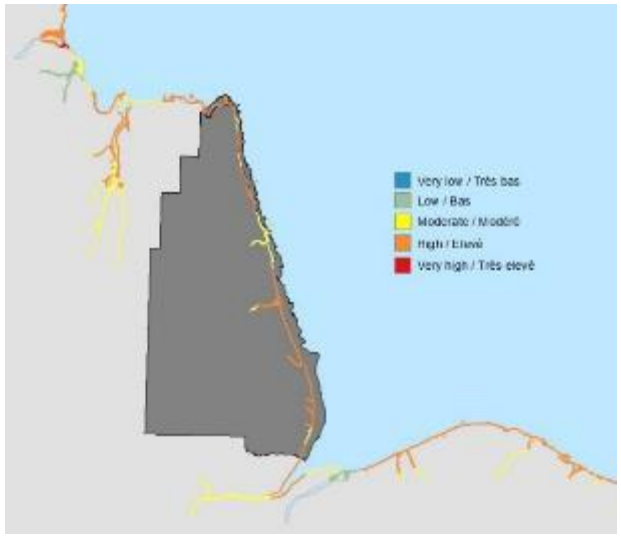
Figure 7a. Preliminary map of coastal sensitivity to climate change. Sensitivity is based on coastal materials, landforms, relief, ground ice, wave height, tidal range, recent trends in sea ice concentration, and projected sea level rise to 2050. Data provided by Natural Resources Canada (Couture and Manson, 2016).



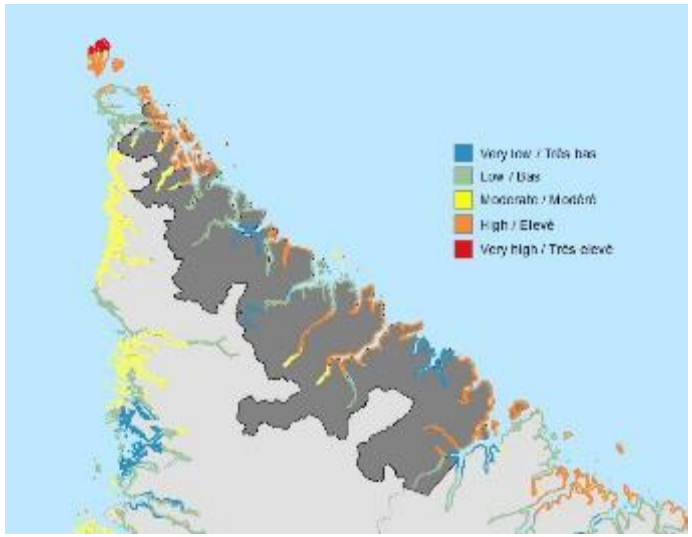
Aulavik and Qausuittuq



Sirmilik and Auyuittuq



Wapusk



Torngat Mountains

Figure 7b. Preliminary map of coastal sensitivity to climate change. Sensitivity is based on coastal materials, landforms, relief, ground ice, wave height, tidal range, recent trends in sea ice concentration, and projected sea level rise to 2050. Data provided by Natural Resources Canada (Couture and Manson, 2016)

2.2.2 Other Effects

Ecosystems and Biodiversity

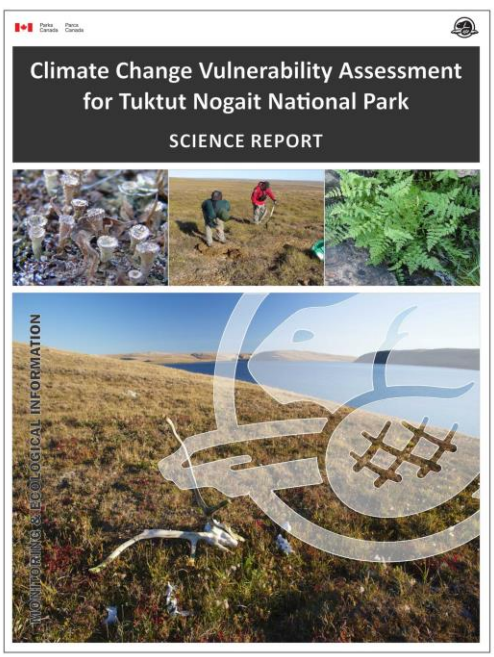
- A decline in marine calcifiers, such as pteropod gastropods, due to ocean acidification will have disruptive affects across the relatively short food chains in the region. The Arctic Ocean is particularly sensitive to ocean acidification due to cooler waters, sea ice processes (i.e., formation and melting) and relatively low carbonate mineral saturation states (Qi *et al.*, 2017; Richter-Menge *et al.*, 2016). The Arctic Monitoring and Assessment Programme provides a review of ocean acidification and its ecosystem impacts (AMAP, 2013).
- An increase in phytoplankton productivity is associated with sea ice conditions (Vilhjálmsson and Hoel, 2005). Note: whether some fish and marine mammal populations increase is uncertain, especially if pteropods and other crustacenas are negatively impacted by ocean acidification.
- The decrease in summer sea ice has made conditions more favourable for some whale species, such as orcas (however their presence could negatively affect narwhal, bowhead, and beluga). Sea ice dependent species, including polar bears and ringed seals, will be adversely affected by the loss of ice (DFO, 2011; Hamilton *et al.*, 2014).
- A range expansion of Pacific salmon species and Atlantic salmon is expected to continue as waters warm (Nielsen *et al.*, 2013). Arctic char populations have declined in some areas due to climate change (Bolton *et al.*, 2011).
- Increased shipping activity due to longer navigation season and ice retreat may increase risk to biodiversity from spills, disturbance, and the introduction of invasive species (e.g., ballast water), as well, increased fishing activity could impact species and their habitat (RSI, 2012).
- 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 (e.g., Cole *et al.*, 2013; Michalak, 2016; Noyes *et al.*, 2009; Stern *et al.*, 2012).

Projected "Last Ice Area" for summer ice
http://www.wwf.ca/conservation/arctic/lia

- Devlin and Finkelstein (2011) documented phytoplankton community changes within the lakes of Sirmilik NP in response to climate change and physiographic controls.
- Sea-level rise and increases in the frequency and magnitude of storm surges are potential threats to shorebird and waterbird nests and breeding habitat on low-lying landforms (Galbraith *et al.*, 2014).
- "Temperature velocities" for vegetation biomes are estimated to move northward (Batllori *et al.*, 2017; McKenney *et al.*, 2011; Warren *et al.*, 2013). However, colonization success will vary with (micro)topography, permafrost conditions, dispersal competition, soil, precipitation patterns, disturbance regimes, pollinators and many other factors (e.g., Jacobs *et al.*, 2014; Lafleur *et al.*, 2010; McKenney *et al.*, 2007; Warren *et al.*, 2013). Nationally, it is estimated that vegetation distribution (biomes) will change in

over half of Canada`s national park (Scott *et al.*, 2002). Increasing "shrubification" of the arctic and alpine tundra will have important consequences for herbivore communities, snow distribution, soil chemistry, albedo effect and other aspects of the ecosystems (Myers-Smith *et al.*, 2011).

- McLennan *et al.* (2012) reported results of recent climate-related research in Canada's Arctic national parks. For instance, a normalised difference vegetation index (NDVI) in Torngat Mountains, Wapusk, Sirmilik, and Ivvavik NPs, demonstrated a 6 to 25% increase in NDVI in the past 23 years, with associated increases in shrub and herbaceous cover.
- Saarela *et al.* (2012) reported extralimital stands of balsam poplar in Tuktut Nogait NP.
- Wildlife species will continue to experience range shifts and changes in abundance. (e.g., National Audubon Society, 2015). Species response to climate change will vary with abiotic, biotic 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). Chen *et al.* (2011) report the median rate of northward migration, for those species where migration is even attainable, is ~16.9 km/decade. Parmesan and Yohe (2003) report an average northward range shift of 6.1 km/decade for birds, butterflies and alpine herbs and an earlier onset of spring events (e.g., arrival, breeding, flowering, nesting) of 2.3 days/decade. The northward shift of some marine species in the northeast Atlantic is projected to be 40 km/decade (Cheung *et al.*, 2009).
- Climate change may have facilitated the recent observation of short-eared owls in Aulavik NP and the first breeding record from the Canadian Arctic Archipelago (Smith *et al.*, 2013).
- Northern collared lemming, polar bear and arctic fox have been identified as the most vulnerable species to climate change, followed by muskox, barren-ground caribou, peregrine falcon and Arctic ground squirrel (Zorn *et al.*, 2017b). The Conservation of Arctic Flora and Fauna working group has prepared a biodiversity assessment status and trends report for the Arctic (CAFF, 2013).
- Changing winter (e.g., decreased insulation, ice layers, freeze/thaw) and summer (e.g., permafrost thaw, increased rainfall) weather conditions will negatively affect lemming and ground squirrel populations, and subsequently reduce prey availability for predators such as Arctic fox (e.g., Fauteux *et al.*, 2015; Gilg *et al.*, 2012; Prost *et al.*, 2013; Prost *et al.*, 2010).
- With projected warming and elimination of sea ice, polar bears will largely disappear from the southern areas of their range by mid-century (Durner *et al.*, 2009; Stirling and Derocher, 2012).
- Increased snow depth and ice layers due to warmer winters (freeze/thaw cycle), will make it more difficult for food grazing and travel by animals such as caribou and muskox (AMAP, 2011).
- In response to earlier snow melt, arctic passerines and shorebirds are laying eggs earlier (Grabowski *et al.*, 2013).
- Insect harassment (e.g., blackflies, mosquitos, oestrids) is expected to increase, further stressing species such as caribou (Vors and Boyce, 2009; Witter *et al.*, 2012).



Science and Traditional Knowledge Climate Change Vulnerability Assessments completed for:

- Tuktut Nogait National Park
- Auyyuittuq National Park
- Ukkusiksalik National Park

Highlights from the Tuktut Nogait Reports

A. Traditional Knowledge Report (Zorn *et al.*, 2017a)

In summary, traditional knowledge gathered through this study pertaining to climate related changes observed in the Paulatuk and Tuktut Nogait National Park region are as follows:

- Respondents consistently told stories of increased temperatures across all seasons. Changes in temperature are having effects on other aspects of weather (e.g., wind patterns, precipitation) and are impacting ice and snow, which in turn, are having substantial impacts on wildlife.
- Many respondents commented on observed changes to wind patterns including changes to wind intensity, timing and direction.
- One of the most pronounced changes to climate observed by respondents is the change in the timing of seasons and its influence on the movement of animals.
- A consistent theme across stories shared on changes in climate in the Tuktut Nogait area is an increase in the unpredictability of weather compared to the recent past.
- There was strong agreement among all knowledge holders that the number of caribou encountered locally has declined in recent years.
- While there is strong agreement among knowledge holders that local numbers in caribou are less than they were 30 or 40 years ago. There still remains uncertainty as to whether this is an indication of a decline in the Bluenose West caribou herd or whether the change in local abundance simply signifies a change in distribution.
- There is a sense among knowledge holders that changes to the local abundance of lichen and changes to seasonal river discharge, water levels, and stream bank erosion have all contributed to a change in the migratory routes of the Bluenose West caribou herd.
- Knowledge holders agree that caribou now tend to migrate to their traditional calving grounds later in the year. This change in migration is generally perceived to be in response to climate change.
- We asked knowledge holders if changes they are seeing on the Land have resulted in a change to the health and fitness of individual caribou. While there have been instances when individual harvested caribou appeared thin or sickly, overall, their health is good. Some knowledge holders notice that

caribou are starting to be thinner than expected but others report that if harvested in late summer (August and September) body weight is generally normal.

- We asked knowledge holders if they have observed changes to the numbers of geese seen on the land in recent years that may be a result of climate change. The majority of knowledge holders have observed increases in geese abundance and there is concern that geese are hyper-abundant and over grazing vegetation in the region.
- There is no observed change in the health of individual geese. Body size is as it was in the past or has increased. Geese tend to be very fat and healthy.
- While geese are plentiful in the region there has been an observed change to the location of their staging areas, the timing of when they travel to Banks Island, and the length of time they remain in areas easily accessible from Paulatuk. These changes have led to increased unpredictability regarding when or where geese can be harvested.
- While the focus of this study was on caribou and geese we also asked knowledge holders to share stories regarding changes they have observed on other animals, especially predators in the region. Several stories relate to an observed increase in predation and harassment on caribou from wolf, wolverine and grizzly bear. The increased presence of predators may have contributed to the shift in local caribou distribution.

B. Science Report (Zorn *et al.*, 2017b)

Present: An ecotype map based on SPOT5 satellite imagery was developed for the park, describing 23 classes with 11 vegetated ecotypes. 53.4% of the park is in ecotypes with moderate to high soil moisture and moderate to rich soil nutrient regimes and these will likely be the most sensitive to climate-related change.

Past: A retrospective analysis of satellite imagery was used to assess changes in the dominance of shrub and sedge ecotypes and changes in growing season. Between 1987 and 2014 average cover of shrub dominant ecotypes increased from 47.0% to 50.4%. Average cover of sedge dominant ecotypes increased from 17.6% to 22.3%. Plant productivity, measured by NDVI, during the peak caribou calving period in the park has doubled between 2000 and 2015. These results indicate that the growing season is beginning earlier in the spring and plant growth is significantly more advanced by the time the Bluenose West caribou herd arrives at their calving grounds in the park. This may result in a phenological miscue in that the peak emergence of flowering plants and new shoot growth may have passed by the time caribou arrive to give birth to their young, possibly leading to reduced calorie and nutrient availability and increased calf mortality.

Future: The Composite AR5 RCP8.5 climate model predicts a substantial increase in average annual temperature of 5 to 6°C for the park by mid-century with the greatest predicted increase during the winter months. A modest increase of 0 to 5% in precipitation is predicted over the same time period. Wildlife vulnerability assessments, using NatureServe's Climate Change Vulnerability Index method, predicts a moderate vulnerability to climate change for caribou, however, the confidence around this result is low due to a range of positive and negative responses in the scientific literature. Northern collared lemming is the species found in the park with the highest predict vulnerability to climate change. The northern collared lemming is a critical food source for several predators in the park and its potential decline may have a serious cascading effect.

- The distribution and impacts of pathogens and parasites are expected to increase with warmer temperatures and the northward migration of species (Marcogliese, 2008; 2016; Pickles *et al.*, 2013). For instance, newly acquired parasites in small mammals (e.g., shrews) are indicative of a northward shift in sub-Arctic species (Richter-Menge *et al.*, 2016).
- Range expansion of butterfly species have been observed in Herschel Island, YK (Leung and Reid, 2013).
- Asynchrony between life history events have been observed. Although photoperiod is not changing, other ecological cues are, such as temperature, river flow, etc…

- Length of the wildfire season and area burned is expected to increase in the southern regions (Boulanger *et al.*, 2013; Wang *et al.*, 2015; Whitman *et al.*, 2015). Wildfire can affect behaviour and reduce available food for caribou (Gustine *et al.*, 2014; Joly *et al.*, 2009).

Visitor Experience

- As the sea ice extent and character changes, shipping activity is expected to increase (Pizzolato *et al.*, 2016). While cruise ship activity is expected to increase in some areas (e.g., Northwest Passage), it may decrease in others (e.g., Hudson Bay) as ice-supported wildlife shifts north (Stewart *et al.*, 2010). Cruise ships provide visitor and socio-economic opportunities, but they also present management challenges. Dawson *et al.* (2016) identifies and evaluates adaption strategies (e.g., disaster management, visitor codes of conduct, etc…). Of interest, Dawson *et al.* (2017) describes the regulatory complexity of operating cruise ships in Canadian waters versus other Arctic areas, which involves over 30 permits and permissions including Parks Canada's. They recommend improvements.
- The potential for polar bear-human conflicts may increase with sea ice loss (Clark *et al.*, 2012; Stirling and Derocher, 2012).
- The length of visitor season will increase.
- Northward migration of some mosquito-borne diseases may occur due to climate change (Chen *et al.*, 2013; Kulkarni *et al.*, 2015). Although sustained populations in the region are unlikely, isolated and ephemeral transmission events of West Nile virus are possible (Hoover and Barker, 2016).
- Decreased ice cover and thickness will negatively impact activities such as ice travel and snowmobiling. Managing such risk will require cross-cultural dialogue and considerations (e.g., for Auyuittuq NP see: Johansson and Manseau, 2012).
- Increased wildfire risk may affect visitor safety and experience.

Assets and Infrastructure

- Thawing permafrost is a concern to assets and infrastructure in the region (e.g., ACIA, 2005; Oswell and Nixon, 2015; Perreault and Shur, 2016). For instance, an assessment of York Factory NHS confirmed an unstable and slowly disappearing land base because of climate including those associated with riverbank erosion, thawing permafrost and ground drainage (Parks Canada, 2007).
- An assessment of Churchill airport (proximate to Wapusk NP) using Engineers Canada's "PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment" (PIEVC, 2008), confirmed that no immediate engineering action is required to address impacts from climate change, however, significant uncertainties and data gaps exist.
- Increased storm intensity and less ice cover increases the risk of coastal flooding and erosion. Projected sea level rise coupled with thawing of coastal permafrost may erode and damage coastal infrastructure (Lemmen *et al.*, 2016).
- A planned retreat of coastal infrastructure may be the most effective action to maintain natural processes and manage assets.

- The length of season and reliability of winter roads and ice travel will be reduced (Lemmen *et al.*, 2008).
- Projected increased snow loads may be a factor with some structures.
- There is an increasing risk to assets and infrastructure by wildfire damage in some areas.

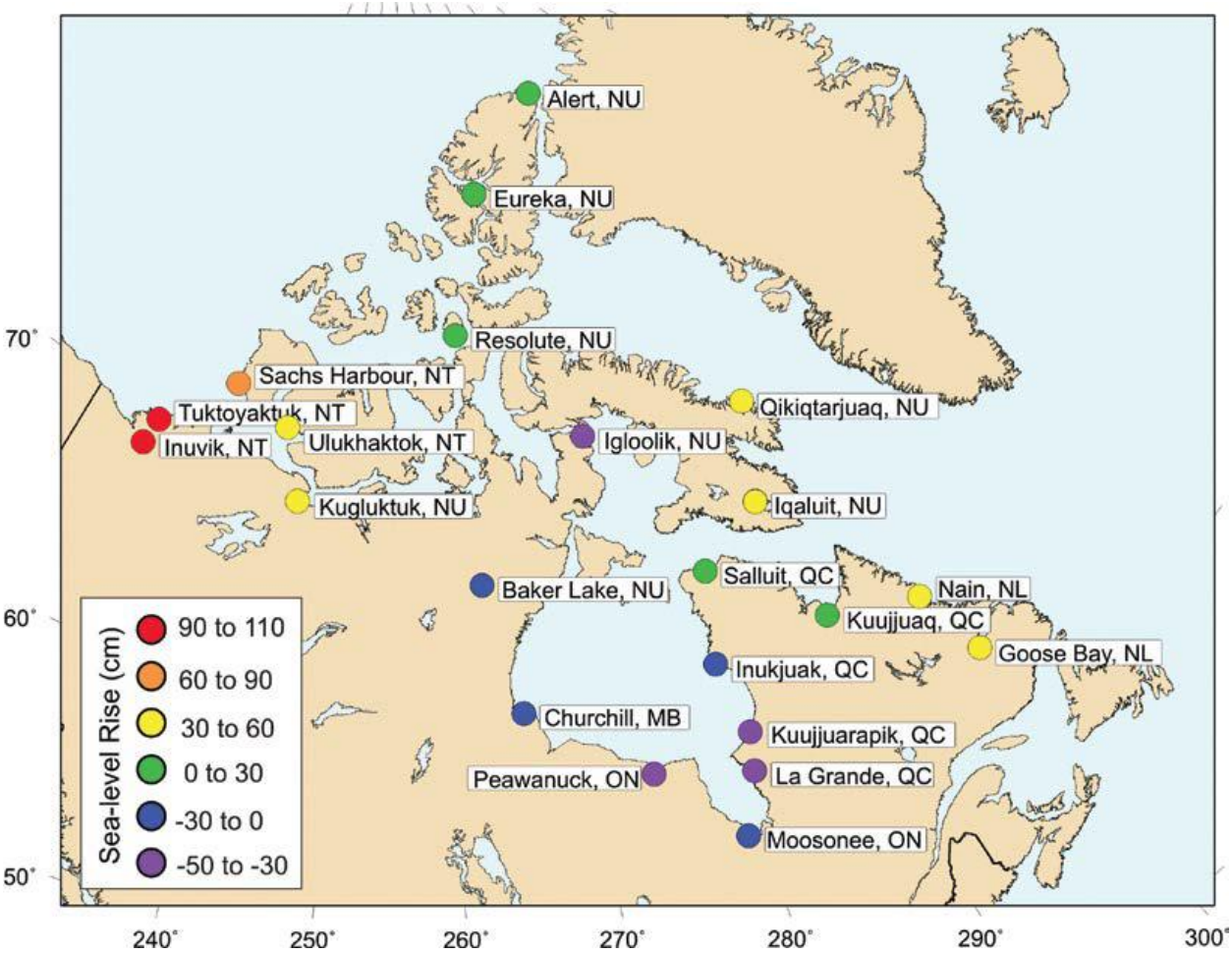


Figure 8. Projected sea-level change at 2100 for the 95th percentile of the high-emissions scenario (RCP 8.5) (James *et al.*, 2014; James *et al.*, 2015).

Cultural Resources

- Traditional practices and ways of life will be affected (e.g., the effect of sea ice loss on marine mammal distribution and access to hunting) (e.g., ACIA, 2005; Arctic Council, 2016; Pearce *et al.*, 2011).
- Direct physical damage of cultural resources by sea level rise, lengthening of open water periods and increase frequency of storm events. For example, Herschel Island (Yukon), a UNESCO World Heritage candidate site, is recognized as being highly vulnerable to sea level rise (Radosavljevic *et al.*, 2016; Westley *et al.*, 2011).
- Permafrost thaw can lead to building destabilization, more rapid decay of organic building materials, and change in use or abandonment if surrounding grounds become too boggy (e.g., Blankholm, 2009; Grossi *et al.*, 2007; Marissa *et al.*, 2016).

- 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).
- Coastal erosion plays both a disturbance and discovery role with archaeological sites, raising fundamental issues about salvage, identification, protection and site management.

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; integrating science across disciplines, scales and cultures; and, responding to changing visitor interests and needs.

Regional Adaptation Resoruce:

- The Arctic Council (http://www.arctic-council.org/) and its working groups the Arctic Monitoring and Assessment Programme (AMAP; http://www.amap.no/) and the Conservation of Arctic Flora and Fauna (CAFF; https://www.caff.is/), are key sources of knowledge. The Arctic Council is an intergovernmental forum promoting cooperation, coordination and interaction among the Arctic States, Arctic indigenous communities and other Arctic inhabitants on common Arctic issues.
- The "*Arctic Resilience Report*" (Arctic Council, 2016) provides adaptation examples and case studies.
- "*What we know, don't know, and need to know about climate change in Inuit Nunangat*" provides a systematic review on climate change in the Arctic (Bolton et al., 2011).
- Pearce *et al.'s* (2011) review of climate change vulnerability in the Inuvialuit Settlement Region provides insights on advancing adaptation planning.
- "Sea Level Rise" (http://sealevelrise.ca/) is an Atlantic region website that supports community education about sea level rise and may be a helpful communication resource.

- The Coastal Archaeological Resources Risk Assessment (CARRA) project helps managers respond to coastal hazard impacts to archaeological resources (Pollard-Belsheim *et al.*, 2014).
- Groulx *et al.* (2014) studied place-based climate change adaptation in Churchill, Manitoba and presents a frame to support local values, communication and collective action.

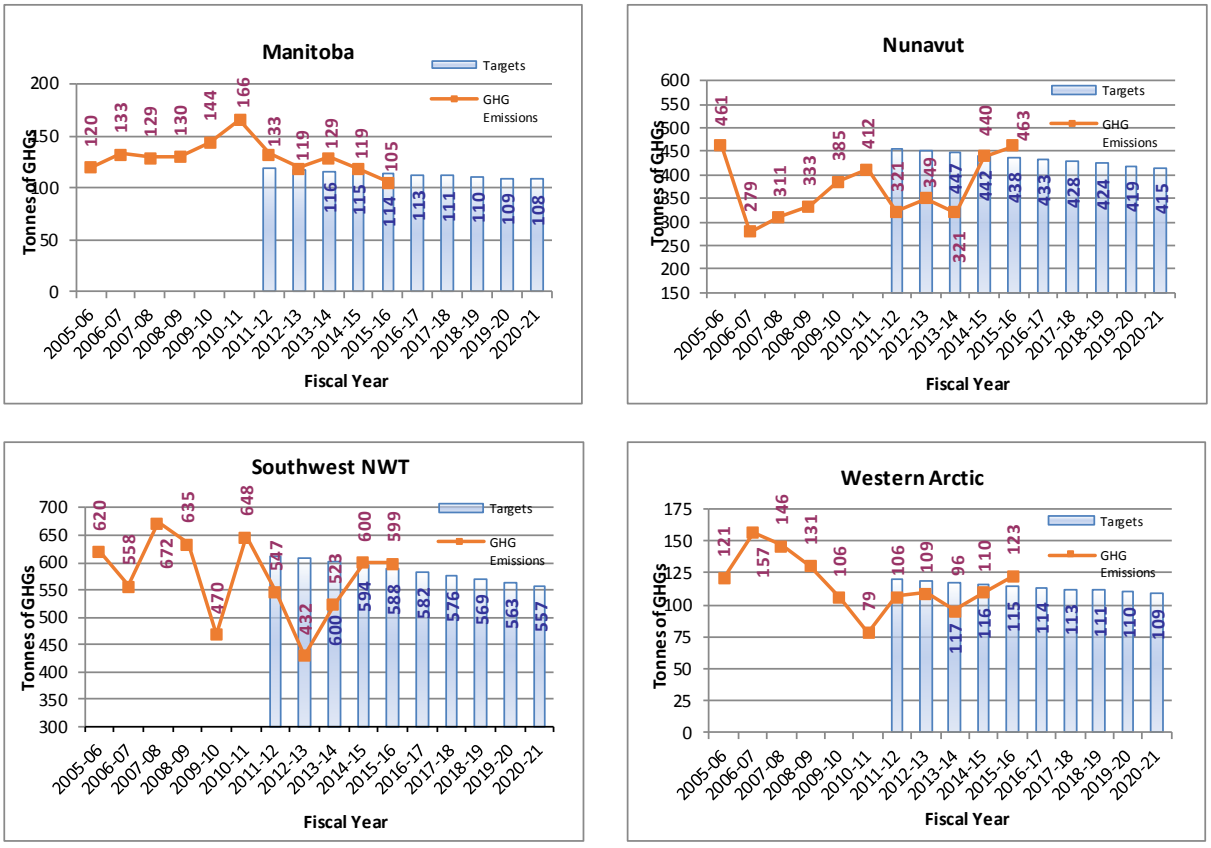
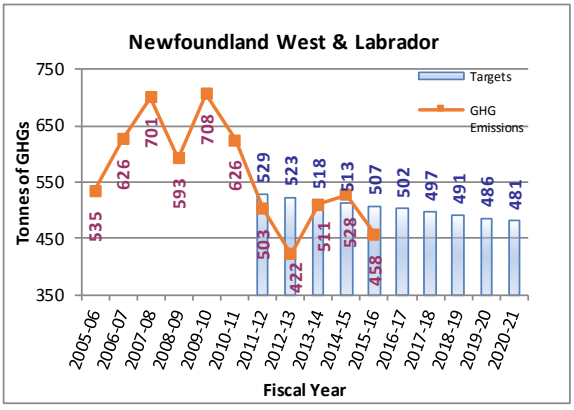


Figure 9. Greenhouse Gas Emissions per Field Unit. Emissions are calculated from energy (e.g., heating, electricity) and fuel expenditures, excluding travel, air charters, and some other sources. GHG emissions from energy cost are adjusted for source (e.g., coal, hydro, diesel, etc...). The targets in these figures are from 2015 reduction targets (Parks Canada, 2015). Revised, lower targets to be communicated in 2017 (Canada, 2016).



3.2 Mitigation

Mitigation refers to human interventions that reduce the source or enhance the sinks of GHG 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.
- Anti-idling and cabin heat-recovery systems in trucks.
- Use energy efficient products, promote energy efficiency and water conservation, reduce waste and support alternative transportation.
- Review Parks Canada (2015) and US NPS (2012a).

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 considered 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, coastal visualization) 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.

- ☑ Quantify and 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.

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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.

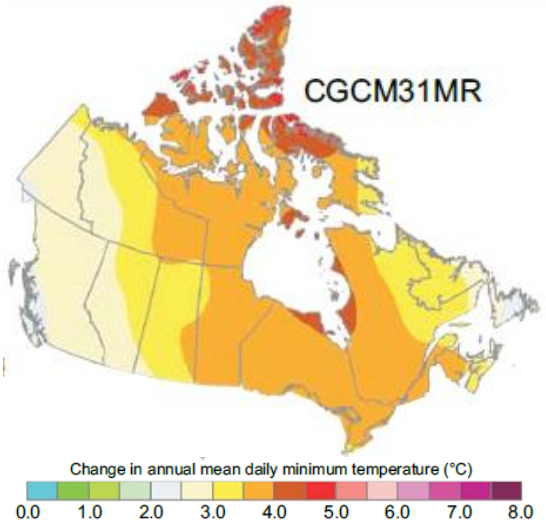

Figure A1. Projected change in annual daily minimum temperature for 2041-2070, relative to 1961-1990 (Price *et al.*, 2011).

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.

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