July 3, 2019

Supplemental Climate Information for Jasper National Park

Prepared by:

Scott Parker, Ph.D.
Office of the Chief Ecosystem Scientist

Parks Canada Parcs Canada

Contents

Preface

This is a supplement to the “Let’s Talks about Climate Change: Mountain Region” (Parker, 2017) report and is intended to support climate change discussions at Jasper National Park.

Future climate projections are modelled with several different greenhouse gas concentration trajectories called **Representative Concentration Pathways (RCP)** (Vuuren *et al.*, 2011). RCPs describe possible climate futures and are named after respective radiative forcing values in the year 2100 relative to pre-industrial values (i.e., +2.6, +4.5 and +8.5 watts/m^2). **RCP 2.6** assumes we take action and greenhouse gas emissions peak in 2010-2020 and decline thereafter. **RCP 4.5** assumes emissions peak around 2040 and then decline. **RCP 8.5** assumes we take no action and emissions continue to rise “status quo” throughout the 21st century. We are currently tracking RCP 8.5.

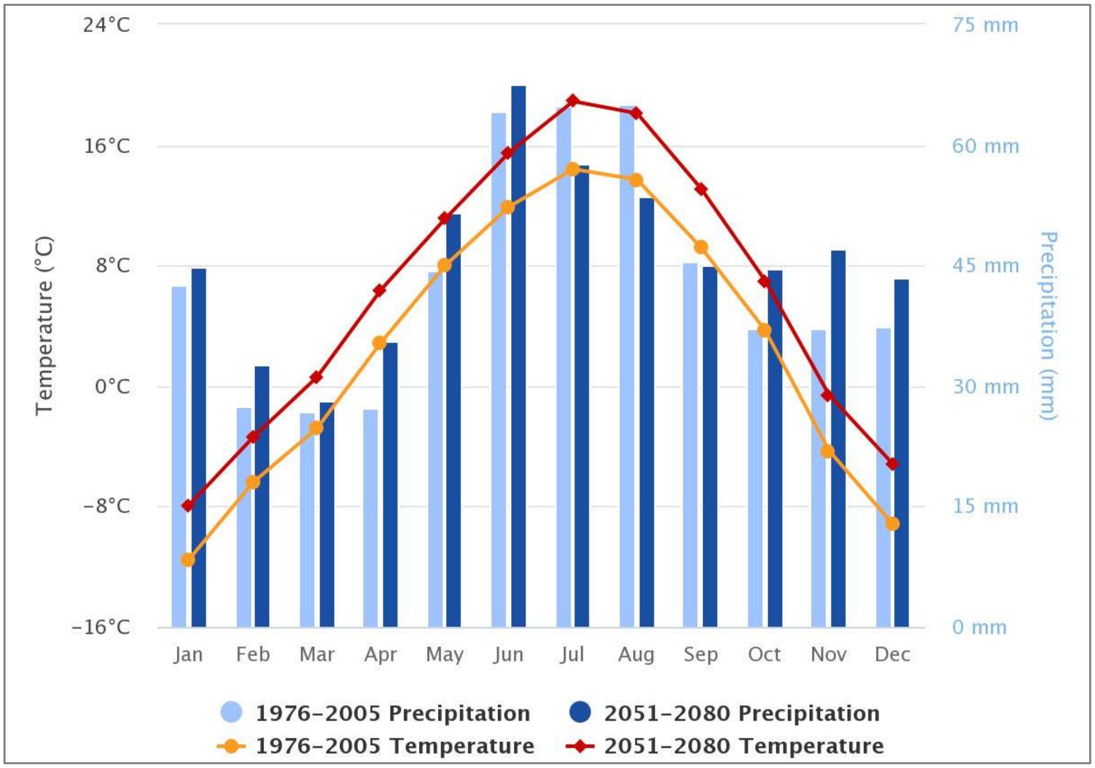
This is a site focussed document and to understand the larger climate change context please consult Canada’s changing climate assessment reports (e.g., Bush and Lemmen, 2019; Warren and Lemmen, 2014) and the Intergovernmental Panel on Climate Change assessment reports (e.g., IPCC, 2014). With respect to adaptation options, review Gross *et al.* (2016), Parker *et al.* (2018), or Rockman *et al.* (2016).

Disclaimer

Views, statements, findings and conclusions are solely those of the author and do not necessarily reflect the views and policies of Parks Canada. Although the author has made every effort to ensure that the information is accurate, complete and correct, neither Parks Canada nor the author can guarantee its integrity. Readers are encouraged to verify with original sources.

Summary Climograph

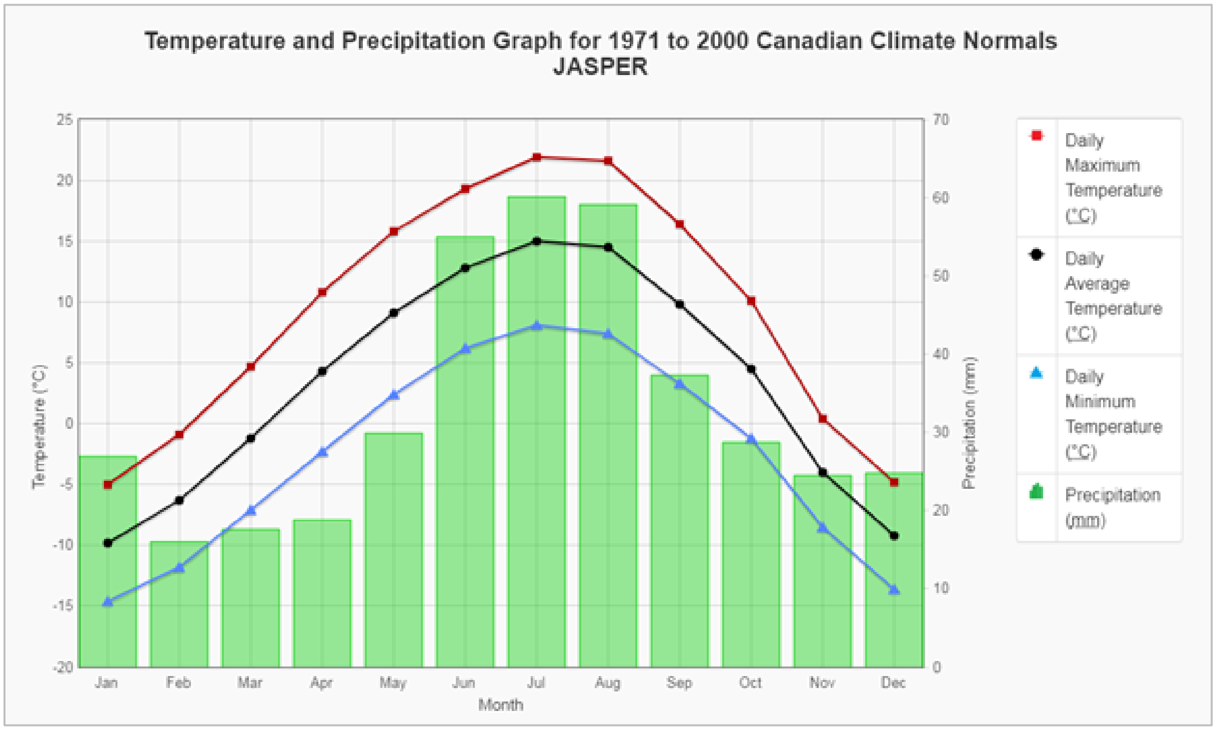
The climograph below illustrates average temperature and precipitation for both the baseline (1976-2005) and future (2051-2080) periods. In general, future temperatures are projected to be warmer for all months, and wetter for all months except July and August.



Climograph for the Municipality of Jasper. Modelled monthly mean temperature and total precipitation for the 1976-2005 baseline and 2051-2080 future projection (RCP 8.5). Figure source: Climate Atlas of Canada (https://climateatlas.ca/).

1. Historic Climate

Climate normals (1971-2000) for the Jasper meteorological station (ID 3053520; 52°53’N, 118°04’W; 1062.2m asl) report (http://climate.weather.gc.ca/climate_normals/) daily average temperatures from -9.8°C in January to 15.0°C in July, with an annual average of 3.3°C. July is reported as the wettest month and February the driest with an average of 60.1mm and 16.0mm of precipitation respectively and an annual total precipitation of 398.8mm. Climate normals are also available for the Jasper East Gate Station (ID 3063523; 53°14’N, 117°82’W; 1002.8m asl). Of interest, using a 1971-2000 baseline the average daily temperature for this station is 3.7°C and a total annual precipitation of 620.2mm, while using a 1981-2010 baseline the average daily temperature increase to 4.1°C and total annual precipitation decreases to 598.7mm.

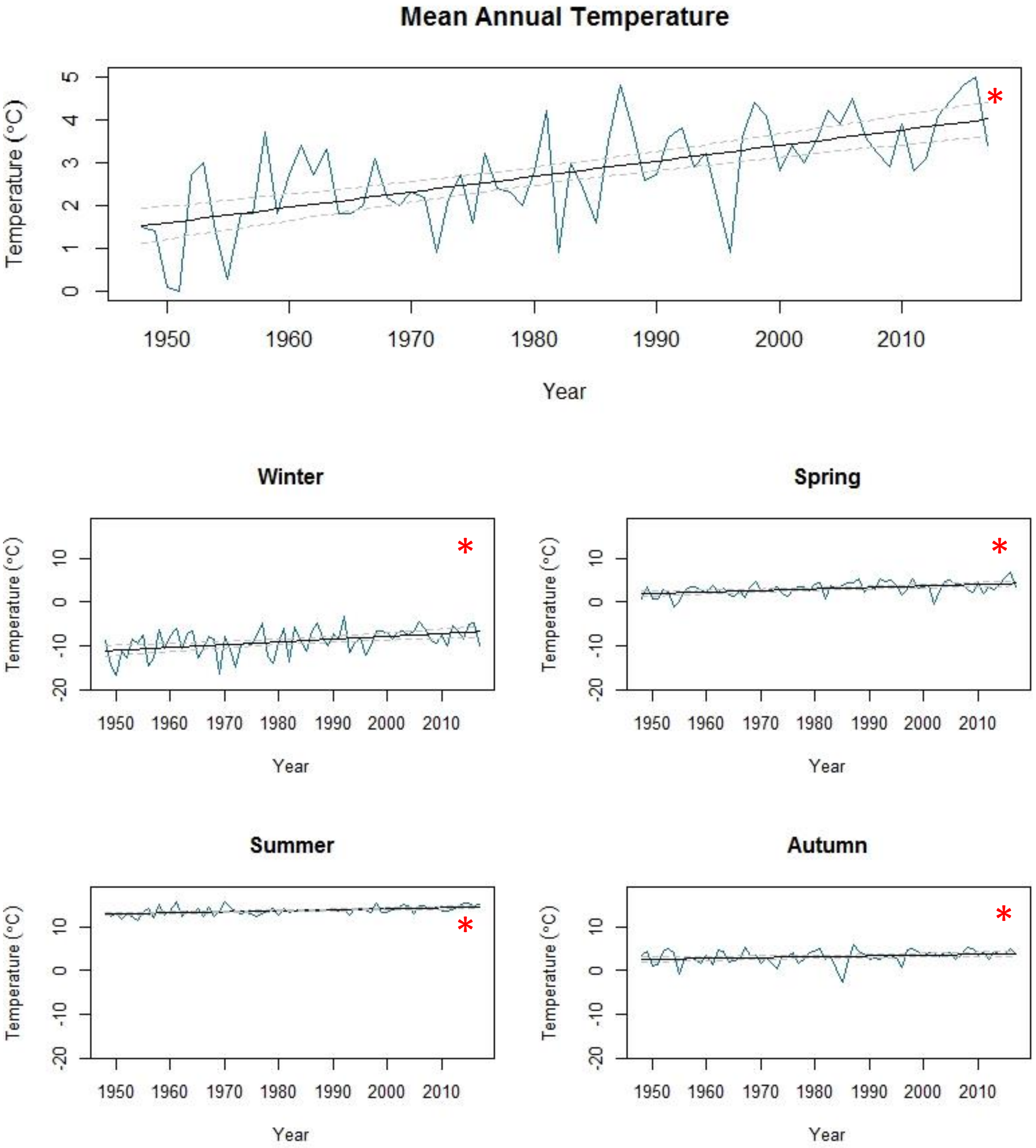


Climate normals (1971-2000) for Jasper (Station ID 3053520). Figure source: Environment and Climate Change Canada, http://climate.weather.gc.ca/climate_normals/.

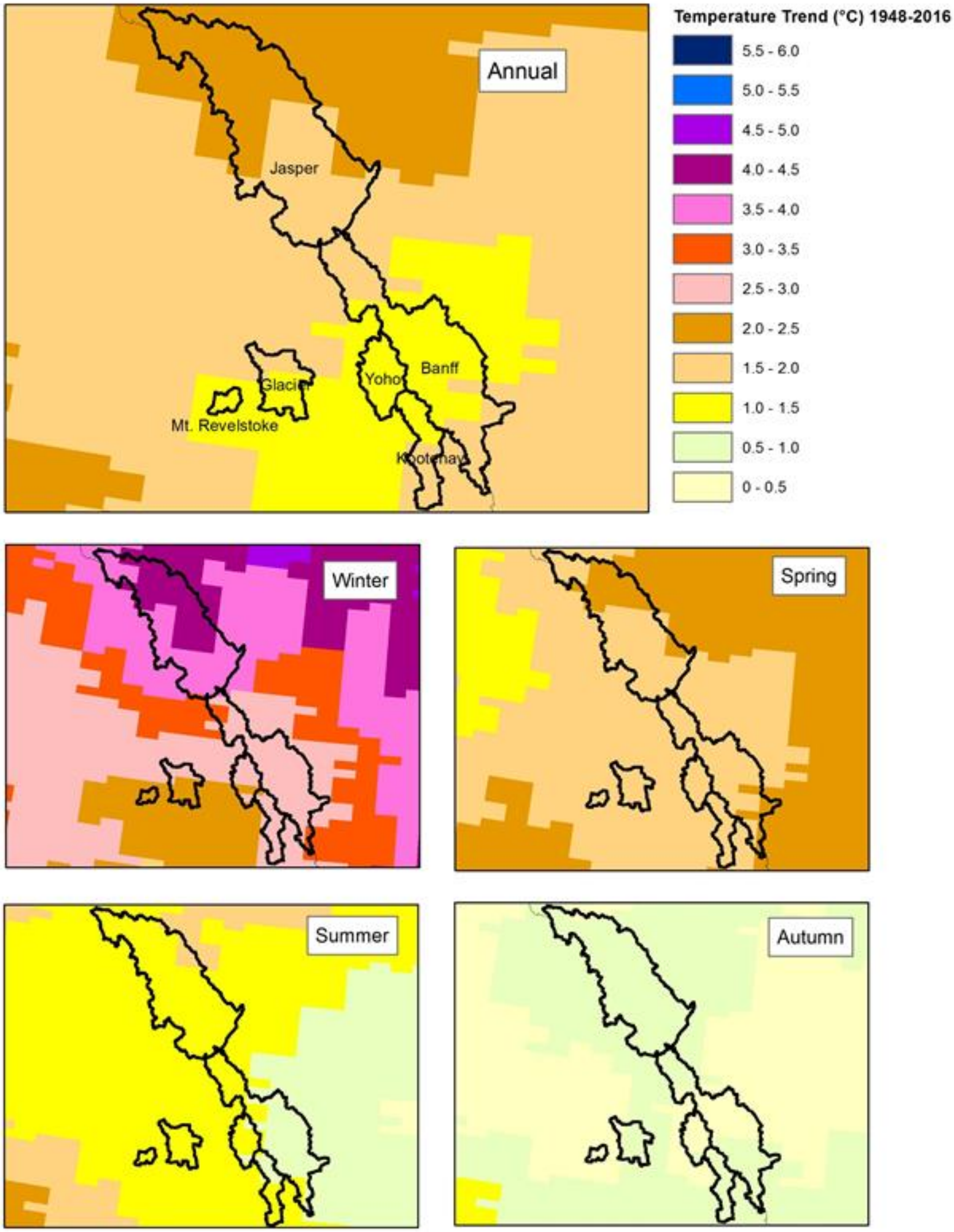
Climatic conditions in Jasper NP are influenced by latitude, elevation, slope, and aspect. For a detailed description of the regional climate, see Janz and Storr (1977). As an example of spatial variability, every 100m increase in elevation results in a decrease in air temperature by about 0.5°C, however temperature inversions are possible, such as when an arctic high-pressure system fills a valley (Gadd, 1986). The continuous high mountain range between Lake Louise and Jasper can produce heavy precipitation and a rain shadow effect can occur in the lower elevations to the east (e.g., between Jasper and the east gate) (Gadd, 1986). Southern aspects receive more solar radiation than northern aspects. As well, catabatic winds can flow off the glaciers and mountains, causing a downwind local cooling effect.

1.1 Temperature

Jasper (3053536) is the closest meteorological station with long-term temperature data (ECCC, 2017). Trends from 1948 to 2017 determined using a generalized linear model (R Core Team, 2017) including 95% confidence intervals. “*” = statistically significant trend ($P<0.05$).



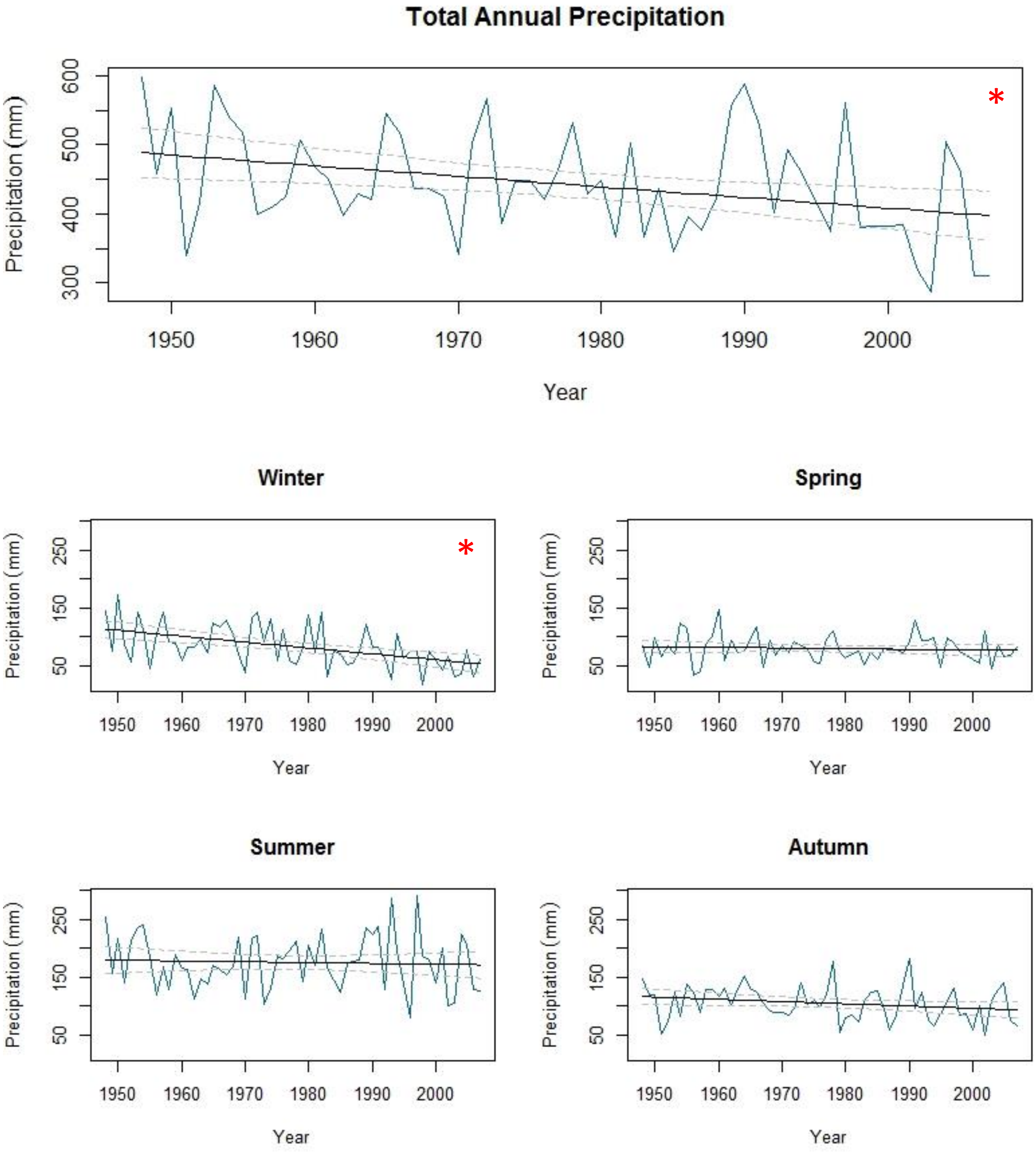
Jasper mean annual and seasonal temperature. A statistically significant ($P<0.05$) increase observed in mean annual and seasonal temperatures. Mean annual temperature has increased by 2.5°C since 1948. Of all the seasons, winter (Dec, Jan, Feb) temperature has increased the greatest, 4.4°C since 1948.



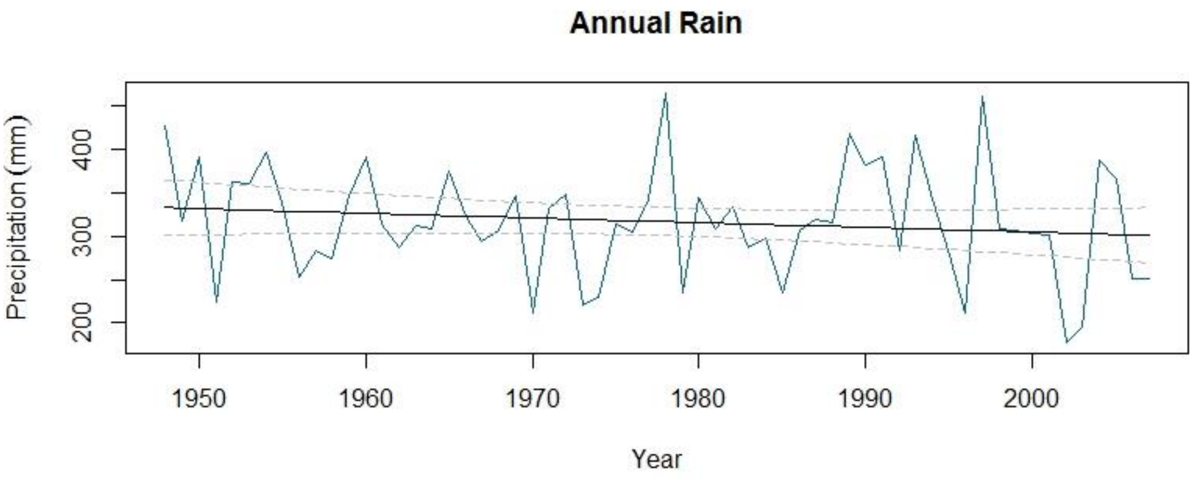
Change in mean annual and seasonal temperatures (˚C) for Jasper and other regional national parks from 1948 to 2016. Canadian gridded data (CANGRD): https://climate-change.canada.ca/climate-data/#/historical-gridded-data.

1.2 Precipitation

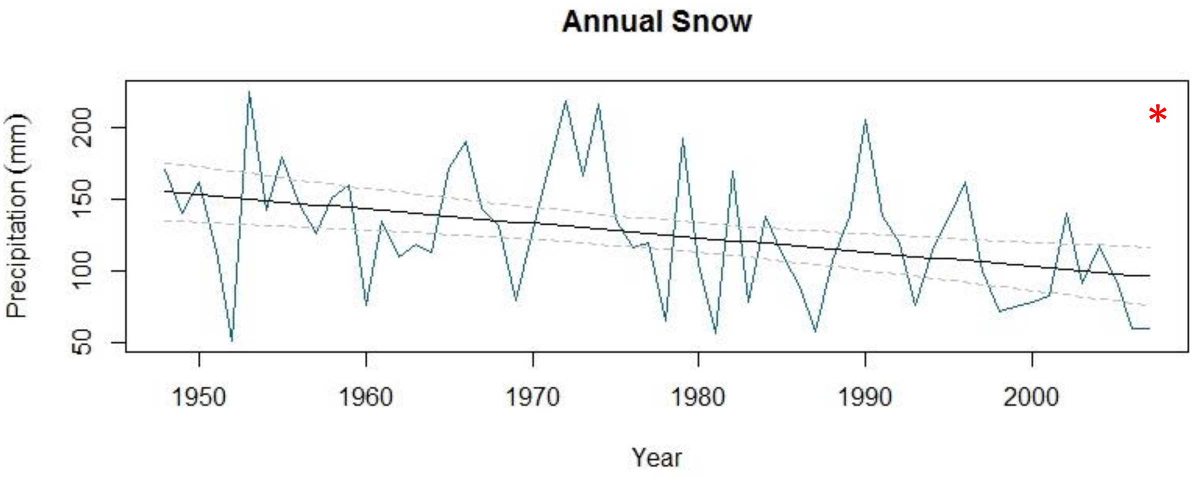
Jasper (8204800) is the closest meteorological station with long-term precipitation data (ECCC, 2017). Trends from 1948 to 2007 determined using a generalized linear model (R Core Team, 2017) including 95% confidence intervals. “*” = statistically significant trend (P<0.05).



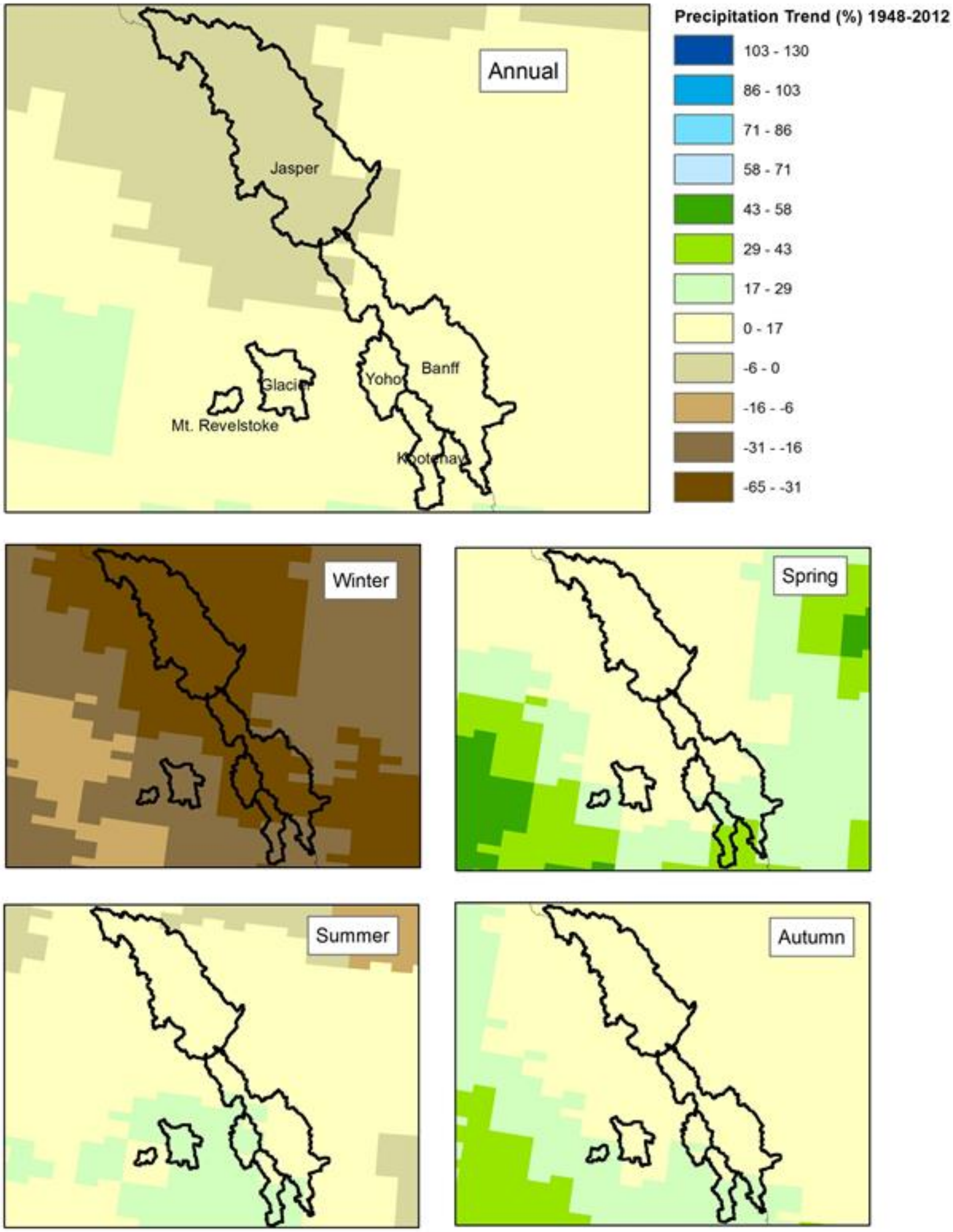
Jasper total annual and seasonal precipitation. Total annual precipitation demonstrated a statistically significant decrease (P<0.05), -90 mm (-19%) from 1948 to 2007. Winter (Dec, Jan, Feb) demonstrated a statistically significant decrease (P<0.05), -60 mm (-53%). The other seasons did not demonstrate a statistically significant trend (P<0.05).



Jasper annual rain did not demonstrate a statistically significant (P<0.05) trend between 1948 and 2007.



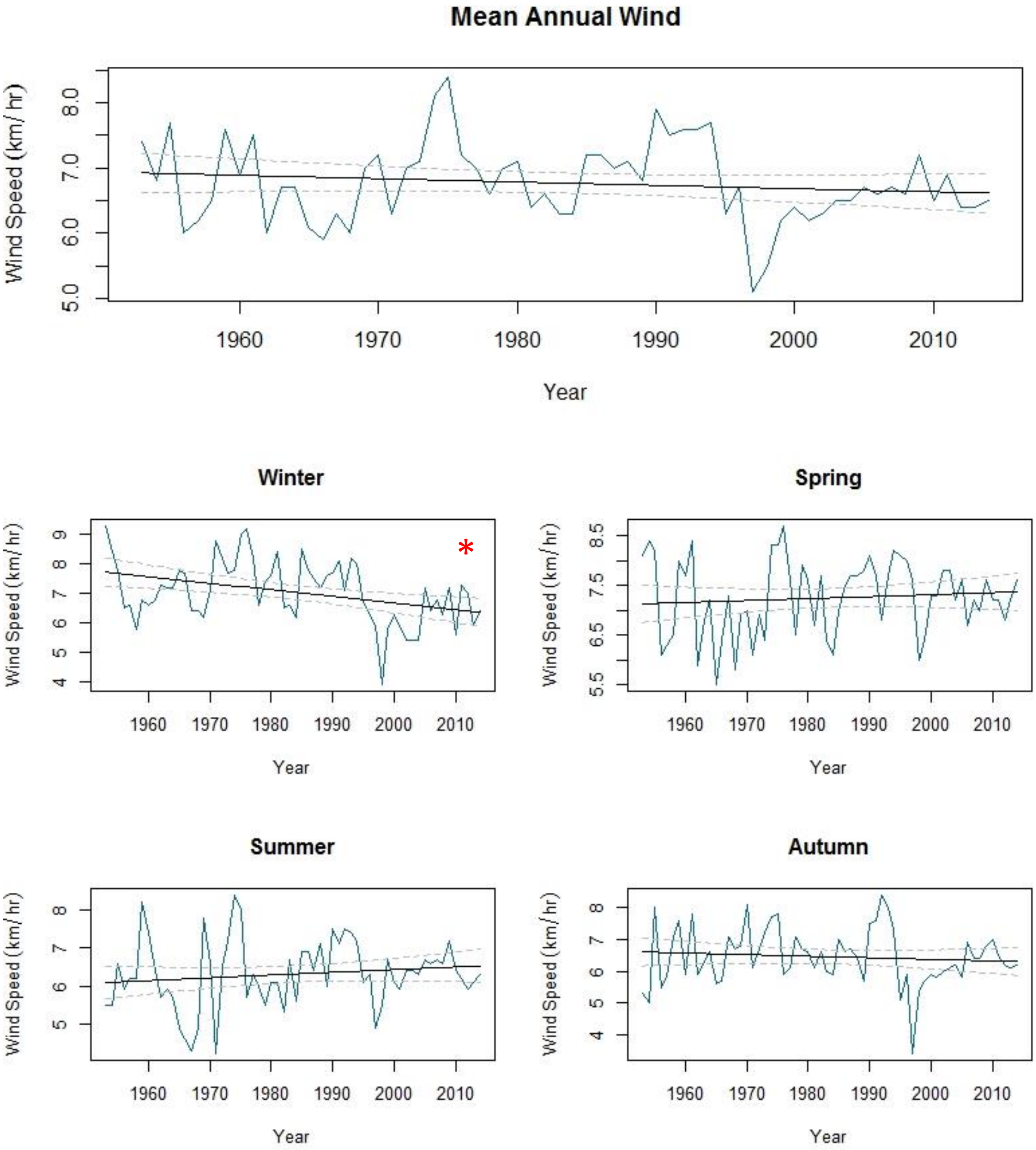
Jasper total annual snow demonstrated a statistically significant (P<0.05) decrease between 1948 and 2007, -58mm (-38%).



Percent change in total annual and seasonal precipitation for Jasper and other regional national parks from 1948 to 2012. Canadian gridded data (CANGRD): https://climate-change.canada.ca/climate-data/#/historical-gridded-data.

1.3 Surface Wind Speed

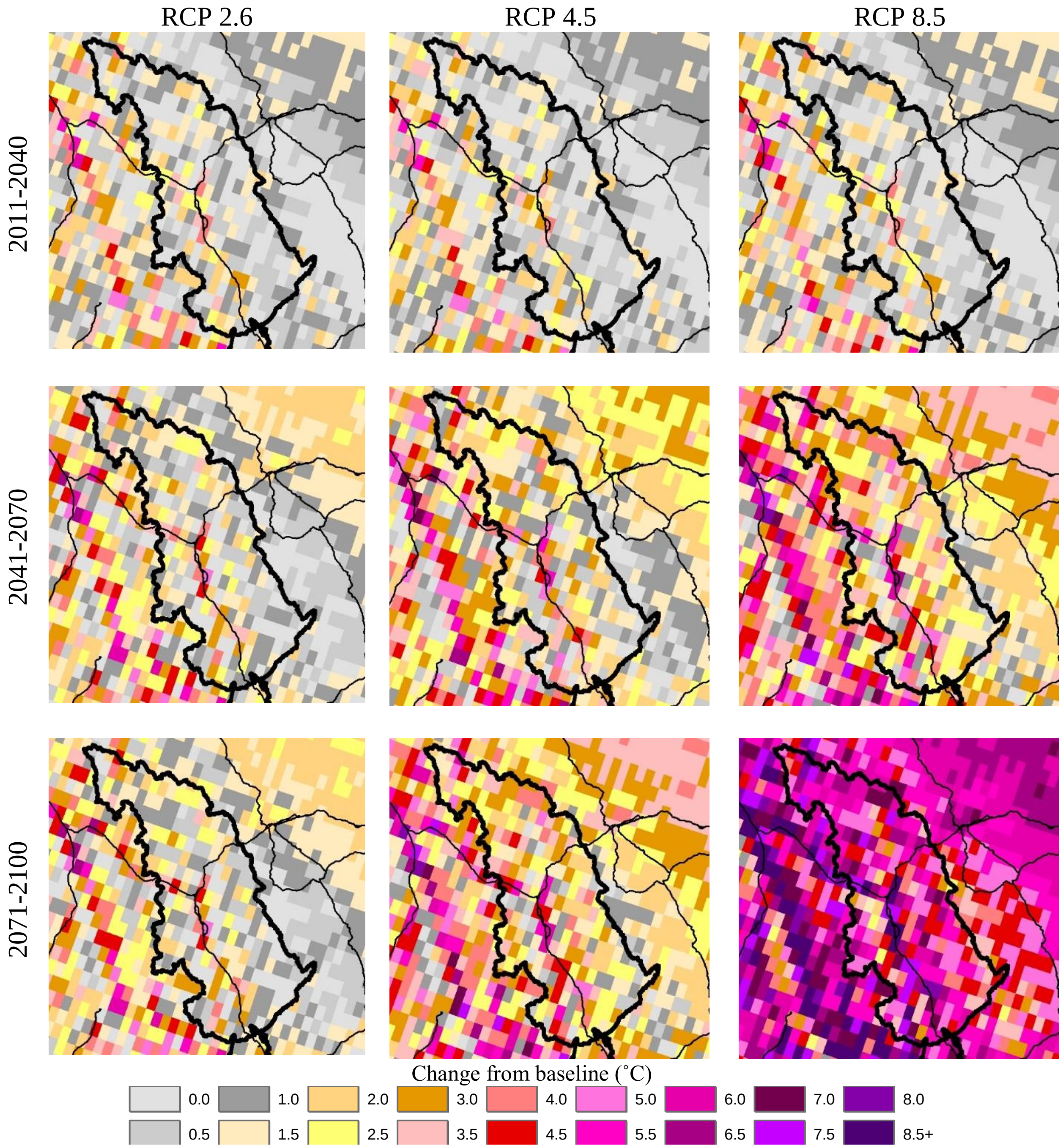
Jasper (3053520) is the closest meteorological station with long-term wind data (ECCC, 2017). Trends from 1953 to 2014 determined using a generalized linear model (R Core Team, 2017) including 95% confidence intervals. "*" = statistically significant trend ($P<0.05$).



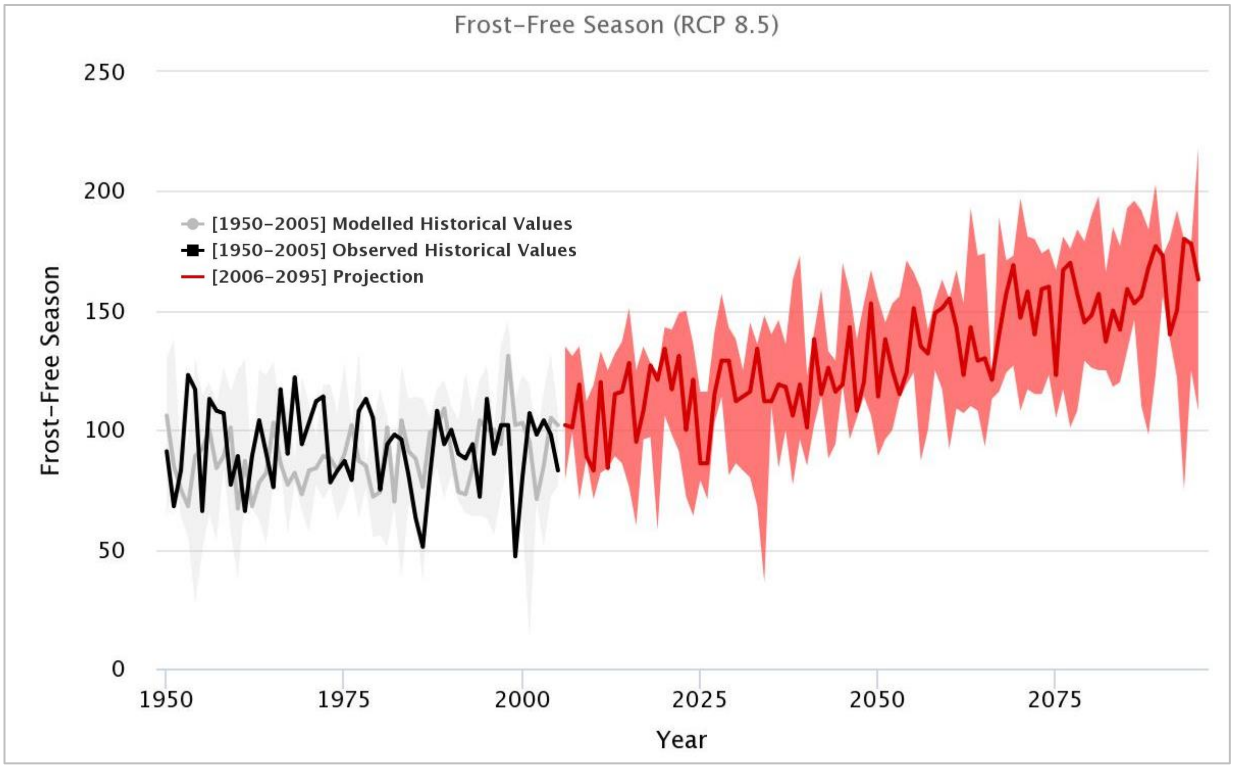
Jasper mean annual and seasonal wind speeds. Mean annual wind speeds did not demonstrate a statistically significant trend ($P<0.05$) between 1953 and 2014. Only winter (Dec, Jan, Feb) demonstrated a statistically significant trend ($P<0.05$), decreasing 1.4 km/hr (-18%) between 1953 and 2014.

2. Projected Climate Trends

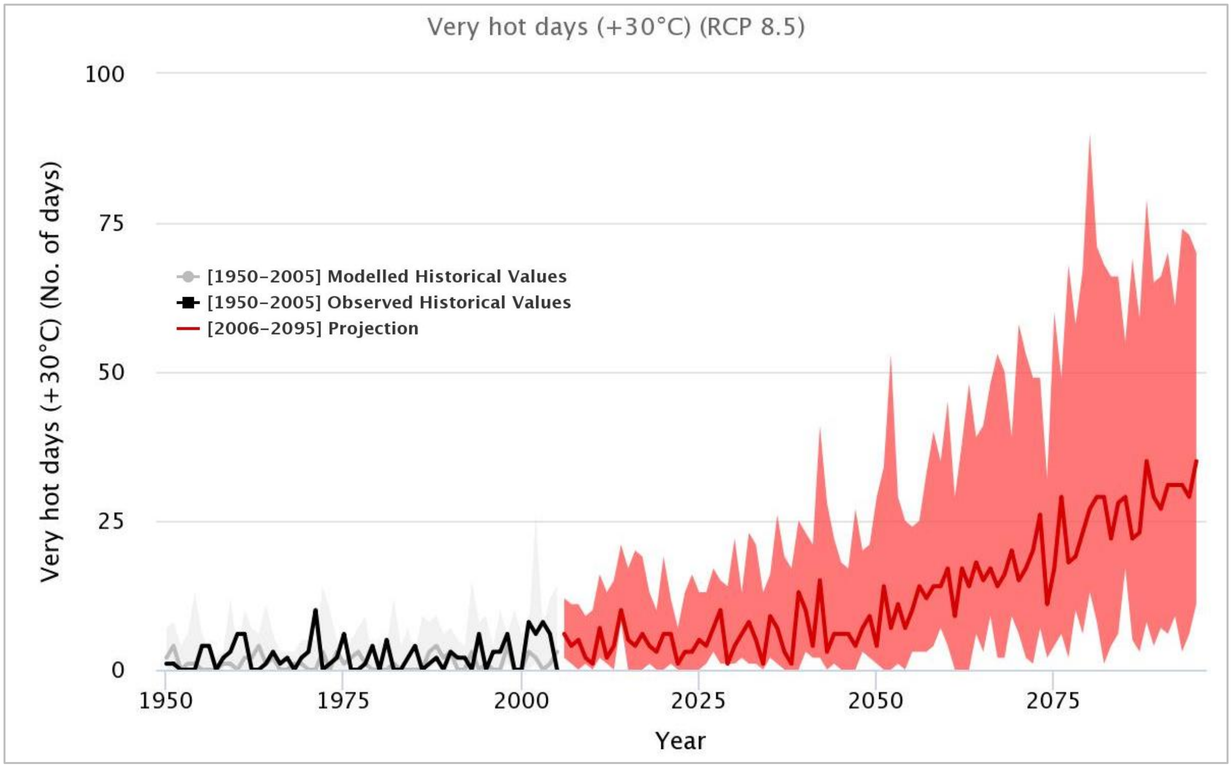
2.1 Temperature



Projected mean annual temperature increase for Jasper National Park from a 1980-2010 baseline. Composite projection of CanESM2, CESM1CAM5, HADGEM2ES and MIROCESM. Data source: Natural Resources Canada, Canadian Forest Service, http://cfs.nrcan.gc.ca/projects/3 (Price *et al.*, 2011). For some areas temperature increases could exceed 8.5°C.

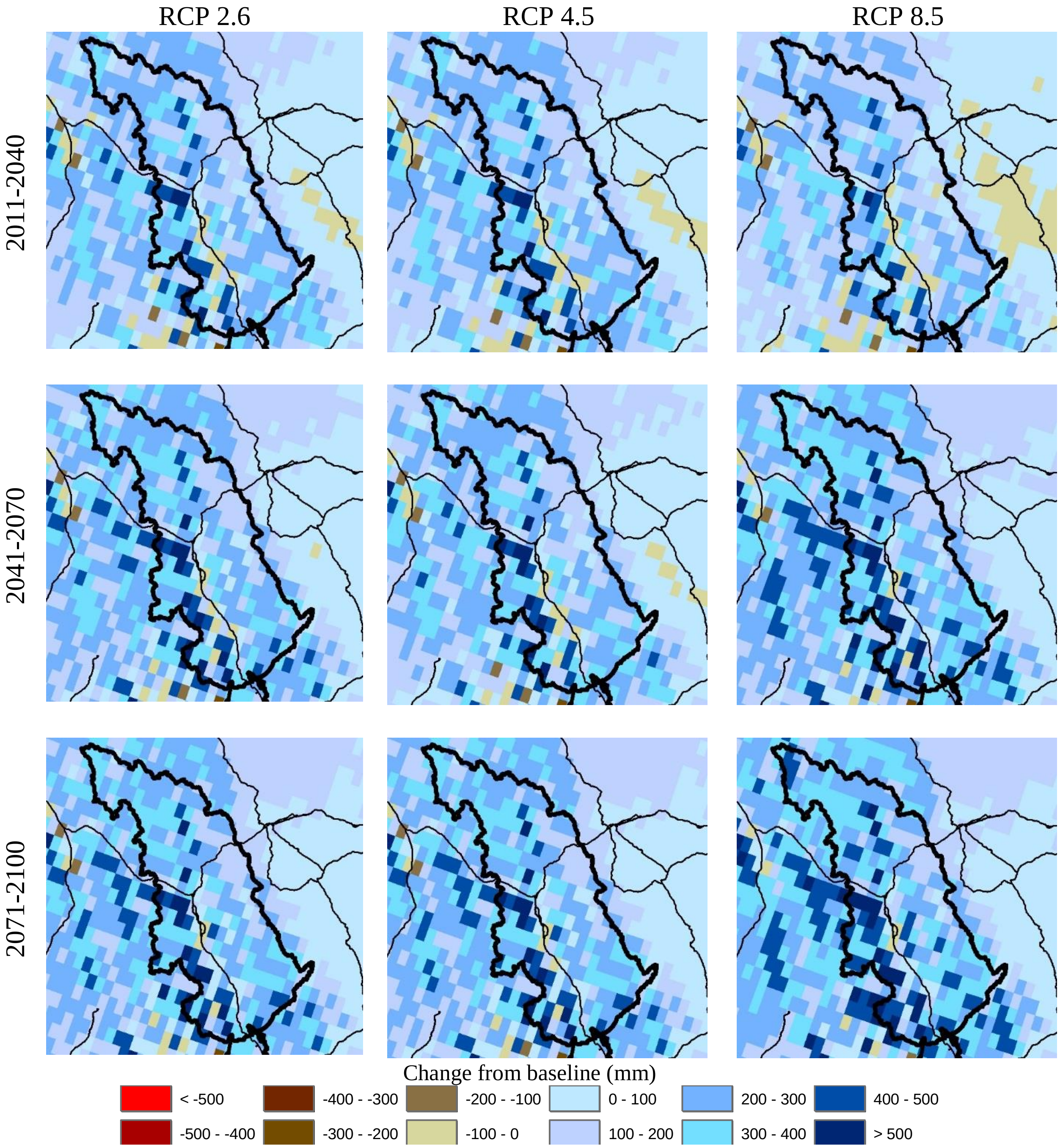


The frost-free season (days) for the Municipality of Jasper is projected to increase from a mean of 92.4 days from the 1976-2005 baseline to 143.5 days (+51 days) by 2051-2080 (https://climateatlas.ca/). Frost-free season approximates the length of growing season (i.e., no freezing temperatures to kill or damage plants).

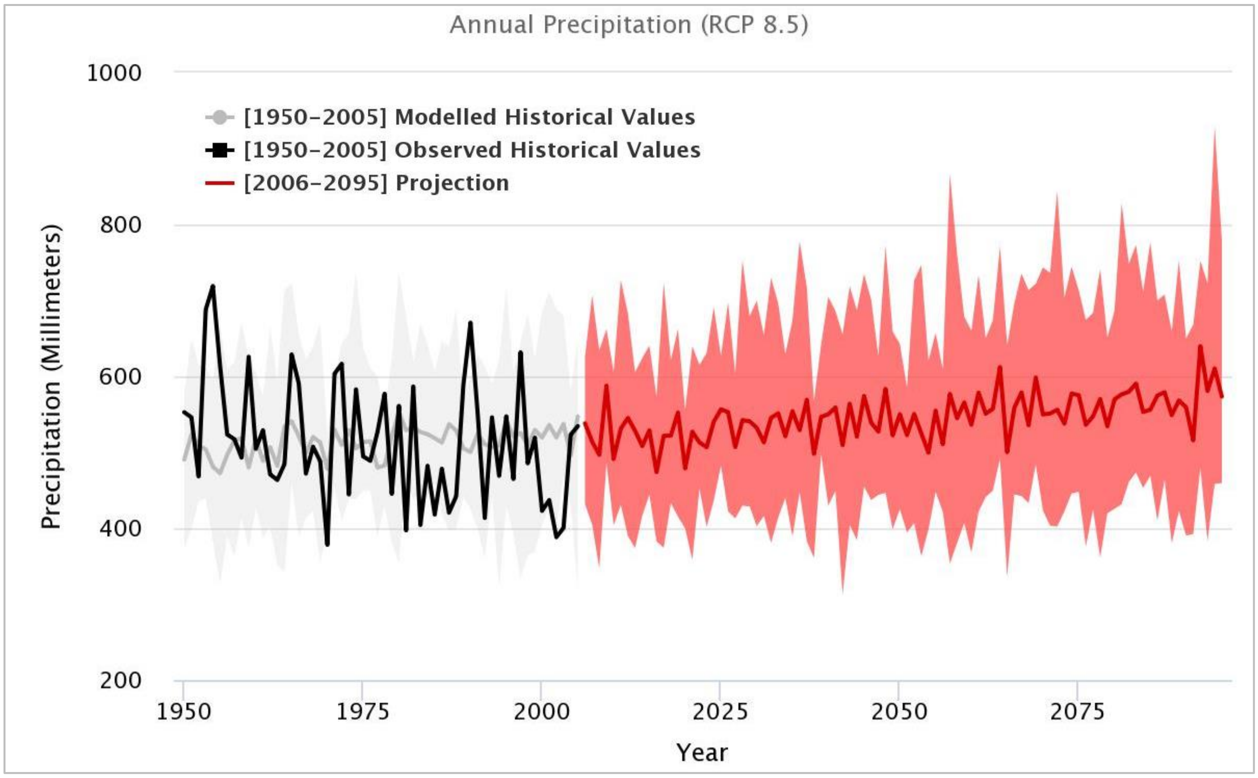


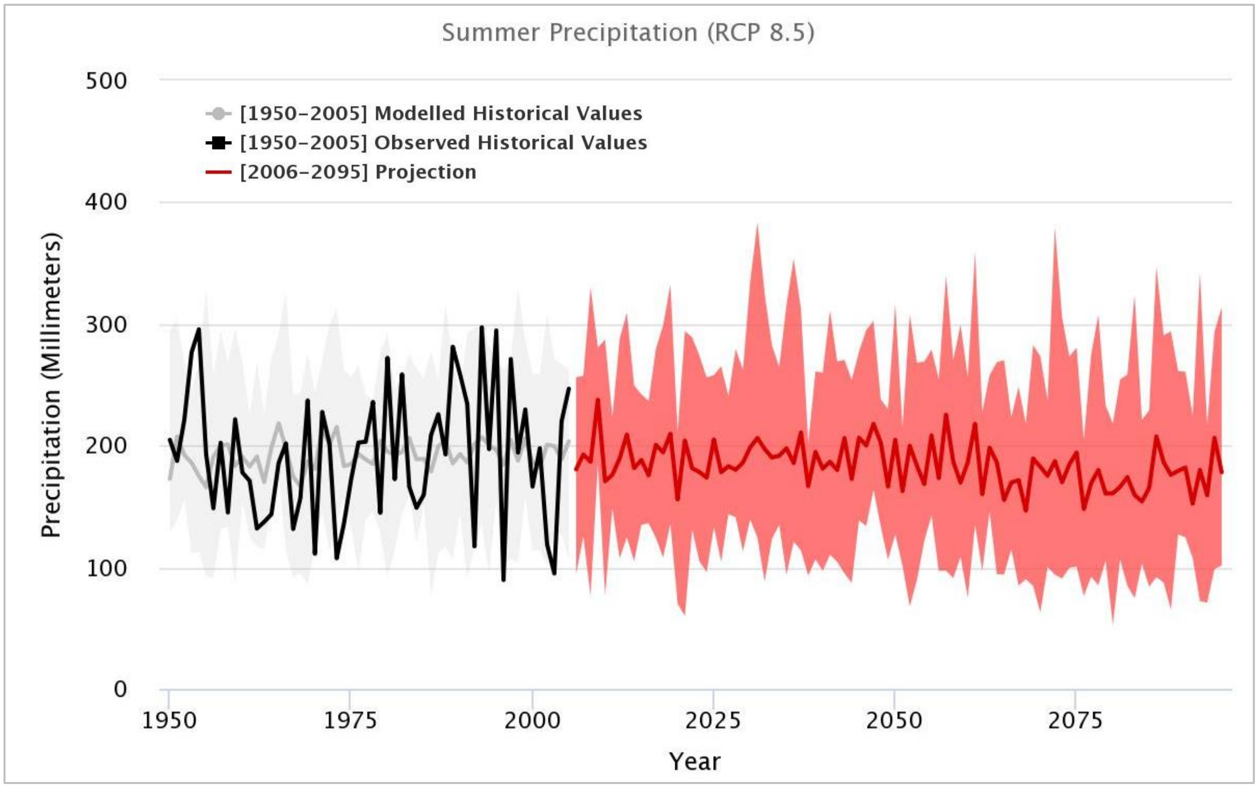
The number of very hot days (+30˚C) for the Municipality of Jasper is projected to increase from a mean of 1.2 days/year from the 1976-2005 baseline to 16.1 days/year by 2051-2080 (https://climateatlas.ca/).

2.2 Precipitation



Projected total annual precipitation change for Jasper National Park from a 1980-2010 baseline. Composite projection of four spatially interpolated downscaled Global Circulation Models: CanESM2, CESM1CAM5, HADGEM2ES and MIROCESM. Data source Natural Resources Canada, Canadian Forest Service, http://cfs.nrcan.gc.ca/projects/3 (Price *et al.*, 2011). For some areas precipitation increases could exceed 600 mm.



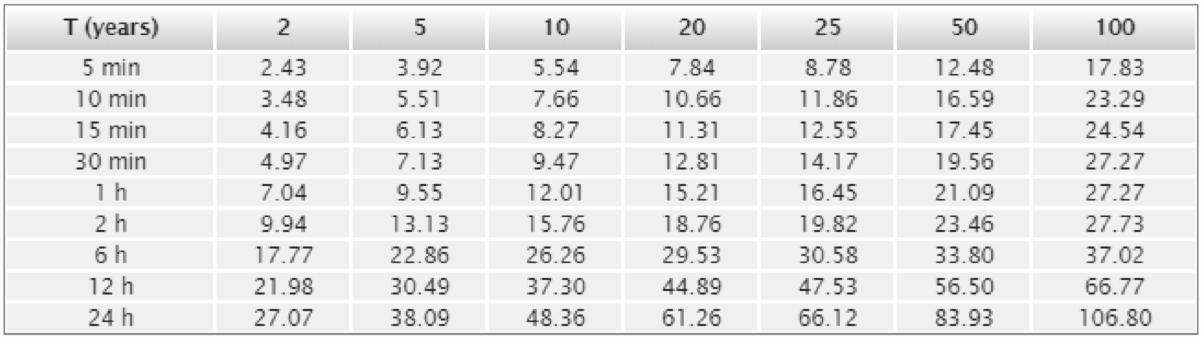


Total annual and summer precipitation days for the Municipality of Jasper. Annual is projected to increase slightly from 520mm to 552mm, while summer is projected to decrease slightly from 194mm to 179mm by 2051-2080 (https://climateatlas.ca/). See Appendix 1 for model variability.

Rainfall Intensity, Duration and Frequency (IDF)

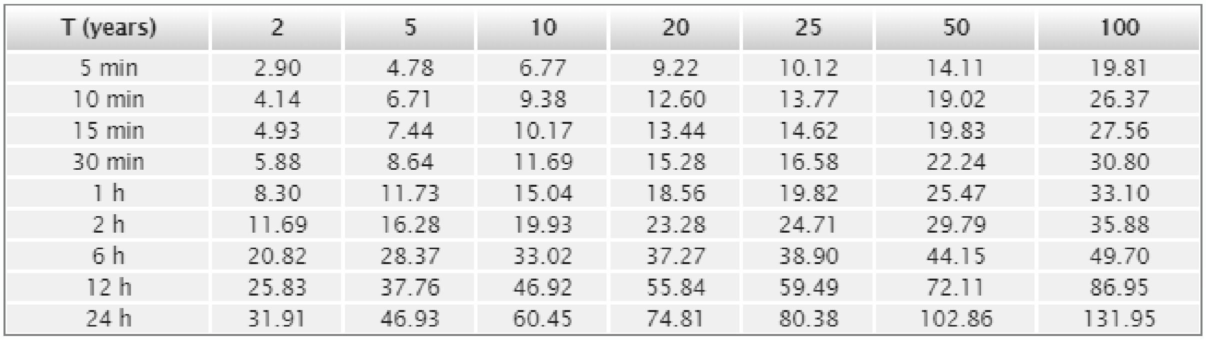
These rainfall IDF values are calculated with IDF_CC Tool 3.0 (http://www.idf-cc-uwo.ca/) using Generalized Extreme Values (Simonovic *et al.*, 2017).

Baseline total precipitation amounts (mm) for Jasper from 1963-1994.



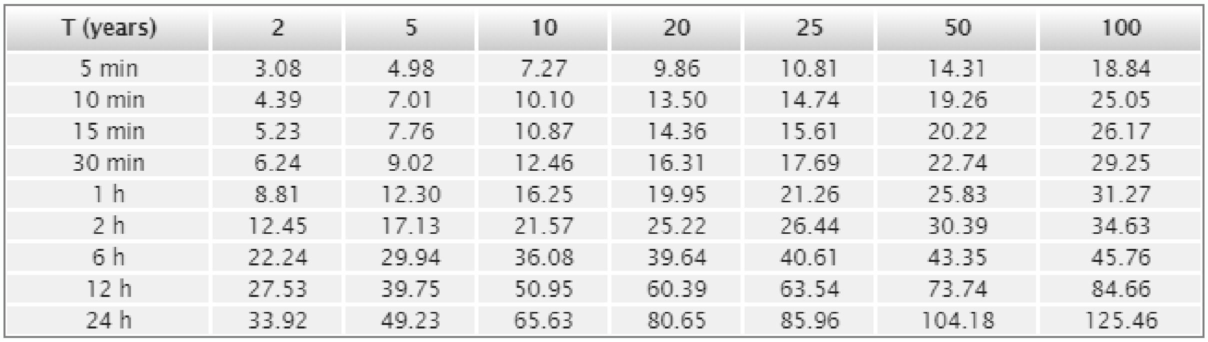
T (years)	2	5	10	20	25	50	100
5 min	2.43	3.92	5.54	7.84	8.78	12.48	17.83
10 min	3.48	5.51	7.66	10.66	11.86	16.59	23.29
15 min	4.16	6.13	8.27	11.31	12.55	17.45	24.54
30 min	4.97	7.13	9.47	12.81	14.17	19.56	27.27
1 h	7.04	9.55	12.01	15.21	16.45	21.09	27.27
2 h	9.94	13.13	15.76	18.76	19.82	23.46	27.73
6 h	17.77	22.86	26.26	29.53	30.58	33.80	37.02
12 h	21.98	30.49	37.30	44.89	47.53	56.50	66.77
24 h	27.07	38.09	48.36	61.26	66.12	83.93	106.80

Projected (2050-2100) precipitation (mm) for Jasper using an ensemble of models and **RCP 4.5**.



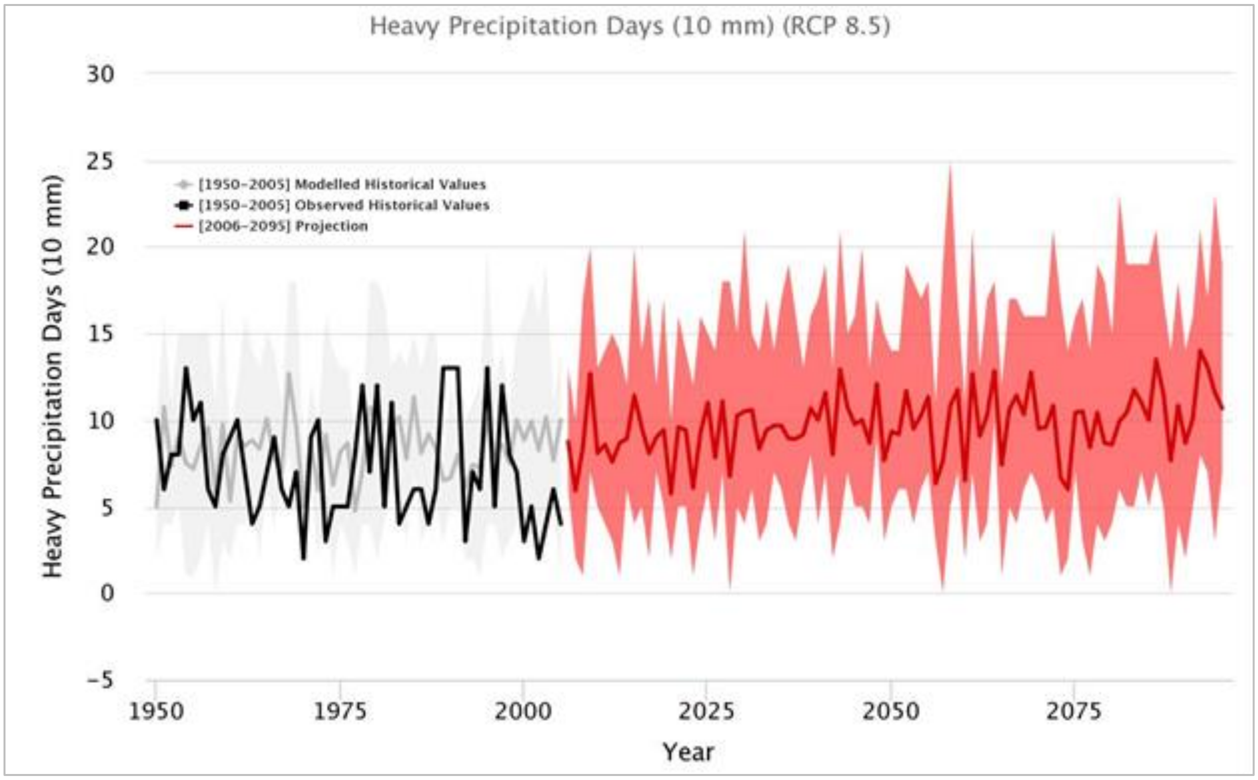
T (years)	2	5	10	20	25	50	100
5 min	2.90	4.78	6.77	9.22	10.12	14.11	19.81
10 min	4.14	6.71	9.38	12.60	13.77	19.02	26.37
15 min	4.93	7.44	10.17	13.44	14.62	19.83	27.56
30 min	5.88	8.64	11.69	15.28	16.58	22.24	30.80
1 h	8.30	11.73	15.04	18.56	19.82	25.47	33.10
2 h	11.69	16.28	19.93	23.28	24.71	29.79	35.88
6 h	20.82	28.37	33.02	37.27	38.90	44.15	49.70
12 h	25.83	37.76	46.92	55.84	59.49	72.11	86.95
24 h	31.91	46.93	60.45	74.81	80.38	102.86	131.95

Projected (2050-2100) precipitation (mm) for Jasper using an ensemble of models and **RCP 8.5**.



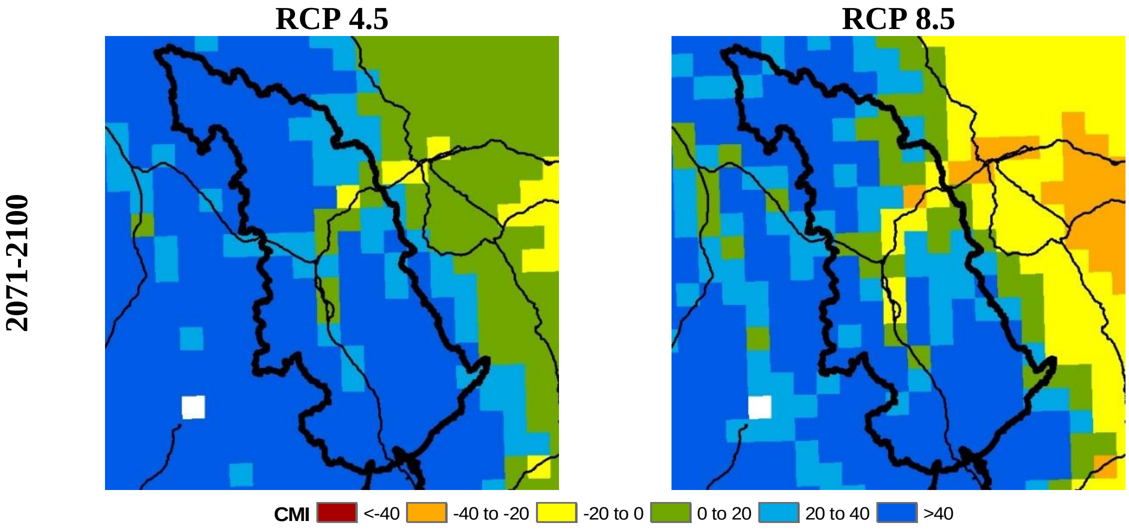
T (years)	2	5	10	20	25	50	100
5 min	3.08	4.98	7.27	9.86	10.81	14.31	18.84
10 min	4.39	7.01	10.10	13.50	14.74	19.26	25.05
15 min	5.23	7.76	10.87	14.36	15.61	20.22	26.17
30 min	6.24	9.02	12.46	16.31	17.69	22.74	29.25
1 h	8.81	12.30	16.25	19.95	21.26	25.83	31.27
2 h	12.45	17.13	21.57	25.22	26.44	30.39	34.63
6 h	22.24	29.94	36.08	39.64	40.61	43.35	45.76
12 h	27.53	39.75	50.95	60.39	63.54	73.74	84.66
24 h	33.92	49.23	65.63	80.65	85.96	104.18	125.46

Jasper (52.88°N, 118.07°W) IDF observations and projections. Observe that today's "one in 100 year" rainfall event (i.e., 27.27 mm/hr) is projected to be closer to a "one in 50 year" event by 2050-2100 and the future "one in 100 year" rainfall event is only projected to increase slightly in intensity (i.e., 31.27 – 33.10 mm/hr).



The number of heavy precipitation days (>10mm) for the Municipality of Jasper is projected to increase slightly from a mean of 8.5 days for the 1976-2005 baseline to only 9.7 (+1.2 days) by 2051-2080 (https://climateatlas.ca/).

Climate Moisture Index



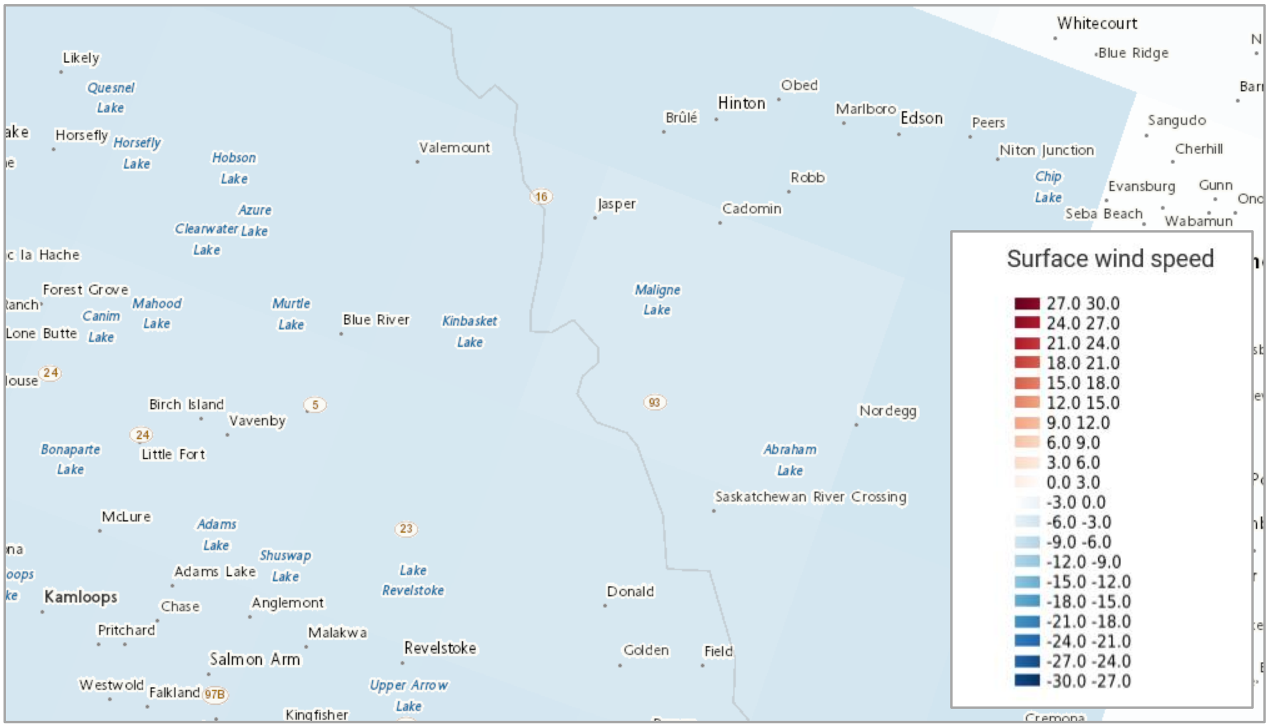
Climate Moisture Index (CMI) is calculated as the difference between annual precipitation and potential evapotranspiration – the potential loss of water vapour from a landscape covered by vegetation (http://www.nrcan.gc.ca/forests/climate-change/forest-change/17772). A positive CMI value indicates wet or moist conditions and a negative indicates dry conditions.

2.3 Wind

The Coupled Model Intercomparison Project Phase 5 (CMIP5) models generally project a slight decrease in mean annual and seasonal surface wind speeds for the region. The data can be accessed and viewed from several sources, including:

- http://climate-scenarios.canada.ca
- https://gcgeo.gc.ca/geonetwork
- https://climate-viewer.canada.ca

However, Cheng *et al.* (2014) project that the frequency and intensity of wind gust events will increase slightly for the region.



Projected decrease in mean annual wind speed in 2046-2065 from 1986-2005 expressed as percentage change (%) (RCP 8.5). Figure source: https://climate-viewer.canada.ca/

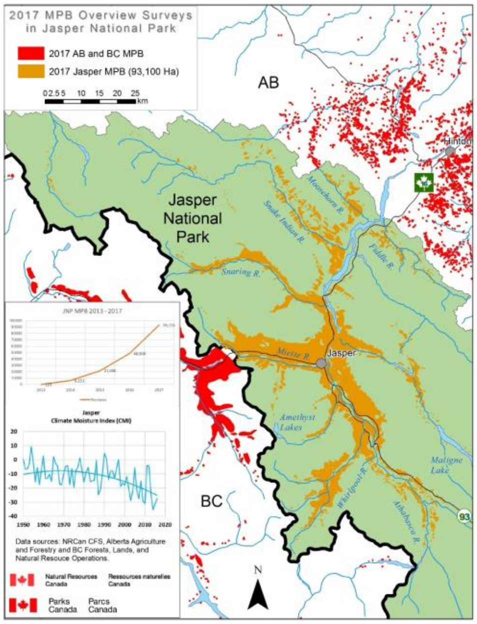
3. Climate Change Impacts

3.1 Species and Ecosystems

In general, the effects of climate change on biodiversity include: shifts in species distribution; changes in phenology; decoupling of interactions (plant-pollinator); reductions in population size; species extinction and extirpation; habitat loss; increased disease and spread of invasive species; competitive exclusion; and, change to ecosystem services (Nantel *et al.*, 2014; Nitsch and Bowman, 2013). Some more specific regional effects include:

- Jones *et al*. (2017) studied stream temperatures in the Crown of the Continent and have reported warming trends and seasonal shifts. Messner *et al.* (2013) reported on impacts of warming waters, introduced brook trout (*Salvelinus fontinalis*) and an increase in zooplankton diversity in the region. In general, increasing stream and lake temperatures (e.g., less glacial inputs, warmer air temperature) will alter habitat conditions and may exceed the thermal tolerance for some cold/cool-water fishes (e.g., Poesch *et al.*, 2016), insects (e.g., Treanor *et al.*, 2013) and plankton communities (e.g., Hobbs *et al.*, 2011; Messner *et al.*, 2013; Strecker *et al.*, 2004).
- Climate change will influence environmental chemistry and pollutants, including an exacerbation of the effects of acid deposition (e.g., lower pH due to higher CO_2 levels), nutrient loading (e.g., intense precipitation/runoff events), and mercury toxicity (e.g., released under anoxic conditions, warmer waters increase the rate of methylation) (e.g., Michalak, 2016; Noyes *et al.*, 2009).
- Roberts *et al.* (2014) report on a change in grizzly bear (*Ursus arctos*) habitat due to climate change, including a general uphill migration of food resources.
- Pika (*Ochotona princeps*), water vole (*Microtus richardsoni*), and least chipmunk (*Tamias minimus oreocetes*) could be threatened as a result of disappearing tundra habitat (e.g., Otto *et al.*, 2015). In addition, pikas appear to lack the physiological ability to cope with high ambient temperatures (e.g., >28°C) (Otto *et al.*, 2015). Mountain sheep, goats and elk all move upslope to graze in alpine tundra during summer and could be affected by a loss of habitat and foraging resources.
- Climate change is cited as a potential factor contributing to caribou (*Rangifer tarandus caribou*) decline (COSEWIC, 2014; Festa-Bianchet *et al.*, 2011). For Jasper NP, Bradley and Neufeld (2012) discuss the interaction of climate and wildlife management in caribou decline.
- Potential bird species turnover for Jasper NP between now and 2050 is 26% of summer residents and 18% of winter residents (see Appendix 2.; Parker *et al.*, 2019).
- An upslope migration of the alpine treeline was reported by Brown (2013) at rates between 0.23 and 1.8 m/yr in the Kanasaskis study area and Roush (2004) at rates of 2.2 m/yr in Kootenay NP. However, it is important to note that species migration is a variable and complex process, influenced by factors such as dispersal mechanisms, soil suitability, solar radiation, soil temperature, permafrost, moisture regimes, etc… (e.g., Davis and Gedalof, 2018; Luckman and Kavanagh, 2000).
- A subsequent reduction or loss of alpine tundra and meadow ecosystems may be a concern in some areas (e.g., Illerbrun and Roland, 2011).
- A change in the composition and structure of high elevation forests is suggested due to warming and a reduction in post-fire tree seedling establishment. A compensatory increase is expected from montane species moving upslope (e.g., alpine larch, Douglas fir, trembling aspen) and upper treeline species whitebark pine (Harvey *et al.*, 2016). However, whitebark pine colonization may be compromised by blister rust (*Cronartium ribicola*) (Tomback *et al.*, 2014).
- Climate change is expected to facilitate the expansion of invasive species, for example, conditions in this region may become suitable for plant species such as African rue and brown knotweed (Chai *et al.*, 2016).
- Floodplain forests may be reduced in some reaches due to declining summer flows (Rood *et al.*, 2008).

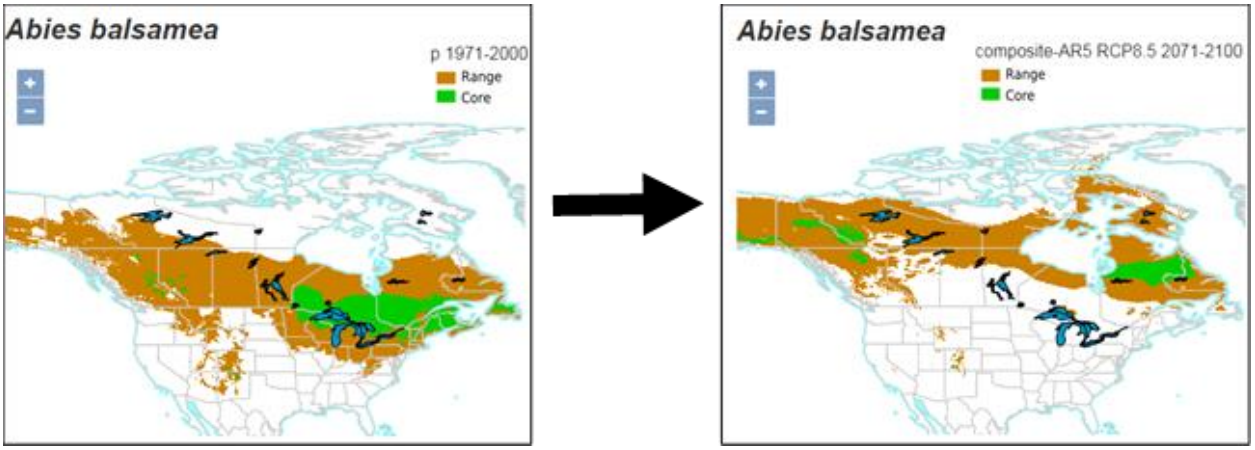
- Drought stress (e.g., 2015 drought in Jasper NP) is linked to declines in aspen and low-elevation spruce forests (Brett, 2018; Hogg *et al.*, 2008; Worrall *et al.*, 2013). Increasing aridity may decrease dominance of spruce, fir, western hemlock, etc… in favour of species such as ponderosa pine, aspen, etc… (Hogg and Bernier, 2005). In extreme events, even drought-resistant parkland species may be replaced by scrub or grassland (Allen *et al.*, 2010; Michaelian *et al.*, 2011).
- Decline in whitebark pine is attributed to infections by white pine blister rust and mountain pine beetle infestations, combined with the effects of climate change and fire suppression (Shepherd *et al.*, 2018).
- A warmer climate is expected to be more favourable for forest insect and disease outbreaks such as mountain pine beetle, western spruce budworm, spruce beetle, forest tent caterpillar, etc… (e.g., Gauthier *et al.*, 2014; Haughian *et al.*, 2012; Sturrock *et al.*, 2011; Weed *et al.*, 2013). Brett (2018) provides an update on the extent and status of forest insect and disease in Jasper NP.
- Climate change and fire suppression are recognized factors contributing to the mountain pine beetle outbreak in Jasper NP (e.g., Bentz *et al.*, 2010; Jasper National Park, 2016).



Plant Hardiness

Plant Hardiness is associated with probabilities of plant survival in relation to average, broad scale climatic conditions. As the climate changes, habitat suitability for plant species also changes (McKenney *et al.*, 2001; McKenney *et al.*, 2014; McKenney *et al.*, 2011).

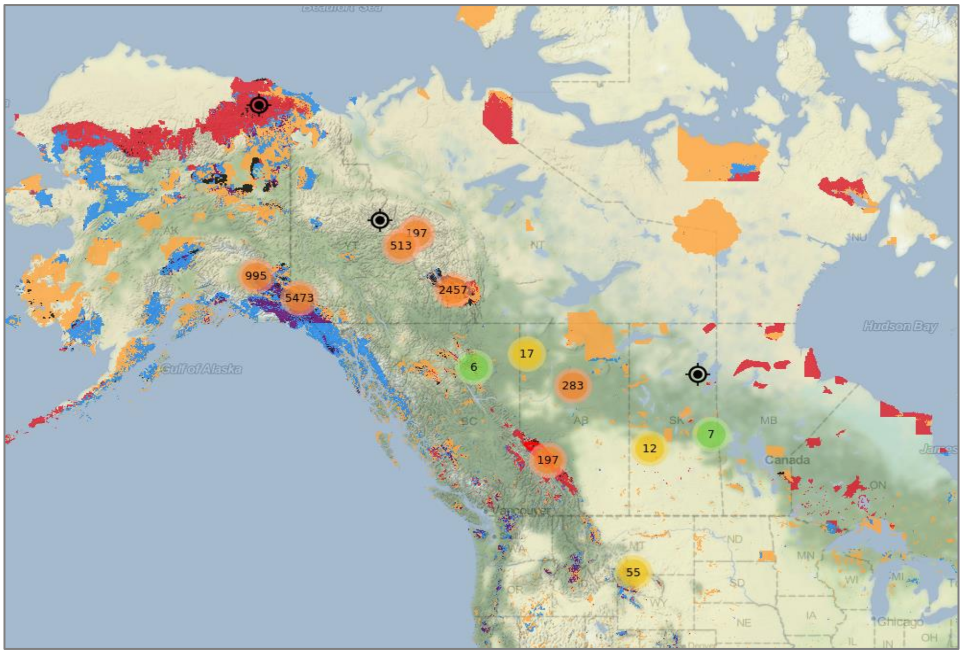
Table below summarizes species climatic distribution based on the Current and ANUCLIM Composite-AR5, RCP8.5 maps and models in the Plant Hardiness of Canada database (http://planthardiness.gc.ca/). Some species may be identified as being within their current climatic range, but may not actually be present in the area. While some of the species reviewed were worsening, no species was projected to be extirpated.



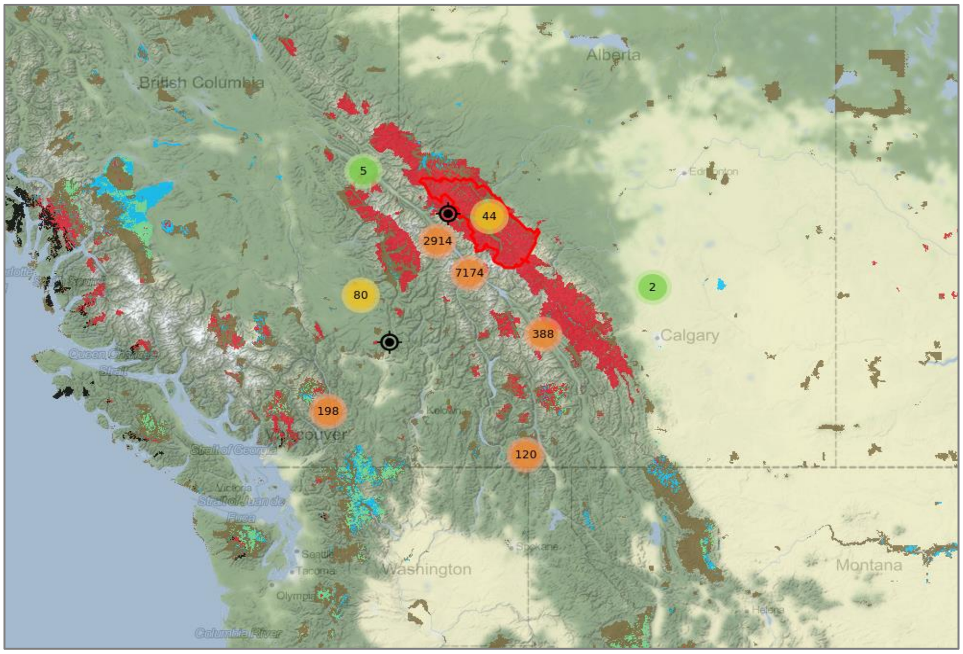
Common Name	Scientific Name	Current Range	2041-2070 Range	Trend by 2070	2071-2100 Range	Trend by 2100
Alpine fir	Abies lasiocarpa	Core	Core	Stable	Core	Stable
Alpine Larch	Larix lyallii	Core	Core	Stable	Range	Worsening
Aspen Poplar	Populus tremuloides	Range	Core	Improving	Range	Stable
Balsam Fir	Abies balsamea	Range	Core	Improving	Range	Stable
Balsam Poplar	Populus balsamifera	Range	Core	Improving	Range	Stable
Black Cottonwood	Populus trichocarpa	Range	Core	Improving	Core	Improving
Black Spruce	Picea mariana	Core	Range	Worsening	Range	Worsening
Bog Birch	Betula pumila	Core	Range	Worsening	Range	Worsening
Douglas Fir	Pseudotsuga menziesii	Range	Range	Stable	Core	Improving
Glandular Birch	Betula glandulosa	Core	Range	Worsening	Range	Worsening
Jack Pine	Pinus banksiana	Range	Range	Stable	Range	Stable
Limber Pine	Pinus flexilis	Range	Range	Stable	Range	Stable
Lodgepole Pine	Pinus contorta	Core	Core	Stable	Core	Stable
Manitoba Maple	Acer negundo	Range	Range	Stable	Core	Improving
Mountain Alder	Alnus crispa	Core	Core	Stable	Range	Worsening
Mountain Spruce	Picea engelmannii	Core	Range	Worsening	Range	Worsening
Rocky Mountain Maple	Acer glabrum	Range	Core	Improving	Core	Improving
Tamarack	Larix laricina	Range	Core	Improving	Range	Stable
Thinleaf Alder	Alnus tenuifolia	Core	Core	Stable	Range	Worsening
Water Birch	Betula occidentalis	Core	Core	Stable	Core	Stable
Western Hemlock	Tsuga heterophylla	Core	Core	Stable	Core	Stable
Western Red Cedar	Thuja plicata	Range	Core	Improving	Core	Improving
White Birch	Betula papyrifera	Range	Core	Improving	Range	Stable
White Spruce	Picea glauca	Range	Range	Stable	Range	Stable
Whitebark Pine	Pinus albicaulis	Core	Core	Stable	Range	Worsening

Climate Velocity

AdaptWest (https://adaptwest.databasin.org/) provides integrative tools that can inform conservation planning, including the following analysis on climate velocity.

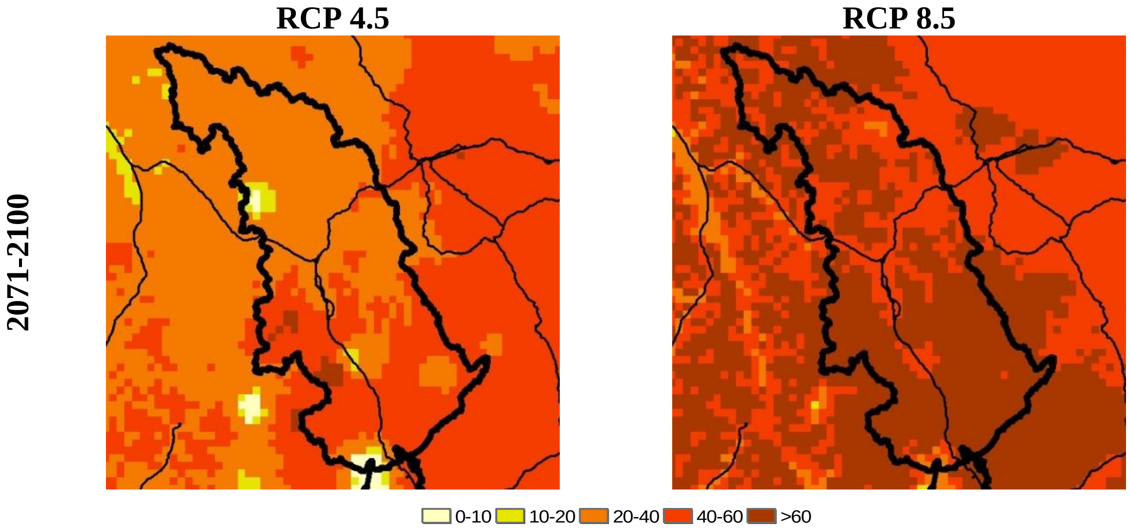


Outgoing cell destination map shows the predicted future locations for all cells (1 km pixels) currently within Jasper NP. Locations are clustered together and the number of cells is represented as the number in the cluster and by the color of the cluster. AdaptWest Climate Displacement Tool, https://adaptwest.databasin.org/pages/climate-displacement-protected-areas.



Incoming cell destination map shows the current locations for all cells expected to occupy Jasper NP in the future. Locations are clustered together and the number of cells is represented as the number in the cluster and by the color of the cluster. AdaptWest Climate Displacement Tool, https://adaptwest.databasin.org/pages/climate-displacement-protected-areas.

3.2 Wildfire

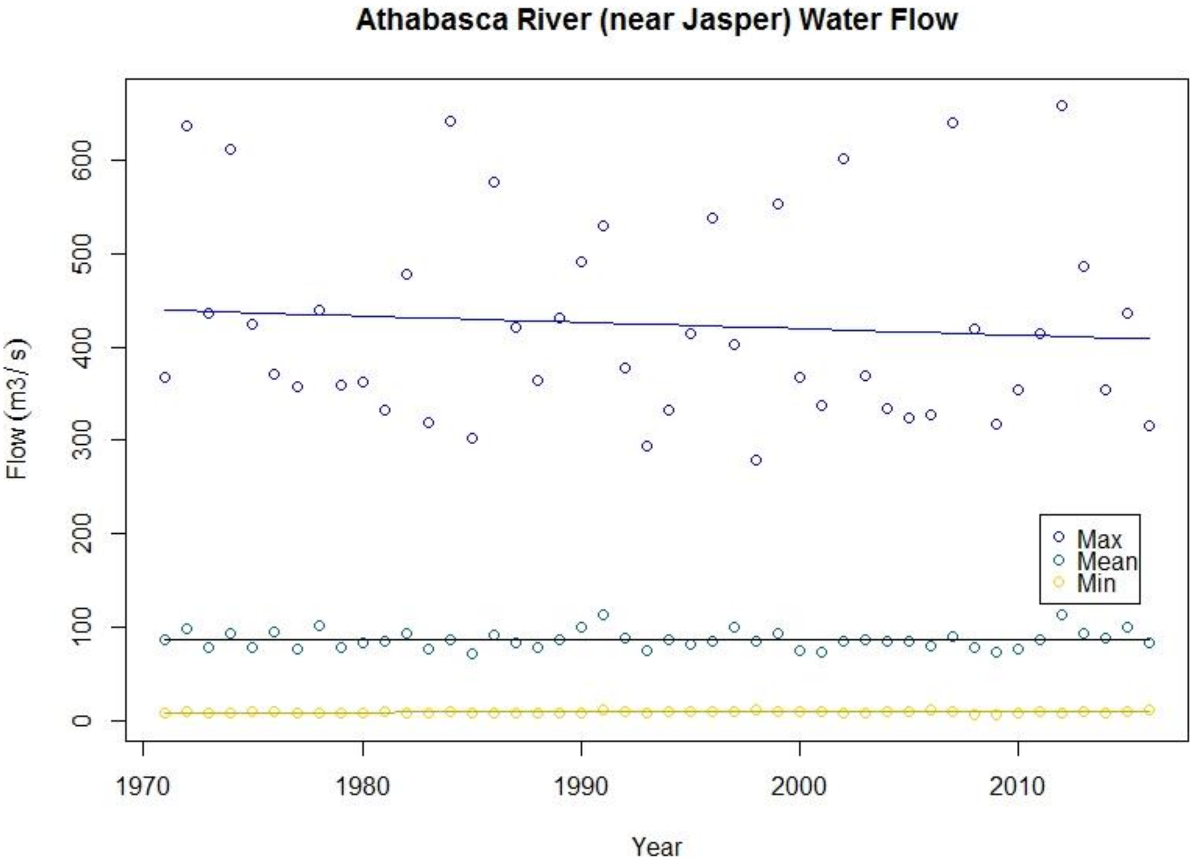


Projected increase in wildfire season for Jasper National Park. Increased length in days from baseline (1981-2010) under RCP 4.5 and RCP 8.5 scenarios. Data source: Natural Resources Canada, http://cfs.nrcan.gc.ca/fc-data-catalogue. For some area the wildfire season could increase by as much as 90 days.

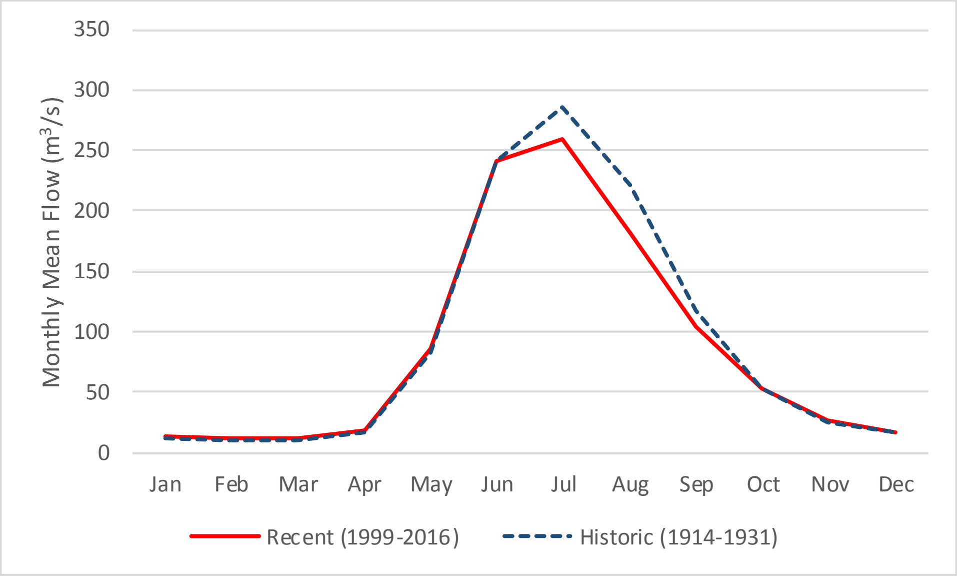
- The frequency, seasonality, extent and severity of wildfires is closely tied to climatic conditions (e.g., Westerling *et al.*, 2006).
- Wildfire season length and frequency of extreme fire weather are expected to increase (e.g., affected by warmer springs and summers, less summer moisture and reduced snowpack) (Jain *et al.*, 2017; Kirchmeier-Young *et al.*, 2019; Kirchmeier-Young *et al.*, 2017; Wang *et al.*, 2017; Wang *et al.*, 2015). Mori and Johnson (2013) project that the probability of large-scale fires in this region will increase with time.
- Flannigan *et al*. (2016) demonstrate that seasonal precipitation must increase 15% to offset every 1˚C rise in temperature. Although variable, a quick scan of the data for Jasper NP suggests that precipitation may not offset temperature.
- Temperature has a positive correlation with lightening (e.g., Price and Rind, 1994; Woolford *et al.*, 2014).
- Wotton *et al.* (2017) project a future (for 2030 and 2090) increase in the number of days where crown fires are likely to occur, as well as an increase in the number of days when fire intensities (e.g., head fire intensity above 10,000 kW/m) could exceed the capabilities of suppression resources (i.e., doubling in some end of century scenarios).
- The suppression of forest fires (e.g., Chavardes and Daniels, 2016; Davis *et al.*, 2016), exclusion of Indigenous people (Binnema and Niemi, 2006) and climate change have all contributed to landscape change in the region over the past century, including the large expansion of coniferous forests (Dinh, 2014; Luckman, 1998; Nelson and Byrne, 1966; Rhemtulla *et al.*, 2002).
- Chavardès *et al.* (2018) examined the historical role of climate variation in fire occurrence in Jasper NP and the 20th century influence of human land use and fire suppression.

3.3 Hydrological Regimes

Changes to temperature (e.g., snow and glacier melt) and precipitation (e.g., intensity, duration, frequency, rain vs snow) affects stream hydrology.



Athabasca River near Jasper annual flow data (Station 07AA002). A statistically significant ($P<0.05$) trend was not demonstrated for mean, max or min annual flows. Trend determined using a generalized linear model (R Core Team, 2017) and data from EC Data Explorer, HYDAT (July 16, 2018) (https://ec.gc.ca/rhc-wsc/). Additional analysis is recommended and could reveal patterns in minimum, maximum, and mean flows and levels, as well as timing and seasonal patterns.



Athabasca River near Jasper mean monthly flow for historic (1914-1931) and recent (1999-2016) period. Apparent decrease in mean monthly flow for summer months in recent period, timing of peak flow appears to be consistent between periods. Data from EC Data Explorer, HYDAT (July 16, 2018) (https://ec.gc.ca/rhc-wsc/).

- A correspondence with the Pacific Decadal Oscillation (PDO) and snowmelt duration was reported (Rood *et al.*, 2016; Whitfield and Pomeroy, 2016). For example, a negative phase of the PDO is frequently associated with cooler and wetter conditions, a time of larger magnitude and duration floods.
- Large rain on snow events are rare (occurring <8% of years) but generate stream flows of great consequence (e.g., Whitfield and Pomeroy, 2016). Warmer winter and spring temperatures increase rain versus snow proportions, thus increasing winter flows and declining snow packs (Paznekas and Hayashi, 2016).
- Eum *et al.* (2017) used high resolution downscaled General Circulation Models (GCMs) and a Variable Infiltration Capacity hydrological model to project hydrological changes in the Athabasca River Basin. For the upper reach at Hinton, they projected an increase in spring and winter flows and a decrease in summer flows. At this location the hydrological regime is influenced by an increase in winter / spring precipitation and earlier snow melt.
- Neupane *et al.* (2018) utilized a Soil and Water Assessment Tool (SWAT) and GCMs to predict hydrological changes in the headwaters of the Athabasca River (upstream of Jasper). While they project an increase in future spring flows, mean annual and summer flows are projected to decline.

3.4 Glaciers and Permafrost

- Glaciers in the region have undergone considerable loss, for instance the long-term average loss in annual length for the Athabasca Glacier is 12 m/year (over 170 years), but has increased to 15-20 m/year more recently (CCRN, 2017).
- Real-time access to the glacial meteorological stations in Marmot Creek and Athabasca Glacier can be found here: http://giws.usask.ca/telemetry/.

- A relevant explanation of glacier fluctuations under the influence of climate is provided by Demuth and Ednie (2016).
- Clarke *et al.* (2015) project that by 2100, the volume of glacier ice in western Canada will shrink by 70 ± 10% relative to 2005. The maximum rate of ice volume loss, corresponding to peak input of deglacial meltwater to streams and rivers, is projected to occur around 2020–2040. Clarke also developed deglaciation animations based on this work, including a series of animations for the Columbia Icefields (http://couplet.unbc.ca/data/RGM_archive/RGM_movie_archive/).
- Demuth and Horne (2017) examined decadal-to-centenary variability in glacier mass changes in Jasper NP. Over the last several decades, the studied glaciers experienced negative annual mass changes (i.e., loss) at a rate equal to or greater than 3 times that of the long-term annualized centenary value.
- Menounos *et al.* (2018) assessed the health of the alpine glaciers in Jasper NP as being in poor condition based on a composite measure including average net mass balance and trends in area, accumulation, and transient snow line.
- Harris (2001) discussed permafrost and active layer variations from 1979 to 1999 at a borehole on Marmot Mountain. Climate change is not explicitly discussed.

3.5 Visitor Experience

- Climate change is an important theme in Parks Canada's visitor communication and interpretation efforts (e.g., https://www.pc.gc.ca/en/nature/science/climat-climate; "Mountains of Change" exhibit at the Banff Park Museum; within exhibits at the Columbia Icefield Centre, etc...). Furthermore, "natural solutions", highlighting the effectiveness of ecosystem-based approaches to adaptation and mitigation, are often used to frame and present Parks Canada's response to climate change (for more information on the concept, see: Bridges *et al.*, 2018; CPC, 2013; NAWPA, 2012).
- The Visitor Experience Branch (contact: Sophie Larouche-Guilbert) is currently compiling a catalogue of climate change adaptation options for visitor experience (see: http://intranet2/our-work/visitor-experience/changements-climatiques/).
- Lemieux *et al.* (2017) and Swartman (2015) examined the perspectives of "last chance tourism" in the context of rapid environmental change at the Athabasca Glacier.
- Due to an earlier spring and warmer summer and autumn conditions, annual visitation to Jasper NP is projected to increase by 6.1-18.5% by the 2050s depending on the climate scenario used. Most of the increase is expected to occur in the spring and autumn (Jones and Scott, 2006; Scott and Jones, 2006).
- Scott and Jones (2005) project that by relying on natural snow, Banff's average ski season at low elevations (1,600 m) could decrease by 66-94% by the 2050s. A more recent climate assessment as part of Lake Louise Ski Area's "Long Range Plan Detailed Impact Analysis" (Golder Associates, 2019; Pidwirny *et al.*, 2018), suggests that warming trends in late autumn will delay snowmaking and potentially affect lower elevation skiing by 2 to 3 weeks by the 2085s (n.b., the November 2016 Alpine Ski World Cup was cancelled due to poor snow conditions at the base). However, relative to other ski areas in western Canada, Lake Louise's higher elevation, colder average winter

temperatures, and greater snowfall are projected to buffer it from the extreme climatic changes over the next few decades. Of note, Marmot Basin has a similar base and top elevation to Lake Louise (Pidwirny *et al.*, 2018).

- 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 by mid-century (Eisen *et al.*, 2016; Ogden *et al.*, 2006). Some mosquito-borne diseases also show a connection to climate change, including West Nile virus (note: besides humans it can infect over 140 species including horses, crows, ravens, etc…) (Chen *et al.*, 2013; Kulkarni *et al.*, 2015).
- A longer and more intense fire season will affect visitor safety and experience (e.g., possible area closures, no campfires, or evacuations).
- Visitor perception and consumer behaviour were studied at Jasper NP using a climate futurescapes approach (Groulx *et al.*, 2017). 22.9% of visitors reported that they would not make the trip to the Athabasca Glacier if conditions change as predicted for 2050, more so (40.7%) if the feeling of naturalness was lost through management interventions (e.g., trail, fence, bridge, helicopter).
- The US National Park Service National Climate Change Interpretation and Education Strategy (US NPS, 2016) and climate change communication toolkit (https://www.nps.gov/subjects/climatechange/toolkit.htm) contains information that may be of interest to park interpreters.

3.6 Assets and Infrastructure

The impacts to Canada's assets and infrastructure from climate change are well documented (e.g., Boyle *et al.*, 2013; Canada, 2017; Palko and Lemmen, 2017; Warren and Lemmen, 2014) and are explicitly mentioned as a concern in Parks Canada's Departmental Plan (Parks Canada, 2017). In light of the information in this report, expected concerns could include:

- Flooding from intense rainfall and rain-on-snow events could overwhelm surface drainage capacity, septic beds, and undersized or debris filled culverts and damage buildings, bridges, trails and roadways.
- Freezing rain or hail damage to buildings and power/communication lines.
- Longer wildfire seasons and more intense fires could increase impacts to infrastructure.
- Longer seasonal use of trails and roads by visitors. There may be less frost damage to roads in milder winters.
- Increased temperatures could lead to premature weathering. Similarly, increased spring rains could lead to premature weathering and deterioration (e.g., building foundations, corrosion, and mold).
- Summer drought increases water demands and may exceed system capacity.
- The energy demands for cooling buildings will increase.
- The Public Infrastructure Engineering Vulnerability Committee (PIEVC) has undertaken various climate change engineering vulnerability assessments in the region (outside parks), including projects on roads and associated structures, stormwater management

systems, and potable water facilities (e.g., Associated Engineering Calgary, 2011; British Columbia, 2010; 2011; PIEVC, 2008).
- Lister et al. (2015) discuss climate change and wildlife-crossing infrastructure, emphasizing the effectiveness of an integrated and adaptive approach.

An assessment of greenhouse gas (GHG) emissions was not in the scope of this report. However, federally the government is committing to reducing GHG emissions by 80% below 2005 levels by 2050 (https://www.canada.ca/en/treasury-board-secretariat/services/innovation/greening-government/strategy.html). Also see Parks Canada's 2015 Master Plan to reduce GHG emissions (Parks Canada, 2015).

3.7 Cultural Resources

- Increased damage or loss of cultural resources is possible during and post- flood, wildfire and other disturbance events (Morgan *et al.*, 2016).
- Efforts to FireSmart (e.g., replace wood shake roofing) may influence the character or cultural integrity of a facility (Morgan *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; Morgan *et al.*, 2016).
- Socio-economic impacts through lose or damage to cultural resources may occur.
- Longer growing seasons and warmer conditions may lead to increased presence and abundance of invasive plant species and pests (Morgan *et al.*, 2016)
- Micro-climates which allow historic gardens to flourish may be affected (e.g., Percy *et al.*, 2015).

4. References

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., *et al.* (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management, 259*(4), 660-684. doi:10.1016/j.foreco.2009.09.001.

Associated Engineering Calgary (2011). *City of Calgary Water Supply Infrastructure, Climate Change Vulnerability Risk Assessment*. https://pievc.ca/city-calgary-potable-water-collection-treatment-and-distribution-system

Bentz, B. J., Regniere, J., Fettig, C. J., Hansen, E. M., Hayes, J. L., Hicke, J. A., *et al.* (2010). Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. *BioScience, 60*(8), 602-613. doi:10.1525/bio.2010.60.8.6.

Binnema, T. and Niemi, M. (2006). 'Let the line be drawn now': Wilderness, conservation, and the exclusion of aboriginal people from Banff National Park in Canada. *Environmental History, 11*(4), 724-750. doi:10.1093/envhis/11.4.724.

Boyle, J., Cunningham, M., and Dekens, J. (2013). *Climate Change Adaptation and Canadian Infrastructure. A review of the literature*. International Institute for Sustainable Development (IISD). http://www.iisd.org/sites/default/files/publications/adaptation_can_infrastructure.pdf

Bradley, M. and Neufeld, L. (2012). Climate and management interact to explain the decline of woodland caribou (Rangifer tarandus caribou) in Jasper National Park. *Rangifer, Special Issue No. 20*. doi:10.7557/2.32.2.2268.

Brett, R. (2018). *2017 Forest Health Conditions in the Rocky Mountains National Parks*. Canadian Forest Service, Norther Forestry Centre.

Bridges, T. S., Bourne, E. M., King, J. K., Kuzmitski, H. K., Moynihan, E. B., and Suedel, B. C. (2018). *Engineering With Nature: An Atlas*. U.S. Army Engineer Research and Development Center, Vicksburg, MS. doi:10.21079/11681/27929.

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

British Columbia (2010). *Climate Change Engineering Vulnerability Assessment. Coquihalla Highway (B.C. Highway 5) Between Nicolum River and Dry Gulch*. B.C. Ministry of Transportation and Infrastructure and Nodelcorp Consulting Inc. https://pievc.ca/british-columbia-ministry-transportation-and-infrastructure-coquihalla-highway-hope-merritt-section

British Columbia. (2011). *Climate Change Engineering Vulnerability Assessment. B.C. Yellowhead Highway 16 Between Vanderhoof and Priestly Hill*. B.C. Ministry of Transportation and Infrastructure and Nodelcorp Consulting Inc. https://pievc.ca/sites/default/files/bcmoti_yellowhead_highway_-_vulnerabuility_report_web.pdf

Brown, R. (2013). *Response of Alpine Treeline Ecotones to 20th Century Climate Change: A Comparative Analysis from Kananaskis Country, Alberta.* (M.Sc.), University of Guelph.

Bush, E. and Lemmen, D. S. (2019). *Canada in a Changing Climate*. Government of Canada, Ottawa, ON. https://changingclimate.ca/

Canada (2017). *Pan-Canadian Framework on Clean Growth and Climate Change first annual report*. Government of Canada. https://www.canada.ca/en/services/environment/weather/climatechange/pan-canadian-framework/first-annual-report.html

CCRN (2017). *Overview of CCRN Activities in Canada's National Parks*. Changing Cold Regions Network. http://www.ccrnetwork.ca/documents/Reports/CCRN_Briefing_to_Parks_Canada.docx

Chai, S. L., Zhang, J., Nixon, A., and Nielsen, S. (2016). Using Risk Assessment and Habitat Suitability Models to Prioritise Invasive Species for Management in a Changing Climate. *PLoS ONE, 11*(10), 11. doi:10.1371/journal.pone.0165292.

Chavardes, R. D. and Daniels, L. D. (2016). Altered mixed-severity fire regime has homogenised montane forests of Jasper National Park. *International Journal of Wildland Fire, 25*(8), 433-444. doi:10.1071/wf15048.

Chavardes, R. D., Daniels, L. D., Gedalof, Z., and Andison, D. W. (2018). Human influences superseded climate to disrupt the 20th century fire regime in Jasper National Park, Canada. *Dendrochronologia, 48*, 10-19. doi:10.1016/j.dendro.2018.01.002.

Chen, C. C., Jenkins, E., Epp, T., Waldner, C., Curry, P. S., and Soos, C. (2013). Climate Change and West Nile Virus in a Highly Endemic Region of North America. *International Journal of Environmental Research and Public Health*, *10*(7), 3052-3071. doi:10.3390/ijerph10073052.

Cheng, C. S., Lopes, E., Fu, C., and Huang, Z. Y. (2014). Possible Impacts of Climate Change on Wind Gusts under Downscaled Future Climate Conditions: Updated for Canada. *Journal of Climate*, *27*(3), 1255-1270. doi:10.1175/jcli-d-13-00020.1.

Clarke, G. K. C., Jarosch, A. H., Anslow, F. S., Radic, V., and Menounos, B. (2015). Projected deglaciation of western Canada in the twenty-first century. *Nature Geoscience, 8*(5), 372-377. doi:10.1038/ngeo2407.

COSEWIC (2014). *COSEWIC assessment and status report on the Caribou Rangifer tarandus, Northern Mountain population, Central Mountain population and Southern Mountain population in Canada*. Committee on the Status of Endangered Wildlife in Canada.

CPC (2013). *Canadian Parks and Protected Areas: Helping Canada Weather Climate Change*. Parks Canada Agency on behalf of the Canadian Parks Council. http://www.parks-parcs.ca/english/CPC%20Climate%20Change%20Report%20FINAL%20engLR.pdf

Davis, E. L. and Gedalof, Z. e. (2018). Limited prospects for future alpine treeline advance in the Canadian Rocky Mountains. *Global Change Biology, 24*(10), 4489-4504. doi:10.1111/gcb.14338.

Davis, E. L., Mustaphi, C. J. C., Gall, A., Pisaric, M. F. J., Vermaire, J. C., and Moser, K. A. (2016). Determinants of fire activity during the last 3500 yr at a wildland-urban interface, Alberta, Canada. *Quaternary Research, 86*(3), 247-259. doi:10.1016/j.yares.2016.08.006.

Demuth, M. N. and Ednie, M. (2016). *A Glacier Condition and Thresholding Rubric for Use in Assessing Protected Area / Ecosystem Functioning*. Natural Resources Canada, Geological Survey of Canada. http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=297892

Demuth, M. N. and Horne, G. (2017). *Decadal-centenary glacier mass changes and their variability, Jasper National Park of Canada, Alberta, including the Columbia Icefield region*. Geological Survey of Canada. doi:10.4095/304236.

Dinh, T. (2014). *Influence of Humans and Climatic Variability on Historic Wildfire Dynamics in Jasper National Park, Alberta, Canada.* (M.Sc.), University of Guelph.

ECCC (2017). *Adjusted and Homogenized Canadian Climate Data (AHCCD)*. Environment and Climate Change Canada. https://www.ec.gc.ca/dccha-ahccd/

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.

Eum, H. I., Dibike, Y., and Prowse, T. (2017). Climate-induced alteration of hydrologic indicators in the Athabasca River Basin, Alberta, Canada. *Journal of Hydrology, 544*, 327-342. doi:10.1016/j.jhydrol.2016.11.034.

Festa-Bianchet, M., Ray, J. C., Boutin, S., Cote, S., and Gunn, A. (2011). Conservation of caribou (*Rangifer tarandus*) in Canada: an uncertain future. *Canadian Journal of Zoology, 89*(5), 419-434. doi:10.1139/z11-025.

Flannigan, M. D., Wotton, B. M., Marshall, G. A., de Groot, W. J., Johnston, J., Jurko, N., *et al.* (2016). Fuel moisture sensitivity to temperature and precipitation: climate change implications. *Climatic Change, 134*(1), 59-71. doi:10.1007/s10584-015-1521-0.

Gadd, B. (1986). *Handbook of the Canadian Rockies: Geology, plants, animals, history and recreation from Waterton/Glacier to the Yukon*: Corax Press.

Gauthier, S., Lorente, M., Kremsater, L., De Grandpré, L., Burton, P. J., Aubin, I., *et al.* (2014). *Tracking climate change effects: potential indicators for Canada's forests and forest sector*. Natural Resources Canada, Canadian Forest Service (CFS), Ottawa. https://cfs.nrcan.gc.ca/publications?id=35231

Golder Associates (2019). *Long Range Plan Detailed Impact Analysis, Lake Louise Ski Area*.

Gross, J. E., Woodley, S., Welling, L. A., and Watson, J. E. M. (2016). *Adapting to Climate Change. Guidance for Protected Area Managers and Planners*. IUCN, Gland, Switzerland. https://portals.iucn.org/library/node/46685

Groulx, M., Lemieux, C. J., Lewis, J. L., and Brown, S. (2017). Understanding consumer behaviour and adaptation planning responses to climate-driven environmental change in Canada's parks and protected areas: a climate futurescapes approach. *Journal of Environmental Planning and Management, 60*(6), 1016-1035. doi:10.1080/09640568.2016.1192024.

Harris, S. A. (2001). Twenty years of data on climate-permafrost-active layer variations at the lower limit of alpine permafrost, Marmot Basin, Jasper National Park, Canada. *Geografiska Annaler Series a-Physical Geography, 83A*(1-2), 1-13.

Harvey, B. J., Donato, D. C., and Turner, M. G. (2016). High and dry: post-fire tree seedling establishment in subalpine forests decreases with post-fire drought and large stand-replacing burn patches. *Global Ecology and Biogeography, 25*(6), 655-669. doi:10.1111/geb.12443.

Haughian, S. R., Burton, P. J., Taylor, S. W., and Curry, C. (2012). Expected Effects of Climate Change on Forest Disturbance Regimes in British Columbia. *Journal of Ecosystems and Management, 12*(1). http://jem.forrex.org/index.php/jem/article/view/152

Hobbs, W. O., Vinebrooke, R. D., and Wolfe, A. P. (2011). Biogeochemical responses of two alpine lakes to climate change and atmospheric deposition, Jasper and Banff National parks, Canadian Rocky Mountains. *Canadian Journal of Fisheries and Aquatic Sciences, 68*(8), 1480-1494. doi:10.1139/f2011-058.

Hogg, E. H. and Bernier, P. Y. (2005). Climate change impacts on drought-prone forests in western Canada. *Forestry Chronicle, 81*(5), 675-682. doi:10.5558/tfc81675-5.

Hogg, E. H., Brandt, J. P., and Michaellian, M. (2008). Impacts of a regional drought on the productivity, dieback, and biomass of western Canadian aspen forests. *Canadian Journal of Forest Research, 38*(6), 1373-1384. doi:10.1139/x08-001.

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.

Illerbrun, K. and Roland, J. (2011). Treeline proximity alters an alpine plant-herbivore interaction. *Oecologia, 166*(1), 151-159. doi:10.1007/s00442-010-1822-y.

IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change (IPCC). Geneva, Switzerland. http://www.ipcc.ch/report/ar5/

Jain, P., Wang, X. L., and Flannigan, M. D. (2017). Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. *International Journal of Wildland Fire, 26*(12), 1009-1020. doi:10.1071/wf17008.

Janz, B. and Storr, D. (1977). *The Climate of the Contiguous Mountain Parks: Banff, Jasper, Yoho, Kootenay*. Meteorological Applications Branch, Applications and Consultation Division, Atmospheric Environment Service, Department of the Environment, Toronto. http://parkscanadahistory.com/publications/report-30.pdf

Jasper National Park. (2016). *Mountain Pine Beetle Managment Plan*. Parks Canada, Jasper, AB. https://www.pc.gc.ca/en/pn-np/ab/jasper/info/plan

Jones, B. and Scott, D. (2006). Climate Change, Seasonality and Visitation to Canada's National Parks. *Journal of Park and Recreation Administration; Vol 24, No 2 (2006)*. http://js.sagamorepub.com/jpra/article/view/1407

Jones, L. A., Muhlfeld, C. C., and Marshall, L. A. (2017). Projected warming portends seasonal shifts of stream temperatures in the Crown of the Continent Ecosystem, USA and Canada. *Climatic Change, 144*(4), 641-655. doi:10.1007/s10584-017-2060-7.

Kirchmeier-Young, M. C., Gillett, N. P., Zwiers, F. W., Cannon, A. J., and Anslow, F. S. (2019). Attribution of the Influence of Human-Induced Climate Change on an Extreme Fire Season. *Earths Future, 7*(1), 2-10. doi:10.1029/2018ef001050.

Kirchmeier-Young, M. C., Zwiers, F. W., Gillett, N. P., and Cannon, A. J. (2017). Attributing extreme fire risk in Western Canada to human emissions. *Climatic Change, 144*(2), 365-379. doi:10.1007/s10584-017-2030-0.

Kulkarni, M. A., Berrang-Ford, L., Buck, P. A., Drebot, M. A., Lindsay, L. R., and Ogden, N. H. (2015). Major emerging vector-borne zoonotic diseases of public health importance in Canada. *Emerging Microbes & Infections, 4*, 7. doi:10.1038/emi.2015.33.

Lemieux, C. J., Groulx, M., Halpenny, E., Stager, H., Dawson, J., Stewart, E. J., *et al.* (2017). "The End of the Ice Age?": Disappearing World Heritage and the Climate Change Communication Imperative. *Environmental Communication*, 1-19. doi:10.1080/17524032.2017.1400454.

Lister, N. M., Brocki, M., and Ament, R. (2015). Integrated adaptive design for wildlife movement under climate change. *Frontiers in Ecology and the Environment, 13*(9), 493-502. doi:10.1890/150080.

Luckman, B. and Kavanagh, T. (2000). Impact of climate fluctuations on mountain environments in the Canadian Rockies. *Ambio, 29*(7), 371-380. doi:10.1639/0044-7447(2000)029[0371:iocfom]2.0.co;2.

Luckman, B. H. (1998). Landscape and climate change in the central Canadian Rockies during the 20th century. *Canadian Geographer-Geographe Canadien, 42*(4), 319-336. doi:10.1111/j.1541-0064.1998.tb01349.x.

McKenney, D. W., Hutchinson, M. F., Kesteven, J. L., and Venier, L. A. (2001). Canada's plant hardiness zones revisited using modern climate interpolation techniques. *Canadian Journal of Plant Science, 81*(1), 129-143. doi:10.4141/p00-030.

McKenney, D. W., Pedlar, J. H., Lawrence, K., Papadopol, P., Campbell, K., and Hutchinson, M. F. (2014). Change and Evolution in the Plant Hardiness Zones of Canada. *BioScience, 64*(4), 341-350. doi:10.1093/biosci/biu016.

McKenney, D. W., Pedlar, J. H., Rood, R. B., and Price, D. (2011). Revisiting projected shifts in the climate envelopes of North American trees using updated general circulation models. *Global Change Biology, 17*(8), 2720-2730. doi:10.1111/j.1365-2486.2011.02413.x.

Menounos, B., Bevington, A., Pelto, B., Tennant, C., and Wheate, R. (2018). *Final Report for State of the Parks Report on Glaciers. Glacier and Jasper National Parks*. University of Northern British Columbia.

Messner, J. S., Maclennan, M. M., and Vinebrooke, R. D. (2013). Higher temperatures enhance the effects of invasive sportfish on mountain zooplankton communities. *Freshwater Biology, 58*(2), 354-364. doi:10.1111/fwb.12062.

Michaelian, M., Hogg, E. H., Hall, R. J., and Arsenault, E. (2011). Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. *Global Change Biology, 17*(6), 2084-2094. doi:10.1111/j.1365-2486.2010.02357.x.

Michalak, A. M. (2016). Study role of climate change in extreme threats to water quality. *Nature, 535*(7612), 349-350.

Morgan, 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/upload/CR-Impacts-Identification-Guide-v4-1.pdf

Mori, A. S. and Johnson, E. A. (2013). Assessing possible shifts in wildfire regimes under a changing climate in mountainous landscapes. *Forest Ecology and Management, 310*, 875-886. doi:10.1016/j.foreco.2013.09.036.

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.

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

Nelson, J. G. and Byrne, A. R. (1966). Man as an Instrument of Landscape Change: Fires, Floods, and National Parks in the Bow Valley, Alberta. *Geographical Review, 56*(2), 226-238. doi:10.2307/212880.

Neupane, R. P., Adamowski, J. F., White, J. D., and Kumar, S. (2018). Future streamflow simulation in a snow-dominated rocky mountain headwater catchment. *Hydrology Research, 49*(4), 1172-1190. doi:10.2166/nh.2017.024.

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., *et al.* (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., *et al.* (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.

Otto, H. W., Wilson, J. A., and Beever, E. A. (2015). Facing a Changing World: Thermal Physiology of American Pikas (*Ochotona princeps*). *Western North American Naturalist, 75*(4), 429-445. doi:10.3398/064.075.0402.

Palko, K. and Lemmen, D. S. (Eds.). (2017). *Climate risks and adaptation practices for the Canadian transportation sector 2016*. Ottawa, ON: Government of Canada.

Parker, S. (2017). *Let's Talk about Climate Change: Mountain Region*. Parks Canada, Gatineau, QC.

Parker, S., Barr, S., and Harrop Archibald, H. (2018). *Climate Change Adaptation Options for Biodiversity: Part 1. Context and Guidance Report*. Office of the Chief Ecosystem Scientist, Parks Canada Agency, Gatineau, QC. doi:10.13140/RG.2.2.31409.02403/1.

Parker, S., Wu, J., Whitaker, D., Bateman, B., Harpur, C., and LePage, D. (2019). *Birds and Climate Change: Summary report on the projected effects of climate change on birds in Canada's National Parks and National Marine Conservation Areas*. Parks Canada, National Audubon Society and Bird Studies Canada.

Parks Canada (2015). *Master Plan For the Reduction of Greenhouse Gas (GHG) Emissions within Parks Canada's Operations*.

Parks Canada (2017). *Parks Canada Agency, 2017–18 Departmental Plan*. http://www.pc.gc.ca/en/agence-agency/bib-lib/plans/dp/dp2017-18/index

Paznekas, A. and Hayashi, M. (2016). Groundwater contribution to winter streamflow in the Canadian Rockies. *Canadian Water Resources Journal, 41*(4), 484-499. doi:10.1080/07011784.2015.1060870.

PCIC (2014). *Statistically Downscaled Climate Scenarios*. Pacific Climate Impacts Consortium, University of Victoria. https://www.pacificclimate.org/data/statistically-downscaled-climate-scenarios

Percy, K., Ward, S., Quintero, M. S., and Morrison, T. (2015). Integrated Digital Technologies for the Architectural Rehabilitation & Conservation of Beinn Bhreagh Hall & Surrounding Site, Nova Scotia, Canada. In Y. N. Yen, K. H. Weng, and H. M. Cheng (Eds.), *25th International CIPA Symposium 2015* (pp. 235-241). Kensington: Int Soc Photogrammetry Remote Sensing C/O School of Surveying.

Pidwirny, M., Bahbahani, K., Goode, J., and Pedersen, S. (2018). *The Lake Louise Ski Ltd. Climate Change Risk and Impact Assessment Report Long-Range Plan, June 2018*. University of British Columbia.

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

Poesch, M. S., Chavarie, L., Chu, C., Pandit, S. N., and Tonn, W. (2016). Climate Change Impacts on Freshwater Fishes: A Canadian Perspective. *Fisheries, 41*(7), 385-391. doi:10.1080/03632415.2016.1180285.

Price, C. and Rind, D. (1994). Possible implications of global climate change on global lightning distributions and frequencies. *Journal of Geophysical Research: Atmospheres, 99*(D5), 10823-10831. doi:10.1029/94JD00019.

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

R Core Team (2017). *R: A Language and Environment for Statistical Computing (ver. 3.4.3)*. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org

Rhemtulla, J. M., Hall, R. J., Higgs, E. S., and Macdonald, S. E. (2002). Eighty years of change: Vegetation in the montane ecoregion of Jasper National Park, Alberta, Canada. *Canadian Journal of Forest Research, 32*(11), 2010-2021. doi:10.1139/x02-112.

Roberts, D. R., Nielsen, S. E., and Stenhouse, G. B. (2014). Idiosyncratic responses of grizzly bear habitat to climate change based on projected food resource changes. *Ecological Applications, 24*(5), 1144-1154. doi:10.1890/13-0829.1.

Rockman, M., Morgan, M., Ziaja, S., Hambrecht, G., and Meadow, A. (2016). *Cultural Resources Climate Change Strategy*. Cultural Resources, Partnerships, and Science and Climate Change Response Program, National Park Service (NPS). Washington, DC. https://www.nps.gov/subjects/climatechange/culturalresourcesstrategy.htm

Rood, S. B., Foster, S. G., Hillman, E. J., Luek, A., and Zanewich, K. P. (2016). Flood moderation: Declining, peak flows along some Rocky Mountain rivers and the underlying mechanism. *Journal of Hydrology, 536,* 174-182. doi:10.1016/j.jhydrol.2016.02.043.

Rood, S. B., Pan, J., Gill, K. M., Franks, C. G., Samuelson, G. M., and Shepherd, A. (2008). Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology, 349*(3-4), 397-410. doi:10.1016/j.jhydrol.2007.11.012.

Roush, W. M. (2004). *A Substantial Upward Shift of the Alpine Treeline Ecotone in the Southern Canadian Rocky Mountains.* (M.Sc.), University of Victoria

Scott, D. and Jones, B. (2005). *Climate Change & Banff National Park: Implications for Tourism and Recreation*. Report prepared for the Town of Banff. Waterloo, ON: University of Waterloo.

Scott, D. and Jones, B. (2006). *Climate Change and Nature-Based Tourism. Implications for Park Visitation in Canada*. University of Waterloo, Department of Geography, Waterloo, ON. http://lib.icimod.org/record/12663

Shepherd, B., Jones, B., Sissons, R., Cochrane, J., Park, J., Smith, C. M., *et al.* (2018). Ten Years of Monitoring Illustrates a Cascade of Effects of White Pine Blister Rust and Focuses Whitebark Pine Restoration in the Canadian Rocky and Columbia Mountains. *Forests, 9*(3), 18. doi:10.3390/f9030138.

Simonovic, S. P., Schardong, A., and Sandink, D. (2017). Mapping Extreme Rainfall Statistics for Canada under Climate Change Using Updated Intensity-Duration-Frequency Curves. *Journal of Water Resources Planning and Management, 143*(3), 12. doi:10.1061/(asce)wr.1943-5452.0000725.

Strecker, A. L., Cobb, T. P., and Vinebrooke, R. D. (2004). Effects of experimental greenhouse warming on phytoplankton and zooplankton communities in fishless alpine ponds. *Limnology and Oceanography, 49*(4), 1182-1190.

Sturrock, R. N., Frankel, S. J., Brown, A. V., Hennon, P. E., Kliejunas, J. T., Lewis, K. J., *et al.* (2011). Climate change and forest diseases. *Plant Pathology, 60*(1), 133-149. doi:10.1111/j.1365-3059.2010.02406.x.

Swartman, B. (2015). *The Business of Last Chance Tourism: Stakeholders' Perspectives.* (M.A.), University of Waterloo

Tomback, D. F., Chipman, K. G., Resler, L. M., Smith-McKenna, E. K., and Smith, C. M. (2014). Relative Abundance and Functional Role of Whitebark Pine at Treeline in the Northern Rocky Mountains. *Arctic, Antarctic and Alpine Research, 46*(2), 407-418. doi:10.1657/1938-4246-46.2.407.

Treanor, H. B., Giersch, J. J., Kappenman, K. M., Muhlfeld, C. C., and Webb, M. A. H. (2013). Thermal tolerance of meltwater stonefly *Lednia tumana* nymphs from an alpine stream in Waterton-Glacier International Peace Park, Montana, USA. *Freshwater Science, 32*(2), 597-605. doi:10.1899/12-100.1.

US NPS (2016). *National Climate Change Interpretation and Education Strategy*. https://www.nps.gov/subjects/climatechange/nccies.htm

Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., *et al.* (2011). The representative concentration pathways: an overview. *Climatic Change, 109*(1-2), 5-31. doi:10.1007/s10584-011-0148-z.

Wang, X. L., Parisien, M. A., Taylor, S. W., Candau, J. N., Stralberg, D., Marshall, G. A., *et al.* (2017). Projected changes in daily fire spread across Canada over the next century. *Environmental Research Letters, 12*(2), 12. doi:10.1088/1748-9326/aa5835.

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.

Weed, A. S., Ayres, M. P., and Hicke, J. A. (2013). Consequences of climate change for biotic disturbances in North American forests. *Ecological Monographs, 83*(4), 441-470. doi:10.1890/13-0160.1.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., and Swetnam, T. W. (2006). Warming and earlier spring increase western US forest wildfire activity. *Science, 313*(5789), 940-943. doi:10.1126/science.1128834.

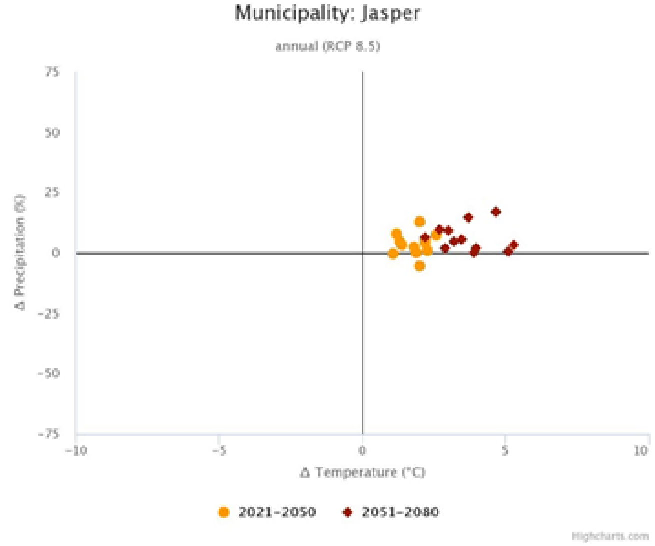
Whitfield, P. H. and Pomeroy, J. W. (2016). Changes to flood peaks of a mountain river: implications for analysis of the 2013 flood in the Upper Bow River, Canada. *Hydrological Processes, 30*(25), 4657-4673. doi:10.1002/hyp.10957.

Woolford, D. G., Dean, C. B., Martell, D. L., Cao, J. G., and Wotton, B. M. (2014). Lightning-caused forest fire risk in Northwestern Ontario, Canada, is increasing and associated with anomalies in fire weather. *Environmetrics, 25*(6), 406-416. doi:10.1002/env.2278.

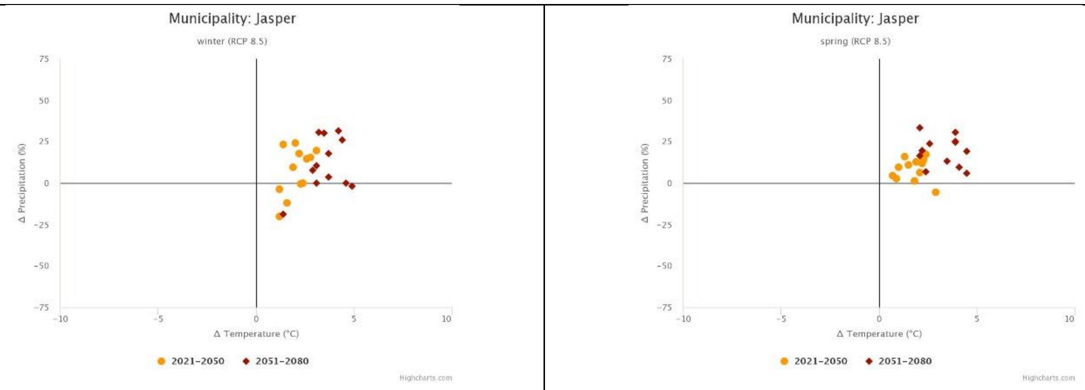
Worrall, J. J., Rehfeldt, G. E., Hamann, A., Hogg, E. H., Marchetti, S. B., Michaelian, M., *et al.* (2013). Recent declines of Populus tremuloides in North America linked to climate. *Forest Ecology and Management, 299*, 35-51. doi:10.1016/j.foreco.2012.12.033.

Wotton, B. M., Flannigan, M. D., and Marshall, G. A. (2017). Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. *Environmental Research Letters, 12*(9), 12. doi:10.1088/1748-9326/aa7e6e.

Appendix 1. Scatterplots of Temperature and Precipitation

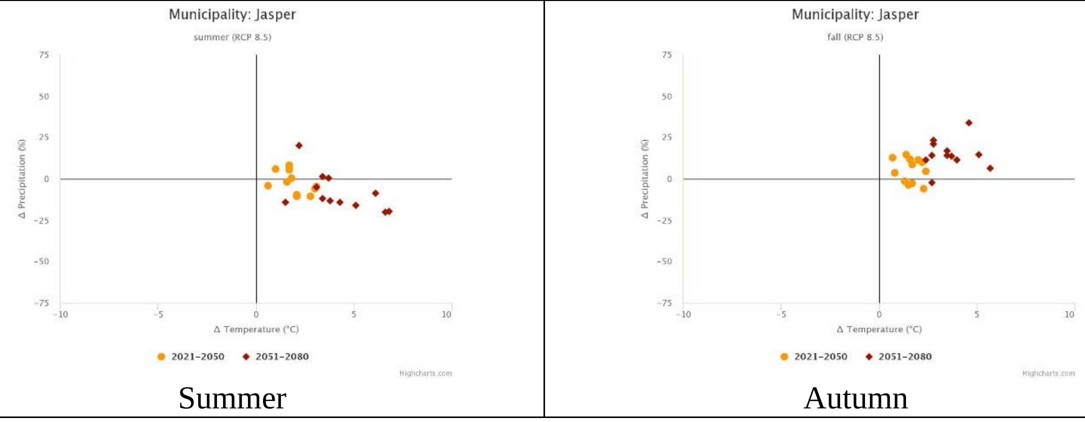


Annual



Winter

Spring



Summer

Autumn

Climate models for the Municipality of Jasper. Each point represents a single model-simulated temperature/precipitation response to the **RCP 8.5** scenario. Statistically downscaled data (Bias Corrected Spatial Disaggregation; BCSD) derived from 12 CMIP5 global climate models (https://climateatlas.ca/; PCIC, 2014). All models project warmer conditions and most an increase in total precipitation, however summer precipitation appears to be the most uncertain (i.e., could be stable, wetter or drier).

Appendix 2. Birds and Climate Change

Parks Canada, National Audubon Society, and Bird Studies Canada assessed the effects of climate change on bird species in Canada’s national parks (Parker *et al.*, 2019). The following table provides a summary for Jasper National Park. Climate suitability projections by 2050 under the high-emissions pathway (RCP 8.5). "Potential colonization" indicates that climate is projected to become suitable for the species, whereas "potential extirpation" indicates that climate is suitable today but projected to become unsuitable. Omitted species were either not modeled due to data deficiency or were absent from the observation datasets. Species are listed by taxonomic order, denoted by alternating background shading.

- Species not found or found only occasionally, and not projected to colonize by 2050
x Species not modeled in this season
^ Species that are highly climate sensitive

Common Name	Summer Trend	Winter Trend
Gadwall	Potential extirpation^	-
American Wigeon	Worsening^	-
Mallard	Potential extirpation^	-
Blue-winged Teal	Stable	-
Northern Shoveler	Potential extirpation^	-
Northern Pintail	Potential extirpation	-
Greater Scaup	Worsening	-
Red-breasted Merganser	Worsening	-
Ruddy Duck	Potential extirpation	-
Ruffed Grouse	x	Improving
Spruce Grouse	x	Worsening
Willow Ptarmigan	Worsening	Worsening
Sharp-tailed Grouse	-	Potential colonization
Common Loon	Stable	-
Red-necked Grebe	Worsening	-
American Bittern	Potential colonization	-
Great Blue Heron	Improving	-

Common Name	Summer Trend	Winter Trend
Northern Harrier	Potential extirpation^	-
Sharp-shinned Hawk	x	Improving
Northern Goshawk	x	Worsening
Bald Eagle	x	Stable
Swainson's Hawk	Potential extirpation^	-
Red-tailed Hawk	Stable	-
Rough-legged Hawk	-	Improving
Killdeer	Improving	-
Solitary Sandpiper	Worsening	-
Greater Yellowlegs	Improving	-
Lesser Yellowlegs	Potential extirpation^	-
Wilson's Snipe	Worsening	Potential colonization
Bonaparte's Gull	Stable	-
Ring-billed Gull	Stable^	-
Black Tern	Stable	-
Rock Pigeon	Improving	Improving
Eurasian Collared-Dove	x	Improving
Mourning Dove	Improving	-

Common Name	Summer Trend	Winter Trend
Great Horned Owl	x	Stable
Northern Hawk Owl	x	Stable^
Northern Pygmy-Owl	x	Improving
Barred Owl	x	Improving
Common Nighthawk	Improving	-
Rufous Hummingbird	Improving	-
Calliope Hummingbird	Stable	-
Belted Kingfisher	Improving	Potential colonization
Yellow-bellied Sapsucker	Improving	-
Red-naped Sapsucker	Improving^	-
Downy Woodpecker	Improving	Improving
Hairy Woodpecker	Improving	Improving
American Three-toed Woodpecker	x	Stable^
Northern Flicker	Stable	Improving
Pileated Woodpecker	Improving	Improving
Merlin	x	Stable^
Olive-sided Flycatcher	Stable	-
Western Wood-Pewee	Stable^	-
Yellow-bellied Flycatcher	Stable	-
Alder Flycatcher	Stable	-
Willow Flycatcher	Improving	-
Least Flycatcher	Improving	-
Hammond's Flycatcher	Improving	-
Dusky Flycatcher	Worsening	-
Pacific-slope Flycatcher	Improving	-
Eastern Phoebe	Improving	-

Common Name	Summer Trend	Winter Trend
Say's Phoebe	Potential extirpation	-
Western Kingbird	Improving	-
Eastern Kingbird	Improving	-
Northern Shrike	x	Stable
Warbling Vireo	Improving	-
Red-eyed Vireo	Improving	-
Steller's Jay	Stable	Stable
Blue Jay	Improving	-
Black-billed Magpie	Potential extirpation^	Worsening
Clark's Nutcracker	Stable^	Stable
American Crow	Improving	Potential colonization
Common Raven	Stable	Worsening
Horned Lark	Potential extirpation	-
Northern Rough-winged Swallow	Improving	-
Tree Swallow	Improving	-
Violet-green Swallow	Stable	-
Barn Swallow	Improving	-
Cliff Swallow	Stable	-
Black-capped Chickadee	Improving	Stable
Mountain Chickadee	Stable	Stable
Chestnut-backed Chickadee	Potential colonization	-
Boreal Chickadee	Worsening^	Worsening
Red-breasted Nuthatch	Improving	Stable
White-breasted Nuthatch	Improving	Stable
Brown Creeper	Improving^	Potential colonization
House Wren	Improving	-

Common Name	Summer Trend	Winter Trend
Winter/Pacific Wren	Improving	Potential colonization
American Dipper	x	Worsening
Golden-crowned Kinglet	Improving	Potential colonization
Ruby-crowned Kinglet	Worsening	-
Mountain Bluebird	Potential extirpation	-
Townsend's Solitaire	Stable^	Potential extirpation
Veery	Improving	-
Swainson's Thrush	Improving	-
Hermit Thrush	Worsening	-
American Robin	Improving	-
Varied Thrush	Stable^	-
European Starling	Improving	Improving
American Pipit	Stable	-
Bohemian Waxwing	-	Stable
Cedar Waxwing	Improving	-
Snow Bunting	-	Stable
Ovenbird	Improving	-
Worm-eating Warbler	Potential colonization	-
Northern Waterthrush	Improving	-
Golden-winged Warbler	Potential colonization	-
Tennessee Warbler	Stable	-
Orange-crowned Warbler	Worsening	-
Nashville Warbler	Potential colonization	-
MacGillivray's Warbler	Improving	-
Mourning Warbler	Potential colonization	-
Common Yellowthroat	Improving	-

Common Name	Summer Trend	Winter Trend
American Redstart	Improving	-
Magnolia Warbler	Improving	-
Yellow Warbler	Stable	-
Blackpoll Warbler	Worsening	-
Yellow-rumped Warbler	Stable	-
Townsend's Warbler	Improving	-
Black-throated Green Warbler	Potential colonization	-
Wilson's Warbler	Worsening	-
Chipping Sparrow	Improving	-
Clay-colored Sparrow	Potential extirpation	-
Brewer's Sparrow	Stable	-
Vesper Sparrow	Stable	-
Savannah Sparrow	Potential extirpation	-
Le Conte's Sparrow	Potential extirpation^	-
Fox Sparrow	Worsening	-
Song Sparrow	Improving	-
Lincoln's Sparrow	Stable	-
Swamp Sparrow	Improving	-
White-throated Sparrow	Stable	-
White-crowned Sparrow	Worsening	Stable
Golden-crowned Sparrow	Worsening	-
Dark-eyed Junco	x	Improving
Western Tanager	Improving	-
Rose-breasted Grosbeak	Improving	-
Lazuli Bunting	Improving	-
Red-winged Blackbird	Improving	-
Western Meadowlark	Stable	-

Common Name	Summer Trend	Winter Trend
Yellow-headed Blackbird	Potential extirpation	-
Rusty Blackbird	Worsening	-
Brewer's Blackbird	Stable	-
Common Grackle	Improving	-
Brown-headed Cowbird	Improving	-
Gray-crowned Rosy-Finch	x	Stable^
Pine Grosbeak	Stable^	Worsening
House Finch	Improving	Improving

Common Name	Summer Trend	Winter Trend
Purple Finch	Improving	-
Cassin's Finch	-	Potential colonization
Red Crossbill	Stable^	x
White-winged Crossbill	Stable	Stable
Common Redpoll	-	Stable
Pine Siskin	Stable	Improving
Evening Grosbeak	Improving	Improving
House Sparrow	x	Improving