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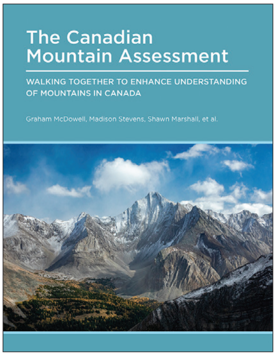

THE CANADIAN MOUNTAIN ASSESSMENT: WALKING TOGETHER TO ENHANCE UNDERSTANDING OF MOUNTAINS IN CANADA

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CHAPTER 5

Mountains Under Pressure

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5.1 Introduction

Mountains in Canada are subject to an array of direct and indirect pressures from human activity and environmental change. The Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) biodiversity assessment discusses these pressures as 'drivers of change', and these drivers are broadly relevant to mountain systems and peoples (Díaz et al., 2019). Pressures such as climate change, land-use development, and the increasing demand for tourism and recreation are tied to the "great acceleration" of increasing human population and activity since 1950 (Steffen et al., 2015). Each pressure drives biophysical, socio-political, cultural, and ecological responses, with effects that vary from region to region, and which may be experienced far beyond mountain areas. These primary pressures are ultimately all driven by human activity, but they interact with natural systems to create secondary pressures such as changes in hydrology or ecology that can compromise the quality of life in mountain environments (e.g., impacts on water quality, health, or food security), representing existential threats to the sustainability of the mountain environments, livelihoods, and gifts of the mountains discussed in Chapters 2 to 4 of this book.

Many pressures, such as land management and governance practices, represent long-standing drivers of change, especially for Indigenous communities. Obvious examples include resource development (e.g., mining, forestry), establishment of infrastructure (e.g., roads, railways, pipelines, towns, ski areas), and land claims (e.g., the establishment of National Parks, which changed access to and 'ownership' of the mountains). Biocultural relationships, socio-ecological values, and socio-economic and political privilege/marginalisation underpin differentiated experiences of these drivers and their associated effects.

Pressures are often interactive and compounding, which can lead to cascading socio-ecological effects, including impacts on community health and wellbeing. Anthropogenic and climatic pressures on mountain landscapes can interact with each other in a complex manner, including in cumulative, synergistic, or additive ways; they also vary in their spatial and temporal scales, making understanding of how they interact essential for adaptation planning. Mitigating further anthropogenic disturbance requires identifying the

* *Due to the CMA's unique approach to engaging with multiple knowledge systems, we suggest that readers review the Introduction prior to reading subsequent chapters.*

patterns of change in these environmental and social pressures and their cumulative effects, and forecasting their impacts into the future (Hirsh-Pearson, 2022).

This chapter focuses on historical and future changes in mountains in Canada from 1950 to 2100, including the anthropogenic drivers of these changes, current and emerging impacts and vulnerabilities, as well as responses to attendant challenges (and opportunities) in mountain systems. Historical changes and future projections for drivers of change are discussed in Sec. 5.2 to 5.6. Sec. 5.7 to 5.12 assess the effects of these pressures on physical, ecological, and socio-cultural systems, including consideration of vulnerability, resilience, and adaptation within these systems.

5.2 Climate Change: Historical Trends and Future Projections

Mountain systems are sensitive to the cumulative effects of climate change. Contemporary climate change includes both natural forcing and anthropogenic components, and these can be difficult to separate. Cooler temperatures during the main phase of the Little Ice Age from the 17th to 19th centuries have been attributed to solar variability and the cooling effects of frequent volcanic activity (Brönnimann et al., 2019). Natural climate forcings such as volcanic events and sunspot cycles are associated with interannual to decadal variability, with fluctuations in radiative balance that can impact biophysical and socio-cultural systems but which often 'balance out' over multi-decadal timescales. Other natural forcings, such as variations in the Earth's orbit around the Sun, act on millennial timescales and influence the Quaternary and Holocene evolution of climate, glaciation, and ecosystems, but with negligible changes over the timescale of focus here, 1950 to 2100.

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 5.1

Brandy Mayes, Kwanlin Dün First Nation, 2022, LC 5.2

Natural processes continue to influence the climate, and the cooling effects of volcanic events are well-known in oral histories. As Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań shared, the Kluane hold stories of the time when the volcano erupted and the ash spread across the Yukon, the time when there were two winters and no summer (LC 5.1).

Many aspects of natural, built, and socio-cultural environments are vulnerable to climate change, but glaciers provide an intuitive and visible indicator that naturally integrates short-term fluctuations ('weather') to provide a clear signal of the cumulative impacts of climate change. The Little Ice Age was characterised by widespread glacier advance, with cool summers in the Little Ice Age also affecting harvests and growing conditions across much of the world. The onset of glacier retreat coming out of the Little Ice Age was largely associated with natural climate forcing, but accelerated and intensified glacier retreat since the 1970s is almost entirely due to anthropogenic climate forcing from the buildup of carbon dioxide and methane in the atmosphere (Marzeion et al., 2014). The accumulation of these greenhouse gases represents a direct and steadily increasing warming influence that is also affecting the hydrological cycle and circulation patterns in the ocean and atmosphere. The Intergovernmental Panel on Climate Chang (IPCC) (2021) notes that there has been no significant solar variation over the period 1950 to present, and that anthropogenic forcing from greenhouse gases is now much stronger than natural forcing of the climate system.

The pressures of climate change on cryospheric, hydrological, and ecological systems, food security, wildfire, extreme weather, mountain hazards, built infrastructure, mountain recreation, and ways of life produce cascading impacts in mountain regions. As Brandy Mayes, Kwanlin Dün First Nation, explained, increased heat and precipitation due to climate change affects the salmon, which feed the land, the bears, the trees, and which are felt in the salmon camps (LC 5.2).

Weather patterns and climate normals—the average weather over 30 years or more—are changing across Canada and the world, but mountain environments are sensitive to a range of particular climate change processes and considerations. This includes basic questions of whether warming varies with elevation, as well as questions of how climate change is impacting physical features (e.g., glaciers, hazards), ecological niches, and socio-cultural activities that are specific to high elevations. The following sections assess historical trends and future climate change projections specific to major mountain regions in Canada.

5.2.1 *Historical temperature trends*

Numerous research studies provide multi-year meteorological records from high-elevation and alpine sites in mountain regions in Canada (e.g., Marshall, 2014; Pradhananga et al., 2020; Rasouli et al., 2019). At some sites these records extend long enough to estimate a climate normal, but they do not have the duration, continuity, or homogeneity to support detection and analysis of climate change trends. Where multi-decadal records from mountain regions are available, they typically correspond to low elevations (e.g., valley-bottom or coastal sites), such as in the analysis of Whitfield (2014) in the Kananaskis Valley (ca. 1400 m).

Data from alpine environments or higher elevations, above about 1600 m, are mostly collected through short-term research studies or may be available as seasonal records (e.g., from Parks warden stations, ski areas, or fire lookouts). Such observations are also concentrated in populated areas. Given the limited extent of multi-decadal station data, it is difficult to assess climate change trends in mountain regions in Canada or their variation with elevation. Hindcasts from numerical weather prediction models, known as climate reanalyses, offer insight into regional- to national-scale climate patterns and their historical variability. Climate reanalyses use available observational constraints to drive numerical weather models in 'retrospective' mode, essentially using the atmospheric physics and coupled surface-atmospheric processes embedded within the model, constrained by available data, to provide a detailed reconstruction of past climate.

Historical climate trends in mountain regions in Canada are assessed based on the ERA5 climate reanalysis for the period 1950–2020. This climate reanalysis, from the European Centre for Medium-Range Weather Forecasting (ECMWF), provides hourly climate reconstructions from 1950 to present, with a longitude-latitude resolution of 0.25°C (Hersbach et al., 2020). Because this has complete spatial and temporal coverage, it is valuable for assessing decadal-scale climate change trends in mountain and northern regions, where station data is generally sparse.

Average temperatures increased in all of the mountain regions in Canada from 1950 to 2020, with warming rates from 0.06 to 0.35°C per decade (Table 5.1). Western Canada has seen the greatest temperature increases, with the Pacific Maritime and Boreal Cordillera regions warming at roughly twice the national average. Temperature increases in eastern Canada are comparatively modest, and are below the national average. This is consistent with the broad national picture documented in Bush & Lemmen (2019), where trends are based on station records. Overall, western mountain regions in Canada have warmed at rates exceeding the national average, but this is not true of the eastern or high Arctic mountain regions in Canada.

Contrasting seasonal patterns are embedded within the overall warming trend. Nationally, winter warming is more than twice the rate of summer warming, 0.28°C vs. 0.13°C per decade. Winter warming is pronounced in northwestern Canada, with rates exceeding 0.6°C per decade in the Boreal and Taiga Cordillera. In contrast, the Atlantic Maritime and Eastern Subarctic regions experienced modest winter cooling over the period 1950–2020. The overall pattern of temperature trends is consistent with a climatological shift in the jet stream. This shift has led to stronger and more persistent ridges over western Canada and a trough over eastern Canada, associated with northerly (cold) air advection. Decadal-scale trends in atmospheric circulation show signs of persistence in this setup, which accompanies a more 'wavy' jet stream (i.e., meridional flow with strong ridge and trough structures,

Table 5.1: Historical climate trends of major mountain regions in Canada, calculated from the ERA5 global climate reanalysis. Trends *dT/dt* and *dP/dt* are calculated from a linear regression over the period 1950–2021, expressed as rate of change per decade. Changes ΔT and ΔP refer to differences in the mean values from 1991–2020 relative to 1951–1980. Bold values highlight large departures from the average Canadian trends.

Climate Trends and Changes (1950–2020), Mountain regions in Canada

	dT/dt (°C dec⁻¹)			*ΔT (°C)*	*dP/dt (% dec⁻¹)*			*ΔP (%)*
Mountain Regions	*DJF*	*JJA*	*ann*	*ann*	*DJF*	*JJA*	*ann*	*ann*
Pacific Maritime	0.36	**0.56**	**0.35**	1.49	1.6	**3.7**	0.4	1.6
Montane Cordillera	0.38	0.23	0.26	1.08	**-3.9**	2.1	-0.2	-2.3
Boreal Cordillera	**0.67**	0.20	0.31	1.31	1.6	1.8	**1.9**	6.6
Taiga Cordillera	**0.62**	0.13	0.25	1.14	2.2	-0.2	0.7	2.9
Atlantic Maritime	0.06	0.12	0.07	0.41	1.8	0.7	0.0	0.5
Eastern Subarctic	-0.06	0.14	0.06	0.46	-2.6	-1.9	**-1.3**	-5.4
Arctic Cordillera	0.01	0.22	0.11	0.53	-2.3	**3.5**	**1.9**	9.1
All of Canada	0.28	0.13	0.17	0.74	-0.6	0.6	0.6	2.5

vs. zonal flow). This kind of shift as a response to Arctic warming and sea ice loss has been widely discussed in the literature (Cohen et al., 2014; Francis & Vavrus, 2012, 2015).

Warmer summer temperatures are being experienced in all mountain regions in Canada, with trends equal to or exceeding the national average. Warming in the Pacific Maritime region stands out in particular, with a rate of 0.56°C per decade, which is four times the national average. The Montane and Arctic Cordillera regions are also experiencing strong summer warming, and a range of processes that include albedo feedbacks from declining snow and ice cover (Pepin et al., 2015) and increased atmospheric moisture and downwelling longwave radiation (Williamson et al., 2020) may contribute to the amplified mountain warming.

Elevation-dependent warming

Numerous studies suggest that high elevation mountain regions may be highly sensitive to climate change, a phenomenon known as elevation-dependent warming (EDW; Diaz & Bradley, 1997; Hock et al., 2019; Pepin et al., 2015; Rangwala & Miller, 2012). Climate model studies generally find a systematic increase in warming with elevation in future climate projections (Giorgi et al., 1997; Kotlarski et al., 2012; Palazzi et al., 2019). Pepin and Lundquist (2008) observe that climate change may vary systematically with elevation, but this does not necessarily mean that highest elevations are warming the most. Hence, EDW can be more subtle and complicated than just amplified warming at higher elevations.

Elevation-dependent warming also needs to be considered in the broader context of elevation-dependent climate change (EDCC), as other meteorological variables, energy fluxes, and surface conditions have strong gradients with altitude, and can be expected to respond nonlinearly to climate change. Several climate change feedbacks vary with elevation, such as albedo declines due to reduced snow and glacier cover, the effects of aerosols, changes in cloud cover, and increases in atmospheric humidity and diabatic heating (i.e., heat release from condensation). Increased humidity drives an increase in incoming longwave radiation and also reduces surface fluxes of evaporation and sublimation at high elevations, and their associated cooling influences. Changes in aerosols, clouds, and atmospheric humidity vary with elevation, and not all of these effects will lead to increased climate sensitivity at high elevations.

There is observational evidence for EDW in some parts of the world, although limited long-term *in situ* data are being collected to evaluate this at high elevations in most mountain regions, including those in Canada. Where data are available, observational evidence for EDW in the world's mountain regions is mixed (Hock et al., 2019), although several studies document a strong EDW signal in winter months and for minimum temperatures (Beniston & Rebetez, 1996; Pepin et al., 2015; Sharma & Dery, 2016). This argues for

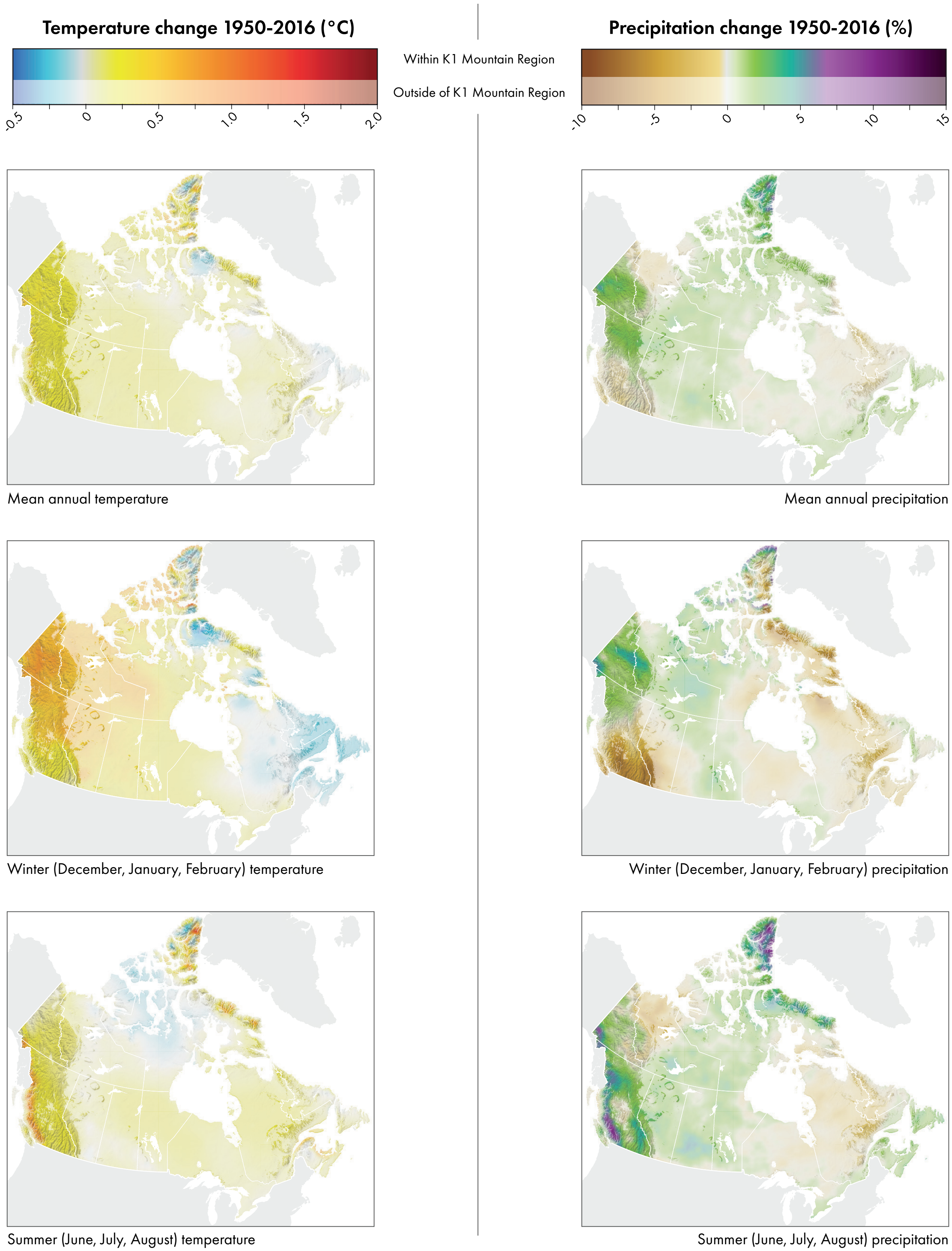

Fig. 5.1: Temperature (left) and precipitation (right) trends in Canada in the ERA5 climate reanalysis, 1950 to 2016, expressed as degrees C of temperature change and % change in precipitation per decade. The top, middle, and bottom rows show the mean annual, winter (December, January, February), and summer (June, July, August) trends. Data from Hersbach et al., 2023.

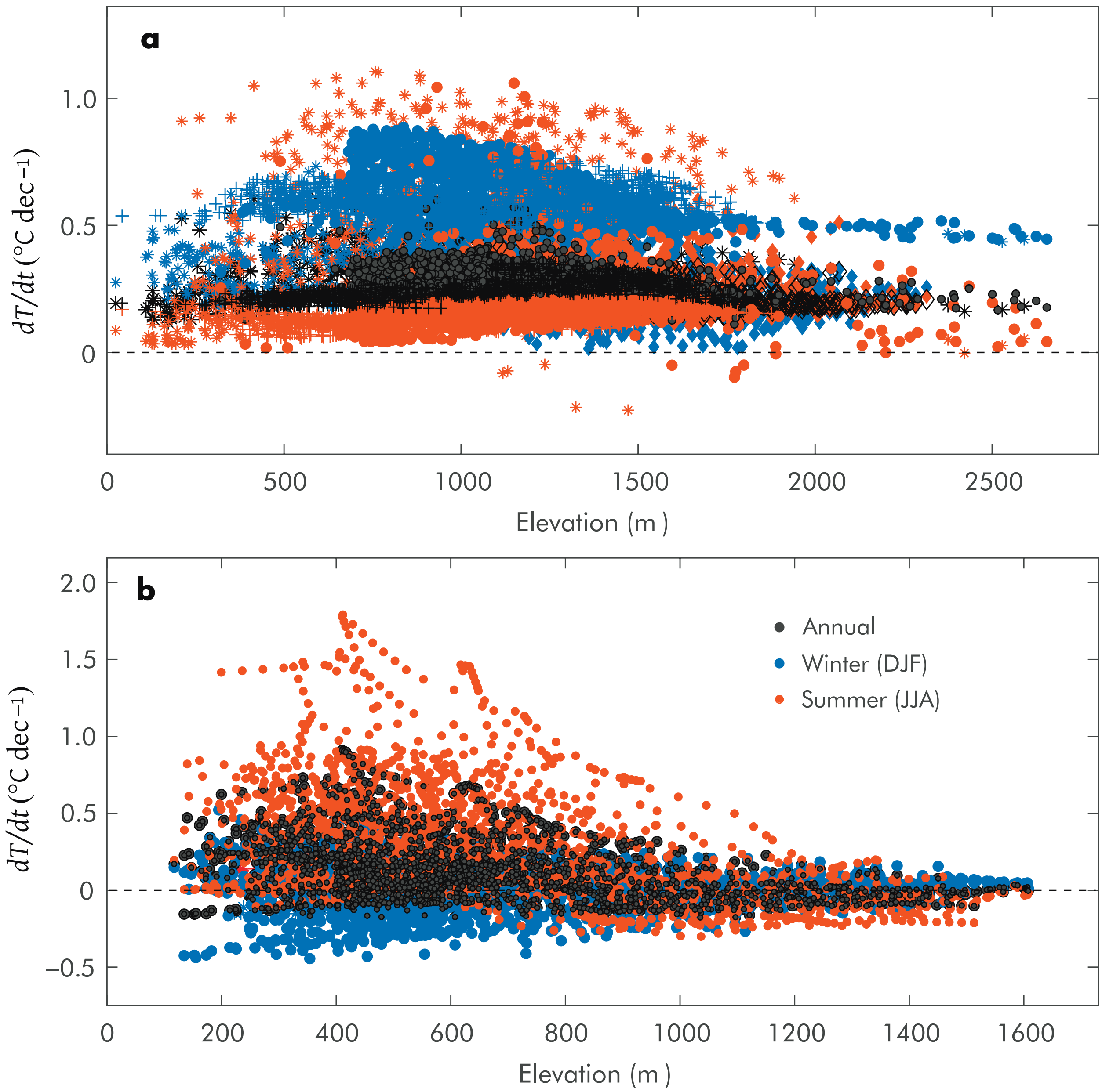

Figure 5.2: Rates of decadal temperature change from 1950–2021 as a function of elevation for each of the ERA5 grid cells in mountain regions of (a) western and (b) eastern Canada. Black, blue, and red symbols are for mean annual, winter, and summer temperatures, respectively. The various symbols in (a) refer to specific mountain regions: Pacific Maritime (asterisks), Montane Cordillera (circles), Boreal Cordillera (diamonds), and Taiga Cordillera (plus signs).

the influence of free-atmosphere conditions such as humidity changes (Williamson et al., 2020) rather than the influence of albedo feedbacks, as albedo effects should be strongest during summer and for maximum temperatures. Pepin and Lundquist (2008) report maximum warming in the elevation band near 0°C, where feedbacks from reduced snow and ice cover or other effects may be accentuated. At higher elevations, it is often cold enough that snow and ice cover are not yet strongly affected by climate change; precipitation still falls as snow, not rain, and seasonal snow cover at high elevations may not (yet) be declining.

The extent to which EDW is occurring within Canada is unclear, and the dearth of high-elevation observational data makes it difficult to assess this. Sharma and Déry (2016) analyse temperature trends from 1950–2010 using interpolated climate station records in the Cariboo Mountains of British Columbia (Montane Cordillera). They report higher rates of warming in this region than the regional and national average, with a statistically-significant trend for the increase of minimum temperature with elevation but the opposite relation for maximum temperatures (i.e., muted warming at higher elevations). The analysis is mostly restricted to elevations below 2000 m, as there are insufficient station records to assess temperature trends above this elevation. Based on climate reanalyses, Williamson et al. (2020) report amplified warming at high elevations in the St. Elias Mountains, Yukon (Boreal Cordillera). This was attributed to increases in humidity and incoming longwave radiation above ~2000 m, also reported by Ochwat et al. (2021). We are not aware of other assessments of EDW in mountain regions in Canada.

There is no systematic pattern with elevation for the ERA5 temperature trends in Canada (Figure 5.2). All mountain regions in Canada are warming (Table 5.1), but only three of the seven major regions (Pacific Maritime, Atlantic Maritime, and Taiga Cordillera) show statistically significant increases in annual warming rates with elevation, from +0.06 to +0.12°C decade^{-1} km^{-1}. Distance from the ocean may be a factor here, as temperature changes are moderated in low-elevation coastal environments. Three other mountain regions in Canada see *less* warming at higher elevations (Montane Cordillera, Boreal Cordillera, and Arctic Cordillera). Temperature changes in the Arctic Cordillera decline with elevation, with a gradient of -0.23°C decade^{-1} km^{-1} (Figure 5.2b). The strongest decline in warming rates with elevation in the Arctic Cordillera is in the summer months, with an altitudinal gradient of -0.48°C decade^{-1} km^{-1}. This may be due to the strong relation between Arctic warming and sea ice loss, which is felt most strongly at sea level; the climate change signal is muted at higher elevations on Arctic icefields.

The strongest EDW signal in Canada is in the summer months and the maximum warming rate is at low- to mid-elevations, roughly 500–1200 m in western Canada and 300–600 m in eastern Canada. This may reflect elevations near the 0°C isotherm and with the strongest changes in snow and ice cover, as observed by (Pepin & Lundquist, 2008). Future warming trends may deviate from this pattern, if the strongest band of warming follows the 0°C isotherm or the summer snowline to higher elevations in the coming decades. It should also be restated that climate reanalyses and most climate models do not resolve the mountain-specific atmospheric and surface processes that may underlie EDCC. There is an acute need for increased high-elevation observations to test the EDW hypothesis in Canada and to fully understand what climate change means for alpine environments (Hik & Williamson, 2019).

5.2.2 *Historical precipitation trends*

Weather station data show mixed precipitation changes across Canada in recent decades, and this is also true of the mountain regions in Canada (Fig. 5.1). Northern Canada has gotten wetter, with observed precipitation increases of 20–50% from 1948–2016 (Bush and Lemmen, 2019). This is reflected in the observations of Brandy Mayes of the Kwanlin Dün First Nation, who notes the increasing unpredictability of precipitation regimes in Yukon Territory (LC 5.3). The magnitude and sign of historical precipitation changes in most of southern Canada are more equivocal, with modest drying in some locations but recent annual precipitation totals within 10% of 20th-century baseline values.

Within the ERA5 climatology, historical precipitation trends also show a complex regional and seasonal picture. Overall, precipitation in Canada increased by 0.4% per decade from 1950–2021, with a decline in winter precipitation (0.8% per decade) offset by increases in precipitation in the spring, summer, and autumn. The Arctic Cordillera is the only mountain region in Canad to follow this overall pattern, with strong increases in summer and annual precipitation (+3.5 and +1.8% per decade, respectively), along with drying

Brandy Mayes, Kwanlin Dün First Nation, 2022, LC 5.3

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 5.4

in the winter season (-2.2% per decade). These are among the strongest precipitation signals in the country. In the Pacific Maritime, Montane Cordillera, and Eastern Subarctic mountain regions, both winter and annual precipitation declined over the historical period. In contrast, the Boreal and Taiga Cordillera regions in northwestern Canada are exceptions to this overall trend, with increased winter precipitation of +1.1 to +1.5% per decade. Summer precipitation changes are regionally variable, but most mountain regions in Canada have seen increased summer precipitation.

It is important to recognize the need to monitor and model surface evaporation rates and soil moisture levels within these considerations, as increased evapotranspiration in a warmer climate can offset increases in precipitation and lead to drier conditions overall. This is difficult to infer or estimate from climate reanalyses, without specific resolution of the mountain environments. This analysis also cannot separate rainfall and snowfall, without sufficient definition of the mountain topography. However, declines in winter precipitation are projected in several of the mountain regions of Canada, at rates of up to -4% per decade. Combined with winter warming, this would lead to reduced winter snowpacks (Sec. 2.3.4). This is echoed in the comments of Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, who discussed the shifting seasons and the increasing unpredictability of the snow and ice seasons (LC 5.4).

5.2.3 *Caveats and research gaps*

The ERA5 climate reanalysis used here has a longitude-latitude resolution of 0.25 degrees (Hersbach et al., 2020). Over Canada, this translates to ~28 km in latitude by ~5 to 20 km in longitude, with finer coverage in northern Canada. At this resolution, reanalyses do not resolve detailed mountain weather and climate processes. Nor will they capture details of precipitation and snowpack distribution in the mountains, alpine ecological, hydrological, or cryospheric conditions, or atmospheric processes such as cold air drainage or the phase of precipitation in the mountains. However, climate reanalyses provide a good representation of regional-scale historical temperature and precipitation trends in different mountain regions in Canada. This is valuable in the context of the CMA, as long-term climate conditions in mountain regions in Canada are not well-observed or documented. Targeted high-resolution modelling studies are needed to construct mountain meteorological and climate change processes in more depth, including a detailed assessment of EDCC. The effects of changing wind and circulation patterns on precipitation trends also require further exploration.

5.2.4 *Future climate projections*

Recent reports of the IPCC (IPCC, 2021; 2022) present global climate change scenarios for an ensemble of global climate models and for different assumptions about future emissions, known as 'shared socio-economic pathways' (SSPs) (Riahi et al., 2017). Model projections were coordinated and compiled through the sixth international Coupled Model Intercomparison Project exercise, known as CMIP6.

Sobie et al. (2021) assess the CMIP6 archive for the ensemble of climate model projections over Canada, illustrated in Fig. 5.3 and demonstrating the wide range of potential climate futures in Canada. There are differences between the climate models, but the dominant factor is the future emissions trajectory. SSP1 describes a scenario for global cooperation and emissions reductions similar to what has been pledged in the Paris Agreement (i.e., achieving net-zero emissions by mid-century), while SSP5 is the opposite scenario, representing a world with intensive ongoing development, limited global cooperation, and minimal adoption of climate mitigation policies, giving continued increases in greenhouse gas emissions. This is essentially our current trajectory, although effective implementation

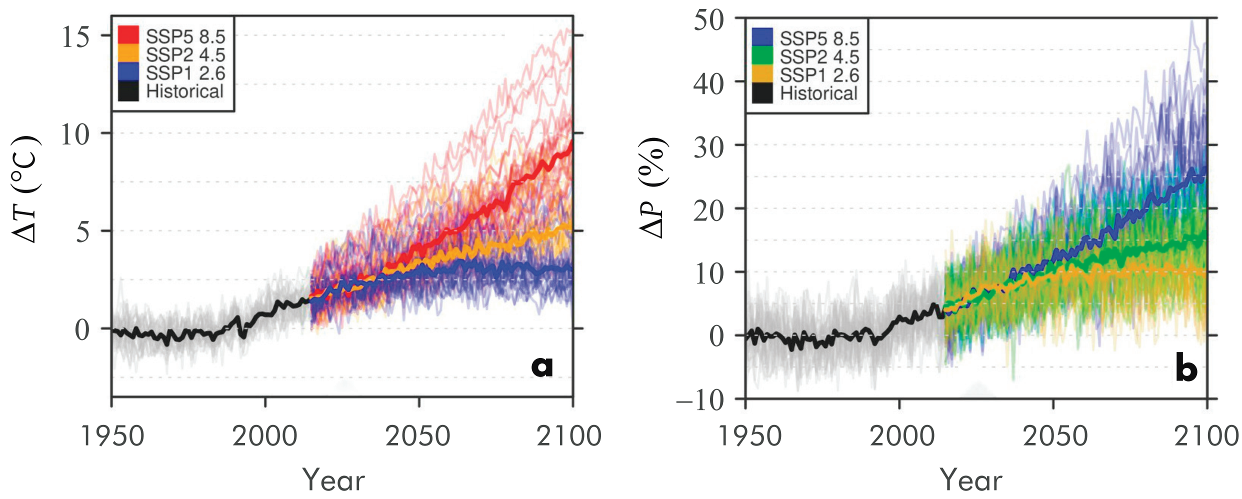

Figure 5.3: Projected (a) temperature and (b) precipitation changes over Canada to 2100 from the suite of CMIP6 climate models for scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5, after Sobie et al. (2021). Each line indicates individual model results, with the colours indicating the SSP scenario and the heavy lines showing the mean of all models for each SSP scenario.

of current global emissions reductions pledges would deflect us from this scenario and set the world on a course closer to SSP2.

The Canada-wide projections in Fig. 5.3 indicate a warmer, wetter country, overall, although temperature and precipitation changes in future decades depend a great deal on the emissions trajectory. There is ongoing climate change in the next two decades with all scenarios, due to inertia in the climate system and the time required for large-scale emissions reductions (i.e., through the necessary transformation of energy and transportation systems). For SSP1, where emissions are aggressively reduced and the buildup of greenhouse gases in the atmosphere is eliminated by mid-century, the climate system stabilises and average warming over Canada reaches about 2.5°C, accompanied by a 10% increase in annual precipitation over Canada. For SSP2 and SSP5, climate change continues through the century but there are radical differences in the national average by the year 2100, depending on how much global greenhouse gas emissions can be reigned in. For SSP2, Canada warms by about 5°C by 2100, with a 15% increase in average precipitation, while SSP5 projections indicate a mean warming of almost 10°C, with a ~25% increase in annual precipitation. There is considerable spread in the model forecasts for 2100, associated with the climate sensitivity of different global climate models. This means that forecasts for 2100 are highly uncertain; climate change in Canada might be moderate relative to the ensemble mean forecast, but changes in Canada could also be even more severe.

Detailed future climate change projections over Canada were analysed in the 2019 Canada's Changing Climate report (Bush & Lemmen, 2019) and show the same essential picture of a warmer, wetter Canada in future decades, but there are important regional differences. CMIP6 projections for end-of-century from the most recent version of the Canadian climate model, CanESM5 (Swart et al., 2019) are shown in Fig. 5.4 to 5.6.

Table 5.2 compiles projected future temperature and precipitation conditions over the major mountain regions in Canada for the period 2071–2100. Results are presented for the CMIP6 simulations from CanESM5 for scenarios SSP1, SSP2, and SSP5, based on the gridded climate model data that intersects each mountain region. Results are also shown for the full Canadian land mass. All regions are expected to experience significant warming by end-of-century, with warming trends of 0.3–0.5°C per decade for SSP1 and 0.9–1.6°C per decade for SSP5. As is well documented elsewhere (e.g., Bush & Lemmen, 2019), the northern regions of Canada experience the most acute warming; the Arctic Cordillera, Eastern Subarctic, and Taiga Cordillera all see annual mean temperature increases that exceed the national average. Warming is most dramatic in the winter months

Table 5.2: Projections of future climate conditions for the different mountain regions in Canada. Calculated from the CMIP6 simulations of the CanESM5 Earth system climate model, based on the mean of 10 simulations (i.e., a 10-member ensemble) for the historical period (1850–2014) and future projections (2015–2100) from the SSP1-2.6, SSP2-4.5, and SSP5-8.5 emissions scenarios. The baseline climatology is from 1971–2000 and the SSP projections are the means for the period 2071–2100. Trends are calculated from 2000–2100, expressed as decadal rates of change, and winter (DJF), summer (JJA) and mean annual values are denoted *w*, *s*, and *a*. Bold values highlight large departures from the average Canadian trends.

Projected Temperature and Precipitation Conditions, 2071–2100: CanESMS-CMIPS

					Temperature Trends, 2000–2100 (°C dec^{-1})									
	Annual Temperature (°C)				*SSP1-2.6*			*SSP2-4.5*			*SSP5-8.5*			
Mountain Region	*Ref*	*SSP1*	*SSP2*	*SSP5*	*w*	*s*	*a*	*w*	*s*	*a*	*w*	*s*	*a*	
Pacific Maritime	2.7	6.2	7.6	10.5	0.3	0.3	0.3	0.5	0.5	0.5	0.9	1.0	0.9	
Montane Cordillera	0.4	4.0	5.5	9.0	0.3	0.3	0.3	0.5	0.5	0.5	0.9	1.1	0.9	
Boreal Cordillera	-5.1	-1.4	0.4	4.0	0.3	0.3	0.3	0.6	0.5	0.6	1.2	1.0	1.1	
Taiga Cordillera	-7.8	-3.3	-0.9	3.6	0.5	0.3	0.3	1.0	0.5	0.7	1.8	0.9	1.3	
Atlantic Maritime	0.2	4.9	6.9	10.7	0.5	0.3	0.3	0.8	0.5	0.6	1.4	1.0	1.2	
Eastern Subarctic	-6.5	-0.3	2.2	6.6	0.7	0.3	0.4	1.1	0.6	0.8	1.8	1.2	1.4	
Arctic Cordillera	-21.1	-13.6	-10.6	-5.7	0.8	0.2	0.5	**1.5**	0.3	0.9	**2.7**	0.6	1.6	
All of Canada	-2.2	2.6	4.8	8.9	0.5	0.3	0.4	0.9	0.5	0.7	1.6	1.0	1.2	

					Precipitation Trends, 2000–2100 (% dec^{-1})									
	Annual Precipitation (m)				*SSP1-2.6*			*SSP2-4.5*			*SSP5-8.5*			
Mountain Region	*Ref*	*SSP1*	*SSP2*	*SSP5*	*w*	*s*	*a*	*w*	*s*	*a*	*w*	*s*	*a*	
Pacific Maritime	1.72	1.92	1.97	2.11	1.3	0.8	1.2	1.6	**0.5**	1.6	2.7	**-1.7**	2.6	
Montane Cordillera	0.99	1.18	1.23	1.33	1.5	1.9	1.9	2.3	1.9	2.5	3.6	1.6	3.7	
Boreal Cordillera	0.86	1.06	1.15	1.35	1.6	2.2	1.9	2.5	3.1	3.1	4.7	4.1	5.3	
Taiga Cordillera	0.48	0.62	0.68	0.82	1.9	2.2	2.2	3.4	3.2	3.7	5.4	4.9	6.2	
Atlantic Maritime	1.21	1.42	1.46	1.52	1.5	1.0	1.3	3.0	**0.8**	1.7	5.4	**0.0**	2.3	
Eastern Subarctic	0.85	1.09	1.15	1.25	2.4	1.3	1.7	3.8	2.0	2.8	6.3	1.6	3.9	
Arctic Cordillera	0.27	0.39	0.44	0.58	**4.1**	2.3	2.5	**7.1**	**3.7**	**4.4**	**13.6**	**7.2**	**8.5**	
All of Canada	0.69	0.81	0.86	0.96	1.7	1.3	1.5	3.3	1.8	2.5	5.9	2.9	4.3	

in northern and eastern Canada, particularly for the Arctic Cordillera, but this is not the case for lower latitudes in southwestern Canada, where summer warming rates exceed the winter warming. Fig. 5.4 plots the projected century-scale temperature increases for each mountain region and the two end-member scenarios, SSP1 and SSP5. Fig. 5.6 illustrates the projected warming by 2050 within each mountain region of Canada.

Projected precipitation changes in each mountain region also have some systematic regional and seasonal structure. Mean annual precipitation changes generally scale with the amount of warming, and as a percentage are greatest in the Arctic Cordillera (Table 5.2 and Fig. 5.5, 5.6). The high rates of warming and wetting in the high Arctic are associated with a number of climate processes, including extensive sea ice loss in the high-emissions scenarios. Winter precipitation increases are greatest in all mountain regions, from 1–4% per decade for SSP1 and 3–14% per decade for SSP5. This bodes well for potential increases in winter snowpack in the mountains, although there is a trade-off against warming, which will cause a greater fraction of precipitation to fall as rain rather than snow at lower elevations (DeBeer et al., 2021; Mortezapour et al., 2022). This may increase the intensity of rain-on-snow driven flooding but projected frequency of rain-on-snow events is highly location-dependent (López-Moreno et al., 2021). Increases in high-elevation snowpack can be expected in most regions, though lower latitudes in the Pacific and Atlantic Maritime regions, where winters are relatively mild, may see increased winter rainfall rather than snow accumulation at high elevations.

Summer precipitation also increases across mountain regions in Canada in most of the future

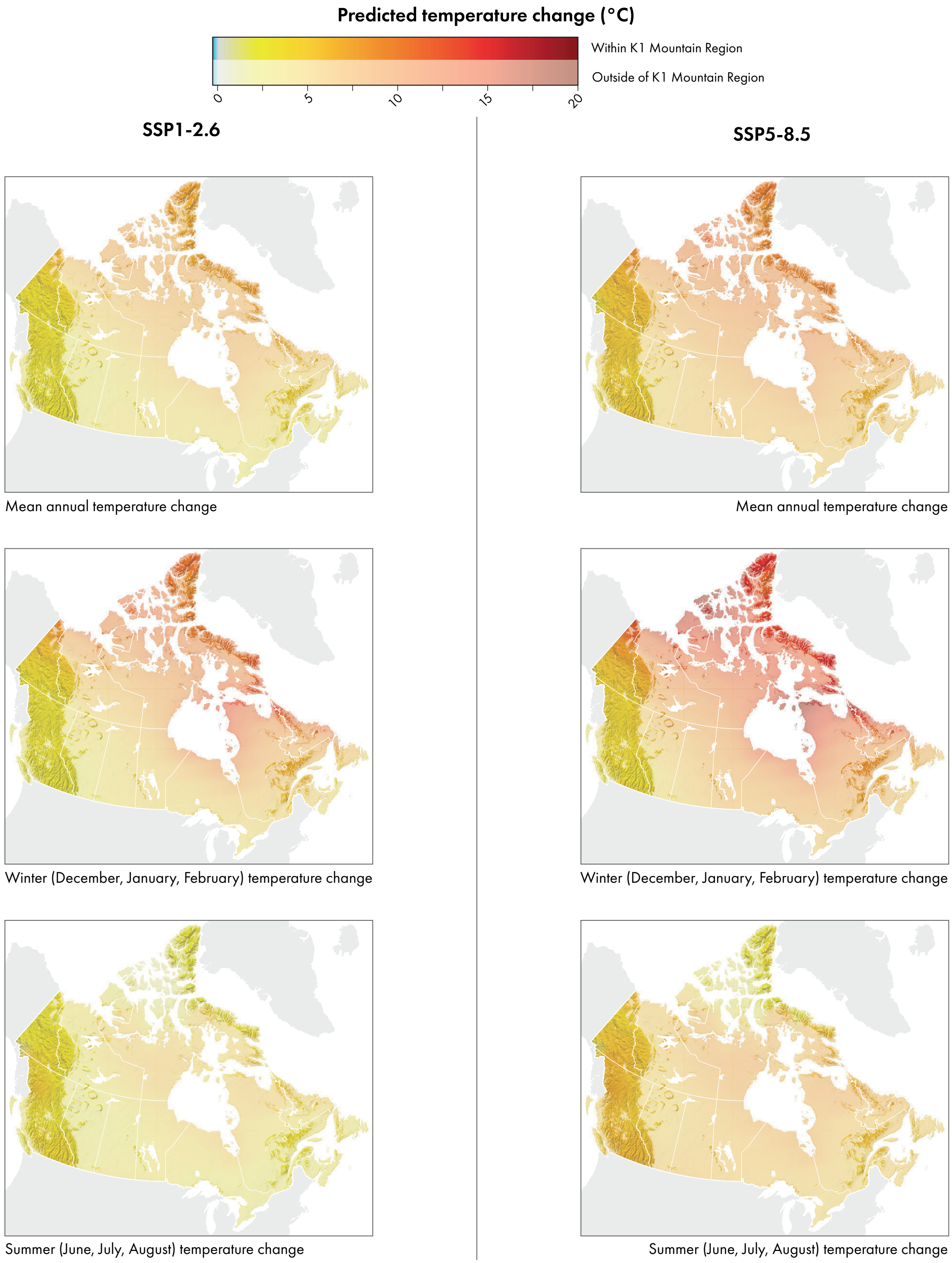

Figure 5.4: Projected temperature changes in 2050 relative to the reference period 1971–2000 for scenarios SSP1-2.6 (left) and SSP5-8.5 (right). Top, middle, and lower panels show the mean annual, winter (December, January, February), and summer (June, July, August) temperature anomalies, respectively, calculated from the mean CanESM5 temperature projections for the period 2036–2065. Data from Swart et al., 2019, 2019a, 2019b.

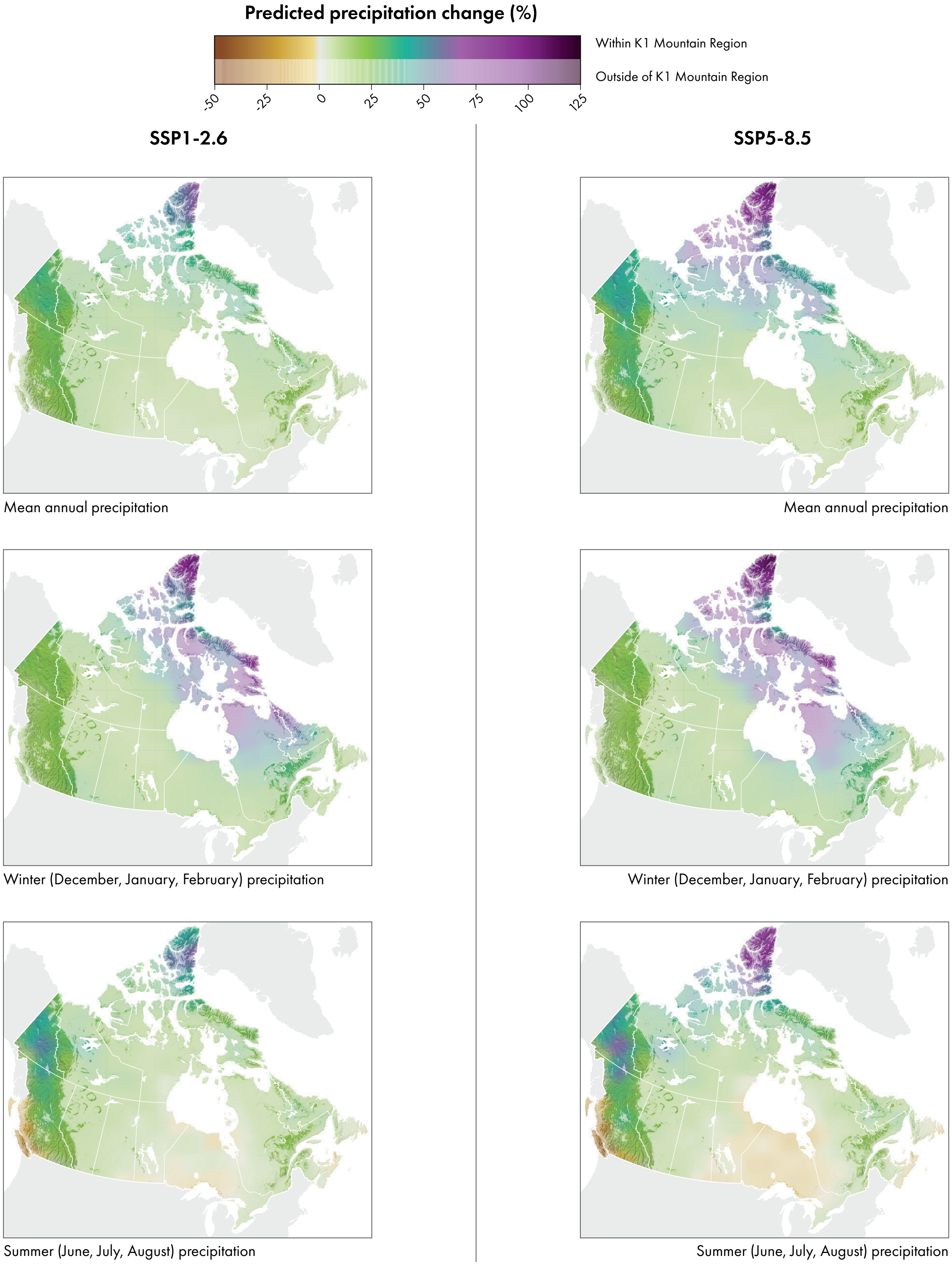

Figure 5.5: Projected precipitation changes (%) in 2050 relative to the reference period 1971–2000 for scenarios SSP1-2.6 (left) and SSP5-8.5 (right). Top, middle, and lower panels show the mean annual, winter (December, January, February), and summer (June, July, August) precipitation anomalies, respectively, calculated from the mean CanESM5 precipitation projections for the period 2036–2065. Data from Swart et al., 2019, 2019a, 2019b.

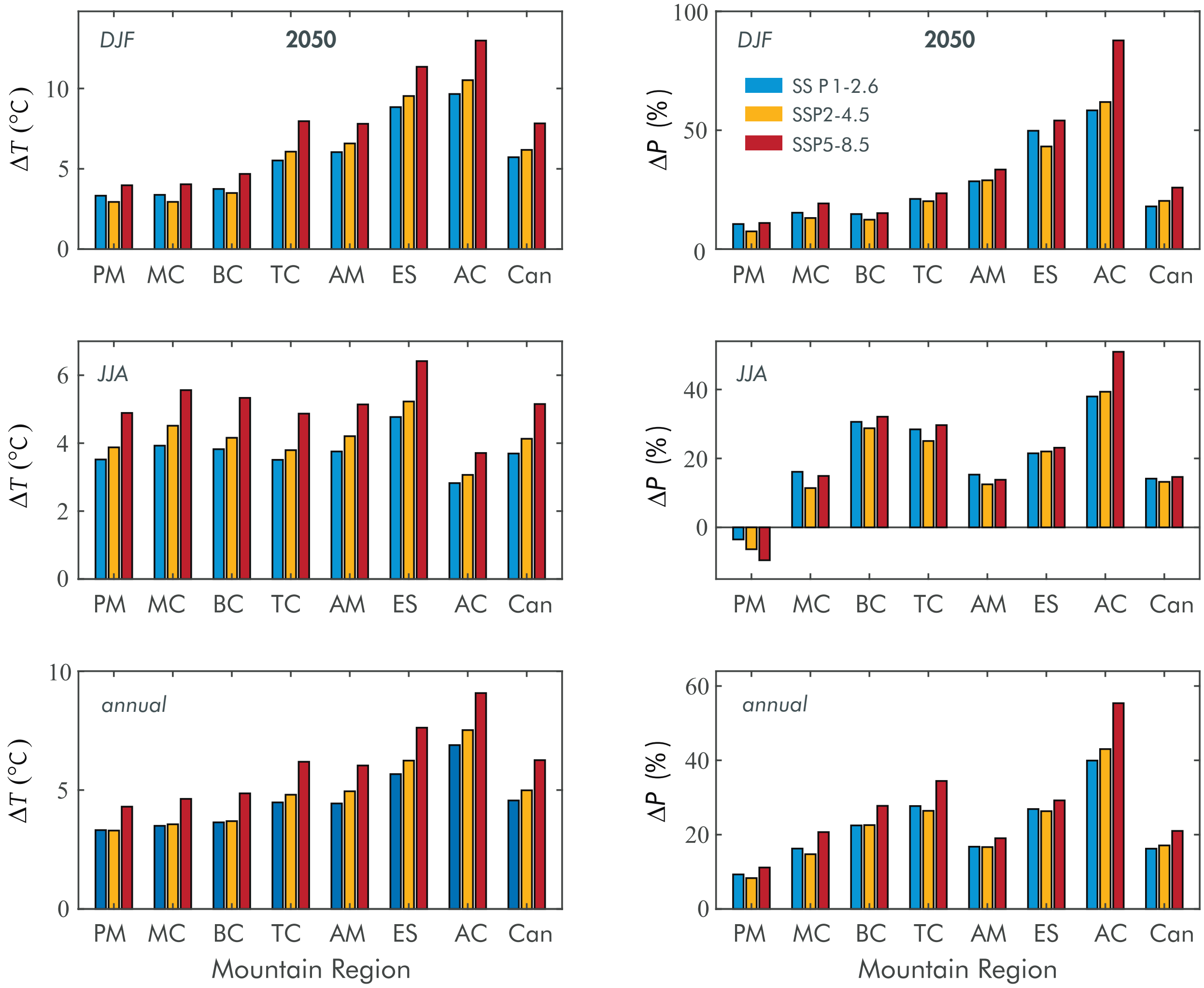

Figure 5.6: Projected temperature and precipitation changes in 2050 for the mountain regions in Canada and for all of Canada (Can) for future climate scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 (Riahi et al., 2017). Anomalies are calculated from average conditions over the period 2036–2065 relative to the 1971–2000 baseline climatology. Simulations are from the CanESM5 model of the Canadian Centre for Climate Modelling and Analysis. Data from Swart et al., 2019.

climate change scenarios, although summer precipitation trends are weaker than the winter and annual values (Table 5.2). Scenario SSP5 is a notable exception, with summer precipitation projected to decline in the Pacific and Atlantic Maritime regions. Both of these coastal regions are projected to see a shift to warmer and drier summers, accompanied by modelled decreases in summer cloud cover. This weather setup is associated with greater wildfire risk, heat stress on lakes, rivers, and ecosystems, and high rates of glacier mass loss (e.g., WMO, 2022).

Climate change scenarios have been examined over specific mountain regions in Canada in several previous analyses, most commonly within investigations of future changes in snow, glaciers, or hydrological systems (Clarke et al., 2015; Islam et al., 2017; Mortezapour et al., 2022). Future climate scenarios in the Montane Cordillera region have received the most attention (e.g., Murdock et al., 2013). The prediction of warmer, wetter conditions in future decades is unanimous in the published literature, but changes in precipitation vary geographically and seasonally. Drier summers are projected in southwestern Canada in many studies (Bush & Lemmen, 2019; Murdock et al., 2013), which would negatively impact the ecology, wildfire risk, stream and lake temperatures, freshwater availability, alpine snowpack, and glacier melt rates in mountains of the Pacific Maritime and Montane Cordillera regions.

5.2.5 *Caveats and research gaps*

The climate models used for these future scenarios do not resolve the mountain topography, so they cannot explicitly capture the detailed meteorological or climatological processes or elevation-dependent considerations that need to be understood for climate change impact assessment or adaptation activities in mountain regions. This is a clear gap in future climate change scenarios. Regional climate models help to bridge this gap and provide improved representation of precipitation patterns in mountain regions, but most regional climate modelling studies to date in Canada have resolutions of 10s of km, which do not explicitly resolve mountain slope or alpine processes (e.g., Murdock et al., 2013; Perroud et al., 2019). This makes it difficult to directly assess considerations such as local orographic precipitation processes, the rain-to-snow transition, snow avalanche hazards, or alpine ecological, hydrological, and glaciological processes as a function of elevation.

As an example, climate models generally predict increases in high-elevation precipitation in a warmer climate, but it is difficult to resolve changes in the snowline (rain to snow transition) and to predict the impacts on snow accumulation at upper elevations. There is broad consensus that snow accumulation and snow cover will decline at low elevations in the mountains, but numerous modelling studies project increases in snow accumulation at high elevations (e.g., Schnorbus et al., 2014; Shannon et al., 2019). There is limited direct data to assess this for the historical period. There is a chance that high-elevation snow accumulation has been increasing, or could increase in future decades, although such a trend is not evident for recent climate change in hydrological and glacier mass balance studies in the Montane Cordillera (Islam et al., 2017; Pradhananga & Pomeroy, 2022). High-elevation snow and precipitation observations are needed to assess this in the different mountain regions in Canada.

The overall structure of EDCC is highly uncertain in mountain regions in Canada. There is a narrative that warming is amplified in global mountain regions and at high elevations (e.g., Beniston et al., 1997; Palazzi et al., 2019; Toledo et al., 2022), but this is not well-documented in Canada (see Sec. 5.2.1). The influences of continentality, latitude, and regional climate change trends may dominate the elevation dependency in Canada, e.g., Arctic amplification in association with sea ice loss and increasing humidity; strong warming in western Canada in association with Pacific warming and changes in atmospheric circulation (Bush & Lemmen, 2019). Within a given mountain range, however, there are theoretical reasons to anticipate an elevation dependency as well (Pepin et al., 2015; Rangwala & Miller, 2012). Changes in snow, ice, and vegetation cover, atmospheric humidity, cloud conditions, and atmospheric lapse rates all influence surface climate conditions differently as a function of elevation, and these interactions need to be better understood to inform climate downscaling strategies and construction of high-resolution climate scenarios in alpine regions in Canada.

Additional studies of future climate projections in mountain regions in Canada should also consider ensembles of climate models. We restrict the analysis to the Canadian climate model here, CanESM5, with results based on the average of multiple realisations, but a rigorous analysis is needed to consider multiple climate models and to assess the skill of different models over the historical period in different regions of Canada.

5.3 Land Cover and Land Use Pressures

Development of land and waterways for industrial, agricultural, energy production, and municipal needs represents a significant anthropogenic pressure in some of the mountain regions in Canada, with direct impacts on ecosystems, hydrology, Indigenous lands and ways of life, and sacred cultural sites. Land use changes are introduced by a wide array of human activities, including clearing of land for industry (e.g., mines, quarries, forestry, oil and gas production), conversion to agriculture, horticulture and pastoralism; development and expansion of urban communities and transportation networks including road, rail, and human-use trails and; supporting infrastructure such as water treatment plants and landfills. The plentiful water supply and steep slopes in mountain areas are supportive of hydroelectric power generation, but hydroelectric facilities can have a large landscape footprint when they involve dams and flooding of the land to create reservoirs. These economic development activities and encroaching infrastructure all disrupt the biophysical environment, with particular concerns around natural hazards, habitat fragmentation, and loss of connectivity. They may also disrupt and displace existing human activities, relationships, and values in the landscape, with consequences for social, cultural, and economic life, including in Arctic regions (Povoroznyuk et al., 2022). This has been steadily documented through history, both by Indigenous knowledge sources and scientific studies.

5.3.1 *Changes in land cover*

Mountain regions in Canada are covered by a wide range of surface types (see Chapter 2). Changes in land cover occur through both natural and human pressures (Hermosilla et al., 2018; Lambin & Geist, 2008), and can occur over both short (daily) and long (decadal) timescales. Deforestation or wildfire, for example, are two mechanisms for rapid land cover changes. Perennial snow cover and afforestation represent two slower mechanisms for land cover change. Changes in land cover have profound impacts on biodiversity and ecology (Sala et al., 2000), but also affect global and regional climate (Feddema et al., 2005; Mahmood et al., 2014) and hydrology (Matheussen et al., 2000; Quinton et al., 2019; VanShaar et al., 2002).

Rapid land cover changes have been observed in the Torngat Mountains (Davis et al., 2021b), where shrub-covered terrain has expanded over the past 30 years. A Canada-wide land cover change analysis for the period 2000–2011 found decreases in needle-leaf forests and attributed this to wildfires and the mountain pine beetle outbreak in the Montane Cordillera (Pouliot et al., 2014). To our knowledge, no studies to date have focused specifically and comprehensively on land-cover change in the mountain regions in Canada.

We use the annual land cover classification derived for all of the forested regions in Canada (Hermosilla et al., 2018, 2022) to examine land cover change in CMA mountain regions (Fig. 5.7) between 1985 and 2019. Regions with little or no forest cover, including the Arctic Cordillera, Interior Hills North, Eastern Subarctic, and Taiga Cordillera, are not included in this analysis, as the dataset only covers forested regions. For the remaining regions, striking patterns of land cover change emerge.

The area of perennial snow and ice declined in nearly all regions, by 24 to 78%. This change reflects the declines in mountain glaciers and snowpacks described in Sec. 5.7. The only region to see an increase in snow and ice over this period was the Atlantic Maritime and Boreal Shield—and it is unclear if this is due to a small sample size, or the availability and timing of imagery used in the classification. Areas with extensive snow and ice coverage such as the Montane Cordillera and Pacific Maritime saw corresponding increases in rock and barren terrain, as deglaciation exposes barren alpine landscapes. The remaining mountain regions saw decreases in barren terrain, and this is most likely a result of forest expansion. All mountain regions saw increases in the area of broadleaf forests (+14% to +141%), and with the exception of Interior Hills Central region, all mountain regions saw substantial increases in the area of mixedwood forests (+41% to +422%). The magnitude of some of these increases may be due to small sample sizes, but they clearly indicate the need for further research on land cover changes in mountain regions in Canada.

5.3.2 *Changes in land use*

The three major land uses in Canada can be categorised as 'Cities and Farms', 'Shared Lands', and 'Large Wild Areas' (Fig. 5.8). This classification follows a global framework of land use classification (Locke et al., 2019). Cities and Farms represent the areas across Canada and its mountains with the highest level of land use and cover modification compared to historical baseline conditions. Those are the parts of the country that have the highest pressure from human settlement and agriculture (Coristine et al., 2018). The mountain ecosystems in that land use class have seen the highest level of modification and have seen extensive biodiversity loss. The 'Shared Lands' category is dominated by resource extraction uses such as forestry. The impact on biodiversity in these areas is less pronounced than in the 'Cities and

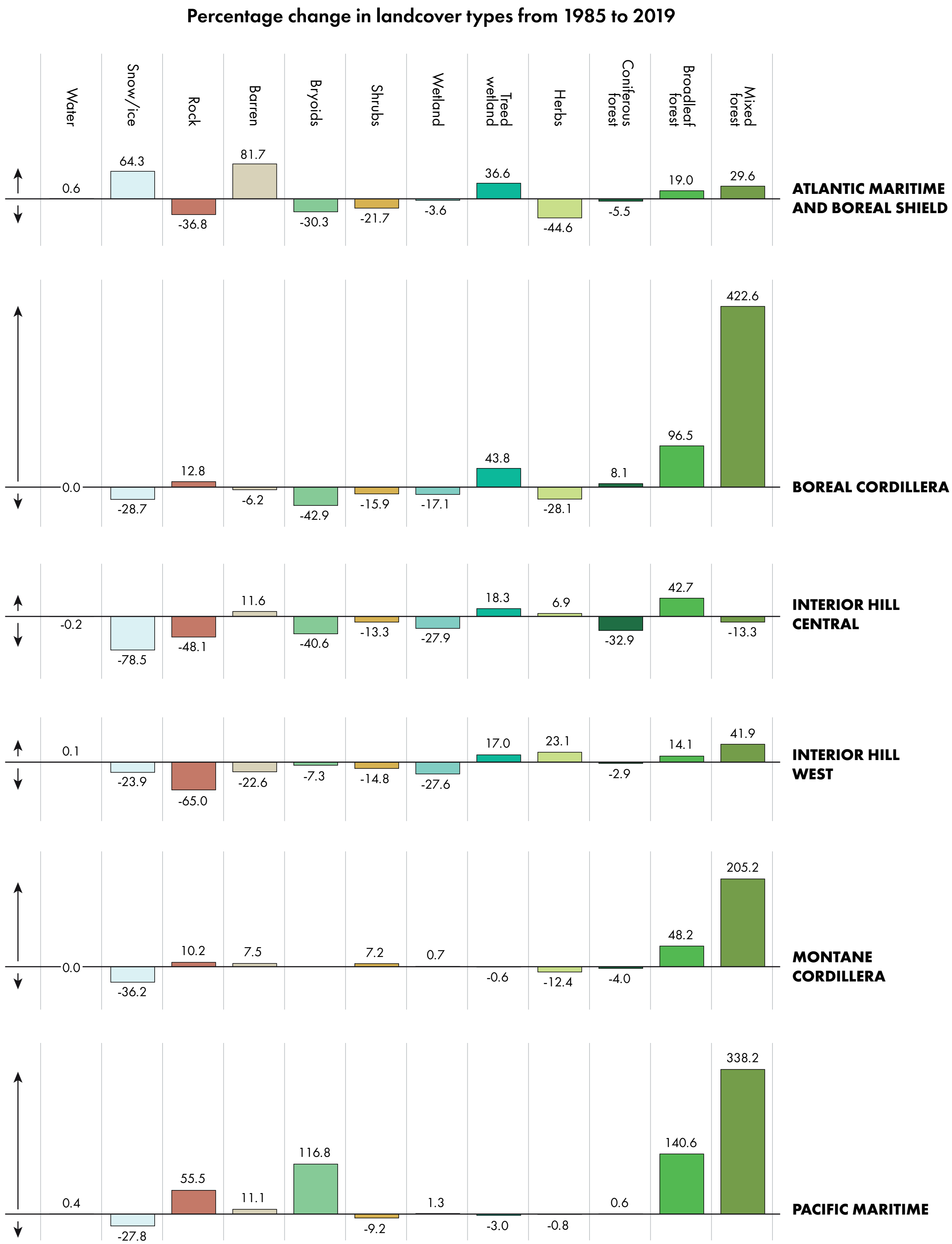

Figure 5.7: Percentage change in land cover types from 1985 to 2019 for six different mountain regions in Canada, as a percentage of the area in 1985. Columns are coloured according to the land cover type. Analysis based on the land cover dataset of Hermosilla et al., 2022.

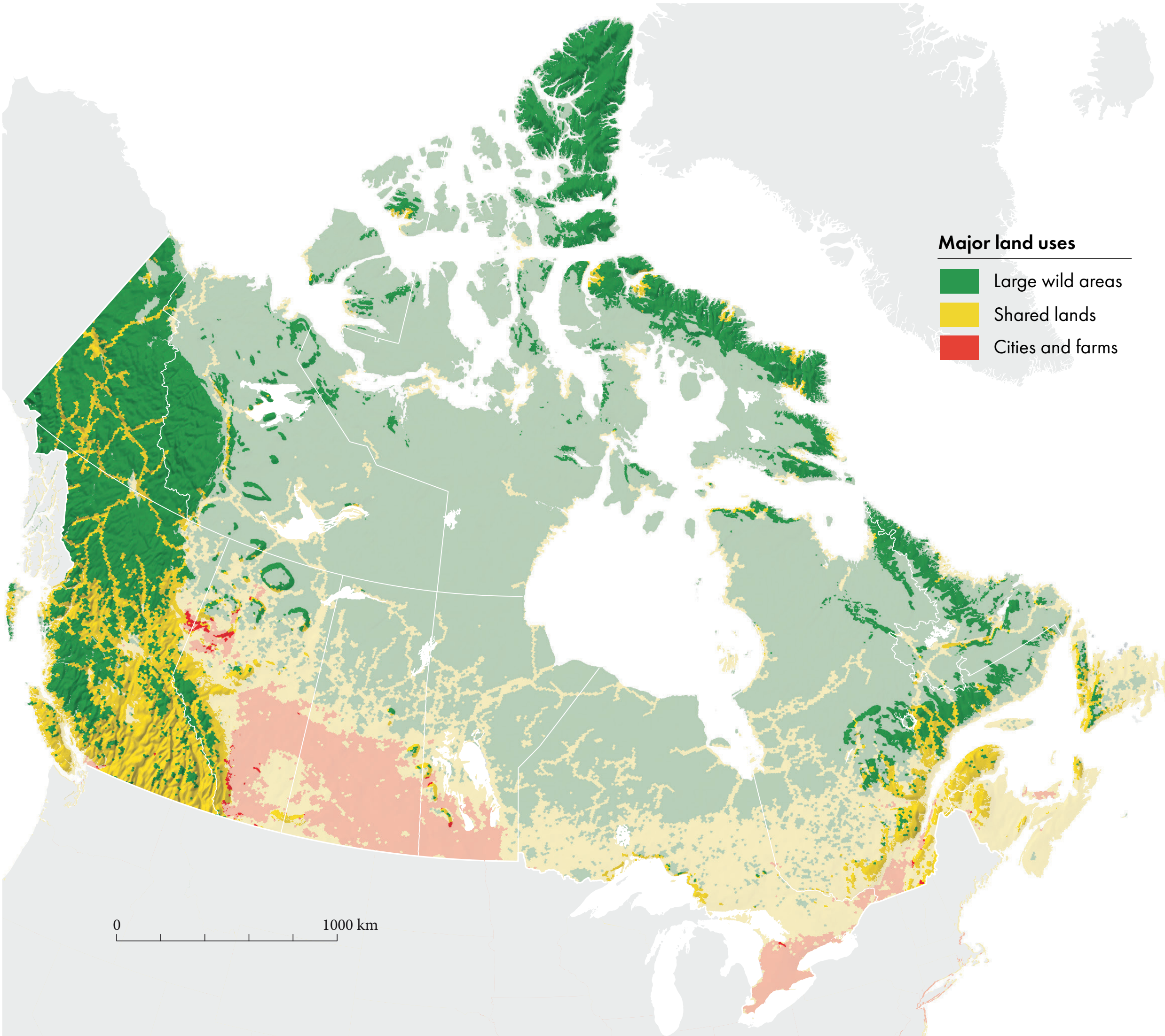

Figure 5.8: Map of major land uses across Canada. Bolded colours represent mountain regions. Data from Locke et al., 2019.

Farms' category, but still present. The mountains of this category are largely impacted by forestry operations related to access corridors, roads, and timber removal.

As a result of human modification, only about 40% of remaining forests have high ecosystem integrity globally (Grantham et al., 2020), with values only slightly higher in Canada. The least impacted and modified areas in Canada and its mountains can be found primarily in the North in the 'Large Wild Areas' part of the country. Mountain ecosystems and functions are least affected by direct human pressures in these parts of the country, but indirect impacts related to climate change and the proliferation of invasive species are having a large effect on that part of Canada due to the high latitudes generally facing greater changes than other parts of the country (Sec. 5.2). 'Large Wild Areas' in northern Canada as well as the Rocky Mountains represent some of the largest areas of forest with high integrity globally (Grantham et al., 2020).

A recent study on anthropogenic pressures across Canada (Hirsh-Pearson et al., 2022) concluded that some of the most ecologically intact areas of the country can be found in northern mountain regions, where 95% of the area has been classified as ecologically intact. In the southern montane regions, roughly 66% of the area is still

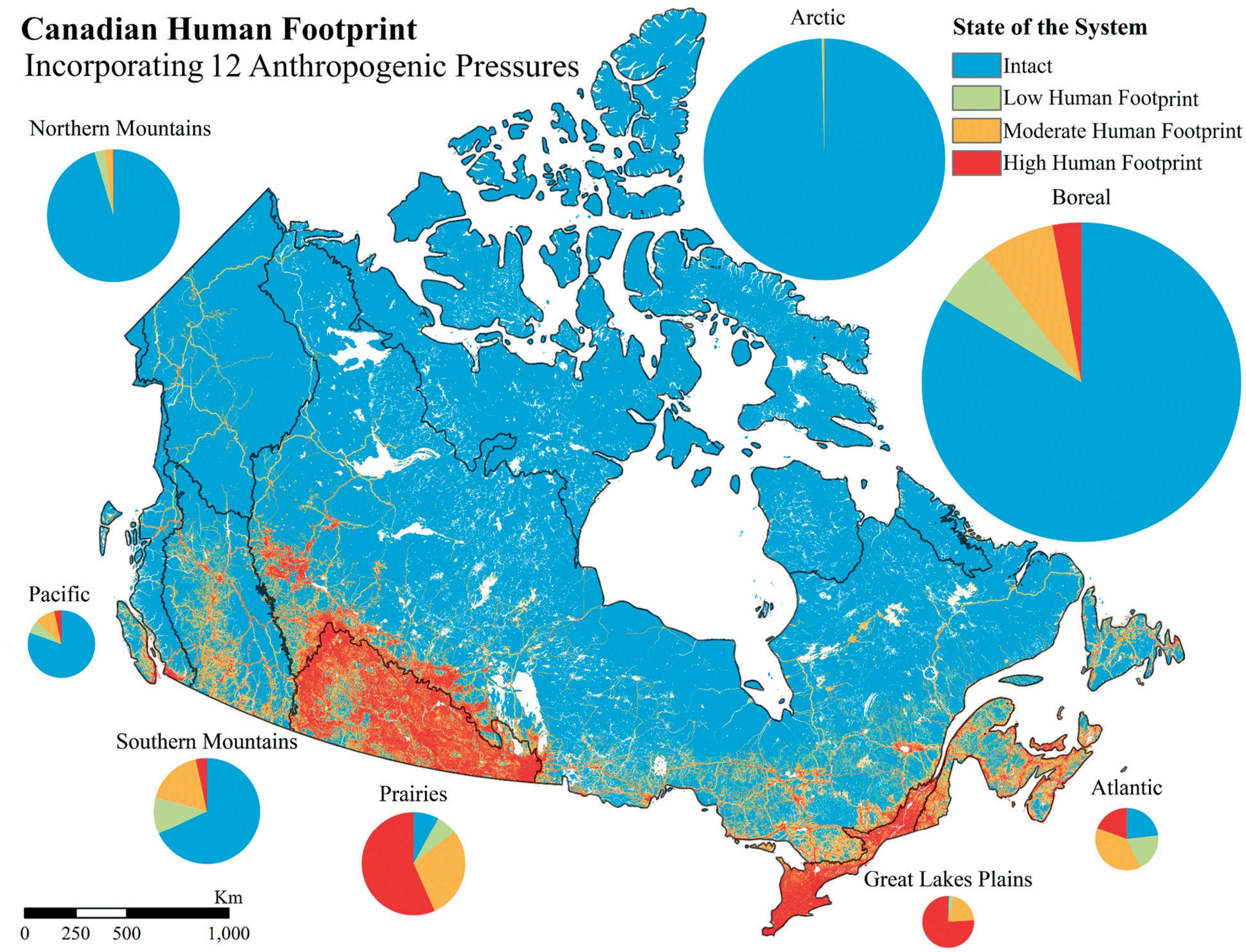

Figure 5.9: Anthropogenic stressors and human footprint across Canada in 2016 (from Hirsh-Pearson, 2022).

ecologically intact (Fig. 5.9). For this work, individual anthropogenic pressures such as roads, crop land, and population density are combined into a human footprint metric that is meant to represent the cumulative anthropogenic pressure across Canada as well as globally (Venter et al., 2016). The highest anthropogenic pressures in Canada are roads (see also Poley et al., 2022), crop land, and population density. Forestry, built environments and pasture lands contribute to the pressure values as well, but each of them contributes less than 10% to the human footprint scores generated for Canada. Combining anthropogenic pressures data with information on climate change impacts would further help us in assessing the health of our mountain ecosystems.

To the best of our knowledge, there are no specific future land use and land cover change predictions available for the entire country that would help us predict potential future pressures on mountain ecosystems in Canada. There are some efforts available, however, to quantify land use risk at a global scale in the form of global land systems analysis (Kehoe et al., 2017; van Asselen & Verburg, 2012). Those efforts are not specific to mountain ecosystems and primarily focus on agricultural development (Kehoe et al., 2017). This kind of information can be of use for planning protected areas for biodiversity conservation into the future (Schuster et al., 2022), however, we would ideally want Canada-specific information on predicted future land use and land cover in order to best estimate the associated impacts on mountain ecosystems.

5.3.3 *Demographic changes*

There is no dedicated approach to understanding demographic changes specifically in mountain regions in Canada, although broad demographic traits and recent trends can be found in census surveys conducted across the country. The delineation of mountain boundaries using geomorphological standards rarely matches enumeration units from census surveys (e.g., the K1 definition of Kapos et al., 2000; McDowell & Guo, 2021), although assumptions can be made about demographic traits in the mountain regions of Canada from census data outside of these defined mountain boundaries.

Global gridded population datasets such as from the Center for International Earth Science Information Network (CIESIN) can also provide a starting point for looking at broad demographic trends in the mountain regions of Canada. We use the gridded population dataset from CIESIN (2018) to observe long-term population changes in mountainous areas. As Table 5.3 below shows, population increases within the mountains in Canada are generally slower than the national average rate of increase from 2000 to 2020. The three major mountain regions with relatively large human settlements (Atlantic Maritime and Boreal Shield, Montane Cordillera, and Pacific Maritime) all experienced below national average population increases over the past two decades. Notably, migration out of the Interior Hills Central mountain region since 2000 was close to 7%, a significant loss of inhabitants in the region.

To explore more recent demographic change in the mountains, we used a similar approach with federal census data from Statistics Canada (2022) from 2016 and 2021, selecting census subdivisions (municipalities) where >50% of the jurisdictional area overlapped with K1 mountain boundaries (McDowell & Guo, 2021). We find that the Pacific Maritime and Montane Cordillera in the west, and the Atlantic Maritime and Boreal Shield mountain regions in the east, demonstrate significant variability in population change, with some municipalities within the mountainous census subdivisions experiencing population decreases of up to 20% and others increases of >15% from 2016 to 2021. Overall, municipalities in these mountain regions experienced an average population growth of 7.2% from 2016 to 2021, slightly higher than the national average growth rate of 5.2%. Gender ratios (expressed as the number of males per 100 females) do not show any significant change from 2016 to 2021 (99.2 to 99.7). However, males are over-represented in mountain regions in Canada relative to the national average, with national gender ratios of 96.5 in 2016 and 97.1 in 2021.

5.4 Resource Development Pressures

5.4.1 *Resource extraction and development*

Resource extraction activities such as mining, oil and gas development, and logging all involve land-use changes (Sec. 5.3), which can be highly visible in mountain regions. Mining scars and clear-cuts often persist for decades in mountain environments, where soil development and reforestation can be slow. These directly alter

Table 5.3: Approximate population count by major mountain regions, clipped to the CMA's 10 mountain regions using the CIESIN global gridded population dataset for the years 2000 and 2020. Note: population numbers do not necessarily account for socio-cultural significance or human presence on the landscape.

Major Mountain Regions	*2000 population*	*2020 population*	*Percent change in population 2000–2020*
Arctic Cordillera	190	253	33.3%
Eastern Subarctic	606	622	2.7%
Atlantic Maritime and Boreal Shield	161,891	183,537	13.4%
Boreal Cordillera	33,402	45,734	36.9%
Interior Hills Central	4922	4596	-6.6%
Interior Hills North	4	5	30.8%
Interior Hills West	16,591	22,110	33.3%
Montane Cordillera	848,967	1,020,490	20.2%
Pacific Maritime	38,441	49,861	29.7%
Taiga Cordillera	132	201	52.2%
Total mountain population	1,105,146	1,327,409	20.1%
National estimate	29,591,177	37,309,968	26.1%

ecological and hydrological function, causing habitat loss and changes in habitat connectivity. In addition, many resource extraction pressures do not necessarily involve land-use changes, including hunting and fishing, harvesting of herbs, berries, and medicines, and water extraction or diversion for industry, communities, or energy production. Unsustainable hunting, fishing, and harvesting activities can represent a significant pressure on ecosystems and biodiversity.

Most water extraction and use in mountain regions is non-consumptive (e.g., municipal water supplies or run-of-river hydroelectric projects), although water quality and temperature is altered as the water is used, treated, and returned to the rivers. Where water is diverted to reservoirs, there will be increased heating and evaporative losses, also affecting the downstream water supply. There can also be consumptive water use by irrigation and industry, affecting both water quantity and quality. For instance, where water is diverted to snow-making activities in ski areas, most of the water remains within the catchment and returns to the system. However, this can introduce chemicals into the environment and may represent a transfer between streamflow and groundwater recharge, which can in turn impact base flows or rivers or aquifer levels. Moreover, substantial energy is required for the snow-making itself, which feeds back on natural systems through increasing demand for power.

The extractive nature of resource development has invasive and colonial elements that go beyond just land-use changes. Local and remote human activities can act as sources of pollution that compromise soil, air, and water quality in mountain regions. Learning Circle participants, including Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, expressed concern that resource extraction activities can also introduce toxic chemicals to the soils, air, and water (LC 5.5).

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 5.5

Many aspects of pollution in mountains in Canada are similar to broader concerns in Canada and globally, but there are also several mountain-specific concerns (McCune et al., 2019). Wildfire smoke has increasingly negative impacts on air quality, felt strongly in many mountain regions due to their proximity to forest cover and the way that high elevations intersect air flows (e.g., Yao et al., 2020). Persistent organic pollutants that have been banned in Canada since the 1980s, such as polychlorinated biphenyls (PCBs) and Dichlorodiphenyltrichloroethane (DDT), continue to melt out of old glacier ice in the Canadian Rockies (Blais et al., 2001). As described in Mountain Environments, these legacy contaminants are being released to alpine streams in low but measurable quantities. Deposition in mountain environments contains other far-travelled pollutants as well, such as heavy metals from upstream industrial activity (e.g., smelters). Mining activity and oil and gas development can also produce toxic tailings that contaminate soils and enter the hydrological system. As an example, high concentrations of selenium released through coal mining activities are well documented in western Canada and internationally, with negative impacts on water quality and aquatic ecosystems (Orr et al., 2006; Rudolph et al., 2008).

5.4.2 *Logging pressures*

Resource development and extraction such as mining and logging activities have cascading implications for the economies, cultures, and health of mountain communities across Canada, especially of Indigenous People. The impacts from the loss of intact forest are described by Watson et al. (2018) as "Fragmentation and degradation of the forest make a traditional lifestyle no longer tenable, pushing indigenous peoples off their land, and driving people to adopt production systems that are incompatible with the maintenance of intact forests. As traditional forest peoples become increasingly sedentary and connected to urban markets, gender roles, diets and cultural values also change. These changes in the lifestyles of indigenous and traditional peoples create greater dependence on urban markets for provisioning, which can lead to effects that erode their cultural identities. Indeed, for many indigenous forest peoples their cultural sense of self is inextricably linked to intact forests."

Degradation and loss of intact forests in mountain regions in Canada is significant due to logging and climate change. These pressures are also interrelated with the socio-political institutions including land tenure, land use planning and forest management that date back many decades if not hundreds of years. Forest management systems in eastern Canada, for example, are based on centuries of colonial and neo-colonial relationships with forest ecosystems and forest peoples including Indigenous Peoples (see Section 4.8.1). Mi'kmaq for example, have been legally excluded from pursuing forest-based livelihoods including logging as a result of Supreme Court decisions such as *R. v. Marshall, R. v. Bernard*:

> *The Supreme Court ruled that Mi'kmaq people should not be allowed to utilise the timber resources on Crown land in New Brunswick and Nova Scotia because they had not done so in 1760–61. Logging was not perceived to be a traditional occupation or need of the Mi'kmaq people, unlike fishing. Fishing was thought to be a traditional need and way of subsistence for those living along the coast or on the water* (Graham, 2015, p. 2).

These kinds of decisions, which assume Indigenous Peoples' cultures and livelihoods are static and frozen in time (e.g., 1760), have been highly contested.

Loss of forest resources due to widespread logging in eastern Canada and elsewhere has had significant ecological impacts in mountains. One example is the fate of the white cedar, as described by Campbell and Laroque "to allow naturally occurring eastern white cedar to disappear from the Nova Scotian landscape would be to allow a piece of living natural history to fall to the wayside, removing a significant cultural icon that connects us to the past" (Leddy, 2013).

One solution to this emerging problem of forest ecosystem degradation and associated impacts on biodiversity, livelihoods, and cultures involves the support of the leadership of Indigenous Peoples, including the respect for Indigenous title, knowledges and forest management practices (Berkes & Davidson-Hunt, 2006; Watson et al., 2018). "Although comprehensive global analyses are lacking, some regional data reveal the remarkable contribution of stewardship by forest peoples to sustaining high-integrity forest systems, often in the face of substantial pressures to liquidate forest timber or mineral resources" (Watson et al., 2018).

There is generally limited development in the Arctic mountain ranges of northeastern Canada, but impacts from developments in the western Arctic and subarctic regions are more significant and comparatively better described. The mountains of Yukon Territory are sites of significant forestry and mining activity, with a long history of developments and plans to continue this pattern. Resource development in these mountain spaces follows a similar pattern to other sites further south in Canada, with sites in higher terrain accessed by a network of roads which act as conduits for impacts, magnifying any point specific impacts in the mountains and acting as a potential barrier for wildlife and a conduit for human traffic and disturbance (Coffin, 2007; Trombulak & Frissell, 2000).

Resource development in the Yukon mountains is also noteworthy for a strong history of, and potential for, both downstream and upstream impacts (Webster et al., 2015). Wanda Pascal of the Teetl'it Gwich'in Nation (a Learning Circle participant) noted how the placement of a fibre optic cable to a mine in the Richardson Mountains increases the potential for natural hazards to disrupt communications links in the mountains (LC 5.6). Mountain spaces can be particularly high-consequence environments for resource development due to the potential for impact pathways to carry downstream effects into other lower elevation ecosystems. Whether due to increased runoff due to deforestation, or increased sedimentation in valley bottom rivers, downstream effects have been noted in relation to historic Yukon mines (Pentz & Kostaschuk, 1999).

Wanda Pascal, Teetl'it Gwich'in, 2022, LC 5.6

5.4.3 *Mining and fossil fuel pressures*

Mining and fossil fuel production result in significant pressures affecting mountain environments and the communities associated with and downstream of mines. British Columbia alone has 173 mines that have produced over 300,000 tonnes of ore, including 21 operating mines (Bellringer, 2016; Office of the Auditor General of British Columbia, 2022). Most of these mine sites have associated pollution concerns. Water contamination is the most common threat presented by mountain-region mines. Acid mine drainage is a concern at more than a third of mountain mine sites, and remediation is expensive. It is estimated that mitigating acid mine drainage at the Tulsequah Chief mine in northwestern British Columbia will alone cost $60 million (British Columbia Ministry of Energy, Mines and Petroleum Resources). Selenium pollution of watershed systems is a common product of coal mining. Reproductive failures and deformities of fish in the Elk River valley watershed of southeastern British Columbia are attributed to Selenium sourced in waste rock dumps from the Teck Sparwood coal mine (Bellringer, 2016). And as was spectacularly demonstrated by the 2014 mine tailings pond collapse at the Mount Polley mine, instability and collapse of tailings piles and ponds is an ever-present problem (Bellringer, 2016). The Mount Polley tailings pond collapse spilt 24 million cubic metres of mine waste into Quesnel Lake in the Montane Cordillera. Watershed pollution is not the only risk. For example, the abandoned Thetford asbestos mines in the Maritime mountain region south of Quebec City, which closed in 2011, are responsible for asbestos contamination of the surrounding communities exceeding government limits and are associated with significantly increased risks of cancer (Belleville, 2011).

Oil and natural gas production also present significant pressures for mountain regions. Oil and gas pipelines cut across mountains, valleys, rivers, and permafrost, disrupting animal migration routes and providing access to once once secluded areas. While spills are not common, even small spills can be locally devastating. Canadian pipelines leak about 1000 barrels per year (Canada Energy Regulator statistics). Gas and oil leakage from abandoned wells is a significant problem, especially for Alberta. Hydraulic fracturing (fracking), the practice of injecting fluids at high pressure into 'tight' oil-bearing strata risks pollution of groundwater and aquifers, and has resulted in the triggering of earthquakes (induced seismicity). Above all, fossil fuels are the prime contributor to global warming as their combustion releases CO_2, a potent greenhouse gas, into the atmosphere.

5.4.4 *Invasive species*

Like pollution, invasive species pose a broad challenge to ecosystem health, but there are several specific considerations in mountain regions. Invasive and non-native species of plants and animals can be deliberately or accidentally introduced into mountain environments through recreational or industrial activities, where they may proliferate at the expense of native species and ecosystem functioning. For instance, the spread of spotted knapweed has altered plant community composition and arthropod health in grasslands of the montane west (Foster et al., 2021), and eastern brook trout introduced to mountain lakes have successfully out-competed the endangered westslope cutthroat trout, leading to genetic hybridization of native species and reducing alpine fish biodiversity (Pacas & Taylor, 2015; Schindler & Parker, 2002). Elder Hayden Melting Tallow, Siksika Nation (Blackfoot Confederacy), discussed such changes in the composition of species affect the web of kinship relationships that form the backbone of Blackfoot ways of knowing, threatening their sacred relatives (LC 5.7).

Mountain pine beetle, although native to western Canada, has heavily impacted many mountain regions of Canada, killing wide swaths of mature forest in regions east and north of its native range. Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań described the effects of the spruce bark beetle on the forests of the Yukon (LC 5.8). Whirling disease is a parasite affecting salmonid fish populations that was discovered in Johnston Lake in Banff National Park in 2016, and has since spread to other freshwater sites in the Alberta foothills (Veillard & James, 2020). Like the spread of mountain pine beetle, whirling disease is enabled by warming temperatures (Nehring & Walker, 1996), though it also requires a vector, and is often associated with tourism and visitation.

5.5 Growing Pressures from Mountain Tourism and Recreation

Pressures from increasing tourism and recreation visitation and the attendant increase in supporting infrastructure (e.g., transportation networks to create access) represent another significant anthropogenic pressure in mountain regions, particularly those near urban population centres in southern Canada. Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, explained how these activities have significant impacts on her Nation's Traditional Territory (LC 5.9).

Mountain tourism and recreation can also involve significant disturbance and displacement through land use and land cover changes, particularly in the case of ski areas and golf courses, resulting in landscape fragmentation, slope erosion, and loss of habitat connectivity (Ladle et al., 2019; St. Louis et al., 2013). Mountain tourism and recreation also drives increased vehicle congestion and costs of living for nearby communities, resulting in increased threats to human health and well-being. These impacts can extend to non-human animals as well, such as concerns regarding the impact of increased traffic on polar bears in the case of the Torngat Mountains National Park (Maher & Lemelin, 2011). Protection of infrastructure to service tourism and recreation activities has resulted in changes in forest fire and flood control management practices, altering species composition and threats from hazards. As Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań explained, these alterations to fire management regimes carried out in part to shape visitors' experiences in parks, including in Kluane National Park on her Nation's Traditional Territory, displaced longstanding Indigenous practices of care for the landscape (LC 5.10).

Further, mountain recreation and tourism can contribute to a loss of sense of place and the erosion of associated place attachment through increased competition for resources, such as recreational areas, and displacement of local people by 'amenity migrants' (Lemelin et al., 2012; Maher & Lemelin, 2011). For Indigenous Peoples, these experiences represent the ongoing effects of colonial displacement from many mountain areas. Access to mountain recreation opportunities—particularly in parks and protected areas—is widely known to be inequitable, and Indigenous Peoples on whose territories these activities take place frequently experience barriers to accessing these places. Dawn Saunders Dahl, Métis (Red River Ojibwe), described the experience of working with Stoney Nakoda youth who felt alienated from the parks other visitors enjoyed (LC 5.11).

As the population of mountain communites in Canada grows and the number of people seeking adventure tourism experiences increases, the popularity of mountain-focused recreation activities is also on the rise. Though the sparse availability of data makes this change difficult to quantify, especially at wide geographic scales, limited studies and datasets demonstrate a significant shift. For example, Parks Canada reports a 28% increase in visitation at the seven mountain parks between 2010 and 2020 (Parks Canada Agency, 2021) and Helicat Canada—the group that represents commercial helicopter and snowcat skiing operations—reported a 20% increase in skier days between 2013–15 and 2016–18

Hayden Melting Tallow, Siksika Nation, Blackfoot Confederacy, 2022, LC 5.7

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 5.8, LC 5.9, LC 5.10

Dawn Saunders Dahl, Métis (Red River Ojibwe), 2022, LC 5.11

Dawn Saunders Dahl, Métis (Red River Ojibwe), 2022, LC 5.12

(Helicat Canada, 2019). The increasing popularity of nature-focused recreation and tourism has impacts on both natural environments and human mountain community dynamics.

Gaudreau (1990) explains that ecosystems are vulnerable to many negative effects caused by recreation, including habitat modification, wildlife disturbance, and the introduction of new or invasive species, and Burgin & Hardiman (2012) contend that a paradigm shift is required to better reflect ecological priorities in outdoor recreation management. While there are data gaps related to specific species, a general finding that recreation disturbs many forms of wildlife is well documented, especially motorised recreation in the mountain west. For example, snowmobiling displaces mountain caribou from suitable habitat and has been a factor in their population decline (Seip et al., 2007). Mountain goats are also sensitive to motorised recreation, with one study showing that they are "moderately to strongly disturbed" by all-terrain vehicles (ATVs) nearly half the time (St-Louis et al., 2013). Non-motorized recreation can also be problematic, with Voyer et al. (2003) demonstrating that hiker activity disturbs pikas, causing them to initiate antipredator behaviour which reduces foraging time. Mountain caribou were also shown to be sensitive to non-motorized backcountry skiing in Gaspesie National Park in Quebec (Lesmerises et al., 2018).

Certain forms of recreation (hunting, fishing) have more direct impacts on populations. Wildlife managers are sometimes challenged to sustainably manage fish and wildlife populations with recreational value in the absence of quality data, a finding Lofroth and Ott (2007) confirmed for wolverines, which have experienced unsustainable harvests in some population units in British Columbia. A legacy of stocking in mountain lakes has also affected alpine ecosystems, as exemplified by in Banff National Park, where historic stocking practices displaced now at-risk native species (bull trout, westslope cutthroat trout) with other species (brook trout, rainbow trout) considered more desirable to anglers at the time (Schindler, 2000). Studies from other non-Canadian jurisdictions also detail the challenges faced by managers when confronting this legacy (Chiapella et al., 2018). The impacts of this legacy are felt downstream as well, highlighted by the words shared by Hayden Melting Tallow of the Siksika Nation (Blackfoot Confederacy) and Dawn Saunders Dahl, Métis of the Red River Ojibway people, regarding the introduction of non-native fish species to improve angling for recreators (LC 5.7, LC 5.12).

Fishing and hunting can, however, also be a tool for conservation, with multiple studies documenting the results of attempts—some successful and some not—to manage certain wildlife populations through selective harvest of others. For example, Paul et al. (2003) describe efforts to selectively harvest brook trout in favour of restoring native cutthroat trout in a Rocky Mountain stream, while Serrouya et al. (2017) evaluate the efficacy of moose harvest as a means of reducing wolf populations and therefore improving mountain caribou survival in southeastern British Columbia. In addition, hunting and angling associations have played a substantial role in funding and advocating for wildlife conservation, with several examples from the mountains of western Canada detailed in Heffelfinger et al. (2013).

With regards to ecosystem impacts, limited attention is being paid to the impacts of recreational activities on the physical environment, such as ecological degradation associated with hiking and human-use trails (Nepal & Way, 2007) and the shift away from 'low-impact relaxation holidays' towards adventure tourism vacations (e.g., ATV tours), which have greater impacts on sensitive alpine ecosystems (Burgin & Hardiman, 2012). This relatively limited body of research reveals important gaps in our understanding, some of which include waste generation (e.g., McConnell, 1991; Nepal, 2016), impacts on biodiversity (e.g., Geneletti & Dawa, 2009; Lynn & Brown, 2003; Stevens, 2003; Tolvanen & Kangas, 2016), and the impacts on habitat of alpine species (e.g., Immitzer et al., 2014).

While academic literature on this topic is limited, the impacts of mountain recreation in

Canada have been acutely observed and felt by many Indigenous Peoples. Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, shared her observations regarding the impacts of activities such as rafting, mountain biking, and fly fishing on the natural environment (LC 5.13). Given that visitation to mountain regions in Canada is on the rise, the lack of literature at the nexus of tourism, visitation, and the natural environment represents an important gap. A gap that is highlighted by tourists' expectations and the level of acceptable change they are willing to endure, particularly in relation to environmental degradation (Needham et al., 2004, 2011).

Mountain communities are also experiencing the effects of a growing interest in mountain-based recreation. Destination management and marketing organisations have, in some circumstances, been so successful that their role is shifting to a focus on preserving the nature of the community and experience, rather than simply attracting visitors. Mountain communities are confronted with different phenomena related to visitors or newcomers. Some are experiencing high levels of nature-based tourism, even 'overtourism' which contributes to lower levels of visitor satisfaction while hiking and mountain biking (Kohlhardt et al., 2018; Needham et al., 2011), and in some cases this has led to conflict between users, particularly on multi-use trails (Neumann & Mason, 2019). Other communities are host to high rates of second home ownership (Mcnicol & Glorioso, 2014), and still others are hubs for 'amenity migration' (Gripton, 2009), which sees the movement of mobile workers or retirees to areas with outstanding recreational or environmental qualities (Chipeniuk, 2004). There is a growing body of literature on the challenging effects of short-term rentals on housing markets, and while there are few studies focused on mountain communities in Canada (e.g., Petit et al., 2022), studies from other jurisdictions provide useful evidence for this issue (e.g., Combs, et al., 2020).

Recreation and tourism have been actively promoted by mountain communities in recent decades as a strategy through which to facilitate an economic transition away from declining resource industries like forestry. Residents of many areas acknowledge the importance of tourism to the vitality of the community (Nepal, 2008; Perehudoff & Rethoret, 2021). However, the growing number of people coming to communities to experience their recreational assets brings challenges. Nepal and Jamal (2011) detail some of the common issues faced by emerging 'resort communities', including local concerns about economic leakage (i.e., through amenity developers hiring non-local crews), "enclavic" developments that happen on the outskirts of town and therefore draw visitors away from downtown, and specific planning challenges. Kelly and Williams (2007) describe one such challenge in their analysis of water supply in Whistler, British Columbia, where the high water demands of visitors, especially in the peak summer tourism season when natural water supplies in mountain communities are often at their lowest, has required development of innovative solutions. These challenges are also evident in Indigenous communities, where tourism-related development has encroached on both access to and use of ancestral lands evident in the story shared by Keara Lightning of the Nehiyaw, Samson Cree First Nation (LC 5.14).

Most literature to date focuses on recreation and tourism impacts on mountain communities, which generally emerges from western communities like Whistler, Banff/Canmore, and interior British Columbia resort communities like Revelstoke and Rossland. These works collectively point to a need for mountain communities to improve planning capacity, including bolstering available datasets, in order to better understand and respond to the challenges posed by increasing rates of nature-based tourism and recreation.

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 5.13

Keara Lightning, Nehiyaw, Samson Cree First Nation, 2022, LC 5.14

Dawn Saunders Dahl, Métis (Red River Ojibwe), 2022, LC 5.15

Yan Tapp, Gaspeg First Nation, 2022, LC 5.16, 5.17

Gabrielle Weasel Head, Kainaiwa Nation, Blackfoot Confederacy, 2022, LC 5.18

Hayden Melting Tallow, Siksika Nation, Blackfoot Confederacy, 2022, LC 5.19

5.6 Changes in the Governance of Mountain Spaces

Legal and jurisdictional decisions over 'ownership' of the mountains have a strong impact on development, access, and the availability of these spaces for Indigenous cultural or recreational practices. The establishment of the mountain National Parks in Alberta, British Columbia, and later in Yukon Territory displaced some of these Indigenous practices, including hunting and fishing rights. Governance of the national parks regions and development of settler infrastructure in these regions (e.g., towns, ski areas) have direct impacts on the gifts of the mountains (Fig. 5.10). As Dawn Saunders Dahl (Métis, Red River Ojibwe) explained, the parks have long excluded Indigenous Peoples in the Canadian Rockies around Banff and Jasper National Parks (Montane Cordillera) from accessing the places where governance is passed down from generation to generation, disrupting their systems of governance (LC 5.15). As Yan Tapp, Gaspeg First Nation explained, these same tensions exist in eastern Canada with respect to private ownership, land management, and access to traditional lands (LC 5.16, LC 5.17).

A major component of Indigenous/settler relations in much of Canada, in particular surrounding governance of land, is based on treaties. Mountain environments in Canada (with the exception of much of British Columbia) are within the territories of many treaties, including the major numbered treaties (e.g., Treaties 6, 7, 8, and 11 cover much of the Canadian Rockies). The treaties made provisions for co-existence of Indigenous Peoples and settlers upon the ceded territories. Per the spirit of these documents, Indigenous consultation and co-governance surrounding land and environment (or governance in unceded territories) must be adhered to and upheld, in keeping with key tenets of the UN Declaration of the Rights of Indigenous Peoples (UNDRIP, 2007). As provinces and the federal government adjudicate land claims, and as modern day treaties are negotiated and renegotiated with First Nations, Métis, and Inuit governments across Canada, governance of mountain landscapes is shifting and evolving.

As discussed in Mountains as Homelands, colonialism brought non-Indigenous populations to mountain regions in Canada, which generated and continues to exert pressures in new ways—especially in the areas of governance, consultation, and overall viewpoints on *who* the mountains are for—or more specifically, who has the right and responsibility to guide the trajectory that mountain environments take in an era of environmental change. Learning Circle participants—including members of the Blackfoot Confederacy Gabrielle Weasel Head (Kainaiwa Nation) and Elder Hayden Melting Tallow (Siksika Nation)—spoke extensively about the pervasive and ongoing effects of colonial dispossession, settlement, and extraction in mountain spaces. By actively excluding and suppressing Indigenous governance and stewardship, they explained, the colonial model of land management resulted in fragmentation of the landscape, disrupted kinship relationships among people and other-than-human beings, and initiated a pattern of unsustainable extraction which continues to obstruct opportunities for a livable future for future generations in mountain places (LC 5.18, LC 5.19).

Figure 5.10: A sequence of historical and repeat photographs from the Mountain Legacy Project (MLP) collections (http://explore.mountainlegacy.ca/) overlooking the town of Jasper from The Whistlers in Jasper National Park shows significant changes in land cover associated with the establishment of the Park and changes in governance. The original photograph (M.P. Bridgland, Dominion Land Surveyor) from 1915 (top) depicts a patchy mosaic of mixed-age coniferous stands (A), and the early development of the town of Jasper (B). Small-scale farmsteads were established in the Athabasca Valley in the 19th century by Métis peoples, who were evicted from the Park after it was established in 1907; while not visible in these images there are legacies of these pre-Park activities on the landscape today (C). The first repeat photograph taken in 1998 by MLP crews (middle) shows much of the pre-existing patchwork has been replaced by dense, maturing coniferous stands (D), and the treeline ecotone has moved upslope (E). The town expanded well beyond its 1915 outline. The subsequent repeat photograph also taken by MLP crews in 2022 (bottom) shows the pervasive effects of a new disturbance, mountain pine beetle, as indicated by the red-grey hue of dead pine stands (F). To mitigate increased fire risk, recent mechanical thinning projects have reintroduced some of the patchwork on the bench above the townsite (G).

Daniel Sims, Tsay Keh Dene First Nation, 2022, LC 5.20

The UN Declaration of the Rights of Indigenous Peoples (UNDRIP) recognizes that Indigenous Peoples have a right to meaningful consultation and input into activities that occur in mountain environments, in both political-/socio-cultural spheres and economic spheres (UNDRIP, 2007). Indigenous Nations' abilities to exercise these rights are complicated by the persistence in legal proceedings of colonial definitions of territorial boundaries and governing authorities, which are often incongruent with Indigenous laws and governance of their Traditional Territories in place since time immemorial (LC 5.20). It is clear from the literature that there has been increasing engagement with Indigenous consultation surrounding mountain and mountain-adjacent environments, such as the Columbia River basin (Cohen & Norman, 2018; Cosens, 2012; Mouat, 2016; Sandford et al., 2014); landmark legal cases asserting Indigenous rights to territories and resources have considerably advanced the presence of Indigenous definitions of place in the context of Canadian law (Borrows, 1999, 2015; Christie, 2005; Rosenberg & Woodward, 2015); and the proliferation of Indigenous Protected and Conserved Areas (IPCAs) represents growing recognition of Indigenous stewardship rights (Plotkin, 2018; Zurba et al., 2019). Yet, the literature surrounding

COMMUNITY-LED RECREATION PLANNING IN SOUTHEAST BRITISH COLUMBIA

In British Columbia, use of public lands—which cover 94% of the area of the province—has traditionally been governed through a series of regional-scale resource management plans. These plans were intended to set a strategic direction for use of the resources that surround mountain communities and drive their economies (Government of British Columbia, n.d.-a). Two decades have elapsed since many of these plans were completed, and the land management context has changed substantially. The provincial government is modernising its approach to land use planning in order to reflect current drivers of land management, including a commitment to reconciliation with Indigenous Peoples (Government of British Columbia, n.d.-b). However, while the government works to develop this process and repair foundational government-to-government relationships with Indigenous Nations, land use pressures persist, leaving many communities seeking venues through which to take a more active role in setting a course toward a desirable future.

Many such examples centre on use of public lands for recreation and adventure tourism. The Columbia Valley Recreation Planning Initiative is bringing local and Indigenous communities, the provincial government, recreation groups, and land users together to develop a Recreation Strategy for public lands in the region. As a first step in the process, the groups collaborated to create a set of land use principles and ground rules that would guide plan development. The Shuswap Trails Alliance (and associated Regional Trails Roundtable and Trails Working Group) serves as a strategic meeting point for the various organisations involved in implementing a regional Trails Strategy. The strategy was developed in 2006 to unify various trail plans through a common focus on sustainability, inclusion, and health (Fraser Basin Council, 2019). The strategy was championed by the Secwepemc Nation, which continues to serve as lead government partner of the initiative, ensuring that regional trail work upholds their traditional values while also respecting their rights and title (Nadeau & Rethoret, 2021).

Multiple other examples exist, some of which were analysed by Nadeau and Rethoret (Nadeau & Rethoret, 2021) in an attempt to identify pathways and best practices for communities looking to engage in similar planning initiatives. Some of the best practices that emerged included developing meaningful partnerships with Indigenous governments, involving settler governments early in the process, ensuring public interests are well-understood and incorporated, and securing adequate funding to both develop and implement the plan.

mountains in Canada still displays a lack of engagement about the idea of what meaningful co-governance of mountain environments in Canada would look like. Absent this, as Gabrielle Weasel Head (Kainaiwa Nation, Blackfoot Confederacy) suggests, the consequences could be dire for Indigenous sovereignty in mountain environments (LC 5.18).

Indigenous/settler conflicts and pressures are not the only socio-cultural pressures that occur in mountainous areas in Canada. The possibilities for other sorts of friction points, including tensions between locals and outside companies/actors also exist, such as questions surrounding mining, tourism, and other forms of economic development which occur in mountain environments. While the literature here is more robust and does a better job at outlining these potential conflicts, there is also a marked bias in the literature towards examples in western Canada versus other mountainous areas in the country (Chipeniuk, 2005; Hudson & Miller, 2005; Jamal & Getz, 1999; Needham & Rollins, 2005; Nepal, 2008; Nepal & Jamal, 2011; Neumann & Mason, 2019; Sadler, 1983; Saremba & Gill, 1991). While this points towards key conflicts that are occurring in the West, such an emphasis also indicates consequential shortcomings in consideration of Indigenous/settler conflicts over economic-development pathways in other mountainous regions in Canada.

Emerging Threats and Impacts on Mountain Systems

"Mountains are like people, they are always changing"
—Tim Patterson, Lower Nicola Indian Band, Scw̓éxmx, Nlaka'pamux (Thompson) Nation (LC 5.21)

The different pressures that are acting on mountain regions in Canada have a compounding influence on a wide range of physical, ecological, and social systems. Sec. 5.7 to 5.11 elaborate on the changes that are documented within each of these systems and the cascading stresses and threats associated with these changes.

Tim Patterson, Lower Nicola Indian Band, Scw̓éxmx, Nlaka'pamux (Thompson) Nation Confederacy, 2022, LC 5.21

5.7 Threats and Impacts from a Changing Cryosphere

5.7.1 *Changes in snowpack*

Snow cover change is typically diagnosed from *in situ* observations (Vionnet et al., 2021) and gridded blends of observations, analysis, and remote sensed products (Mudryk et al., 2018). As trends vary with elevation, estimated trends from coarse-resolution products can be more uncertain in alpine regions than in others. Changes in air temperature and precipitation (Sec. 5.2) have had profound global impacts on the snow cover processes of high mountain catchments (Hock et al., 2019), and the majority of snow cover changes observed in the mountain regions of Canada have been reported in the high-mountain Cordillera and Pacific Maritime ranges (DeBeer et al., 2021). During the past several decades, western Canada has had a widespread reduction in spatial and temporal extents of snow cover, decreases in snow depth, and shorter snow-covered periods by 1 to 2 months, generally due to earlier spring melt (Brown et al., 2020; DeBeer et al., 2021; Mudryk et al., 2018; Musselman et al., 2021). In the Boreal Cordillera, spring snow cover declines were observed at elevations up to and above 5000 m a.s.l. (Williamson et al., 2018). As the seasonal change in melt and accumulation occurs, there is evidence that the seasonal distinction between accumulation and ablation is increasingly blurred (Musselman et al., 2021).

In the Atlantic region, no trends have been detected for snow-cover changes in the mountains of the Gaspesie Peninsula (Fortin & Hetu, 2014), but a south-north gradient of decreased maximum snow accumulations and spring snow cover duration was found in southern Quebec (Atlantic and Boreal Shield), with increases in maximum snow and spring duration in northern Quebec (Eastern Subarctic) (Brown, 2010). Satellite data and ground observations point towards decreasing snow cover durations and maximum snow depths in the Arctic Cordillera (Brown et al., 2021), especially for maritime locations (Callaghan et al., 2011).

Warmer temperatures are a dominant cause of the snow cover extent decrease (Brown & Robinson, 2011). Increased air temperatures can enhance snowmelt due to an increase in available energy. Under continued warming, there is an increased likelihood of mid-winter melts (Musselman et al., 2017). Midwinter melt can cause ice growth at the snow-soil interface of seasonally or permanently frozen soil and impact runoff processes (Sec. 2.4; Marsh & Woo, 1984). However, a shift to earlier melt periods also means snowmelt occurs with lower available melt energy (López-Moreno et al., 2013; Marsh et al., 2012; Pavlovskii et al., 2019). Counterintuitively, this then manifests as slower snowmelt (Musselman et al., 2017; Pomeroy et al., 2015).

Warmer temperatures also affect the phase of precipitation, and the transition from snow to rain drives significant changes in streamflow (Musselman et al., 2018). These transitions are particularly sensitive during warm air precipitation (near 0°C) (Harder & Pomeroy, 2014; Jennings et al., 2018; Mekis et al., 2020) and at lower elevations (Shea et al., 2021) with substantial spatial variability in the sensitivity of these transitions (Jennings et al., 2018). Widespread warming will increase rain-on-snow events at mid- to high-elevation areas that are still covered by snow in the spring (Corripio & López-Moreno, 2017; McCabe et al., 2007; Musselman et al., 2018).

Warmer temperatures can also affect the redistribution of snow. Warmer, wetter, and older snow is less susceptible to blowing snow transport (Li & Pomeroy, 1997) and therefore reduced sublimation loss and transport. In a study in the Montane Cordillera, Pomeroy et al. (2015) found that a warming of 5°C reduced blowing snow transport by up to 50%, and decreased sublimation by 30%. The change in snow cover distribution then impacts the rate and timing of ablation (Debeer & Pomeroy, 2017). The impact of warming snow covers on avalanche formation remains an open question (Strapazzon et al., 2021). However, there is evidence for decreased mid-winter low-elevation avalanches and an increase, even in mid-winter, in the occurrence of wet-snow avalanches (Strapazzon et al., 2021). Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, also described an increase in sloughing activity as a consequence of climate change and melting permafrost, which presents significant hazards for people travelling on the landscape (LC 5.22).

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 5.22

Warmer and wetter snow intercepted in the forest canopy is more likely to quickly unload and fall to the ground as the retention of intercepted snow is highly temperature dependent (Ellis et al., 2010; Lundquist et al., 2021) despite snowfall interception efficiency being generally insensitive to air temperature (Hedstrom & Pomeroy, 1998). Snow that is intercepted by the forest canopy is prone to high sublimation rates (Pomeroy et al., 1998). However, the phase of this unloading is somewhat unclear, and may be from meltwater in the canopy (i.e., liquid) or solid snow/ice cover (Lundquist et al., 2021). Increases in air temperature can result in snowmelt under the canopy to become more long-wave radiation dominated (Lundquist et al., 2013).

Patches of late-lying or perennial snow and ice are used by caribou for seeking relief from flies and for cooling during warm summer days (Ion & Kershaw, 1989). Correspondingly, their reduction and disappearance can influence animal behaviour. Alpine perennial snow patches, small ice bodies without significant movement, are subject to permafrost conditions and can therefore preserve organic materials for thousands of years (Andrews & MacKay, 2012). A marked reduction in snow- and ice-patch area has been found in Canada and Europe (Farnell et al., 2004; Ødegård et al., 2017), both leading to the exposure of valuable archeological artefacts and to fears about their accelerated loss.

Projected changes in snow regime in the Montane Cordillera have been synthesised by DeBeer et al. (2021). Over the coming decades, climate warming will result in a shift of precipitation from snow to rain, especially noticeable during shoulder seasons, at lower elevations, and in southern regions, as well as more frequent rain-on-snow events, warmer and wetter snow, more mid-winter rainfall and melt events, and earlier spring melt and snow cover depletion. Future snow regimes are expected to see similar shifts for the Pacific Maritime region, with earlier onset of snowmelt and a shift towards rain-dominated regimes especially noticeable for lower elevations (Islam et al., 2017; Schnorbus et al., 2014; Sobie & Murdock, 2022). Recent change and projected future change varies strongly with elevation, so projected changes in snow storage dynamics have a large spatial variation. Spatial and elevation gradients in precipitation and snowpack and how they will change are not well quantified.

The Arctic as a whole is expected to see declines in snow cover (5–10%/decade) and maximum snow accumulations (10% per decade) by 2050 (Mudryk et al., 2018). Mountain regions of eastern Canada (Eastern Subarctic and Atlantic Maritime and Boreal Shield) are also expected to see declines in snow cover duration and maximum snow accumulations, with greater impacts near the coast (McCrary et al., 2022).

Trends in snow-cover extent, duration, and SWE observed across Canadian mid-latitudes in recent decades are expected to continue and possibly speed up in the coming decades (Aygün et al., 2020). The projected future trends depend on the climate scenarios and climate model used, the snow modelling scheme used, and the study area. Despite the predominant signal of an overall predicted decrease in snow regime metrics across mid-latitude cold regions, some studies have projected asymmetric changes in SWE depending on the current temperature regime. For example, while an overall decrease in SWE is projected for three river basins in British Columbia, with the largest reductions found in the Campbell River basin where cold seasons temperatures are already close to the freezing level, SWE is projected to increase at higher elevations in the Upper Columbia River basin, as precipitation increases while cold-season temperatures remain below freezing (Schnorbus et al., 2014). However, projections of future precipitation and phase partitioning are uncertain at local scales due to the uncertainty associated with EDW, the lack of high-elevation data to assess precipitation in climate models, and the high spatio-temporal variability in precipitation. This limits our capacity to assess future changes in SWE. Sensitivity analysis, where a possible change in precipitation and temperature is applied to current weather to simulate future conditions, can provide insight as to how snow regimes may change in response to climate change (Rasouli et al., 2015).

5.7.2 *Changes to glaciers*

Multiple studies have estimated rates of past and current glacier area and volume change in mountain ranges in Canada. These include global assessments (Hugonnet et al., 2021; Pfeffer et al., 2014) to regional studies (Bolch et al., 2009; Menounos et al., 2019) and to specific mountain ranges such as the Canadian Rockies (Henoch, 1971; Tennant et al., 2012; Tennant & Menounos, 2013, DeBeer and Sharpe, 2007), the Torngats (Barrand et al., 2017; Way et al., 2014, 2015), the Cariboos (Beedle et al., 2015), the St. Elias Mountains (Clague & Evans, 1993; Flowers et al., 2014), the Canadian Arctic Archipelago (Dowdeswell et al., 2007; Thomson et al., 2011), and southern Baffin Island (Svoboda & Paul, 2009). There are also visual comparisons from repeat photography that help illustrate the change (Sansaverino et al., 2016).

Overall, there is large agreement that glaciers in Canada are shrinking and losing area, volume, and mass (Gardner et al., 2013; Hugonnet et al., 2021; Schiefer et al., 2007; Wouters et al., 2019), and that rates of glacier thinning and area change are accelerating. Long-term mass balance estimates from models and observation data show sustained mass loss since the 1960s in Arctic Canada (Noël et al., 2018; Sharp et al., 2011), the Pacific Cordillera and Montane Cordillera (Menounos et al., 2019; Moore & Demuth, 2001; Pradhananga et al., 2021; Shea et al., 2013), and the Boreal Cordillera (Barrand & Sharp, 2010; Chesnokova et al., 2020). Comparisons between individual approaches and studies are challenging as the time periods and study regions are rarely consistent.

Rates of glacier mass change, calculated from repeat digital elevation models derived from spaceborne remote sensing, have been published for all mountain glaciers using the common period 2000–2019 (Hugonnet et al., 2021). Here, we extract the average rate of glacier mass change over the period 2000–2019 for all glaciers in the individual mountain regions, and calculate regional averages (Fig. 5.11).

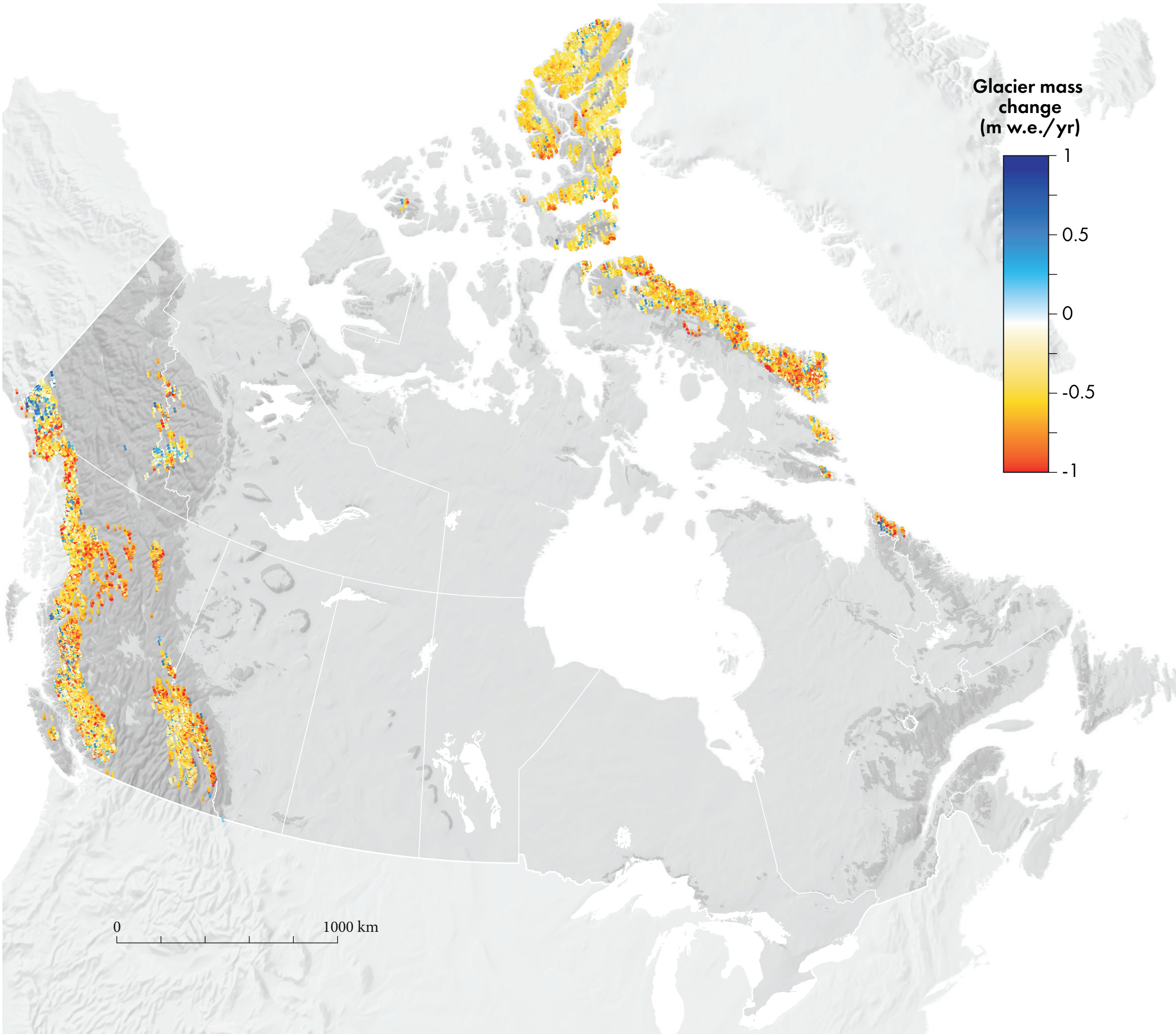

Figure 5.11: Rates of glacier mass change across Canada between 2000 and 2019, expressed in metres of water equivalent. Each dot represents an individual glacier. Data from Huggonet et al., 2021.

Average rates of glacier mass change (expressed as metres of water equivalent [m w.e.]) in mountain ranges in Canada are consistently negative, and vary between -0.36 and -0.56 m w.e. yr^{-1}. Also known as specific mass balance, these rates can be thought of as the average annual thinning (when negative) or thickening (when positive) over the glacier area. The highest average thinning rates in Canada are found in the Eastern Subarctic, Boreal Cordillera, and Montane Cordillera regions. The rates of mass change in Canada for the period 2000–2019 are less negative than those observed in Alaska, Iceland, New Zealand, and Central Europe, but more negative than in Central Asia and the Russian Arctic (Hugonnet et al., 2021).

The specific mass balance differs from the total mass balance or mass change, which is calculated from the specific mass balance times the glacier area. Due to its extensive glacierized area, the Arctic Cordillera experienced the greatest mass loss in Canada over the last two decades. From 2000–2019, glaciers in Canada lost ~2.2 million cubic kilometres of ice, for a total mass loss of ~1900 GT, which is enough to raise global average sea level by 5 mm.

As the current total glaciated area in western Canada is greater than what was present

7000–8000 years ago at the peak of deglaciation (Briner et al., 2016; Menounos et al., 2009), glacier changes today reveal landscapes and cultural practices frozen in time. An 8000-year history of caribou harvesting on Thandlat mountain, for instance, was recently exposed in the southern Tutchone territory of Kluane National Park due to glacier retreat (Cruickshank, 2005).

Projections of future glacier change in Canada are limited. In a regional simulation of glacier retreat across western Canada, Clarke et al. (2015) found that by 2100, glaciers of the western Canadian Cordillera will experience ~70% (RCP2.6) to ~95% (RCP8.5) reductions of both area and volume, relative to 2005 values. Only a few glaciers are predicted to remain in the Interior and Rocky Mountain regions by the end of the 21st century. For example, Haig Glacier, located on the eastern slopes of the Canadian Rockies, is estimated to completely disappear by 2080 (Adhikari & Marshall, 2013). South of the Canadian Rockies, glaciers of the Blackfoot-Jackson Basin of Glacier National Park, in Montana, are expected to completely disappear by 2030 (Hall & Fagre, 2003). On the other hand, coastal maritime glaciers, in particular those in the northwestern Coast Mountains of British Columbia, are predicted to survive but in a diminished state (Clarke et al., 2015). Estimates of glacier mass loss by 2050 are not sensitive to the climate scenario used in the simulation, but the extent of glacier retreat in the second half of this century depends on the magnitude of ongoing climate change.

There are no comparable studies for the glacierized regions of other mountain ranges in Canada, but estimates can be obtained from global studies. For example, Shannon et al. (2019) assessed global glacier volume change relative to 2011 conditions under the RCP8.5 climate change scenario. Within their global scenario, they project a complete (100%) retreat of glaciers in western Canada and a decline of 47 ± 3% for glaciers and ice caps in Arctic Canada, with the survival of these ice masses linked to an increase in snowfall relative to the present day. Estimates for these regions are consistent with global studies from Huss & Hock (2018) and Radic & Hock (2014).

While these large-scale studies of glacier evolution over the upcoming decades provide a consistent overview of glacier behaviour, they do not include local phenomena and various glaciological and climate processes that could either accelerate or slow down the retreat of individual glaciers, which limits their usefulness for local, basin-specific adaptation. Large-scale models often employ simplified melt models, for instance, rather than a full description of surface energy balance processes. Effects of katabatic winds, changing cloud cover, snow avalanching and redistribution, and many other local processes are complex and are not resolved at large scales, so are commonly neglected.

As a specific example, realistic representations of glacier albedo and its evolution over space and time are rarely included in models. Wildfire activity can lead to the deposition of soot on the glacier surface, and increase surface melt through a reduction in surface albedo (Aubry-Wake et al., 2022; Keegan et al., 2014; Marshall & Miller, 2020). Williamson & Menounos (2021) show that mountain glacier albedo is declining across North America, and the decline is correlated not only with rising temperature but also with the deposition of soot from wildfires. Aubry-Wake et al. (2022) found that glacier albedo at Athabasca Glacier in the Canadian Rockies gradually decreased after the onset of regional wildfires, and remained low for two years. Forest fire occurrence in western North America is increasing, in part due to warmer spring and summer temperatures and earlier snowmelt (Gillett, 2004; Westerling et al., 2006), and future fire activity under climate change scenarios is projected to increase extreme fire danger (Abatzoglou et al., 2019; Bedia et al., 2014; Stocks et al., 2003). Understanding the linkage between wildfire activity and glacier melt will be important to improve predictions of glacier melt.

Alpine glacier terminus collapses are also becoming a common sight on glaciers, and are attributed to the collapse of subglacial channels in combination with ice thinning and reductions in ice flux (Egli et al., 2021; Stocker-Waldhuber et al., 2017). Large blocks of ice are lost during such collapses, but this calving process is rarely accounted for in mass balance estimates of alpine glaciers. While most reports of these processes are in the Alps, similar features have been observed in western Canada. A related phenomenon that has been studied for Alberta's Columbia

Glacier is glacier detachment (Rippin et al., 2020). Glacier detachment and subsequent fragmentation lead to loss of ice supply to lower reaches of the glacier, which can then become stagnant. The remnants of the glacier tongue then waste away over a period of years to decades. This process seems to be underway for other glaciers of the Columbia Icefield as well.

Where the lower glacier is heavily debris-covered, it can be insulated from the sun and warm air, allowing the remnant ice to persist much longer. Many glacierized regions in Canada feature relict/buried ice or ice-cored moraines of this type, which are slowly melting and subsiding but may well outlive the main glacier that used to nourish them. Wenkchemna Glacier, behind Moraine Lake in the Canadian Rockies, is a good example of this kind of feature (Gardner, 1987), but buried ice and ice-cored moraines are widespread (e.g., Hayashi, 2020; Langston et al., 2011). These types of buried ice at the edge of the glacier can lead to instability and mass wasting in the marginal area of the glacier, as observed for Boundary Glacier (Mattson & Gardner, 1991).

Glacier retreat opens new terrain for proglacial development, a change already occurring globally (Shugar et al., 2020). A proglacial lake appeared in 2006 at Peyto Glacier in the Canadian Rockies, and has continuously expanded in concert with ongoing glacier retreat (Pradhananga et al., 2021). New proglacial lake development as glaciers retreat were also observed by Geertsema and Clague (2005) at the Tulsequah Glacier in northwestern British Columbia. The presence of proglacial lakes can impact glacier retreat by increasing ice volume loss through calving. There has been an increase in the number of studies examining the response of lake-calving glaciers to climate change, but limited studies focus on Canadian glaciers (Chernos et al., 2016). Overall, a combination of growing proglacial lakes and thinning glaciers is likely to enhance calving rates and accelerate glacier retreat. Proglacial or subglacial lake development is also linked to hazards such as glacier lake outburst floods (Clague & Evans, 1997).

Glaciers are also spaces of human connectivity and identity, with particular historical significance for Indigenous communities in the montane west and north (Cruikshank, 2005b). Many human systems such as agriculture, fisheries, hydropower, potable water, recreation, spirituality, and demography adjacent to and beyond the glacierized regions of the mountains in Canada are impacted as glaciers progress towards near-complete disappearance (Carey et al., 2017; Drenkhan et al., 2022; Milner et al., 2017). In addition to threatening water resources by decreasing streamflow in summer, glacier retreat increases the risk of natural hazards affecting mountain communities, especially glacial lake outburst floods (Frey et al., 2010). Glacier retreat also impacts biochemical processes in alpine lakes and streams (Milner et al., 2017). As agents of erosions, glaciers deliver sediments and nutrients downstream (Hood et al., 2015; Hudson & Ferguson, 1999). They also help to maintain cooler temperatures in glacier-fed lakes and streams, supporting aquatic ecosystems and fish habitat that are adapted to these conditions (Lencioni et al., 2015; Milner et al., 2001). Glaciers, as hotspots of mountain recreation and tourism, provide opportunities for visitors to the mountains to engage with the consequences of anthropogenic climate change. As they continue to retreat, so too do these educational and engagement opportunities.

5.7.3 *Changes in permafrost*

"In the north we have permafrost. It's melting at a rate that we can't even keep monitors in it without them starting to sink away."—Brandy Mayes, Kwanlin Dün First Nation, Yukon (Boreal Cordillera) (LC 5.23).

Permafrost in Canada is warming and thawing (Biskaborn et al., 2019; Derksen et al., 2018), though few long-term borehole temperature records exist in mountains, and there, even fewer above the valley floors, to quantify the rate of warming (Gray et al., 2017). As Elder Mary Jane Johnson, Lhu'ààn Mân Ku Dań First Nation, and Brandy Mayes, Kwanlin Dün First Nation stated, Indigenous Knowledge Holders are keenly aware

Brandy Mayes, Kwanlin Dün First Nation, 2022, LC 5.23 of ongoing permafrost thaw, which has serious consequences for buildings, roads, and infrastructure, in addition to the increased risk of mass movements in the mountains (LC 5.24, LC 5.25). Wanda Pascal of the Teetl'it Gwich'in Nation also highlighted the implications of mountain permafrost thaw and other climate change-related hazards for the safety of using traditional trails in mountain areas, describing a large sinkhole she and her grandson encountered while travelling in her Traditional Territory (LC 5.26).

Because air temperature is the major driver of permafrost change, most permafrost in mountains in Canada will undergo warming during and beyond the 21st century, with stronger consequences expected for higher greenhouse gas emission scenarios (Hock et al., 2019). Permafrost warming is usually accompanied by permafrost thaw, the loss of some or all of the ice in a volume of ground. For example, when the active layer, which freezes and thaws seasonally, thickens, some part of the underlying permafrost will thaw during summer. This may lead to a lowering of the ground surface, or to landslides. Alternatively, if temperatures many metres deep gradually approach 0°C, the proportions of ice and water present in soil change. Less ice and more water in the soil reduce its mechanical stability and make it more permeable for water. As a consequence, a location can be underlain by thawing permafrost for a long time while impacts arising from the gradual loss of ice in the ground develop and persist. This can include impacts on ecosystems, water quality, geohazards, and livelihoods. Some are easily visible, such as the retrogressive thaw slumps of the Peel plateau (Kokelj et al., 2021), whereas many others, such as impacts on food security (Calmels et al., 2015) are gradual and often hidden from view.

Permafrost in mountains, its changes, and related impacts have been observed and studied in more detail in the European Alps and in the Scandes. While climate, geology and human interaction with the land are different in Europe, some inference about permafrost change in mountains in Canada, and its consequences, can be made based on this research (similar to the inference in Gruber et al. (2017). Permafrost thaw will affect sediment budgets and geohazards, hydrology, water quality, and ecosystems. The specific character and diversity of impacts and the pathways connecting climate to permafrost to physical impacts to impacts on people in Canada (for example as reduced food security and health) are important gaps in research.

Anticipating future impacts often relies, in part, on computer simulations. While coarse-scale Earth-system model simulations agree on a global reduction of permafrost extent and volume (Fox-Kemper, 2021) with further climate change, the regional and topographic patterns of these changes in mountains can only be understood with high-resolution simulations that are not currently available for mountains in Canada, except in few limited studies (e.g., Bonnaventure & Lewkowicz, 2011; Way et al., 2018). Methods for simulating permafrost change in mountains exist and their application in Canada is underway (Sec. 2.4.3).

The very sparse monitoring, the lack of simulation products for informing the assessment of (future) hazard regimes related to permafrost, and the near absence of research that explicitly considers how mountain topography affects permafrost and its change are important

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 5.24

Brandy Mayes, Kwanlin Dün First Nation, 2022, LC 5.25

Wanda Pascal, Teetl'it Gwich'in, 2022, LC 5.26 gaps in knowledge about permafrost in mountains in Canada. In a 2014 workshop (Gruber et al., 2015), experts from diverse fields in science and engineering found that little was known about permafrost in the mountains of Canada and that research and public perception in Canada were biased towards lowland areas. Likely, this is due to the concentration of infrastructure and settlements in valleys or in gentle terrain, and to easier access on gentle slopes. It is, therefore, not surprising that in much of the literature cited in this assessment, research on permafrost in mountains in Canada does not investigate the influence of mountain topography on permafrost. As a consequence, our ability to understand permafrost environments in mountains in Canada, and to anticipate their future changes is severely limited.

5.8 Threats and Impacts from Changing Water Resources

5.8.1 *Changes in water supply*

Hydrological change in the mountains of Canada has been studied on multiple time scales. Over centuries to a few millennia, hydrological changes are recorded in the sediments of mountain lakes and valleys (Desloges & Gilbert, 1998; Desloges & Gilbert, 1995; Heideman et al., 2018; Menounos & Clague, 2008; Schiefer et al., 2011; Wilkie & Clague, 2009; Wolfe et al., 2011), and in tree rings (Fleming & Sauchyn, 2013; Hart et al., 2010a, 2010b; Mood & Smith, 2021; Sauchyn et al., 2015). Sediment cores from Lake Athabasca indicate that the last several hundred years have been a period of relatively high water availability in the Montane and Boreal Cordilleras, subsidised by glacier retreat since the end of the Little Ice Age around 150 years ago. Lake levels 2000–5000 years ago may have been 2–4 m lower than present (Wolfe et al., 2011). Paleoclimate reconstructions from tree-rings in the Oldman and South Saskatchewan watersheds indicate that droughts in the montane Cordillera had similar frequency but greater severity in the pre-instrumental period (before we measured precipitation and streamflow) back to 1400 years before present (Axelson et al., 2009). A tree ring reconstruction for two rivers near metro Vancouver in the Pacific Maritime mountain region found that more multi-year low-flow conditions occurred recently (1992 to present) than the pre-instrument reconstruction period from 1711–1992 (Mood & Smith, 2021). The Pacific Decadal Oscillation has a marked influence on these long-term hydrological proxy records (Hart et al., 2010b).

Over recent decades, the volume and timing of water flowing down from the mountains in Canada has changed as the climate changes. Rood et al. (2005) found decreasing annual streamflows in the southern Canadian Rockies over the last century. However, these changes are not applied equally over the year. While late summer streamflows were declining, winter streamflow was found to be increasing due to more frequent rain or snowmelt events. The hydrological changes experienced in individual mountain regions depend on the basin characteristics, and whether they are dominated by glacial melt or snow.

In mountains where glaciers are present, long-term trends in streamflow are often tied to the concept of “peak water.” As glaciers retreat, they initially produce more meltwater, causing a gradual increase in streamflow. As glaciers continue to retreat, they cross an area threshold, which results in an overall decrease in glacier melt contribution to streamflow. This decrease is expected to be especially noticeable in late summer flow, when glacier melt contributions are at the highest but other sources of water, such as rainfall and snowmelt, are reduced (Clarke et al., 2015). The point at which a glacier switches from increasing to decreasing melt contribution is termed “peak water,” and this signal helps assess how glacier contribution to streamflow is evolving over time.

Multiple studies have observed decreasing trends in streamflow from glacierized watersheds in central and southern British Columbia and in southwestern Alberta which implies that peak water has passed in this region (Bliss et al., 2014; Casassa et al., 2009; Demuth et al., 2008; Rood et al., 2005; Stahl et al., 2008; Stahl & Moore, 2006). However, conflicting evidence highlights the complexity of these systems. For example, both Clarke et al. (2015) and Moore et al. (2020) predicted a peak water for the Columbia River headwaters near 2020, and Moyer et al. (2016) suggested that Bridge Glacier was near or at peak water, contradicting the decreasing trend observed in southern Alberta and British Columbia.

Similarly, Naz et al. (2014) did not identify a significant trend in annual or summer glacier melt for the Bow River above Banff from 1891–2007.

A few studies have sought to project future streamflow conditions in glacial watersheds using hydrological models. Chernos et al. (2020) estimated that peak water would occur mid-21st century, along with a decrease of up to 58% in late summer streamflow by 2100 for the Upper Athabasca River basin. Marshall et al. (2011) provided an estimate of future glacier contribution to streamflow on the eastern side of the Canadian Rockies using a statistical analysis of past conditions, finding a near disappearance of glacier volume by the end-of-the-century and a strong reduction in late summer flow. As glacier melt helps to buffer streamflow variability, both at the inter-annual, seasonal scale and at the event scale, the predicted glacier retreat will leave downstream environments more vulnerable to hot and dry periods (Fig. 5.12).

While many studies observe and/or project declining late summer streamflow in glaciated mountains in Canada, these trends become harder to detect—or may even show contradictory changes—in smaller catchments. This is because streamflow is controlled by more than just glacier change, and multiple processes and interactions occur within a watershed that can enhance or diminish observable changes in streamflow.

Hydrological changes are also occurring in snow-dominated mountain watersheds, with and without glaciers. DeBeer et al. (2016) conducted a review of hydrological changes for the interior of western Canada, within the Montane Cordillera. They found statistically significant declines in annual flows for smaller river basins, including those draining the eastern slopes of the southern Canadian Rockies. However, they do not distinguish between mountain and prairie landscapes in their synthesis. Furthermore, the timing of peak snowmelt runoff is shifting earlier in the year (Aygün et al., 2020a; DeBeer et al., 2016; Zhang et al., 2001). The magnitude of peak runoff either shows no significant trend or a negative trend, typically attributed to decreased snow accumulation due to a shift from snow to rain. This is supported by (Cunderlik & Ouarda, 2009), who find that annual peak flows are constant or declining in much of western Canada. Additionally, some natural hydrographs are exhibiting a decline in late summer flows, and an increase in winter flows (Rood et al., 2008; Zhang et al., 2001), attributed to lower melt contributions in late summer and increased winter streamflow from increased winter rainfall and snowmelt.

Downstream effects from Arctic mountain regions are also impacting northern communities. Mountains are drivers of weather, the sources of rivers and sediment, and create aquatic en-

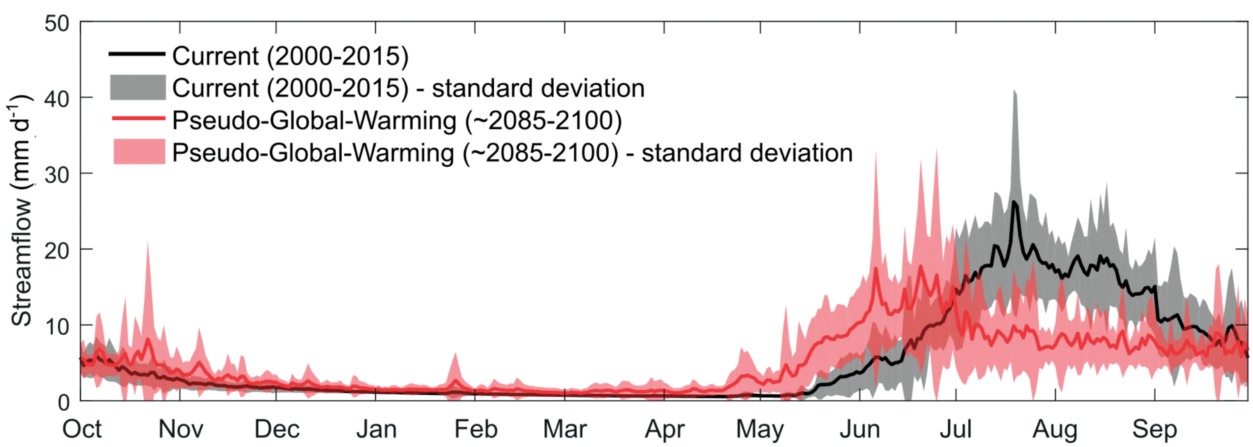

Figure 5.12: Change in simulated streamflow in the Peyto Glacier Research basin, for heavily glacier-covered (50% in 2005) and near complete glacier retreat (3% glacier-cover in for the 2085–2100 period) under an RCP 8.5 scenario. Adapted from Aubry-Wake et al., 2023.

vironments that support cold-water ecological habitats. While in some of the mountains of Arctic Canada the human footprint is limited, changes occurring in the mountains do affect downstream communities and aquatic ecosystems. Changes to snowpacks and glaciology across the mountains of Baffin Island, and other islands in the Eastern Arctic may alter char fisheries in low-elevation coastal rivers and streams, with consequences for the livelihoods of Inuit communities who fish there.

Although hydrological research in the Montane Cordillera has established that groundwater is an important, sometimes dominant, contributor to low-flows (e.g., Hayashi, 2020) and references therein; see Chapter 2), there is little information on how groundwater storage and discharge are *changing* across the mountains in Canada. The drivers of mountain surface hydrological change have implications for groundwater dynamics too. In particular, groundwater recharge may be changing as snowmelt occurs earlier in the year, and higher temperatures cause increased evapotranspiration. In colder/higher mountains, changes in glacier melt and permafrost are likely to alter groundwater dynamics (Somers & McKenzie, 2020). One of the only Canadian studies on this topic found slightly declining late-summer groundwater levels in British Columbia observation wells over 20–30 years of observation (Allen et al., 2014). This presents a substantial research gap in our understanding of mountain water resources in canada and improved observation well coverage would be an asset to advancing our understanding.

Observed changes in flood or drought frequency are difficult to establish due to their infrequent occurrence and typically poor quality data (Whitfield, 2012). For the Bow River at Banff, a well-studied and long-term mountain hydrometric station, Whitfield & Pomeroy (2016) found a significant negative trend for all floods over the last 100 years. However, when distinguishing between generation processes (either rain on snow or snowmelt), no trends were detected. Increasing extreme precipitation and flooding events are expected in western mountain regions in Canada as the atmosphere continues to warm (Pacific Climate Impacts Consortium, 2021). Landscape changes can compound climate-driven changes in flooding intensity. For example, catchments disturbed by wildfire experience significantly higher peak flows than undisturbed catchments in the eastern Rocky Mountains (Mahat et al., 2016). Learning Circle participant Brandy Mayes (Kwanlin Dün First Nation) described experiencing higher flood frequency and intensity in the Yukon River Basin:

> In the last couple of years, Whitehorse and the Yukon has had more snow and rain than we've ever had. And we used to be a very dry climate. And they figure it's because the oceans are warming and creating more precipitation in our environment because it flows through this whole valley. This year, some areas are 180% more snow than ever historically recorded. And we're all preparing for floods—big time. We got flooded last year, in some areas really badly and this year they figure it's going to be worse [....] We'd call that part of climate change and how it's affecting our environment." (LC 5.27)

Brandy Mayes, Kwanlin Dün First Nation, 2022, LC 5.27

The trends observed in glacier-free, snow-dominated basins are expected to continue in the coming decades, with earlier snowmelt and higher winter flows. These shifts will be more pronounced in regions near the freezing temperature than in very cold regions (Aygün et al., 2020; Barnett et al., 2005; Rasouli et al., 2019; Stewart et al., 2004). This means that low elevation mountain basins are more susceptible to climate change. The predicted change in magnitude of peak snowmelt streamflow is not consistent across studies, due to the high sensitivity to the winter precipitation phase under a warmer climate (Minville et al., 2008; Wang et al., 2016). Snowmelt rates are also expected to change. In the "slower snowmelt in a warmer world" hypothesis, Musselman et al. (2017) suggested that shallower snowpack will

A’Ą̈Y CHÙ’ (SLIMS RIVER) DIVERSION, KLUANE NATIONAL PARK AND RESERVE, YUKON TERRITORY

Glacier retreat is one of the most visual manifestations of global climate change, with well-documented impacts on water supply in mountain areas. In Kluane National Park and Reserve, Yukon Territory, the retreat of Kaskawulsh Glacier has led to an even more profound impact on glacial runoff: water diversion to an entirely different drainage system (Clague & Shugar, 2023).

Kaskawulsh Glacier is one of the largest glacier systems in Canada, spanning a total area of about 1095 km^2 (Foy et al., 2011). A vast accumulation area in the St. Elias Icefields feeds several tributary glaciers which converge to create the main trunk of the Kaskawulsh, which is about 70 km in length. Like most glaciers in Canada, the Kaskawulsh has been thinning and receding, and in May 2016, retreat of the Kaskawulsh terminus passed a drainage divide and resulted in an episodic shift in meltwater routing from a northward direction, via A’ą̈y Chù—the Slims River—to a southern drainage route into the Alsek River system. A’ą̈y Chù feeds Lhù’ààn Mân’ (Kluane Lake) and the Yukon River system, so this drainage reorganisation means that the vast amount of meltwater running off from the Kaskawulsh system is now routed to the North Pacific Ocean south of Dry Bay, Alaska, rather than the Bering Sea (Shugar et al., 2017).

This water piracy event has hydrological and ecological impacts that are still evolving (McKnight et al., 2021). The level of Lhù’ààn Mân’, Yukon’s largest lake, has dropped by more than 2 m and A’ą̈y Chù is largely dried up. In combination with decades of fine silt and sediment deposition from the glacier runoff in this valley, this aridification and exposed sediments along the lake shore have created a large reservoir of readily-mobilised dust. The region experiences persistent, often gusty, katabatic winds from the St. Elias Icefields which are channelled down A’ą̈y Chù, generating frequent dust storms with significant air-quality impacts on the southern shores of Lhù’ààn Mân’ (Bachelder et al., 2020).

Changes in the level of Lhù’ààn Mân’, reduced inflow, and greater wind-blown sediment are having impacts on lake ecology and access to the lake for fishing activities. There are also direct impacts of dust storms on air quality and visibility for residents of Kluane First Nation (e.g., Figure 5.13), as described by Elder Mary Jane Johnson, Lhu’ààn Mân Ku Dań First Nation (LC 5.28).

Gùdia Mary Jane Johnson, Lhu’ààn Mân Ku Dań, 2022, LC 5.28

Figure 5.13: A dust storm at the A’ą̈y Chù (Slims River) inflow to Lhù’ààn Mân’ (Kluane Lake) in August 2018. Photo by Gertrudius, CC-BY-SA 4.0.

melt earlier and more slowly compared to deeper and later-lying snowpacks. This is due to declining snow-covered areas and a snowmelt season shifting toward earlier periods with lower available energy. No consistent signal is expected for summer streamflow in snow-dominated basins: increased evapotranspiration could result in a decrease in summer flows, but increased precipitation could also lead to an increase in flow.

These predicted changes are exemplified by the snow-dominated Saint Charles River basin with headwaters in the hills of Charlevoix, QC, studied by Cochand et al. (2019). In the basin, winter stream discharges are predicted to increase by about 80, 120, and 150% for low, medium and high emission scenarios due to warmer winters, leading to more liquid precipitation and more snowmelt, for the 2071 to 2100 period compared to 1970–2000 period. The summer stream discharges were predicted to fall by about 10, 15, and 20% due to earlier snow-melt runoff and an increase in evapotranspiration. The annual mean stream discharge showed little change. Additionally, intense rain events on frozen ground could cause more frequent high winter flows in the future.

Similar changes were discussed by Rasouli et al. (2019) in a study of the hydrological response to climate change in three mountain basins in the mountain west. They projected an increased rainfall fraction of precipitation, and a hydrological regime shifting towards rainfall dominated, with the largest shifts in basins that are currently warmer. Annual streamflow did not change despite an increase in precipitation, as reductions in snow sublimation and increased evapotranspiration offset the changes in precipitation.

In addition to retreating glaciers, shifting precipitation phase and volume, increasing temperatures and evapotranspiration, the mountain landscape is also evolving. Changing land cover complicates the predictions of how water will be stored and flow in the upcoming decades. For example, the growth of proglacial lakes as glaciers retreat increases water storage in the basin, potentially increases evaporation, and influences the streamflow temperature (Bird et al., 2022). Vegetation colonisation of recently deglaciated areas also changes the hydrological functioning of the basin by increasing evapotranspiration (Carnahan et al., 2019). The primary succession and soil development in the proglacial environment has been well-studied, with multiple case studies in varied glacierized environments (Burga et al., 2010; Glausen & Tanner, 2019; Jones & Henry, 2003; Schumann et al., 2016).

Trends in mountain streamflow are the integration of many interacting hydrological processes which can obscure the basin response to climate change. For example, Harder et al. (2015) found no trends in streamflow in the Marmot Research Basin between the 1970s and 2010s, in southern Alberta. This lack of change in streamflow occurred despite substantial changes in the basin forest cover due to large cut block or small forest gap clearing and increasing air temperature, and a shift in precipitation patterns and decreasing snow accumulation at lower elevation in the basin, despite ongoing changes in both land cover and climate in the region.

Understanding of hydrological change in the mountains in Canada has advanced in recent years, but remains limited by the short time series available with which to conduct trend analysis. These short records make it difficult to distinguish long-term trends, such as those linked to anthropogenic change, from natural variability linked to phenomena like the pacific decadal oscillation. Another general gap in streamflow change assessment is the lack of studies outside of western Canada. However, some studies may have been missed in our assessment if they do not explicitly refer to mountains. This is even more pronounced when considering other mountain regions in Canada, such as the Atlantic Maritime and Boreal Shield, where hydrological assessments might include mountain regions but not explicitly characterise their study area as mountains (e.g., Assani et al., 2021). Finally, we have very limited information of past or future changes in mountain groundwater dynamics across Canada as available observation wells have shorter time series available than surface water gauging stations.

5.8.2 *Water quality*

For many, mountain streams evoke a sense of pure, cold flowing waters, setting a standard for freshwater quality (i.e., the phrase "as clear as a mountain stream"). Those that travel in the mountains know that glacial runoff that is routed through subglacial environments is another thing entirely, commonly running brown (i.e., highly turbid) due to a high suspended sediment load. Given time for the silt and clay to settle out, these waters do develop into clear mountain streams, joining snowmelt, rainfall runoff, and groundwater springs to supply resplendent alpine lakes and ultimately flow downhill to feed most of the major river systems of Canada.

Moreover, glaciers and permafrost are potentially important sources of contaminants to alpine streams, rivers and lakes as glaciers melt and permafrost thaws. Glacial meltwaters, in particular, have been shown to dramatically increase fluxes of mercury and persistent organic pollutants to downstream lakes, observations consistent across the Montane Cordillera (Blais et al., 2001; Blais et al., 2001; Lafreniere et al., 2006), Boreal Cordillera (Zdanowicz et al., 2018), and Arctic Cordillera regions (MacInnis et al., 2019; St. Pierre et al., 2019; Sun et al., 2020). Considerably less is known about the potential for mobilisation of contaminants by permafrost thaw to waterways, but its impact is likely heterogeneous across mountain environments, with some areas experiencing high concentrations of largely particle-bound contaminants with thaw (e.g., St. Pierre et al., 2018) while others may experience little to no impact.

In addition to their role as 'water towers', mountain waters are a source of *cold* water that is essential to the aquatic ecosystems and fish habitat in mountain and downstream environments (Isaak et al., 2010; Richter & Kolmes, 2005; Wehrly et al., 2007), including essential salmon spawning areas in eastern and western Canada (e.g., Moore et al., 2013). Stream temperature is a critical factor for aquatic ecological health, including influences on aquatic biodiversity, the distribution of species, nutrient turnover, dissolved oxygen levels, and metabolic activity (Demars et al., 2011; Isaak et al., 2015; Moore et al., 2013). Snow and glacier melt are a source of 'ice water' that helps to maintain lower stream temperatures and support aquatic habitat, buffering the effects of climate warming (Isaak et al., 2015, 2016). This source of cold water is diminishing as mountain snow and ice recede from the landscape and as snowmelt runoff shifts to earlier in the summer, leading to warmer maximum stream temperatures in July and August (Isaak et al., 2016; Moore et al., 2013).

Stream temperature is not routinely or systematically monitored in mountain regions in Canada, so there is limited understanding of the seasonal and altitudinal evolution of temperatures and how these are changing as a consequence of atmospheric warming, reduced glacier inputs, and changing seasonality of snow melt. Moore et al. (2013) describe a statistical model to estimate maximum stream temperatures in British Columbia, with percentage of glacier cover in a catchment included as one of the variables. This builds on well-developed observation networks and statistical models for stream temperature in the U.S. Pacific Northwest, including several contributions specific to mountain streams (e.g., Isaak et al., 2017). Other applications in western Canada include statistical stream temperature modelling of Daigle et al. (2010) in the Okanagan. These efforts relate the seasonal temperature evolution to air temperature and a range of empirical environmental influences.

MacDonald et al. (2014) measured and modelled two summers of temperature data for Star Creek, a forested mountain-slope setting on the eastern slopes of the Rockies, and discussed the importance of groundwater inputs in maintaining low water temperatures. Roesky and Hayashi (2022) discuss the complexity of generalisations for a groundwater-fed stream in a different setting on the eastern slopes of the Rockies. Groundwater inputs at this site are sourced from a seasonal alpine lake, and summer warming of lake waters leads to the transmission of relatively warm water through the groundwater system. This indicates that alpine lake hydrological inputs and thermal conditions need to be considered along with glacier, snowmelt, rainfall, and groundwater inputs in modelling of stream temperatures.

These studies provide insights into empirical and process-based models of stream temperature in alpine environments, though such models and the observations to inform and constrain the models are restricted to a small number of research studies, primarily in the Montane Cordillera. Systematic monitoring of these alpine hydrological systems at select sites is needed to advance understanding and support of water resources and fisheries managers, and further investment in process-based models is likely needed, given the rapidly changing climate, cryosphere, and hydrological conditions in these catchments.

Hayden Melting Tallow, Siksika Nation, Blackfoot Confederacy, 2022, LC 5.29

These changes can undermine statistical models that are based on historical conditions. As noted in other chapters of the CMA, primary research studies are also needed in eastern and northern Canada, especially involving the integrated impacts of climate, hydrological, and ecological changes and site-specific stressors.

Intensive, exploitative human activities have had profound impacts on water quality in the mountains. Dam construction for hydropower generation or water resource management is one of the most dramatic manifestations of this. Dam construction necessitates the building of access roads and the dam itself, clear cutting and slashing/burning, as well as the flooding of surrounding areas during reservoir creation, all of which can influence water quality. During the construction phase, these activities are associated with increased soil erosion and leaching of nutrients and carbon into lake environments (Kelly et al., 1980). Longer term impacts of dams on water quality in Canada have included reduced fish production due to drastic water level fluctuations (Stockner et al., 2005), and the enhanced production of greenhouse gases and neurotoxic methylmercury in flooded soils (Kelly et al., 1997) with the subsequent bioaccumulation of methylmercury through reservoir food webs (Bodaly et al., 1984; Hall et al., 2005).

5.9 Risks and Vulnerability from Changing Mountain Hazards

The mountain regions in Canada are subject to a host of natural hazards, including earthquakes, landslides, avalanches, floods, debris flows, storms and extreme precipitation events, wildfires, epidemics, heatwaves and cold temperatures, which have caused injury, death, damage and destruction. People have inhabited the mountains since time immemorial, living with and anticipating the dangers posed by natural hazards (Cruikshank, 2001). For example, Hayden Melting Tallow (Siksika Nation, Blackfoot Confederacy) speaks of the Piikani being aware that the mountains were shaking, and anticipating the Frank Slide (LC 5.29). Today, growing numbers of people are inhabiting, travelling through, and visiting mountain regions, increasing exposure to the increasingly volatile dynamics of mountain environments (Hock et al., 2019). Likewise, proximate human pressures such as mining, forestry, and infrastructure development are degrading mountain environments and, consequently, intensifying the frequency and magnitude of natural hazards (e.g., Gardner & Dekens, 2007, Hetu et al., 2015, Roberts et al. 2004). This tight coupling between environmental and social dynamics is at the heart of vulnerability research (Adger 2007), although such research per se is still limited in the context of rapidly changing mountain systems in Canada.

The magnitude and frequency of landslides, avalanches, floods and wildfires have predominantly increased due to climate change, deforestation/logging practices, and mining (e.g., Geertsema et al., 2006; Germain et al., 2005, 2011; Guthrie et al., 2010; Roberts et al., 2004). For instance, the high mountains of western Canada and high latitudes of northern Canada are experiencing some of the greatest warming rates on Earth and are some of the most sensitive areas to climate change, in part because ecosystems and natural processes in these areas are intimately linked to changes in the cryosphere. Evidence is mounting that warming will further reduce permafrost and snow and ice cover in high mountains (Huss et al., 2017), which in turn destabilises many slopes due to glacier debuttressing, alpine permafrost thaw and displacement, changes in rainfall regimes, the formation and sudden drainage of glacier- and moraine-dammed lakes, avalanches and glacier surges (Chiarle et al., 2021; Clague & Shugar, 2023; Sobie, 2020). This unravelling of slopes alters water and sediment delivery to and transport by streams, with impacts on subalpine and alpine ecosystems.

Large landslides and debris flows in western Canada in particular appear to be on the increase (Cloutier et al., 2016; Evans & Clague, 1994; Geertsema et al., 2006; Huggel et al., 2012), especially in recently deglaciated terrain (Holm et al., 2004; Deline et al. 2021) and regions of permafrost thaw.

Gùdia Mary Jane Johnson, Lhu'ààn Mân Dań, 2022, *LC 5.30*

Brandy Mayes, Kwanlin Dün, 2022, *LC 5.31*

As Lhu'ààn Mân Dań Elder Gùdia Mary Jane Johnson shared in the CMA Learning Circle, "you could see where the mountainside had come down, and that's happened in all kinds of areas where I live because of the melting permafrost" (LC 5.30). Brandy Mayes, Kwanlin Dün First Nation, also spoke of the effects of melting permafrost on critical infrastructure, with sinkholes appearing in the access road to the airport (LC 5.31).

The frequency and magnitude of avalanches in the eastern and western mountain regions also appear to be on the increase, in part due to expanding logging, transportation, and pipeline infrastructure in mountain regions, in addition to changing snowpacks (Anderson & Mcclung, 2012; Clarke & McClung, 1999; Germain et al., 2009, 2011; Fortin & Hetu, 2009). Mining and related activities in the mountains also destroy much of the natural forest cover, leading to an increase in the extent of avalanches and mass movements (Sinickas et al., 2016). Moreover, the frequency of extreme and fluctuating meteorological events, such as droughts, heatwaves, wildfire, and extreme precipitation events is increasing. Such events can also compound, resulting in increased vulnerability to major flood events, such as those experienced in the Bow Valley, Alberta in June 2013 and southwestern British Columbia in November 2021. The latter was associated with atmospheric rivers that advected warm, humid air masses from the subtropical Pacific to southern BC, leading to heavy orographic rainfall when the air masses were forced upwards by the Coast Mountains.

Although documentation of such dynamics in mountain systems in Canada is relatively limited to date in the peer-reviewed literature, observed and expected increases in mountain hazards calls attention to the importance of research capable of identifying, and informing responses to address, the root causes of vulnerability. In most cases, this will involve close collaboration with local and Indigenous communities, including studies initiated/conducted by those at the frontlines of mountain hazards (and other pressures affecting people in and adjacent to mountain areas). Here, well developed literature related to social vulnerability (e.g., Adger, 2006; Turner et al., 2003; Ribot, 2011), risk (e.g., Simpson et al., 2021), and resilience (e.g., Berkes et al., 2003; Folke et al., 2010) could be instructive, particularly such work that has been carried out in other mountain regions worldwide (e.g., Carey et al., 2012; Ford et al., 2013; Huggel et al., 2020, McDowell et al., 2021a) .

5.10 Threats and Impacts on Ecosystems

5.10.1 *Changes in treeline and shrubification*

A significant amount of attention has been given to understanding how treelines have changed over the past century (Harsch et al., 2009), and more specifically, over the last few decades when the impacts associated with climate change have been more pronounced. Treeline position is controlled by a number of different factors, including herbivory, snow, and temperature, with soil temperature postulated to be the most significant predictor of treeline position (Körner & Paulsen, 2004). The advance of treeline higher up mountains requires the production of viable seed, uphill dispersal, germination and establishment. The expectation with climate change is that the upper limit of where trees can survive, and ultimately establish, will increase as warming continues.

An advance of treeline has occurred in the MacKenzie Mountains of the Taiga Cordillera mountain region (Mamet & Kershaw, 2012), in the Kluane Region of southwest Yukon (e.g., Danby & Hik, 2007; Dearborn & Danby, 2020), and in the Pacific Maritime mountain region on Vancouver Island (Jackson et al., 2016). In the Montane Cordillera mountain region, treeline advance has occurred across the Rocky Mountains (e.g., Trant et al., 2020; Davis et al., 2020). In the Eastern Subarctic mountain region, treeline advance has occurred in the Mealy Mountains (Simms & Ward, 2013; Trant & Hermanutz, 2014). However, there are also examples where treeline advance has not occurred, including in the Atlantic Maritime and Boreal Shield mountain region where treelines in Gaspesie show densification but not advance (Dumais et al., 2014), perhaps due to the short duration of snow cover (Renard et al., 2016). While treeline advance has been documented in the Montane Cordillera mountain region, variability and limitations of more extensive advance may be limited to soil quality and availability beyond the current location of treeline as well as geomorphic and topographic processes (Davis et al., 2018; Macias-Fauria & Johnson, 2013). Other reasons for observed limitations in treeline advance include seed predation, competition with existing vegetation, and the presence (or absence) of disturbance events, such as fire.

In addition to changes in treelines, the density of trees has also increased across many mountain regions of Canada. This increase in density can take different forms including the encroachment of trees into previous open areas and the infilling of open canopy forests. Infilling of trees in the forest-alpine-tundra transition over the past century, and in many cases, over the past few decades, has occurred in the Rocky Mountains (Montane Cordillera mountain region) (Davis et al., 2020; Stockdale et al., 2019; Trant et al., 2020), on Vancouver Island (Pacific Maritime mountain region; (Jackson et al., 2016), MacKenzie Mountains (Taiga Cordillera mountain region; Mamet & Kershaw, 2012), in Gaspésie (Atlantic Maritime and Boreal Shield mountain region; Bailey et al., 2015), and in the Mealy Mountains of Labrador (Eastern Subarctic mountain region; Trant & Hermanutz, 2014). There are also reports of krummholz (<2 m in height) changing to trees (>2 m in height) in the Rocky Mountains (Montane Cordillera mountain region (Trant et al., 2020), a phenomenon attributed to changes in winter wind and snow transport, not just more favourable growing season temperatures, that allow for this shift to occur (Maher et al., 2020). The causal relationship between winter snow and ice damage leading to stem mortality, and in many cases krummholz with multiple leaders, has been documented in Mont Mégantic, QC (Atlantic Maritime and Boreal Shield mountain region; Lemieux & Filion, 2004).

There are many ecosystem consequences related to treeline and shrub advance, with implications on alpine-tundra species. As forest and woody shrub species' ranges expand higher in elevation, there is limited area for the alpine-tundra species to expand into, as land area decreases with elevation. For the Pacific Maritime mountain region, and parts of the Montane Cordillera and Boreal Cordillera mountain regions, alpine-tundra habitat is predicted to decrease by approximately 97% by 2065, based on shifts in biogeoclimatic zones (Hamann & Wang, 2006). Thus, the fate of many alpine-tundra species is precarious. An example of this occurred in Glacier National Park (Montana, just south of the Montane Cordillera mountain region) where four of seven alpine-tundra plant species declined significantly over a 13-year period at the lower edge of their range (Lesica & McCune, 2004). While the majority of discussion, up to this point, has revolved around vegetation, the resulting changes to habitat have important implications for most animals using these areas. For example, in Torngat Mountains National Park (Eastern Subarctic mountain region), there have been increased sightings of boreal bird species, as the habitat and climate become hospitable to more southern species (Whitaker, 2017). Elder Gùdia-Mary Jane Johnson (Lhu'ààn Mân Ku Dań), explains how greening of the mountains in Kluane National Park is affecting the range of bighorn sheep, and how the proliferation of grasses are impacting the abilities of gophers (Arctic ground squirrels) to avoid predation (LC 5.32).

In northern mountain regions (Boreal Cordillera, Taiga Cordillera, Arctic Cordillera, Interior Hills North, Eastern Subarctic), where shrubs are the dominant woody vegetation at lower eleva-

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 5.32

tions, changes in shrub abundance and cover—termed 'shrubification'—are an important driver of mountain ecosystems. Similar to the changes in trees observed south of the latitudinal treeline, shrub density and biomass often decreases with elevation. For example, in Torngat Mountains National Park (Eastern Subarctic mountain region), shrubification was most noticeable in low elevation riparian areas, with less changes observed at higher elevation (Davis et al., 2021a). This pattern has also been seen in the Arctic Cordillera and Taiga Cordillera mountains regions.

Positive aspects of shrubification include increased above and below ground carbon storage and potential increase in summer forage for caribou. However, increased shrubification has other consequences for alpine-tundra ecosystems, including increased snow depths around taller shrubs, decreased albedo, soil nutrient dynamics, and changes in quality and quantity of light reaching the surface as canopy closure increases (Myers-Smith et al., 2015). Increased shade from shrub canopies alters the moisture regime and the competition dynamics of nearby plant and animal communities. For example, observations from across the Arctic (including many locations within the Arctic Cordillera, Taiga Cordillera and Eastern Subarctic mountain regions) show decreased lichen and moss abundance as shrub height increased (Elmendorf et al., 2012). These changes in mountain vegetation are being detected across scales from plot level observations to regional analyses using remotely-sensed data products, such as Normalised Difference Vegetation Index (NDVI) and also across Knowledges, specifically Inuit Qaujimajatuqangit (Inuit Traditional Knowledge).

Changes in alpine-tundra related to shrubification have important consequences for northerners. Inuit Knowledge in Nunatsiavut (Eastern Subarctic mountain region) has documented increased shrub growth (Siegwart Collier, 2020) with important implications around travel safety. There are also increased travel risks for northerners as shrubification creates better hiding places for polar bears and complicates summer and winter travel. There is also a lot of attention being paid to the changes that shrubification has on access to foods. Inuit *Qaujimajatuqangit* (Knowledge) on changes to berry quality and quantity has been extensively documented across the Arctic Cordillera and Eastern Subarctic mountain regions (Boulanger-Lapointe et al., 2020). Using ecological experiments and approaches, increased shade under shrub canopies can decrease the amount and quality of berry plants that are an important cultural food for people across Iniut Nunangat (Boulanger-Lapointe et al., 2020).

5.10.2 *Changes in stream ecosystems*

Rapid glacier loss has altered mountain stream ecosystems. Mountain streams historically fed by cold, turbid, and rapid glacial meltwater are transitioning to warmer, clearer, and slower states as glaciers disappear (Brahney et al., 2021). This shift towards more benign streams could promote the upstream colonisation of species previously intolerant of harsh mountain glacial waters. For example, Brahney et al. (2021) found that benthic algal communities were more diverse in streams within catchments less influenced by glaciers in the Montane and Pacific Cordillera. However, while the upstream recruitment of species should benefit general mountain stream biodiversity, increased colonisation could also result in loss of highly specialised species adapted to glacial meltwater (Cauvy-Fraunié & Dangles, 2019). Increased biomonitoring of aquatic ecosystems across mountain regions in Canada is needed to better understand the rate of specialised meltwater diversity loss and upstream colonisation as glaciers continue to disappear.

A consequence of species colonisation into mountain streams is the potential for biotic invasion. Nuisance and invasive species, previously constricted to lowland aquatic environments because of overly harsh headwaters, could move into mountain streams as they become warmer and clearer. Indeed, nuisance algae species have begun to bloom in mountain streams with declining glacial meltwater inputs in the Montane Cordillera (Brahney et al., 2021). The diatom *Didymosphenia geminata*, while native to North America, can form pervasive blooms in clear, cold-water streams with low phosphorus concentrations (Bothwell et al., 2014; Brahney et al., 2021). Also known as rock snot, these blooms can clog potential macroinvertebrate and fish habitat while also producing an unattractive odour and appearance (Brahney et al., 2021). As glaciers disappear, subsequently lowering phosphorus availability, mountain streams could become increasingly susceptible to these blooms with potential consequences for higher trophic levels (Brahney et al., 2021).

Similarly, glacier ice loss could raise mountain stream temperatures beyond the physiological tolerances of species adapted to cold waters. In the Pacific Cordillera, glacial meltwater inputs cool important Pacific salmon migratory pathways, keeping waters below the thermal threshold of most salmon species (Pitman & Moore, 2021). As glaciers disappear, warmer waters thermally stress migrating salmon, potentially harming their reproductive success (Pitman & Moore, 2021). Bull and westslope cutthroat trout also rely on mountain snow and ice to provide cold water habitat (Heinle et al., 2021). The loss of cold-water inputs could constrict the range of these already at-risk species to headwater streams with poorer prey quality (Heinle et al., 2021). Further monitoring of headwater streams is needed to better quantify thermal habitat loss and its consequences for mountain fishes as stream temperatures continue to warm.

Historic introductions of non-native species further challenge mountain aquatic biodiversity. Many alpine lakes in the Montane Cordillera were stocked with non-native trout species, such as brook and brown trout, in the 20th century to provide recreational fishing opportunities (Donald, 1987). An unintended consequence of these introductions is hybridization and competition between exotic and native salmonids, mainly bull, westslope cutthroat, and rainbow trout (Sinnatamby et al., 2020). These native species are now listed as Threatened or of Special concern, depending on the population, by the Committee on the Status of Endangered Wildlife in Canada (Sinnatamby et al., 2020). As warming streams further constrict bull and westslope cutthroat trout habitat upstream, these native species will likely become increasingly stressed with ongoing climate change (Heinle et al., 2021).

5.10.3 *Changes in mountain wetlands*

As mentioned in Gifts of the Mountains, wetlands provide unique ecosystem services to various species. Wetlands are resilient ecosystems, however much like other ecosystems in the mountain regions, they are suffering the consequences of anthropogenic climate change and intervention. Moreover, most of the literature on the pressures on wetlands has focused on lowland regions. The future of mountain wetlands is uncertain. Given climate change and other anthropogenic pressures, changes in sensitive factors such as soil-water balance and biodiversity are unclear and are likely to vary across elevations. Predicting what will happen with mountain wetlands in future decades is therefore difficult, especially as climate change is likely to affect mountain ecosystems disproportionately, and the extent to which mountain wetlands are or will be affected by land use change is unknown.

According to the Global Peatland Assessment, agriculture is the main activity degrading peatlands in North America, followed by the petroleum industry in Canada (UNEP, 2022). The water drainage of wetlands has consequences at biological level as well as chemical. Aside from the destruction of the surface vegetation, drainage of peat is implemented for mining, peat harvesting for horticultural use, agriculture and road construction (Wildlife Conservation Society Canada, 2021). Drained peat promotes the oxygenation process, thus emitting carbon dioxide into the atmosphere which will otherwise be captured under waterlogged conditions. Wetland drainage can also leave wetlands vulnerable to wildfires, formerly a reprieve from fire, could turn into fuel (Turetsky et al., 2011).

Many wetlands in the mid and high elevation areas might not be targeted for agriculture or peat harvesting due to the rough topography and remote location, however, there are plenty of wetlands in the intermountain valleys that are being affected by the mining industry (BC Mining Law Reform, 2021). Several mining projects are well underway, or scheduled to start in the future in sensitive wetland areas with contaminated waste plans that may not protect wetlands or inadequate reclamation plans (BC Mining Law Reform, 2021). Mining affects wetlands by degrading the soil and water quality which has a cascade effect from microbial to larger animal and plant communities (Garris et al., 2018; Orr et al., 2006b). Peat harvesting in the mountains is uncommon, however, and in British Columbia specifically has reduced significantly since its peak at the start of the 20th century (Demwell, 2019; North American Wetlands Conservation Council Committee, 2001). Flooding of wetlands for reservoir creation for hydroelectricity production is also a threat through vegetation loss, and greenhouse gas emissions due to methane release (Harris et al., 2022).

How climate change will affect wetland carbon storage largely depends on the extent to which these wetlands have been modified by humans through land-use changes (Petrescu et al., 2015). Small changes in the delicate balance between long-term climatic conditions, short-term weather events, ecology, hydrology, soil biochemistry, and geomorphology can cause large shifts in the carbon dynamics of wetland ecosystems (Page & Baird, 2016), and in peatlands these changes can reverse the sign of net carbon fluxes, from uptake to emission.

Degradation due to anthropogenic activities are affecting the peatlands' carbon storage capabilities. Greenhouse gas emissions from degraded peatlands in Canada and the United States are estimated to equal 89 Mt CO_2eq yr^{-1} (UNEP, 2022). Without a better sense of the extent of mountain peatlands, their storage capacity, and conservation state, we do not know how much of those emissions mountain peatlands might be contributing to global carbon sources and sinks.

The predicted response of wetlands to climatic change will vary across different wetland types: rain-fed wetlands might maintain structure and function, while wetlands that rely on snow and groundwater inputs will likely be more sensitive to climate change (Wu & Roulet, 2014). Changes in snow cover affect the plant and microbial community during the growing season, influencing biochemistry as changes in water table dynamics due to drought do (Bombonato & Gerdol, 2012; Coletti et al., 2013; Robroek et al., 2013; Wu et al., 2020). Sphagnum moss dominated wetlands, however, have been shown to control their local water table, remaining moist under regional drought (Kettridge & Waddington, 2014). Which has led some scientists to suggest that those wetlands may serve as climate change refugia in the future (Stralberg et al., 2020). Information about how wetlands in the mountains will be affected by changes in snow cover, rain patterns, and evaporation rates is scant.

Warming of other mountain regions and consequent glacier melt has shown to increase the mean wetland area, as evidenced in the Bolivian Cordillera Real, where warming and glacier melt has been ongoing for the last 30 years (Dangles et al., 2017). Wetland cover showed high inter-annual variability which was correlated to precipitation intensities. Peat formation, or paludification, might require a long—thousands of years—and steady input of water to these areas, however. It is highly probable that multiple basin areas below glaciers have been or will transform to seasonal wetland areas in mountainous areas of Canada.

Peatland restoration and conservation is currently being introduced as a nature-based solution in global climate policy debates, as a viable way for countries to reduce emissions as part of their climate commitments. More attention should therefore be paid to these ecosystems, particularly in mountain regions where "Arctic and Montane Wetlands are being marked at particular risk from climate change with profound consequences for wetland ecosystem services" (Convention on Wetlands, 2021). Canada is one of the few countries that has mentioned peatlands as part of their Nationally Determined Contributions; however, Canada is missing key information on wetland ecosystems in mountain areas, namely inventorying and carbon accounting (FAO, 2022).

5.10.4 *Changes in wildlife, human, and more-than-human relations*

Research studies of the northern mountains in Canada have focused primarily on the physical environment, tracking cryospheric and hydrological changes. Caribou populations are an exception to this, with numerous studies examining current and historical caribou habitat and dynamics in Yukon Territory and Nunatsiavut (e.g., Andrews et al., 2012; Belanger et al., 2019; Hegel et al., 2010, 2012; Macander et al., 2020). In the mountains of the Yukon, consistently expanding programs of resource extraction threaten the integrity of critical habitat for caribou (e.g., McKay et al, 2021), and as a result impact the ability of a variety of Indigenous communities including the Inuvialuit, *Leon Andrew, Nę K'ə Dene Ts'ı̨lı, 2022, LC 5.33*

Daniel Sims, Tsay Keh Dene First Nation, 2022, LC 5.34

Pnnal Bernard Jerome, Micmacs of Gesgapegiag, 2022, LC 5.35

Gwich'in, Trondek Hwech'in, Dene and others to harvest caribou during the critical winter period when travel by skidoo into the higher ground is possible. Hunters from the Inuvialuit communities of the Mackenzie Delta have pursued caribou, wolf, grizzly and other species in the Richardson Range, while the Vuntut Gwich'in and Trondek Hwech'in have used the southern areas of the Richardson Range, the Ogilvie, Wernecke, and Dawson Ranges, for hunting and gathering valued resources.

Elder Leon Andrew of the Nę K'ə Dene Ts'ı̨lı Nation told a story from his homelands in the Mackenzie Mountains of the relocation of culturally important species such as beavers and moose across their Traditional Territory as a result of climate change, making it challenging to rely on Indigenous knowledges of where animals move in the landscape (LC 5.33). Some understand these changes as resulting, at least in part, from a lack of adherence to expectations of reciprocal relationships with the land. Daniel Sims, Tsay Keh Dene First Nation, shared a story to explain that the failure to show respect for mountain environments could lead to the mountains getting their revenge on people, by taking the animals away. "...If we don't share the proper respect to the animals, the animals will get their revenge. It could be them disappearing, it could also be them just getting their revenge in that sense" (LC 5.34).

For the small non-Indigenous population of the boreal and mountain ecosystems of northwestern and Arctic Canada, the mountains exist primarily as sites of resource extraction, including oil, gas, coal, minerals and timber. These activities are largely currently confined to the mountains of British Columbia and the Yukon, where mining and forestry are the primary activities. With greater industrial activity in these regions, comes increased linear disturbance (in the form of roads and transmission lines) and thus increased barriers to animal movement and increased human access and disturbance (Apps et al., 2013; Johnson et al., 2015; Seip, 1992; Wittmer et al., 2007)). Habitat disturbance resulting from resource extraction causes declines in woodland caribou populations in particular through disturbance-mediated apparent competition (Wittmer et al., 2013), whereby disturbance creates favourable conditions for predators (wolves, wolverines) that prey on caribou (Lamb et al., 2022; McNay et al., 2022; Serrouya et al., 2021)

Wildlife populations and wildlife-human relations are also changing considerably in other regions of Canada. Elder Bernard Jerome, Micmacs of Gesgapegiag, observed that caribou populations in the Chic-Choc (Appalachian) Mountains began to decline around 1935, dropping to less than 50 animals in the herd, due to losses of habitat and extractive activities (e.g., copper mining, oil exploration) in the mountains (LC 5.35).

5.11 Impacts on Socio-Cultural Systems

Mountain environments are complex and dynamic social-ecological and social-cultural systems that face a web of pressures and management challenges. Literature addressing the patterns of livelihood, health and wellbeing, and subsistence use of the mountains of Canada remains scarce, especially studies of the impacts of changing pressures on mountains on the livelihoods and knowledge systems of the many First Nations, Métis, and Inuit communities of these regions.

5.11.1 *Threats to Indigenous livelihoods and knowledge systems*

Mountain communities, most especially Indigenous communities, have been impacted via reduced access to traditional resources, cultural practices, and food and water security, all of which have long-standing and multifaceted effects on individual and community health and wellbeing. In a trend observed among Indigenous communities across Arctic and Subarctic Canada, for example, the rising costs of fuel and equipment are enforcing a pattern of wage labour to support harvesting, which is limiting the time that is available to some participants to fulfil their own subsistence needs (Laidler et al., 2009; Natcher, 2009; Wenzel, 2013). This changing quantum of available time is playing out against a backdrop of changing local environmental conditions as a result of anthropogenic climate change, as well as the challenges of maintaining, transferring and using Indigenous ecological knowledge (Ford et al., 2016; Pearce et al., 2011). All these factors are acting to alter patterns of land use, and fundamentally altering the role that mountains across Canada are playing in the livelihoods of Indigenous communities, most especially those in the North (e.g., Ford et al., 2015).

Additionally, the severing of Indigenous knowledges from spaces such as mountains means that knowledge on how to contend with the pressures that mountain environments inherently present to its inhabitants—knowledge on how to contend with avalanches, flash floods, landslides, sea ice loss etc. are lost or are not able to be transferred effectively between groups, presenting new hazards to inhabitants of these spaces—increasing the risk for negative outcomes for all (Gearheard et al., 2006; Pearce et al., 2011; Whyte, 2016); Learning Circle participants, including Patricia Joe (Kwanlin Dün First Nation) and Wanda Pascal (Teetl'it Gwich'in Nation) reflected on the importance of Indigenous knowledges in learning to adapt to changing environmental conditions (LC 5.36, LC 5.37). The question is often asked, "What can we do/what could we have done to prepare for these pressures?", and it is also too often answered by Indigenous communities, 'We have the answer, but we are not given a platform to share it' (Whyte, 2016).

Changes in governance of mountain spaces extend to who has the right and responsibility to create knowledge about mountain systems, what this knowledge looks like, and how it is produced. As Gabrielle Weasel Head, Kainaiwa Nation, Blackfoot Confederacy, explains, colonial erasure of Indigenous communities as distinct Peoples obscures the root causes of the changes occurring in mountain systems and beyond. The violent and destructive changes imposed on Indigenous Peoples have affected Indigenous Nations in many different ways, and addressing questions of how places are known requires elevating place-based ways of knowing, embedded in language, and defining concepts such as sustainability, wellbeing, and resilience (LC 5.38). These experiences take place within a broader context of socio-cultural change occurring in Canada (e.g., The Truth and Reconciliation Commission's 94 Calls to Action), with increasing efforts to decolonize, pluralize, and democratise the environmental sciences and related fields (Liboiron, 2021; Wong et al., 2020).

Patricia Joe, Kwanlin Dün First Nation, 2022, LC 5.36

Wanda Pascal, Teetl'it Gwich'in, 2022, LC 5.37

Gabrielle Weasel Head, Kainaiwa Nation, Blackfoot Confederacy, 2022, LC 5.38

MOUNTAINS OF THE GASPE PENINSULA: THE COMPLEX INTERACTION BETWEEN RECREATION, CONSERVATION, AND FIRST NATION LAND ACCESS

The mountains of the Gaspe Peninsula showcase the intersecting pressures and tensions between conservation, recreational development and Indigenous access and stewardship of Traditional Territory. The mountains of the Gaspé Peninsula, in south-eastern Quebec, can be grouped under three mountains ranges: the McGerrigle mountains, the Mont Albert massif and the Chic-Chocs Range. The name Chic-Chocs comes from the Mi'kmaq word, sigsôg, meaning "impenetrable barrier" or "rocky mountains." The area is the traditional land of the Gespe'gewa'gi, the seventh District of the Mi'gma'gi that includes two on-reserve Mi'kmaq communities (Gesgapegiag and Listuguj) and one off-reserve.

Long cold winters and a short, but warm growing season characterise the region, permitting the development of a dense boreal forest cover, except on the steepest slopes. Despite reported mean annual snowfall exceeding 6 m on the highest summit of the Chic-Choc range (1268 m), winter snowpack on the summits is extremely thin, due to the strong prevailing northwesterly winds redistributing snow to the krumholz and boreal forest below the summits (Davesne et al., 2017; Fortin & Hetu, 2014). The thin snow cover on the alpine summit sustains permafrost on the summit and the development of patterned ground (French & Bjornson, 2008; Gray et al., 2009, 2017). No clear evidence of changes in temperature, snow depth, or snow density could be found in the study area over the last four decades (Fortin & Hétu, 2009; Fortin & Hetu, 2014). This snow-dominated climate and steep terrain also result in high avalanche hazards, threatening roads and other infrastructure (Dubé et al., 2004; Germain et al., 2005, 2009).

The combination of climate and elevation gradient creates a unique landscape with a high diversity of habitat and species, with alpine and arctic tundra vegetation. The endemic vascular flora and lichens found in the Chic-Chocs have led to the hypothesis that these mountains were nuntakas, or ice-free, during the maximum extent of the Wisconsin glaciation (McMullin & Dorin, 2016). The Chic-Chocs are a refuge for many species, many of which typically occur in the Arctic and the western mountains of North America (McMullin & Dorin, 2016). This unique vegetation supports the last herd of caribou south of the St. Lawrence River. This population has been in constant decline since the end of the 19th century, and has been the focus of multiple studies (Frenette et al., 2020; Nadeau Fortin et al., 2016; Turgeon et al., 2018).

The Chic-Choc and McGerrigle mountains are also at the headwaters of important rivers crossing the territory. The rivers in the area are also fisheries, with many of them supporting Atlantic salmon habitat (Kim & Lapointe, 2011). To protect the unique ecosystems of the Gaspe peninsula mountains, the Gaspesie National Park provincial park was created in 1937. Additionally, land outside of the provincial park boundary falls within a varied system of protected land, from wildlife and ecosystem reserves with various restricted access and activities. The Parc de la Gaspesie is a prime tourism destination for outdoor recreationalists across the province and draws high visitation rates during the summer, supporting the economy of the remote region, while supporting conservation efforts within the park. Elder Bernard Jerome, Micmacs of Gesgapegiag, described how Mi'kmaq communities in the region spoke up to protect declining populations of Atlantic salmon by protecting habitat and advocating for a temporary moratorium on recreational sport fishing in the region, after which populations rebounded, and now support a healthy recreational fishing economy (LC 5.39).

Pnnal Bernard Jerome, Micmacs of Gesgapegiag, 2022, LC 5.39

Yan Tapp, Gespeg First Nation, 2022, LC 5.40

Pnnal Bernard Jerome, Micmacs of Gesgapegiag, 2022, LC 5.41

Yan Tapp, Gespeg First Nation, 2022, LC 5.42

The Chic-Chocs and McGerrigle mountains, both within and in the surrounding area of the provincial park, are key recreation areas for the surrounding towns and cities. In winter, it is a hub for ski touring. To increase participant safety of this recreational activity, an avalanche forecasting centre, Avalanche Quebec, was founded in 1999. It is the only avalanche forecasting system east of the Canadian Rockies. In addition, multiple guided ski touring operations have since developed in private, leased public lands or within the provincial park boundaries. Through adventure tourism, the revitalization of towns in this remote region has been fostered. For example, Murdochville, a copper mine and smelter, that closed in 1999, has seen redevelopment in recent year linked with ski tourism, and is now a well-developed ski destination for Quebec residents.

These different uses of the territory, the homeland of First Nations, the protection of natural ecosystems with conservation effort, and tourism revitalising a remote region, are individually all beneficial endeavours. However, the interaction between these three uses leads to tensions. For example, in wintertime, tensions arise between the different users and goals of the park, with concern for caribou habitat conservation and ski touring access. In winter 2022, two popular ski touring areas were closed as the caribou herd moved in the area, reducing access to recreation. This increasing conservation effort and privatisation of the land has significant consequences for the local First Nations, who are seeing access to their traditional land for community hunting and fishing reduced. These tensions results in confrontations between the government officials enforcing the conservation rules on crown land, the local landowners, and the Indigenous Peoples, as shared by Yan Tapp, a member of the local Gaspeg First Nation, who spoke of restricted river access for fishing and the lack of communication and difficult interactions between private landowners, game wardens and First Nation members (LC 5.40) and Elder Pnnal Bernard Jerome, who described historical restrictions on hunting and fishing rights (LC 5.41).

There is a lack of communication between the conservation and recreation policy decision-making and the access to the land that exists for the Mi'kmaq People. The tensions regarding land access were also re-surfacing during the Covid pandemic when visitation numbers in the Gaspésie region increased due to the suspension of international and inter-provincial travel. In response to the overwhelming numbers of visitors, many recreation facilities were closed to prevent the degradation of the sites. These restrictions also applied to local people, such as members of the Gaspeg First Nation, who had been using these sites and showing good stewardship. Yan Tapp discussed the rise of tourism due to Covid and subsequent land restrictions, highlighting their impacts on his community's ability to access important places in their Traditional Territory for activities like hunting and fishing (LC 5.42).

The mountains of the Gaspe Peninsula highlight the complexities in assessing mountain systems across Canada based on language and peer-reviewed literature only. Many reports and assessments of conservation efforts in the region are in French, making them more difficult to find and integrate in large, English-based assessments such as this current effort. Multiple sources of information to understand the intersecting pressures occurring in the mountains of the Gaspe Peninsula also occur in non-peer reviewed publications. Not including French language or grey literature, such as government reports, would indicate a limited understanding of this landscape, when in fact, a reasonable volume of work has been completed in the region.

5.11.2 *Threats to community health and wellbeing*

There is limited literature concerning community health and wellbeing specifically within a mountain context in Canada. Of the relatively few health-related publications that are explicitly set in the context of mountains in Canada, the majority focus on health and safety of those undertaking mountain-based recreational activities (e.g., Boyd et al., 2009; Curran-Sills & Karahalios, 2015; Strapazzon et al., 2021) or the impacts of wildfire on air quality in mountain valleys (e.g., Yao et al., 2020). Among these, several studies focus on the dynamics of health and injury around specific recreational activities (e.g., climbing, mountain biking, snowblading, skiing, snowboarding) (Ashwell et al., 2012; Bratton et al., 1979; Bridges et al., 2003; Cameron et al., 2011; Needham et al., 2004) while others discuss hazards and health outcomes related to avalanche survival, and search and rescue incidents (Boyd et al., 2009; Curran-Sills & Karahalios, 2015; Strapazzon et al., 2021; Wild, 2008).

Additionally, there are certain topic areas where a cohesive mountain literature is lacking, but which are more broadly applicable. For example, there is a growing literature on negative mental health impacts (e.g., reduced well-being, trauma, anxiety, depression, suicide and substance use) related to acute and chronic experiences of disaster (e.g., wildfires, floods) and climate change, and there is strong likelihood that these will increase in the future in mountain regions, as elsewhere (Bratu et al., 2022; Cunsolo & Ellis, 2018; Obradovich et al., 2018).

5.11.3 *Threats to mountain tourism and recreation*

As discussed in the the Homelands and Gifts chapters, mountains are host to recreational pursuits that contribute to mountain cultures and drive many mountain economies in Canada. More and more people want to visit mountains. This fact is made evident by the popularity of outdoor culture, through National Geographic and Lonely Planet, and online platforms like YouTube or Instagram. With greater numbers seeking mountain experiences and thus the materials and infrastructure to access these experiences, the unique requirements for mountain travel have led to the proliferation of goods and services for outdoor recreational pursuits.

However, these fragile environments are subject to intense climatologic and anthropogenic pressures, the cumulative impacts of which threaten the very conditions upon which the mountain tourism industry was built, as Learning Circle participants Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, and Dawn Saunders Dahl (Métis, Red River Ojibwe) described (LC 5.43, LC 5.44).

Gùdia Mary Jane Johnson, Lhu'ààn Mân Dań, 2022, LC 5.43

Dawn Saunders Dahl, Métis (Red River Ojibway), 2022, LC 5.44

While the literature on the physical impacts of climate change in mountainous environments is well-established (Hock et al., 2019), studies examining the implications of this change on mountain tourism and recreation in Canada are lacking. Of the existing literature, an overwhelming proportion has focused on the ski resort industry, primarily in Eastern Canada (Scott et al., 2003, 2019), and suggests that due to warmer temperatures and shifting hydrological regimes, ski season length will likely decrease, potentially limiting operations to the degree that some resorts will no longer be viable (Steiger et al., 2022).

Beyond impacts to the ski resort industry, the direct impacts of climate change on mountain tourism and recreation in Canada is relatively under-studied. There is limited literature exploring the impacts of glacial retreat and permafrost thaw on mountain tourism and recreation, a consequential gap given the growing global body of literature which highlights increases in natural hazards (rockfall, slope instabilities, emergence of proglacial streams and lakes) occurring in these environments (Deline et al., 2021; Mourey et al., 2019; Purdie & Kerr, 2018; Ritter et al., 2012; Watson & King, 2018), and the recent decision to dismantle the iconic Abbot Hut due to safety concerns related to cryospheric degradation (Hik et al., 2022). The impacts of changing ecosystems on mountain tourism has received similarly little attention. For example, despite modelling projections that suggest forest fires could increase in frequency and magnitude throughout mountainous regions in Canada (Global Climate and Health Alliance, 2021), the impacts on tourism and recreation in these areas appears to have been under-studied both in terms of the short term (Hystada & Keller, 2006) and long-term impacts (Hystad & Keller, 2008).

Even less understood in the Canadian context are adaptations to, and opportunities that arise, as a result of climate change. The most studied adaptations stem from the ski resort industry, where advances in snowmaking has allowed resorts to overcome shorter and more variable ski seasons, and the development of summer tourism opportunities such as chairlift-assisted mountain biking and hiking (e.g., Gilani et al., 2018; Needham et al., 2004) has provided alternative revenue streams. Globally, this topic has been comparatively better studied, revealing a range of adaptation strategies the mountain tourism and recreation industry have employed, including the use of geotextile blankets to slow glacier retreat by increasing albedo (e.g., Huss et al., 2021), the installation of ladders to maintain iconic climbing routes and access to alpine huts (e.g., Mourey & Ravanel, 2017), and the introduction of boat tours on large pro-glacial lakes (Purdie et al., 2020).

Climate-related change has been demonstrated to impact visitation in mountain tourism destinations. For example, a study in the Canadian Rocky Mountain Region projected that because of warmer weather visitation would increase up to 36% by 2050, but would decrease by 2080 due to significant environmental change (Scott et al., 2007), such as a reduction in perceived aesthetics (Groulx et al., 2019; Weber et al., 2019). However, change in landscape aesthetics, particularly glacier retreat, has also been identified as a key factor motivating tourists. 'Last chance tourism', the idea that visitors are attracted to destinations threatened by climate change because their visit represents a unique opportunity to experience a place before they disappear, is an important phenomenon prompting tourists to visit to the Athabasca Glacier in the Canadian Rockies (Groulx et al., 2019).

While visitation appears to be increasingly studied in the Canadian context, a great deal of uncertainty persists due to a lack of understanding regarding the relationship between visitation and the impact of climate-related change on shifts in seasonality (Hoy et al., 2016), hazards (Frank, 2000), environmental conditions required for specific tourism activities (e.g., Pickering et al., 2010), and cultural loss (Hock et al., 2019). The dearth of such research constrains the ability of mountain communities, planners, and local organisations to anticipate changes in visitation and inhibits their ability to develop plans capable of securing desirable and sustainable futures. For example, the majority of visits to Canadian national parks are to the country's mountain parks with approximately $1.48 billion generated annually from tourism activities in the communities of Canmore, Banff, and Jasper alone (Alberta Government, 2012). Thus, the potential economic impacts associated with climate change and mountain tourism are substantial (Gössling & Hall, 2017), but are under-studied in Canada.

5.12 Adaptation to Changing Pressures

Adaptation refers to response to challenges and opportunities associated with changing environmental and social conditions, and is often associated with responses to climate change (Smit et al., 1999). While there is limited evidence of a cohesive body of literature on climate change adaptation in mountain regions in Canada, global scale systematic review work shows that adaptation is indeed occurring in many mountain regions globally (McDowell et al., 2019) (note that this differs considerably from the Canadian Arctic, where adaptation has been widely documented, see: Ford et al., 2014). Documented adaptations in mountain areas are commonly implemented in response to cryospheric and hydrological changes, increased hazards, warming temperatures, and changing seasonality combined with non-climatic stimuli such as new or expanding economic activity (e.g., tourism, mining, energy generation) (McDowell et al., 2019). Notwithstanding emerging evidence of significant adaptation efforts in mountain areas globally (again, not well reported/documented in Canada), evidence of shortcomings in these adaptations relative to the nature of current and projected socio-ecological changes in mountain areas as well as core tenets of keystone global agreements (e.g., Paris Agreement; Sustainable Development Goals) is spurring concern (McDowell et al. 2021b). For example, a recent scoping review by Aylward et al. (2022) highlights literature gaps related to climate-mental health adaptation strategies and future mental health risks. Accordingly, there has been a recent push to better recognize and include mental health as a dimension of both climate change impacts and adaptation assessments (Harper et al., 2022; Hayes & Poland, 2018).

In mountain regions, as elsewhere, Indigenous Peoples and communities have long histories of responding to environmental variation and change, and are known to exhibit significant resilience in this context (Ford et al., 2020). As such, rural communities have much to contribute to adaptation policy and decision-making (AMAP, 2017). Local-scale adaptation is place-based and commonly draws on local and Indigenous knowledge, and historical experience with responding to variability and change. A study of 11 Indigenous communities in the Pacific Northwest (whose territories are both coastal and mountainous) highlight how communities are adapting to broader climatic changes, as well as to changing access and availability of resources, harvesting and processing techniques, knowledge systems, and co-management processes (Wyllie De Echeverria & Thornton, 2019). Recognizing the impacts of changing biodiversity and provisioning ecosystem services to Indigenous livelihoods, the authors promote a Cultural Keystone Indicator Species approach, which focuses on "critical species of both cultural importance and perceptual salience in relation to environmental change" (Wyllie De Echeverria & Thornton, 2019, p. 1449), as a framework for embedding Indigenous knowledges in climate and adaptation research in a way that is holistic, meaningful and empowering.

In another study with four coastal British Columbia First Nations, despite colonisation and industrial fishing pressures which restricted Indigenous management rights and stewardship capacity, evidence shows that core stewardship strategies and teachings around important cultural species remains intact, offering a foundation for reinvigorating local governance practices to support cultural and biological conservation (Eckert et al., 2018). Evidence from other communities highlights certain enablers of adaptation, including strong Indigenous culture and knowledge systems, locally-tailored climate education, collaborative decision-making, and mainstream-

KLUANE FIRST NATION ADAPTIVE FOOD SECURITY STRATEGY

"I remember my dad and my mom always had meat in their fish frame. [...] We can remember people coming and just cutting meat off and my mom and dad would just sit back. [...] I said, 'Dad, why are you letting everybody take meat from your fish frame?' He said, 'I'm not worried because the more I give, the more I get back.'" —Kluane First Nation, 2014, p. 24

In southwest Yukon, in response to observed changes on the land and recognized impacts on traditional food systems, Kluane First Nation (KFN) developed a community food security strategy in 2014. Recognizing both the strong connection between KFN citizens and the land, and the threat of climate and landscape change not only to the natural environment, but also to the survival of First Nations as a people, the strategy emphasises the importance of protecting KFN homelands, waters and resources to build a healthy and sustainable food system for the future.

Participants highlighted many activities that are already taking place to strengthen food security in the community, and recommended action items in several areas. To protect the Traditional Territory in the face of climate change, participants encouraged both conservation and the monitoring of key areas and of impacts on culturally important species. Strengthening cultural practices was a key theme, specifically related to community-wide sharing and trading of traditional foods, community-organised harvesting and food distribution, and the application of ancient wildlife conservation methods. Relatedly, improving engagement with outfitting concessions and improving processes to procure donated meat were deemed priorities. A focus on youth empowerment was also deemed essential, including opportunities for youth to engage in cultural activities and to learn from Elders and Knowledge Holders. Participants also supported the promotion of healthy eating including a wider range of traditional foods within a mixed food system. Improving local food production was also supported, including recommendations to support home and community gardening and greenhouse growing, as well as broader agricultural production, including raising animals for food. Complementarily, a community store and storage facility were proposed, to improve food access. Finally, participants recognized the importance of periodic community celebrations and get-togethers as opportunities to come together and share cultural activities, and engage children and youth.

This adaptive food security strategy is one example of a grassroots community effort to adapt to a changing environment and set a positive path forward for the future.

ing climate adaptation into existing programs (Gauer et al., 2021).

While local-scale autonomous adaptation appears to be especially important in mountain regions, municipalities and higher-level governments are also instituting adaptation plans to provide a framework for decision-making and action. Mountain communities are often disproportionately susceptible to the impacts of climate change due to their isolation, tendency toward resource-based economies, and political underrepresentation (e.g., McDowell & Koppes, 2017). Their reliance on vulnerable mountain gifts and benefits (see Chapter 4), such as the supply and storage of fresh water (Aggarwal et al., 2021) or provision of the assets that fuel tourism-based economies (Knowles, 2019; Scott & McBoyle, 2007), is also a factor.

There is a small but growing body of peer-reviewed literature related to community-scale adaptation in mountain regions in Canada, as well as evidence stemming directly from local adaptation plans and projects. Reports from the *Canada in a Changing Climate* platform review adaptation progress across the various regions of Canada, including mountain regions. Stories from the North tell of the experience developing Yukon's first adaptation plan in Dawson City (Government of Canada, 2021). The plan was created as part of a project that brought together three municipalities in the interest of building adaptive capacity. Similar regional projects have happened elsewhere in mountain regions in Canada—for example a project in the Columbia Basin in British Columbia assembled nine local governments to assess adaptation progress and build skills and knowledge related to identified gaps (Nadeau & Rethoret, 2021). These examples, rooted in their specific mountain geographies and climates, demonstrate the value of place-based approaches to adaptation. The critical role of place-specific information in successful climate action points to a need to expand documentation of community risks, responses, and adaptation experiences in many geographies across Canada.

As detailed in McDowell et al. (2021b), there are significant gaps between known adaptation needs and actual adaptation actions in mountain regions, and there are pervasive issues constraining progress. At an institutional level, a study of four North American regions (some of which are mountainous) identified both barriers and opportunities to adaptation actions. Barriers included a lack of political support and financial resources, as well as challenges in translating knowledge of complex, interacting factors into management actions. Opportunities were identified when collaboration, funding and strong leadership were present (Lonsdale et al., 2017). These findings align with the broader, non-mountain-specific body of knowledge on community climate adaptation planning in Canada (see e.g., Burch, 2010; Dale et al., 2020; Vogel et al., 2020). Lessons from the growing literature on rural climate adaptation (see e.g., Drolet & Sampson, 2017; Vodden & Cunsolo, 2021) are relevant to mountain regions, given that many mountain communities are rural and share some similar adaptation challenges (e.g., small tax bases, demographic changes) and opportunities (e.g., high amounts of local and/or Indigenous knowledges, high rates of community participation).

The management of complex social-ecological systems through periods of change, which can be conceptualised as a form of adaptation (McDowell et al., 2016), is challenging, and tensions and conflicts can often emerge due to differing representations and relationships between diverse stakeholder/rights-holder groups with mountain environments. In this context, different forms of co-management (collaborative management) and/or scenario planning (AMAP, 2017) are commonly used to bring stakeholder and rights-holder groups together to share their visions, priorities and decision-making power in an effort to achieve more holistic and effective management outcomes (Clark & Joe-Strack, 2017; Cruickshank et al., 2019; Danby et al., 2003; Staples & Natcher, 2017). Some such arrangements have been institutionalised as a result of modern land claim agreements, ensuring Indigenous representation in decision-making regarding environmental resource management on their Traditional Territories. While these regimes are imperfect and often critiqued, it is important to recognize that they are in a process of maturation, and that significant gains have been achieved (Clark & Joe-Strack, 2017). In the Yukon context, Staples & Natcher (2017) highlight the important role of gender in such processes, recognizing the importance of women's participation in achieving a positive institutional culture and holistic decision-making, while noting that women and men experience barriers to participation in distinct ways. The vignette on Kluane First Nation above highlights the potential for First Nations to increase their influence on co-management decisions by using food security as a lens through which to re-frame resource issues (Cruickshank et al., 2019).

Despite the efforts and successes noted above, the relatively limited extent of adaptation research and initiatives in the mountain areas of Canada calls attention to the need for increased efforts to study and collaboratively work towards enhanced adaptation action in mountain systems in the country. Here, relatively well developed adaptation research and initiatives from other mountain areas globally (see McDowell et al., 2019)—including engagement with co-development, the political economy of adaptation, community-based adaptation, ecosystem-based adaptation, maladaptation, and adaptation gaps and limits—could prove instructive. However, we also see tremendous opportunity for researchers and communities in Canada to stimulate meaningful innovation in adaptation theory and practice by way of novel insights from the Canadian mountain context.

5.13 Conclusions

The climatic and anthropogenic pressures on mountains in Canada and the resulting threats and impacts described in this chapter are both interconnected and increasing, raising important concerns around the future governance and sustainability of mountain regions. Threats to mountain ecosystems and communities vary considerably across mountain regions in Canada, and are unevenly distributed within and among each region, as well as among downstream communities. The impacts of the pressures of climate change, land use change, and resource development on mountain landscapes described in Mountain Environments (Chapter 2), their political, cultural and spiritual significance elucidated in Mountains as Homelands (Chapter 3), and their contributions to human communities covered in Gifts of the Mountains (Chapter 4), are all increasing as the population in Canada grows and the cascading effects of climate change become more extreme. These pressures are also becoming increasingly entangled, requiring adaptation efforts to consider the interdependencies and tradeoffs among various biophysical and socio-cultural systems.

Mountains are often conceptualised as the water towers of the world, supplying a substantial part of ecological and anthropogenic water demand. The effects of ongoing climate change on water supply and water quality due to glacier and snowpack decline in mountain areas in Canada will only intensify over the coming decades. Changes to ice, snow, and water in the mountains will exert increasing pressures on humans and ecosystems via increasing risks to natural hazards, changes in water resources, and increasing transport and deposition of contaminants. The pathways connecting climate change to changing snowpacks, freshwater supply, and the impacts on people in the mountains and downstream regions are important gaps in our understanding, as are the lack of systematic observational data and simulation products for informing hazard assessment and adaptation.

Colonialism brought non-Indigenous populations to mountain regions in Canada, which generated and continues to exert pressures in new ways. This is especially true in the areas of governance, consultation, and overall viewpoints on *who* the mountains are for—or, more specifically—who has the right and responsibility to guide the trajectories of mountain systems in an era of rapid and profound environmental change. These questions also extend to who has the right and responsibility to create knowledge about mountain systems, what this knowledge looks like, and how it is produced and communicated.

While there is a limited body of literature focused on community health and wellbeing in the context of mountain regions in Canada, there is growing awareness of the negative mental health impacts related to experiences of natural disasters and climate change (Aylward et al., 2022), which are likely to increase in mountains in the future. Of the few health-related publications that are explicitly set in the context of mountains in Canada, the majority focus on health and safety of those undertaking mountain-based tourism and recreational activities. Indeed, mountains are host to recreational pursuits that contribute to mountain cultures and drive many mountain economies in Canada. As climate change and land use change continues to impact mountain environments, information on how socio-cultural and economic systems are responding and adapting will be key. Given that visitation to mountain regions in Canada is on the rise, the lack of literature at the nexus of tourism, visitation, community health and wellbeing, and the natural environment represents an important gap.

Overall, the pressures facing mountains in Canada—namely those of climate change, land use change, resource extraction, development, tourism and recreation demands, and governance of mountain spaces—need to be considered together in evaluating the combined and cumulative impacts of these multiple stressors on the mountain systems of Canada, and in devising and assessing the associated adaptive responses. This is especially needed for local, community-scale adaptation plans and projects, which are commonly implemented in response to climatic drivers combined with non-climatic stressors such as new or expanding economic activity (McDowell et al., 2019). Future research seeking to understand these connections will benefit not only from additional data and monitoring, but also from greater attention to, and better inclusion of, community members and context-dependent cultural information, which has to date has been largely overlooked in favour of modelling approaches that seek to find generalizable patterns. This will require further cross-training and cross-pollination among academic and government researchers and decision-makers engaged in adaptation and mitigation planning, as well as continued engagement with mountain communities, most especially Indigenous communities.

This assessment is not comprehensive, and numerous aspects of mountain pressures were not thoroughly assessed given gaps in author expertise and time constraints (Table 5.4).

Notwithstanding these gaps in our assessment, the CMA found that the existing literature on the changing pressures in mountains gravitates toward the mountains of the west. The Pacific Maritime, Montane Cordillera and Boreal Cordillera regions account for the bulk of research and scholarship on mountain environmental and socio-ecological change, and pressures unique to eastern and Arctic Canada, as well as interior mountain regions, require greater attention. The knowledge gaps described in each section of this chapter are key areas for future research, but one overall priority is the need for more interdisciplinary and transdisciplinary studies in mountain regions in Canada, particularly with respect to questions about the interconnected aspects of pressures, threats, vulnerabilities, and adaptations in mountain regions in Canada. Such efforts, at the intersection of Indigenous knowledges and natural, social, and health sciences, are needed if we are to successfully navigate the rapid and compounding changes affecting mountain systems in Canada.

Table 5.4: Examples of topics not thoroughly assessed in this chapter

Paleo-environments and natural forcings that have driven past changes in mountain regions over timescales of centuries to millennia.
Stresses on mountain ecosystems associated with climate, cryosphere, and hydrological change, and associated implications for biodiversity and ecological integrity.
Changing mountain hazards and extreme weather in mountain regions in Canada associated with climate change.
Recent remote sensing and modelling tools that are creating new capacity to monitor mountain environments, including early warning systems for mountain hazards.
Patterns of migration and population pressures in different mountain regions of Canada.
Initiatives/policies and funding mechanisms to reduce vulnerability and support adaptation in mountain communities.
Recent changes in the governance structures of protected areas and other lands, which show promise for increasing self-determination and sustainable land use practices.

Glossary

Ablation: Processes by which snow or ice are removed, inclusive of melting, sublimation, wind erosion, and mechanical losses such as calving of icebergs or mass loss through avalanches.

Accumulation: Processes by which snow or ice are added to a system, including precipitation, condensation/deposition, wind deposition, and mass deposited through avalanches.

Albedo: The reflectivity of a surface in the solar (shortwave) radiation spectrum, calculated from the ratio of the reflected vs. incoming solar radiation.

Bioaccumulation: The gradual accumulation of chemicals or contaminants within a living organism, often magnified through the food chain.

CanESM5: The Canadian global climate (Earth system) model used for the CMIP6 future climate change projections; CanESM is developed and run by the Canadian Centre for Climate Modelling and Analysis, a research group within Environment and Climate Change Canada.

Clear-cut: A previously forested area where most trees have been harvested and removed, leaving bare ground or stumps.

Climate downscaling: The process of interpolating climate data or climate model output to finer scales where it may better represent local processes and conditions.; this includes a wide range of statistical methods and dynamical (physics/model-based) approaches.

CMIP: Coupled Model Intercomparison Project—an international project that invites the global climate modelling community to perform simulations of historical and future climate change under specified and standardised boundary conditions, allowing an intercomparison of model projections under different climate forcing and emissions scenarios. These results feed into the IPCC analyses and the most recent exercise was CMIP6, feeding the IPCC 6th Assessment.

Downwelling longwave radiation: Infrared radiation emitted from the sky (primarily from clouds and from greenhouse gases) towards the Earth surface.

Elevation-Dependent Warming (EDW): Systematic differences in the rate of warming at different elevations in association with climate change. This is often assumed to mean higher rates of warming at higher elevations, but the relation is more complex than that; there may be no altitudinal pattern, or the greatest degree of warming may be at lower elevations. The research community is now considering this concept more generally as elevation-dependent climate change (EDCC), inclusive of other meteorological variables.

Empirical- and process-based models: Empirical models are statistically based, grounded in observations with a statistical relation that essentially describes a fit to the data. Process-based models are rooted in a physical/mathematical description of the system, typically following principles of conservation of mass, momentum, and energy. These are intrinsically more transferable between sites, but are often limited by an incomplete understanding or representation of the physics at the relevant scales (i.e., by the intrinsic complexity of nature).

Evapotranspiration: Water loss through a combination of evaporation (e.g., for soil or surface water) and transpiration (e.g., vapour loss through plant stomata).

Forcing(s): Drivers of change to a system, typically referring to external agents. For instance, climate forcings include solar radiation (i.e., changes in solar irradiance), volcanic influences (e.g., releases of sulphate aerosols, which have a cooling effect), anthropogenic drivers (greenhouse gas emissions), and many other forcings.

Glacier terminus: The lowest point of a glacier. Glacier ice flows to this point from higher elevations, as ablation exceeds accumulation at lower elevations in glacial systems.

Hydrograph: A graph depicting the discharge of water with time within a river system. This can be over a short period (e.g., a storm hydrograph) or over a year (an annual hydrograph).

Hydrological catchment: The area of land from which water flows into a river, lake, or reservoir.

In situ: Direct observations or measurements from ground control sites, in contrast with remotely sensed or modelled estimates of ground conditions.

IPCC: Intergovernmental Panel on Climate Change

Isotherm: Points with a common temperature, which can be illustrated by a line or surface on 2D or 3D representations of the terrain.

Invasive species: Organisms that are not native to a particular region. They may be benign but this term is usually used for intrusive species that disturb the regional ecosystem dynamics.

Katabatic winds: Downslope winds associated with drainage of air from high-elevation plateaus, where cold air masses create dense air (a thermal high pressure) that drives the cold-air drainage. These are common on large icefields, but are not restricted to glacier environments.

Proglacial lake: Water body adjacent to a glacier terminus, often occupying a basin created through glacial erosion which becomes exposed when the glacier retreats. These are often dammed by glacier moraines. Glacier lake outburst floods usually involve proglacial lakes.

Radiative balance: The net solar (shortwave) and infrared (longwave) radiation balance at a point or averaged over the planet. This includes incoming minus reflected solar radiation and the incoming infrared radiation from the sky/clouds minus outgoing infrared radiation emitted from the surface. Radiation balance is usually positive by day and negative overnight.

Snow cover: The spatial extent or area of snow on the ground.

Snow water equivalent (SWE): The thickness of a water layer one would produce by melting all of the snow at a given location. This essentially converts from the average density of the snowpack to the density of water, to represent the volume of water within the snowpack.

Snowpack: The amount of snow on the ground, expressed through its depth (in cm or m) or its snow-water equivalence.

SSPs: Shared socio-economic pathways: Greenhouse gas emissions scenarios for the 21st century based on various assumptions about global population growth, economic development, and the carbon intensity of the world's energy, transportation, and agricultural systems.

Sublimation: Phase change of snow or ice to water vapour.

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Alpine lakes among peaks of the Cayoosh Range in the Coast Mountains. Photo courtesy of Mary Sanseverino, 2022.