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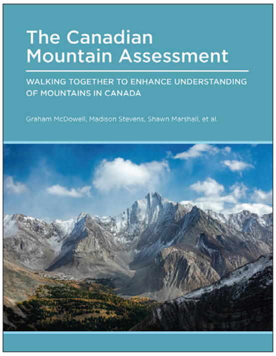

THE CANADIAN MOUNTAIN ASSESSMENT: WALKING TOGETHER TO ENHANCE UNDERSTANDING OF MOUNTAINS IN CANADA

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A bull moose on the move in Kananaskis Country, Canadian Rockies, during the autumn rutting season. Photo courtesy of Abdulla Moussa, 2021.

CHAPTER 2

Mountain Environments

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2.1 Introduction

Mountain environments are characterised by a wide range of geological features, climates, ecosystems, and landscapes. They can be viewed holistically, as regions that are greater than the sum of their individual parts, or they can be broken down into their constituents of rock, snow and ice, water, and plant and animal life. In this chapter, we take both viewpoints, and assess what is known—and not known—about mountain environments in Canada. We assess the state of scientific knowledge with respect to geology and mountain origins; mountain weather and climate; snow, ice, and permafrost; hydrology; ecosystems and biodiversity; hazards; and connections between mountain environments and the surrounding lowlands. Our assessment of the state of scientific understanding is complemented, where possible, with Indigenous knowledges of the same topics. The material in this chapter is foundational to subsequent chapters of the Canadian Mountain Assessment (CMA).

Mountain environments are defined partly by their elevation, which literally and figuratively sets them apart from other landscapes. This elevation is a product of mountain-building processes that have occurred over hundreds of millions of years (Sec. 2.2). But mountains are also defined by their highly complex and heterogeneous nature. Large changes in elevation over relatively small horizontal distances lead to steep slopes and high relief that have cascading effects on weather (Sec. 2.3), water in both frozen (Sec. 2.4) and liquid (Sec. 2.5) forms, and plant and animal habitats and ecosystems (Sec. 2.7). The topographic and meteorological complexity of mountain environments also directly contributes to the hazards associated with these regions (Sec. 2.6). And while mountains may be set apart from their surrounding lowland regions, they are not isolated—viewed through a different lens, the two-way connections between upland and lowland regions can be brought into focus (Sec. 2.8).

Knowledge assessments impose divisions on the knowledge that is presented (Foucault, 1995), and each section of this chapter addresses a separate topic related to mountain environments. However, Indigenous Peoples' knowledges of mountain environments are typically holistic and not easily parsable along traditional scientific categories. Consider for example, connections to the diminutive Straw Mountain in Flagstaff County, Alberta, which are largely related to

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* *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.*

Figure 2.1: Straw Mountain, Flagstaff County, Alberta. Photo courtesy of Daniel Sims, 2011.

Manitou Asinîy (the Manitou Stone) and the Viking Ribstones. Such importance or sacredness of mountain environments is, furthermore, often unique to particular Nations or communities. For example, while Siksika Elder Hayden Melting Tallow stated the mountains are sacred places he is quite clear that he is only speaking for himself and his Nation (LC 2.1).

Hayden Melting Tallow, Siksika Nation, Blackfoot Confederacy, 2022, LC 2.1

Many Indigenous Peoples see a world full of animate entities. Beyond merely recognizing the personhood of other forms of life, many Indigenous Peoples see things that might not be viewed by Western science as animate as alive. This category can range from individual rocks—with perhaps the most famous example being the glacial erratic at Okotoks, Alberta (Fig. 2.2), that once chased Napi—to the planet itself, which Tsek'ehne Elders describe as a living entity. It has even been suggested that cryptids like sasquatch and the wendigo are personifications of the environment itself, although it could equally be said that this interpretation speaks more of settler perspectives than Indigenous worldviews (Blu Buhs, 2009). This perception of being in a very animate world informs Indigenous knowledges of mountains and makes it difficult to separate the "environment" from the other topics in this report. In this context, we have chosen to include some Indigenous knowledges of mountain environments that have been shared with the CMA in subsequent chapters, which are framed in more holistic ways (e.g., Gifts of the Mountains).

Ultimately, our assessment efforts are shaped by the availability of and access to knowledge, both of which impact our assessment of mountain environments in Canada. Indigenous knowledges of mountain environments are extensive, but when such knowledges have not been shared with CMA, have not been recorded in writing, or are expressly private, they cannot be incorporated into our assessment of mountain environments. Similarly, observational studies of mountains in Canada are limited given the expansiveness, remoteness, and challenges to access, which characterise many mountain regions across the country. Notwithstanding these caveats, this chapter provides the first formal assessment of what is known and not known about mountain environments in Canada.

2.2 Origins

"One of the things we all are raised up with, if we are First Nations, Inuit, or Métis people, is the creation of the World."—Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, LC 2.2

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 2.2

Figure 2.2: Big Rock (Okotoks Erratic) is a 16,500 tonne granite boulder found on the prairie south of Calgary, AB. It originated in the upper Athabasca valley, and was carried several hundred kilometres by an ice stream at the end of the Last Glacial Maximum. Photo by Coaxial, CC BY 3.0, 2007.

2.2.1 *Plate tectonics: The driving mechanism for mountain building*

Mountains are the products of a perpetual battle between the tectonic processes that uplift the Earth's surface and the processes of erosion that are constantly wearing it down. Most of these processes operate at rates that are too slow and on too large a scale for direct human observation. The result is that Earth's geography, its distribution of mountain belts and ocean basins, appears, from a human perspective, to be an almost permanent feature of our planet. But mountains and oceans are not permanent. Indigenous origin stories, which form the foundation of their culture and guide societal behaviours and decision making, also contain parallels to geological origin stories and the vastness of time.

The growth and demise of mountains involves tectonic processes that operate over many tens of millions of years (e.g., Müller et al., 2019). Many Indigenous creation stories talk about the creation of the world as well as certain natural features that were created or came into existence after the creation of the world (Snow, 2005). For example, the Fraser Valley contains hundreds of sites, known as transformer sites, where nations like the Stó:lō say their ancestors were turned

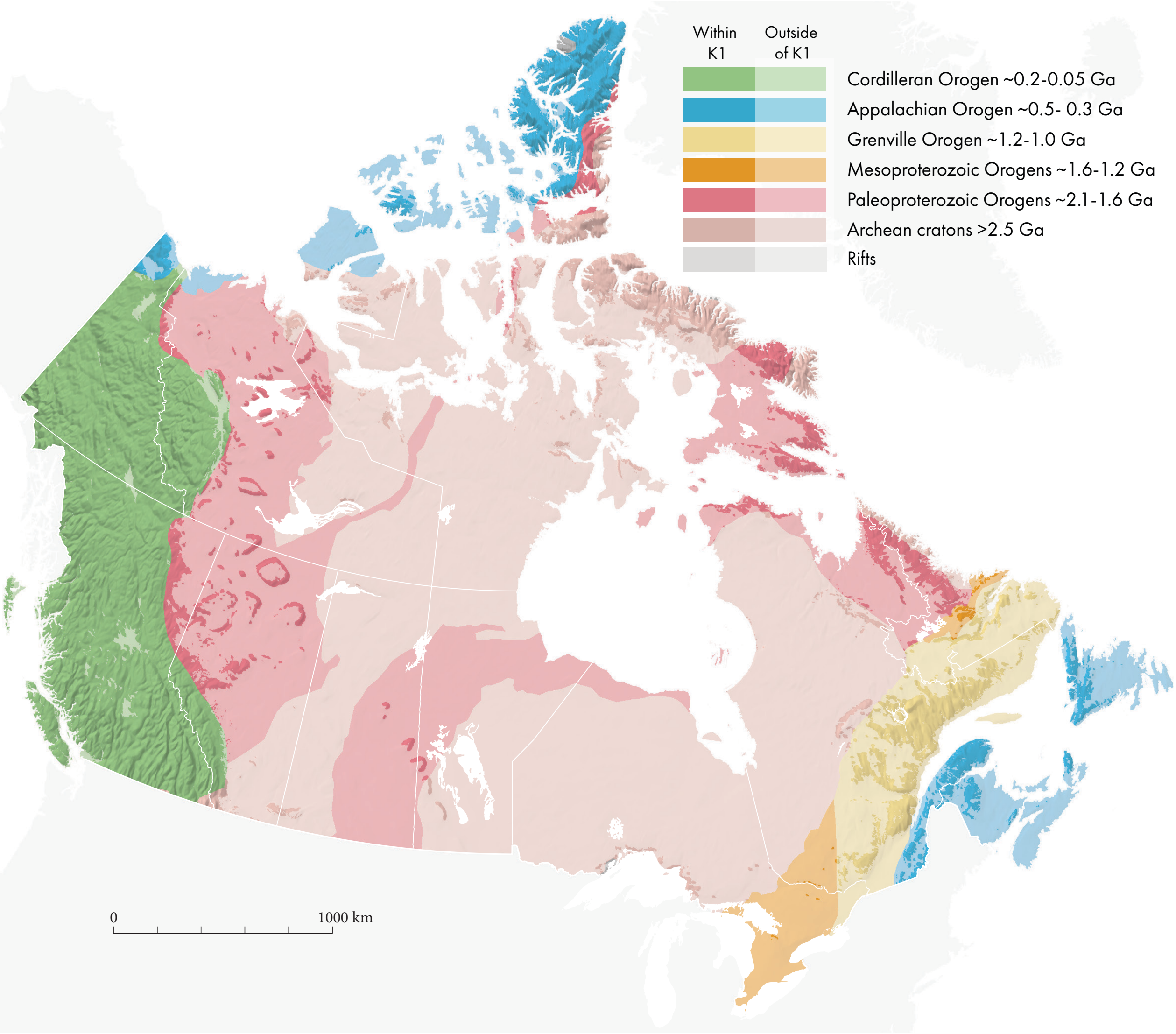


Figure 2.3: Canadian mountain regions (grey) based on McDowell & Guo (2021) superimposed on major crustal divisions and orogens Data from Hasterok et al., 2022.

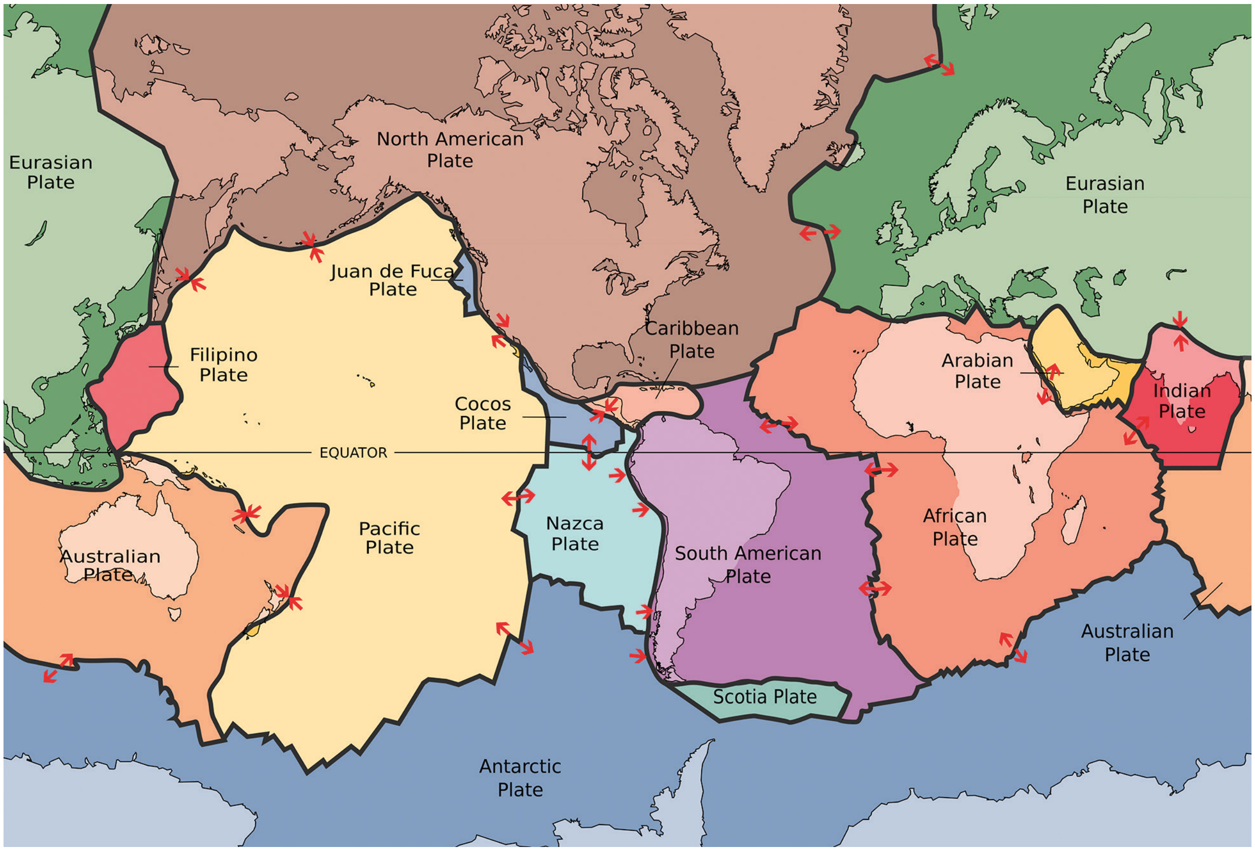


Figure 2.4: Principal plates of Earth's lithosphere at the present day. Image by Scott Nash.

to stone. James Hutton's demonstration, in 1788, of the extraordinarily slow rates of geological processes prompted the Scottish philosopher Playfair (Playfair, 1805) to write "The mind seemed to grow giddy by looking so far into the abyss of time." In our assessment of mountain regions within Canada, we need to be aware of the limits of our ability to understand such enormous spans of 'Deep Time' (McPhee, 1981).

Canada has a landscape defined by its geology. At its core is the Precambrian 'Canadian Shield'—a repository of ancient rocks formed between 4 and 1 billion years ago (e.g., Hoffman, 1988). The shield itself consists of cratons—blocks that have been stable for 2.5 billion years—stitched together and surrounded by mountain belts or orogens formed by the convergence of tectonic plates between 2.5 and 0.54 billion years ago. Time and erosion by water, wind, and ice have bevelled the Shield into a vast low-relief landscape of lakes, wandering rivers, and boreal forests. Surrounding the shield are much younger mountain regions: the Cordillera to the west, the Appalachians to the east and the Arctic Archipelago to the north (Fig. 2.3).

Plate-tectonic processes are responsible for mountain building. The Earth's rigid outer lithosphere is broken into a series of plates (Fig. 2.4) that move very slowly over the softer, more plastic asthenosphere below. Most of Canada lies in the North American Plate, which extends from the mid-Atlantic ridge to the edge of the Pacific Ocean. Tectonic plates are in motion as part of the 'supercontinent' cycle of continental growth, demise, and rebirth: a continual cycle of land and ocean evolution. Eastern Canada lies on a passive margin at the present day—it is in the middle of a plate and so experiences very limited seismic activity and has no volcanoes. In contrast the western margin of North America is an active margin; the continental margin is also a plate boundary. As a result, it has major earthquake-producing faults and numerous volcanoes that appear in the oral histories of First Nations groups in western Canada. The Nuu-chah-nulth peoples of the Pacific Maritime region, for example, speak of mountain dwarfs that not only cause earthquakes, but also warn people about them. In Heiltsuk (Bella Bella, Pacific Maritime region) traditions, earthquakes occur when the being holding up the Earth with ropes periodically adjusts or loses their grip (McMillan & Hutchinson, 2002; Turkel, 2011).

2.2.2 *Ancient orogens of eastern Canada*

The precursor of the North American continent is known as Laurentia. Geological evidence from the eastern mountain regions of Canada indicate that Laurentia broke out of the supercontinent Rodinia between 800 and 550 million years ago (Ma) (Davidson, 2008). The ancient eastern margin of Laurentia is represented by thick limestone successions that record continental-shelf environments similar to the present-day Bahamas, showing that Atlantic Canada lay in the tropics at that time. As Laurentia split off and moved northward it was drawn into a plate collision and subduction zone that ultimately gave rise to the Appalachian mountains (Hibbard et al., 2007; van Staal et al., 1998; Waldron et al., 1998; Williams, 1979).

Maritime and Atlantic Canada, including much of the Atlantic Maritime and Boreal Shield mountain region, consists of the Appalachian orogen. Formed during the Paleozoic era (between 540 and 250 Ma), the Appalachians were once part of a single continuous mountain system extending from Texas to Svalbard. The opening of the Atlantic Ocean separated this orogen into the Appalachians in North America and the Caledonides of Greenland, Ireland, Britain, and Scandinavia. A continuation of the Caledonides into the Arctic basin is referred to as the Ellesmerian orogen and is at least in part responsible for the elevated topography of the northernmost portion of the Arctic Cordillera mountain region.

Evidence for the plate collision that formed the Appalachians and the volcanic arc that it produced occurs throughout the Atlantic Maritime and Boreal Shield region, particularly in the landscapes of the Bay of Islands and Gros Morne National Park. As the Laurentian margin was drawn into the subduction zone, the margin was pulled beneath a deformed mass of sedimentary, igneous, and metamorphic rock known as the 'Humber Arm allochthon'. Remnants of this geologic jumble form the famous Tablelands of Gros Morne National Park (Fig. 2.5). Mountain building continued for another 100 million years, incorporating multiple *terranes*—small crustal blocks with

Figure 2.5: View looking north over a slice of oceanic lithosphere preserved in the Tablelands, Gros Morne National Park, NL. Grey rocks on the left represent ancient oceanic crust. Orange-weathering rocks on the right are representative of the uppermost mantle. Photo courtesy of Phil McCausland, 2019.

distinct geological histories—into the orogen (Cocks & Torsvik, 2011).

2.2.3 *Younger orogens of western Canada*

Together, the Montane Cordillera, Pacific Maritime, Boreal Cordillera, and Taiga Cordillera mountain regions (Fig. 2.6) form the Cordilleran orogen of western Canada. While Laurentia was being incorporated into eastern and northern North America, the future western Cordillera formed the western margin of the supercontinent Pangea, facing the vast expanse of the Panthalassic Ocean. As Pangea began to drift apart, a passive plate margin formed along North America’s west coast. In the shallow sea waters within this passive margin the first complicated, multicellular life forms arose, and are preserved in the famous Burgess Shale fauna (Conway Morris, 1989). But it was not until the break-up of Pangea (at 200 Ma) that the Cordilleran ranges began to form. The rifting of North America away from Africa led to crustal thickening, metamorphism, and the formation of several ranges of mountains along the western margin. At ~75 Ma, the western Cordillera’s most iconic ranges, the Rocky Mountains, were born.

Further north, strike-slip motion (where plates move horizontally past each other) pushed the ‘Yakutat’ continental block northward along the margin. This geologically recent continental collision (Mazzotti & Hyndman, 2002) formed the St. Elias Mountains, which include the highest peak in Canada, Mount Logan (5959 m). The Yakutat block collision was connected to the Cordilleran orogen but involved crustal shortening and uplift associated with continental plate convergence, in contrast to the subduction-zone convergence processes across much of the western cordillera.

The western mountains of Canada are all seismically active, with small- to moderate-sized earthquakes that occur infrequently from a human perspective, but on a regular basis geologically (Lamontagne et al., 2008). Subduction continues beneath Vancouver Island, periodically giving rise to great earthquakes and related tsunamis that have been recorded in First Nations oral histories (Ludwin et al., 2007; McMillan & Hutchinson, 2002). The most recent of these earthquakes occurred on 26 January 1700 (Clague et al., 2000) and was described by Chief Louis Clamhouse:

> This story is about the first !Anaqtl’a or “Pachena Bay” people. It is said that they were a big band at the time of him whose name was Hayoqwis7is, ‘Ten-On-Head-On-Beach’. He was the Chief; he was of the Pachena Bay tribe; he owned the Pachena Bay country. Their village site was Loht’a; they of Loht’a live there. I think they numbered over a hundred persons ... there is no one left alive due to what this land does at times. They had practically no way or time to try to save themselves. I think it was at nighttime that the land shook ... They were at Loht ‘a; and they simply had no time to get hold of canoes, no time to get awake. They sank at once, were all drowned; not one survived ... I think a big wave smashed into the beach. The Pachena Bay people were lost ... But they on their part who lived at Ma:lts’a:s, ‘House-Up-Against-Hill’, the wave did not reach because they were on high ground. Right against a cliff were the houses on high ground at M’a:l-sit, ‘Coldwater Pool’. Because of that they came out alive. They did not drift out to sea along with the others ... (Arima et al., 1991, pp. 230–231).

Volcanoes are common in the western mountain regions, though less active and less well known. The Cascade volcanic province sits above the subduction zone in coastal British Columbia (Fig. 2.7) and includes the recently active Qw’elqw’elústen (Mount Meager) volcano (Hickson et al., 1999; Michol et al., 2008) and Nch’kaỷ (Mount Garibaldi), which last erupted when continental ice sheets covered the region (W. Mathews, 1952). The Anahim Volcanic Belt lies north of the Cascade volcanic province, and trends roughly east-west across the orogen. At the eastern edge of the belt sits the Nazko cone, which last erupted approximately 7200 years before present (Souther et al., 1987). This volcanic belt is thought to record the westward passage of the North American Plate above a mantle hotspot or plume (Kuehn et al., 2015). East of this lies the Wells Gray–Clearwater volcanic complex.

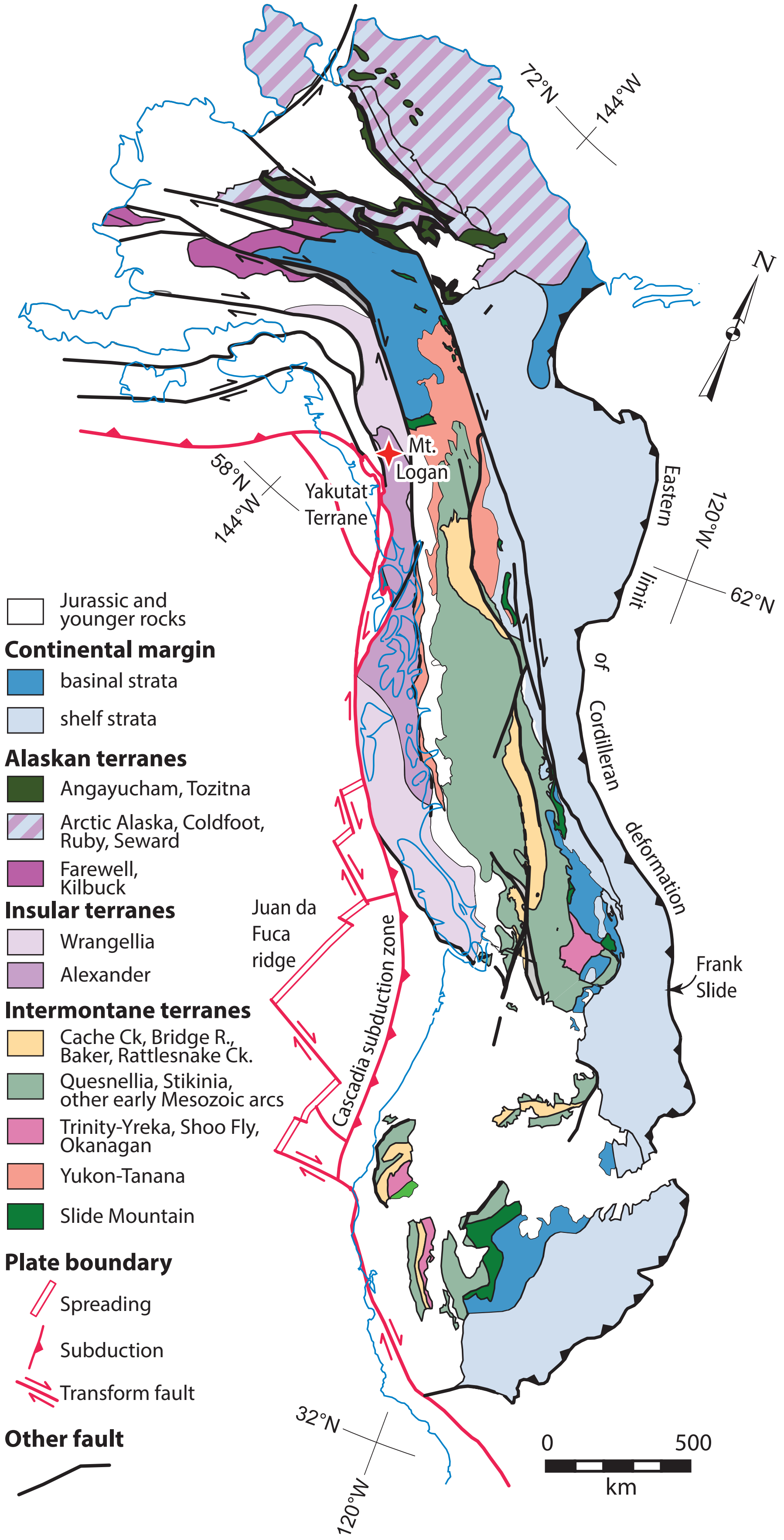
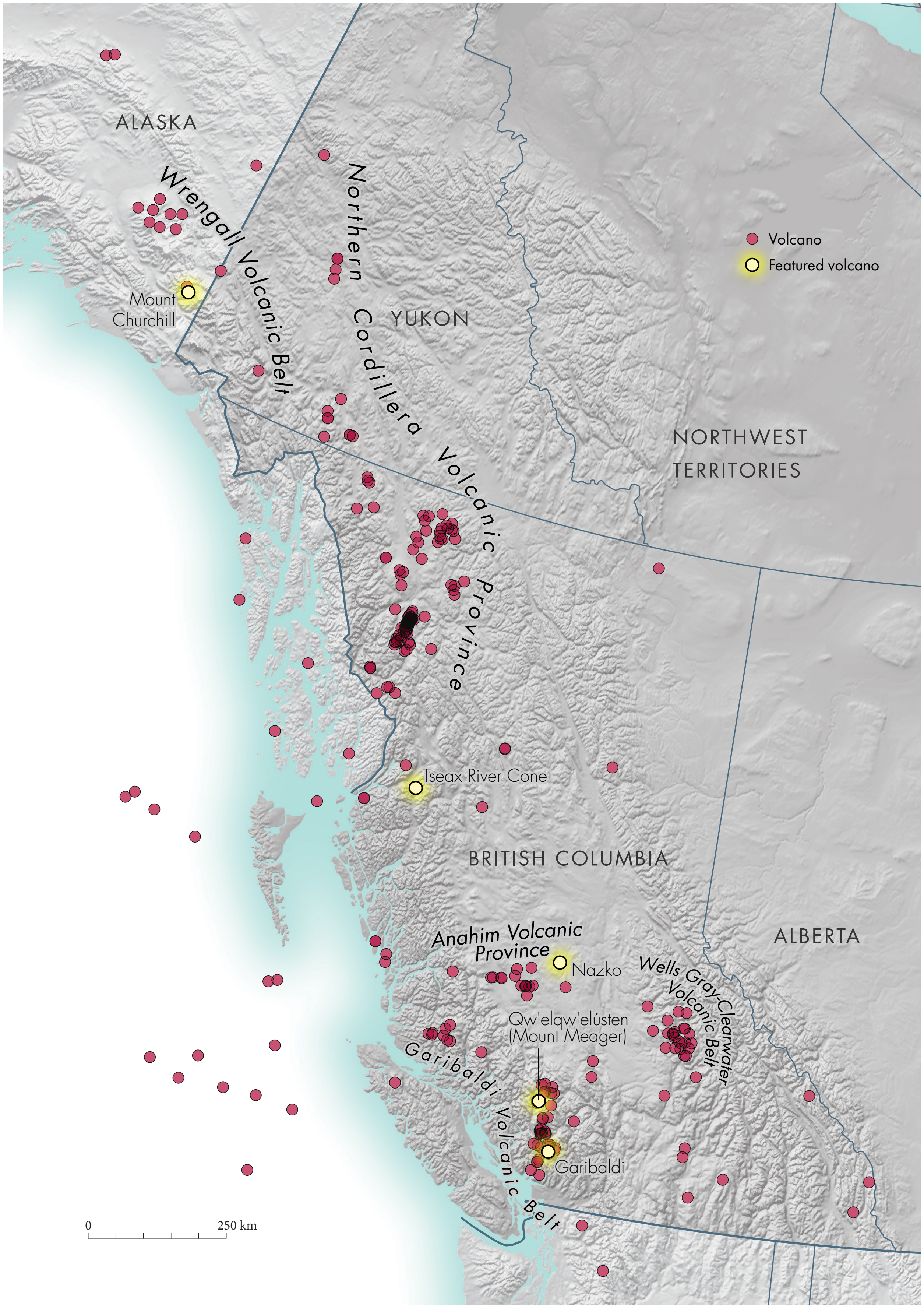


Figure 2.6: Map of the Canadian Cordillera showing terranes accreted to North America and features mentioned in the text. Modified from Colpron & Nelson, 2009.

Figure 2.7 (opposite): Map of volcanoes in western Canada, and volcanic belts and provinces. Volcano locations from the Geological Survey of Canada (http://gsc.nrcan.gc.ca/volcanoes/cat/volcano_e.php; last available June 2012) and the Smithsonian Global Volcanism Program (https://volcano.si.edu/ge/PlacemarkLinks.cfm; accessed April 2023). Locations of the volcanic provinces and belts modified from Edwards & Russell, 2000.


ALASKA
YUKON
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
Wrengall Volcanic Belt
Northern Cordillera Volcanic Province
Anahim Volcanic Province
Wells Gray-Clearwater Volcanic Belt
Garibaldi Volcanic Belt
Mount Churchill
Tseax River Cone
Nazko
Qw'elqw'elústen (Mount Meager)
Garibaldi
● Volcano
○ Featured volcano
0
250 km

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań, 2022, LC 2.3

Pnnal Bernard Jerome, Micmacs of Gesgapegiag, 2022, LC 2.4

Volcanic events in the Northern Cordilleran Volcanic Province (Stikine and Wrangell Volcanic Belts) have played an important part in the history of those who live in the mountains. Some Dene Nations, for example, speak of a volcanic eruption in the past that led to their ancestors leaving the Dene homeland, and which resulted in the subsequent emergence of the different Dene Nations (Moodie et al., 1992). As Lhu'ààn Mân Dań Elder Gùdia Mary Jane Johnson told the Learning Circle, her people speak of a year without summer (LC 2.3). While not definitively identified, it has been postulated that Elder Gùdia Mary Jane Johnson refers to the massive eruption of Mount Churchill around 720–850 CE (Mackay et al., 2022; Moodie et al., 1992), an event that may have driven southward migrations and declines in Indigenous groups in the region (Hare et al., 2004). The eruption of the Tseax cone around 1700 CE in the Nass River Valley (Fig. 2.8), is woven into Nisga'a oral histories, in part because it is the deadliest volcanic event in what became Canada (Corsiglia & Sniveky, 1997; Yannick, 2020). However, volcanic activity has also been thought to offer gifts to Indigenous Peoples. Elder Pnnal Bernard Jerome (Micmacs of Gesgapegiag) described the sacred stones, a form of perforated lava, offered up from the belly of Mother Earth to share her spirit with the people during ceremonies (LC 2.4).

Across all mountain regions, erosional processes continually sculpt the underlying geology of mountain landscapes. Erosion removes rock almost as fast as the mountains rise (Ford et al., 1981; Molnar & England, 1990). The interplay between relative sea level change and crustal rebound following the removal of continental scale ice sheets has led to dramatic changes in coastlines both in the Arctic (Müller & Barr, 1966) and along the Pacific coast (Shugar et al., 2014). The potential energy generated through the uplift and erosion of mountains can also lead to catastrophes for mountain inhabitants, where rockfall and landslides pose significant hazards (see Sec. 2.6).

2.2.4 *Ice sheet histories, landscape sculpting, and deglaciation*

Mountain ranges in the east, the north, and the west of Canada have served as centres of initiation for large ice sheets that repeatedly covered the northern half of North America over the past 2.6 million years (Batchelor et al., 2019; Clark et al., 1993). Flowing outwards from high-elevation regions lifted by tectonic forces, continental ice sheets and their associated erosional and depositional processes have repeatedly sculpted landscapes across Canada (Mathews, 1991), with comparable rates of erosion and sculpting from rivers during ice-free periods (CAINE, 1976; Koppes & Montgomery, 2009). The processes that shape mountain environments can be broadly summarised by elevation and slope angle (Slaymaker, 1990): at the highest elevations and on steeper mid-elevation slopes, glacial processes and mass wasting (i.e., rockfalls, landslides) dominate the landscape. At lower elevations and in valley bottoms, rivers control the sculpting process as they erode and rework the sediment deposited by glaciers and mass movements.

Glaciers and ice sheets are prolific landscape shapers: with each glaciation, the expansion of mountain glaciers and continental ice sheets widens and deepens existing river valleys, rounds lower elevation topography covered by ice sheets, and undercuts summits that remain above the ice (Mathews, 1991). These processes are reflected in the sharp peaks of the Pacific Maritime, Montane Cordillera, and Boreal Cordillera regions and the rounded hills of the interior and the Shield regions. Sediments eroded and carried by glaciers and ice sheets are deposited across the landscape as the ice sheets retreat, and water produced by the melting ice picks up, moves, and deposits these sediments in river valleys and lowland floodplains.

Figure 2.8: Lava beds in Nass Valley, Nisga'a territory, British Columbia. Photo by Darren Kirby, CC BY-SA 2.0, 2022.

Numerous inland lakes were formed during deglaciation in the Mountain, Pacific, and Boreal Cordillera. These lakes, created by temporary ice dams that blocked rivers draining the melting ice sheets, left thick deposits of sand and clay and scoured the landscape when the ice dams broke and the lakes drained catastrophically (Johnsen & Brennand, 2006; Ryder et al., 1991). In addition to shaping the landscape itself, repeated glaciations and deglaciations have impacted species distributions, biodiversity, and genetic diversity (Sec. 2.7) through habitat fragmentation, creation of glacial 'refuges', and exposure and subsequent flooding of continental shelves (Allen et al., 2012; Hewitt, 2000; Shafer et al., 2010).

The most recent period of glaciation peaked between 21,000 and 18,000 years ago, at what is known as the Last Glacial Maximum (LGM). At the LGM, two continental-scale ice sheets covered most of the Canadian landmass: the Cordilleran Ice Sheet, which was centred over the mountains of western Canada; and the Laurentide Ice Sheet, which originated from multiple ice domes centred east of Great Slave Lake, northern Ontario, and Quebec (Dyke & Prest, 1987; Gowan et al., 2016; Marshall et al., 2000). Thick ice sheets covered most of Canada at this time.

The timing of glacier and ice sheet retreat from their maximum LGM extents varies by mountain region. The earliest retreat of the Cordilleran Ice Sheet was likely initiated on the southern and western margins, with ice-free coastal sections possibly offering a viable corridor for human migration by approximately 18,000 years ago (Braje et al., 2020; Darvill et al., 2022; Dulfer et al., 2021; Dulfer et al., 2022; Wade, 2021). An ice-free corridor between the Cordilleran and the Laurentide Ice Sheets was likely not viable for human migration until somewhere between 13,800 and 12,600 years ago (Adler et al., 2022; Clark et al., 2022; Pedersen et al., 2016). There is some evidence to suggest a human presence on lands south of the continental ice sheets as long as 37,000 years ago (Rowe et al., 2022), although many Indigenous

Peoples understand their presence in these landscapes as existing since time immemorial. The Laurentide Ice Sheet has a complex deglaciation history (Dyke & Prest, 1987), with ice domes persisting over northern Quebec and Labrador until approximately 7000 years ago (Ullman et al., 2016). Large icefields currently found on Baffin and Ellesmere Islands in the Arctic Cordillera are remnants of the last glaciation, as these contain residual Pleistocene-age ice (Koerner and Fisher, 2002; Zdanowicz et al., 2002).

While there may be a tension between scientific evidence for the first arrival of humans in North America, the chronology of continental ice sheets, and Indigenous concepts of being present on the land since time immemorial (Wynn, 2007), origin stories from the Blackfoot Nation of the Montane Cordillera clearly reflect the environmental processes related to deglaciation (Zedeno et al., 2021). These oral histories reference the great floods and lakes left behind by decaying ice sheets, the south to north re-vegetation of the deglaciated landscape, and the 'erratic train' of boulders (Fig. 2.2) that was left behind as the Cordilleran and Laurentide ice sheets retreated.

Following the retreat of the Cordilleran Ice Sheet in western Canada, global mean temperatures peaked approximately 8000 years before present. For a period of several thousand years, glaciers were absent over large areas that are now occupied by glacier ice in western Canada (Heusser, 1956; Menounos et al., 2009; Wood & Smith, 2004). In eastern and northern Canada, this thermal maximum was delayed by up to 4000 years due to the slower demise of the Laurentide Ice Sheet over eastern regions. This period of relative warmth prior to the re-establishment and expansion of mountain glaciers (Mood & Smith, 2015) and permafrost (Treat & Jones, 2018) has implications for the occupation of mountain regions by Indigenous Peoples and the establishment of mountain ecosystems over the past 10,000 years.

2.2.5 *Gaps and challenges*

Mountains exist because of a dynamic interplay between deep-time geological processes that lift land upwards, and the erosive effects of ice, water, and wind that grind them down under the force of gravity. They will continue to evolve both in ways that are beyond our ability to perceive, as well as those more rapid and visual processes involving snow, ice, hydrology, ecology, mountain hazards, and human interactions in these environments. A more holistic and integrated approach across these subject areas is needed to improve systems-based understanding of mountains and their future evolution.

In the younger mountain ranges of eastern and western Canada, mapping and biostratigraphy (correlation using fossils) has provided exceptional information on the ages of the rocks and the relationships between the main units. However, even in these relatively well understood orogens there are significant gaps and challenges. For example, controversy has surrounded the polarity of subduction—which slab of plate descended into the deeper mantle during convergence—in the evolution of both orogens (e.g., Johnston, 2008; McMechan et al., 2020; De Souza et al., 2014; van Staal et al., 2015), and more work is needed to resolve these questions. Also poorly understood is the relationship between the Appalachian Orogen and its continuation through the Caledonide Orogen of Europe, Svalbard, and Greenland into Arctic Canada as the Innuitian (or Ellesmerian) Orogen (Fig. 2.1) (e.g., Malone et al., 2019).

The older orogens in Canada pre-date most fossils, so unravelling their history is dependent on isotopic dating, and large areas have been mapped geologically only at reconnaissance scale. The tectonic history of the Canadian Shield records major episodes of mountain building for which the plate-tectonic processes are only beginning to be understood (e.g., Hoffman, 1988; Martins et al., 2022). Most of these former mountain belts have been worn down close to sea-level, but portions of the Grenville and Trans-Hudson orogens, formed during the amalgamation of earlier supercontinents, form the Laurentian and Torngat mountains in eastern Canada. Still more uncertainty surrounds the ancient Archean cratons (Fig. 2.1), which record a tectonic system prior to 2.5 billion years ago that may have been substantially different from modern plate tectonics (e.g., Hamilton, 1998).

2.3 Weather and Climate

Western science defines weather as the day-to-day changes in temperature, precipitation, wind, and clouds, and climate as the long-term average of weather. Or, as the Sami people of Finland have described it, "Climate is recorded. Weather is experienced" (Ingold & Kurtilla, 2000). Mountains are known for their unpredictable and extreme weather, and are on the front lines of climate change (Hock et al., 2019). While scientific research on mountain weather and climate focuses on quantifying and explaining spatial patterns in specific climate variables, this approach may be less relevant to Indigenous Peoples and others living in mountain areas than, for example, the lived experience of weather (Ingold & Kurtilla, 2000; Walsh et al., 2017), its predictability (Walsh et al., 2005; Wilson et al., 2015) or indicators of seasonal changes from animal behaviours (Turner & Clifton, 2009).

Millennia of accumulated experience on the land provide First Nations, Métis, and Inuit Peoples with intimate knowledge and understanding of "human-relevant environmental variables" (Fox et al., 2020; Simpson, 2002; Weatherhead et al., 2010). As Siksika (Blackfoot Confederacy) Elder Hayden Melting Tallow and Kwanlin Dün Elder Patricia Joe stated, the mountains themselves served as indicators of the weather and people learned to read them (LC 2.5, LC 2.6). In contrast, the observational networks used to measure, quantify, and model weather and climate were only established in the past century, and the climate reanalysis models used to describe broad spatial patterns have been developed and refined only in the past 20 years, although they have been applied retrospectively to past climate.

Hayden Melting Tallow, Siksika Nation, Blackfoot Confederacy, 2022, LC 2.5

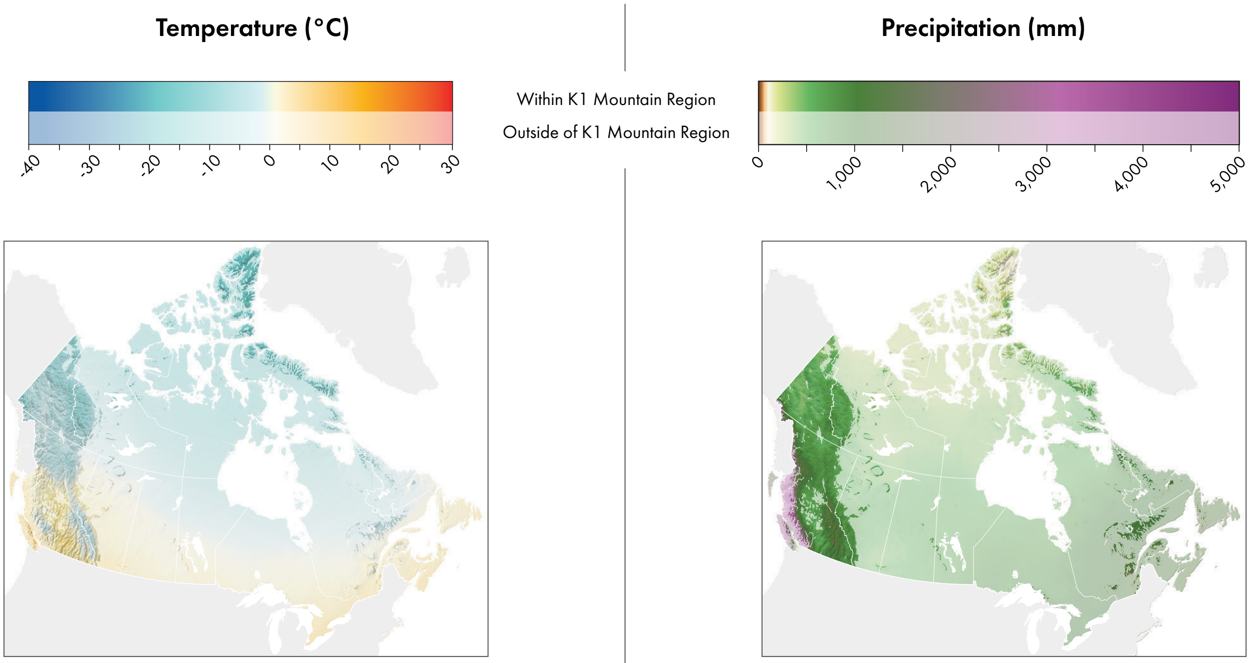
Patricia Joe, Kwanlin Dün First Nation, 2022, LC 2.6

This section describes how air temperature, precipitation, and winds vary across mountain regions in Canada, and identifies the processes that make mountain weather both interesting and challenging. We use existing datasets to broadly characterise the climatology of mountain systems across Canada and assess the understanding of mountain-specific weather processes from both Indigenous and Western scientific perspectives. Few Indigenous perspectives on weather and climate in mountain regions across Canada were shared with us during the Assessment, so this section is limited in its representation of Indigenous understanding of mountain weather and climate processes. For the scientific perspective on mountain weather and climate, we refer throughout this section to the ERA5 global reanalysis dataset (Hersbach et al., 2020) which provides a more complete and consistent meteorological dataset than the sparse station networks often found in mountainous regions.

2.3.1 *Air temperature*

Mountain systems in Canada are characterised by large variations in near-surface air temperature in both space (Fig. 2.9) and time (Fig. 2.10). Mean seasonal and annual temperatures shown for the period 1991–2020 are based on the ERA5 reanalysis dataset (Hersbach et al., 2020) and are given in Table 2.1. From a climatological point of view, latitude and distance to the ocean control the spatial distribution of temperature across the different Canadian mountain regions (Fig. 2.9). The Pacific Maritime region stands out for being warm with mild winters (mean winter temperatures of -4.5°C) relative to the rest of Canada (mean winter temperatures of -20°C). The Arctic Cordillera region is on the other end of the spectrum, characterised by extremely cold conditions with mean annual temperatures of -16°C and mean winter temperatures of -30°C.

In mountain regions, the elevation of the 0°C temperature threshold is critically important for processes such as snow and ice melt, frozen ground, and precipitation phase (rain versus snow) at the surface (Mekis et al., 2020). Mountain regions in Canada that experience mean annual temperatures near 0°C are found in low-elevation and coastal regions of southern Canada (Pacific Cordillera and Atlantic Maritime).

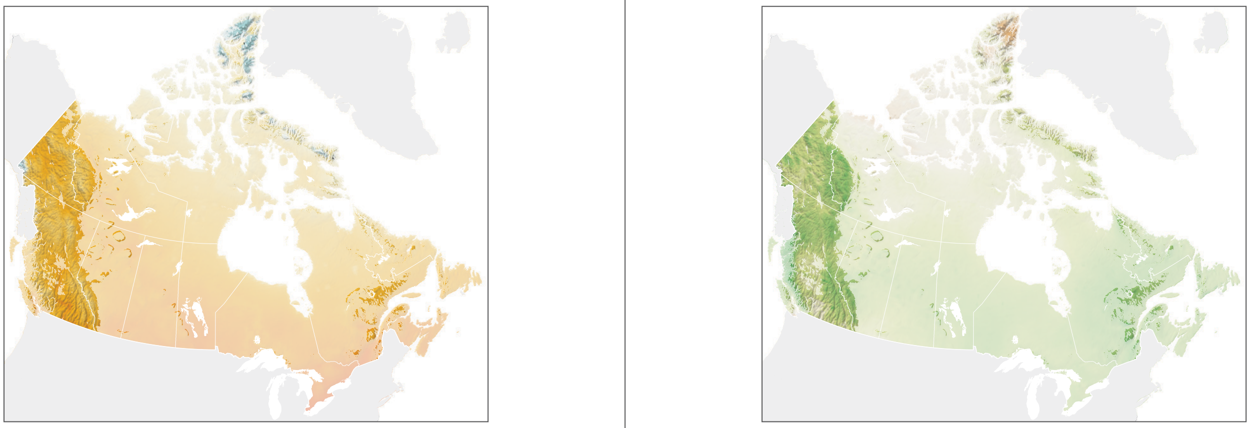


Mean annual temperature

Mean annual precipitation

Winter (December, January, February) temperature

Winter (December, January, February) precipitation



Summer (June, July, August) temperature

Summer (June, July, August) precipitation

Figure 2.9: Maps showing the average annual, winter (December, January, and February), and summer (June, July, and August) air temperature (left) and precipitation (right) across Canada. This baseline climatology (1991–2020) is calculated from the ERA5 climate reanalysis. Data from Hersbach et al., 2020.

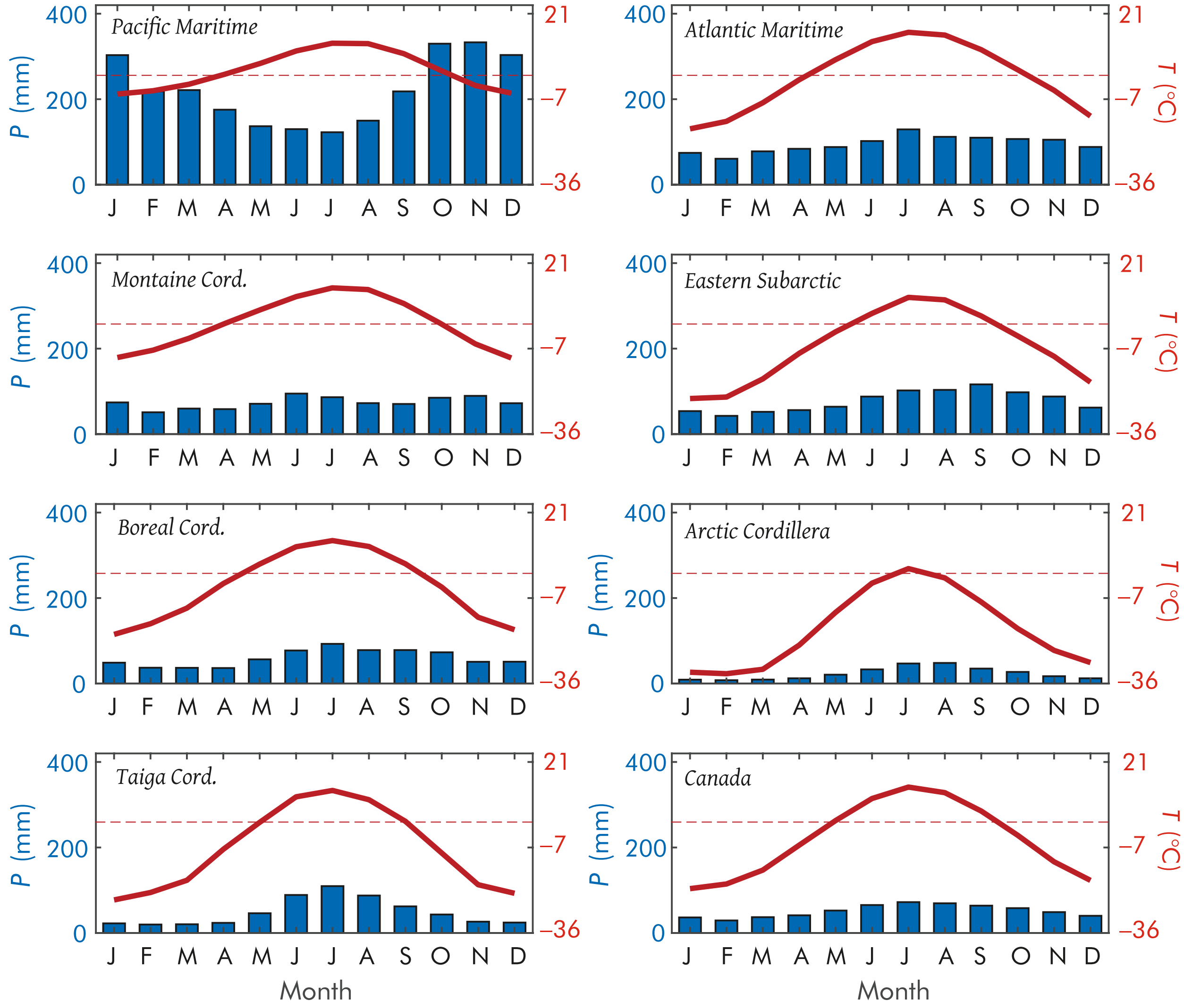


Figure 2.10: Baseline climatology (1991–2020) for monthly air temperature (red curve) and precipitation (blue bars) for the major mountain regions in Canada, calculated from the ERA5 climate reanalysis by averaging all ERA5 grid cells over each mountain region. Data from Hersbach et al., 2020.

Within a given mountain region, elevation strongly controls the spatial variability of temperature. On average, temperatures decrease with elevation at a rate known as a lapse rate or temperature gradient. In the Montane Cordillera, the mean annual lapse rate is -5.2°C km^{-1} (Shea et al., 2004), which means that on average the temperature decreases by 5.2°C for every 1000 m increase in elevation. A more negative lapse was found in springtime (-6.0°C km^{-1}) when strong temperature contrasts exist between snow-free valley bottoms and snow-covered peaks. In the eastern Montane Cordillera (Canadian Rockies) and the Pacific Cordillera, the lapse rate is generally larger for maximum temperatures than for minimum temperatures (Stahl & Moore, 2006; Wood et al., 2018). Lapse rates in the Arctic show similar ranges and are often weaker due to strong inversion structures, with links to atmospheric circulation patterns (Marshall et al., 2007).

Minimum temperatures in valley bottoms are particularly sensitive to the overnight accumulation of cold air in valley bottoms (Sakiyama, 1990), which reverses the lapse rate and leads to the formation of temperature *inversions* where colder air is found at lower elevation. Inversions are common in the eastern Canadian Rockies (Wood et al., 2018) and the Yukon (Burn, 1994), and are more frequent during winter when cold and continental polar air masses from northern Canada

Table 2.1: Average annual (ann), winter (DJF: December, January, and February), and summer (JJA: June, July, and August) temperature and precipitation in the main mountain regions of Canada and across all Canada (last row). The values were calculated from the ERA5 global climate reanalysis, with a resolution of 0.25 degrees and are based on all ERA5 grid cells covering Canada and each of the CMA mountain regions.

ERAS baseline climatology (1991–2020), Canadian Mountain Regions

	T (°C)			*P (m)*		
Mountain Region	*DJF*	*JJA*	*ann*	*DJF*	*JJA*	*ann*
Pacific Maritime	-4.5	11.2	2.9	0.84	0.38	2.60
Montane Cordillera	-9.1	12.4	1.5	0.21	0.25	0.92
Boreal Cordillera	-17.7	11.5	-3.1	0.13	0.27	0.73
Taiga Cordillera	-23.6	11.0	-7.1	0.07	0.31	0.62
Atlantic Maritime	-14.1	15.1	1.0	0.25	0.37	1.23
Eastern Subarctic	-19.3	9.5	-4.6	0.16	0.30	0.94
Arctic Cordillera	-30.0	1.4	-16.0	0.03	0.14	0.32
All of Canada	-20.0	12.3	-3.9	0.12	0.24	0.69

move southwards (Cullen & Marshall, 2011). The formation of valley cold pools represents a challenge for meteorological models, in particular in the Canadian Rockies (Vionnet et al., 2015). Temperature inversions are also very frequent in the Arctic, Taiga and Boreal Cordilleras (O'Neill et al., 2015; Smith & Bonnaventure, 2017) where they influence the spatial distribution of permafrost (Bonnaventure & Lewkowicz, 2013). Temperature inversions are not restricted to valley bottoms and can be observed at larger scales due to the continuous loss of heat from snow and ice-covered surfaces, particularly during dry and clear conditions. This is especially the case in the Arctic during the long and dark winter (Lesins et al., 2010).

Other weather phenomena, such as Chinook events in the eastern Canadian Rockies and the Foothills (Montane Cordillera), can also influence the lapse rate. During such events, air is warmed as it descends to the surface, and the lapse rate approaches -10°C km^{-1} (Cullen & Marshall, 2011). Chinook events can bring rapid warming and snowmelt in the depths of winter in the Canadian Rockies (Nkemdirim, 1996, 1997; Mekis et al., 2020). More details about the Chinook, an iconic wind of the mountains in Canada, are given below in the section dedicated to mountain winds.

Mountain glaciers modify the distribution of air temperature in their vicinity. For example, during the melt season, the temperature of the snow and ice at the surface of glaciers cannot exceed 0°C. Observations from the Pacific Maritime region (Shea & Moore, 2010) and the Arctic Cordillera (Marshall et al., 2007) show that the air immediately above the glacier surface is cooled and, as it is denser, it flows downward in a thin layer above the glacier. Consequently, air temperatures above glaciers are typically lower than off-glacier temperatures at the same elevation during the summer months (i.e., when the surrounding terrain is snow-free).

Mountains in Canada are increasingly affected by extreme air temperatures in summertime. Recently, in June 2021, an unprecedented heat wave known in the media as the "heat dome" impacted the southern parts of the Pacific and Montane Cordilleras with local temperatures reaching values well above 40°C (Vasquez, 2022). During this heat wave, the all-time heat record in Canada was eclipsed three days in a row with air temperatures reaching 46.1°C, 47.9°C, and 49.6°C in the village of Lytton, located on the lee side of the Pacific Maritime ranges. This heat wave was associated with the presence of a large-scale and persistent high-pressure ridge centred over the region that prevented the transport of cooler, moist Pacific air into the region. Ridges are also associated with clear skies (i.e., sunny conditions) and sinking air that warms adiabatically, similar to Chinook winds, contributing to the hot, dry weather.

Similar circulation patterns are related to droughts in the Pacific and Montane Cordilleras and in the adjacent regions of interior British Columbia and of the Prairies (Bonsal et al., 2011;

Stewart et al., 2019). Droughts in mountains in Canada are a combination of anomalously low precipitation (Sec. 2.2.2) and high air temperatures (Bonsal et al., 2011). The occurrence of wildfires in the Montane Cordillera is also controlled by the same large-scale atmospheric circulation patterns that favour heat waves (Johnson & Wowchuk, 1993). Wildfires, in turn, can create their own thunderstorms—heat from intense wildfires causes humid air to rise rapidly into the atmosphere, producing pyrocumulus clouds (Stewart et al., 2019). In some conditions, lightning activity in pyrocumulus clouds can lead to new fire ignitions (Kochtubajda et al., 2017).

2.3.2 *Precipitation*

Precipitation can occur as liquid, ice, or a combination of the two when temperatures are near 0°C (Mekis et al., 2020; Stewart et al., 2015). We use total precipitation (the sum of all liquid and solid precipitation) extracted from ERA5 reanalysis data to compare precipitation across mountain regions in Canada. Average annual, summer, and winter precipitation data (Fig. 2.7, Fig. 2.8, and Table 2.1) for the period 1991–2020 highlight the importance of mountain regions as 'water towers' (Vivrioli et al., 2007).

The Pacific Maritime region stands out for being exceptionally wet, with annual precipitation four times greater than the rest of Canada (Table 2.1). The Pacific Maritime ranges are directly affected by moisture-laden westerly storms and atmospheric rivers coming off the Pacific Ocean. Atmospheric rivers, which transport warm and moist tropical air towards the West Coast in narrow bands, can contribute up to one-third of the total annual precipitation in coastal British Columbia (Sharma & Dery, 2020). The Arctic Cordillera is on the other end of the spectrum, characterised by dry conditions (0.32 m annual precipitation). The Taiga Cordillera region in northwestern Canada is also relatively dry, with a mean annual precipitation of 0.62 m. All other mountain regions in Canada receive precipitation totals that exceed the national average.

The ERA5 reanalysis data used to derive this precipitation climatology will underestimate precipitation in the high mountains (Mott et al., 2018). For instance, measurements from ice cores and glacier mass balance studies in the St. Elias mountains, Yukon, indicate annual precipitation totals of ~2 m at elevations of 2500–3000 m in the St. Elias Icefields (Ochwat et al., 2021; Zdanowicz et al., 2014), which is an order of magnitude higher than the 0.28 m of precipitation received at Burwash Landing (806 m) in the adjacent valley bottom. Similar decreases in precipitation are observed going west to east across the continental divide of the Canadian Rockies (Adhikari & Marshall, 2013).

Mountain ranges are significant obstacles to atmospheric flow. When moist air encounters a mountain range it is forced to rise. This leads to cooling, condensation, and precipitation in a process known as orographic precipitation (Roe, 2005). Orographic precipitation is heaviest on windward sides of mountain ranges, with strong vertical gradients of precipitation given the right atmospheric conditions (Thériault et al., 2022). These gradients do not typically extend to the top of a mountain range, however, as the greatest rates of uplift, condensation, and precipitation tend to occur lower down the mountain. Orographic precipitation has been studied in the Arctic Cordillera (Fargey et al., 2014; Hanesiak et al., 2010), the Montane Cordillera (Liu et al., 2016; Milrad et al., 2015; Shea et al., 2004), and the Pacific Maritime (Jarosch et al., 2012; Mo et al., 2019; Sharma & Dery, 2020). In lower-elevation ranges, the mountains may not produce strong precipitation gradients, but they can affect the distribution and phase of precipitation, as shown in studies from the Atlantic Maritime and Boreal Shield region (Chartrand et al., 2022; Ressler et al., 2012).

While the windward sides of mountain ranges receive the highest precipitation totals, lee slopes can also experience heavy precipitation events associated with orographic forcing. The eastern side of the Montane Cordillera, for example, although associated with a drier climate, can experience frontal storm systems associated with easterly winds that lead to heavy precipitation and massive flooding (Liu et al., 2016). Convective precipitation, due to surface heating which lifts air parcels into the atmosphere, can also occur over complex terrain (Kirshbaum et al., 2018) and can weaken or reverse the standard precipitation gradient. For example, the highest amounts of precipitation observed in the 2013 Alberta floods were associated with convective precipitation at lower elevations (Kochtubajda et al., 2016). This convective activity was embedded in a three-day cyclonic storm (19–21 June 2013) during which more than 200 mm of rainfall was reported at locations on the eastern side of the Canadian Rockies (Pomeroy et al., 2016). Rainfall intensity plays a key role in the flooding risks associated with mountain precipitation (Weingartner et al., 2003), particularly in steep mountain creeks.

Atmospheric and meteorological factors that determine the *phase* of precipitation (rain, snow, or other) vary across mountain regions in Canada (Harder & Pomeroy, 2014; Poirier et al., 2019). The freezing level broadly describes the elevation where rain turns to snow. In atmospheric river events, shifts in the freezing level can determine whether flooding occurs or not (Newton et al., 2019). For example, in the atmospheric river event and flooding in southern British Columbia in November 2021, freezing levels were as high as 2000 m (Gillett et al., 2022). Anomalously warm conditions were also a factor during the June 2013 Alberta flooding, as precipitation fell as rain to elevations of up to 2500 m during the first two days of this storm event. Progressive cooling as the storm went on caused rain to change to snow at higher elevations, preventing an even more severe flooding event (Pomeroy et al., 2016). Rain-on-snow events can contribute to rapid snowmelt and downstream floods. Most of the melt during such events is due to the advection of warm and moist air over the snow surface, as opposed to melt energy in the rain itself (Sec. 2.4.1). Rain-on-snow events are common in the Pacific Maritime mountains, the Montane Cordillera, and eastern Canada (Cohen et al., 2015; Suriano, 2022), and are becoming more common in northern Canada. As described by Brandy Mayes of the Kwanlin Dün First Nation, precipitation regimes in mountain regions are being affected by climatic changes that include ocean warming (LC 2.7).

Brandy Mayes, Kwanlin Dün First Nation, 2022, LC 2.7

2.3.3 *Mountain wind systems*

Mountains modify large-scale atmospheric flows and create wind systems specific to mountain environments. For Indigenous people in the Arctic, winds affect all types of travel, and can be a significant safety consideration (Ford et al., 2019). Mountains of the Canadian Arctic Archipelago influence the wind patterns at some of the low-lying Arctic communities such as Iqaluit and Cape Dorset in Nunavut (Nawri & Stewart, 2008) and favour the occurrence of blizzards (Hanesiak et al., 2010). Cold air flows known as katabatic winds commonly descend off the large ice caps in the Arctic Cordillera due to high pressures created by cold, dense air that develops in the plateau regions of these ice caps (Gardner et al., 2009). This air flows downslope and can have a considerable fetch, building to strong and persistent off-glacier winds.

Similar winds are generated by the large icefields of western Canada (Stenntng et al., 1981; Shea & Moore, 2010; Ayala et al., 2015). The process is particularly strong in summer months, when the surrounding terrain and air heat up but the glacier surface does not warm beyond the melting point, 0°C. This creates a strong thermal and pressure gradient. The contrast of heating and cooling between the Rockies and the Prairies can also create atmospheric circulations between the mountain and the adjacent plains (Thyer, 1981). The interaction between large-scale, regional, and local wind systems can create complex atmospheric circulation patterns in the surroundings of large glaciers such as the Columbia Icefield in the Rockies (Conway et al., 2021). Katabatic winds also drive local cooling that suppresses the development of soil and vegetation in glacier forefields.

The complex topography of mountains presents many corridors that modify and channelize low-level winds. Strong winds due to wind channelling in mountain valleys can generate waves on valley lakes, affecting chemical and biological processes (e.g., Quesnel Lake in the Montane Cordillera; Thompson et al., 2020). Wind channelling also occurs in the St. Lawrence Valley, the Laurentian Mountains, and the Adirondack Mountains in the United States (Carrera et al., 2009). In winter, this channelling can produce a layer of cold air close to the surface, increasing the occurrence and intensity of freezing rain events such as the 1998 Ice Storm (Roebber & Gyakum, 2003) that occurred in and around the St. Lawrence Valley.

In the Coast Mountains of British Columbia (Pacific Maritime), winds are channelized in the deep valleys, fjords, and inlets that connect the interior of British Columbia to the coast (Bakri et al., 2017a; Jackson & Steyn, 1994). Depending on the gradient of pressure across the Coast Mountains, these winds can be inflows, with air moving from the coast to the interior, or outflows, with air moving from interior to the coast. Outflows are mainly observed during the winter when cold, high-pressure air masses sit over the interior east of the Coast Mountains. Combined with the warmer air at lower pressure found along the coast, it creates a pressure gradient that pushes the cold air through the valleys, fjords, and inlets. Large wind speeds (above 80 km h^{-1}) and associated extreme wind chill (below -30°C) can be observed during outflow events (Jackson, 1996).

The Squamish winds are common winter outflows in the Howe Sound region of British Columbia (Pacific Maritime), named after the Skwxwú7mesh (Squamish) First Nation of the region. Pressure gradients across the mountain passes of Vancouver Island create the Qualicum wind, an outflow that creates strong westerly winds and potentially dangerous sailing conditions in the Strait of Georgia on the eastern side of Vancouver Island (Bakri et al., 2017b).

CHINOOK WINDS

The most well-known mountain wind in Canada is the Chinook: a strong, warm, and dry westerly wind that descends the lee slopes of the Canadian Rocky Mountains in southern and central Alberta (Nkemdirim, 1996, 1997). Chinook winds on the eastern side of the Montane Cordillera are linked to orographic precipitation (Sec. 2.2.2) on the windward side. Warm and moist Pacific air that is forced to ascend the western side of the mountains cools, condenses, and loses moisture through precipitation. This adds latent heat to the air mass. As this drier air traverses the continental divide and descends on the eastern slopes, the descending air pressurises and warms faster than it cooled on the upslope side, which leads to warm winds at the surface. The phenomenon is associated with a wide band of clouds parallel to the mountains, known as the Chinook arch. The arch demarcates the precipitation bands over the mountains which help to fuel the Chinook. Many of the strongest Chinooks are associated with intense low pressure systems off the coast of British Columbia or the US Pacific Northwest, which can produce high winds and draw warm, moisture-laden air from the subtropical Pacific (also known as 'Pineapple Express' systems or atmospheric rivers).

Chinook winds occur all year around but are particularly noticeable in winter when they can lead to strong increases in near-surface air temperature (up to 25°C in less than a day) and high wind speeds in southern Alberta (Nkemdirim, 1991). In November 2011, successive Chinook wind-storms with gust wind speeds reaching more than 140 km h^{-1} led to massive damage in southern Alberta (Hugenholtz, 2013). On average, Chinooks occur about 50 days per winter (Nkemdirim, 1997) and the associated high temperatures and wind speeds can quickly remove large amounts of snow due to melt and sublimation (Sec. 2.3.1) (Golding, 1978; Macdonald et al., 2018). The term Chinook originates from the Lower Columbia River area, where the Chinookan nations experienced similar weather (Ballou, 1893; Costello, 1895). Commonly, Indigenous terminologies used in Western language are spatially disconnected from their origins. In the case of the Chinook, the local Indigenous term for this wind is *masta ganutha* in Nakoda[1] and *si'kssópoistsi* in Siksika (Frantz & Russell, 2017).

Daily (or diurnal) wind systems are also widely found in mountains in Canada at different scales. These wind systems are driven by heating and cooling cycles in the lower atmospheric layers. Slope wind systems can develop along the side walls of valleys, such as in the Kananaskis valley in Alberta (MacHattie, 1968). Slope winds are upslope in daytime when the sun warms the exposed slopes and the heated air rises above them. On the contrary, during nighttime, the cooled air near the surface flows downslope and collects in the valleys. Valley winds flowing along the valley axis are another manifestation of diurnal wind systems in mountains in Canada (Sakiyama, 1990).

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[1] https://dictionary.stoneynakoda.org/#/E/chinook

2.3.4 *Gaps and challenges*

Our understanding of mountain weather and climate is incomplete due to limited availability or inclusion of Indigenous knowledges within our assessment and a systematic lack of station observations. Ground-based observations of mountain weather are crucial for short-term weather forecasting, long-term climate assessment, and to improve our understanding of the complex interactions between mountains and the atmosphere. The density of active meteorological and hydrological stations varies across Canada (Fig. 2.11), with very few stations established at high elevations. The Montane Cordillera has more than 6 stations per 10,000 km² (Table 2.2), while high-latitude mountain regions show a very low density of stations (0.1 stations per 10 000 km² in the Eastern Subarctic).

Active stations used to forecast weather and streamflow belong to a range of federal, provincial, territorial, and municipal networks, and may have been deployed only recently. These active stations are not necessarily suitable for climate change assessments that require long-term and consistent meteorological data (Mekis & Vincent, 2011; Vincent et al., 2012). Consequently, the number of stations available for climate change assessments drops significantly across the country (Fig. 2.12) and for all mountain regions in Canada (Table 2.2). Only the Montane Cordillera has more than 1 station per 10,000 km² that can be used for climate assessment. The Pacific Maritime and Taiga Cordillera regions only have climate stations in nearby valleys and coastal areas. This lack of in-situ data makes climate change assessments a challenge for Canadian mountain regions.

Precipitation measurements, including amounts, intensity, and phase, are one of the greatest challenges in understanding and characterising the climate of mountainous regions (Lundquist et al., 2019). Most stations that measure precipitation are located in valleys, at lower elevations, where less precipitation generally occurs. At higher and colder elevations, precipitation measurements are challenged by winds (Kochendorfer et al., 2022) and snowfalls that cover gauges (Rasmussen et al., 2012). Local processes such as wind redistribution of snowfall (Mott et al., 2018) are not captured by typical measurement networks.

Low precipitation amounts also present a challenge to both measurement networks and models (Schirmer & Jamieson, 2015). This is the case in the Arctic, where light snow (known as diamond dust) can fall continuously but at a rate that is too low to be measured by standard all-weather gauges. A combination of ground instruments, new technologies such as hotplate precipitation gauges (Rasmussen et al., 2011; Thériault et al., 2021), and space-borne remote sensing is essential to map precipitation. However, satellite measurements of weather and climate conditions in mountainous terrain are limited by spatial resolution, repeat frequency, and the presence

Table 2.2: Number and density of stations measuring precipitation and/or temperature for the main CMA mountain regions. The information is provided for active stations that were used in the ECCC operational systems for weather and hydrological forecasting (Carrera et al., 2015; Fortin et al., 2018) between 1 January–31 May 2022 and for climatological stations from the Adjusted and Homogenized Canadian Climate Data (Mekis & Vincent, 2011; Vincent et al., 2012). The density represents the number of stations per 10,000 km².

Regions	*Number (density) of active stations*	*Number (density) of climatological stations*
Arctic Cordillera	–*	3 (0.1)
Atlantic Maritime and Boreal Shield	64 (3.3)	3 (0.2)
Boreal Cordillera	31 (0.6)	18 (0.4)
Interior Hills	17 (1.4)	3 (0.2)
Montane Cordillera	330 (6.4)	57 (1.1)
Pacific Maritime	37 (2.4)	0 (0.0)
Eastern Subarctic	1 (0.1)	1 (0.1)
Taiga Cordillera	6 (0.2)	0 (0.0)

* Not covered by the two ECCC operational forecast systems considered in this section.

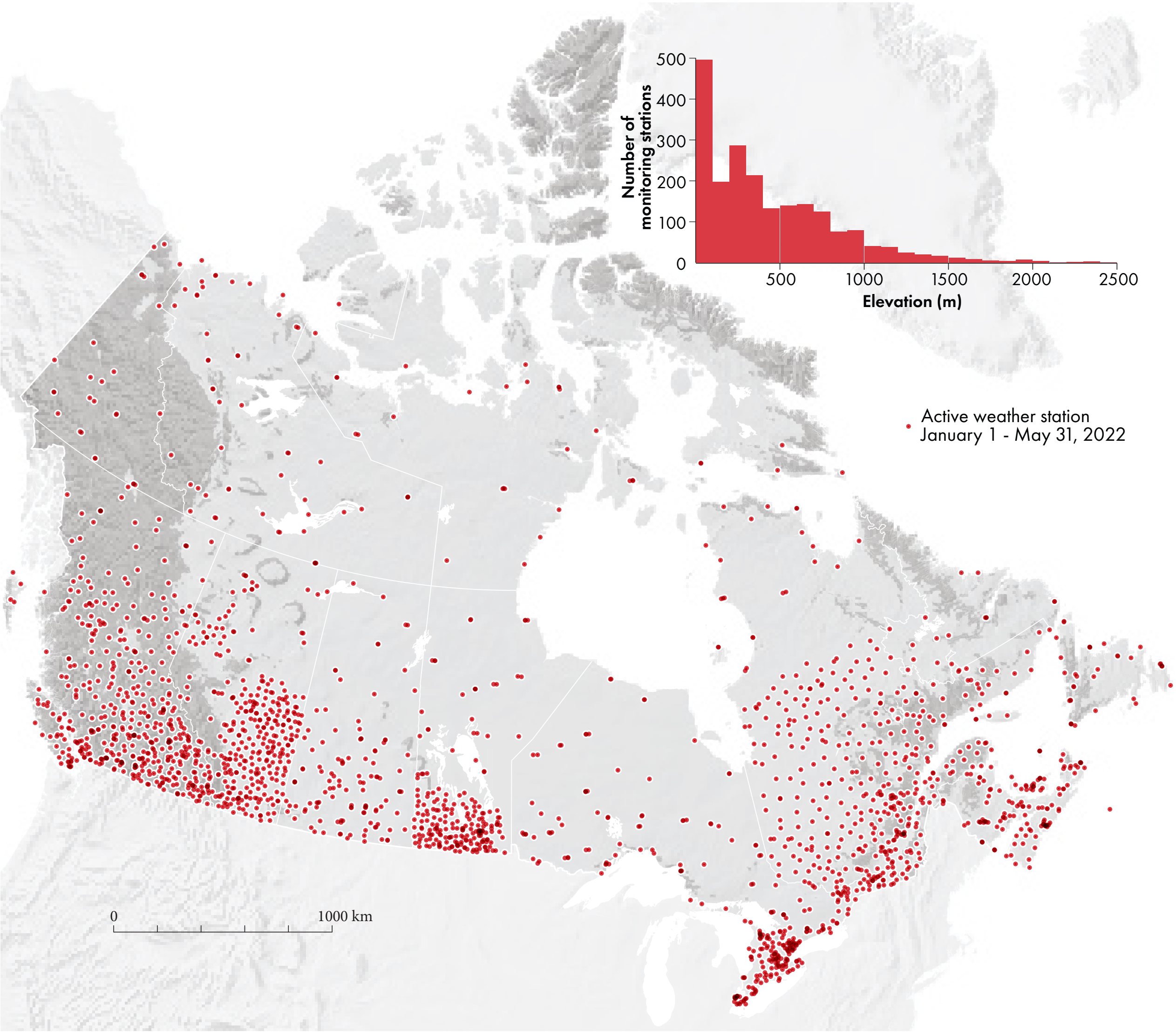

Figure 2.11: Active stations reporting precipitation and/or temperature that were used in the Environment and Climate Change Canada (ECCC) operational systems for weather and hydrological forecasting (Carrera et al., 2015; Fortin et al., 2018) between 1 January–31 May 2022. Inset histogram shows the elevation of these stations. Note that Nunavut, north of 70°N, is not covered by the two ECCC forecast systems considered in this section.

of clouds. New satellite missions aim to address the issue of low precipitation in the Arctic by deploying a far-infrared sensor sensitive enough to measure Arctic clouds and precipitation (Libois & Blanchet, 2017), and existing satellites are being used to map snow depths (Lievens et al., 2019).

As with precipitation and temperature, a full characterization of wind patterns across mountain regions in Canada remains a challenge due to a lack of observations. Atmospheric models have been used to simulate complex wind flows in the Bow River Valley (Vionnet et al., 2015) and snow redistribution in the Montane Cordillera (Vionnet, Marsh et al., 2021). In both studies, the models were tested with observations from a dense network of meteorological stations deployed to cover a large range of elevation from valley bottom to alpine crests (Fang et al., 2019). The complexities of wind modelling make it difficult to provide accurate estimates of wind resources in the context of wind farm developments (Pinard et al., 2009) and accurate simulations of the mountain snow cover affected by wind-induced snow redistribution. These challenges are due to a still-limited

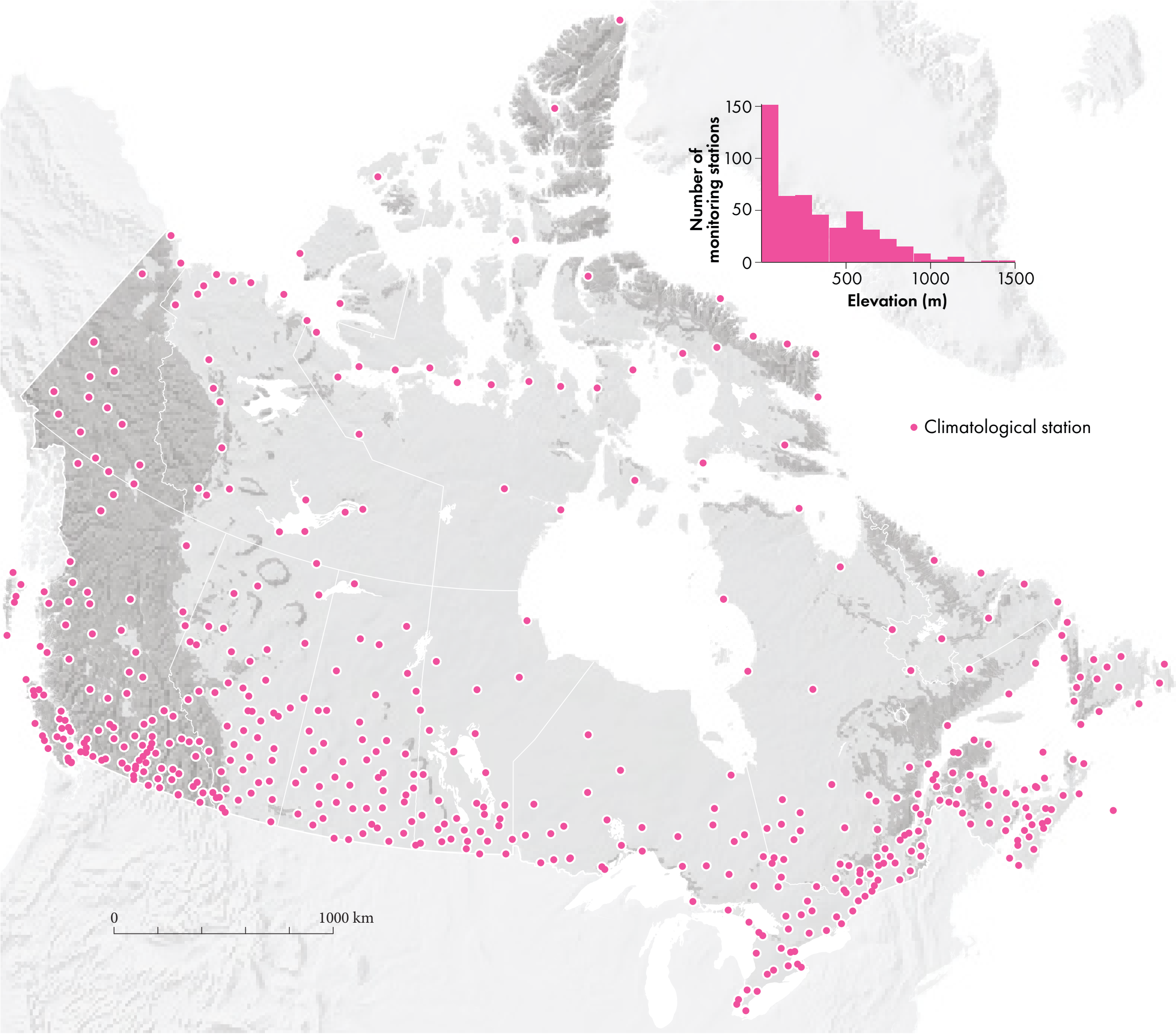

Figure 2.12: Long-term climatological stations reporting precipitation and/or temperature from the Adjusted and Homogenized Canadian Climate Data. Data from Mekis & Vincent, 2011; Vincent et al., 2012.

understanding of the complex multi-scale flows in mountainous terrain (Aksamit & Pomeroy, 2018a; Helgason & Pomeroy, 2012).

2.4 Snow, Ice, and Permafrost

Mountain regions in Canada are home to deep and prolonged winter snowpacks, glaciers, and permafrost (ground that remains below 0°C for at least two consecutive years). Elevation, proximity to oceans, and latitude determine winter snow accumulations and persistence: high-elevation snow that does not melt in the summer eventually becomes compressed into glacier ice and flows downhill. Mountain glaciers are both key indicators of ongoing climate change and central figures in Indigenous oral knowledge systems (Cruikshank, 2001). The cryosphere figures prominently in the stories of the Tlingit and Champagne-Aishihik First Nations of the Boreal Cordillera (Cruikshank, 2007), and glacier-fed rivers in the Pacific Maritime region are home to the eulachon, a cultural keystone species for the Nuxalk Nation. While we have divided this section into snow, glaciers, and permafrost, this division may seem arbitrary to an Indigenous point of view. For example, given the life cycle of glaciers, where would we include the consciousness attributed to glaciers by Indigenous Peoples in Yukon (Cruikshank, 2005)?

Our assessment of mountain snow, ice, and permafrost (all part of the cryosphere) flows from the preceding assessment of mountain meteorology. However, we acknowledge that it is not possible to summarise all Indigenous knowledge of the cryosphere, given the way knowledge is transmitted and the broad diversity of Indigenous cultures and knowledge systems related to the mountain regions of Canada.

2.4.1 *Mountain snow*

Seasonal snow is a defining characteristic of our mountain regions and the rivers they feed (Immerzeel et al., 2020), and streamflows across much of Canada are dominated by seasonal snow melt. As a critical water resource (Dyer, 2008; Hamlet & Lettenmaier, 1999; Woo & Thorne, 2003, 2006), snow also has a wide range of ecosystem functions (Callaghan et al., 2011; Rand et al., 2006), regional climate impacts (Chapin et al., 2005; Pulliainen et al., 2020; Zhang, 2005), and socio-economic value (Sturm et al., 2017). For First Nations, Métis, and Inuit communities, snow can also be an essential material used to construct shelters (Furgal & Seguin, 2006), a predictor of animal behaviours (Turner & Clifton, 2009), a facilitator of winter transportation (Routledge, 2020), and an indicator of changing seasons (Turner et al., 2000).

While snow typically blankets Canadian mountain regions for much of the year (Mudryk et al., 2018), the actual amount of water stored in mountain snowpacks is a deceptively challenging question to answer. Snow can be measured directly at point locations through ground observations or through remote sensing observations from satellites or aircraft (both piloted and remotely piloted). Given the enormous spatial scales of mountain regions in Canada, snowpacks are also frequently modelled with inputs from regional climate networks or weather models (Largeron et al., 2020; Marsh et al., 2020; Wrzesien et al., 2018). Each approach—whether it is ground observations, remote sensing, or modelling—has its own unique challenges and limitations.

We focus here on snow accumulation and melt processes in mountain environments, discuss the ways that snow is measured or modelled, and examine what is known about the current distribution of snow, and how snowpacks are changing in Canadian mountain regions.

Snow accumulation

Snow can be measured in terms of its area, depth, density, and mass (also expressed as snow water equivalence, SWE). SWE is a function of snow depth and density, and it represents the amount of water stored in the snowpack, which is what matters for water managers, flood forecasters, and hydrologists (Sec. 2.5). Snow depths can be highly variable, and particularly so in mountain environments, due to complex terrain and weather patterns (Sec. 2.3). Snow density is generally less variable. Fresh snowfall has a lower density than a deep snowpack, and high- and low-elevation snowpacks in the same region can have very different densities depending on storm characteristics and the progression of the spring melt season.

Snowfall totals are governed by temperature and precipitation, which are ultimately a function of elevation, latitude, prevailing winds, and topography. In mountain environments snow can occur at temperatures well above 0°C (Kienzle, 2008), and orographic precipitation associated with mid-latitude or Arctic storm systems can bring solid precipitation to mountain systems in Canada year-round.

Snow accumulation on the ground varies with land cover and local wind patterns: forests can intercept up to 60% of the snow that falls, increase the spatial variability of snow on the ground, and decrease the amount of snow available for melt (Lv & Pomeroy, 2020; Pomeroy et al., 2007; Varhola et al., 2010). How much a forest affects snow accumulation depends largely on the forest type. In alpine environments, wind redistribution of snow is another critical process (Winstral et al., 2002) that produces complex snow distribution patterns that reflect the prevailing winds and the topography (Essery et al., 1999). Snow redistribution by wind enhances losses of snow directly back to the atmosphere through sublimation (see below), but also leads to the formation of perennial snow patches or aniuvat (Inuktitut) that persist through the summer months and are fundamental to the creation of alpine micro-habitats visited and used by a wide variety of mammals, birds, and insects (Rosvold, 2016). Archaeological evidence gathered from the margins of melting snow and ice patches in the southern Yukon, on or adjacent to the territories of Carcross-Tagish, Champagne and Aishihik, Kluane, and Kwanlin

Dun First Nations, indicate that snow patches were specialised hunting grounds for caribou, and feature prominently in the the traditions of all four First Nations (Farnell et al., 2004; Hare et al., 2004; Strand, 2003).

Avalanches also redistribute snow from high elevation (and low melt rate) regions to low elevation (and high melt rate) regions (Strasser et al., 2018), creating areas of extreme snow depth at the base of steep slopes (Bernhardt & Schulz, 2010). Avalanches occur in steep terrain where there is sufficient snow loading, and wind-transport of snow is often a key factor in avalanche formation (Bernhardt & Schulz, 2010). There can be tremendous human and economic costs of avalanches (Stethem et al., 2003) and they represent a significant hazard for winter recreation (e.g., ski touring, ice climbing) in mountain areas.

Ablation

The removal of snow from the landscape occurs through either melt (solid to liquid) or sublimation (solid to gas). Together, the processes of melt and sublimation are known as ablation. Our current scientific understanding of snow and ice ablation processes in Canadian mountain environments depends almost entirely on a handful of ground-based observations that are limited in both space and time (Table 2.3). Long-term and comprehensive observational networks in the mountains are exceedingly rare, with the Canadian Rockies Hydrological Observatory[1] a notable exception.

Ablation occurs when there is surplus energy at the snow or ice surface, and it is driven by the energy exchange between a snow/ice surface and its environment (Anderson, 1968). While sublimation can occur at any temperature, melt does not occur until the temperature of the snow/ice surface is raised to 0°C. Air temperatures can be used as a simple metric for snow and ice melt (Shea et al., 2009), but process-based studies use a surface energy balance approach which defines all the possible energy gains and losses from a volume of snow or ice.

Accounting for each energy component individually allows researchers to study what drives melt in different environments, and to develop models that can be transferred to (and from) other regions. Shortwave radiation—the energy received from sun—has been identified as the main source of melt energy at Montane Cordillera sites in western Canada (Burles & Boon, 2011; Ebrahimi & Marshall, 2016; Marshall, 2014; Munro, 1991) and in the St. Elias Mountains (Wheeler & Flowers, 2011; Ochwat et al., 2021). Full energy balance studies in other Canadian mountain regions are largely absent. However, low-elevation Arctic and sub-Arctic studies (Ohmura, 1982) point to the balance between longwave (thermal) energy lost from the surface and gained from the atmosphere as a major component of the energy balance (Lackner et al., 2022). A warmer atmosphere increases the amount of longwave received at the surface.

Shortwave radiation changes with latitude, day of year, clouds, slope angle, and wildfire smoke (Aubry-Wake et al., 2022), but also with elevation: more energy reaches the surface at higher elevations due to the thinner atmosphere above (Saunders et al., 1997). And the net amount of shortwave energy at the surface is highly dependent on the reflectivity (or albedo) of the surface. Snowpacks with darker surfaces due to wildfires (Aubry-Wake et al., 2022), mineral dust, pollution, or snow algae (Engstrom et al., 2022) absorb more solar energy, and a reduced snow cover in Arctic and alpine regions due to ongoing climate warming may lead to an albedo feedback effect (Déry & Brown, 2007). Recent work has shown a strong connection between glacier albedo, snowline elevation, and wildfire across western North America (Marshall & Miller, 2020; Williamson & Menounos, 2021). Significant advances in snow energy balance and hydrology have been made in the Prairie regions of Canada, with many of the principles directly transferable to mountain regions (Debeer & Pomeroy, 2017; Pomeroy & Essery, 1999; Pomeroy & Li, 2000).

Blowing snow entrains small snow particles into the atmosphere where they can quickly sublimate, so dry, windy environments that are typical of alpine or polar regions promote sublimation (Essery et al., 1999). Wintertime sublimation losses can range from 1% to 30–40% of total winter-time precipitation, but it is highly variable between studies (Mott et al., 2018a). In the

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[1] https://research-groups.usask.ca/hydrology/science/research-facilities/crho.php#Data

Table 2.3: Long-term snow and ice research sites within mountain regions of Canada.

Site	*Region*[1]	*Latitude (°N)*	*Longitude (°W)*	*Elevation (m)*	*Notes / References*
Wolf Creek, YT (1992–present)	BC/TC	61.52	135.52	660–2080	snow hydrology, energy balance, meteorology, permafrost (Janowicz et al., 2004; Rasouli et al., 2019)
Marmot Creek, AB (1962–1986; 2004–present)	MC	50.95	115.15	1600–2825	snow hydrology, snow energy balance, meteorology (Fang et al., 2019; Munn & Storr, 1967)
Conrad Glacier, BC (2015–present)	MC	50.81	116.92	1825–3235	glacier mass balance, energy balance, alpine permafrost, glacier dynamics (Pelto et al., 2019)
Fortress Mountain, AB (2013–present)	MC	50.83	115.21	2000–2300	snow accumulation and energy balance, hydrology, groundwater, RPAS (Schirmer & Pomeroy, 2020)
Place Glacier, BC (1965–present)	PM	50.43	122.60	1850–2550	glacier mass balance, meteorology, hydrology (Moore & Demuth, 2001)
Peyto Glacier, AB (1965–present)	MC	51.67	116.53	2150–3150	glacier mass balance, meteorology, hydrology (Demuth et al., 2006; Pradhananga et al., 2021)
Haig Glacier, AB (2000–present)	MC	50.72	115.30	2450–2800	glacier mass balance, meteorology, ice dynamics (Marshall & Miller, 2020)
Axel Heiberg Glacier, NU (1962–present)	AC	79.50	90.84	80–1782	glacier mass balance, meteorology (Thomson et al., 2017)
Foret Montmorency, QC	AMBS	47.32	71.15	600–1000	snow accumulation, snow melt, energy balance, snow chemistry (Plamondon et al., 1984)
Trapridge Glacier, YT (1969–2019)	TC	61.23	140.23	2250–2800	glacier dynamics, subglacial hydrology (Frappe & Clarke, 2007)
Rogers Pass, BC (1965–present)	MC	51.28	117.51	800–2800	meteorology, avalanche (Bellaire et al., 2016)

1 Regions: BC = Boreal Cordillera; TC = Taiga Cordillera; MC = Montane Cordillera; PM = Pacific Maritime; AMBS = Atlantic Maritime and Boreal Shield; AC = Arctic Cordillera

Boreal Cordillera in the Yukon, Marsh et al. (2019) found annual sublimation losses between 6 and 14%, while Pomeroy & Li (2000) reported losses of 22%, and Macdonald et al. (2009) reported losses between 19–81%. Snow losses due to sublimation in Arctic and sub-Arctic mountain environments (Arctic Cordillera, Taiga Cordillera, Interior Hills North) may be lower, as extreme cold temperatures limit sublimation (Ohmura, 1982).

Snowfall intercepted by forest canopies is susceptible to even greater rates of sublimation losses (Pomeroy et al., 2012). In the Okanagan basin, greater rates of sublimation were observed at higher elevations, where the winds are stronger, temperatures are colder, and there is less vapour pressure in the atmosphere (Jackson & Prowse, 2009). Forest composition, age, and disturbances such wildfire, logging, or pests alter the surface energy balance and affect both snow melt and snow accumulation patterns (Boon, 2012; Burles & Boon, 2011; Pomeroy et al., 2012; Winkler et al., 2014). Maximum SWE decreased up to 25% in pine-beetle defoliated stands in the Montane Cordillera (Winkler et al., 2015), and modelling experiments showed that snowpacks in the Montane Cordillera are highly sensitive to reductions in snow albedo following wildfires (Qian et al., 2009).

Rain-on-snow events can produce significant streamflow responses due to: warm rain advecting energy to the surface of the snowpack and infiltrating into the snowpack; the refreezing of this infiltrated water which releases latent heat; and large sensible and latent heat fluxes from the warm, humid air above the snow pack. Often the advected energy flux is small (Marks et al., 1998) and the turbulent heat fluxes to the snowcover are the dominant contributors to rain-on-snow melt events (Marks et al., 1998; Pomeroy et al., 2016). Pomeroy et al. (2016) identified that a late-spring and early-summer event in the Montane Cordillera had a greater ground heat-flux energy input than typical mid-winter events (e.g., Marks et al., 1998). In the Pacific Maritime and western Montane Cordillera, Trubilowicz and Moore (2017) found that large rain-on-snow events associated with atmospheric rivers can also include significant amounts of snow-melt runoff, contributing to flooding. A rain-on-snow event in the eastern Canadian Rockies contributed to one of the most expensive natural disasters in Canadian history at the time (June 2013 Bow River flood) (Pomeroy et al., 2016). This complex flooding event combined intense precipitation from active convective systems and enhanced runoff generation from snowmelt and rainfall runoff at higher elevations (Vionnet et al., 2020).

Continuous monitoring and detailed snow and ice energy balance studies across a range of elevations, land cover types, and mountain regions will improve our understanding of mountain snowpacks, and how they will respond in the future. Complex interactions between climate change, extreme heat events, and wildfire darkening of mountain snowpacks and glaciers also require further research.

Ground observations of snow

Direct observations of snow depth and snow mass are made by manual or automated methods (Kinar & Pomeroy, 2015). Snow depth is measured manually with simple snow rulers or automatically with acoustic or laser ranging sensors. Snow mass is measured automatically with snow pillows that record the weight of the overlying snowpack, or special sensors that measure the attenuation of cosmic (from the sky) or gamma (from the earth) radiation due to snow mass. Historically, snow mass has been measured manually and at regular intervals during accumulation and melt seasons with snow sampling tubes. Snow density is measured manually with calibrated snow sampling tubes or snow density pits, but it can also be calculated from automated measurements of snow depth and snow mass.

In mountain regions worldwide, direct observations of snow are sparse and biased towards lower elevation, lower latitude, and more accessible sites (Brown et al., 2021; DeBeer et al., 2021; Vionnet et al., 2021). Between 1 January and 31 May 2019, the total number of SWE observation sites in Canada was 1193. Of these 1193 sites, 1053 were manual snow course measurements, and 98 were automated snow pillows (Fig. 2.13). Snow measurement sites are concentrated in the southern populated regions of Canada with the majority located in Ontario and British Columbia. Manual and continuous snow monitoring sites in western Canada range in elevation between 500–2500 m, but manual observations in Ontario and Quebec are typically found below 750 m. There are no manual or automated snow measurements in the Torngats and no automated measurements in the Taiga Cordillera or Boreal Cordillera. Very few snow observations are made in the Arctic Cordillera. Citizen science efforts such as the Community Snow Observations project (Crumley et al., 2021) offer the potential for knowledge co-creation with recreational users and Indigenous communities in the mountain regions of Canada to help fill the gap in our measurement network.

Direct measurements of snowfall volumes can be made using weighing precipitation gauges, but these gauges typically undercatch snowfall amounts as wind blows snow across the top of the weighing gauge (Goodison, 1978; Rasmussen et al., 2012). Ground-penetrating radar (GPR) has been used to measure snow accumulation on Arctic glaciers (Sylvestre et al., 2013), but the technique has limited applicability for shallow snowpacks or forested areas.

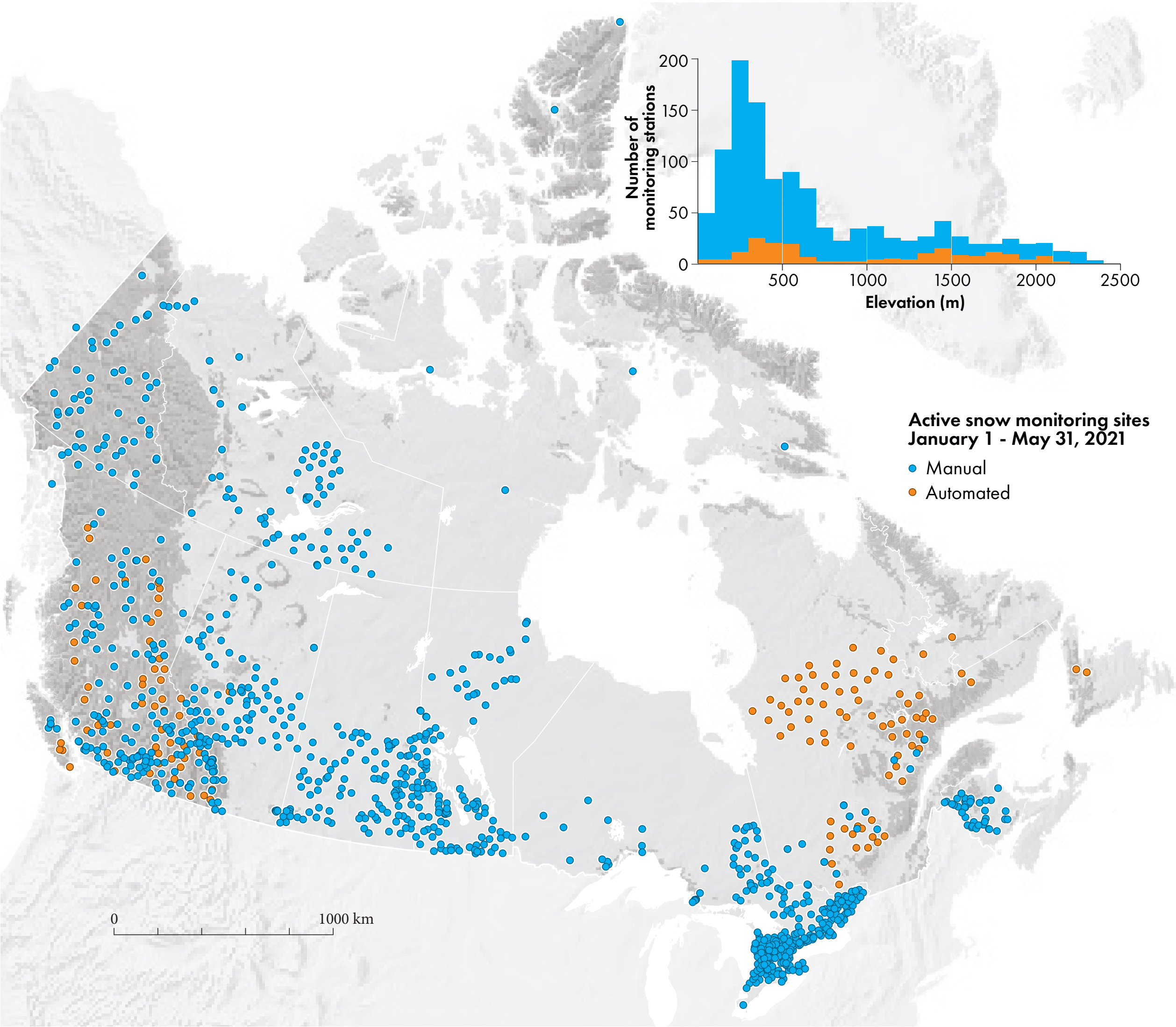

Figure 2.13: Manual (blue) and automated (orange) snow water equivalent measurement locations in Canada, that were active between 1 January–31 May 2021. Data from Vionnet et al., 2021.

Table 2.4: Number and density of snow monitoring sites in the main CMA mountain regions. The information is provided for stations that were active between 1 January–31 May 2021 and for climatological stations that have reported data for at least 30 years. The density represents the number of stations per 10,000 km^2.

Regions	*Number (density) of active stations*	*Number (density) of climatological stations*
Arctic Cordillera	0 (0.0)	0 (0.0)
Atlantic Maritime and Boreal Shield	23 (1.2)	8 (0.4)
Boreal Cordillera	57 (1.2)	50 (1.0)
Interior Hills	24 (1.9)	14 (1.1)
Montane Cordillera	245 (4.8)	231 (4.5)
Pacific Maritime	39 (2.5)	37 (2.4)
Eastern Subarctic	0 (0.0)	1 (0.1)
Taiga Cordillera	17 (0.5)	14 (0.4)

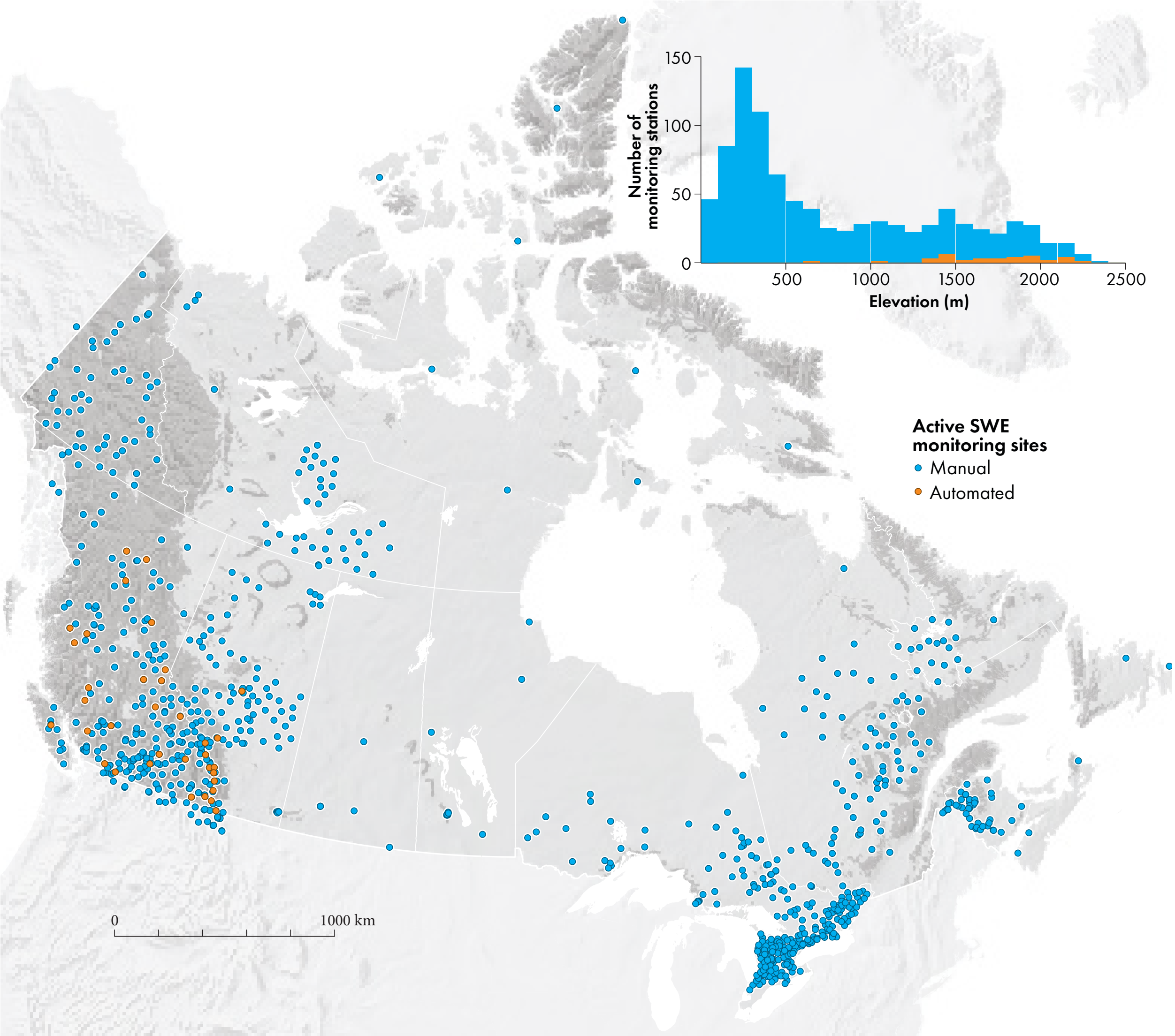

Figure 2.14: Manual (blue) and automated (orange) snow water equivalent (SWE) measurement locations that have reported data for at least 30 years. Data from Vionnet et al., 2021.

Remote sensing of snow

Snow is highly reflective (Warren, 1982), and this property allows snow-covered area to be reliably measured through satellite remote sensing (Rango, 1993; Rango, 1996). Persistent cloudiness in mountain environments (Sec. 2.3) and missing northern coverage through the polar winter present major obstacles to space-based observations of snow cover (Hall et al., 2002).

Until recently, there has been a tradeoff between satellite repeat intervals and spatial resolution: MODIS satellites have a spatial resolution of 250 m and acquire imagery daily over the entire planet, while higher spatial resolution satellites such as Landsat (30 m, Dozier, 1989) or Sentinel (20 m, Drusch et al., 2012) have repeat intervals on the order of 5–16 days. Snow monitoring from space is challenged by the substantial cloud cover in mountainous regions that often masks the snow surface (Gascoin et al., 2015). The high spatial variability of mountain snowpacks (Blöschl, 1999) also poses a challenge for coarse-resolution remote sensing platforms (Bormann et al., 2018), but recent increases in both spatial resolution and temporal frequency of lower-cost 'constellations' of satellites provides an avenue for detailed snow cover studies in mountain regions (Cannistra et al., 2021). However, there is currently no publicly available high-resolution snow cover product for mountain regions in Canada.

Remote sensing of snow depth with high precision and resolution is also possible through the use of (a) overlapping aerial photos and photogrammetry or (b) Light Detection and Ranging (LiDAR) laser scanners. Both technologies can be used from either piloted or remotely piloted aircraft, and snow depth studies from space are now feasible (Largeron et al., 2020). In these studies, a snow-free elevation map is first generated from a summer acquisition. By subtracting the snow-free elevation map from an elevation map created in winter, the snow depth can be mapped with high precision (Dozier et al., 2016). The snow density required to calculate SWE from remotely sensed snow depths can be obtained through coincident manual snow surveys (Brown et al., 2019), calculated from automated observations of snow depth and SWE, or modelled.

Snow depth surveys using LiDAR or photogrammetry have been conducted in the Montane Cordillera (Cartwright et al., 2021; Harder et al., 2020; Hopkinson et al., 2012; Mortezapour et al., 2020; Vionnet et al., 2021) and LiDAR is currently being used by water managers in some municipalities in the Pacific Maritime region (e.g., Floyd et al., 2020). Initial comparisons of LiDAR snow depths against ground observations in the Columbia Basin (Montane Cordillera) suggest that LiDAR may underestimate snow depths by 12% (Menounos et al., 2020). However, there are no published LiDAR snow depth surveys from other mountain regions, likely due to the cost of LiDAR scanners and aircraft time, and the challenges of conducting remotely piloted aircraft surveys in winter.

Satellite-based synthetic aperture radar (SAR) has been used to detect the presence of liquid water in snowpacks (Baghdadi et al., 1997), and recent improvements in spatial and temporal resolution have made it practical for mountain regions (Darychuk et al., 2022). There have been several attempts to use SAR to map SWE in mountain regions, with varying degrees of success (Bernier et al., 2002; Dozier et al., 2016). Reliable satellite-based observations of snow depth, SWE, and liquid water content across all of the mountain regions in Canada would be invaluable for a wide range of applications that include hydroelectric power generation, flood forecasting, and seasonal wildfire forecasting.

Modelling of snow

Models of snow accumulation and melt, combined with ground-based observations and remote sensing can be used to estimate snow pack development—and disappearance—across large, unmonitored regions (Mudryk et al., 2015; Vionnet et al., 2021; Wrzesien et al., 2018). These models are limited by the availability and quality of input data, and in many cases by their resolution: snow depths are incredibly varied across mountain landscapes, and high-resolution models that cover large areas can be computationally expensive. Coarse resolution models can underestimate SWE in alpine regions (Wrzesien et al., 2018).

A snowpack model that incorporates ground observations and remote sensing information to estimate peak SWE (Fig. 2.15) shows the greatest snowpack volumes in Pacific Maritime and Montane Cordillera regions, which corresponds with

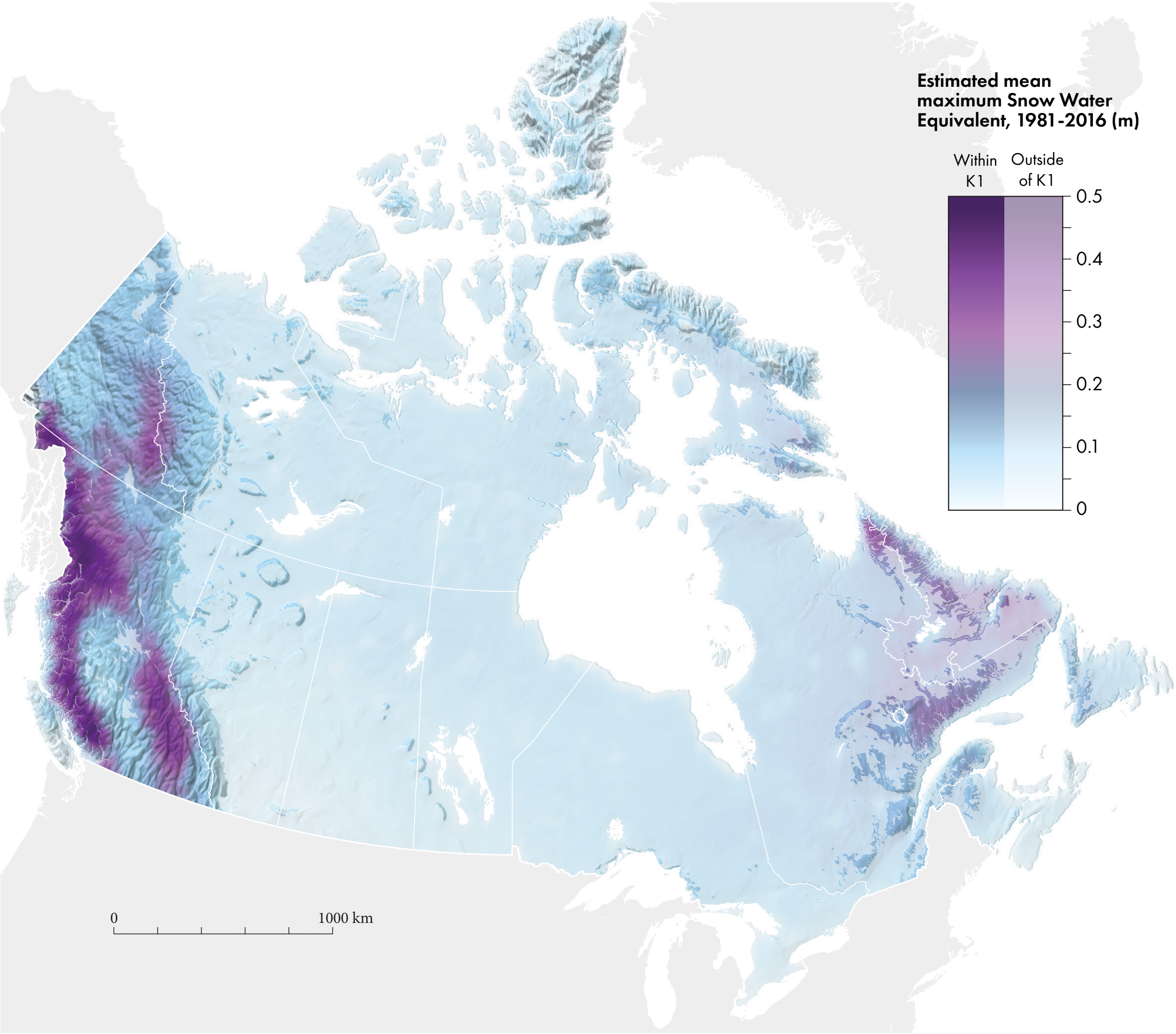

Figure 2.15: Modelled mean maximum snow water equivalent (SWE), 1981–2016. Data from Mudryk et al., 2015.

the high precipitation rates in these mountain regions (Sec. 2.3). However, this likely underestimates snow accumulation in the mountains as the ground resolution and model structure cannot capture mountain-specific processes of snow accumulation and redistribution (e.g., Sec. 2.3.6). Substantial progress in modelling snow in the complex terrain of western Canada (www.snowcast.ca) has been made with the next generation of hydrological models (Marsh et al., 2019, 2020). Combined with ground-based and satellite validation (Wayand et al., 2018), these models will advance our knowledge of current snow volumes and distribution, and how these might be expected to change in the future.

2.4.2 *Mountain glaciers*

In western and northern mountain regions, glaciers are a defining characteristic of mountain landscapes, and they have been meeting points for Indigenous and Western academic knowledge systems since the late 18th century (Cruikshank, 2005). For many Indigenous Peoples in these regions, glaciers figure prominently in oral traditions as sentient beings that "... listen, pay attention, and respond to human behaviour" (Cruikshank, 2001). In the case of the Champagne and Aishihik First Nations, the glaciers in Tatshenshini-Alsek Park provide a direct connection to the past when one of their ancestors, Kwäday Dän Ts'ìnchi, was found beside a glacier by hunters in 1999. Colloquially known as Canada's Iceman, Kwäday Dän Ts'ìnchi succumbed to hypothermia while travelling from the coast into higher elevation regions inland (Beattie et al., 2000; Hebda et al., 2017; Holden, 1999). The location where Kwäday Dän Ts'ìnchi was found, and the approximate time he lived (1450–1700 CE) provide important context for environmental and glacier change in the region (Cruikshank, 2005).

In the Montane Cordillera, the area covered by glaciers has reduced by over 25% from the maximum area that occurred in the Little Ice Age (LIA) in the 1850s (Luckman, 2000). There has been no systematic study of glacier area and volume declines since the LIA in any other mountain regions in Canada. The existence of glaciers, and their current distribution, depend on sufficiently cold temperatures, high quantities of snowfall, or some combination of the two (Shea et al., 2004). Wind redistribution and topographic shading can lead to the persistence of snow and ice year-round in regions that are otherwise unfavourable to the existence of glaciers (Debeer & Sharp, 2009). Glaciers across Canada come in a wide range of shapes and sizes: from endless Arctic icefields to long valley glaciers to small cirque glaciers that hide in the shadows of high mountain peaks. Decaying valley glaciers that are covered by debris, and rock glaciers related to slow downslope movements of buried frozen ground, are also characteristic in the mountain regions of Canada (Bevington & Menounos, 2022; Charbonneau & Smith, 2018; Evans, 1993; Luckman & Crockett, 1978).

Glaciers are typically measured by their area, their volume, and whether they are gaining or losing mass. Satellites offer relatively reliable methods for measuring glacier extents and areas (Bolch et al., 2009; Pfeffer et al., 2014; Sidjak, 1999) and how glacier areas have changed in the past (Chapter 5). According to the satellite-derived Randolph Glacier Inventory (RGI) there are over 33,600 glaciers in Canada, with a total area of approximately 204,000 km^2 (Table 2.5) (Pfeffer et al., 2014). For this assessment, we have grouped individual RGI glaciers into the CMA mountain regions and calculated their statistics. The largest concentrations of glacier ice are found in the Arctic Cordillera (11,740 glaciers with a total area of 145,000 km^2), the Pacific Maritime (10,129 glaciers with a total area of 34,559 km^2) and the Boreal Cordillera (4150 glaciers with a total area of 18,385 km^2). There are approximately 6244 glaciers with a total area of 5891 km^2 in the Montane Cordillera.

Glacier depth and volume can be measured directly with custom-designed ice radar systems or with low-frequency ground penetrating radar (Adhikari & Marshall, 2013; Pelto et al., 2020), though the logistics make it challenging to do so over large glaciers. Instead, glacier depth and volume are often modelled (Clarke et al., 2015) or approximated based on glacier area (Radić & Hock, 2010). Glacier mass and volume change can be measured on the ground (the glaciological approach) using a network of accumulation measurements at the end of winter and snow and ice ablation measurements at the end of summer (Beedle et al., 2014; Østrem & Brugman, 1993; Young & Ommanney, 1984). In recent years however, the geodetic approach, where changes in glacier surface elevations are calculated between two points in time, and then converted to a volume and mass change, have become prominent. Recent Canadian studies have derived surface elevations from topographic maps (Tennant & Menounos, 2013), air photo interpretation (Schiefer et al., 2007), LiDAR measurements (Pelto et al., 2019), and spaceborne radar and satellite imagery (Menounos et al., 2019). Most recently, elevation changes between 2000 and 2019 were calculated for all glaciers outside the Greenland and Antarctic ice sheets (Hugonnet et al., 2021), and this data has been used to compute average mass changes for glaciers in the CMA regions (Chapter 5).

Each year, a glacier will gain or lose mass (or remain the same) depending on the dominant weather conditions (Shea & Marshall, 2007). In years when glaciers lose mass, summers are typically warmer and drier, and winters have lower than average snow accumulation (or both). In years of mass gain, the opposite would be true. A wide range of glacier mass balance models have been applied in the Montane Cordillera and Pacific Maritime regions (Anslow et al., 2008; Clarke et al., 2015; Marshall et al., 2011; Munro, 1991; Shea et al., 2009), with relatively little work in the Boreal Cordillera (Wheler et al., 2014) and the Arctic Cordillera (Gardner et al., 2011; Sharp et al.,

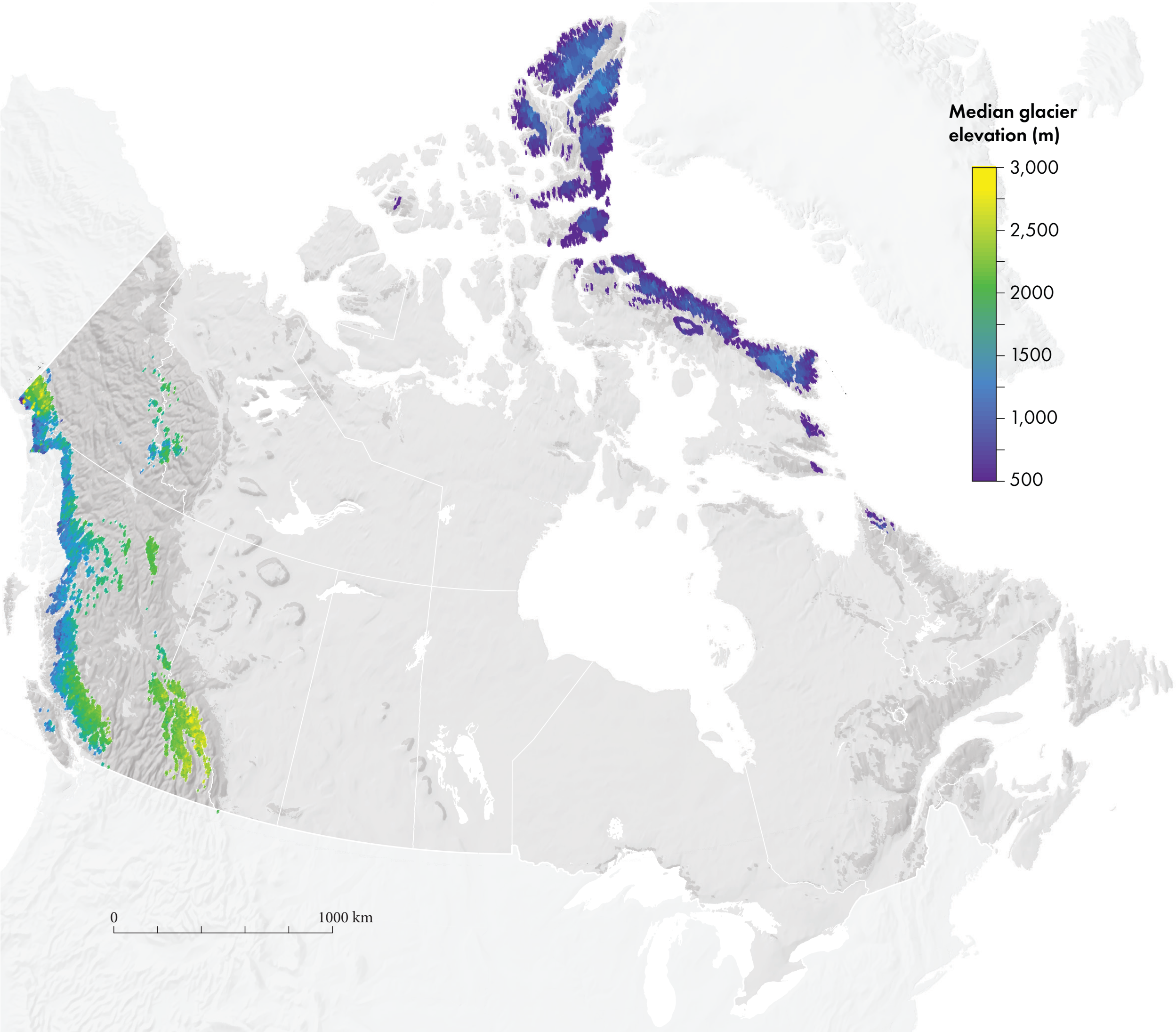

Figure 2.16: Median glacier elevations derived from the Randolph Glacier Inventory (Pfeffer et al., 2014). Each point represents an individual glacier.

Table 2.5: Glacier counts, total glacier area, and median glacier elevation for mountain regions in Canada, extracted from the Randolph Glacier inventory (Pfeffer et al., 2014) and the regional average surface elevation change rate from 2000–2019 (Hugonnet et al., 2021).

Region	*Glacier count*	*Total glacier area (km^2)*	*Median glacier elevation (m)*	*Average Rate of Glacier Mass Change (m w.e./yr)*
Arctic Cordillera	11,740	145,617	908	-0.41 +/- 0.29
Atlantic Maritime	0	0	–	–
Boreal Cordillera	4150	18,385	1957	-0.45 +/- 0.37
Interior Hills Central	0	0	–	–
Interior Hills North	7	112	536	-0.48 +/- 0.36
Interior Hills West	0	0	–	–
Montane Cordillera	6244	5891	2314	-0.44 +/- 0.34
Pacific Maritime	10,129	34,559	1763	-0.38 +/- 0.34
Eastern Subarctic	103	20	813	-0.56 +/- 0.46
Taiga Cordillera	1234	656	1987	-0.36 +/- 0.38

2011). Recent modelling work is focused largely on projecting future glacier change and streamflow response (Naz et al., 2014; .

The climatic setting of a glacier can be inferred from its median elevation (Fig. 2.16, Table 2.5). Glaciers in warmer and wetter climates, such as the Pacific Maritime, have lower median elevations than their continental counterparts in the Montane Cordillera. Glaciers at higher latitude settings (Arctic Cordillera, Boreal Cordillera, and Taiga Cordillera) exist at much lower elevations due to the colder climate, shorter melt season, and reduced shortwave radiation. The median glacier elevation is closely related to the long-term equilibrium line altitude (ELA), which varies between regions. The annual ELA shifts up and down each year in response to the glacier mass balance and is often approximated as the elevation of the transient snowline at the end of the summer melt season. Observational studies of glacier ELAs have been conducted in western Canada (Jiskoot et al., 2009; Schiefer & Menounos, 2010; Shea et al., 2013; Tennant et al., 2012), the Torngat Mountains of the Eastern Subarctic (Way et al., 2014), and the Arctic Cordillera (Miller et al., 1975, 2013).

2.4.3 *Mountain permafrost*

Nearly half of Canada is underlain by permafrost, and a significant proportion of this is in mountainous terrain (Gruber et al., 2015). Permafrost is hidden beneath a surface layer (the active layer) that undergoes seasonal freezing and thawing. As a subsurface phenomenon, permafrost cannot easily be observed remotely, and its distribution and change are less understood than for glaciers or snow. The presence and character of permafrost influence local hydrology (Sec. 2.4), ecosystems, infrastructure, as well as greenhouse gas emissions (Hock et al., 2019). Mountain permafrost thaw has been linked to large mass movement events (Deline et al., 2021; Gruber & Haeberli, 2007) in the mountains of western Canada (Chiarle et al., 2021; Cloutier et al., 2016; Friele et al., 2020; Geertsema et al., 2006) and nearby Alaska (Coe et al., 2018; Huggel et al., 2008).

The presence and character of permafrost is related to the interacting effects of climate, topography and ground conditions such as subsurface materials, vegetation, and snow depth (Davesne et al., 2017; Gruber et al., 2015; Hasler et al., 2015; Péwé & Brown, 1973). Even though air temperature conventionally decreases with increasing elevation, wintertime inversions (Bonnaventure & Lewkowicz, 2013; O'Neill et al., 2015) and cold-air drainage and pooling can cause permafrost to exist in valley bottoms while adjacent slopes are warmer and permafrost free. These effects are especially strong in continental and polar environments and have been described in the Taiga Cordillera (Burn, 1994) and the Arctic Cordillera (Smith & Bonnaventure, 2017). In mountains, glaciers and alpine permafrost are often found in proximity. In wetter areas, glaciers would be expected to dominate the landscape, whereas in drier areas, permafrost will dominate (Haeberli & Burn, 2002). Rock glaciers are visible indicators of permafrost (Haeberli et al., 2006) and have been used to infer its presence in regions of Canada (Charbonneau & Smith, 2018), the United States (Janke, 2005), and other mountain ranges (Boeckli et al., 2012; Schmid et al., 2015).

Borehole temperature measurements are used to confirm the existence of permafrost. Only a few such studies from mountain regions in Canada exist: in the Boreal Cordillera (Bonnaventure & Lewkowicz, 2011; Lewkowicz & Ednie, 2004), the Montane Cordillera (Hall et al., 2001; Harris, 2001; Harris, 1997), and the Atlantic Maritime (Allard & Fortier, 1990; Davesne et al., 2017; Gray et al., 2017). The Global Terrestrial Network for Permafrost (GTN-P, as of 9 December 2022) identifies just over 50 borehole temperature measurement sites in these mountain regions, with most located in valleys and in Yukon (Taiga Cordillera). Only 10 of these are deeper than 10 m, and no data from these sites are available on GTN-P.

The simulation of permafrost in mountains is challenging because the steep topography causes micrometeorology, snow redistribution, ground materials, and temperatures to vary over short distances. Models have been used to estimate the distribution and likelihood of permafrost in mountains in Canada (Gruber, 2012b; Lewkowicz & Bonnaventure, 2008; Obu et al., 2019), but not to simulate permafrost depth, temperature, or future permafrost changes in detail. Climate reanalysis data (Sec. 2.2) has been used to drive global permafrost models with mountain components over multiple decades (Cao et al., 2019; Endrizzi et al., 2014; Fiddes & Gruber, 2014), and it

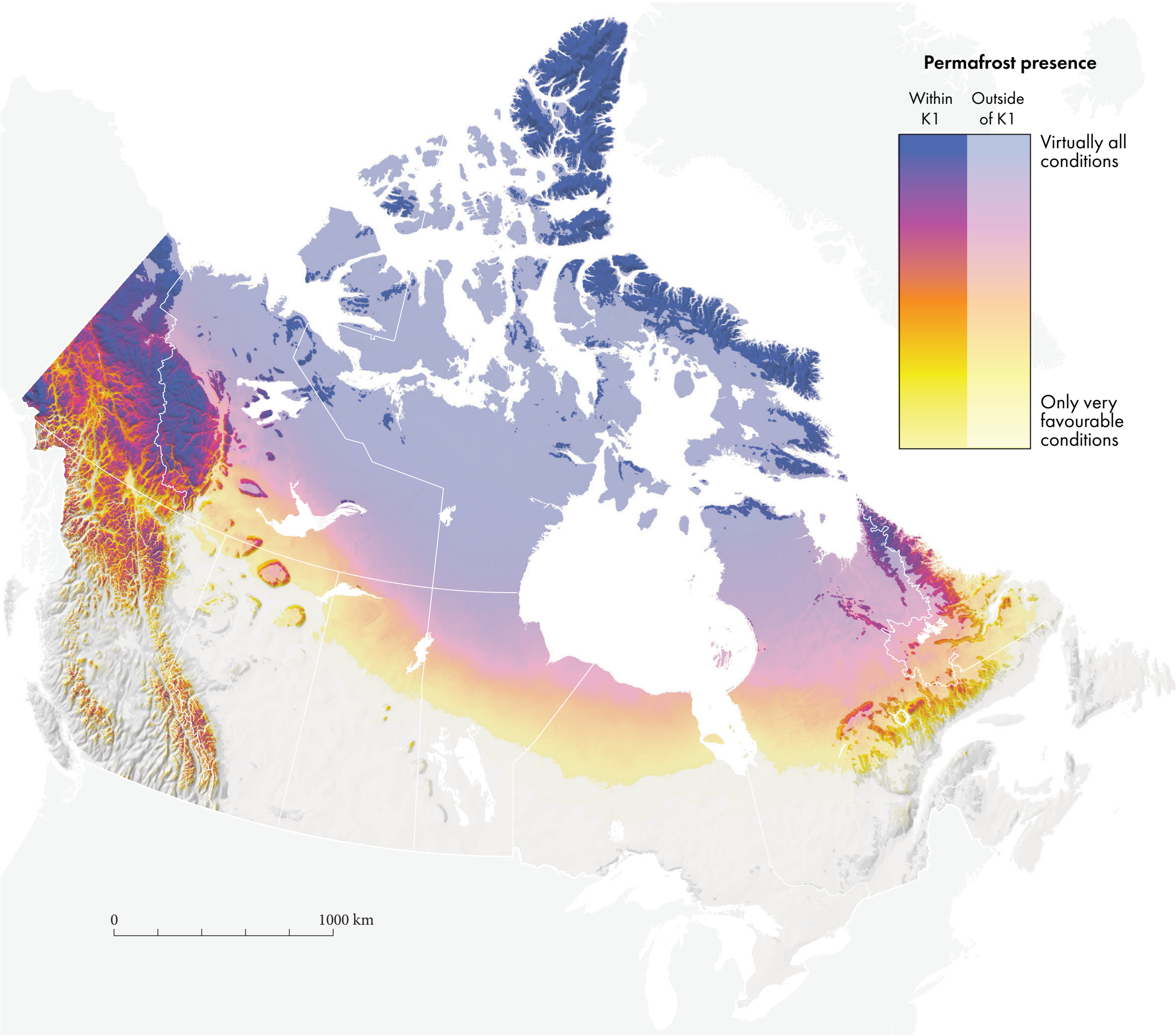

Figure 2.17: Permafrost distribution in Canada. Data from Gruber, 2012.

is possible to simulate inversions/cold-air pooling (Cao et al., 2017) and to improve the computational efficiency in simulations with high spatial resolution (Fiddes et al., 2015; Fiddes & Gruber, 2012). However, soil temperatures produced directly in climate reanalyses are problematic due to the coarse spatial resolution and are subject to bias (Cao et al., 2020). Overall, even though suitable methods exist, permafrost in mountains in Canada is not yet represented well in simulation studies, and this is an active area of research.

2.4.4 *Gaps and challenges*

Inventories and monitoring of both snow and glaciers will provide downstream communities and water managers with critical information for understanding future changes in water supply. Improved observational networks for both snow accumulation and snow melt, combined with airborne and spaceborne observations, are needed in all mountain regions to develop and test models of wind redistribution of snow, surface energy exchange, and interactions between different mountain ecosystems and the cryosphere. High-resolution atmospheric and hydrological models of mountain snow accumulation, redistribution, and melt could be developed in conjunction with targeted field campaigns to provide the validation data that is needed to evaluate and calibrate models, towards operational forecast capabilities.

Ground-based monitoring of mountain snowpacks, glaciers, and permafrost conditions is logistically challenging, but critical. These observations should be supplemented with routine annual airborne or satellite-based observations with a systematic approach to monitoring surface changes as a function of altitude, and expanded to unmonitored regions. For glacier change, such studies should include a range of glacier sizes to evaluate the sensitivity of glaciers to future climate change. A detailed inventory of LIA glacier volumes and extents, as well as the timing of maximum extent could be used to test models of historical glacier mass balance and dynamics to improve future projections.

Five needs for permafrost research and development in mountain regions across Canada were identified in a 2014 workshop (Gruber et al., 2015). These needs include: (1) to understand processes and phenomena related to ground temperatures, ground ice, effects on water and rock-slope stability, and the interaction with vegetation in mountains; (2) to develop simulation capabilities that would support site assessment and hazard analysis; (3) long-term monitoring of permafrost and related phenomena to inform stakeholders, understand ongoing changes, and to develop and test models; (4) complementary baseline data to support permafrost research, such as high-elevation meteorological stations and snow observations; (5) communication and integration of research results in planning and decision-making. Though mountain permafrost can be highly variable, knowledge gained from polar permafrost studies can be applied as the governing physical principles are the same and many insights and tools may be transferred. Indigenous knowledges of mountain permafrost and permafrost thaw (e.g., CMA Learning Circle, Day 2) provides insights into the need for and benefits of more holistic knowledge co-creation approaches (Latulippe & Klenk, 2020; Wright et al., 2022).

2.5 Water

Mountains are the source of much of the world's freshwater resources (Viviroli et al., 2007), as they receive more precipitation than adjacent lowlands, experience less evapotranspiration, and can store water as snow and ice for short and long-term release. Mountain meltwater produces dry-season runoff and prolongs water availability downstream, which is why mountains are sometimes referred to as the world's water towers (Immerzeel et al., 2020). Many of the largest rivers in Canada have their headwaters in mountain regions and provide important water resources downstream. The South Saskatchewan River Basin exemplifies the role of mountains in water supply: 75% of the South Saskatchewan River flow as it crosses the Prairies is sourced from mountain sub-basins (Toth et al., 2009). CMA Learning Circle participant Hayden Melting Tallow of the Siksika Nation, Blackfoot Confederacy, identified the continuum between snow, ice, and streamflow on the eastern slopes of the Canadian Rockies: "And where does the water come from? It comes from the glaciers, melting it comes water. And what do the glaciers form from? It's the clouds, it rains and it comes down as rain or snow. And where do the clouds get the water from? It comes from the ocean. So there's a continuum there" (LC 2.8).

The vast majority of research on mountain water systems and generation has focused on the Montane Cordillera and Pacific Maritime Mountain regions (McDowell & Hanly, 2022). To understand how hydrological processes operate in the mountain regions of Canada, research has been centred on the measurement and simulation of processes like snowmelt, interflow, evapotranspiration, and groundwater flow in cold mountain regions with complex topography and steep slopes. Our understanding of how mountain groundwater and surface water systems are integrated remains somewhat limited and there are very few studies of mountain water systems in eastern Canada. As the climate changes, many studies are focused on measuring/simulating past and future changes to mountain hydrological systems in Canada given the potential impact on water resources.

Hayden Melting Tallow, Siksika Nation,
Blackfoot Confederacy, 2022, *LC 2.8*

2.5.1 *Mountain flow regimes*

Seasonal changes in streamflow (the hydrological regime) are controlled by water inputs (e.g., rain and snowmelt), water losses (e.g., evaporation and plant transpiration), and storage changes in soils, lakes, wetlands, groundwater, or reservoirs (Woo & Thorne, 2003). Mountain hydrological regimes in Canada can be grouped according to the main driver of flow variation: snow-dominated (*nival*), rain-dominated (*pluvial*), glacier-dominated (*glacial*), and hybrid (Fig. 2.18).

Snow- and glacier-dominated systems have low flows during the winter when nearly all precipitation falls as snow, and experience peak flows in late spring and early summer when the snow melts, known as spring freshet (Pike, 2010; Woo & Thorne, 2003). Watersheds with significant glacier area (e.g., Pacific Maritime and Montane Cordillera) see high flows extended later into the summer (Déry et al., 2009). As glaciers store snow and ice during wet, cool years, and release more water in dry, warm years, they act as buffers against streamflow variability (Moore et al., 2020;

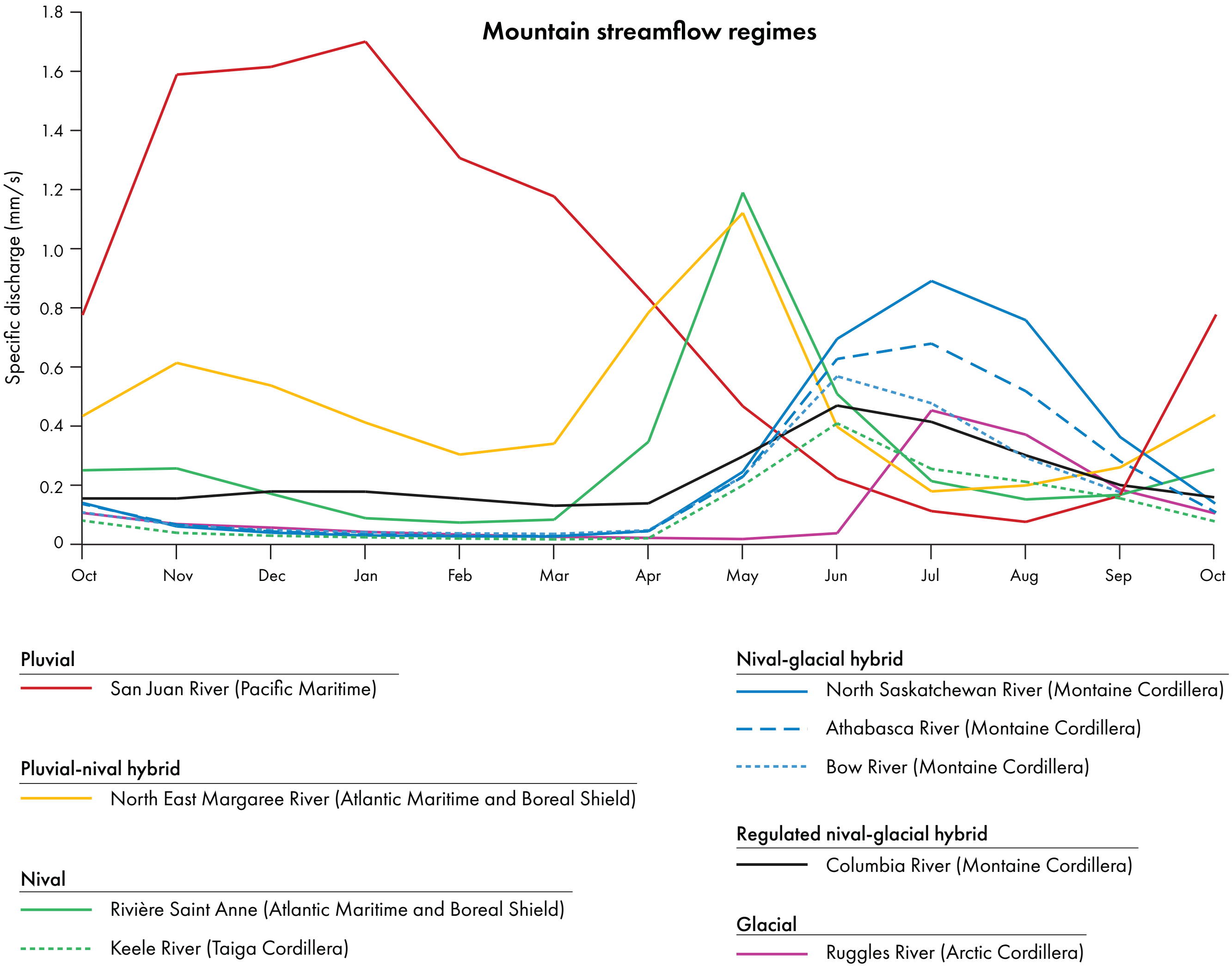

Figure 2.18: Annual hydrographs of specific monthly discharge for selected mountain rivers across Canada. Data from the Water Survey of Canada Historical Streamflow Data (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html).

Van Tiel et al., 2021). River systems dominated by rain are found at lower elevations and near the coasts, including in the Pacific and Atlantic Maritime and Boreal Shield mountain regions. Here, streamflow patterns more closely follow precipitation patterns, and periodic high flows occur during the fall and winter (Déry et al., 2009; Pike, 2010). Many mountain watersheds, especially at larger scales, have hybrid hydrological regimes, and are influenced by some combination of rain, snow melt, and/or glacier melt.

Changes in watershed storage will affect the annual *hydrograph*, which illustrates seasonal changes in streamflow. The amount of water that is stored in a watershed depends on the physical characteristics of the catchment area including the thickness and texture of soils, geology, abundance, and volume of lakes (Woo & Thorne, 2003). River regulation in the form of dams and reservoirs—both human and natural—can reduce the peaks in an annual hydrograph and moderate both high and low flows on an annual basis (Nazemi et al., 2017). Indigenous knowledge of the role of beavers in water storage and ecosystem management has led to their re-introduction to mountainous watersheds in Washington State (Jordan & Fairfax, 2022; Sherriff, 2021) for water regulation.

2.5.2 *Mountain surface hydrological processes*

The flow in mountain rivers is controlled by hydrological processes that occur throughout these complex watersheds. Our understanding of how these processes work has been developed through research in mountains and lowlands alike. However, mountains exhibit some unique hydrological behaviours owing to their cold temperatures, steep slopes, and soil and vegetation patterns. A wide range of studies in the mountain regions of Canada have sought to improve our understanding of key mountain hydrology processes (Fig. 2.19). These processes include:

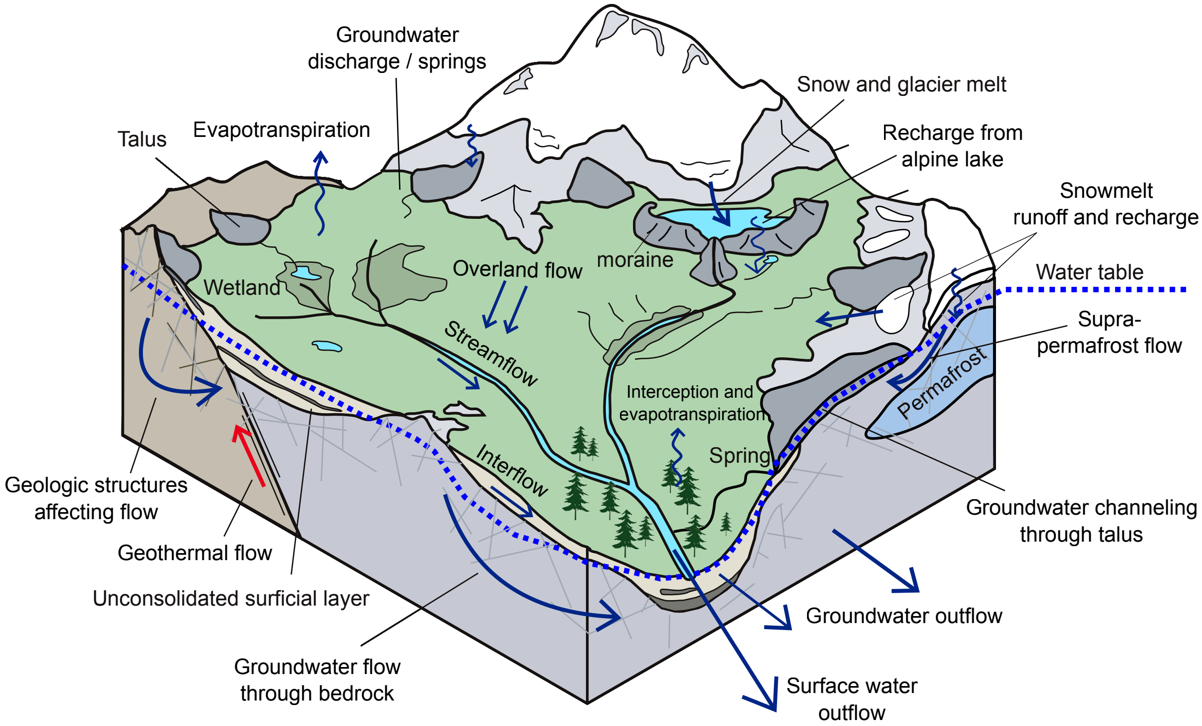

Figure 2.19: Schematic of hydrological processes with an emphasis on groundwater surface water interactions. Modified from Somers et al., 2019.

- Interception by vegetation, where precipitation does not reach the ground or is delayed (Lv & Pomeroy, 2019, 2020; Williams et al., 2019)
- Snow redistribution in the form of blowing snow and avalanches, which results in uneven snowpack and influences snowmelt timing (Aksamit & Pomeroy, 2018a, 2018b, 2020; Dery et al., 2010; Macdonald et al., 2009)
- Snowmelt, including the energy fluxes that control the rate and spatial variability of snowmelt and subsequent contribution to streamflow (Braun & Slaymaker, 1981; Debeer & Pomeroy, 2017; Dornes et al., 2008; Woo & Thorne, 2006)
- Glacier melt, including the energy fluxes that drive glacier melt, and the timing/pathways of streamflow contributions from glaciers (Henoch, 1971; Comeau et al., 2009; Jost et al., 2012; Hirose & Marshall, 2013; Bash & Marshall, 2014; Marshall, 2014; Brahney et al., 2017; Chernos et al., 2020)
- Infiltration of precipitation into the subsurface (Barrett & Slaymaker, 1989; Lilbaek & Pomeroy, 2007)
- Runoff/overland flow, where water travels along the ground surface during intense precipitation/rapid melt or over impermeable surfaces (Carey & Quinton, 2005; De Vries & Chow, 1978)
- *Interflow*, the lateral flow of water through the shallow subsurface, facilitated by larger pores in soil (Chanasyk & Verschuren, 1983; Kim et al., 2004)
- *Evapotranspiration*, the combined evaporation of water from the ground and water transpired through vegetation (Brown et al., 2014; Langs et al., 2021; Matheussen et al., 2000; Wang et al., 2015)
- Groundwater flow through the saturated zone of the subsurface (Campbell et al., 2021; Foster & Allen, 2015; Hood & Hayashi, 2015) and the hydrogeology of different mountain regions

Below we describe three research themes that have advanced our understanding of hydrological processes in the mountain watersheds in Canada: (1) the role of cold temperatures, (2) the importance of complex mountain topography, and (3) peak flow regimes. While these themes speak to specific processes related to water in the mountains, the overall importance of mountains for downstream ecosystems and communities was described by Patricia Joe of the Kwanlin Dün First Nation, a river People whose wellbeing depends on the mountains upstream (LC 2.9).

Patricia Joe, Kwanlin Dün First Nation, 2022, LC 2.9

The relatively cold temperatures experienced in many of the mountain ranges in Canada mean that cryosphere phenomena, like snowmelt, glacier melt, frozen soil, and permafrost are important controls on streamflow generation. Snowmelt makes a large, often dominant, contribution to mountain streamflow and groundwater recharge in nearly all mountain regions in Canada (Campbell & Ryan, 2021; Pomeroy et al., 2012; Woo & Thorne, 2006). In glacierized watersheds, glacier meltwater helps to sustain late summer streamflow after the snowpack has been depleted (Déry et al., 2009; Stahl & Moore, 2006). A variety of studies have quantified the contribution of glacier melt to streamflow in Alberta and British Columbia (Marshall et al., 2011; Bash & Marshall, 2014; Brahney et al., 2017; Chernos et al., 2020; Comeau et al., 2009; Henoch, 1971; Jost et al., 2012) most frequently using hydrological models. For example, approximately 10% of annual river flow comes from glacier ice and snow melt in the Illecillewaet River, in the unregulated headwaters of the Columbia River Basin, BC. In August, when snow has been depleted, glacier inputs account for 25% of streamflow despite glaciers only covering 4.9% of the watershed area (Hirose & Marshall, 2013). Permafrost and frozen soils in colder catchments act as low-permeability layers which limit the infiltration of rain or snowmelt into the soil and cause enhanced surface runoff compared to warmer catchments (Carey & Quinton, 2005; Woo et al., 2008).

Complex mountain topography causes slope, aspect, and shading to exert important controls on any hydrological process that is influenced directly or indirectly by solar radiation (Marsh et al., 2012). In the Northern Hemisphere, north-facing slopes receive less solar radiation than south-facing slopes, which allows snow and frozen soil to persist later into the spring, influences the types of vegetation, and increases the likelihood of permafrost occurrence (Woo et al., 2008). This effect is more pronounced at higher latitudes. Carey and Woo (2001) found that snow disappeared up to two months earlier on south-facing slopes in Wolf Creek, Yukon. The type and abundance of vegetation was found to differ according to slope and aspect—even more than elevation—in the Kluane Region of southwest Yukon (Dearborn & Danby, 2017). Differing vegetation on north- and south-facing slopes in turn affects evapotranspiration rates, soil moisture and interception patterns (Carey & Woo, 2001) with cascading influence on streamflow. Furthermore, aspect can be an important consideration in how mountain hydrological systems respond to perturbation like changes in forest cover (Ellis et al., 2011; Pomeroy et al., 2012).

Mountain basins in Canada present unique characteristics and risks related to floods. Several recent severe flooding events in Canada have centred on mountains, including the June 2013 Alberta and November 2021 southwestern British Columbia events that led to widespread flooding in both steep mountain creeks and large river floodplains. The 2021 heat dome event also led to extremely high flows in many mountain river systems in western Canada due to rapid snow and ice melt (White et al., 2022). *Debris flows* triggered by intense precipitation have been identified throughout the Boreal Cordillera, Pacific Maritime, and Montane Cordillera (VanDine, 1985).

While flooding is not unique to mountain regions, mountains receive more precipitation than lowlands (Sec. 2.3.2), are subject to atmospheric rivers that can drive high flows, particularly in the Pacific Maritime mountain region (Sharma & Dery, 2020), and have higher slope angles that move water rapidly into steep mountain creeks (Wohl, 2013). Rain-on-snow events can drive high river flows in mountain watersheds where rainfall partially melts the snowpack (Loukas et al., 2000; Musselman et al., 2018). In southwestern British Columbia, rain-on-snow events were found to enhance the total runoff of heavy rainfall events (> 40 mm) by 25% on average over rainfall alone (Trubilowicz & Moore, 2017). Since snowpack and air temperatures vary widely with elevation (Sec. 2.2), the altitude-area distribution of a watershed (hypsometry) influences how quickly snowmelt happens and therefore the magnitude and timing of peak streamflow (Pomeroy et al., 2016; Shea et al., 2021). Saturated and frozen soils during snowmelt or intense rain limit infiltration into the subsurface and further enhance runoff and streamflow (Fang & Pomeroy, 2016; Mccartney et al., 2006; Pomeroy et al., 2016). Forest disturbances such as logging and wildfire affect the magnitude of peak flows in mountain river systems by reducing snowfall interception, allowing more snow accumulation, and altering the rate of snowmelt runoff (Ellis et al., 2013; Pomeroy et al., 2012; Schnorbus & Alila, 2004; Whitaker et al., 2002; Winkler et al., 2015; Zhang & Wei, 2014).

2.5.3 *Mountain lakes and reservoirs*

Several thousand alpine and subalpine lakes dot mountains across Canada. High-elevation alpine lakes of the Montane Cordillera tend to be small and nutrient-poor, with low dissolved carbon and species diversity (Hauer et al., 1997; Murphy et al., 2010). Proglacial lakes and glacier-fed lakes are often high in suspended sediment (Leonard, 1986), which gives these lakes their famous bright blue or green appearance. Snowmelt is the main water input to small high-elevation lakes which can be fully flushed in a matter of days during the snowmelt period (Hauer et al., 1997). Later in the year, groundwater can play an important role in the water balance of alpine lakes (Hood et al., 2006; Roy & Hayashi, 2008). Fish stocking in some high-elevation lakes previously barren of fish has caused nutrient levels to increase (Schindler, 2000). Larger valley bottom lakes of the Montane Cordillera are often deep (> 100 m), with retention times of 3–5 years (Hauer et al., 1997). A large survey of 560 lakes in coastal British Columbia (Pacific Maritime Mountain region) showed that evaporation accounts for a median of 9.6% of lake losses and that lake geochemistry was partly controlled by geology (Gibson et al., 2018). Bottom sediments from both small and large mountain lakes serve as indicators of past climatic and ecological variations (see Chapter 5).

Dams and reservoirs are constructed and operated in many mountain regions for hydroelectric generation, water supply and/or flood control. Both natural lakes and reservoirs can have a dampening effect on peak flows as they provide storage capacity to the watershed (Woo & Thorne, 2003). The Columbia River basin in Canada and the United States has the highest number of dams in the world, and those on the Canadian part of the river generate about half of British Columbia's hydroelectricity. Viewed through a historical lens, the construction of dams and flooding of traditional Indigenous territories without proper consultation or compensation, as in the case of the Williston Reservoir (Fig. 2.20) and Tsek'ehne lands and settlements in the Montane Cordillera, is highly problematic (Sims, 2010).

Dams alter the hydrological regime by storing water during times of high flow and releasing it during times of low flow, which results in a less variable annual hydrograph (Nazemi et al., 2017). On a daily basis, flows downstream of hydroelectric dams are affected by electricity demand (Rood et al., 1999). For example, the snow-dominated mountain headwaters of the Peace River saw lower peak flows and higher winter discharge after the construction of a major hydroelectric facility in 1968 (Peters & Prowse, 2001). Mountains in the Atlantic Maritime and Boreal Shield regions also host many hydroelectric dams, and studies here have shown that dam operation style also determines the impact on flows (Delisle, 2021; Landry et al., 2014). Dams that are operated as "run-of-the-river" dams aim to limit large changes in storage and therefore upstream and downstream flow patterns remain similar. Run-of-the-river dams also do not require large reservoirs and are now common throughout Canada (Olofsson et

Figure 2.20: The "Plug" at the north end of the Finlay Reach of the Williston Lake Reservoir where the Finlay River enters. Caused by strong south winds, the "Plug" completely blocks the river with logs created by the formation of the reservoir in 1968 (Yunker, 2022), until north winds unpack it. Photo courtesy of Daniel Sims, 2012.

al., 2022). Dams have environmental, economic, and social impacts beyond hydrological changes of mountain rivers. This includes trapping sediment, impeding fish passage, and risks to water quality which are further discussed in Sec. 4.6 and Sec. 5.8.

2.5.4 *Mountain groundwater*

Groundwater (water stored underground in the saturated pore spaces of soil and rock) is an important source of streamflow in mountain systems, particularly during low flow conditions, making it an important resource in times of water stress (Hayashi, 2020). Furthermore, many mountain communities across Canada, like Banff and Jasper, Alberta, extract groundwater for municipal water supply (Anderson & Radic, 2020). Groundwater can be recharged by rain (pluvial), snowmelt (nival), both (hybrid) and/or from rivers, lakes, and wetlands (Allen et al., 2010). Groundwater moves slowly compared to surface water, so it continues to discharge to mountain streams and rivers when no precipitation is falling, and is known as *baseflow*. Groundwater increases the hydrological buffering capacity of mountains in a similar way to snow and ice storage, except that groundwater flows year-round (Somers & McKenzie, 2020). A baseflow index, which can be calculated as the ratio of long-term baseflow to total discharge (Beck et al., 2013, 2015; Smakhtin, 2001), gives an overview of the hydrogeologic regions in Canada and groundwater contributions to streamflow (Fig. 2.21). The baseflow index is an approximate measure of the amount of groundwater contributed to a stream or river over the long term. Western mountain regions shown in Fig. 2.21 tend to have a higher baseflow index than the adjacent prairies, but lower than the Canadian Shield.

Hydrogeologic studies in the mountain regions of Canada highlight the movement of groundwater through both shallower coarse deposits and underlying bedrock aquifers. Talus slopes, moraines, and alluvial deposits have been identified as zones of substantial groundwater storage in headwater catchments of the Montane Cordillera (Christensen et al., 2020; Hood & Hayashi, 2015; Kurylyk & Hayashi, 2017; Mcclymont et al., 2010; Roy & Hayashi, 2009; Szmigielski et al., 2018). The coarse sediments of proglacial moraines, for example, were found to be a key store of groundwater in a small alpine headwater catchment in Yoho National Park, BC. Annual fluctuations in groundwater storage are much smaller than annual snowpack storage but are an important source of discharge during low flow periods in autumn and winter (Hood & Hayashi, 2015).

Groundwater also flows through bedrock aquifers, and geology is an important control on bedrock groundwater flow (Campbell et al., 2021; Campbell & Ryan, 2021; Smerdon et al., 2009; Spencer et al., 2021; Welch et al., 2012). Watersheds with more permeable/fractured bedrock in the Rocky and Columbia Mountains (Montane Cordillera) were found to have higher winter base flows than those with low-permeability bedrock (Paznekas & Hayashi, 2016). In the Okanagan region of British Columbia, groundwater recharge to bedrock was estimated at 27% of annual precipitation and approximately 2% of annual precipitation flowed out of the catchment through bedrock (Voeckler et al., 2014). A recent study of the Elbow River, AB, indicated that water residence time ranged from <5–10 years and that bedrock groundwater aquifers with high storage capacity and transmission rates may contribute 60% of annual streamflow (Campbell et al., 2021).

Groundwater outflow from mountain watersheds can contribute to groundwater resources downstream from the mountains themselves, in what is known as mountain block recharge. One study in the Pacific Maritime region estimated that 45% of a coastal aquifer recharge (used for municipal water supply) came from mountain block recharge (Doyle et al., 2015). Deep groundwater circulation does occur in the mountain regions of Canada, often associated with hot springs and highly deformed rock (Grasby & Lepitzki, 2002; Van Everdingen, 1991). Circulation depths of up to 3.8 km below ground surface have been estimated based on water chemistry, but deep circulation is rare relative to flow through shallow fractured bedrock (Grasby et al., 2016; Grasby & Lepitzki, 2002; Yonge & Lowe, 2017). Groundwater pollution in mountain environments (Chapter 5) can be an incredibly difficult problem to solve, given the relatively slow rates of groundwater transmission and connectivity of groundwater and surface water systems (Winter, 1995).

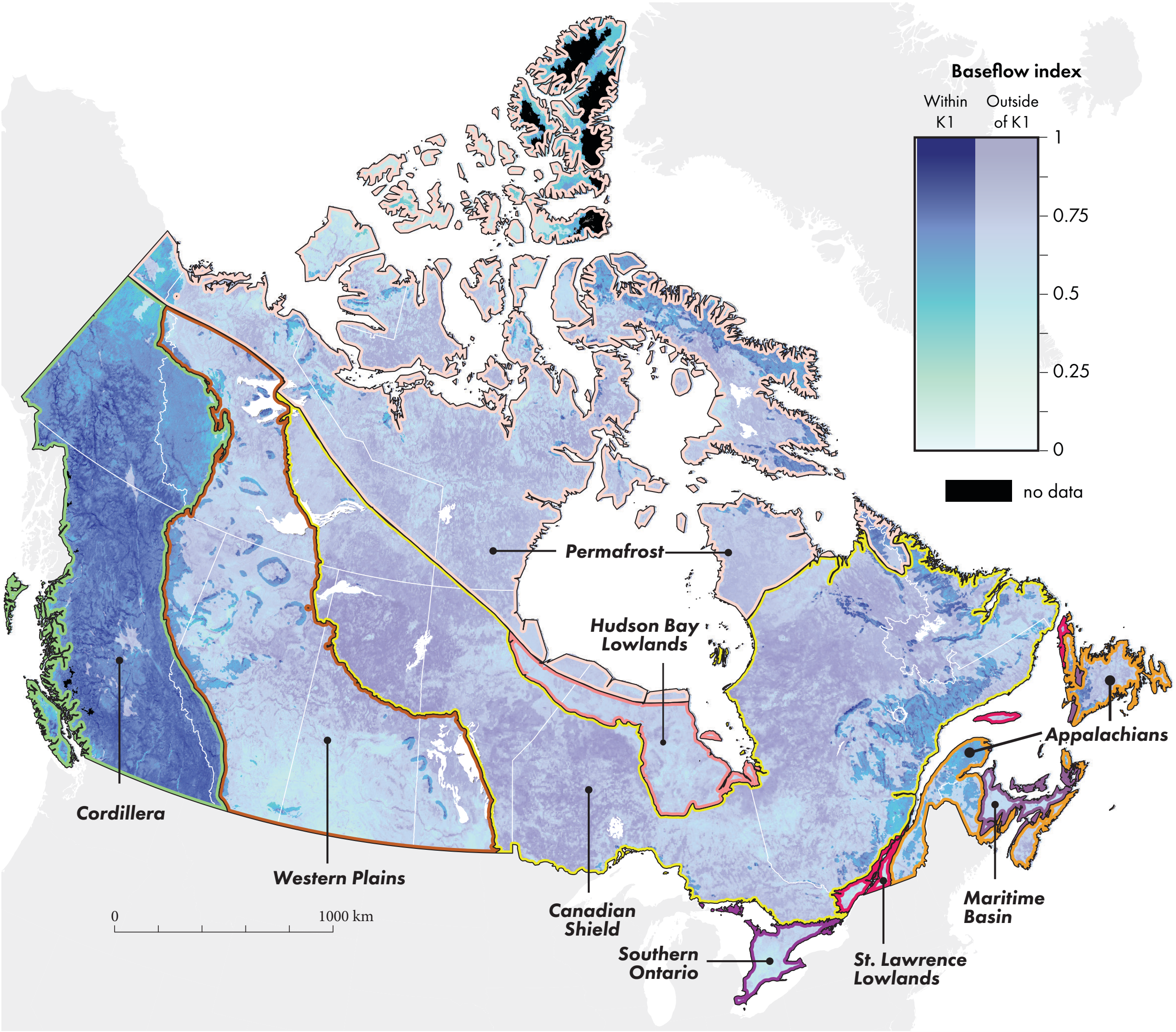

Figure 2.21: Map showing the hydrogeological regions of Canada (modified from (Sharpe et al., 2008) and a baseflow index (BI) that indicates areas of high (BI = 1) and low (BI = 0) groundwater contributions. Baseflow index (Beck et al., 2015) from the Global Streamflow Characteristics Dataset (https://www.gloh2o.org/gscd/).

While understanding of mountain groundwater in Canada has grown considerably in recent decades, observation wells are still lacking in mountains, particularly below 1–2 m depth, due to the difficulty in access and expense of drilling. The vast majority of mountain groundwater research in Canada is focused on the Montane Cordillera, and hydrogeological conditions in other Canadian mountain regions may be much different. Studies also tend to be local, with limited research on mountain block or mountain front recharge from the Montane Cordillera to the Prairies, or in any mountain regions in Canada.

2.5.5 *Mountain wetlands*

Wetlands occur in most ecoregions of the world and are characterised by a water table that is consistently near the ground surface. The connection between mountains and wetlands was noted by Pnnal Bernard Jerome of the Micmacs of Gesgapegiag on Day 2 of the CMA Learning Circle: “We gather medicines in the marshes...the marshes depend on the water that’s coming from the mountains” (LC 2.10). Wetlands provide a wide variety of ecosystem services: water quality improvement, flood risk mitigation, water retention, support for biodiversity, and carbon management (Zedler & Kercher, 2005). While the cool temperatures and generally higher annual precipitation of high elevation regions favours the formation of wetlands and peatlands (Cooper et al., 2012), mountain wetlands are usually smaller in area than lower elevation wetlands and are confined by topography (Chimner et al., 2010).

Peatlands are a specific type of wetland that contribute significantly to the global carbon cycle. These ecosystems have effectively accumulated carbon through millennia and have had an overall cooling effect on the climate since the late Holocene (Frolking & Roulet, 2007; Yu et al., 2010). Peatlands cover only 3% of land on Earth (Gorham, 1991; Yu et al., 2010), and yet they accumulate more carbon than all other vegetation types in the world combined (IUCN, 2021). Small changes in the delicate balance between long-term climatic conditions, short-term weather events, ecology, hydrology, and geomorphology can cause shifts in the carbon dynamics of these ecosystems (Page & Baird, 2016) and can even reverse the sign (source or sink) of net carbon fluxes.

Despite their importance, wetlands and peatlands in the mountain regions of Canada have been largely overlooked in regional studies and inventories, possibly due to accessibility for data collection, and very little Indigenous knowledge of mountain wetlands has been reported. In the United States, the Rocky Mountains are home to several thousand square kilometres of peatland, most of which occur at elevations below 1500 m above sea level (Cooper et al., 2012; Morrison et al., 2014; Warner & Asada, 2006). Mountain regions in Canada contain an estimated 13,000 km² of peatlands, but this estimate, together with the Canadian Wetland Inventory, ignores a large portion of the Montane Cordillera, as well as the Boreal and Taiga Cordilleras (Ducks Unlimited Canada, 2022; Tarnocai et al., 2011). A recent remote sensing approach to map wetlands performed poorly in the Boreal and Taiga Cordilleras due to a lack of training data for the model (Mahdianpari et al., 2020). Ground truthing in these areas, in direct partnership with local Indigenous communities, would help confirm the presence and characteristics of mountain wetlands. Without proper mapping and functional understanding, wetlands will be poorly represented in regional and global studies. The ecosystem services of mountain wetlands and projected changes are further discussed in Chapters 4 and 5, respectively.

Pnnal Bernard Jerome, Micmacs of Gesgapegiag, 2022, LC 2.10

2.5.6 *Mountain water quality*

Water quality can be considered from several perspectives that include temperature, sediment, and chemistry. Water pollution from human activities is addressed separately in Chapter 5. Water temperature dynamics have been studied in the Montane Cordillera and Pacific Maritime Mountain regions where cold-water fish and amphibians rely on cooler stream temperatures for survival (Friele et al., 2016; Mee et al., 2018). Solar radiation dominates the thermal regime of mountain streams and lakes (Harrington et al., 2017; Leach & Moore, 2011; Richards et al., 2012). Consequently, reduced shading from forest harvesting or wildfires can increase mountain stream temperatures (Moore et al., 2005; Wagner et al., 2014). The albedo of mountain streams is another important factor in heat absorption of mountain streams, which is influenced by turbidity and aeration (Mcmahon & Moore, 2017). Hydrological setting also controls mountain stream temperatures, as groundwater inputs cool streams during the summer (Macdonald et al., 2014). For example, springs emerging from an inactive *rock glacier* (small lenses of ice covered by seasonally frozen rock debris) in a headwater stream in Banff National Park were found to cool the peak summer stream temperature by 5°C, creating a thermal refuge for fish (Harrington et al., 2017). Evaporation from mountain streams also acts to limit daily maximum stream temperature in summer (Szeitz & Moore, 2020).

Sediment transport is a natural process in mountain streams and lakes. Landscape changes such as wildfire, forestry, hydropower development and river engineering can impact sediment loads, and increased sedimentation affects mountain stream ecosystems (Hedrick et al., 2013). Broadly speaking, the per area sediment yields of mountain regions in Canada are lower than the Prairies, given less erodible materials (Church et al., 1999). Periodic events such as flood flows, landslides and glacier changes account for large amounts of sediment transport in mountain systems (Heideman et al., 2018). For example, a study of suspended sediment concentrations and lake sediment cores in the Green Lake Basin, BC (Montane Cordillera) revealed that a summer rainstorm in 1991 transported more sediment than any other event in the previous 3000 years (Menounos et al., 2006). Wildfires in the Montane Cordillera region have been observed to increase total and peak streamflows (Mahat et al., 2016) and increased suspended sediment concentrations (Martens et al., 2019; Silins et al., 2009) and nutrient loads (Silins et al., 2014). Although hundreds of stream-gauging stations in Canada have some archival sediment data, continuous sediment data from the Water Survey of Canada is not available after the year 2000 (https://wateroffice.ec.gc.ca/search/sediment_e.html).

Turbidity refers to the clarity of a body of water and the amount of suspended sediment. Turbidity is an important water quality variable that relates to a suite of physical, chemical and biological processes. Mountain headwaters—with the exception of glacially fed streams (H. Slemmons et al., 2013)—tend to be relatively clear and turbidity increases downstream with erosion and the amalgamation of multiple tributaries (Whitfield, 1983). Light penetration into stream, river or lake waters is limited in high turbidity systems, which affects photosynthesis, primary production, and the ability of visual predators like fish to find their prey. Suspended sediment particles are active participants in chemical weathering reactions that may, in especially turbid waterways, overwhelm biological processes. Depending on which minerals are present, turbid systems can be sources (Interior Hills North; Zolkos et al., 2018) or sinks (St. Pierre et al., 2019) of greenhouse gases like carbon dioxide.

Water source and streamflow regime are key controls on the water quality in mountain rivers. A regional watershed classification across the Pacific Maritime region linked topography, streamflow regime, and water quality (quantified using dissolved organic carbon concentrations, (DOC)) to identify 12 major watershed types (Giesbrecht et al., 2022). Glacierized mountain watersheds were associated with the lowest DOC concentrations, while the small, lower elevation rain-dominated watersheds were recognized as DOC hotspots with snow-dominated and more continental (e.g., Fraser and Skeena Rivers) watersheds exhibiting intermediate DOC concentrations. Such differences in water quality likely extend to other organic matter-associated nutrients, like nitrogen and iron, and largely result from differences in climate that control soil accumulation and decomposition rates and the timing and intensity of peak flows that control contact times between waters and the surrounding soils and sediments (Bhatia et al., 2021). A glacial stream in the Montane Cordillera also had lower concentrations of other solutes, such as calcium, sodium, sulphate and chloride than a non-glacial stream due to higher specific discharge that limited water-rock contact times and solute supply from the surrounding soils (Lafreniere & Sharp, 2005). In contrast, a study of the Canadian Arctic Archipelago found that runoff from glacierized basins was an important source of iron and manganese to the ocean (Bhatia et al., 2021). Regional-level analyses of water quality and water quality characterizations similar to Giesbrecht et al. (2022) are lacking for other mountain regions in Canada.

2.5.7 *Hydrological modelling*

In tandem with advances in physical understanding of hydrological processes in mountains, a large body of research has worked to improve how these processes are modelled in mountain environments. Hydrological models can cover a wide range of complexities, from simple empirical models, to fully distributed physically based models. Hydrological models have been applied across different mountain regions in Canada to better understand streamflow dynamics (Fang et al., 2013; Pomeroy et al., 2016; Voeckler et al., 2014), forecast flood events (Quick & Pipes, 1977), and to simulate streamflow changes related to climate change (Kite, 1993; Shrestha et al., 2012; Islam et al., 2019; Whitfield et al., 2002) and/or land cover change (Ellis et al., 2013; Mahat et al., 2015; Pomeroy et al., 2012; Springer et al., 2015).

Past modelling efforts have established the value of breaking mountain basins into smaller areas (hydrological units) based on characteristics such as slope, aspect, elevation, soils, vegetation (Kite & Kouwen, 1992). For example, in a snow-dominated catchment in Wolf Creek, Yukon (Taiga Cordillera), snowmelt and streamflow simulations were improved by dividing the model domain into smaller units based on slope and aspect (Dornes et al., 2008). The incorporation of physically based energy balance equations also gives more accurate simulation of cold regions processes (Debeer & Pomeroy, 2017) and allows for stream temperature modelling which is of importance for ecosystems (Macdonald et al., 2014). The cold regions hydrological model (Pomeroy et al., 2007) has been applied to several study sites in the Montane Cordillera (Debeer & Pomeroy, 2017; Ellis et al., 2013; Fang & Pomeroy, 2020; Rasouli et al., 2019) and presents a method to use physically based hydrological formulations to improve process representation in cold regions.

Several challenges remain in simulating mountain hydrological systems in Canada. Despite the demonstrated importance of groundwater in feeding low flows, relatively few studies have coupled groundwater flow models to surface water models (Cochand et al., 2018; Foster & Allen, 2015; Voeckler et al., 2014), instead relying on a simple "bucket" parameterization for groundwater processes. We therefore do not have a clear understanding of how groundwater and surface water systems interact at different scales or the necessity of including distributed groundwater flow in mountain hydrological models. Additionally, uncertainty in meteorological model forcing leads to uncertainty in hydrological simulations (Thorne & Woo, 2006; Islam & Dery, 2017).

2.5.8 *Gaps and challenges*

While great progress has been made in characterising mountain water systems in Canada, several knowledge gaps remain. First, the vast majority of the literature reviewed in this section is focused on the Montane Cordillera and Pacific Maritime regions. A smaller but substantial body of research has focused on watersheds of the Boreal Cordillera in the Yukon. Very little research has been done on mountain hydrological systems in the Atlantic Maritime and Boreal Shield, Taiga Cordillera, and Interior Hills mountain regions. The focus on western Canada is not surprising given the size and abundance of mountainous terrain and the proximity to large population centres and downstream agricultural regions. However, this leaves a clear geographic knowledge gap where the mountain regions of eastern, central, and (to some extent) northern Canada have seen little hydrological research. Furthermore, mountains play a role in municipal water supplies, tourism, and conservation. The main water source for Quebec City (population of 300,000), for example, is a small mountain lake in the Atlantic Maritime and Boreal Shield region (Cochand et al., 2018; Ville de Québec, 2022)

Second, our understanding of mountain surface water and groundwater systems have advanced largely in parallel, and there remains a need to integrate groundwater and surface water studies. One challenge is that many mountain groundwater studies focus on small headwater catchments and are not easily scaled up to watershed or basin scales. We also lack observation wells in mountains, especially those deeper than a few metres, providing limited calibration targets for hydrological models. Hydrogeological models are also generally more computationally expensive than surface water models, and more research is needed to determine the adequacy of simplified groundwater flow modules in simulating low-flows. This may be particularly important when projecting future low-flow conditions under climate change, given the importance of groundwater in feeding rivers during dry periods.

Third, while a substantial body of work has focused on how mountain water systems are changing, there remain several knowledge gaps. Again, there is little analysis of how/if mountain streamflow is changing outside of the Montane and Boreal Cordilleras. There is very little research into how mountain groundwater systems are changing anywhere in Canada. In both surface and groundwater studies, trend analysis is limited in some cases by short observational records, which can sometimes be augmented with long-term proxy data. Expected future changes in mountain water systems and the consequences for downstream users and communities are explored in Chapter 5.

While we acknowledge the wide diversity of Indigenous viewpoints and cannot speak to all of them, water frequently emerges as a central theme in culture, health, spirituality, and sustainability of Indigenous communities within and downstream of mountain regions (Blackstock, 2001; Sanderson, 2008; Simms et al., 2016). Our assessment lacks direct examples of Indigenous knowledge with respect to mountain water systems, and it is clear that greater efforts must be made to co-generate knowledge with Indigenous and Western scientific viewpoints, with the goal of building more holistic approaches to understanding mountain water systems (Wilson et al., 2019).

2.6 Mountain Hazards

The mountain regions of Canada are subject to a host of natural hazards, including earthquakes and volcanoes, mass movements (landslides, rockfalls, debris flows, debris floods, and avalanches), floods and extreme precipitation events, wildfires and heatwaves, and extreme cold temperatures. The types and magnitude of risk from specific hazards vary significantly between mountain regions. Three components are important to understanding the regional diversity of mountain hazards and their impacts. First, mountain regions are tectonically, geomorphically, and hydrologically active due to elevation- and aspect-driven variability in relief, energy, and moisture, creating the conditions for active landscape change. Second, mountain regions are socio-culturally diverse, with settlements ranging from small, isolated communities to large population centres having distinctive social, cultural, economic, and political features that lead to differentiated experiences of mountain hazards (Chapters 3, 4, and 5). Third, mountains and adjacent lowlands are linked by flows of air, water, materials, wildlife, people, goods, and services (Sec. 2.8), and these highland-lowland linkages have increased in magnitude and importance in the past few decades.

2.6.1 *Indigenous perspectives on mountain hazards*

Recounting her experiences in the Richardson Mountains, Wanda Pascal of the Teetl'it Gwich'in Nation (a CMA Learning Circle participant) told a story of encountering a landslide path to illustrate the ways in which natural hazards affect the ways people move through the mountains, reshaping ancestral trails and the landscape of the mountains themselves (LC 2.11).

The "Frank Slide" of 29 April 1903 (Cruden & Martin, 2007) was another such event, in which ~80 Mt of rock fell from Turtle Mountain (Fig. 2.22) on the settler community of Frank, despite warnings from the Piikani Nation (Blackfoot Confederacy). Hayden Melting Tallow of the Siksika Nation (Blackfoot Confederacy) described the event at the CMA Learning Circle:

> Piikani people...have been in that area for thousands of years, and the Europeans came and found some coal in that area.... The Piikani people were warning the people there: 'Don't live (there), don't build your house (there). Build it farther, because that mountain is shaking' because they knew that. They didn't listen to them (saying): 'Oh they're just savages...' and stuff like that. They didn't believe in their way of thinking and their knowledge and their knowing. Then they all settled in that area, and one night, the whole thing came down. The mountain came down and it buried a whole town......Underneath, the town is still there, and there are some bodies down there too.....So our elders and our stories and our tales, they should be an addition to predicting what's going to happen. Those Blackfoots knew what was going to happen. That's why it's really important for us as

Wanda Pascal,
Teetl'it Gwich'in, 2022,
LC 2.11

Hayden Melting Tallow,
Siksika Nation, Blackfoot
Confederacy, 2022, LC 2.12

Figure 2.22: Turtle Mountain, showing the debris field of the 1903 Frank Slide. The debris from the Frank Slide is the white material spread over the valley floor. A new highway and railway have been built across the debris field since 1903. Photo courtesy of David J.F. Thomas and AlbertaSouthWest.com.

> knowledge keepers to pass on that information and the technology that they were brought up with for thousands of years—how to use your sixth sense like the animals. They live with the animals and it's all in balance. That type of knowledge can be used today to predict a lot of things. (LC 2.12)

2.6.2 *Hazard types and frequency*

Scientific research on the risks and spatial and temporal dimensions of natural hazards in mountains in Canada is largely focused on the Montane Cordillera and Pacific Maritime Cordillera (Blown & Church, 1985; Church & Miles, 1987; Jakob et al., 2017; VanDine, 1985), and in particular on quantifying and mitigating hazards where they have disrupted or otherwise affected railway and pipeline corridors, roads, and mining activities (e.g., Gartner & Jakob, 2021; Kromer et al., 2015; Macciotta et al., 2015). There is also evidence to suggest that catastrophic landslides approximately 1000 years before present disrupted salmon runs on the Fraser River, which led to the abandonment of Tsilhqot'in settlements in the region (Hayden & Ryder, 1991).

Several high magnitude and damaging events have been studied extensively, such as the Mount Cayley volcanic eruptions (Evans & Brooks, 1991; Stasiuk et al., 2003), the Mount Meager and Mount Joffre landslides (Bovis & Jakob, 2000; Friele et al., 2020; Guthrie et al., 2012) on Lil'wat territory in southwestern British Columbia, the Frank Slide in 1903 on Nakoda/Blackfoot territory, and the Bow River watershed floods in 2013 (Whitfield & Pomeroy, 2016), which affected a number of territories in south-central Alberta. Chronic hazards along major infrastructure routes or in populated areas have also been studied. These include snow avalanches in the Rogers Pass area of Glacier National Park, BC (Bellaire et al., 2016), debris flows along the Sea to Sky Highway 99 north of Vancouver (Church & Miles, 1987; Clague et al., 2003; Hungr et al., 1999), and repeated high magnitude

Gùdia Mary Jane Johnson, Lhu'ààn Mân Dań, 2022, LC 2.13

Keara Long Lightning, Nehiyaw, Samson Cree First Nation, 2022, LC 2.14

Daniel Sims, Tsay Keh Dene First Nation, 2022, LC 2.15

and damaging floods in the lower Fraser River Valley in 1898, 1948, and 2021.

Intense precipitation (Sec. 2.3.2) combined with steep mountain streams and creeks can produce rapid and damaging flood events (Jakob et al., 2016), such as the 2021 atmospheric river in southern British Columbia and the 2013 Bow River floods. Post-colonial development can also impact the severity of an event: Semá:th X̱ó:tsa (Sumas Lake), in the Fraser Valley, was both a form of natural flood protection and an incredibly valuable natural resource for the local Stó:lo people until it was drained in the 1920s for agriculture (Dick et al., 2022). In the 2021 floods, the lake was reconstituted with floodwaters that brought evacuations and large economic losses to farmers and communities that occupied the former lake bed (Olsen, 2021), but the event was also viewed by some members of the Semá:th First Nation as a sign that "the spirit of X̱ó:tsa was alive and well" (Ross et al., 2022).

Permafrost thaw poses a hazard for infrastructure and remote communities in the Taiga Cordillera and Arctic Cordillera (Arenson & Jakob, 2015; Ford et al., 2010), and has been linked to slope failures in the Boreal Cordillera (Huscroft et al., 2004). Alpine permafrost thaw specifically contributes to increased rockslides and slope failures (Clague, 2009) as the frozen water found in weathered rock and soils can act as a glue that holds unstable slopes together. In the CMA Learning Circle, Gùdia Mary Jane Johnson, a Lhu'ààn Mân Dań Elder, spoke of creeks being blocked by 'big hills' and noted that "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 2.13).

2.6.3 *Gaps and challenges*

Mountain hazards have not been systematically studied in most mountain regions of Canada, particularly through an interdisciplinary lens or through frameworks of vulnerability, adaptation, or loss and damages. There is emerging global attention to early warning systems around natural hazards and risks to vulnerable communities, and much of this is relevant to natural hazards in the populated mountain regions of Canada. Hazard assessment and warning systems require both increased surveillance capacity, near real-time monitoring systems, improved process-based models of mountain systems, and social science research to identify concerns and inform adaptation and mitigation activities that minimise vulnerability and risk. In particular, changes in hazard frequency and magnitude due to ongoing and future climate change (Beniston, 2003) need to be considered with respect to vulnerability assessments and emergency planning at community levels (Pearce, 2003).

2.7 Ecosystems and Biodiversity

This section assesses the state of knowledge with regards to the ecosystems and biodiversity of mountain environments and includes forests, alpine tundra, and alpine streams. According to Keara Lightning of the Samson Cree First Nation, the natural world is central to Indigenous societies (LC 2.14). It also offers many important gifts to people living in and beyond mountain areas, as described in Chapter 4. Across latitudinal and elevation gradients, abiotic (non-living) and biotic (living) factors that drive patterns of flora and faunal diversity are explored. Ongoing changes in mountain ecosystems—particularly, those driven by humans—were also recurring themes in the CMA Learning Circle. Daniel Sims, Tsay Keh Dene First Nation, shared that "[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 2.15). Changes in mountain ecosystems and biodiversity, and the drivers of change, are discussed in Chapter 5.

2.7.1 *Terrestrial mountain ecosystems*

Mountains are home to a wide range of ecosystems (Fig. 2.23). This includes snow and ice, lakes and rivers, wetlands, forests, and alpine-tundra with transition 'ecotones' between them. These ecosystems, depending on their latitude, elevation, and proximity to the ocean or large lakes, vary significantly in their structure and function. For example, the above-ground biomass and carbon storage is highest in low-elevation productive forested ecosystems (Hagedorn et al., 2019). Conversely, for below-ground carbon storage, the highest values are found in montane wetland ecosystems where nutrient poor conditions and cold temperatures result in low rates of organic matter decomposition (Xiao et al., 2019). Functional attributes also vary by ecosystem type, including differences in habitat and resource availability. Species composition, one important metric of biodiversity, is strongly associated with ecosystem type, and thus the distribution of these ecosystems informs biodiversity across mountain landscapes. Other ways

Figure 2.23: The Blakiston Valley in Waterton Lakes (Paahtómahksikimi) National Park and the Traditional Territory of Niitsitapii (Blackfoot) and K'tunaxa is home to a diverse range of ecosystems and land cover types. Scars from the Kenow wildfire can be seen at the end of the valley. Photo courtesy of Charles Hayes, Mountain Legacy Project.

of understanding biodiversity, including cultural values, species distributions, and abundance are expanded upon in Sec. 2.6.3.

Land cover

Broadly classified land cover types can be mapped over large regions from satellite data. A recently published dataset (Hermosilla et al., 2022) that builds on a decade of land cover classification work (Coops et al., 2020; Gómez et al., 2016; White et al., 2014; Wulder et al., 2018) provides annual (1985–2019) land cover classifications for regions south of the treeline, yielding the ability to track land cover changes through time (Chapter 5).

While mountains are often imagined as rocky, snow-covered peaks, the mountain regions of Canada included in this satellite-based classification are predominantly forested (Fig. 2.24). These include coniferous, broadleaf, and mixed wood forests. Other land cover classes include herbs, shrubs, and bryoids; wetland and wetland-treed; and barren, rock, snow/ice, and water. The Boreal Cordillera region (Fig. 2.25), for example, contains snow, rock, and barren ground at its highest elevations, but is defined by extensive coniferous forests, shrubs, and wetlands. Broadleaf and mixed-wood forests dominate the Interior Hills Central region, while coniferous forests are the largest component of the Atlantic Maritime and Boreal Shield, the Interior Hills West, Montane Cordillera, and Pacific Maritime regions.

Compared to terrestrial land cover types, ice, snow, and water cover a small portion of Canadian mountain environments. However, these cryo- and hydrological features are crucial for the supply of freshwater and support diverse aquatic ecosystems. Here, we briefly outline snow and ice, and water contributions to the land cover composition of mountain landscapes in Canada. Changes in land cover types are examined in Chapter 5.

Glaciers are an important feature in most of the mountain regions in Canada. In the Arctic and high elevation regions, such as the Arctic Cordillera, Boreal Cordillera, and Pacific Maritime, glaciers cover more than 10,000 km^2, respectively (Table 2.5) but make up a very small proportion of

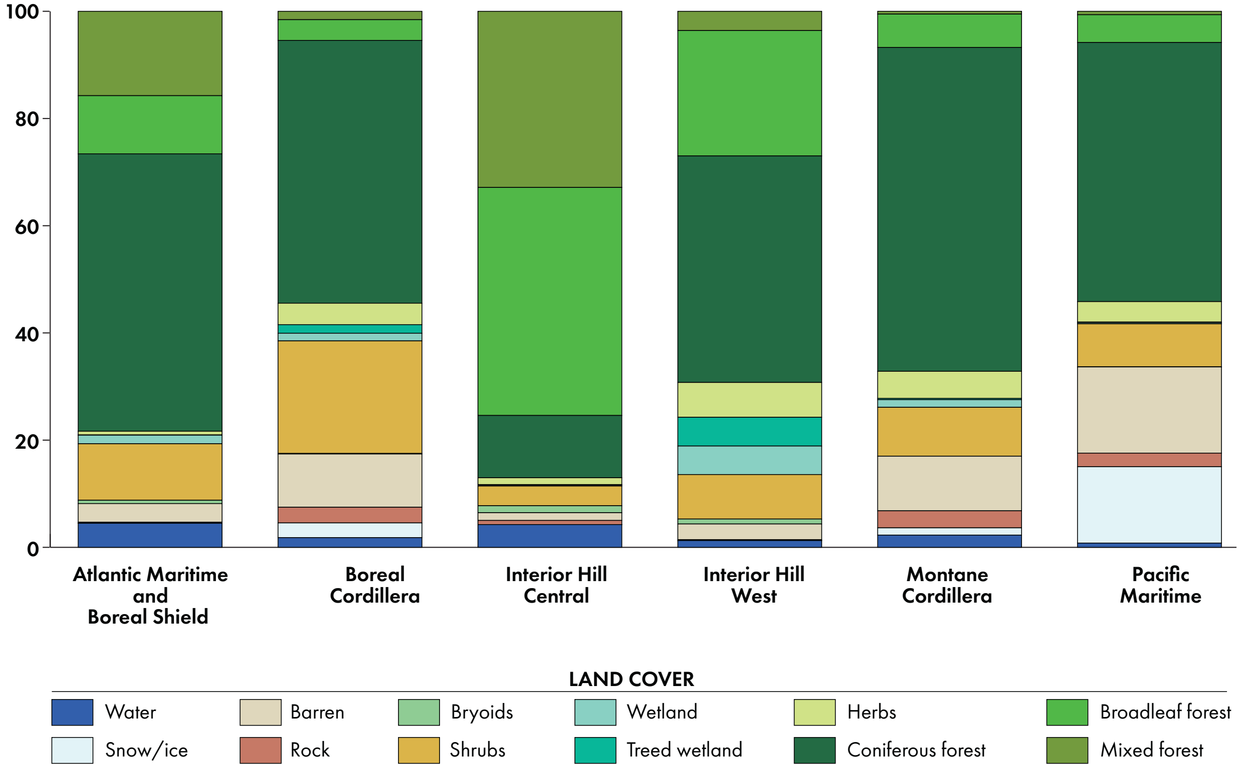

Figure 2.24: Percent total land cover for six CMA major mountain regions in 2019, following the classification of Hermosilla et al., 2022. Data from https://opendata.nfis.org/mapserver/nfis-change_eng.html.

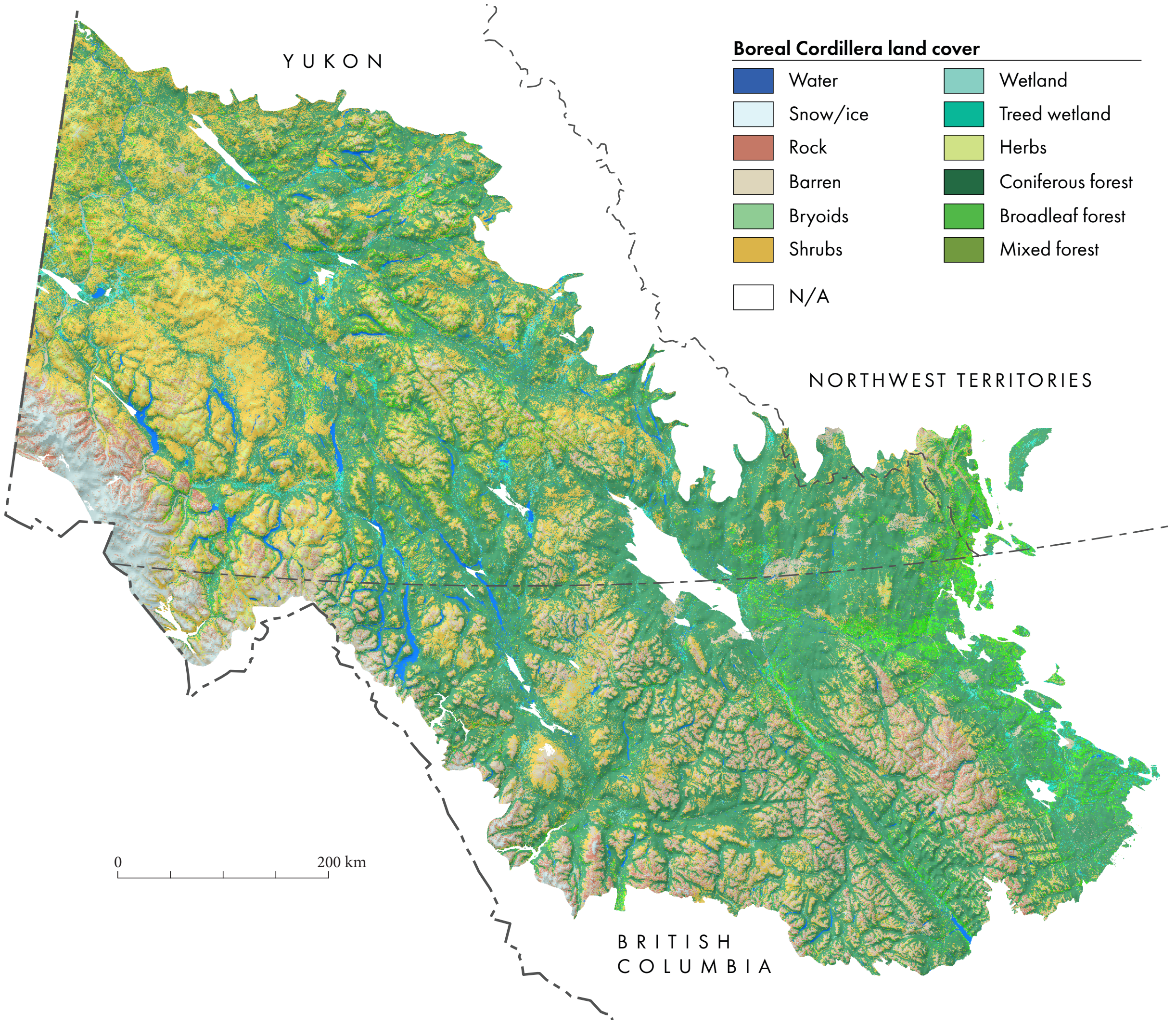

Figure 2.25: Classified land cover for the Boreal Cordillera mountain region in 2019, following the classification of Hermosilla et al., 2022.

the total land cover. Seasonal snow, on the other hand, covers a substantial portion of all mountain regions in Canada in winter, and transitions to barren and vegetated landscapes in summer. However, Arctic and alpine landscapes support many perennial or semi-permanent snowpacks that persist into summer, and adjacent ecosystems are adapted to snow cover and colder conditions.

Glaciers and snowfields supply networks of lakes, streams, and rivers which transport water, nutrients, sediment, and organisms from alpine regions to landscapes below (Sec. 2.4). Freshwater features are found in all mountain systems in Canada, though again cover a small fraction of mountain landscapes compared to terrestrial cover types. Mountain lakes and rivers are fed by a mix of glacier and snow melt, groundwater, and precipitation, and the relative proportions of these differing inputs can alter the biodiversity and services supplied by water bodies (Milner et al., 2017) .

Ecological gradients

The most pronounced ecological gradient across mountain regions occurs with changes in elevation. The structure and function of ecosystems across elevation gradients depends on several factors, including aspect, latitude and proximity to coastal environments. For mountains in southern Canada, the low elevation ecosystems are predominantly covered by coniferous closed-canopy forests, with some exceptions in the Atlantic Maritime and Boreal Shield region, where deciduous species can comprise the majority of the forests (Fig. 2.24). For mountains that extend above the elevational limit of trees, tree density decreases with elevation, resulting in a more open canopy forest as you move up the mountain. The 'treeline' is referred to as the upper elevation limit of trees growing over 3 m in height (Körner, 2012). The upper elevational limit of trees is thought to be controlled by climate factors, whereas lower in elevation, non-climate (likely biotic factors) may be more important (Ettinger et al., 2011). Species that grow as trees at lower elevations often have stunted growth forms above the treeline, such as krummholz, which will be discussed below. The combined high-elevation open canopy forest, treeline, and trees with a growth form less than 3 m in height, are referred to as the forest-alpine-tundra ecotone. Above the forest-alpine-tundra ecotone, the alpine-tundra extends towards the mountain top, though the distribution of vegetation is often quite variable, driven by soil availability and other site characteristics. Northern mountains, such as those in the Arctic Cordillera, and parts of the Eastern Subarctic and Taiga Cordillera mountain regions, are either north of the latitudinal limit of trees or north of where closed-canopy forests occur. In these northern regions, the dominant woody vegetation is deciduous shrub species, including dwarf birch, willows, and alders.

In addition to latitudinal and elevational gradients, aspect can also play an important role in mountain ecosystems. North-facing slopes, particularly in more northern mountain regions (Arctic Cordillera, Taiga Cordillera, Boreal Cordillera) generally have more persistent late-lying snow patches which results in a shorter growing season but potentially more protection for low-lying vegetation from spring frost events. Conversely, south-facing slopes have higher levels of solar radiation, which, in addition to a longer growing season, can increase soil temperature and have a deeper active layer (Dearborn & Danby, 2017). Aspect influences the position of the treeline with, generally, south-facing slopes having higher treelines than north-facing slopes, and also strongly influences the composition of plant communities (Dearborn & Danby, 2017).

Another important factor that shapes mountain ecosystems lies below the ground. For trees, there is a significant body of scholarship that demonstrates a hidden mycorrhizal fungal network that allows different tree species (*Betula papyrifera* and *Pseudotsuga menziesii)* to communicate and share nutrients (Simard, 2021; Simard et al., 1997). This recent holistic approach has important implications for understanding how mountain ecosystems function and respond to disturbance and climate change (Reithmeier & Kernaghan, 2013), and it mirrors long-standing Indigenous perspectives on the importance of holistic monitoring and knowing of associations among ecosystem components (Jessen et al., 2022).

Mountain corridors

Whether it is in the higher elevation alpine-tundra or in the lower elevation forest ecosystems, mountains provide important corridors for people and wildlife. Indigenous Peoples, for millennia, have moved through mountain landscapes for a variety of purposes including for trading and hunting. In Nunatsiavut and Nunavik (Eastern Subarctic mountain region), Inuit travelled between communities in northern Labrador and Kangiqsualujjuaq along the Koroc River, through the Torngat Mountains for trade, social, and other cultural reasons (Cuerrier et al., 2019). Megan Dicker, Inuit, Nunatsiavut, described the ongoing importance of mountain paths in northern Labrador for helping people to travel safely and reach their homes (LC 2.16). Glaciers in the St. Elias range were described as travel corridors by Eyak, Athapaskan, and Tlingit groups in the region (Cruikshank, 2001). For many wildlife species, high- and low-elevation mountain corridors in Canada are important for habitat connectivity that is needed to satisfy a variety of requirements. These corridors can provide seasonal or daily access to climates and habitats that offer adaptive benefits for thermoregulation and increased access and variation of food. Mountain corridors are critically important large-scale landscape

Megan Dicker, Inuit, Nunatsiavut, 2022, LC 2.16 connectivity features and are the focus of ongoing conservation efforts (Hilty & Jacob, 2021).

2.7.2 *Landscape management and disturbances*

Mountain landscapes have been managed and stewarded by Indigenous Peoples for millennia in a diversity of ways that cannot be fully represented here. In this section we provide examples of landscape management from different mountain regions of Canada. Indigenous fire stewardship—also referred to as 'cultural' or 'good' fire—has been practised by most Indigenous Peoples in the mountains of what is now called Canada. The reasons for using fire vary tremendously but include clearing of land and enhanced food production with the added benefit of limiting catastrophic wildfires (Brookes et al., 2021) and enhancing overall biodiversity (Hoffman et al., 2021). In the Pacific Maritime mountain region, Indigenous Peoples used fire to increase resource productivity and predictability (Turner et al., 2011). In the Eastern Subarctic mountain region, fire was also used by Inuit in Labrador to manage plant communities and improve soil fertility (Oberndorfer, 2020). Across Canada, including the mountain regions, the use of fire by Indigenous Peoples was actively suppressed by colonial policies and practices, which can affect the harvest of berries, for example (Gottesfeld, 1994). While Indigenous fire stewardship continued in some regions, despite colonialism, there has been a resurgence of Indigenous communities using fire to manage landscapes (Hoffman et al., 2022).

Historically, natural wildfires have played an important role in many Canadian mountain regions, especially in the Montane Cordillera and the Boreal Cordillera (Amoroso et al., 2011; Chavardes et al., 2018; Van Wagner et al., 2006). In some of the mountain regions across Canada, there are detailed fire histories, though the majority are concentrated in the western areas of mountains in Canada (Hallett et al., 2003; Harvey et al., 2017; Power et al., 2011), with some from eastern Canada (Lauzon et al., 2007). A century of forest fire suppression policies at provincial and federal levels has transformed the overall forest structure. A high frequency of fires cleared the understory of young trees, resulting in an open forest dominated by older, larger trees with thick, fire-retardant bark (Naficy et al., 2010). With the suppression of fire, forests became denser with greatly reduced understory vegetation as little light reaches the forest floor (Van Couwenberghe et al., 2011). For higher elevation subalpine ecosystems, fire drives increases in plant diversity, though this pattern decreases with elevation (Coop et al., 2010). Another important factor influencing fire in mountain ecosystems is that over a century of livestock grazing reduced fine fuels, such as grasses and forbs (Keane et al., 2002), and allowed the establishment of more flammable species such as cheatgrass (*Bromus tectorum*; Diamond et al., 2009). From a management perspective, the accumulation of wood fuel and more flammable species in the understory of most forests, combined with warmer, drier summers related to climate change, has resulted in an increased frequency, severity and extent of wildfires. The frequency of catastrophic fires is a significant concern for many mountain communities (Hoffman et al., 2022).

Insect herbivory is also a significant disturbance factor in mountain ecosystems across Canada. For example, periodic outbreaks of mountain pine beetle in the Montane Cordillera region have been documented over the past century (Axelson et al., 2018; Taylor & Carroll, 2003) with a large-scale outbreak, beginning in the late 1990s to 2015, killed more than half of British Columbia's merchantable pine (Dhar et al., 2016). While carbon storage in pine beetle-affected areas is recovering (Mcewen et al., 2020), the interaction between fire severity and outbreak severity influences, and complicates, the recovery trajectories (Talucci and Krawchuk 2019). In mountain regions of eastern Canada, some insect species have outbreaks in higher elevation open-canopy forests. For example, at Mont Mégantic, QC, in the Atlantic Maritime and Boreal Shield mountain region, reconstructed insect outbreaks of spruce budworm have been observed every 20–40 years over the past century (Filion et al., 1998). In the northern mountain regions, insect herbivory occurs more often at non-outbreak levels but is still an important factor for understanding ecosystem dynamics and the consequences for carbon storage (Silfver et al., 2020). In addition to fire and the insect species discussed above, mountain regions are affected by a range of other natural and human disturbance factors.

2.7.3 *Mountain biodiversity*

Many wild species make the mountains their home, either exclusively or seasonally, each with varying but important levels of ecological and cultural significance. Mountains not only support a richness of wildlife and ecosystems, but many of these are rare, rapidly declining, or at risk of disappearing in a rapidly changing world. Despite the iconic status of many mountain ecosystems and species, much of the mountain biodiversity in Canada is poorly documented and remains to be described. At times public perception is shaped more by romanticism and/or myth than reality.

While we are unable to provide an exhaustive list of the biodiversity in each mountain region, we explore terrestrial and aquatic mountain ecosystems, some of the iconic mountain species, threatened ecosystems and species, and the need to conserve mountain biodiversity.

Mountain ecosystems

Mountain ecosystems are diverse, and this diversity is often compressed into relatively small areas as ecosystems rapidly transition in response to changes in altitude. From floodplain forests and wetlands along river valleys to high alpine meadows and snow-covered peaks, the high diversity of mountain ecosystems can often be witnessed by simply looking at the mountain. While the classification and description of mountain ecosystems is incomplete in Canada, each mountain region often has distinct altitudinal zones that drive the types of the ecosystems that occur:

Valleylands in mountains often include lakes, rivers, streams, and wetlands. These range from the rocky and barren river valley of the Akshayuk Pass in Auyuittuq National Park in the Arctic to the rich bottomlands of the Creston Valley, BC. Valleylands often have lowland ecosystems not found at higher elevations such as Black Cottonwood (*Populus balsamifera ssp. trichocarpa*) riparian forests in the Rocky Mountains, and seasonal flooding can be an important natural process.

Foothills occur along the base of mountains. In the southern mountain regions of Canada, the foothills can be a wide forested transition zone between valleylands and montane zones. Foothills in the rain shadow of the mountain are often grassland or shrubland. In the Rocky Mountains, the foothill zone extends along the eastern flank of the mountains and is dominated by rolling Rough Fescue (*Festuca hallii*) grasslands.

Montane ecosystems occur on the slope of the mountain. There can be high diversity of ecosystems within this zone with warmer temperatures, more moisture, and less snow in the lower regions. Aspect and wildfire can also play an important role in shaping ecosystems in the montane zone. Montane ecosystems range from British Columbia's inland temperate rainforests dominated by Western Cedar (*Thuja plicata*) and Western Hemlock (*Tsuga heterophylla*) to the Trembling Aspen (*Populus tremuloides*) and Balsam Poplar (*Populus balsamifera*) forests of the Boreal Cordillera. In treeless mountain regions such as the Torngat Mountains in Labrador, the montane zone is dominated by alpine heath of Dwarf Huckleberry (*Vaccinium caespitosum*), Mountain Cranberry (*Vaccinium vitis-idaea*), bearberry (*Arctostaphylos uva-ursi*), and Black Crowberry (*Empetrum nigrum*).

Subalpine ecosystems mark a transition between the alpine and montane zones. In treed environments there is typically a marked difference in the character and composition of forest ecosystems. Wind, cloud and fog cover, and avalanches play an increasingly important role in ecosystem dynamics in the subalpine zone. In the Atlantic Maritimes and Boreal Shield region, subalpine communities can include stunted Black Spruce (*Picea mariana*) mixed with heath shrubs including Sheep Laurel (*Kalmia angustifolia*), Labrador Tea (*Ledum groenlandicum*), and Alpine Blueberry (*Vaccinium uliginosum*). In the Montane Cordillera, the subalpine zone is often characterized by Lodgepole Pine (*Pinus contorta*), Engelmann Spruce (*Picea engelmannii*), and Subalpine Fir (*Abies lasiocarpa*).

Alpine ecosystems occur at the top of the mountain above the treeline (in forested regions). In the Northern Appalachians, such as the Chic-Choc Mountains on the Gaspé Peninsula in eastern Québec, dominant vegetation includes low heath shrubs such as Alpine Blueberry and arctic-alpine wildflowers including Lapland Diapensia (*Diapensia lapponica*). In the Boreal and Taiga Cordillera, such as the Selwyn Mountains along the Yukon-Northwest Territories border, alpine vegetation is characterised by of crustose lichens, mountain avens (*Dryas* spp.), and heath shrubs with sedges (*Carex* spp.) and cottongrasses (*Eriophorum* spp.) associated with wetter sites.

Mountain systems in Canada contain a high diversity of other ecosystems. For example, in the northernmost mountain ranges in Canada, the Arctic Cordillera on Ellesmere and Devon Islands, the mountains are largely ice covered, with arctic-alpine plants, mosses, and lichens in the lowlands. Many mountains such as the Richardson and Ogilvie Mountains in the Yukon have large areas characterised by barren talus slopes and steep cliffs.

Threatened mountain ecosystems

Mountain ecosystems across Canada are at risk because of industrial forestry, mining, energy development, expanding urban and second home areas, and recreation. Climate change is also resulting in increased temperatures, extreme heat, drought, and extreme winds (Pörtner et al. 2022).

There are more than 120 mountain ecosystems documented from Canada that are ranked as globally imperilled or vulnerable (Table 2.6 (*NatureServe Explorer*, 2023)). This represents almost 40% of all the threatened ecosystems that are currently documented in Canada. The International Union for the Conservation of Nature (IUCN) lists an additional seven mountain ecosystems from Canada that are now on the *IUCN Red List of Ecosystems*, including Rocky Mountain Dry Lower Montane and Foothill Forest and Rocky Mountain Subalpine and High Montane Conifer Forest (Ferrer-Paris et al., 2019). Several other ecosystems including Northern Rocky Mountain Subalpine Woodland and Parkland and Rocky Mountain Aspen Forest and Woodland are assessed as Near Threatened (Comer et al., 2022).

The number of threatened mountain ecosystems is likely higher. Many ecosystems, particularly in the north of Canada, have not been described and assigned status ranks. Threatened

Table 2.6: Examples of threatened mountain ecosystems from Canada.

Common Name	*Mountain Zone*	*NatureServe Rounded Global Rank**	*Distribution in Canada*
Sitka Spruce—Bigleaf Maple / Devil's-club—Salmonberry / False Lily-of-the-Valley Forest	Forest and Woodland	G1	BC
Limber Pine / Rough Fescue Woodland	Foothills	G3	AB
Black Cottonwood / Bluejoint Riparian Forest	Valleyland	G2	AB
Subalpine Fir—White Spruce—(Lodgepole Pine) / Splendid Feathermoss Forest	Montane	G3	AB, BC, YT
Subalpine Fir—Engelmann Spruce / Rusty Menziesia—Grouse Whortleberry Forest	Subalpine	G3	AB, BC
Limber Pine Scree Slope	Subalpine	G3	AB
Eastern Lichen Fell-field	Alpine	G3	QC
Eight-petal Mountain-avens—Alpine Bistort Alpine Dwarf-shrub Meadow	Alpine	G3	AB
Parry's Rush / Creeping Sibbaldia Alpine Snowbed	Alpine	G3	AB
Northern Appalachian Alpine Tundra	Alpine	G3	NB, QC

*NatureServe Ranks

Rank	*Definition*
G1	Critically Imperilled—At very high risk of extinction or elimination due to very restricted range, very few populations or occurrences, very steep declines, very severe threats, or other factors.
G2	Imperilled—At high risk of extinction or elimination due to restricted range, few populations or occurrences, steep declines, severe threats, or other factors.
G3	Vulnerable—At moderate risk of extinction or elimination due to a fairly restricted range, relatively few populations or occurrences, recent and widespread declines, threats, or other factors.

mountain ecosystems range from ecosystems that are restricted to small areas of Canada to ecosystems that once occurred over large areas but are threatened because of historical and continuing habitat degradation and loss.

Mountain wildlife

There are thousands of species in Canada that inhabit mountain ecosystems ranging from alpine plants such Pink Mountain-heather (*Phyllodoce empetriformis*) to iconic mammals including Mountain Caribou (*Rangifer tarandus caribou*). Some species are restricted to mountain habitats, while other species inhabit mountains seasonally or during migration. Biodiversity, in terms of the number of unique species, generally decreases with elevation and latitude. However, if land area is taken into account (i.e., there is significantly less alpine-tundra habitat compared to forest habitat, given the conical shape of mountains), then mountain biodiversity actually increases with elevation (Körner & Spehn, 2019).

Many species of mountain wildlife are restricted to specific mountain zones and ecosystems. For example, Collared Pika (*Ochotona collaris*) are only found in alpine talus slopes interspersed with small meadows in Yukon and neighbouring Alaska. However, many mammals and birds have seasonal mountain migrations or move between altitudinal zones. Dall Sheep (*Ovis dalli*) spend summers grazing in alpine meadows, move to steep cliffs to give birth, and spend winters at lower, south-facing elevations that have less snow depth. A review of mountain habitat in British Columbia found that 95 species of migratory birds used alpine, subalpine, and montane forests, 25% of which have conservation status (Boyle & Martin, 2015).

Bears are one of the most iconic mountain species, and three species of bear are found in the mountain regions of Canada. Black Bear (*Ursus americanus*) are the most common and widespread, while Polar Bear (*Ursus maritimus*) are restricted to the mountain habitats of the Arctic Cordillera and the Eastern Subarctic. Grizzly Bear (*Ursus arctos horribilis*) are perhaps the most iconic of mountain bears and have seasonal migration patterns based on food availability. Most Grizzly Bears found in southern Canada are now restricted to mountain regions that include the Pacific Maritime, Montane Cordillera, Boreal Cordillera, and Taiga Cordillera (COSEWIC, 2012).

Both grizzly bears and caribou showcase the important role of mountains as a refuge for wildlife, as their formerly large ranges have been dramatically reduced to isolated mountain regions. Other mammals that require large home ranges and have been pushed into the refugia mountain environments include Grey Wolf (*Canis lupus*), Wolverine (*Gulo gulo*), and Cougar (*Puma concolor*). As a result, the Rocky Mountains are one of the last regions in North America to have maintained intact assemblages of large mammals (Sanjayan et al., 2012).

The refugia of intact habitats that have been retained in mountain ecosystems are also important ecological corridors. The Yellowstone to Yukon corridor that winds through the Montane and Boreal Cordillera (Chester, 2015) and the Two Countries One Forest corridor that connect the Appalachians with the Atlantic Maritime and Boreal Shield mountain region (Bateson, 2005) provide important north-south corridors for wildlife. In addition to animal movements, these mountain corridors are important to help plants and ecosystems shift to changing climate (Chester & Hilty, 2019).

Threatened mountain species

Mountain regions comprise 24% of the land area of Canada (McDowell & Guo, 2021) but support approximately one-third of species assessed as at risk[2] by the Committee on the Status of Endangered Wildlife in Canada (Canada, 2018). Many of these threatened species are primarily restricted to mountain ecosystems.

Porsild's Bryum (*Haplodontium macrocarpum*) (Threatened) is a moss that is most common in western mountain ranges, preferring sites that are constantly moist during the growing season. Mountain Holly Fern (*Polystichum scopulinum*) (Threatened) grows on rock outcrops in the mountains of the Tulameen River area in southwestern

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[2] 233/705. Species at Risk Registry database. Species assessed as Extirpated, Endangered, Threatened, or Special Concern. Excluding marine mammals and marine fishes from total number. Query completed in January 2023.

CONSERVING THE ICONIC MOUNTAIN CARIBOU

While widespread, caribou are often associated with mountains (Fig. 2.26). Mountain caribou is an important subsistence and cultural species for Indigenous Peoples of the Montane Cordillera region and Indigenous-led conservation efforts are supporting recovery efforts of this iconic species (Lamb et al., 2022). In eastern Canada, the last herd of the Caribou-Atlantic-Gaspésie population can be found in the mountains of Gaspe. In the 19th century, this eastern population of caribou was distributed throughout New England and the Canadian Maritimes but is now restricted to fewer than 120 adults that inhabit mountain plateaus in the Atlantic Maritime and Boreal Shield region (COSEWIC, 2014b), and its numbers continue to decline (Webb, 2021). As Elder Pnnal Bernard Jerome, of the Micmacs of Gesgapegiag, explained: "We used to have caribou, like everybody else. But back in 1935 they started to dwindle. It's even worse now...the environment that the caribou lives on is being depleted" (LC 2.17).

Mountain caribou have adapted to the deep snow of mountains. Historically, Mountain caribou spend the winter foraging at lower elevations and move to higher elevation in the spring and summer to feed and have their calves. Recently, these migrations have been disrupted, or even abandoned, by some herds (COSEWIC, 2014a) (COSEWIC 2014b). Despite being listed under Canada's *Species at Risk Act*, Mountain caribou have continued to decline rapidly as a result of industrial forestry and energy development that has greatly reduced the amount and quality of habitat (Nagy-Reis et al., 2021; Palm et al., 2020).

Pnnal Bernard Jerome, Micmacs of Gesgapegiag, 2022, LC 2.17

Figure 2.26: Mountain caribou (*Rangifer tarandus caribou*) in the interior temperate rainforest of central British Columbia. Photo courtesy of David Moskowitz, www.davidmoskowitz.net.

British Columbia and on Mont Albert in the Gaspé Peninsula, Quebec.

Many species use mountain regions for breeding, including several populations of Sockeye Salmon (*Oncorhynchus nerka*) in British Columbia and at-risk species such as Bicknell's Thrush (*Catharus bicknelli*) (Threatened) in Quebec, Black Swift (*Cypseloides niger*) (Endangered) in Alberta, and Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*), Threatened in Alberta and of Special Concern in British Columbia. Many threatened birds and insects are found in mountain regions as part of a broader range such as Bank Swallow (*Riparia riparia*) (Threatened) and Wood Thrush (*Hylocichla mustelina*) (Threatened).

More than 100 species are restricted (endemic) to mountain regions in Canada. These comprise approximately 40% of all of the nationally endemic species that have been documented to date (Kraus et al., 2023). These include the Vancouver Island Marmot (*Marmota vancouverensis*) of the Pacific Maritime mountain region, Lake Louise Arnica (*Arnica louiseana*) in the Montane Cordillera, Mont Albert Goldenrod in the Atlantic Maritime region in Quebec, and the Ogilvie Mountains Collared Lemming (*Dicrostonyx nunatakensis*) that is restricted to the Ogilvie Mountains in north-central Yukon. Less than 10% of mountain endemic species in Canada have been assessed as secure in terms of their conservation status, and an unknown number are vital to Indigenous lifeways. For example, Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dań Nation, described the importance of caribou leaves, a species of sage (*Artemisia spp.)* used as medicine and traded across many Nations in the Pacific Maritime region, which is threatened by development of mining access infrastructure in her Traditional Territory (LC 2.18).

Gùdia Mary Jane Johnson, Lhu'ààn Mân Dań, 2022, LC 2.18

Mountain regions in Canada are hotspots of nationally endemic species as well. These include Haida Gwaii, Ogilvie Mountains, Kluane, Gaspésie, Vancouver Island, Okanagan Similkameen, Central Yukon Plateau, and sites in western mountain parks in Canada (Banff, Jasper, Waterton) (Kraus et al., 2023). Several of the hotspots coincide with glacial refugia that were likely ice-free during the Last Glacial Maximum (Fernald, 1925). The best known of these is the unglaciated region called Beringia, which extends from the Lena River in Russia east to the Mackenzie River in the Northwest Territories (Hultén, 1937) and is part of the Taiga Cordillera. This region formed a broad connection between Asia and North America during the last glaciation. Refugia have also been described from multiple sites in the northwestern Canadian Arctic Archipelago (Dyke, 2004), the west coast and islands of the Pacific Maritime region, and possibly in the Montane Cordillera (Clark et al., 1993; Marr et al., 2008).

2.7.4 *Aquatic ecosystems and biodiversity*

As with terrestrial ecosystems, diverse aquatic ecosystems are also found throughout mountain regions in Canada, and many aquatic ecosystems include species endemic to mountain environments. Mountain stream ecosystems are typically composed of fish and communities of bacteria, algae, and aquatic macroinvertebrates that grow attached to the rocks of streambeds. Water source (Sec. 2.4) is a critical determinant of aquatic biodiversity: glacier melt, snow melt, and groundwater sources form distinct environments with varying temperature, discharge, turbidity, and nutrient availability, all of which affect ecosystem complexity (Milner et al., 2017).

Rivers

Algae, along with bacteria, serve as the dominant primary producer in many mountain streams. These photosynthetic organisms form the base of mountain stream food webs and are critical to the success of higher trophic levels in environments with little other productivity. Glacial meltwater (Fig. 2.27) has a strong effect on the composition of algal communities, as few species tolerate frigid, rapid, and turbid glacial flows. These harsh conditions shape distinct communities compared to streams fed by more benign sources, like groundwater (Brahney et al., 2021; Roy et al., 2010). Low algal diversity is common in glacial streams as only few diatom specialists can tolerate the frequent stream disturbances (Gesierich & Rott, 2012). As the influence of glacial meltwater wanes and snowmelt and groundwater increasingly contribute to stream flow, chlorophytes (i.e., green algae), chrysophytes, and cyanobacteria colonise mountain streams, contributing to diverse and productive algal communities (Roy et al., 2010).

Evidence from alpine streams globally indicates that water source is also an important determinant of benthic macroinvertebrate community structure (Milner et al., 2017). Temperature is a particularly strong filter of macroinvertebrate communities in mountain streams. Only cold-water specialists, such as *Diamesa*, are typically found in frigid glacial meltwaters (Milner et al., 2001). In snow and groundwater fed streams, warmer temperatures support the colonisation of temperature sensitive stoneflies, mayflies, and caddisflies (Milner et al., 2001). Although these patterns are well documented in mountain regions around the world, studies focused on benthic macroinvertebrate communities in Canadian mountain streams are lacking, and a key knowledge gap persists as to the extent of macroinvertebrate diversity endemic to Canadian mountain streams. Two stonefly species endemic to alpine streams in Northern Montana and Wyoming, just south of the Montane Cordillera region in Canada, have recently been listed under the U.S. Endangered Species Act (Giersch et al., 2017; Muhlfeld et al., 2020). However, it is unknown whether the range of these endangered species extends into Canada.

Mountain streams provide habitat to diverse fishes across Canada. Although the steep, turbulent flows inherent to high-alpine streams impede fish colonisation, many species are found in lower elevation montane streams with gentle gradients and stable streambeds (Pitman et al., 2020). Again, cold temperatures are a key feature that enable healthy fish populations, particularly for species endemic to mountain waters. For example, the endangered Westslope Cutthroat trout (*Oncorhynchus clarkii lewisi*) of the Montane Cordillera thrive in mountain streams with specific thermal zones bookended by frigid glacial waters and mild low-elevation waters (Heinle et al., 2021). Bull trout (*Salvelinus confluentus*), whose range extends northwards from the Montane Cordillera into the Taiga Cordillera, are similarly constrained to cold-water streams (Heinle et al., 2021; Mochnacz et al., 2021). In the Atlantic Maritime region, mountain streams provide critical spawning habitat for Atlantic salmon, as Elder Pnnal Bernard Jerome, Micmacs of Gesgapegiag, shared during the Learning Circle (LC 2.19). To the west, Pacific salmon migrate up mountain streams to reproduce each fall in the Pacific Maritime (Pitman et

Figure 2.27: Glacier meltwater from the Saskatchewan Glacier in Banff National Park. Photo courtesy of Joseph Shea, 2021.

Pnnal Bernard Jerome, Micmacs of Gesgapegiag, 2022, LC 2.19

al., 2020). Pacific salmon rely on mountain glaciers to provide and maintain critical spawning habitat. Streams within previously glaciated valleys also provide salmon low-gradient streams with stable streambeds necessary for reproduction (Pitman et al., 2021). Glacial meltwater inputs also cool important salmon migratory paths, keeping stream temperatures within the thermal tolerance range of salmon (Pitman & Moore, 2021).

Lakes

Mountain lakes are diverse aquatic ecosystems with distinct benthic (bottom) and pelagic (water column) communities. In addition to algal and macroinvertebrate communities living along lake bottoms, fish, phyto- and zooplankton communities are all commonly found in mountain lakes.

Phytoplankton are primary producers that live in the water columns of mountain lakes and ponds. Like algae in mountain streams, phytoplankton form the base of mountain lake food webs and are an important source of energy for grazing macroinvertebrates and zooplankton (Mcnaught et al., 1999). Planktonic algae additionally serve as crucial sentinels of climate change in mountain lakes (Moser et al., 2019; Parker et al., 2008). Phytoplankton produce photosynthetic pigments that are readily preserved in the sediment of lake bottoms (Vinebrooke & Leavitt, 1999). As lake environments change over time, fossilised pigments record phytoplankton responses, providing a proxy for how changing climates impact mountain lake ecosystems across millennia (Karst-Riddoch et al., 2005; Vinebrooke et al., 2010). For example, novel sediment core research on alpine lakes in the Montane Cordillera identified that phytoplankton community structure rapidly shifted following the last glacial maxima (Vinebrooke et al., 2010). This sensitivity to climate change makes phytoplankton a useful tool for further studying climate change in mountain environments. Similarly, phytoplankton are useful bioindicators of more local lake processes, like fish stocking, catchment glacier loss, and nutrient deposition (Moser et al., 2019; Parker et al., 2008).

Zooplankton, a group of animal plankton, also contribute to the biodiversity of mountain lakes. These plankton feed on phytoplankton and serve as important food sources themselves for alpine fishes. This integration of top-down and bottom-up food web dynamics make zooplankton a strong target against which to measure environmental change. Many studies use zooplankton as biomonitors to measure the ecological effects of historic non-native fish stocking (Donald et al., 2001; Redmond et al., 2018) and eradication (Beaulieu et al., 2021; Parker et al., 2001; Parker & Schindler, 2006) in alpine lakes in the Montane Cordillera. Zooplankton are also used as a model group to study how climate (Loewen et al., 2019; Strecker et al., 2004), geography (Loewen et al., 2019; Strecker et al., 2004) and water quality (Swadling et al., 2000) impact mountain lake ecosystems.

Little is known about the extent of phyto- and zooplankton diversity across mountain regions in Canada. Although regional surveys in western Canada have contributed knowledge to zooplankton diversity in the Pacific Maritime (Loewen et al., 2019; Strecker et al., 2004) and Montane Cordillera regions (Anderson, 1974; Loewen et al., 2019), this group remains understudied in most other mountain regions in Canada. Phytoplankton diversity is similarly poorly studied. Given the importance of these planktonic groups in alpine lake food webs and their sensitivity to environmental change, there is an urgent need to further monitor phyto- and zooplankton throughout Canada as mountain ecosystems continue to change.

2.7.5 *Gaps and challenges*

Regarding mountain environments, knowledge co-creation has been best developed with respect to mountain biodiversity and conservation. Recent examples include grizzly bear monitoring and conservation by the Heiltsuk First Nation, mountain goat monitoring by the Kitasoo Xai'xais First Nation in the Pacific Maritime (Housty et al., 2014; Jessen et al., 2022), and mountain caribou conservation by the West Moberly First Nations and Saulteau First Nations in the Montane Cordillera (Lamb et al., 2022). Paleoecological studies are largely absent from our assessment and represent a significant gap in our understanding of mountain ecosystems. Another significant exclusion were the detailed fire histories that exist for some sites in some mountain regions, though a compilation of paleoecological and fire history data as a knowledge co-generation project would be an invaluable contribution. One of the most significant gaps when preparing this section was the lack of species-specific and mountain species data, especially in the biodiversity section. Many biodiversity studies are limited spatially and thus hard to extrapolate across entire mountain regions. These same studies are also often taxa specific. Another interesting area of inquiry that is not presented in this section is the ‘sky island’ hypothesis (McCormack et al., 2009) that considers high elevation areas in terms of their relative isolation to other sky islands and could be explored to answer questions around endemic species and speciation more broadly. There was little information found on sky islands in the Canadian context.

2.8 Connections between Mountains and Lowland/Coastal Environments

Mountains shape the way that air moves and water flows, and in turn, how and whether animals (including humans) and plants disperse across their slopes. Connections between mountains and lowland/coastal environments are therefore omnipresent and fundamental to the health and wellbeing of people and ecosystems across Canada. Elder Patricia Joe, Kwanlin Dün First Nation, spoke to this connection during the CMA Learning Circle gathering: “We would not be river people if it wasn’t for the mountain people. It’s the mountains that make the river” (LC 2.20).

Patricia Joe, Kwanlin Dün First Nation, 2022, LC 2.20

While alpine valley communities immediately recognize the role that mountains play in their day-to-day life, the role of mountains in affecting people and places can extend hundreds to thousands of kilometres downstream, where their importance may be more often overlooked (see Chapter 4).

At a basic level, highland-lowland connections occur in two directions: 1) air masses that originate and organisms that move from marine and other lowland areas, transporting water, nutrients and contaminants to the mountains; and 2) fluxes of air, water and materials from the mountains to lakes, rivers, and coastal waters downstream. Upstream movements and fluxes are closely coupled with those downstream and in many cases operate as a cycle, such that changes in the larger earth system (e.g., oceanic changes) have implications for the mountains and the ecosystems that depend on them.

The nature and strength of the connections between mountain and lowland environments may differ substantially over time and space, driven by local combinations of weather, climate, hydrology, and biology. For example, along the Pacific coast, connectivity is simultaneously defined by annual cycles in rainfall, snow, and/or glacial melt that determine river hydrology (Moore, 1992), the atmospheric transport of pollutants to high mountain regions (Blais et al., 1998), and subsequent chemical export downstream to networks of lakes and rivers (Milner et al., 2017), as well as the migration of anadromous fish species out to their oceanic feeding grounds and their ultimate return to freshwaters to spawn. In inland mountain regions, connections are largely defined by annual cycles of snow and ice melt that control river/lake hydrology. This is also true in the Arctic, but with the additional influence of the transition between polar day and night that affects biological production and atmospheric deposition of compounds from distant locales (Law & Stohl, 2007). Along the Atlantic coast, the snowmelt season is a primary driver of river hydrology (Sec. 2.5), whereas local weather, sea ice formation, and oceanography impact fog formation and atmospheric deposition at higher elevations. In coastal mountain regions, one additional factor to consider is that the impact of alpine exports on receiving marine environments also depends on largely seasonal oceanographic processes like upwelling/downwelling and sea ice formation/melt.

Connections between mountain and lowland environments are implicit throughout this chapter (e.g., Chinook and gap/outflow winds in Sec. 2.3; river and stream flow in Sec. 2.5) and elsewhere in the assessment. The idea of connection between mountain and lowland environments is, however, rarely considered explicitly in the peer-reviewed literature. In this section, we therefore highlight major themes that allude to the impact that broader earth system processes have on mountain environments and the role of mountains in structuring downstream ecosystems. Oftentimes, these themes reflect regional interests and concerns, rather than processes common to all—or even multiple—mountain regions in Canada.

2.8.1 *Upstream movements of air, water, materials, and organisms*

Long range transport and atmospheric deposition

Orographic processes are crucial in both generating and intercepting air masses. Along with water, these air masses are also responsible for the long-range transport and subsequent deposition of nutrients, metals and organic contaminants to alpine forests (Evans & Hutchinson, 1996; Lin et al., 1997), snow (Blais et al., 1998) and ice (Beal et al., 2015). Air masses transport metals and contaminants released by both natural and anthropogenic (industrial activities, metropolitan areas) processes over long distances before these compounds are deposited at high elevations, where cold temperatures and precipitation can favour deposition. For example, the deposition of persistent organochlorine compounds to western Canadian snowpacks increases 10- to 100-fold between 770 and 3100 metres above sea level (m.a.s.l.) due to colder temperatures that prevent re-volatilization (Blais et al., 1998). In the Arctic, the annual transition from 24-h daylight to 24-h darkness can also promote the deposition of light sensitive compounds, like mercury, to snow and ice in alpine environments (Environment and Climate Change Canada, 2016). In the Atlantic Maritime and Boreal Shield regions, particular attention has been paid to the role of fog in transporting metals and hydrogen ions (responsible for acidification) to the mountains (Schemenauer, 1986; Schemenauer et al., 1995).

Anadromous fish migration

The annual migration of anadromous fish species from the ocean to upland environments to spawn represent crucial events for mountain ecosystems. This is especially true in the Pacific Maritime and Boreal Cordillera regions, where the annual return of Pacific salmon species (*Oncorhynchus* sp.) from oceanic feeding areas to their natal streams is of immense cultural and ecological significance (Chapter 4). As spawning fish die, their remains decompose, acting as an important source of marine-derived nutrients to both freshwater and terrestrial mountain headwater ecosystems (Gende et al., 2002). Salmon-derived nutrients permeate the soils, insects, trees, influencing terrestrial and freshwater food webs of the coastal temperate rainforest (Gende et al., 2002; Reimchen et al., 2003). Bears, in particular, play a critical role in facilitating the "salmon resource wave," transferring 50% or more of spawning salmon to streamside areas (Levi et al., 2020). The resource wave is associated with changes in riparian plant community composition and diversity (Hocking & Reynolds, 2011), increases in bird abundance and diversity near salmon-bearing streams (Wagner & Reynolds, 2019) and strongly influences bears' abilities to build fat stores for the winter months (Levi et al., 2020). Changing water temperatures and levels, combined with dam construction and other forms of intensive human activities (e.g., commercial fishing), are devastating Pacific salmon populations along the Pacific coastline with biological, social and cultural ramifications for the communities (human, trees, bears) that depend on them, as Brandy Mayes, Kwanlin Dün First Nation, described during the CMA Learning Circle gathering (LC 2.21).

Brandy Mayes, Kwanlin Dün First Nation, 2022, LC 2.21

Figure 2.28: Sun-dried eulachon, Fishery Bay, Nisga'a Nation. Photo courtesy of Brodie Guy, www.brodieguy.com, 2018.

While the resource wave associated with Pacific salmon species is well understood, Western academic literature lacks knowledge in the role that other anadromous fish species play in the coastal mountain regions of Canada. The annual migration of eulachon (*Thaleichthys pacificus,* Fig. 2.28) to the lower reaches of mountain rivers and streams along the Pacific coast is of huge cultural significance (Moody, 2008). Early spring eulachon runs historically provided humans and other animals with a high fat food source when food was otherwise scarce (Moody, 2008). In recent decades, eulachon populations have declined significantly and become extirpated in some streams and rivers. Although the exact reasons for these declines are unknown, climate change, fisheries practices and bycatch, forestry, and pollution may all have played a role (COSEWIC, 2013; Moody, 2008).

In parts of the Columbia River basin, the migration of American shad (*Alosa sapidissima*) may also represent an increasingly important source of marine-derived nutrients as salmon populations decline (Haskell, 2018). In the Atlantic Maritime and Boreal Shield region, the role of marine-derived nutrients and contaminants in mountain systems is less well known, though recent studies from non-mountainous areas of New Brunswick and Prince Edward Island have demonstrated food web incorporation of marine-derived nutrients from both rainbow smelt (*Osmerus mordax*; Landsman et al., 2018) and Atlantic salmon (*Salmo salar*; Bryson et al., 2022). In the Arctic, the migration of arctic char (*Salvelinus alpinus*) may have a more subtle effect on freshwater food webs, and specific nutrient subsidies were undetectable in the study lakes (Swanson et al., 2010). Additional work is needed to fully resolve the complexity of these subsidies for mountain ecosystems, especially for non-Pacific salmon species and areas outside of the Pacific Maritime and Boreal Cordillera regions.

2.8.2 *Downstream movements of air, water, materials, and organisms*

Downstream impacts of glacial meltwaters

The impacts of glacial meltwaters on downstream ecosystems and communities are growing areas of study in Canadian mountain systems, given the changes that have already occurred and are predicted to occur in glacierized systems. Many western Canadian communities rely on glacier-fed systems as drinking water and irrigation sources and are highly vulnerable to the impacts of glacial retreat on water supply (Anderson & Radić, 2020; Schindler & Donahue, 2006). In some cases, glacial retreat is associated with the complete hydrological reorganisation of mountain watersheds with important implications for downstream ecosystems. The 2016 redirection of ‘A’ą̈y Chù’ (Slims River) away from Lhù’ààn Mân’ (Kluane Lake) following the retreat of the Kaskawulsh Glacier is one such example. As the primary inflow to the lake, the redirection of ‘A’ą̈y Chù’ towards the Alsek River significantly lowered lake water levels (Shugar et al., 2017) with potential implications for temperature and productivity in the southern basin of the lake (McKnight et al., 2021).

As repositories for atmospherically deposited nutrients and contaminants, glacial meltwater fluxes also have potentially important implications for the health and function of downstream aquatic ecosystems. Between 2007 and 2012, a 1°C increase in temperature resulted in a ~10-fold increase in the delivery of glacial meltwater from the Northern Ellesmere Icefield (Grant Land Mountains) to Lake Hazen in the Arctic Cordillera (Lehnherr et al., 2018). Changes in the glacial headwaters were associated with changes in lake turnover, increasing fluxes of mercury (St. Pierre et al., 2019), organic contaminants to the lake (MacInnis et al., 2022; Sun et al., 2020), and enhanced carbon dioxide consumption by chemical weathering in the turbid meltwater-fed rivers (St. Pierre et al., 2019).

In the Montane Cordillera, glacial meltwaters have also been found to be important sources of persistent organic pollutants to alpine lakes (Blais et al., 2001; Lafreniere et al., 2006), impacting bioaccumulation in resident aquatic invertebrates (Blais et al., 2003). Differences in water quality between glacial and non-glacial streams represent important functional differences for downstream ecosystems, affecting whether freshwater ecosystems are sinks or sources of carbon dioxide from the atmosphere and the bacteria, phytoplankton, zooplankton, invertebrates, and fish that call these systems home. In more temperate mountain ranges, the complete loss of glaciers has the potential to alter water quality in downstream ecosystems, as well as impact the habitat suitability for key fish species (e.g., thermal refugia important for such cold-water species as Pacific salmon (Pitman et al., 2020).

Downstream impacts of permafrost thaw

Northern mountain regions like the Taiga Cordillera, and Interior Hills North and West, are increasingly being impacted by permafrost thaw. Hillslope thermokarst processes like retrogressive thaw slumps have the ability to rapidly move large amounts of materials previously immobilised in frozen soils to downstream ecosystems. For example, over 100 million tons of sediment is deposited in the Mackenzie Delta, NWT, yearly (Carson et al., 1998). These materials make their way into waterways across the region (Keskitalo et al., 2021; Kokelj et al., 2021; Zolkos & Tank, 2020) and act as significant barriers and hazards to human and animal travel across these mountain landscapes. According to Wanda Pascal of the Teetl’it Gwich’in Nation (a CMA Learning Circle participant), “[Everything is] going to be affected one way or another because we’re downstream” (LC 2.22).

At least initially, thaw slumps tend to increase the concentrations of particle-bound organic

Wanda Pascal, Teetl’it Gwich’in, 2022, LC 2.22 carbon (Keskitalo et al., 2021; Shakil et al., 2020) and mercury (St. Pierre et al., 2018), which can persist through stream and river networks over tens of kilometres. The cumulative impacts of these headwater dynamics have important consequences for large river systems like the Mackenzie River, where increases in the flux of both dissolved inorganic and organic carbon since the 1970s are consistent with permafrost thaw dynamics across its watershed (Tank et al., 2016). The effects of these mountain/hillslope processes are then exported to nearshore environments in the Beaufort Sea (Kokelj et al., 2021).

Landslide effects on freshwater and coastal environments

Extreme events, like landslides, can completely alter the connections between the mountains and downstream ecosystems. In some cases, the impacts of these events may be short-lived (weeks to months), whereas other impacts may last much longer (years to decades or longer). In November 2020, ~13.3 million m^3 of rock fell into proglacial Elliot Lake in the Cascade Mountains of the British Columbia coast (Geertsema et al., 2022). The resultant outburst flood and tsunami cascaded through Elliot Creek and the Southgate River, destroying key salmon spawning habitats and generating a turbidity current more than 60 km downstream in Bute Inlet. The turbidity current increased deep-water turbidity in the fjord by 200%, reduced salinity and reversed 70-year trends of warming waters and oxygen loss at depth (Geertsema et al., 2022). Although climate change may have contributed to the Elliot Creek event, landslides have been a feature of coastal mountain environments on both the Pacific and Atlantic coasts of Canada since time immemorial. In 1663, a large earthquake triggered the collapse of the Saguenay Fjord basin, widespread landslides, the damming of the Saguenay River, and a turbidity current in the fjord that lasted 28 days as the river eroded landslide debris (Syvitski & Schafer, 1996). While turbidity currents may be relatively short-lived effects of these events, they can efficiently transport and bury large quantities of organic matter from mountain landscapes, effectively augmenting the role of fjords as global carbon sinks over long periods of time (Hage et al., 2020, 2022).

Biological communities impacted by these events can take much longer to recover. Such events can destroy fish spawning and rearing habitat and act as a barrier to fish reaching their spawning grounds. In 2018, the Big Bar Landslide along the Fraser River in the British Columbia Interior effectively prevented the passage of threatened Pacific salmon stocks to their spawning grounds. Extensive interventions, in close collaboration between local First Nations and the federal and provincial governments, including transport of salmon past the slide site, have been undertaken to secure salmon recovery to the upper reaches of the Fraser River.

Impacts of mountains on oceanic circulation

The impacts of mountain systems on ocean environments, though, are much broader than turbidity currents in fjords. Along the Pacific coast, high rainfall, deep snowpacks, and glacial meltwaters from the region's mountains result in consistently large, but seasonally variable freshwater fluxes to the northeast Pacific Ocean. Large freshwater fluxes to the coastal Pacific Ocean are also responsible for the formation of eddies that transport land-derived nutrients and iron to the ocean interior (Cullen et al., 2009; Ladd et al., 2009). The cumulative impact of these freshwater fluxes is sufficient to generate a contiguous boundary current that moves clockwise around northern North America (Carmack et al., 2015). The boundary current, coined the "riverine coastal domain," is perpetuated through the Arctic by freshwater inflows like the Mackenzie River and the annual sea ice cycle (Carmack et al., 2016). Freshwater sources in the Arctic, some of which originate in the Taiga Cordillera, Interior Hills North, Arctic Cordillera, and neighbouring Greenlandic mountain regions, are detectable within the Labrador Current, which is a major driver of oceanic circulation and climate across the Atlantic (Khatiwala et al., 1999). Exports from the Atlantic Maritime and Boreal Shield regions contribute water and materials to the St. Lawrence River and some smaller rivers that discharge to the St. Lawrence Estuary. These riverine inputs affect stratification and circulation in the estuary, ultimately influencing the estuary's connections to the Gulf of St. Lawrence and the Atlantic Ocean (Khatiwala et al., 1999).

2.8.3 *Gaps and challenges*

Geographic coverage and regional interests

Mountain systems in Canada and the environments to which they are connected inevitably are incredibly diverse. The available scientific literature therefore often reflects specific regional interests, like the role of fog in the Atlantic Maritime region or the role of permafrost thaw in the mobilisation of carbon in the Interior Hills North and West regions. Arguably, the most well understood of the regions with regard to connections is the Pacific Maritime, where the cultural, ecological and economic importance of anadromous fish species has expediated our still evolving understanding of highland/lowland connections. While highland/lowland connections in most other regions (e.g., Arctic Cordillera, Taiga Cordillera, Boreal Cordillera) are less well understood—or described scientifically—than the Pacific Maritime, there was a near complete paucity of peer-reviewed literature on connectivity from the Interior Hills Central and Eastern Subarctic regions, which warrants immediate attention.

A prime opportunity for transdisciplinarity

In all respects, Western science lags behind Indigenous knowledge systems when it comes to recognizing and understanding the importance of the connections between highland and lowland areas. Elder Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dán, describes the importance of viewing these systems as interconnected: "We can't just think of mountain environments as being singular. We need to think of it as a whole. When we're thinking of one mountain, it doesn't mean that we isolate that one mountain, we're thinking of what is happening on that whole mountain area" (LC 2.23).

Gùdia Mary Jane Johnson, Lhu'ààn Mân Ku Dán, 2022, LC 2.23

Table 2.7: Examples of topics not comprehensively assessed in this chapter

Findings from other biodivesity assessments
Indigenous knowledges of mountain geology, meteorology, hydrology, and ecology
Snow avalanches
Alpine lake and river ice
Spatial variability of mountain snowpacks
Mountain paleoenvironments
Hydrogeology of mountain regions
Advances in high-resolution modelling of mountain weather and hydrology
Mountain wildfire causes and impacts

To better understand and appreciate the reciprocal connections between mountain and low-lying and coastal environments requires holistic thinking and transdisciplinary approaches—the meaningful engagement with different scientific disciplines and ways of knowing, bridging atmospheric sciences, geomorphology, freshwater and marine sciences, and ecology with Indigenous knowledge systems.

2.9 Conclusions

Mountain regions in Canada may occupy a small area, but they fill many critical roles: as archives of the geological history that has shaped the landscape (Sec. 2.2); as weather generators and influencers (Sec. 2.3); as hosts for glaciers and snowpacks (Sec. 2.4); as sources of streamflow (Sec. 2.5); as dynamic terrain that presents numerous hazards (Sec. 2.6); as homes for complex ecosystems and endangered species (Sec. 2.7), and as corridors for migration and travel, both upstream and downstream (Sec. 2.8). Our assessment is not exhaustive (Table 2.7). Rather, it attempts to cover a broad range of subjects related to Mountain Environments, to provide examples from both Indigenous knowledges and scientific expertise, and to identify where gaps in knowledge and challenges in understanding mountain environments exist. The gaps and challenges are many.

First and foremost, we cannot speak for the Indigenous groups that have not shared or cannot share their knowledge of mountain environments. This is apparent in the imbalance between scientific literature and Indigenous viewpoints throughout the chapter. Western science has, for many years, worked to understand different aspects of mountain environments in isolation, without consideration of more holistic approaches. Co-generation of knowledge, let alone proper consultation with local Indigenous leaders and communities, is absent from most mountain research projects (Wong et al., 2020).

It is easy to say that "more research is needed," but it might be more useful to say that "better research is needed." Future research should aim to address issues and subjects that are of direct relevance to communities within and downstream of the mountains, and should work across disciplines, rather than within. For example, the impacts of climate change on glaciers and snowpacks, combined with models of hydrology and streamflow chemistry, could be used to bracket future changes in stream properties (e.g., flow, temperature, chemistry) with direct linkages to ecosystem function. Improved observational networks—for weather, streamflow, water quality, ecosystem health—are a common thread. Remote sensing, modelling, and machine-learning methods offer the possibility to fill knowledge gaps within remote mountain regions, but these rarely capture the true complexity of physical and biological systems in the mountains, and data are essential to train and test these methods. Current scientific methods also fail to capture holistic viewpoints and the animate characteristics of mountain environments, which is why co-generation of knowledge will be critical for future research examining mountain environments in Canada.

Glossary

Ablation: Processes that remove mass from a glacier, such as melt, sublimation, and calving.

Active margin: Active transition zone between continental and oceanic tectonic plates.

Albedo: The amount of light reflected by a surface; affects the amount of solar energy absorbed by the surface.

Asthenosphere: A high pressure and high temperature layer of the mantle that lies directly below the lithosphere.

Atmospheric deposition: Process whereby precipitation, aerosols, and pollutants are moved from the atmosphere to the surface.

Atmospheric river: A narrow band of warm and moist air that can extend from the tropics to sub-polar regions.

Baseflow: Portion of streamflow that is sustained between precipitation or snow/ice melt inputs to a river system.

Benthic: Ecological region associated with the bottom of a water body.

Chinook: A term commonly referring to warm dry winds blowing east out of the Rockies in southern Alberta during the winter months; they exist due to the physical environment of the area and as such are not limited to a particular time of year, although their impact is most pronounced when it is cold. Similar winds exist in other parts of the world, including the Puget Sound area of Washington State, which is the Traditional Territory of the Chinook Nation.

Craton: A stable and relatively unchanging portion the Earth's crust that forms the core of continents.

Cryosphere: Components of the Earth's climate system that are frozen: snow, glaciers, ice sheets, permafrost, sea ice.

Debris flows: Masses of water, soil, and fragmented rock that move rapidly down hillslopes and channels.

Endemic: A plant or animal species that is restricted to a certain area.

Evapotranspiration: Loss of water from a surface through evaporation and plant transpiration.

Glacial refugia: Areas that remained ice-free during the Last Glacial Maximum, and permitted the survival of flora and fauna for post-glacial succession.

Glacier mass balance: The change in mass of a glacier over a given time period; a positive balance means the glacier is gaining mass, while a negative balance means the glacier is losing mass. Often used to discuss glacier health.

Hydrograph: A graph of water flow (e.g., cubic metres per second) past a specific point over time.

Hydrological regimes: Seasonal distribution of flow over time in a river system. The main flow regimes in mountain environments include snow-dominated (*nival*), rain dominated (*pluvial*), glacier-dominated (*glacial*), and hybrid systems.

Inversion: An atmospheric condition in which temperatures increase with altitude above the surface; common in winter and in mountain valleys.

Last Glacial Maximum (LGM): Most recent period of continental scale glaciation, which peaked approximately 24,000 years before present.

Lapse rate: The rate of temperature change with increasing altitude (often expressed as a positive, though temperatures generally decrease with increasing altitude). Lapse rates are sometimes applied to other meteorological variables as well, e.g., changes in precipitation with altitude.

Lithosphere: The solid outer part of the Earth, composed of brittle continental and oceanic crust and the upper part of the mantle.

Manitou Asinîy: Also known as the Manitou Stone or Iron Creek Meteorite. This 145 kg iron meteorite was originally located near Straw Mountain, AB, and was part of a religious complex including the Viking Ribstones. It was stolen by Methodist missionary George McDougall in 1866 in an attempt to attract people to his mission at Pakan and is currently at the Royal Alberta Museum.

Orographic precipitation: Precipitation that occurs when moist air masses encounter hills and mountains and are forced to rise, causing cooling, condensation, and precipitation.

Orogen: Elongated regions of deformation that border *cratons*; product of mountain building (*orogeny*) that occurs in convergence zones along continental margins.

Passive margin: Inactive transition between continental and oceanic tectonic plates.

Pelagic: Ecological region associated with the water column.

Permafrost: Ground that is permanently frozen (less than 0°C).

Sublimation: Phase change of water from solid to gas, or gas to solid.

Turbidity: A measure of the clarity of a waterbody. High turbidity streams carry higher concentrations of suspended sediment.

Viking Ribstones: Located south of Philips, AB, in Beaver County, the "ribstones" are three quartzite bounders carved to look like stylized bison. Part of the same religious complex as Manitou Asinîy, the two largest stones remain in place and now form the centre of an Alberta Historic Place.

Wetlands: A distinct ecosystem characterised by a water table that is at or near the surface.

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