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Climbing through Climate Change in the Canadian Rockies: Guides' Experiences of Route Transformation on Mt. Athabasca

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Abstract: Mountain guides play an important role in the provision of nature-based tourism activities, such as mountaineering, in alpine environments around the world. However, these locales are uniquely sensitive to climate change, and despite extensive documentation of bio-geophysical changes, there are few studies evaluating the impacts of these changes on mountaineering routes and the livelihood of mountain guides. This constrains adaptation planning and limits awareness of potential loss and damage in the mountain tourism sector. In response, our study explored mountain guides' lived experiences of working on Mt. Athabasca in Jasper National Park, Canada, to reveal the effects of climate change on mountaineering routes and implications for the mountain guiding community. To do this, we used a mixed methods approach that combined spatio-temporal trend analysis, repeat photography, and semi-structured interviews with mountain guides. We found that rising temperatures and changing precipitation regimes in the Mt. Athabasca area are driving glacial retreat and loss of semi-permanent snow and ice, which is impacting climbing conditions and objective hazards on mountaineering and guiding routes. Guides' experiences of these changes varied according to socio-economic conditions (e.g., financial security, livelihood flexibility), with late-career guides tending to experience loss of guiding opportunities and early-career guides facing increased pressure to provide services in more challenging conditions. Our findings offer novel insights that identify salient issues and bolster support for actions in response to the concerns of the mountain guide community. This study also underscores the need for further research, as the underlying issues are likely present in mountaineering destinations globally.

Keywords: climatic change; guiding; mountaineering; nature-based tourism; adaptation; risk management; Rocky Mountains; cryosphere; Canada

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1. Introduction

Nature-based tourism (NBT) is a form of tourism in which travelers are attracted to a specific destination because of that environment's natural and often unique features (e.g., wildlife, mountains, glaciers) [1]. A subset of NBT is mountain tourism, an 'activity that takes place in a defined geographical space, such as hills or mountains, with distinctive characteristics and attributes inherent to the landscape, topography, climate, biodiversity and local community' [2]. Globally, this industry comprises ~16% of tourism activities [3] and includes outdoor leisure and sports activities centered on mountain landscapes and ecosystems, such as hiking, skiing, and mountaineering.

Mountaineering, an NBT activity [4,5], is a sport that involves ascending and navigating mountains and steep, rugged terrain via rock climbing, ice climbing, and snow and glacier travel [6]. Mountain guides are key service providers in the mountaineering tourism industry. As highly trained and experienced mountain professionals certified by national or international guiding associations, they facilitate safe and rewarding NBT activities in mountain areas [7]. Their livelihoods and safety, and that of their guests, are highly dependent on the unique conditions of mountain areas, which often include features such as snow, ice, and high-relief terrain. However, these same features make mountains uniquely sensitive to climate change. Indeed, mountain regions are among the most climate-impacted environments globally [8], warming at an accelerated rate relative to their lower elevation counterparts [9]. The impact of this rapid warming is acutely felt in the mountain cryosphere, where glaciers are receding [10], extensive regions of permafrost are thawing [11], and snow depth, extent, and duration are decreasing [10]. Such changes have dramatically effected mountain guides, their guests, and mountain communities involved in NBT activities [12–14]. For example, mountaineering has become more physically and technically challenging due to increased slope gradients on snow/ice and glacier routes [15–17] and changes in glacier forefields and surface morphology (e.g., changes in crevasses and bergschrunds, destabilization of moraine slopes) [17,18]. Hazards associated with mountaineering have also increased. Increases in rockfall frequency and magnitude have been observed in relation to glacier retreat and permafrost thaw [18–22], and permafrost degradation has contributed to the destabilization of alpine infrastructure throughout the European Alps [23,24], New Zealand [25,26], and the Canadian Rockies [27]. These changes have shortened the window for when good climbing conditions can be found due to the absence of snow and ice [16,22,28] and increased the frequency of summer rockfall events [20], at times to the extent that routes are no longer climbable in summer months [15,29].

Despite extensive documentation of the physical changes in the mountain cryosphere as well as expected trajectories of climate change in mountain areas, research examining how the degradation of the mountain cryosphere is affecting mountaineering routes and mountain guides' experiences of this change remains limited in Canada [13]. The paucity of such research limits our ability to understand mountain guides' lived experiences of cryospheric changes and the influencing socio-economic conditions, constrains adaptation planning, and stymies awareness of potential loss and damage (L&D) in the mountain tourism sector. In response, this study examined the effects of climate change on commonly guided mountaineering routes on Mt. Athabasca in Jasper National Park, as well as the individual experiences of mountain guides working in this region of the Canadian Rockies.

Our analysis is informed by a contextual vulnerability approach [30], wherein vulnerability (i.e., susceptibility to harm) is conceptualized as a function of exposure, sensitivity, and adaptive capacity [31]. Exposure refers to the nature of climate-related stresses, while sensitivity refers to whether such stresses are relevant for those that are exposed to climate-related changes, including mountain guides [32]. Adaptive capacity refers to the ability to respond to exposure sensitivity in a way that moderates harm or exploits new opportunities [32]. Because the conditions that affect sensitivity and adaptive capacity are largely social (i.e., the nature of dependence on the environment, access to economic resources, professional training, risk aversion/acceptance), this framing calls attention to the importance of examining both social and climatic conditions when endeavouring to understand lived experiences of climate change [33]. Given the importance of physical and social conditions to our analysis, we developed a mixed methodology combining spatio-temporal trend analysis of climatological data, repeat photography, and semi-structured interviews with mountain guides, as described below.

2. Study Area

This study focused on the implications of climate change for mountaineering and guiding activities on Mt. Athabasca (3491 m a.s.l., 52.1800° N, 117.1950° W) in Jasper National Park (Alberta) of the Canadian Rockies. Located on the eastern edge of the Columbia Icefield, Mt. Athabasca was first climbed in 1898 by Norman Collie and Herman Woolley. This feat, enabled in part due to the completion of the Canadian Pacific Railway (1885), brought thousands of visitors, including mountaineers, to the Canadian Rockies for the first time [34]. To these early mountaineers, western Canada represented boundless opportunity and the subsequent influx of climbers saw the establishment of many new mountaineering routes in the area. However, in the late 19th century, access north towards the icefields and Mt. Athabasca was still a considerable challenge. This changed in the early 1940′s when the 'Wonder Trail', a 230 km path linking Lake Louise (south) to Jasper (north), was transformed into a single lane road known as the Icefields Highway [35]. Access was further improved in 1961 with the completion of the Icefields Parkway (ibid.), a two-lane highway that provides unparalleled access to mountains along the spine of the southern Canadian Rockies, including Mt. Athabasca. Today, Mt. Athabasca is one of the most summitted 11, 000-foot peaks in the range and is considered to be 'the bread and butter' of Canadian Rockies mountain guiding. Herein, we focus on the peak's main climbing routes, including the Ramp, Silverhorn, North Face, North Face Bypass, Hourglass, and Athabasca–Andromeda (AA) Col (Figure 1).

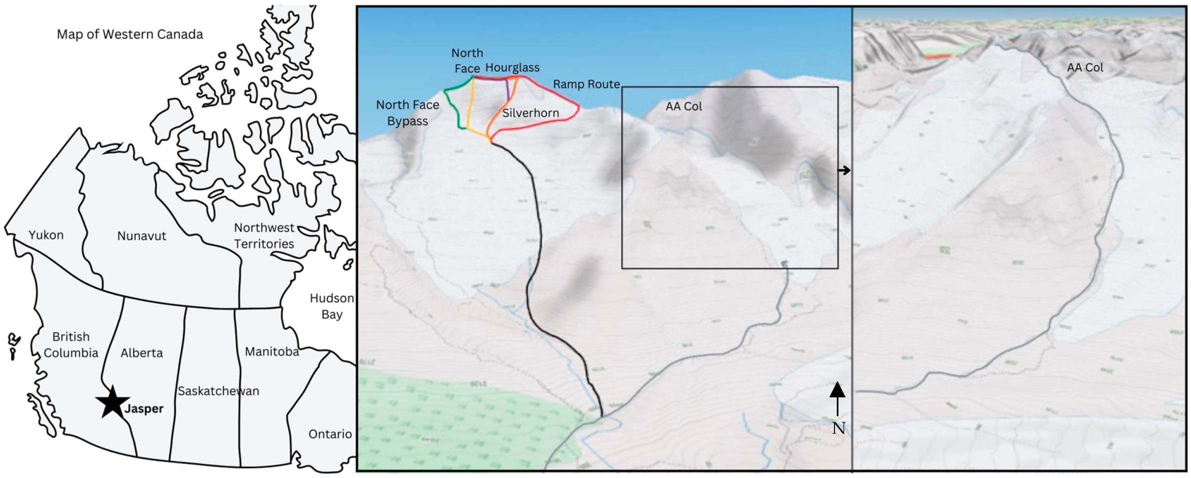

Figure 1. Map of the Columbia Icefields, Mt. Athabasca, and popular climbing routes.

To access mountaineering routes on Mt. Athabasca, climbers use either the North Glacier approach or the AA-Col, both of which start on a snowcoach road used to access the Athabasca Glacier for commercial tours. The North Glacier approach involves a 2 km walk up the road before ascending a trail to a large lateral moraine, which is then followed to an elevation of ~2600 m. Here, climbers access the North Glacier and begin a leftward traverse towards the base of climbing routes starting along the north face. The AA Col approach involves a 3 km walk down the snowcoach road, followed by a trail that ascends a moraine as it traverses towards Mt. Andromeda, eventually arriving at the amphitheater between Mt. Athabasca and Mt. Andromeda. The North Glacier route leads to five different mountaineering routes on Mt. Athabasca (the Ramp, Silverhorn, North Face, North Face Bypass, Hourglass) and the AA-Col approach leads to the AA-Col climbing route. These routes, summarized in Table 1, range from simple (e.g., the Ramp, AA-Col) to technically challenging (e.g., the Hourglass), require ~1500 m elevation gain, and involve travel on moraines, glaciated terrain, snow, ice, and rock. The grades assigned to climbing routes on Mt. Athabasca vary according to the source and throughout time. The grades presented here are from the *Rockies West* (Volume 3) guide book written by David Jones [36].

The guides that work on Mt. Athabasca reside primarily in the towns of Canmore, Banff, and Jasper, which are international guiding hot spots largely due to the access they provide to the iconic Canadian Rockies. The Canadian Rockies are widely considered to be "one of the finest ranges on earth, with unique possibilities for excitement in all aspects of mountaineering" [37]. Steep north faces and impressive alpine ridgelines give rise to abundant, world-class snow and ice climbs that have attracted mountaineers and mountain guides to these 'gateway' communities for over 100 years [38]. As a result, mountain culture and the importance of mountaineering permeates the communities of Canmore, Banff, and Jasper. Canmore is home to the head offices of the Alpine Club of Canada (ACC), established in 1906, which has been at the forefront of establishing Canada as a world-class mountaineering destination. Reflecting this, one of the oldest guiding outfits in Canada and now a premier guiding service, Yamnuska, was founded in Canmore and continues to operate out of the town today. Canadian Mountain Holidays (CMH), the first and largest heli-skiing operation in the world, which has expanded to hiking, mountaineering, and via ferrata, is based in Banff. Jasper, home to numerous guiding operations (e.g., Rockaboo), is basecamp for expeditions on Mt. Robson, the tallest peak in the Canadian Rockies. The effect of mountain guiding and mountaineering on the towns of Canmore, Banff, and Jasper continues to grow, representing an important component of the communities' cultural heritage and an invaluable sector of the economy.

Table 1. Grade and description of the climbing routes on Mt. Athabasca based on Rockies West [36].

Climb	Grade		Route Description
	Alpine Grade [1]	YDS [2]	
Ramp	PD	Not graded	Traverse across the North Glacier, stopping just before the base of a steep shoulder feature (the Silverhorn). From here, begin a right-trending traverse on a snow ramp, leading to a saddle that connects to the West ridge. The ridge can be followed to a false summit and onto the true summit. (3–6 h from road)
Silverhorn	AD-	Not graded	Traverse across the North Glacier, past the Ramp to the base of a steep shoulder. From here, cross the bergschrund and climb 300 m directly up the shoulder on a steep, 40° to 45°, snow and ice slope. The shoulder will give way to a false summit and a ridge which can be taken to the true summit. (4–6 h from road)
North Face	D	5.7–5.8	Traverse across the North Glacier, past the Silverhorn and into a bowl below the main face. The route begins below a noticeable weakness near the east end of the rock band on the face above. Cross the bergschrund and start directly up the face, towards the weakness. The slope will steadily steepen from 40 to 60-degrees on snow and ice. Near the top trend right, towards the crux, a steeper pitch of mixed climbing, which leads to the summit.
North Face Bypass	AD	5.5	To the left of the North Face route, cross the bergschrund and climb 6 pitches of steep snow and/or ice to the end of a flatter stretch of the North ridge. Follow the ridge for 3 pitches to the top of a steep rock step, traverse right, to and up the 'Scottish gully', connecting to the summit ridge and onto the summit.
Hourglass	D	5.7–5.8	To the right of the North Face route, follow a steep and narrow ice gully, which forms where the North Face rock band ends and hanging seracs begin, to the top of the Silverhorn. From here, take the ridge to the summit.
AA Col	PD	Not graded	From the amphitheatre, scramble up a rock step to gain the AA glacier above the icefall. Staying left, cross the bergschrund and ascend a steepening snow, ice, or scree slope to the AA Col. From the col follow the West ridge to the top of the false summit and onto the true summit.

[1] Alpine grade—a measure that integrates and summarizes multiple aspects of a route (e.g., technical difficulty, length, severity of terrain etc.) to describe the overall degree of commitment and difficulty, ranked from easiest to hardest (F, PD, AD, D, TD, ED). [2] YDS (Yosemite Decimal System)—a numerical grading system that refers to rock climbing difficulty based on the difficulty level of a routes hardest move. 5 refers to 5th class terrain, with numbers after the decimal indicating increasing levels of difficulty.

3. Methods

Methodological approaches that combine research elements from both natural and social sciences are increasingly recognized as fundamental to the study of climate change vulnerability in mountain regions [39], including in a climbing context [14,40]. In response, this study developed a mixed methodology incorporating spatio-temporal trend analysis, repeat photography, and semi-structured interviews with mountain guides.

3.1. Spatio-Temporal Trend Analysis

Spatio-temporal trend analysis was conducted to detect patterns in temperature and precipitation near Mt. Athabasca. A Mann–Kendall test was performed to identify statistically significant trends in the mean, minimum, and maximum air temperature as well as rainfall, snowfall, and total annual precipitation (cumulative measure of all forms of precipitation) between 1910 and 2022. The Theil–Sen slope method [41] was then used to quantify the magnitude of detected trends. These tests were performed annually to provide a wholistic understanding of the changes observed as well as seasonally (i.e., winter, spring, summer, and fall months) to better understand when these changes are occurring relative to the mountaineering season.

Data were obtained from Environment and Climate Change Canada from the 'Golden A' station located at 51°17′57.000″ N, 116°58′56.000″ W, at an elevation of 784.90 m. This meteorological station is approximately 98 km (straight-line distance) from Mt. Athabasca and was chosen because it is the closest meteorological monitoring station to the study area that provided a consistent dataset for the entire study period covered in the repeat photography images (1918–2022). While this station provides a good approximation of climatological trends in the area, as demonstrated in [42], it is likely subject to systematic overestimation in temperature due to its low elevation relative to the Mt. Athabasca area, which ranges from 1900 m to 3400 m. To provide greater insight into changes in the Mt. Athabasca area, the same analysis was performed for average temperature and accumulated precipitation between 1 January 2016 and 31 December 2022 on data collected from an Automatic Weather Station (AWS) located 1 km from the terminus of the Athabasca Glacier (1966 m a.s.l.). This analysis is supplementary as data collection began in the summer of 2015 and only provides a snapshot into the last 8 years in the Mt. Athabasca area.

3.2. Repeat Photography

Ground-based repeat photography refers to the practice of capturing two or more photographs from the same location, of the same scene, at different points in time [43]. This technique is an effective method for describing or quantifying ecological and geomorphological changes over time. In mountain regions, repeat photography has been employed by numerous studies evaluating glacial recession, as demonstrated in [44–50]. These studies have either repeated historical snapshots taken by explorers and mountaineers, or images captured systematically for land surveying purposes. In Canada, the Dominion Land Survey (DLS) produced the first topographic maps for the western provinces using photogrammetry and theodolite measurements [51]. The resulting legacy of ~120,000 high-resolution photographs provide an invaluable reference for assessing changes in the Canadian cordillera over the last century. The Mountain Legacy Project (MLP; https://mountainlegacy.ca/, accessed on 16 July 2023) is a multi-disciplinary research group that works with the image collection and has repeated ~10,000 images since its inception in 1998 [52].

One of the earliest existing photographs of Mt. Athabasca was captured by DLS surveyor Arthur Oliver Wheeler in the summer of 1918. Wheeler established camera stations on Wilcox Ridge above the Athabasca glacier for the Interprovincial Boundary Survey. The images from the Wilcox Ridge No. 1 station (52.2286° N, 117.2230° W) provide unobstructed views of the adjacent north face of Mt. Athabasca (Figure 2). The historical images were originally repeated by MLP researchers in August 2011. These image pairs showcase close to a century of glacial recession on Mt. Athabasca. We undertook a second repeat of the historical images in August 2023 to capture changes that had occurred in the intervening 12 years from the first repeat. Photographs were taken with a 51.4 megapixel FujiFilm GFX50s medium format digital camera with a 32–64 mm F4 zoom lens, a Novoflex panoramic head, and tripod. Gridded printouts of the historic photographs were used to determine the correct location of the original photograph and align each repeat photograph through the camera viewfinder.

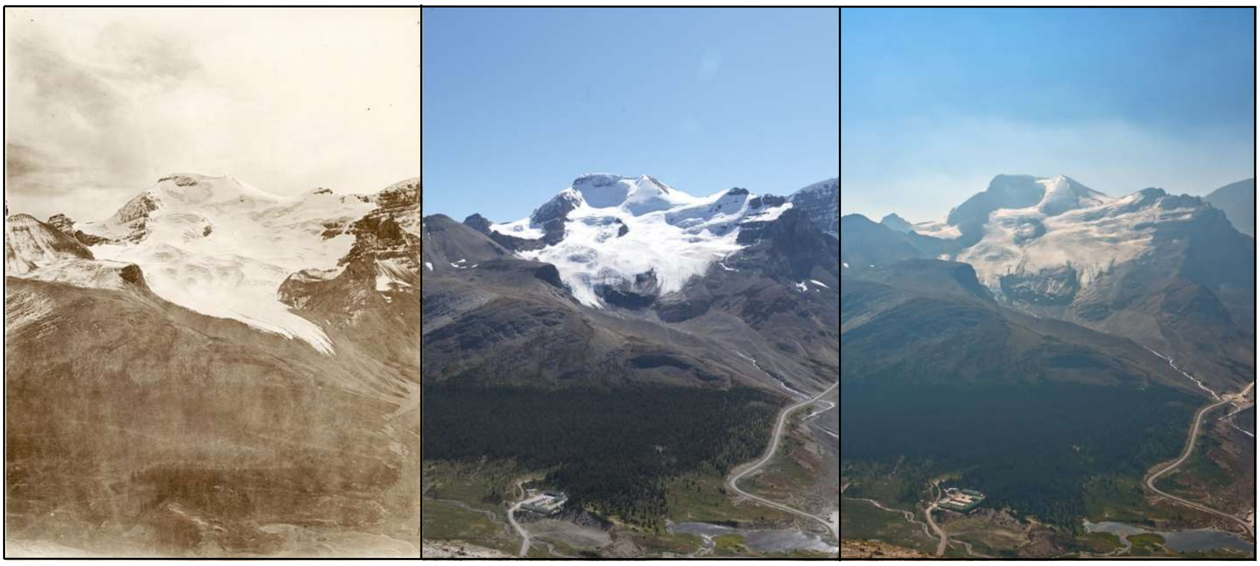

Figure 2. Triptych of historical and repeat images for Mt. Athabasca in Jasper National Park. The historical image (**left**) was captured by A.O. Wheeler as part of the Interprovincial Boundary Survey in 1918. The second image (**centre**) was captured by MLP researchers in August 2011. The third image (**right**) was captured by Katherine Hanly and James Tricker in August 2023. Historical image courtesy of Library and Archives Canada. Repeat images courtesy of the Mountain Legacy Project, University of Victoria. All images are available at https://explore.mountainlegacy.ca/ (accessed on 16 July 2023).

The quality of the new repeat image captured in 2023 was affected by smoke from nearby wildfires and poor lighting on the steeper sections of Mt. Athabasca. We edited this image in Affinity Photo to improve clarity and increase shadow lighting. All three images were aligned using the Image Analysis Toolkit developed by MLP researchers [53] and uploaded to the MLP Explorer website (https://explore.mountainlegacy.ca/stations/show/1096, (accessed on 16 July 2023)). We analyzed the historical and two repeat images in Affinity Photo by delineating the extent of the glacier for the three images. These extents were then overlayed onto the new repeat image, along with the climbing routes, as described in the study area section.

3.3. Semi-Structured Interviews with Mountain Guides

Semi-structured interviews with mountain guides were used to gain insight into the relevance and implications of climate-related changes on Mt. Athabasca for guiding activities. This methodology has proven to be particularly effective at revealing the personal experiences and perceptions of mountain guides [12,16,28]. Certified mountain guides (i.e., guides officially recognized by national or international guiding associations to possess certain qualifications) working in the Canadian Rockies were invited to participate in an interview (~45 min long) regarding climate change. A total of 30 interviews were conducted between 13 March and 11 June 2023. The sample was predominantly male (90%, $n = 27$), a gender bias that is representative of the current Canadian [54] and American [14] mountain guiding profession. The guides' average age was 50 years old and almost all (90%, $n = 27$) were fully certified guides, meaning that these individuals had completed all required training and examination courses to receive a mountain guiding designation (e.g., ski, rock, alpine, hiking). Three (10%) guides were apprentice guides, an individual who had completed the first phase of training and assessment courses and worked under the supervision of a certified guide to gain experience needed to complete the certificate program. The age of the guides in the survey was above average [54], as many younger guides declined to participate, stating they felt unqualified to speak to climate-related changes due to the brevity of their career thus far. On average, guides had 22 years (range = 4 to 44 years) of experience guiding in the Canadian Rockies, which was found to be closely representative of the population (30%: 10–20 years, 25%, 20+ years [54]). These guides worked between 20 and 250 days a year in terrain that involved snow, ice, or glacial travel with the majority (57%) spending between 100 and 150 days in this terrain annually.

Interviews were conducted using a set of predetermined open and closed-choice questions. These interviews were designed to strike a balance between structure and flexibility, enabling thorough exploration of emergent themes and time for follow-up questions tailored to the mountain guides' responses. Discussions were focused on the guides' perspectives, experiences, and insights into cryospheric changes in the Canadian Rockies region and their level of exposure sensitivity, adaptation, and vulnerability to such changes. All interviews were digitally recorded (with consent), transcribed, and imported into NVivo for data analysis. To analyze the data, a content analysis was performed [55]. Content analysis provides a systematic approach to the creation of inferences from verbal, visual, or written data, as well as their quantification and description. Key to this research approach is its ability to elaborate on quantitative findings with rich qualitative data that can reveal meanings, consequences, and context [56]. To apply this technique to the interview responses, all references to Mt. Athabasca, related approaches, and climbing routes were identified to create a database of responses relevant to the study foci. These responses where then coded according to observations of change in the physical environment (e.g., rising temperature, changing precipitation regime, loss of ice and snow), the implications of these changes (e.g., altered climbing conditions, increased objective hazards), and how guides are responding to these changes (e.g., changing routes, avoiding routes). Codes for such content were then summed and normalized, and simple summary statistics were generated. These statistics were analyzed and compared to identify key findings in the data, at which point qualitative data were used to provide insight into and elaborate on key findings, revealing the lived experiences of climate change by mountain guides.

4. Results & Discussion

4.1. Climatological Conditions at Mt. Athabasca Are Changing Rapidly

Statistically significant increases in minimum and mean air temperatures were found between 1 January 1910 and 31 December 2022. The greatest increases occurred in the minimum (0.043 °C/year) and mean air temperatures (0.028 °C/year), with the smallest increase in maximum air temperature (0.0011 °C/year) (Figure 3). Seasonally, statistically significant increases in the minimum, maximum, and mean air temperatures over the study period were observed across winter, spring, summer, and fall, with two exceptions: maximum air temperature in spring and mean air temperature in fall. The greatest average warming occurred in winter months (0.026 °C/year) and the least occurred in the fall (0.007 °C/year). Minimum air temperatures consistently demonstrated the greatest increases across all seasons, resulting in a decrease of 21 days with sub-zero temperatures (2 h threshold) between 2016 and 2022 at the Athabasca moraine (average decrease of 3.25 days/year).

Since 1910, mean air temperature at the Golden ECCC station has increased by 3.12 °C (Figure 3). This value is almost three times greater than the average temperature increase in global mountain regions, which is reported to be approximately 1.09 °C (0.95 to 1.20 °C) since 1850 [57]. Over the last two decades, the average rate of warming was found to be 0.55 °C, a magnitude on the upper threshold of warming observed in recent decades in the mountain ranges of Western North America, the European Alps, and High Mountain Asia over recent decades (0.3 °C $\pm$ 0.2 °C per decade) [57]. This greater warming could be the result of the low elevation of the weather station (784.9 m a.s.l.). For comparison, warming observed at the Athabasca moraine, which is 1182 m higher at 1966 m a.s.l., was on average

0.40 °C/year over the last decade. This increase in temperature is still indicative of rapid warming, but more in alignment with trends in global mountain regions.

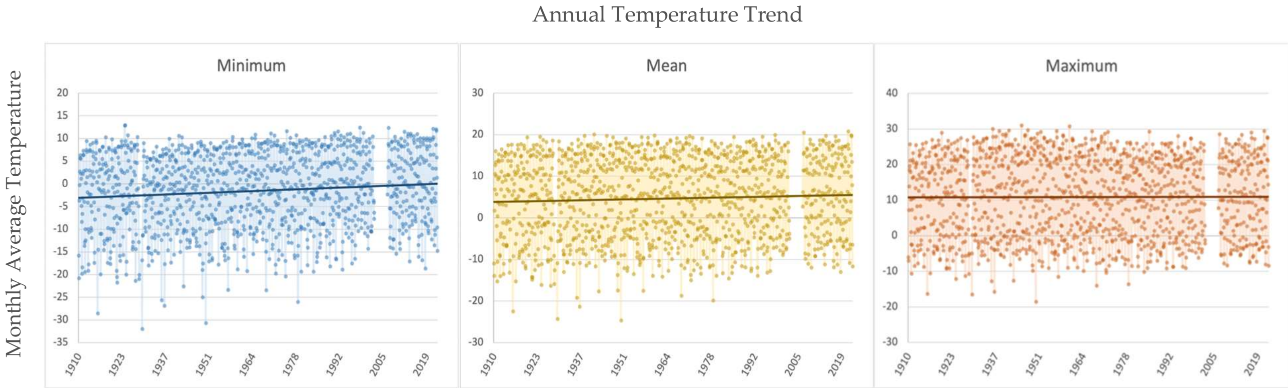

Figure 3. Annual trends in minimum, mean, and maximum temperature based on monthly averages from 1 January 1912 to 31 December 2022.

Statistically significant increases in rainfall (0.002 mm/year) and total precipitation (0.002 mm/year) and a non-significant decrease in snowfall were observed between 1910 and 2022 (Figure 3). During winter months, a statistically significant increase in rainfall and decrease in total precipitation were detected. Trends regarding snowfall were less clear; however, the simultaneous increase in rainfall and decrease in total precipitation suggests winter snowfall is decreasing. Statistically significant increases in rainfall were observed in spring, summer, and fall months (very small magnitudes) and total precipitation in spring and summer. Snowfall trends remained unclear during these months.

These trends indicate that rainfall is increasing throughout all seasons and that snowfall is decreasing in winter months (Figure 4), a finding consistent with rising temperatures and in good alignment with the global literature [10]. Between 1982 and 2020, annual snow cover extent (−3.6% ± 2.7%) and duration (−15.1 days ± 11.6) have decreased, with the greatest negative trends observed in winter months and the greatest positive trends observed in spring months [58]. While there is less consensus regarding higher elevation snowfall trends in Canada [58], the findings presented are consistent with observed [59,60] and projected [61] decreases in low-elevation snowpacks. These changes are likely driven by rapid warming, particularly at minimum temperatures, which have contributed to an increase in the rain-to-snowfall ratio and greater in-season melting [59].

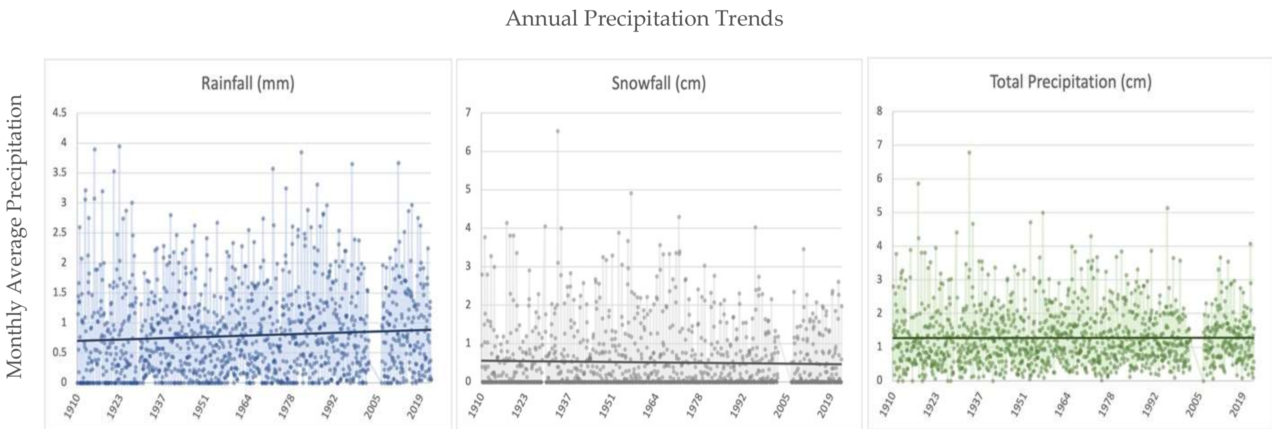

Figure 4. Annual trends in rainfall (mm), snowfall (cm), and total precipitation (cm) based on monthly averages from 1 January 1912 to 31 December 2022.

The implications of these changes for mountaineering routes and activities are potentially significant. Rising temperatures are the predominant driver of glacier recession [10], which is one of the most concerning and widespread climate-related changes altering mountaineering routes [12,16,28]. Indeed, between 1966 and 2014, the nearby Athabasca Glacier decreased in area from 18 to 16.9 km^2 (6%), the exposed ice area increased from 4.3 to 9.0 km^2 (109%), and the snow/firn area decreased from 13.6 to 7.9 km^2 [62]. For mountaineering, the cumulative effect of these changes is a decrease in the amount of glaciated terrain on routes, an increase in the amount of bare ice on routes, and increasing slope angles on the glacier surface (e.g., 14.2° to 16.8° on the Athabasca Glacier [62]). Such alterations are likely amplified by a decrease in snowfall and increase in within-season melting [59].

Further, the observed dramatic increase in minimum temperature (consistent with the literature [59]) and increase in rainfall are important factors impacting the conditions required for safe mountaineering. For example, an overnight freeze, when the cryosphere returns to a frozen state after a period of daytime warming, is an important consideration for mountaineers. A thawed or thawing cryosphere retains elevated water content, a phenomenon enhanced by increased rain-to-snow ratio, which reduces shear strength and can trigger cryospheric hazards, such as avalanches, and geomorphologic processes, such as thaw settlement and increased creep rates, which lead to dynamic destabilization events [24]. These changes enhance the objective hazards for mountaineers and mountain guides, who are exposed to climate-related cryospheric changes because of their livelihoods.

4.2. Changing Climatic Conditions Are Transforming Climbing Routes on Mt. Athabasca

The triptych of historical and repeat images (Figure 4) demonstrates significant changes in the mass, extent, and depth of the North Glacier on Mt. Athabasca (Figure 5). In 1918, the photograph shows the tongue terminating close to the valley floor, near the present-day road. By 2011, the tongue had retreated up the valley to the first headwall and by 2023, it further receded, exposing almost the entire headwall. Changes in the margins of the upper portions of the glacier are also apparent, notably along the north face as well as the north-east and west ridgelines, where significantly more rock has been exposed throughout time. In addition to changes in volume and extent, the North Glacier has thinned. This is evident in the growth of a prominent rock below the north face and emergence of new exposed rock on the more north-westerly aspects of the mountain. These findings, in combination with the rapid warming trends identified in Section 4.1, are consistent with the literature, which states that glaciers in the area are retreating and thinning and firn/snow areas are shrinking [62], largely driven by increases in air temperature [63]. It is also likely that these processes are amplified by feedback loops in both mountain climates and glacier dynamics [9]. Reflecting this amplification is a notable acceleration in the rate of snow and ice loss since 2011 (Figure 5), a finding in alignment with existing research reporting that the greatest volume of glacial retreat in western Canada (1985–2005) is in the Canadian Rockies [64], an area that has seen an 8-fold increase in rate of retreat since 2011 [63].

Change in the colour of the glacier's surface throughout the repeat images indicates change in the albedo, the proportion of radiation reflected by a surface. Mountain snow and ice surfaces are typically bright white and have high albedos, reflecting great amounts of solar radiation. In 1918, this appears to be the case. The glacier is relatively white in appearance with a few darker patches scattered throughout. In 2011, the upper half of the glacier is bright white and transitions to a more greyish colour towards the toe. However, in the 2023 image, most of the glacier surface has experienced darkening. The consistent lowering of albedo throughout the images is in alignment with the literature, which has found widespread declines in mountain glacier albedo across North America, associated with rising temperature (identified in Section 4.1) and forest fire deposition [65]. This is important because net radiation at the glacier surface controls melt [66], so the observed lowering of albedo throughout the images has likely facilitated greater absorption of solar radiation and driven accelerated melt processes over time [67,68].

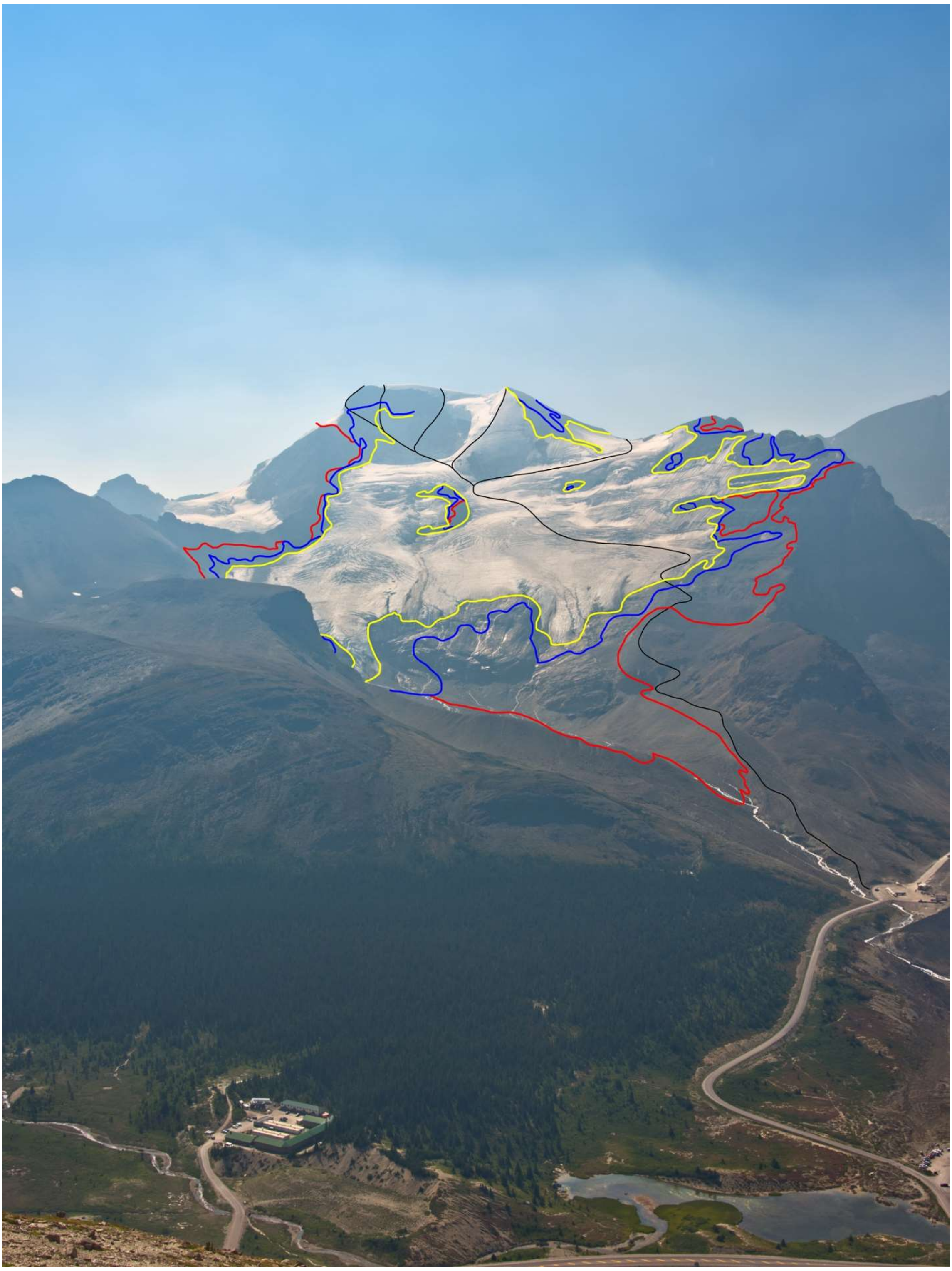

Figure 5. The second repeat of Mt. Athabasca captured in August 2023. The red lines indicate the extent of the glacier in 1918, the blue lines indicate the 2011 extent, and the yellow lines indicate the 2023 extent. The common climbing routes are delineated in black.

The loss of ice and snow has significant implications for the approach and climbing routes on Mt. Athabasca. Evident in Figure 5, all routes travel through or underneath an area that has experienced significant glacial loss. For example, the North Glacier approach now requires climbers to walk on scree and unstable material for longer distances to get on the actual glacier, at which point the route traverses under the rapidly deglaciating north, north-west face, increasing exposure to overhead hazards such as rock and serac fall. On the climbing routes, similar processes have occurred. Notably, once at the col on the Ramp route, the prominent shoulder that leads to Mt. Athabasca's ridgeline is now almost entirely ice free. Such dramatic change in the terrain alters the landscape of risk as it transitions from ice and snow-related objective hazards to rock, creating new hazard management challenges for guides and climbers. Similarly, on the north face routes, particularly the North Face and North Face Bypass, prominent loss of ice has exposed a great deal of rock and unstable material, which in turn has increased and changed the character of the objective hazards on these routes.

4.3. Changing Route Conditions Are Impacting Guiding Activities

All mountain guides stated that the approach and/or climbing routes on Mt. Athabasca have been altered by climate change. For example, climate-related changes were observed by 83% (n = 25) of mountain guides on the approach routes (e.g., North Glacier, AA-Col) to Mt. Athabasca, of which 100% (n = 25) observed and/or encountered significant loss of glacial ice:

> *"The lower North Athabasca glacier, places that the glacier used to be, and where I used to ice climb, now it's an ablating edge of a glacier. . . so now we walk up on rock for another, oh man, I don't know, 300–400 m before we get to the place where we even have ice."*
>
> (G14)
>
> *"The Athabasca Andromeda glacier. . . that edge of ice is gone now and places that we used to teach ice climbing [on] the glacier is back 100 m or more 200 m and it's thinned out [so] as you get up to that place now where we used to rope up. . . and start our travel. . . Now that's rock and the glacier is way over there."*
>
> (G14)

The loss of glacial ice has made it necessary to walk a longer distance to reach the glacier and changed the terrain that guides and their clients must travel through, which has altered the character of approach routes. Indeed, 30% (n = 9) of guides described an increase in the slope gradient on the North Glacier and AA-Col approaches, consistent with findings from the nearby Athabasca Glacier where the gradient of the glacier surface has increased from 14.2° to 16.8° [62]. Previous research has associated glacier surface steepening with the temperature–elevation relationship, wherein glacial ice thins more rapidly at lower elevations compared to that at higher elevations [16]. This imbalance in the rate of thinning can increase the overall glacier slope, an effect amplified in areas with steep headwalls—characteristic of the terrain on Mt. Athabasca. For example, on the North Glacier approach, guides described how the glacier has *"become a lot steeper. . . you used to be able to walk up and down it pretty easily. Now, your kind of pitched out climbing."* (G5). Pitched out climbing refers to a steep section of a route that requires a rope between two belay stations in order to secure a climber in case of a fall. This strategy is used when the terrain becomes exposed or steep enough that a fall would result in significant injury or death. The switch from easy walking for beginners to pitched out climbing is indicative of major changes in the relative difficulty of the approach routes on Mt. Athabasca.

Notably, 63% (n = 19) of guides felt that these changes were associated with an increase in objective hazards on both approach routes. For example, some guides (33%, n = 10) observed an increase in rockfall associated with the loss of glacial ice on both approaches. Given that the approaches to Mt. Athabasca occur in comparatively low-elevation terrain, most of the observations were related to the periglacial environment in the glacial forefield, which can be challenging to navigate [15,69,70]. On both approaches, mountain guides identified ice-cored moraines, "a discrete body of glacier ice buried underneath sediment" [71], as particularly problematic. The presence of glacial ice under the debris layer makes these landforms unstable and prone to rockfall and landslides, because underlying ice can act as a sliding plane for debris [72]. In addition, the degradation of underlying ice can reduce the landform's shear strength, increasing the probability of mass movement events. This makes these moraines potentially hazardous to travel on and around. For example, one guide described dangerous change in the lateral ice-cored moraine on the North Glacier approach: *"that whole lateral moraine has been retreating and melting away and steepening up... so there's been some big slides of that material sliding down and it's threatened some guides."* (G14). Similarly, on the AA-Col approach, *"there's potentially ice core moraine as well, on the AA-Col approach to Athabasca-Andromeda, there was a big rockslide there back in 2012 or 2013"* (G15). Such events increase the objective hazards associated with navigating glacial forefields on the Mt. Athabasca approach routes.

Mountain guides have also experienced climate-related changes on climbing route(s) on Mt. Athabasca, including the North Face (63%, $n = 19$), Ramp (53%, $n = 16$), Silverhorn (23%, $n = 7$), AA-Col (23% $n = 7$), Hourglass (17%, $n = 5$), and North Face Bypass (7%, $n = 2$). Across all climbing routes, the biggest changes observed were changes in climbing conditions (e.g., loss of ice, change in snow cover, increase in slope gradient) and an increase in objective hazards (e.g., rockfall).

The loss of glacial and alpine ice has exposed a significant amount of rock on all climbing routes, altering their character. For example, *"the ramp on Mt. Athabasca, I mean, that thing is getting smaller every year, it's like just wasting away."* (G3), *"the north aspect of the Silverhorn, is all rock in the summer."* (G15), and *"the AA col approach now is almost all rock."* (G15). Ice loss on the AA-Col has been so significant that some guides stated the summit of Mt. Athabasca can now be reached without stepping foot on the glacier: *"They go up the side on rock and avoid the glacier and I think they've scrambled all the way to the top of Athabasca, they don't even touch the glacier."* (G14). On the Hourglass, guides described how historically, *"people were on that [route] all the time and it was good, and it was snow and ice covered and that just doesn't exist anymore."* (G4) and as a result, the route is *"just completely different than it used to be"* (G5). On the North Face Bypass, loss of ice has so dramatically altered the route it may no longer be climbable:

> *"And for the last 10 years or 20 years, we've been doing the North Face Bypass, which you get to towards the base of the face, but you go left into gullies that come off of the traditional route up Athabasca... We were able to do it in good conditions and short rope the whole thing. Just keep people moving and put in a nice row of steps in the right snow conditions. I don't know if those snow conditions will exist again because the ice is gone. Now in those gully and it's rock. So will we ever be able to do that?"*
>
> (G14)

In cases where the terrain is quite technical (i.e., steep, exposed), loss of ice can also change the technical difficulty of climbing on routes. On the North Face route, loss of ice was principally noticed on the crux, which historically was described as a short pitch of easy, mixed climbing and *"now, is quite a large rock step on the north face"* (G20). This loss of ice is evident in Figure 5, where the historic extents are clearly demarcated, and has changed the crux from a comparatively simple snow and ice pitch to rocky terrain that is more difficult to climb and find adequate protection.

> *"The North Face of Athabasca, the first time I climbed it I think was in 1981 and there was 10 ft to 15 ft of rock exposed, and it was 5.5 rock, and it was quite reasonable... Now I bet it's like 100 m of rock exposed and it's no longer 5.5. The last time I guided that I was definitely dry tooling and... it was a search for gear where there used to be ice screw [placements], where you could sink in right to below the face in the 1980s. Now we need stubbies [because there is] not enough ice depth. That's quite a serious ascent."*
>
> (G14)

In addition, changes in snow cover on Mt. Athabasca were observed by 47% ($n = 14$) of guides. Most guides observed and/or encountered changes on the North Face (23%, $n = 7$) and Ramp (17%, $n = 5$), while fewer reported changes in snow cover on the Silverhorn (7%, $n = 2$) and AA-Col (3%, $n = 1$). Consistent with the literature indicating that mountain snowpacks in the Canadian Rockies are experiencing earlier melt onset [73,74], the majority of guides (93%, n = 27) stated that an increase in the rate of seasonal snow melt is driving changes in snow cover:

> *"You used to go climb the North face of Athabasca all through the summer on snow and now you kind of want to get it June or maybe even May, May/June when there's snow."*
>
> (G9)

Loss of snow can make travel more challenging for guides and harder on the body. When snow covers the glacier, guides can kick steps into the slope, creating a snow staircase for guests to ascend. However, when guides are working on bare ice, they and their clients must spend more time on the front points of their crampons, exacerbating muscle fatigue in the calf and increasing the fall hazard.

An increase in the slope gradient was observed on climbing routes on Mt. Athabasca, including the Ramp (20%, n = 6), Silverhorn (10%, n = 3), North Face (7%, n = 2), and AA-Col (3%, n = 1). As described above, the retreating and thinning of glacial ice contributes to a steepening of the glacier surface [17]. An increase in the slope gradient can increase the likelihood of a fall and can also slow progress, increasing exposure to other objective hazards (e.g., rockfall, weather): *"so, they are exposed to the hazard for longer to the point where it's no longer justifiable."* (G12). Almost all guides who identified a change in the slope gradient, (89%, n = 8) related it to the loss of semi-permeant alpine ice and glacial retreat. For example, on *"the Ramp route on Athabasca, that used to be an easy walk up and it's not anymore as that glacier is receding... it used to be kind of a glacier bench, you walk across, you kind of traverse it. Now, it's a 45-degree slope."* (G13). Similarly, *"the North Face of Athabasca is steeper"* (G11), on the Silverhorn *"you're actually starting to have to do some climbing moves on steeper glacial ice sections."* (G6), and the AA-Col *"terrain is becoming steeper and more technical"* (G12).

More than half of the guides (57%, n = 17) reported an increase in rockfall on at least one climbing route on Mt. Athabasca, with most citing an increase on the North Face (30%, n = 9) and Ramp (30%, n = 9). Of these guides, 100% (n = 17) stated that the increase in rockfall was related to glacial recession and/or loss of alpine ice:

> *"Mount Athabasca has a north face route that used to have a small rock step and when I left in early like 2004, it was already a much bigger rock step. And I think just generally what we're seeing with features like that is the amount of glacial recession on these faces has exposed a lot of loose rock. So, now I actually avoid that route, certainly in the heat and certain times of the years, I just would not venture onto that route because of the rockfall."*
>
> (G30)

> *"There's definitely more rockfall for sure because the faces are melting out. Like the Silverhorn now has rocks sticking through it all over the place."*
>
> (G15)

Glacial retreat and loss of alpine ice have progressively produced increasing amounts of ice-free terrain and these areas are full of unstable material, which can become a starting zone for rockfall [17]. This phenomenon is exacerbated when glacier recession reveals highly fractured and unstable rock, particularly at the glacier margins (*ibid.*). As a result, guides described routes on Mt. Athabasca, such as the AA-Col as *"a shooting gallery"* (G12) and the Hourglass as a non-option because it been so severely altered *"you can't really safely climb it"* (G19), in fact *"there's even been a fatality [associated] with heat and rock fall there."* (G14).

In addition to glacial retreat, increasing temperature plays an important role in rockfall hazard [21,22,40,75–78]. Consistent with trends presented in Section 4.1, guides have observed an increase in temperature and decrease in overnight freezes, which has significantly increased the rockfall hazard on the Ramp:

> *"The rockfall hazard, it's gone from a manageable problem if you get up really early and have a cold night too. But there is no such thing as a cold night for all of June, July, August, September anymore, you can be guaranteed it won't freeze. So, then it's doesn't*

matter what time you go, it's just you're dodging missiles the whole time, which is pretty hard to justify too."

(G12)

Climate-related changes on access routes, climbs, and objective hazards are highly consequential for mountain guides working in the Canadian Rockies because *"the bread-and-butter of guiding is climbing classic routes like Athabasca"* (G28). Mt. Athabasca has the notoriety and desirability of being an '11,000 er' but is unique in its accessibility, as all routes up the mountain start within 3 km of the parking lot, and its variety, since routes range from easy to very technical. These factors make the mountain a logistically simple, more affordable (clients), and more profitable (guides) one-day trip for a wide range of beginner to expert clients, but also make it very hard to replace:

"I could try to come up with an alternate, a good alternate plan B to Mount Athabasca. And there's like there's nothing, like where do you go? I don't know, I don't know where you go. I mean, especially in the conditions, if the general conditions in the range are such that Mt. Athabasca is not a reasonable objective, then where else would you go? I don't know. Up onto the Wapta Icefield maybe, but that's not doable in a day. That's a multiday trip right away, staying at the Bow Hut or something. And otherwise, yeah, where do you go?"

(G22)

Given the importance of Mt. Athabasca to the guiding industry, it is unsurprising that 87% (*n* = 26) of mountain guides stated they are adversely affected by climate-related changes on the mountain. However, not all guides are affected in the same way. For example, those (*n* = 4, 13%) that work predominantly in one location (i.e., lodge-based) or have endeavoured to find alternative guiding-related employment streams (e.g., risk management in other sectors) indicated that they have relatively low sensitivity to contemporary climate-related changes due to their limited reliance on guiding on Mt. Athabasca. Sensitivity was also related to the guide's age, level of certification, and employment status, variables that are often correlated (Table 2). For example, older mountain guides tend to have a higher level of training (e.g., IFMGA vs. ACMG) and more frequently work as independent contractors, which provides greater flexibility. Such guides (*n* = 22, 73%) were found to be less sensitive on average to climatic changes on Mt. Athabasca, as many of these characteristics provide greater access to financial resources and livelihood stability (e.g., length of time in workforce, development of client base, fee schedule) and therefore reduce the pressure to work on Mt. Athabasca when conditions are more challenging. One indirect measure of this is that, on average, more senior guides work 22 fewer days per year in snow, ice, and glaciated terrain than their early-career colleagues. Indeed, early-career guides (*n* = 4, 13%) indicated feeling financial pressures that drive them to work on Mt. Athabasca despite changing conditions: *"it pushes us into this really awkward position where either we do something different for a living or we accept an ever-increasing risk level, which is basically what we're doing."* (G12).

Another contributing factor could be related to clientele. While late-career guides often described working with return guests who welcomed suggestions regarding alternative or lesser-known mountaineering routes, early-career guides were still developing this client base and, as a result, tended to spend more time guiding clients on the 'classic' and 'easy' routes. However, *"a lot of the classic easy routes up mountains or around mountains are through places that are probably some of the most highly impacted"* (G19). For these reasons, early-career guides appeared to be more sensitive to climate-related changes on Mt. Athabasca, an insight that illustrates the role of socio-economic factors in shaping differentiated experiences of climate change amongst mountain guides. In this context, however, we emphasize that individual circumstances can lead to unique experiences for individual guides that do not follow this pattern, including the fact that senior guides might face unique pressures to spend time on Mt. Athabasca in challenging conditions (e.g., due to specific job requirements such as those associated with search and rescue).

Table 2. Demographic profiles of mountain guides sensitive to climate-related changes on Mt. Athabasca (n = 26). The two guide cohorts presented below were defined by their sensitivity (i.e., less or greater pressure to work under challenging conditions) to climate-related changes.

		Less Pressure to Work in Hazardous Conditions		More Pressure to Work in Hazardous Conditions	
Count		22		4	
Average age		51		39	
Certification	IFMGA	68%	n = 15	25%	n = 1
	ACMG	32%	n = 7	75%	n = 3
Employment status	Independent contractor	53%	n = 19	43%	n = 3
	Guide service employee	47%	n = 17	57%	n = 4
Average years of experience		24		8	
Average days spent on snow, ice, or glaciated terrain		103		135	
Guide career stage		Late-career guides		Early-career guides	

Being exposed and sensitive to changing conditions on Mt. Athabasca does not necessarily mean that guides are vulnerable, as high adaptive capacity can, in principle, ameliorate exposure sensitivity. And guides are adapting—the majority of guides (73%, n = 22) have responded by reducing their guiding activities in the area, insofar as this is possible given the considerations mentioned above, going as far as to say: *"I doubt I'll ever guide the North Face of Athabasca again."* (G14). The reduction in guiding activities on Mt. Athabasca involves 'activity substitution', when guides adapt to unsuitable conditions by changing the originally contracted activity, or 'spatial substitution', when guides change the location of their contracted activity [12,28]. The ability to utilize these adaptation options might be greater among more experienced guides due to their (potentially) greater knowledge of alternative route/terrain options [79]. Regardless, changing activities raises guides' operational costs by increasing their time and effort (e.g., researching alternative mountaineering routes or exploring different activity options) without increasing their fees for service, resulting in reduced profit margins [14]. For those still working on the mountain, more demanding approaches and climbing conditions and enhanced objective hazards present growing threats to health and safety. In all cases, vulnerabilities are apparent, and the situation raises important questions about L&D [80] for those whose livelihoods are connected to the mountain.

Mountain guides who experience loss of guiding opportunities face significant economic impacts. Since *"one of the most guided things is Mt. Athabasca"* (G9), losing this terrain and having limited alternative options could translate into fewer or more logistically intensive (and therefore less profitable) workdays for mountain guides. Further, Mt. Athabasca has historically been the site of many introductory mountaineering courses: *"Snow and ice long weekends, that was kind of my bread and butter for a lot of years. Every long weekend you're at the icefields, along with everyone else, doing the three-day snow and ice courses and then climbing Mt. Athabasca."* (G7). These instructional courses are more lucrative for mountain guides because of the high guide-to-client ratio; however, loss of snow and ice is making simple terrain on the mountain too complex and hazardous for teaching:

> *"We've got an alpine ice climbing course that we use to teach people the skills that they would need to know to do big north faces on alpine ice routes, like the north face of Athabasca and that sort of thing. And we really have to either change the venues [North Glacier] that we used to use to be able to teach people those skills or change the venues [Mt. Athabasca] that we use for the actual summit days."*
>
> (G13)

Loss of guiding opportunities extends beyond economic impacts and includes the loss of intangible cultural heritage associated with mountaineering and mountain guiding. Mountaineering was internationally recognized by UNESCO as a threatened practice in 2019, when it was inscribed on the Representative List of the Intangible Cultural Heritage of Humanity and identified as priority to safeguard [81]:

"I personally kind of wonder how valuable those skills even are because alpine ice climbing is kind of, it's just, it's shrunken to a very limited number of routes with a very limited time window. And I kind of wonder if that's even gonna be a thing in years to come."

(G13)

This in turn could have broader implications for guiding history and culture:

"What is Mt. Athabasca going to look like in 20 years?... Our climbing history isn't super long here in Canada. We're looking at maybe getting close to 150 years of mountaineering history and for generations these big features are what the Pioneers or the godfathers of the climbing world would have been climbing. And the new guides of the new era, they will look up at those features and be like, 'oh man, I wish I could have done that. That would have been so awesome.' But now those features are turning into just nasty rock faces."

(G6)

The issues faced by guides working at the frontlines of climate change have cascading effects for clients, the mountain-focused NBT sector, and mountain communities more broadly. At present, little is known about the broader recreational, economic, and social implications of changing mountaineering conditions, representing important new avenues of research.

4.4. Study Limitations

The results of this study are subject to several limitations. The meteorological monitoring station used to identify trends in air temperature and precipitation was distant from the study site and located at a relatively low elevation. However, there is a well-documented lack of meteorological monitoring stations in Canada's alpine environment [82] and of the stations that do exist, several experience challenges related to the measurement of solid precipitation [83,84]. These factors constrained our ability to include data from a more representative station [82] and underscore the need to expand climatological monitoring in Canada's alpine regions, especially in relation to snowfall [84]. This study was also affected by the characteristics of our sample, which was biased towards late-career mountain guides. Future studies with a greater focus on early-career guides would complement our findings and provide additional insight into differentiated experiences of climate change amongst guides.

5. Conclusions

Rising temperatures and changing precipitation regimes in the Mt. Athabasca area are driving rapid glacial retreat and the loss of semi-permanent snow and ice on the mountain, which in turn are impacting climbing conditions and objective hazards on popular mountaineering and guiding routes. We found that when faced with the same climate-related changes, late-career guides tended to experience loss of guiding opportunities while early-career guides tended to experience increased pressure to provide the same services under more hazardous conditions. These results show how socio-economic conditions such as financial security and livelihood flexibility shape differentiated experiences of climate change and demonstrate the importance of contextual vulnerability approaches in revealing lived experiences of climate change. Our work also revealed the emergence of hard biophysical limits to adaptation (e.g., the total loss of routes on Mt. Athabasca) and consequent forced (undesirable) transformations of guiding livelihoods, as well as associated L&D. These are new and important findings in a climate change and mountaineering context and topics that warrant further research attention, as the underlying issues are likely to be present in other mountaineering destinations globally.

Our analysis points to several leverage points for navigating the challenges identified herein. For example, Clarke and colleagues [85] indicated that robust GHG mitigation efforts could preserve ~20% (by 2100) of the glacier ice that characterizes many of the region's iconic mountaineering routes. However, given inevitable losses of snow and ice, it will also be essential to address the socio-economic determinants of vulnerability to climate-related changes on Mt. Athabasca and other peaks in the region. One opportunity could be to provide content related to climate change adaptation in Assessment and Training Programs offered by the Association of Canadian Mountain Guides (e.g., climate change-specific assessment and decision-making tools). This could help to better prepare early-career guides for climate-related issues encountered while guiding. Ultimately, mountain guides and guiding services are in the best position to determine which activities will effectively address their concerns and needs. However, transdisciplinary research, such as that presented here, can play an important role in characterizing salient issues and bolstering support for actions that respond to the concerns of those striving to climb through climate change. While this study is grounded in the Canadian context, our research focus and approach are relevant for other mountain areas where rapid changes in mountain environments portend significant challenges for mountain guides and NBT more broadly.

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