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Climate Change and the Future of Ski Tourism in Canada's Western Mountains

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Abstract: Winter, snow, and mountains, epitomized by the world-renowned Rocky Mountain range, are an integral part of Canada's sport-culture identity and international tourism brand, yet the climate change risk posed to this important ski tourism region remains uncertain. This study used the ski operations model SkiSim 2.0 to analyze the climate risk for the region's ski industry (26 ski areas in the province of Alberta and 40 in British Columbia) with advanced snowmaking, including changes in key performance metrics of ski season length, snowmaking requirements, holiday operations, and lift and terrain capacity. If Paris Climate Agreement targets are met, average seasons across all ski areas decline 14–18% by mid-century, while required snowmaking increases 108–161%. Regional average operational terrain declined only 4–9% in mid-century, as the largest ski areas were generally more climate resilient. More pronounced impacts are projected under late-century, high-emission scenarios and in low latitudes and coastal British Columbia regions. When compared with continental and international ski tourism markets, Western Canada has relatively lower climate change impacts, which could improve its competitiveness. The results inform further research on demand-side as well as the winter sport-tourism industry and destination-scale climate change adaptation and mitigation strategies.

Keywords: climate change; ski industry; winter sport; sustainable tourism; adaptation; mountains

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1. Introduction

Mountain regions across the world are experiencing rapid climate change, with average temperature increases outpacing the global mean by an estimated 25 to 50 percent since around 1950 [1]. Snow cover, glacier, and permafrost decline are widely observed, and continued warming will accelerate exposure to related climate-induced natural hazards as well as impact the aesthetic, spiritual and cultural values associated with mountains [2,3]. Many mountain regions are "near the hard limits of their natural adaptation capacity" [4] (p. 28), emphasizing mountain communities' high vulnerability to climate change and the imperative to increase resiliency. Dependence on climate-sensitive livelihoods, including tourism development expansion and shifting population demographics—including increased amenity migration [2,3], means mountain communities dependent on winter sport tourism are increasingly at risk of climate change [4–6]. Understanding the extent and timing of climate change risk and potential adaptation strategies remains a priority knowledge gap in most mountain destinations [5].

Ski tourism is a complex and interrelated socio-ecological system in mountain regions that influences fragile alpine habitats and endemic and endangered biodiversity; sport, recreation, and culture; livelihoods and community well-being; accessible housing; and local water and energy security. A review of climate change and the global ski and mountain tourism industry concluded the multi-billion-dollar international ski industry is in the early stages of a climate-induced transition [5,6]. Across a range of climate models and methodologies, research on ski tourism markets in North America [7–9], Europe [10–15], Asia [16–18], and the southern hemisphere [19,20] identifies broad common patterns of climate change impacting ski tourism operations, natural snowfall and the conditions required for snowmaking with variable localized climate change impacts and implications. In Canada, analysis of physical climate risk on the ski industry (supply and demand-side) has focused on the eastern ski markets in Ontario and Québec over the last 20 years [7]. While there has been much speculation in the media about the impacts of climate change on the larger Western Canadian market, it remains a priority gap, which this research addresses [21].

Using the ski operations model SkiSim 2.0 [11], this study aims to analyze the physical climate impacts in Western Canada, including changes in key performance metrics of natural snowpack, ski season length, snowmaking requirements, and holiday operations across a range of low- to high-emission climate futures. Assessing climate impacts for 40 ski areas in British Columbia (BC) and 26 ski areas in Alberta (AB) using the common modeling parameterization of the SkiSim 2.0 model, this research provides the first climate change and ski tourism operation analysis in the Western Canada region and allows for comparisons of results at the national, continental and international scales. Within Western Canada, this research sets the foundation for discussions and future research on effective climate strategies for local winter sport industries and ski tourism destination communities, including the capacity to meet future ski tourist demand, adaptation planning and feasibility of recently proposed new ski resort developments. More broadly, this research takes a tourism-systems approach to discuss interscalar climate implications, contribute to the climate change adaptation-mitigation nexus, and inform the winter-sport tourism industry transformation to a warmer and decarbonized economy of the future.

Study Area: Skiing in Canada's Western Mountains

Winter, snow, and mountains, epitomized by the world-renowned Rocky Mountain range and over 74 ski areas (32 in AB and 42 in BC) [22], are an integral part of Canada's national sport culture identity and international tourism brand. Western Canadian ski markets represent an average of 48% of Canada's annual skier days (2.3 million in AB, 5.9 million in BC), and over 1 million regional residents consider themselves active skiers (537,802 British Columbians, 473,649 Albertans) [22,23]. Western Canada is also a global ski tourism destination. Several resorts like Whistler, Lake Louise, Kicking Horse, and Revelstoke are listed as top ski destinations by high-profile tourism media such as Snow Magazine, World Atlas, and Oyster and attract over 2 million international skiers from the US, UK, Australia, New Zealand, Germany, and Mexico [22]. Transitioning from natural resource extraction-based industries, rural and remote mountain communities in AB and BC have focused on amenity migration, with outdoor recreation and sport tourism, and specifically the expansion of ski tourism, as a central strategy [24]. In BC, ski areas stimulate $1.4 billion in incremental visitor spending and create over 18,800 full-time equivalent jobs in the province [25]. This represents a significant portion of the provincial tourism market (9% of total tourism revenues and 13% of the tourism GDP contribution [25]). While ski tourism demand has remained steady, revenues and profitability have declined since the early 1990s [22,26]. Despite stable demand and diminishing profits, the Canadian ski tourism industry is predicting new skier markets will lead to regional market growth of 13.3% by 2030 [22]. These ski industry projections do not include any legacy of recent COVID-19 pandemic disruptions or future climate change impacts in the region or on competitors.

Understanding the range of potential climatic futures and ski industry adaptive capacity is essential to climate adaptation and tourism planning across Canada's Western ski industry, from individual ski area management to mountain community development strategies to regional tourism, water, and energy policy. For example, while there is significant debate on the (mal)adaptation of snowmaking [27–30], Scott et al. [31] find that snowmaking effectiveness and sustainability are highly context-specific. Energy and water sources and costs, existing infrastructure, local microclimates, global emission futures, and even tourist perceptions play a role in determining whether snowmaking is viable or desirable in the future. Snowmaking has been an integral climate adaptation across much of the global industry since the 1980s, with many regions highly reliant on machine-made snow for over 20 years [31]. Western Canada has relatively limited snowmaking infrastructure capacity on ski terrain. Of the ski resorts that reported their snowmaking capacities, an average of 25% of skiable terrain is covered by snowmaking, with individual resorts ranging from no coverage to 100% [32]. Unlike Eastern Canadian markets, which are already highly dependent on snowmaking and visitors expect groomed snow and icy conditions, Western Canada is known for being the "powder highway". Greater reliance on machine-made snow may not meet skier expectations for snow quality. How snowmaking may perform as an adaptation in the west requires additional research into its ability to meet the physical changes of future climate scenarios.

As Canada's mountainous regions continue to experience warming and the resulting loss of snow and ice cover [33], there are far-reaching consequences for tourism, sport, recreation, livelihoods, culture, real estate, and community resilience in Canada's winter-sport tourism-dependent mountain communities [34,35]. Ski areas in Western Canada already rely heavily on four-season activity diversification (mountain biking, hiking, and events), increasing summer activities to reduce the economic risks of adverse weather and snow conditions during the winter [34]. The internationally renowned ski destination Whistler Resort Municipality now reports peak visitation in the summer rather than winter, while ski destinations across Canada are seeing growth in four-season activities [35]. The importance of summer-sports tourism will only increase under climate change [6]. These climate influences on the seasonality of ski and mountain tourism patterns and resulting socio-ecological impacts in fragile alpine ecosystems and small isolated communities have not yet been sufficiently studied in Canadian contexts [21]. Understanding how winter seasons will be affected by future climate scenarios is essential for both industry and community stakeholders to inform investment and development, especially as ski industry stakeholders are increasingly required to disclose information about physical climate risks and both adaptation and mitigation responses. Having accurate information regarding the projected localized climate change impacts would allow ski areas to reduce operational maladaptation and the risks of perceived greenwashing by improving the transparency and legitimacy of climate actions and communications.

2. Materials and Methods

The SkiSim2.0 ski operations model analyzes climate risks for 66 of the 74 operating ski resorts in the Canadian provinces of BC (40 of 42 are included in this study) and AB (26 of 32), including projected changes in key operational metrics of ski season length, natural snowfall, snowmaking requirements, and operations during key holiday periods [21]. To enable comparisons across regional markets, a priority identified by Steiger et al. [5], this analysis used model parameterizations and a common set of ensemble climate scenarios from Coupled Model Inter-comparison Project (CMIP) Phase 5, which has been extensively used in studies in eastern North America, Europe, and China, as well as applied to all Winter Olympic Games locations. Details on historical climate data, climate change scenarios, and the SkiSim2.0 model parameterizations used for this study are provided below.

2.1. Baseline Climate Data and Climate Change Scenarios

Daily weather data, including temperature (maximum, minimum, and mean), precipitation (rain and snowfall), and snow depth (where available), were obtained from the Meteorological Service of Canada [36] and the National Oceanic and Atmospheric Administration (NOAA) [37] for the 30-year (1981–2010) baseline period from 53 unique climate stations. Climate stations were chosen to represent each ski area based on (1) proximity (latitude and longitude, elevation) and (2) data availability for the variables and baseline period. Rural and mountain regions globally face challenges with a low-density of climate stations; some areas in this study had limited climate stations available, particularly at elevations of ski operations (i.e., not the valley floor). Therefore, the closest or most applicable (based on elevation, aspect, and localized knowledge of microclimate where possible) station(s) were chosen (average distance between ski area and climate station was 11 km, and maximum distance was 31.4 km). Where a suitable representative climate station was unavailable, the ski area was not included in the study. The proximity of the 43 selected climate stations allowed the representation of 57 ski areas (with differential adjustments for elevation, as outlined below). For the remaining 9 ski areas, an additional 10 climate stations were combined, wherein minor data gaps (missing weeks or months) at a primary climate station were filled through interpolated data from a nearby secondary climate station. In all cases, gaps of less than 5% of daily observations were filled. Where available, daily snow depth data was also obtained to train and refine the natural snow and snowmaking modules in the SkiSim model.

This study used an ensemble of 16 CMIP-5 and 17 CMIP-6 global climate models, developed by the World Climate Research Programme for the IPCC Fifth and Sixth Assessment Report [4], driven by five GHG emissions scenarios: RCP4.5 and RCP8.5 [from CMIP5], SSP245, SSP370, and SSP585 [from CMIP6]. These five climate change scenarios were selected to represent a range of possible emission futures, with RCP 4.5 and SSP245, representing lower emission scenarios consistent with the full achievement of current emission reduction pledges to the Paris Climate Agreement, leading to a 2.7 °C global average temperature increase by 2100 [38]. RCP 8.5 and SSP585 represent a high-emissions trajectory where countries fail to achieve current emission reduction pledges to the Paris Climate Agreement, leading to an estimated 4.4 °C increase by 2100 [38]. SSP370 represents a mid-range emission scenario, resulting in 3.6 °C by the end of the century [38]. While the rapid and deep emission reduction pathways of RCP 2.6, SSP119 and SSP126 are the only pathways that result in limiting warming to below the 2 °C target of the Paris Agreement, the literature increasingly considers these scenarios unlikely [39,40] and thus is not included. The Long Ashton Research Station (LARS) stochastic weather generator [41] then downscaled the monthly temperature and precipitation ensemble scenarios from CMIP-5 and -6 for mid- (2040–2069) and late-century (2070–2099) to daily resolution at the 52 climate station locations. LARS was selected because it has been identified as the best-performing weather generator to simulate North American precipitation statistics [42,43]. These synthetic weather time series were used for all time periods (baseline and future periods). While tourism or business planning do not generally consider late-century time horizons, this study included these scenarios to explore the long-range future of winter tourism and facilitate community discussions on implications for regional cultural identity and rural/small town economies that characterize the study area [35].

2.2. Ski Season Simulation Model

This study uses the SkiSim2.0 model, which includes (1) a physical snow model of the natural snowpack, (2) a snowmaking production module producing outputs across the entire ski area elevation range (in 100 m intervals), and (3) refined industry-based ski operations decision rules. Each of these model components is explained below, and further details on the SkiSim model are provided in Steiger [11].

The SkiSim2.0 models the natural snowpack using two parameters: (a) snowfall temperature (or precipitation typing) and (b) degree-day factors (snow-water equivalent melt), calibrated from the observed daily snow depth data over a 30-year observation period (1981–2010 baseline) from the closest climate station to the ski area. Snowfall temperature calibrations define a lower value that represents the temperature threshold for 100% snow and an upper value for the 100% rain threshold and linearly interpolate the snow-rain ratio between these two values. Snowfall measurements are then used for model calibration to compare observed versus modeled cumulative snowfall per season. Degree-day factor calibration is evaluated with a multi-year analysis of days with snow cover (snow depth threshold of 1 cm or more) per season to define the amount of snow water equivalent that is melted per 1 °C using a mean daily temperature that increases sinusoidally between 21 December and 21 June.

Following the snow model calibration, SkiSim simulates the natural snow-based ski season from the climate station's daily precipitation and temperature data and calculates additional snowmaking requirements to achieve the minimum 30 cm snow depth for ski operations. The model assumes ski groomers prepare the snow surface, which results in a snowpack density of approximately 400 kg/m^3 [44], and undertakes analysis at the critical elevation of each individual ski area. The critical elevation is the highest elevation where the ski lift system accesses skiable terrain, which allows skiing even when conditions at the lowest elevations are not suitable. Most of the ski areas in this study (50) use the base elevation as the critical elevation, while 16 ski areas have a substantial vertical wherein the mid- or upper mountain lift elevation is considered the critical elevation (i.e., skiing at high elevations can occur independent of conditions at base elevations). Climate station data was adjusted to this critical altitude based on a generalized lapse rate (temperature at 0.65 °C/100 m) and (precipitation at 3%/100 m) to represent the altitudinal difference between the station and the altitude of its corresponding ski area.

The snowmaking production module represents advanced operational capacity and industry-defined decision-making, which includes avoiding snow production when it is warmer than −5 °C, as efficiency declines rapidly and costs increase substantially. Because the Christmas-New Year holiday (defined as 15 December to 5 January) represents an economically important period, if needed, the model activates an 'emergency snowmaking' decision rule (with snowmaking up to −2 °C) to support sufficient snow base for operations. SkiSim2.0 snowmaking module therefore produces (a) an early season dense base layer (40 cm) to provide a durable foundation for ski operations; (b) improvement snowmaking to respond to mid-season melts and repair high traffic areas to enable continuous ski operations until the planned season end (usually in late March to early April in the study area); and (c) emergency snowmaking during warm temperatures (−2 °C or warmer) in the two weeks preceding the economically important Christmas-New Year holiday period. SkiSim2.0 records daily snowmaking production whenever combined natural and machine-made snow depth is insufficient for safe ski operations (minimum 30 cm) throughout the industry-defined snow-making period (between 1 November and 1 April in the study area). Potential snowmaking hours per day are calculated by linearly interpolating minimum and maximum temperatures to simulate the daily variation of temperature, and both daily and seasonal snowmaking requirements are recorded.

Data on the differing snowmaking system capacities across all 66 Western Canada ski areas is not available; therefore, this analysis assumes a standard advanced snowmaking production rate of approximately 10 cm/day, which represents the current capacity of many ski areas and the potential capacity other ski areas could reach with additional investment into snowmaking system upgrades. Like other regional studies, this snowmaking capacity is assumed across all skiable terrain and therefore represents a more climatically adapted operational state than currently exists in some ski areas. Because of the very long ski seasons in some parts of the study area, the potential season opening and closing dates were extended to allow SkiSim to model such extended seasons that are not typical in Eastern Canada and some other regional markets. For this study, ski areas are considered operational if snow depth (natural or combined with machine-made snow) exceeds 30 cm during the regionally defined potential operating season (1 October to 31 May).

Additional ski operations indicators, including "terrain days" and "skier intensity", developed by Scott et al. [7,9] to represent estimated changes in ski operations capacity across an entire regional market, were also included in this study. These indicators recognize that disruption in operations at some high-capacity ski areas may have cascading implications for ski tourism in a region and assess cumulative change in operational ski terrain and lift capacity at the regional scale, as well as the resulting implications for skier density or crowding (number of skiers per acre).

3. Results

The study found decreased average ski season length and increased snowmaking requirements across the Western Canadian ski market, with more pronounced changes under high-emissions scenarios (RCP8.5, SSP585) and longer timelines (2080s). The following analyzes outline the diverse impacts under the range of climate futures for key ski industry indicators, including: (1) ski area operational impacts—changes in viable ski days and snowmaking needed to support ski operations; (2) regional market capacity—changes in total available skiable terrain and lift capacity; and (3) economic viability—changes in likelihood of meeting economic indicators in the literature (including 100-day rule and key holiday operations). Study area projections are then compared with national, North American, and international ski markets in the discussion.

3.1. Ski Area Operational Impacts

Season length (with advanced snowmaking capacity): The average baseline season length (1980–2010) with advanced snowmaking across the ski areas in the study area was 155 days, with ski areas in BC slightly higher at 156 days and AB averaging 153. Within Western Canada, there are substantial differences in modeled baseline season length, as some coastal resorts like Grouse Mountain have average seasons under 100 days and others, such as Whistler, over 200 days.

As climate change accelerates throughout the 21st century, ski areas across Canada's western mountains are projected to experience shorter average season lengths across all scenarios (see Table 1), with more pronounced season length reductions in longer-term, high-emission scenarios. While resorts in BC have longer average baseline seasons than AB, they are projected to see greater changes because of the proximity to marine climate influences in some of their coastal region ski areas. If high-emission trajectories continue (RCP8.5 and SSP585), even by mid-century (2050s), BC ski areas are projected to experience an average 21% season length reduction, with lesser 14–16% average losses in AB. By the 2080s, season length losses under high-emission scenarios are projected to nearly double, reaching 36–39% in BC and 26–30% in AB. Very different outcomes are projected under lower-emission futures. If current emission reductions pledged under the Paris Climate Agreement are achieved (RCP4.5 and SSP245), AB may on average maintain as much as 90% of current ski seasons in the 2050s (average of 139 days) and 87% in the 2080s (average of 133 days). Season length reductions are more pronounced in BC, maintaining 83% of baseline season length in the 2050s and 78% in the 2080s (average of 131 and 121 days, respectively).

Table 1. Ski season-length with snowmaking (days and percentage reduction compared to baseline).

Region	Baseline (Days %Δ)	2050s RCP 4.5 (%)	SSP 245 (%)	SSP 370 (%)	RCP 8.5 (%)	SSP 585 (%)	2080s RCP 4.5 (%)	SSP 245 (%)	SSP 370 (%)	RCP 8.5 (%)	SSP 585 (%)
Alberta	153	138 (−10)	140 (−8)	134 (−13)	132 (−14)	128 (−16)	133 (−13)	132 (−14)	118 (−23)	114 (−26)	107 (−30)
British Columbia	156	130 (−17)	131 (−16)	131 (−16)	123 (−21)	122 (−21)	123 (−21)	119 (−23)	108 (−30)	98 (−36)	94 (−39)
Western Canada	155	134 (−14)	135 (−13)	133 (−14)	127 (−18)	126 (−18)	126 (−18)	125 (−19)	115 (−26)	105 (−32)	103 (−33)

Subregional season length impacts are diverse and consistent with the literature, influenced by latitude, elevation, and maritime climate. The five ski areas facing the greatest season length losses are all located in BC, south of the 50th parallel, have base elevations below 1000 m, and four of the five are in coastal regions. Inland ski areas, including central BC and AB, as well as those in more northern latitudes and at higher elevations, are more resilient to projected changes in climate.

Snowmaking: Western Canada ski resorts currently require 64 cm of snowmaking annually on average (Table 2). Similar to season length, results demonstrate that BC currently has a lower reliance on snowmaking (baseline of 55 cm) than AB (baseline of

76 cm) but will see greater increases in snowmaking needs under future climate change (upwards of a 400% increase over baseline by late-century under high-emission scenarios). AB is projected to require a relatively less, yet still substantial, two-fold increase in the same high-emission scenarios. By mid-century, Western Canada ski areas will require a 108–161% increase in snowmaking (based on low and high emissions scenarios) to limit losses in season length to those presented in Table 1. BC will require a greater increase in snowmaking (138–198%) than AB (75–121%) during this time and will surpass AB's annual average snowmaking needs under the 2050s high-emission scenarios.

Table 2. Snowmaking production increase (relative to baseline under future climate scenarios.

Region	Baseline (cm)	2050s RCP 4.5 (%)	SSP 245 (%)	SSP 370 (%)	RCP 8.5 (%)	SSP 585 (%)	2080s RCP 4.5 (%)	SSP 245 (%)	SSP 370 (%)	RCP 8.5 (%)	SSP585 (%)
Alberta	76	+96%	+121%	+75%	+79%	+102%	+127%	+234%	+111%	+150%	+218%
British Columbia	55	+154%	+199%	+138%	+146%	+193%	+208%	+401%	+214%	+287%	+401%
Western Canada	64	+126%	+161%	+108%	+114%	+149%	+169%	+321%	+164%	+221%	+313%

3.2. Regional Market Capacity

Ski areas vary considerably in size (acres of skiable terrain) and lift capacity; thus, the climate impacts at each ski area represent a variable portion of the region's ski market. Small and often community-run ski areas, less likely to have advanced snowmaking capacity and financial capacity to invest in large capital projects or withstand consecutive poor revenue seasons, are therefore more vulnerable to the impacts of climate change. While small ski areas are often essential for local community outdoor recreation and the development of skiing demand, losses of these smaller ski areas will have less of an impact on overall regional ski market capacity, relative to the potential loss of one of the 13 large resorts, which would reduce system capacity and have negative implications for skier experiences, including increasing lift wait times and crowding. To understand Western Canada's capacity to meet ski tourist demand (current and planned growth [22,25]) and potential impacts on ski tourist experiences under climate change, this analysis examined potential changes in market-level terrain days, lift capacity and skier intensity. Collectively, skier intensity, lift capacity, and terrain days provide insight into the total number of skiers the region could serve over a season under the range of future climates, with implications for destination market share and marketplace-scale capacity management [9].

Overall, the 66 ski areas included in this study represent 88% (approximately 79,000 acres) of Canada's total skiable terrain and 39% (approximately 378,000 lift rides per hour) of Canada's total lift capacity (calculated based on data reported by ski areas [20]). BC represents a much larger area of skiable terrain (over 59,900 acres) and lift capacity (over 256,500 lift rides per hour) with 10 major ski resorts, each with over 2000 acres and 10,000 lift rides per hour. AB has over 19,200 acres of skiable terrain and a 121,600 skier per hour lift capacity, but only large three resorts with over 2000 skiable acres and 10,000 lift capacity and many smaller communities with ski areas of only a few acres.

Terrain days represent the daily skiable area in operation for each individual ski area, aggregated to the regional market scale to provide a metric of system capacity (i.e., the cumulative acres of skiable terrain operational at all ski areas over an entire season). Western Canada has a baseline average of over 121.9 million acre days and can expect 4% losses in acre days by the 2050s under low emissions, increasing to 9% losses by the 2080s (see Table 3). Under high-emissions futures, the region is projected to experience 9% to 26% reductions in mid- and late-century. While AB was more resilient to climate change in terms of operational impacts, this sub-region is projected to experience higher losses in skiable terrain (−31%) than BC (−24%) under high-emission scenarios. This is primarily the result of substantial impacts on one of its four major ski resorts, but conversely, may highlight market opportunities for nearby ski areas in both AB and BC with relatively limited climate impacts.

Table 3. Projected changes in average skiable terrain and lift capacity.

Region	Baseline AC = Acre Days L = Seasonal Lift Capacity	2050s RCP 4.5 (%)	SSP 245 (%)	SSP 370 (%)	RCP 8.5 (%)	SSP 585 (%)	2080s RCP 4.5 (%)	SSP 245 (%)	SSP 370 (%)	RCP 8.5 (%)	SSP 585 (%)
Alberta	AC = 2,947,653	−6%	−12%	−4%	−6%	−11%	−11%	−31%	−12%	−19%	−30%
	L = 121,948,271	−3%	−7%	−1%	−3%	−6%	−7%	−22%	−7%	−13%	−21%
British Columbia	AC = 8,425,237	−3%	−7%	−3%	−4%	−8%	−7%	−23%	−9%	−16%	−25%
	L = 262,941,173	−1%	−5%	−1%	−2%	−6%	−5%	−20%	−7%	−14%	−22%
Western Canada	AC = 11,394,386	−4%	−9%	−4%	−5%	−9%	−8%	−25%	−10%	−17%	−26%
	L = 385,621,227	−2%	−6%	−2%	−2%	−6%	−6%	−21%	−7%	−14%	−22%

Lift capacity indicates the potential seasonal lift capacity for each ski area based on stated lift capacity per hour (based on self-reported data [32]), assuming all lifts are operating from 9 a.m. to 4 p.m. during the entire season-length (modeled operational days). The lift capacity of individual ski areas is then aggregated to estimate the total capacity for the Western Canada ski market. The region has a baseline seasonal average lift capacity of approximately 385.6 million rides across the 66 ski areas. Assuming each of the 8.2 million reported average annual skier visits [22] takes 10 lift rides per day, current skier visits use approximately 20% of Western Canada's total lift capacity. By mid-century, as average season length shortens, market-wide seasonal lift capacity is projected to decrease only slightly (2%) in both low- and medium-emission scenarios. While regional season length losses are projected at 14% in low-emissions short-term futures, losses in skiable terrain days and lift capacity losses are only 2%, which demonstrates the proportional impact based on ski area size and capacity. The more limited impacts on larger resorts demonstrate the importance of a regional market perspective. Under longer timeframes and high-emission scenarios, Western Canada average lift capacity, terrain days and season length losses are closer, at 22%, 26% and 33%, respectively, suggesting some of the larger resorts are experiencing climate impacts that have greater implications for the overall regional market. In the 2080s, lift capacity is reduced by less than 15% in low- and medium-emission scenarios but up to 22% in high-emission scenarios, resulting in only 380 million lift rides across the entire region (down from 407 million currently). If skier visits remain consistent, demand will be using 26% of supply capacity (up from only 20% in the baseline).

Skier intensity is calculated based on the annual average number of skiers per acre-day (i.e., operational terrain) at the regional ski market scale and provides insight into potential crowding. Baseline utilization intensity is estimated at 0.7 skiers per acre-day of operational terrain (see Table 4). This calculation is based on a pre-COVID decade average in regional skier visits (8.2 million [22]) and assumes an even distribution of skiers across all available terrain and operating days. While an even spatial and temporal distribution is not the observed pattern, assuming demand and distribution patterns remain largely unchanged, this metric demonstrates potential trends in crowding as supply-side changes in capacity occur. Skier utilization intensity is anticipated to increase to between 4% and 10% skiers per acre-day under low- and high-emissions scenarios, respectively, by mid-century. By the late 20th century, crowding could intensify up to 35% under high-emission scenarios. AB will experience greater crowding, up to 42%, versus only 33% in BC.

Table 4. Changes in skier intensity (skiers per terrain acre) under future climate scenarios.

Western Canada Average	Baseline Skier Intensity	2050s RCP 4.5	SSP 245	SSP 370	RCP 8.5	SSP 585	2080s RCP 4.5	SSP 245	SSP 370	RCP 8.5	SSP 585
Current Skier Visits (8.2 million)	0.67	0.7	0.74	0.7	0.71	0.74	0.73	0.9	0.75	0.81	0.9
Projected Skier Visit (9.3 million)	0.76	0.8	0.84	0.79	0.8	0.84	0.83	1	0.85	0.92	1

It is notable that if future skier visits approximated industry-estimated regional market growth of 13.3% by 2030 (reaching 9.3 million skier visits annually on average), skier intensity would be over 1 skier per acre-day (a 30% increase) and reach 30% of the region's lift capacity (up from 20% currently). Any new supply added by the opening of new ski areas would reduce terrain and lift capacity utilization rates but would require several large new resorts to substantially reduce region-wide utilization rates.

3.3. Economic Viability

Season Segments: Within a ski season, the New Year holiday (20 December–4 January) and March school break holiday (1–20 March) are noted by Scott et al. [7,9] as key operational periods in North American markets because they represent high skier visitation season segments. A key finding is that ski areas in Western Canada remain reliably operational in these essential seasonal segments across all climate scenarios. Early season (1 November–19 December) and late-season (21 March–30 April) segments, while currently reliable in Western Canada, are projected to experience substantial losses (up to 52% and 28%, respectively), with potentially greater losses in BC (up to 58% of early season and 36% of late season ski day losses). While some ski areas in this region may open in the pre-season (before 1 November) and post-season (May and beyond) when anomalous snow conditions allow (e.g., Nakiska's earliest opening on 26 October 2019 for a "preview weekend" following an early cold period [45]), these season segments are not usually reliable in terms of natural snowpack or the conditions to produce enough snow for operating.

Economic Viability: To further assess the economic viability of each ski area within the Western Canada ski market under future climate scenarios, two key indicators that have been used in the literature are evaluated: (1) a 100-day or more season-length [46,47], and (2) operational conditions during the Christmas–New Year season segment [7,9,12]. Consistent with the literature, a threshold of achieving both metrics in 70% of all seasons was considered indicative of climate resilience and continued economic viability (see Table 5). Importantly, the study area remains highly resilient to climate change on both metrics, with all but one ski area currently meeting both criteria and the regional average falling to between 83–86% in the 2050s and as low as 71% under high-emission scenarios in the 2080s (Table 5). Further research on the relationship between season length, operating costs, demand and revenue, and adaptation investments is needed in this region to improve insight into the economic prospects of the ski industry in Western Canada under climate change. Ultimately, only the companies or communities that operate ski areas can accurately assess the financial viability of ski areas as climate change impacts operating costs, demand, and visitor temporal and spatial substitution dynamics.

Table 5. Percentage of ski areas meeting both indicators of economic viability (100+ day season-length and operational during the New Year Holiday segment) with a probability of >70% under current and future climate scenarios.

Region	Baseline (Meeting Criteria/Total)	2050s RCP 4.5 (%)	SSP 245 (%)	SSP 370 (%)	RCP 8.5 (%)	SSP 585 (%)	2080s RCP 4.5 (%)	SSP 245 (%)	SSP 370 (%)	RCP 8.5 (%)	SSP 585 (%)
Alberta	26/26	88	88	88	88	85	88	85	85	85	81
British Columbia	39/40	85	85	83	83	83	83	83	75	70	65
Western Canada	65/66	86	86	85	83	83	85	83	79	76	71

4. Discussion

This study expands the geographic scope of climate change and ski tourism research in North America, finding that broad climate change patterns of season length contraction, increased snowmaking needs, and reduced available terrain and lift capacity seen globally [5] are also prevalent across Western Canada. Understanding and comparing the specifics of the projections within regional markets can inform individual ski area management strategies for community and provincial climate action and tourism planning [21]. Comparing inter-regional climate risks relative to other continental and international markets is essential for destination and national tourism marketing and development policy. The multi-scalar implications of the results of this study are therefore examined below.

4.1. Intra-Regional Climate Risk

Intra-regional results show BC currently has a longer baseline season, yet throughout all future scenarios, AB becomes more climate resilient and maintains a 100-day average season across all scenarios. In their review of the ski industry and climate change literature, Steiger et al. [5] noted the discrepancy between observed and modeled ski seasons in some studies and emphasized the importance of assessing model performance against metrics of ski operations. A comprehensive dataset of historical ski industry performance was not available for Western Canada. To examine SkiSim model performance in the study area, multiple data sources of ski industry performance over the last decade were combined. Self-reported ski season length for the five-year period of 2015/16 to 2020/21 (not including 2019/2020 due to COVID disruptions) was available for 37 ski areas in the study area (obtained from [32,48]). For these ski areas, average seasons begin on November 26 and last until April 14 (a 139-day season). The average reported season was longer at the 12 ski areas in AB (155 days) than for the 25 BC ski areas (131 days). When comparing the SkiSim baseline average season (1981 to 2010) for the same 37 ski areas with reported average season data available, SkiSim was found to overestimate season length in both AB (160 days simulated vs. 155 days reported) and more so in BC (163 days simulated vs. 131 days reported).

This intra-provincial range is consistent with previous applications of SkiSim in other regional markets, and the overestimation in BC is influenced by two model parameterizations: snowmaking infrastructure and business models. The assumption of 100% snowmaking terrain coverage is much higher than the reported coverage at the 25 BC ski areas (14%), yet it was made to enable comparisons with AB (with a reported average of approximately 70% terrain coverage) and other regions of Canada and the US where coverage exceeds 90% [21]. For ski areas with ample natural snow that do not need the assumed extra snowmaking capacity, SkiSim2.0 will not activate snowmaking, leading to no overestimation of the ski season. At ski areas with limited snow resources, the assumed additional snowmaking capacity is utilized, and modeled ski seasons can be substantially longer as a result. For example, at Sunshine (AB), which has only 1% snowmaking terrain coverage [32], the reported and modeled season lengths were within 3 days. In contrast to Big White (BC), which has no snowmaking capacity [32], the modeled season with advanced snowmaking is 28 days longer than the reported average season.

Differing business models also influence operational approaches to season opening and closing. Ski areas with average reported seasons approaching or exceeding 200 days (e.g., Lake Louise, Marmot Basin, Norquay, Sunshine, Whistler) do not end their season at a fixed date but rather cease operations based on available snow conditions. In contrast, several ski areas in the study area will begin and/or cease operations at a specified date regardless of snow conditions (e.g., ski areas in National Parks close because of wildlife regulations) [34,35]. To model these long seasons, an unconstrained end-of-season date was used in this study, which overestimated season length at several BC ski areas with fixed closing dates by three to four weeks. Unfortunately, comprehensive data on these key operational heuristics that would inform multiple model parameterizations to reflect current management practices is not available for all ski areas in the study area. Where such information on snowmaking capacity and management approaches is available, the SkiSim model can be parameterized to represent individual ski area operations and site-specific performance metrics, which are best to inform local climate risk assessment and adaptation planning.

Recent record warm winters provide analogies for future climate change-impacted ski seasons, demonstrating additional insights into the intra-regional model results and impacts on tourist demand. Consistent with SkiSim projected futures, AB ski areas demonstrate more climate resilience because of their colder temperatures and greater snowmaking capacity. Environment Canada data indicates that in AB, 2011/2012 and 2015/2016 are the second and third warmest winters on record, with 6.1 °C and 5.5 °C above the 1971–2000 normal [49]. In BC's Pacific Coast and South Mountains, the 2014/2015 season was the warmest and second warmest winter since records began in 1948, with regional average temperatures 2.9 °C and 3.4 °C above the 1971–2000 normal [49]. While the temperature departures are larger in AB, the observed season length from 2015/2016 and skier visits from both seasons demonstrate that losses are not as significant as in BC. With average daytime high winter temperatures in southern AB in the −5 °C to −15 °C range [49], even these near-record warmer temperatures provide the temperatures required for efficient snowmaking and natural snowfall. Compared to the five-year average season length, AB's anomalously warm season was six days longer. Conversely, the average ski season length reported by the 25 BC ski areas during this region's anomalously warm season was 13 days, or 10%, shorter than the available five-year average for the province.

The implications of warmer weather on economic viability similarly demonstrate greater resilience in AB. AB season length and skier visitation remained relatively constant across the 2008–2018 decade, despite the 2011/12 and 2015/16 record warm winters [22]. Operating ski areas in the province remained constant or grew following these years [22]. BC's record warm winter coincided with substantial declines in operational ski areas and skier visits. Province-wide, the Canadian Ski Council [22] reports that skier visits to BC's 46 ski resorts declined by 1.43 million, or −24%, versus the previous three-year average, and there were only 39 ski areas operating the following winter, seven less than before the record warm winter. It is uncertain to what extent the record warm winter contributed to this loss of operating ski areas, but considering this analogy represents less than SkiSim's RCP4.5 2050 scenario in terms of season length losses, further research on the implications of climate change on economic viability and demand-side shifts would be valuable. Future research to investigate the characteristics of the ski areas lost after the record warm winter in BC and determine regional, elevational, size, corporate structural and other factors that may have led to their closure would be useful to inform destination communities and enable them to adapt proactively to future changes projected. While the impact of record warm winters in BC was much greater, there remains uncertainty across Western Canada as to the implications of multiple consecutive shortened seasons.

4.2. Inter-Regional Comparison

Because Western Canada is a national and international ski destination, it is important to compare the projected impacts of climate change in this regional market with others across North America and internationally. Figure 1 provides a comparison of the projected impacts of common climate change scenarios (RCP 4.5-low emissions and 8.5-high emissions) on multiple North American regional ski markets assessed with the SkiSim model. Other studies that use different methodologies and that have been found to not model observed seasons as accurately as SkiSim (see comparisons in [7,9]) are not included in this comparison. Western Canada's 155-day current average season length is 14%, 34%, 29% and 37% longer, respectively, than Quebec, Ontario, and the United States northeast and mid-west regional baseline seasons (Figure 1). Across Canada, baseline snowmaking requirements are the lowest in Quebec (31 cm), followed by BC (55 cm), Ontario (63 cm) and AB with the largest current average use of snowmaking (76 cm) (Figure 1). The United States ski regions have greater baseline snowmaking requirements than their more northern competitors in Canada, with the Northeast requiring an average of 81 cm and the Midwest requiring 107 cm.

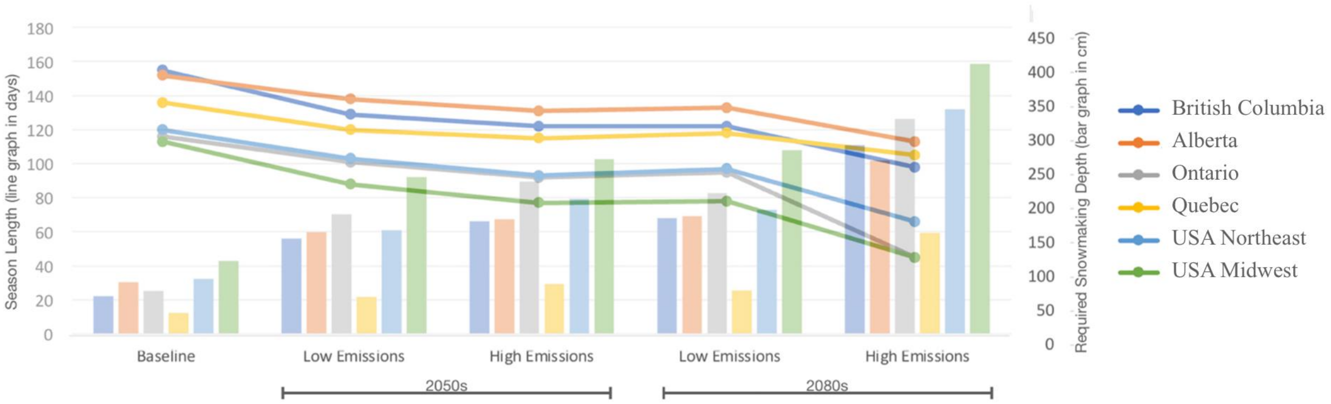

Figure 1. Continental comparison of projected ski season losses and snowmaking requirements in regional markets [7,9].

As climate change accelerates, particularly under high-emission and end-of-century horizons, inter-regional impact disparities become apparent (see Figure 1). In the 2080s under high emissions, Quebec and AB have season-length losses under 30% and remain operational for over 100-day season-lengths (106 and 107, respectively). BC has greater season length losses of 38% and drops slightly below an average 100-day season to 96 days, yet remains resilient compared with Ontario and the US Midwest, where season length declines to 46 days and 67 days, respectively. The major declines in season length combined with required snowmaking increases of 545% and 355%, respectively, could result in a nearly total loss of the ski tourism market in Ontario and the US Midwest market by the end of this century [7,9]. The US Northeast fares slightly better with a 45% decrease in season length and a 308% increase in snowmaking production [7], but results in a season length of only 67 days, which does not meet economic viability criteria. While Quebec and Western Canada remain more resilient to season length losses, snowmaking needs still increase significantly in both regions (+377% in QC and +401% in AB). Major differences lie in snowmaking capacity, currently estimated at 90% for Quebec and only 25% for western Canada, which would require massive infrastructure investments in Western Canada. Both regions maintain a similar percentage of regional ski areas based on the above economic viability criteria. Overall, this demonstrates that within North America there will remain a Western and an Eastern ski tourism market, but that Canada might see a net increase in ski tourists as demand patterns shift to respond to changing supply availability. Considering the US ski tourism market of 55 million average annual skier visits [50] is significantly larger than Canada's 19 million, this could have major implications for resorts and surrounding community infrastructure.

Internationally, comparing Western Canada to key ski markets, including the origins of skiing in Scandinavia, the heart of ski culture in the European Alps, and new Asian markets, demonstrates a contraction of the entire international ski tourism market due to climate change [5]. Scandinavia shows comparable results to Western Canada, with over 70% of Norway's ski areas remaining economically viable (over 100-day season-length and operational during the December holiday period) in even high-emission scenarios by the end of the century [12]. Under the same climate scenario, even after losing nearly half its baseline season, Sweden maintains an average season length of 104 days with a snowmaking increase of 353% [10]. Both are comparable to Western Canada. In the European Alps, the Tyrol region was projected by Steiger [11] for 85% reductions in season length under high-emissions long-term horizons, suggesting less resilience to climate change than Western Canada. China's large and diverse ski tourism market, already highly dependent on snowmaking (baseline of 187 cm), averages a 117-day season, which could contract by up to 61% in high-emission long term futures. However, China's Heilongjiang region may outperform Western Canada, while Xinjiang, Qinghai and Jilin are more vulnerable [16].

These variable risks across continental and international scales will shift demand for international ski tourism patterns as skiers transfer from climatically vulnerable regions to relatively resilient areas [5,51]. This redistribution of global demand pressures to relatively resilient ski tourism markets such as Western Canada, Sweden or Norway may be constrained by infrastructural (lift capacity), terrain (skier intensity) limitations, and tourist preferences for ski culture amenities. Further research may also explore concepts of "last-chance tourism", including tourist motivations, education and awareness of climate change, and the contradictory impacts of increased travel using carbon-intensive transportation [52] to witness landscapes vanishing due to climate change in the context of the remaining resilient ski tourism destinations [35,53,54]. As climate change accelerates, the ski industry and destination stakeholders across North America discuss a significant shift to four-season activities [34,35]. Future research exploring shifting seasonality and the extent to which new activities may replace traditional winter activities in ski destinations, as well as the socio-ecological impacts of such activities amidst climate change, would be valuable.

5. Conclusions

The results of this study demonstrate Western Canada has relatively low physical climate risks compared with other national, continental, and international ski tourism markets, yet it is still projected to experience shortened seasons and increased snowmaking requirements to maintain ski tourism operations. Greater impacts are projected in the southern, coastal, and high plateau sub-regions. The results highlight snowmaking as an essential adaptation for this region to respond to later snowfall, earlier spring melt, and mid-season temperature and snowfall variability. These results, combined with the currently limited snowmaking capacity, have an important implication for both academia and industry, suggesting a need for future research investigating the effectiveness and impacts of further investment in snowmaking infrastructure, especially in areas with limited water resources and high-carbon-intensity electricity grids [21]. Furthermore, as Western Canada is home to the "powder highway" of ski resorts, visitor expectations of powder skiing versus a future experience of more machine-made snow may result in changing tourist patterns or a need to rebrand the Western Canada ski experience for industry stakeholders. Academia may explore ski tourism responses to compounding climate impacts, which remain uncertain and a priority research area [5,7,34]. Further research is also needed to understand the dynamics of market contraction, skier congestion, spatial substitutions (and associated emissions), the loss of small grassroots ski areas and sport participation, and how successive warm winters may influence tourist behavior [21]. While SkiSim2.0 does not simulate demand, seasonal tourism shifts or indirect implications of climate change, the results from this comparable analysis of North America's continental ski tourism supply-side climate risk allow for a system-wide perspective that provides ski industry and destination communities with information about future operational shifts that can be used to prepare for new demand patterns and inform adaptive responses to climate change [21]. Combining this foundational climate risk research with future research that engages sport and tourism industry leaders, adaptation technology developers, tourists, and community stakeholders in the research process using decision-based methodologies such as narratives, adaptation pathways and transition management will improve evidence-based climate resilient transformations in ski tourism [5,6,21,35,51].

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