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Impacts of climate change on artificial and natural snow cover on ski resorts: the case of Alps ski resorts

Diploma Thesis

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DIPLOMA THESIS ASSIGNMENT

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LANDSCAPE ENGINEERING
LANDSCAPE PLANNING

Thesis title:

Impacts of climate change on artificial and natural snow cover on ski resorts: the case of Alps ski resorts

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Preface:

Weather and climate are intrinsic components of the tourism experience, influencing tourist demand, comfort and satisfaction, as well as tourism operations (e.g. water supply, energy costs, insurance costs) and environmental resources critical to the industry (e.g. glaciers, biodiversity, water levels, snow). A changing climate has the potential to significantly influence this economically important and climate-sensitive sector (Dawson J. & Scott D. (2013).

Climate change has the potential to significantly impact the winter tourism sector, particularly the ski industry, which has been identified as one of the most vulnerable industries to climatic change. Ski resorts have long been dealing with variability in seasonal temperature and natural snowfall, leading to early adaptive interventions and investments in research and development aimed at sustaining longer and more reliable snow seasons. Despite technological advances in snowmaking machinery and application, and the modernization of business plans, even the most sophisticated adaptation strategies still cannot shelter ski areas from the current and expected impacts of climate change. The implications of climate change vary substantially by market segment and geographic region and will depend on the impacts experienced by competitors. Understanding how the entire ski marketplace may transform, and may be influenced by changes to individual ski areas, can help ski resort managers as well as municipal, state, and federal decision-makers establish sustainable development plans and future management strategies.

Objectives of thesis:

This study reviews the main scientific literature on the relationship between climate change and the ski industry. The findings generally point to a significant impact of climate change on the ski industry caused by a reduction in the natural availability of snow and a contraction in the duration of seasonal conditions suitable for skiing. The problem is real and should not be ignored in the study and management of tourism in mountain regions. However, the impacts vary between different areas and are mainly associated with the elevation of the ski resorts, their infrastructures for snowmaking, and the various climate models, emission scenarios, time horizons, and scales of analysis used. The study highlights the need for scientists to harmonize indicators and methodology to allow for better comparison of results from different studies and increase the clarity of conclusions transmitted to land managers and policy makers. Additionally, a better integration of uncertainty in the model's outputs and a more accurate treatment of the snowpack on ski slopes is necessary to provide more accurate indications of how this sector will respond to climate change.

Methodology:

This thesis implements a combination of mixed research methodologies and strategies, which are complementary. This study aims to model the impact of climate change on the ski sector in the Alps by using individual ski areas as case studies. The methodologies used take into account snowmaking technologies and elevation differences at each ski area, and use generic lapse rates to calibrate projections for temperature change. By incorporating these refinements and modeling every ski area in the region, the study aims to determine which ski areas are more vulnerable under different time horizons and climate change scenarios. Consequently, analyzing the data via Esri ArcGIS and Computer-aided design software (CAD), providing questionnaires, and SWOT table is the main driving force alongside the methods mentioned above apply in this research area.

Literature review:

One study focused on analyzing the vegetation composition and diversity in the Nízke Tatry region of Slovakia. The research aimed to compare the vegetation on ski pistes to the vegetation next to or off of ski pistes. The method involved sampling plots in the montane and alpine zones, with a focus on grassland habitats and not surveying forest plant communities. Samplings were taken in three different positions: directly on the ski piste, on the edge, and off-piste. The analysis aimed to identify relationships between environmental variables, the elements of management, and the positions of individual samples, and how they affect the abundance of species and vegetation richness. The results of the study showed that within unmanaged sites, human impact on vegetation is mainly through the occurrence of synanthropic plant species, and on ski runs where a combination of cutting and seeding is used as the management method (Kňazovičová et al., 2018).

Another study examined the impact of ski resorts on alpine ecosystems by studying the vegetation of plots on and next to ski pistes in 12 ski resorts in the Swiss Alps, at altitudes between 1750 and 2550 meters above sea level. The study sites represented a variety of vegetation types, mostly alpine grasslands on acidic or calcareous bedrock and dwarf shrub heath, and were chosen based on machine-graded or ungraded ski pistes with natural or artificial snow, resulting in four different ski piste types. The study found that ski pistes harm the species richness in alpine grassland and dwarf shrub vegetation. The research design involved fitting the type of plot pairs, i.e. the kind of piste treatment of the piste plot in the couple, and the interactions of pair type and piste, which indicated if the difference between plots on and near the piste depended on the type of piste treatment (Wipf et al., 2005).

Another article discusses the phenomenon of second homes and its environmental consequences, such as the building up of extra land and the use of additional fuel to get there. The authors analyze the user groups and reasons for using second homes, and pose the following questions: does a dense urban residential environment increase the use of second homes? Does a lack of private garden in the primary house increase the use of second homes? Does a lack of local green areas within 300 meters of the primary residence increase the use of second homes? Does a lack of outdoor recreation parks within 1 kilometer of the primary residence increase the use of second homes? Through a survey, the authors found that the first statement is true and disproved the third and fourth statement. They also found that the use of second homes increases if the users live in apartments and decreases if they live in a private house, although respondents disagreed that this statement described their situation. Overall, the results of the survey show that the use of second homes is more significant in densely urban areas (Strandell A. & Hall C. M. 2015).

Another study focused on the mountainous areas in central Japan and aimed to understand the role of ski resorts as refuges for herbaceous, wetland, and forest floor plants. The authors used two methods: Phytosociological investigation and Measurement of canopy closure. The study used vegetation surveys to investigate the species composition and characteristics of plant communities in plots at seven different site types within a ski resort: forests, an abandoned ski slope, an area under the gondola lines, forest waterfronts, open waterfronts, edges of ski slopes, and active ski slopes. The study found that on the abandoned ski slope, under the gondola lines, at the edges of ski slopes, and on the ski slope, canopy closure was low, tall herbs were present, and species diversity was high. There were significant differences between each relationship among sites, although there was no significant difference between forests and forest waterfronts, between the abandoned ski slope and the site under the gondola lines, between the active and abandoned ski slope, and between the ski slope and open waterfronts. The highest diversity index value was for forest waterfronts, followed by the site under the gondola lines, edges of the ski slope, open waterfronts, the abandoned ski slope, the active ski slope, and forests. The study also investigated how different sites and management strategies such as mowing, provide a habitat for various plants (Kubota, Hitomi & Shimano, Koji. 2010)

The proposed extent of the thesis:

50 Pages

Keywords:

Climate change, Snow cover, Ski resorts, Fragmented parcels, The Alps

Recommended information sources

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DIPLOMA THESIS AUTHOR'S DECLARATION

I hereby declare that I have independently elaborated the diploma/final thesis with the topic of:
Impacts of climate change on artificial and natural snow cover on ski resorts: the case of Alps ski resorts, and that I have cited all the information sources that I used in the thesis and that are also listed at the end of the thesis in the list of used information sources. I am aware that my diploma/final thesis is subject to Act No. 121/2000 Coll., on copyright, on rights related to copyright and on amendment of some acts, as amended by later regulations, particularly the provisions of Section 35(3) of the act on the use of the thesis. I am aware that by submitting the diploma/final thesis I agree with its publication under Act No. 111/1998 Coll., on universities and on the change and amendments of some acts, as amended, regardless of the result of its defence. With my own signature, I also declare that the electronic version is identical to the printed version and the data stated in the thesis has been processed in relation to the GDPR.

Date

Kseniia Shamrikova

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ABSTRACT

Climate change is a major threat to the ski industry, as it can lead to shorter ski seasons and less reliable snowfall. This study examines the impacts of climate change on the artificial and natural snow cover at ski resorts in the Alps, with a focus on the challenges and opportunities for the ski industry and local economies. The study will use a combination of observational data and numerical models to assess the changes in snow cover patterns, snow quality, and the ski season length in the Alps, and to evaluate the effectiveness of snow-making systems and other adaptation measures. The research will also explore the social and economic implications of climate change on winter tourism in the Alps, including the effects on local communities, ski resort operators, and other stakeholders. The ultimate goal of this research is to contribute to a better understanding of the challenges and opportunities posed by climate change for the ski industry and winter tourism in the Alps, and to provide insights into how the industry can be more resilient and sustainable in the face of a changing climate.

KEYWORDS: Climate change, Snow cover, Ski resorts, Fragmented parcels, The Alps

ABSTRAKT

Změna klimatu představuje významnou hrozbu pro lyžařský průmysl, protože může vést ke kratším lyžařským sezónám a méně spolehlivé sněhové pokrývce. Tato studie zkoumá dopady změny klimatu na umělou a přírodní sněhovou pokrývku v lyžařských střediscích v Alpách, se zaměřením na výzvy a příležitosti pro lyžařský průmysl a místní ekonomiky. Studie využije kombinaci pozorovacích dat a numerických modelů k posouzení změn vzorů sněhové pokrývky, kvality sněhu a délky lyžařské sezóny v Alpách a k vyhodnocení účinnosti systémů umělého zasněžování a dalších adaptačních opatření. Výzkum se také bude zabývat sociálními a ekonomickickými důsledky změny klimatu na zimní cestovní ruch v Alpách, včetně dopadů na místní komunity, provozovatele lyžařských středisek a další zainteresované strany. Hlavním cílem tohoto výzkumu je přispět k lepšímu porozumění výzvám a příležitostem, které změna klimatu představuje pro lyžařský průmysl a zimní cestovní ruch v Alpách, a poskytnout poznatky o tom, jak se může toto odvětví stát odolnější a udržitelnější tváří v tvář měnícího se klimatu.

KLÍČOVÁ SLOVA: Změna klimatu, Sněhová pokrývka, Lyžařská střediska, Fragmentované parcely, Alpy

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1. Introduction

Weather and climate are intrinsic components of the tourism experience, influencing tourist demand, comfort and satisfaction, as well as tourism operations (e.g. water supply, energy costs, insurance costs) and environmental resources critical to the industry (e.g. glaciers, biodiversity, water levels, snow). A changing climate has the potential to significantly influence this economically important and climate-sensitive sector (Dawson J. & Scott D., 2013).

Climate change has the potential to significantly impact the winter tourism sector, particularly the ski industry, which has been identified as one of the most vulnerable industries to climatic change. Ski resorts have long been dealing with variability in seasonal temperature and natural snowfall, leading to early adaptive interventions and investments in research and development aimed at sustaining longer and more reliable snow seasons. Despite technological advances in snowmaking machinery and application, and the modernization of business plans, even the most sophisticated adaptation strategies still cannot shelter ski areas from the current and expected impacts of climate change. The implications of climate change vary substantially by market segment and geographic region and will depend on the impacts experienced by competitors. Understanding how the entire ski marketplace may transform, and may be influenced by changes to individual ski areas, can help ski resort managers as well as municipal, state, and federal decision-makers establish sustainable development plans and future management strategies.

For example, beach destinations are often affected by hurricanes and typhoons, while ski resorts are dependent on adequate snowfall. Political instability, natural disasters, and health epidemics can also have a significant impact on tourism. Additionally, local policies and regulations can either encourage or discourage tourism development. The changing climate and its impacts on the natural environment can also influence tourism, with some destinations becoming less attractive due to environmental degradation and others becoming more popular due to the increased availability of natural resources. Therefore, it is important for the tourism industry to be mindful of the relationships between tourism, the natural environment, and the various factors that can impact both (Becken & Hay, 2007).

The Alps are a popular winter tourism destination, attracting millions of visitors each year who come to enjoy winter sports such as skiing and snowboarding. However, as the climate changes, the ski industry is facing a number of challenges. Rising temperatures and changes in precipitation patterns can result in shorter and less reliable ski seasons, which can have a significant impact on the industry and local economies. In addition, changes in the snow cover can affect the quality of the skiing experience, with a decrease in snow depth and coverage reducing the length of ski runs and the overall skiing area. The impact of climate change is particularly pronounced in low-altitude ski resorts, where the ski season can be severely impacted by milder temperatures and a lack of snow (Abegg et al., 2007).

Indeed, the representation of the snowpack in numerical models is a complex task that requires a careful balance between complexity and accuracy. The snowpack is influenced by many different climate variables, such as temperature, precipitation, wind, and solar radiation, and these variables can interact in complex ways. Models that use a high temporal resolution, such as daily or hourly data, can provide a more detailed representation of the snowpack, but they also require a large amount of data and computational resources. On the other hand, less complex models, such as monthly or seasonal models, can provide a simpler representation of the snowpack, but they also entail the risk of oversimplification as many processes are parameterized. In general, the choice of a model depends on the specific needs and goals of the user. For example, if the goal is to understand the long-term evolution of the snowpack, a seasonal or annual model may be sufficient, while if the goal is to simulate the daily changes in the snowpack, a high temporal resolution model may be required. Regardless of the choice of model, it is important to validate the results against observational data and to consider the uncertainties and limitations of the model. Additionally, it is important to consider the potential impacts of climate change on the snowpack, as these can have important implications for winter tourism and other snow-dependent industries (Hennessy et al. 2003; Scott et al., 2008; Steiger, 2007; Steiger & Mayer, 2008).

2. Objectives

The objective of this research is to examine the impacts of climate change on the artificial and natural snow cover at ski resorts in the Alps, with a focus on the challenges and opportunities for the ski industry and local economies. The study will use a combination of observational data and numerical models to assess the changes in snow cover patterns, snow quality, and the ski season length in the Alps, and to evaluate the effectiveness of snow-making systems and other adaptation measures. The research will also explore the social and economic implications of climate change on winter tourism in the Alps, including the effects on local communities, ski resort operators, and other stakeholders. The ultimate goal of this research is to contribute to a better understanding of the challenges and opportunities posed by climate change for the ski industry and winter tourism in the Alps, and to provide insights into how the industry can be more resilient and sustainable in the face of a changing climate.

In this framework, The research will be based on the following framework:

1. Literature Review: A comprehensive review of the existing literature on the impacts of climate change on snow cover at ski resorts, including the scientific and technical aspects, as well as the social and economic implications.
2. Data Collection: Collection of observational data on snow cover and climate in the Alps, including satellite imagery, weather station data, and other relevant sources.
3. Modeling: Development and application of numerical models to simulate the changes in snow cover patterns and the ski season length under different climate scenarios. The models will be validated against the observational data.
4. Analysis: Analysis of the results of the modeling and data collection to identify the key factors affecting the artificial and natural snow cover at ski resorts in the Alps, and to assess the effectiveness of snow-making systems and other adaptation measures.
5. Impacts Assessment: Assessment of the social and economic implications of climate

change on winter tourism in the Alps, including the effects on local communities, ski resort operators, and other stakeholders.

6. Recommendations: Development of recommendations for the ski industry and other stakeholders on how to enhance the resilience and sustainability of winter tourism in the face of a changing climate.

7. Conclusions: Synthesis of the key findings and recommendations, and identification of areas for future research.

3. Literature review

This part of the document is a summary of research papers and writings by other important groups. Its purpose is to introduce key concepts and principles that are often discussed in related literature. It's split into two parts: one that looks at the current issues in the field, and another that looks at potential solutions for the future.

3.1 Theoretical foundation

The ski tourism industry in the Alps is facing significant challenges in the coming decades, including demographic change and climate change. As Witting & Schmude, 2019 denoted, demographic change as will result in aging skiers and declining skier demand, while climate change will lead to a decreasing number of operating days, reduced snow reliability, and increasing operating costs in some destinations. The impact of these factors on skier demand has been quantified for Austria but not for the German Alps. To address this gap, a demand-side study was conducted on the Sudelfeld ski area in Bavaria, German Alps. The study estimates the impact of climate and demographic change on skier days and future turnover at the destination. Additionally, the study provides a rough indication of how many non-skiing tourists need to be won by the destination to compensate for the calculated changes in demand (Witting & Schmude, 2019).

The results of the research on the climate change impacts indicate a significant snow reduction in the natural availability and a contraction in the duration of suitable ski season condition. This highlights the need for scientists and policymakers to take the problem seriously and develop appropriate strategies for managing tourism in mountain regions. However, there are significant differences in the impact of climate change between different areas due to various factors such as elevation of ski resorts, infrastructures for snowmaking, and differences in climate models, emission scenarios, time horizons, and scales of analysis used. To increase the clarity of conclusions transmitted to land managers and policy makers, it is necessary for scientists to harmonize indicators and methodology to enable better comparison of results from different studies. Moreover, a better integration of uncertainty in the model's outputs and the treatment applied to the snowpack in ski slopes is necessary to provide more accurate indications of how this sector will respond to climate change (Burdalo et al., 2014).

In summary, the review highlights the need for a coordinated approach to studying the impact of climate change on the ski industry. This will ensure that policymakers and land managers have accurate information to develop appropriate strategies for adapting to the challenges of climate change in the industry.

This thesis highlights the significant challenges facing the ski tourism industry in the Alps due to demographic and climate change. The findings suggest that destinations need to adapt their marketing strategies to attract non-skiing tourists to compensate for the decline in skier demand. Additionally, investments in climate resilience and sustainability are needed to ensure the long-term viability of ski tourism in the Alps.

3.1.1 100-day rule

The 100-day rule, which was first proposed by Witmer in 1986, suggests that for a ski resort to be considered successful, it should have a snow cover of at least 30 centimeters for a minimum of 100 days between December 1st and April 15th (only applicable in the Northern hemisphere) in at least 7 out of 10 seasons (Witmer, 1986). Although it was never intended to be a strict "rule" but rather a guideline, it continues to be widely used by researchers to assess the reliability and profitability of ski resorts and ski areas. In reality, these two factors depend on various other factors, such as the ability to make artificial snow and the size of the resort. Additionally, achieving the minimum 100-day goal is just the basic requirement, and having a longer skiing season is considered ideal (OECD, 2007).

When assessed using the 100-day rule, all ski resorts in the Alps are currently considered to be reliable in terms of snow cover. However, it is anticipated that by the end of the century, this reliability will decrease significantly, with approximately 50% of resorts in Switzerland and only 5% of resorts in Bavaria meeting this criterion (Rojas, Doctor, & Fragnière, 2018).

3.2 Climate change impacts for ski tourism

Numerous ski resorts have often recovered smoothly from the challenges posed by a single season with inadequate snowfall when it follows a string of seasons with abundant snow. Ski resort managers have grown accustomed to this pattern. However, due to shifting climate conditions, we are now witnessing a shift in the norm. Limited natural snowfall and temperatures that used to resemble previous seasons are increasingly becoming the standard. Consequently, the financial strain caused by a single subpar ski season can no longer be alleviated by relying on a series of seasons that are either average or better than average in terms of snowfall.

Also, In light of forecasted models indicating an anticipated increase in global temperatures exceeding 2 degrees Celsius by 2020 and surpassing 4 degrees Celsius by 2050, along with the concurrent projection that a greater portion of precipitation will manifest as rainfall rather than snowfall (as articulated by the Intergovernmental Panel on Climate Change, 2007), ski area administrators are compelled to proactively accommodate the prospect of enduring a sustained succession of seasons characterized by suboptimal snow conditions.

According to the research of König and Abegg in (1997), a relatively small temperature increase of just 2 degrees Celsius could lead to the elevation of the snow line in Switzerland, from 1200 meters above sea level (masl) to 1500 masl. This change in climate conditions could result in a decrease in the number of ski resorts considered "snow reliable" to only 63%. This classification is based on criteria such as ski areas having at least 100 days of snow-covered seasons with a minimum of 30 centimeters of snow.

Elsasser and Bürki's (2002) study took this further, projecting that if the snow line were to rise even more, reaching 1800 masl, the number of "snow reliable" ski resorts in Switzerland would decrease to just 43%.

Similarly, a study by Abegg et al,. in (2007) examined the concept of "natural snow reliability" in Austria, France, Germany, Italy, and Switzerland. Under the climate conditions of 2007, they found that 91% of the 666 operating ski areas met the criteria for being considered "snow reliable." However, when considering different temperature scenarios, such as an increase of 1 degree Celsius, the number of such ski areas dropped to 75%. Under a 2-degree Celsius scenario, this number decreased further to 61%, and under a 4-degree Celsius scenario, it plummeted to 30%. Notably, Germany was expected to be the most heavily impacted, with a 60% reduction in "snow reliable" ski areas under a 1-degree Celsius scenario, while Switzerland experienced the least impact, with only a 10% reduction under the same scenario.

In addition to studies that assess how climate change affects the viability of regional ski resorts, there are several investigations that focus on understanding how climate change impacts the duration of average ski seasons. These season length studies have been conducted in various countries, including Australia, Sweden, Canada, and the United States. They consistently use a benchmark known as the "100-day rule" to gauge economic sustainability. In simple terms, this rule means that ski seasons should ideally last for at least 100 days each year to remain financially viable.

Some researchers, such as Galloway in (1988) and Whetton et al., in (1996), have expressed concerns about the ability of Australian ski resorts to maintain 100-day seasons. They project a reduction in the number of days with reliable snow cover to around 60 to 75 days per season by the 2070s and 2090s.

Similarly, in Sweden, researchers Moen and Fredman in (2007) anticipate a decrease in the number of skier days at resorts to as few as 64 to 96 days within the same timeframe.

In Canada, McBoyle & Wall in (1987) employed a scenario that doubled atmospheric CO2 levels (a sophisticated modeling approach at that time) to estimate reductions in ski season lengths. They projected declines ranging from 30% to 40% in a region near Lake Superior and up to 80% to 100% in the southern Great Lakes area near Georgian Bay. The same methodology indicated that skiable days in southern Quebec, Canada, could decrease by 50% to 70%. Similar reductions were projected for the Lower Laurentian Mountains of Quebec, Canada (McBoyle & Wall, 1992), and in Michigan, USA (Lipski & McBoyle, 1991).

The implications of climate change on the global ski industry could be significant, but some researchers, such as Scott et al., (2003); Mills, et al., (2006); and Scott et al., (2007), argue that many early impact models may overstate these effects because they do not consider the widespread use of snowmaking as an adaptation strategy. These researchers were among the first to incorporate snowmaking into their analyses of climate change's impact on ski tourism. Consequently, their findings suggest that ski season lengths in the same Canadian regions modeled by earlier studies may only decrease by 1% to 13% in the 2020s and 7% to 32% in the 2050s. These estimates indicate a considerably smaller impact compared to studies that do not account for snowmaking.

However, it's important to note that these studies do not factor in the temperature reductions that occur at higher elevations (where ski resorts are often located) or the likelihood of more precipitation falling as snow rather than rain. This suggests that impacts may still be overestimated, especially for ski areas at higher elevations.

Acknowledging this limitation, studies by Dawson & Scott in (2007) and Steiger in (2010) have attempted to incorporate the influence of temperature changes at different elevations. Steiger in 2010 also refined modeling techniques to consider other factors like aspect and slope, which can significantly affect a mountain's ability to maintain an adequate snowpack.

In addition to various minor limitations that hinder our thorough comprehension of how climate change affects the ski industry, the most significant constraint is the lack of consideration for the collective impacts of change across individual ski resorts and among regional ski areas. Our inability to grasp the varying degrees of vulnerability among specific ski areas, and even disparities between regional or international ski markets, is partly due to the diverse range of research methods employed to assess climate change's effects on the ski sector. Consequently, it's not feasible to directly compare findings between different studies, despite there being a substantial body of over 30 published studies dedicated to modeling climate change impacts on alpine skiing (Scott et al., 2012). This is unfortunate because the entire ski industry isn't uniformly susceptible to climate change; rather, it's the particularly fragile ski areas operating within a given region. Failing to establish a comprehensive understanding of the entire ski market or the global ski industry hampers our ability to comprehend the regional or global implications of climate change. This limitation significantly curtails the capacity of ski area and regional decision-makers, planners, and developers to formulate and execute adaptation strategies geared towards addressing the anticipated impacts of climate change.

Furthermore, one of the earliest investigations into the effects of climate change on mountain tourism in Europe was conducted by Koenig and in (1997). Their study focused on winter tourism in the Swiss Alps and underscored how heavily it relies on climate conditions and the availability of sufficient snow for snow-based activities. This research emerged during the 1980s when a three-year stretch of limited snowfall resulted in significant economic losses for the lodging and transportation sectors.

Koenig and Abegg's (1997) study aimed to understand the potential consequences of rising temperatures on the future availability of suitable snow conditions. Their findings indicated that a temperature increase of about 0.3 degrees Celsius would lead to a 300-meter rise in the elevation of consistent snow cover in the central Alps and a 500-meter increase in the Prealpine region (Table 3.2.1) (Figure 3.1). Additionally, they anticipated a delay in the arrival of the first snowfall of the season and a reduction in the duration of snow cover by up to one month.

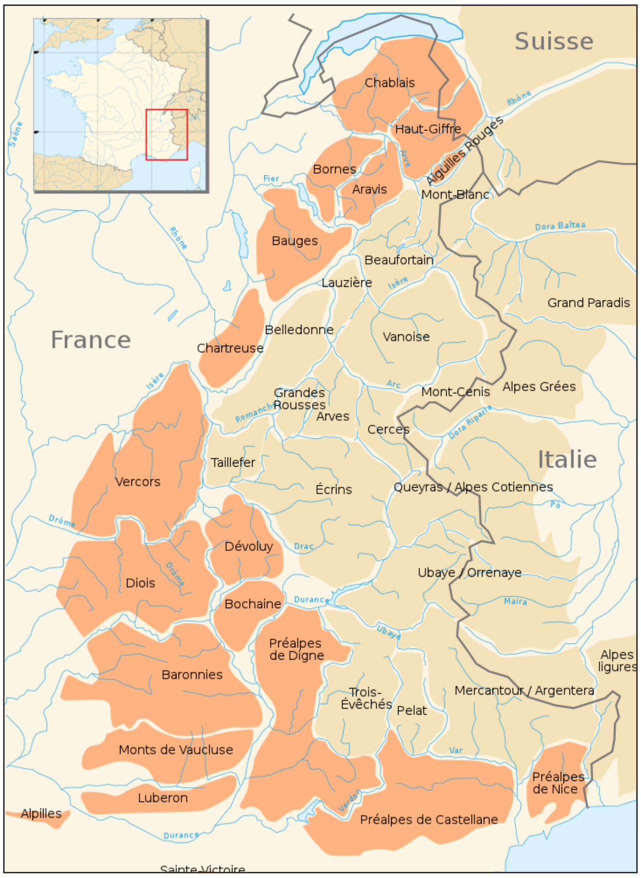


Figure 3.1: Prealpine regions (Giffre & Rouges, 2010)

Under these changing climate conditions, reliable snow cover would only be guaranteed in ski resorts situated above 1200 meters above sea level (m.a.s.l), which includes 85% of the Swiss Alps' resorts. However, if temperatures were to rise by 2 degrees Celsius, the snow line would ascend to 1500 m.a.s.l. In such a scenario, only 63% of the ski slopes would remain feasible. Ski resorts at higher altitudes, such as those in the Grisons canton and Valais, would continue to offer good skiing conditions even with a 2-degree Celsius temperature increase.

In a subsequent study conducted in the same region, Elsasser and Bürki in (2002) projected that if the snow line were to shift further upwards to 1800 m.a.s.l., only 44% of the ski runs and a mere 2% of the ski lifts would remain operational.

The impacts of climate change on mountain tourism in Europe have raised several concerns, particularly in regions reliant on winter tourism like the Swiss Alps. Koenig and Abegg (1997) conducted an early study on winter tourism in this area, highlighting its strong connection to climate conditions and the availability of sufficient snow for winter sports. This study was prompted by a period in the 1980s when three consecutive years of low snowfall resulted in substantial economic losses in the lodging and transportation sectors.

Country	Region	Climate change scenario used	Minimum altitude snow-reliable under CC	Snow pack duration	Snow depth	Loss of ski season	Others impacts	Study
Switzerland	Alps	+ 0.3 8C; +28 C, no change pa (IPCC)	1200 m; 1500 m	–	–	–	63% resorts remain reliable	Koenig and Abegg (1997)
Switzerland	Alps	+1 8C; +2 8C; +4 8C					Resorts remain reliable: +1 8C (142 of 164); +2 8C (129 of 164); +4 8C (78 of 164)	Abegg et al. (2007)
	Alps	A2 +4 8C (2071–2100) + 1 (mm/day) precipitation (HIRHAM4; RCM)	–	50 days (2000 m); 110 days (1000 m)	55%	–	Reduction snow fall: 90% (1000 m); 45–60% (2000 m); 30–40% (3000 m)	Beniston et al. (2003)
Italy	Alps	+1 8C; +2 8C; +4 8C no change p	1650 m; 1800 m; 2100 m	+1 8C = 35% (1400 m); 15% (1800 m); 12% 2300 m	–	–	36 stations reliable; 79 reliable stations; 137 rs	Mercalli et al. (2007); EURAC (2007)
Austria	Alps	+2 8C no change p	–	–	–	–	–	Breiling and Charamza (1999)
	Alps	A1 +1 8C; B1 +2 8C; A2 +4 8C	–	–	–	–	Ski reliable areas: +18 – 19%; +28 – 43%; +48 – 82%	Steiger and Abegg (2013)

Table 3.2.1: Climate change impact and assessments (Summarized studies review)

In subsequent research by Abegg et al., (2007) and OECD (2006), it was confirmed that rising temperatures, by 1, 2, or 4 degrees Celsius, would reduce the number of viable Swiss ski resorts from 164 to 142, 129, and 78, respectively. However, Gonset (2013) suggested that Switzerland's ski industry might be less affected than other European Alpine countries.

Beniston et al., (2003) used climate models to project a 90% reduction in snow quantity at 1000 meters, 40-60% at 2000 meters, and 30-40% at 3000 meters in Switzerland by 2071-2100. This would negatively impact ski tourism. Additionally, for every 1-degree Celsius rise in winter temperature, the snow cover duration in the Alps would decrease by an average of 15-20 days. A 4-degree Celsius increase would result in a reduction of about 50-60 days at 2000-2500 meters and between 110 and 130 days at around 1000 meters. Uhlmann et al., (2009) confirmed the uncertain future of Swiss ski resorts at lower altitudes, noting local variations depending on factors like slope and orientation.

In the Italian Alps, Mercalli et al., (2006, 2007) projected that a 2 or 4-degree Celsius rise would elevate the snow line by 300 and 600 meters, respectively. Even a temperature increase of less than 1 degree Celsius could lead to significant snow cover loss at altitudes below 1400 meters, with a 35% reduction in annual snow cover duration for every 1-degree Celsius rise. At higher elevations, a 1-degree Celsius rise would result in an average snow depth reduction of 15% at around 1850 meters and

12% at 2300 meters. Ski resorts in the Italian Alps generally have higher altitudes, but they would still be affected. Based on projections, if temperatures rise by 1 degree Celsius, 131 out of 167 Italian ski resorts (above 1650 meters) would remain viable for winter sports. At a 2-degree Celsius increase, 88 resorts (above 1800 meters) would be viable, and at a 4-degree Celsius rise, only 30 resorts (above 2100 meters) would remain viable.

Austria's ski industry has also faced scrutiny due to climate change. Studies by Breiling and Charamza (1999) suggested that a temperature rise of up to 2 degrees Celsius at 2000 meters, with no change in precipitation, would not severely impact ski resorts. However, at middle altitudes, even a 0.8-degree Celsius increase could have significant consequences. Artificial snowmaking has been recognized as a strategy to mitigate climate change effects, but it may not suffice in all cases. Additionally, the number of days suitable for making artificial snow would decrease by about 33% with a 2-degree Celsius temperature rise. Steiger (2012) noted a reduced reliance on natural snow conditions in recent years due to improved snowmaking techniques but at higher costs. Steiger and Abegg (2013) analyzed how climate change might affect winter tourism in Austria using criteria like the "100-day rule." Their findings showed that with temperature increases of 1, 2, and 4 degrees Celsius, the available ski areas for skiing and snowmaking would reduce by 81%, 57%, and 18%, respectively. A 2-degree Celsius increase would require more than 50% of ski areas to increase snowmaking by 100-199%.

In summary, climate change poses significant challenges to ski tourism in Alpine regions, affecting snow conditions and ski resort viability. Various adaptation strategies, including snowmaking, have been considered, but the impacts are complex and depend on factors like altitude and local conditions.

Moen and Fredman (2007) conducted a study in Sweden between 1961 and 1990, during which the temperature increased by an average of 2 degrees Celsius. Interestingly, the precipitation levels remained relatively stable, but the depth of snow cover decreased by 8 centimeters. This reduction led to a shorter potential ski season, measured by the number of days with at least 30 centimeters of snow cover. A more detailed analysis was carried out for the Salen region in southwest Sweden under two climate change scenarios: A2 (projecting around +5 degrees Celsius and a 45% increase in precipitation) and B2 (projecting approximately +2.5 degrees Celsius and a 15% increase in precipitation). Under scenario A2, they estimated a significant 66% reduction in snowfall and a substantial 96-day reduction in the ski season. Scenario B2 resulted in a 44% decrease in snowfall and a 64-day reduction in the ski season.

Lopez-Moreno et al., (2009) focused on the Pyrenees region, predicting a substantial decline in snow cover duration by 78% at 1500 meters under climate change scenario A2 (which forecasted a temperature increase ranging from 2.4 to 4.1 degrees Celsius, with an average change of 3.1 degrees Celsius) for the period 2070–2100. At 3000 meters, the decrease was less pronounced at 20%. Under climate change scenario B2 (projecting a temperature increase ranging from 0.9 to 2.3 degrees Celsius, with an average change of 1.3 degrees Celsius), they anticipated a 44% reduction in snow cover duration at 1500 meters and an 11% decrease at 3000 meters. Additionally, they forecasted a 70% reduction in snow volume at 1500 meters and an 11% reduction at 3000 meters under scenario A2. For scenario B2, the reduction in snow volume was estimated to be 32% at 1500 meters and 5% at 3000 meters.

Specifically, for the Aragonese Pyrenees in Spain, a study concluded that ski resorts would generally remain viable in the near term (2040) under climate change scenario A2. However, lower altitude areas would require artificial snowmaking due to higher temperatures, especially during March. It was predicted that by the latter half of the century, only resorts at altitudes of 1750–1800 meters or higher would guarantee snow viability.

Pons-Pons et al., (2012) used the snow cover change scenarios from Lopez-Moreno et al., (2009) to simulate skiability at three ski resorts in Andorra: Arcalı´s, Pal-Arinsal, and Grand-Valira. They considered scenarios with temperature increases of +2 and +4 degrees Celsius, as well as scenarios with the same temperature increases but including artificial snowmaking. The results showed that, relying solely on natural snow availability, there would be a 30% reduction in the ski season duration at the lowest areas of Pal-Arinsal with a +2 degrees Celsius temperature increase. With the introduction of artificial snowmaking, the reduction was slightly less at 25%. Under the +4 degrees Celsius temperature increase scenario, all three resorts would be significantly impacted, with the ski season duration reduced by 95% at Pal-Arinsal, 17% at Grand-Valira, and 27% at Arcalı´s. The study's overall conclusion was that snowmaking would not fully mitigate the challenges arising from temperature increases in the lower-altitude skiing areas of Andorra.

3.2.1 IPCC reports

The International Panel on Climate Change (IPCC) is a group that includes all the countries in the United Nations and is supported by the UN itself. It is based in Geneva, Switzerland, and has some of the world's top scientists who study climate change. The main job of the IPCC is to gather and review data and scientific research on climate change, although it doesn't conduct research itself. Periodically, it compiles this information into reports that come out every 5 to 7 years. The most recent report, the sixth assessment report, is quite new. It's important for research on climate change because the IPCC is the biggest effort in the world to gather scientific research on this topic, so its reports are a crucial source for understanding climate change (IPCC, 2022).

Based on the latest projections, here's what can be said about the three regions we're focusing on in this thesis:

- In New Zealand, the average temperature has gone up by 1.1°C over the past century. New Zealand will continue to see less snow cover and thinner snow, and its glaciers will keep getting smaller. Winter rainfall will also become more common.
- North America is warming up even faster than the global average, especially as you go further north and particularly during winter. North America is

also experiencing a significant decrease in glaciers and snow cover. Winter precipitation is expected to increase, leading to more snow only in very northern regions or places with high altitudes. The rise in winter temperatures will make winter rain more common. Additionally, the Rocky Mountains will see a reduction in their snow coverage, similar to the rest of North America.

- In Europe, the temperature is also increasing more than the global average, and there will be fewer extremely cold days and frosty periods. Snow cover, glacier length, and the duration of snow seasons will all continue to decrease, as they have been doing. The European Alps will have less snow cover at elevations below 1500-2000 meters.
- Aside from looking at specific regions, the report also examines changes expected in mountains worldwide. It predicts that the snow line and freezing level will rise in altitude, and glaciers all over the planet will continue to shrink, even if we were to immediately stop the rise in temperatures altogether.

3.2.2 The Alpine Convention

The Alpine Convention is an agreement among all the countries that share the European Alps, such as Germany, Austria, Switzerland, Liechtenstein, Slovenia, France, Italy, and Monaco. It also includes the European Union (EU). This agreement has been in place since 1995. Its main goal is to provide a platform for these Alpine countries to work together more effectively on issues related to sustainability and the future well-being of the region. One of its primary concerns is the climate crisis, which it sees as a significant threat to all its member nations. While the Alpine Convention doesn’t primarily focus on ski tourism, its publications are still important because they address the overall health of the region, which inevitably includes the ski resort industry, a crucial sector in the area (The Alpine Convention, 2022).

In one of its publications titled “Climate Action Plan 2.0,” it’s noted that around 40% of communities in the Alps heavily rely on tourism, especially winter tourism in nearly all cases in the Alpine region. The report emphasizes that there’s been a notable shift in what tourists are looking for. Nowadays, tourists are increasingly interested in sustainable vacation options and tend to prefer destinations where they know that environmental protection is a top priority. The report concludes that there’s a need for a shared strategy among the Alpine countries to modernize the region, and this plan’s implementation is expected to start with the publication of the report (The Alpine Convention, 2021).

In another publication called “Climate Change – How it affects the Alps and what we can do,” the Alpine Convention examines the facts and statistics related to climate change in the Alpine region. Climate change is impacting the Alps more severely than many other areas, with the average temperature in the Alps rising twice as fast as the global average in the Northern Hemisphere. The surface area of glaciers in the Alps has decreased by half since 1850, and it’s projected to shrink to just 30% of its original size with a one-degree Celsius temperature increase. For each additional degree of temperature rise, another ten percentage points of glacier surface will disappear. The publication acknowledges that all forms of tourism are at risk due to the increasing number of natural disasters caused by climate change. Therefore, diversifying tourism will be an important strategy for the future (The Alpine Convention, 2017).

3.3 Climate change impacts on future snow, ice and rain runoff in a Swiss mountain catchment

Water resources in the Alps are expected to go through significant changes in the next few decades. It’s crucial to study how climate change will affect areas with hydropower facilities. The Earth’s climate is changing; global surface air temperatures are predicted to continue rising, and there will be less snow and ice in various climate scenarios throughout the 21st century (IPCC, 2014). The impact on global hydropower potential is complex, but for Europe, there’s a projected loss of about 6% in hydropower potential by 2070 compared to the average potential between 1961 and 1990 (Lehner et al., 2005). Most regions are expected to experience a decline, except for Scandinavia (Field et al., 2014).

In Alpine areas like the Rhone basin (Beniston et al., 2014) and others with hydropower stations (Swiss Society for Hydrology and Limnology (SGHL) and the Swiss Hydrological Commission (CHy), 2011), a slight trend towards reduced annual runoff is expected. Switzerland, for instance, heavily relies on hydropower, covering about 56% of its electricity production (SGHL and CHy, 2011), making it highly dependent on water availability year-round. High-altitude hydropower stations that rely on snow and ice melt will be particularly affected by changing runoff patterns in the coming decades (Hänggi et al., 2011; Addor et al., 2014). This is due to the observed long-term trend of shrinking glaciers since the late 19th century (Bauder et al., 2007; Paul et al., 2007; Zemp et al., 2015). Additionally, there has been a decrease in the number of days with snowfall, particularly at lower to mid-elevations, from the 1980s until 1999 (Laternser and Schneebeli, 2003). Days with continuous snow cover and the volume of glacier ice, which act as natural water reservoirs, are projected to further decline or even disappear within the 21st century (CH2014, 2014; Huss et al., 2008).

Catchments with minimal glacier coverage will transition from being snow-dominated to rain-dominated, leading to changes in the seasonal distribution of runoff with more in winter and less in summer. However, the annual runoff is expected to remain relatively stable (CH2014, 2014; Zierl and Bugmann, 2005). In glacier-dominated catchments, annual runoff initially increases up to a certain point but then declines as the glaciers shrink. The timing of peak discharge varies depending on the catchment characteristics and location (Farinotti et al., 2012; Huss et al., 2008). For high-altitude hydropower stations, the long-term disappearance of glacier ice is likely to result in reduced productivity compared to today (Finger et al., 2012; SGHL and CHy, 2011). Finger et al., (2012) demonstrated that up to one-third of production in the Vispa Valley could be lost due to declining glacier area, projected changes in precipitation, and water loss due to inadequate water intakes of existing hydropower infrastructure by 2100.

Studies to predict the timing and magnitudes of these discharge changes cannot be generalized, as suggested by Gaudard et al., (2014), who also found increasing annual runoff sums in the Italian Alps. These studies need to be performed individually for each site. Nevertheless, potential changes in the seasonal distribution are crucial for future water resource management. Even if the effects on the total annual runoff appear small, they will impact water availability for energy production throughout the year. These changes require well-balanced management of runoff from Alpine catchments (CH2014, 2014).

Most studies aiming to predict climate change impacts use a calibrated hydrological model driven with future climate scenario data to project discharge until 2100. However, the approaches differ in methodology, input data, and complexity. In recent years, the quantile mapping approach developed by Panofsky and Brier (1968) has been increasingly used to correct systematic biases in climate model outputs, particularly in the mean and variability (Teutschbein and Seibert, 2012; Themessl et al., 2011). This approach has become a common technique in hydrology for studying the impacts of climate change (Finger et al., 2012; Ravazzani et al., 2016; Vormoor et al., 2015).

In a catchment area that has very few glaciers, the role of snow cover becomes more significant. This is because it is highly responsive to changes in temperature, as demonstrated by analyzing snowfall data from the West Coast of the United States between 1960 and 2002 (Mote, 2006). Similar findings have been observed in modeling studies conducted in Switzerland (Bavay et al., 2013), Finland (Rasmus et al., 2004), and on a global scale (Barnett et al., 2005). Particularly at lower altitudes, the snow cover is exceptionally sensitive to temperature variations (Hantel and Hirtl-Wielke, 2007; Laternser and Schneebeli, 2003). This heightened sensitivity to temperature changes is one of the primary reasons why snow cover plays a crucial role in influencing how runoff behaves (Bavay et al., 2013, 2009; Finger et al., 2015; Horton et al., 2006).

3.4 Impacts of climate and demographic change on future skier demand and its economic consequences

In the coming decades, the ski tourism industry in the Alps faces two significant challenges. Firstly, demographic changes will lead to an aging population of skiers and a decline in the demand for skiing (based on the assessed documents in Austria) (Witting & Schmude, 2019). Secondly, climate change will result in fewer days suitable for skiing, reduced reliability of snow, and increased operating costs in some ski destinations. Both of these factors will influence the travel behavior of ski tourists. This part focuses on these challenges using the Sudelfeld ski area in the Bavarian Alps, Germany, as an example. It assesses how climate and demographic changes will impact the number of skier days (initial visits) and the future revenue at this destination. Additionally, it provides a rough estimate of how many non-skiing tourists need to be attracted to the destination to compensate for the projected changes in demand. The findings indicate that climate change will have a consistently negative effect on skier demand in the 2030s and 2040s (ranging from -13.5% to -31.1%), while demographic change will have mixed impacts (from +1.6% to -31.1%). As a result, the destination's revenue is projected to change significantly, ranging from +11.8% to -56.4% (adjusted for inflation) during the same period compared to the average of the past four winter seasons. Therefore, it is crucial to identify adaptation measures to mitigate potential economic losses in the coming decades.

Adapting to climate change in the ski tourism industry requires considering not only the direct effects of changing weather patterns but also the broader impact of demographic shifts and corresponding societal changes (Figure 3.2). When it comes to snowmaking, ski resort managers should be mindful of the rising costs associated with it and how these costs might affect the pricing of winter sports vacations.

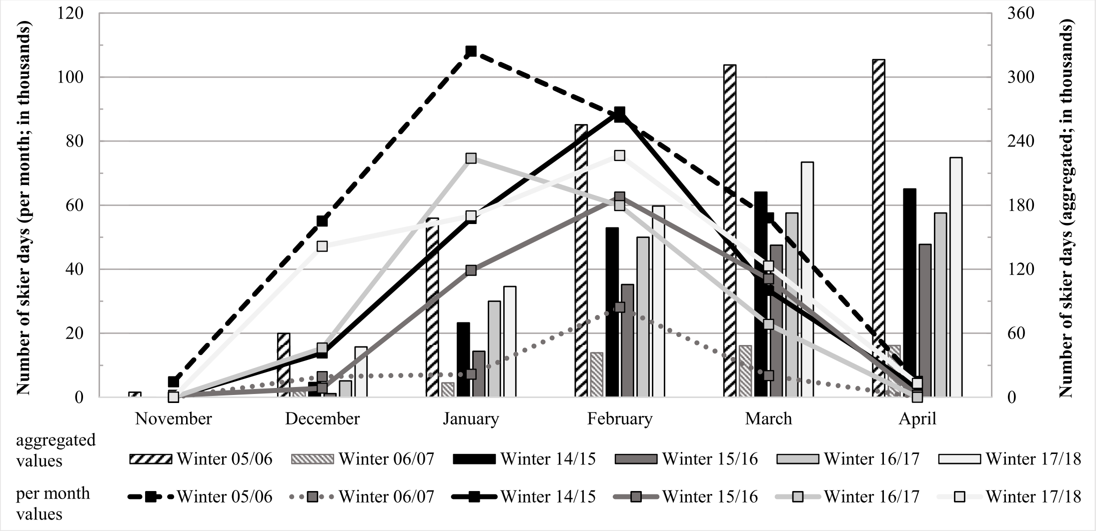


Figure 3.2: Number of first entries for the Sudelfeld ski resort (Witting & Schmude, 2019)

In a general sense, strategies for adaptation should focus on boosting summer tourism and making the "shoulder seasons" more attractive to reduce the industry's dependence on snow. It's crucial to commence these adaptation efforts as early as possible. Additionally, winter tourism destinations need to adjust their marketing strategies accordingly.

Ski tourism holds immense economic significance in many European Alpine regions. The success of ski resorts hinges on two key factors: the quantity and quality of operating days and the distribution of what we call "Optimal Ski Days" (OSDs). OSDs refer to weekends and legal holidays marked by favorable weather conditions, including no precipitation, low wind speed, ample sunshine, suitable temperatures, a snow-covered landscape, and sufficient snow depth on slopes. Climate change significantly affects these factors (Scott & Lemieux, 2010).

Recent research has highlighted several noteworthy trends specific to ski tourism parameters in many German ski resorts. These trends include a decrease in the number of operating days, rising operating costs (especially those related to snowmaking), a shift in the timing of OSDs within a season, and diminishing snow reliability.

However, it's crucial to recognize that these trends impact ski resorts differently, given the varying infrastructure, geographic locations, and snow reliability among ski destinations. Some ski areas, thanks to their favorable high-altitude infrastructure and dependable snow conditions, can still operate successfully. Conversely, those with less advantageous positions and infrastructure are highly vulnerable to these changes.

The German Alps have already experienced the effects of climate change, with rising winter temperatures, decreased snowfall, and reduced snow cover duration. These trends have contributed to a decrease in the number of ski areas in the region over the years (Grimm, Metzler, Butzmann, & Schmücker, 2010).

Winter sports enthusiasts are adapting their travel behavior in response to these climate trends. Some are switching to alternative activities, such as hiking or mountain biking, while visiting the same destinations. Others are choosing different destinations with more reliable snow conditions. Some may postpone or even cancel their winter holidays altogether. Consequently, future revenues generated by ski tourism are expected to remain stagnant or decline in regions with less reliable snow conditions. This has implications for ski lift operators, mountain restaurants, and the accommodation sector, leading to declining sales, decreased consumption, and fewer overnight stays.

In addition to climate change, several macro-scale factors can influence future tourism demand. These include economic conditions, transportation costs, political stability, technological advancements, demographic changes, currency exchange rates, and border agreements. Demographic change, in particular, has been discussed as a key factor influencing tourism demand. In Germany, stakeholders interviewed for this study identified demographic change as the second most important macro-scale factor shaping the future of Alpine skiing, right after climate change. Demographic change will result in an aging skier population and a decrease in skiing demand due to declining populations in the source market.

Demographic change entails significant shifts in a society's population structure, including birth rates, life expectancy, and migration patterns. This study primarily focuses on three key characteristics that underlie population projections for Germany and its federal states: population development, migration patterns (both internal and external), and age structure. These projections reveal population declines, particularly in the total population, due to factors like aging and, in some scenarios, moderate immigration.

There's a notable research gap when it comes to understanding how climate change and demographic shifts impact turnovers in the ski tourism industry. Most research in tourism has concentrated on the supply side, examining aspects like snow reliability, snowmaking requirements, and season length. Demand-side studies have focused on destination choices, changing travel behaviors, and perceptions of climate change. While some studies have highlighted how the behavioral adaptation of ski tourists affects future demand, none have quantified its influence on the number of skier days.

To address this gap in understanding, this demand-side study seeks to estimate the extent to which climate change and demographic shifts affect the number of skier days. It aims to project future changes in turnover for a ski resort in the Bavarian Alps, considering variations in demand during favorable and unfavorable winter seasons. The study's results provide insights into the number of non-skiing tourists, such as hikers or wellness tourists, that ski destinations need to attract to compensate for the calculated changes in demand (e.g. Dawson & Scott, 2013; Müller et al., 2013; Scott, McBoyle, Minogue, & Mills, 2006; Steiger, 2010).

3.5 Environmental impact assessment for the Ski industry

A ski resort and its operations exert significant effects on the environment that surrounds it, and when combined with skiing activities, they form a complex interconnected system. The most destructive aspect is the establishment of the ski resort itself, including the construction of ski slopes, ski lift infrastructure, and ongoing maintenance. In this section, the aim is to provide a clear definition and overview of all the influences on the ecosystem stemming from various activities associated with the ski industry. Equally important is the identification of the affected zone (Flousek, 2016).

Here is a summary of all the impacts:

Direct Impacts: These are the immediate effects resulting from the construction, daily operation, upgrades, and maintenance of the ski resort. They include changes that occur during the creation, operation, enhancement, and upkeep of the ski resort.

- The impact on fragmentation of the landscape and ecosystems
- Influences on the quality of soil and water
- Alterations to the natural vegetation cover
- Effects on various animal species
- Consequences related to the production of artificial snow
- Disruptions caused by excessive light and noise pollution
- Impacts associated with winter activities

Indirect Impacts and Cumulative Impacts of the Ski Industry (Flousek, 2016):

While the majority of the impacts we've mentioned are direct, they can also give rise to indirect or cumulative effects, which can result in substantial harm over time.

In essence, this examination underscores the intricate web of consequences that the ski industry and its associated activities have on the environment, emphasizing that even seemingly direct impacts can lead to broader and more enduring ecological challenges.

3.5.1 The impact on fragmentation of the landscape and ecosystems

The most significant harm arises from the establishment of the ski resort itself, including the creation of ski slopes, ski lift systems, and the routine maintenance required (Flousek, 2016). When developing a new ski resort, substantial changes are made to the natural landscape, involving extensive landscaping efforts to shape and flatten the original terrain. These alterations disrupt the natural appearance of the landscape. Ski resort structures become prominent features in this new environment, essentially taking over the landscape (Flousek, 2016).

To make way for new ski slopes, ski lifts, service facilities, access roads, parking areas, snowmaking systems, and real estate ventures, sections of forested areas are cleared, and previously forested land is transformed to accommodate construction activities (Scott and McBoyle, 2007). However, the construction and ongoing maintenance of a ski resort area do not halt their impact on the natural environment and its conditions. In many cases, efforts are made to enhance the services and comfort provided by ski resorts, which can result in additional adverse consequences. These impacts will be explored further in upcoming chapters (Flousek, 2016).

When it comes to modernizing a ski resort, it typically generates fewer negative effects compared to initial construction. Generally, the scale of work involved is relatively minor and takes place over a shorter period. The primary environmental pressure is concentrated during the construction phase. These modifications are usually carried out during the off-season, coinciding with periods of reduced natural activity. However, the use of heavy machinery during construction can produce significant noise pollution, which can disrupt the lives of many species (Scott and McBoyle, 2007).

3.5.2 Influences on the quality of soil and water

Landscaping represents one of the most profound alterations to the earth's surface and natural plant patterns. It's a powerful tool for making changes both above and below the upper forest line, but it has significant consequences. Landscaping significantly reduces the productivity and variety of plant species. Shrubs vanish, and there's a shift towards favoring sun-loving and less competitive species (Mosimann, 1985; Delgado et al., 2007; Roux-Fouillet, Wipf, and Rixen, 2011).

These changes in vegetation lead to physical degradation and alterations in the chemical properties of the soil. The soil's layers are disrupted, and the valuable humus layer is often lost. Compacted snow on ski slopes increases the soil's ability to conduct heat, making it more susceptible to freezing (Roux-Fouillet, Wipf, and Rixen, 2011; Flousek, 2016; Rolando, Caprio, and Negro, 2017). Some experts, like Gros et al., (2004), consider ski slopes as degraded ecosystems that require soil attributes to be restored. They note that the microbial community in the soil is highly unstable in the initial years and requires a longer time to reach a stable state.

Furthermore, removing vegetation cover and reshaping the terrain on ski slopes significantly alters the soil's hydrological patterns. The soil loses its ability to retain water, leading to more frequent drying out. Deforestation in ski resort areas increases surface runoff, which can result in substantial erosion and the threat of landslides, especially during the spring thaw when snow compresses and melts. The development of ski resorts can negatively impact the watershed's capacity, potentially leading to severe flooding (Arnaud-Fassetta, Cossart, and Fort, 2004; Beniston and Stoffel, 2016).

The construction of ski resorts usually involves deforestation, the creation of supporting infrastructure, and the maintenance of facilities for skiing and snowmaking. All of these activities contribute to destabilizing riverbanks and shorelines, particularly in areas with a high proportion of soft clay sediments (Pintar, Mali, and Kraigher, 2009). Ski slope construction disrupts vegetation, alters the topsoil layer, changes the environmental conditions, and impacts the composition of soil species. Importantly, these disruptions can persist for decades (Flousek, 2016).

3.5.3 Alterations to the natural vegetation cover

The impact of the ski industry on vegetation cover is unquestionably significant. Ski resorts often sit amidst pristine natural landscapes, and the construction and expansion of these resorts disrupt the environment, particularly affecting forested areas and meadows. Moreover, ski resorts contribute to landscape fragmentation, alter species diversity, and lead to a decline in overall species populations. The removal of forested areas, in particular, disrupts the essential functions of forests, such as stabilizing biocenters (as known as TSES in the Czech Republic), watersheds, and controlling soil erosion (Flousek, 2016). Comprehensive studies have explored the complex issues arising from area clear-cutting and fragmentation (Davies et al., 2000; Ewers et al., 2011; Gibson et al., 2013; Haddad et al., 2015).

A comparison between natural alpine meadow vegetation and ski slope vegetation, modified more than two decades ago, reveals that natural meadows exhibit twice the number of seeds in their reproduction cycle and greater species diversity (M. Urbanska, Erdt, and Fattorini, 2004). Additionally, research by Banaš et al. (2012) suggests that even minor differences in snow melting patterns between groomed ski slopes and natural alpine meadows can lead to significant variations in vegetation species diversity.

Large sections of ski slopes are often re-cultivated using commercial grass mixtures, which can have detrimental effects, such as replacing the original diversity of species and potentially leading to genetic erosion through the invasion and proliferation of non-native species (Kangas et al., 2009; Flousek, 2016).

Natural snow cover and the space between the soil and snow act as excellent insulators, maintaining the temperature of the topsoil layer around 0°C and shielding it from deep freezing. In contrast, compacted snow lacks these insulating properties. This alteration disrupts ecological processes in the soil, consequently impacting vegetation. The compaction of snow, both by snow groomers and skiing itself, increases snow density, hardness, and conductivity. It disturbs the balance of gases in the subsurface, causing ice to form on the soil surface. Oxygen levels decrease, and carbon dioxide levels rise. The movement of soil particles in frozen soil mechanically damages plant roots, and changes in microbial activity affect their nutrition and growth. Decreased oxygen levels beneath the ice layer increase plant susceptibility to frost and pathogens (Flousek, 2016; Fahey, Wardle, and Weir, 2019).

As a result, freezing delays plant growth and alters their phenology, as observed in cross-country skiing tracks in Davos during different seasons (Rixen, 2017). However, when artificial snow is added to slopes (snowmaking), native species lose their competitive edge, and plants adapted to snowy conditions dominate. These changes in vegetation are more pronounced on ski slopes with longer periods of snow cover. Surprisingly, fertile soil species prefer natural snow slopes over technically snowed slopes, where one might expect a higher nutrient supply from artificial snow. On slopes with natural snow, the snow cover is generally thinner, the soil freezes more, and the subsequent decomposition of microbial cells releases nitrogenous substances that enhance its nutritional capacity (Flousek, 2016). The diversity of vegetation is significantly influenced by the movement of heavy machinery like snow groomers during snow adjustments. Especially at the beginning and end of the winter season, when snow cover is thin, the soil surface is damaged, directly affecting vegetation. Over time, with repeated snow accumulation and pressure on the slopes, the number of species, the extent of vegetation, and above-ground biomass production decrease, accompanied by biochemical changes in plants (Kammer, 2002; Pielmeier et al., 2007; Flousek, 2016).

3.5.4 Effects on various animal species

The construction of ski resorts within forested areas often creates conflict zones between different ecological habitats. This spatial disruption and disturbance in areas where environmental impact assessments are absent can lead to irreversible consequences (Rolando, 2005; Flousek, 2016; Rolando, Caprio, and Negro, 2017).

Studies focusing on beetles (specifically Carabidae and Elateridae) have demonstrated significant alterations in beetle communities on downhill ski tracks and their immediate surroundings, including a five-meter buffer from the forest. On these ski slopes, only a minimal fraction (less than 0.5%) of the beetle species found in the forest habitat can be located. While the total number of species in both groups may increase on the ski slopes compared to forested areas, most of these species are actually colonizers from lower elevations. Researchers regard ski slopes as substantial barriers to the natural movement of forest beetles, resulting in the fragmentation of forested areas into isolated “islands” of vegetation (Strong, Dickert, and Bell, 2002).

Interestingly, invertebrates demonstrate a higher level of diversity in areas with abundant vegetation cover, regardless of altitude. However, the presence of detached vegetation on ski slopes can hinder the colonization of these areas by ground-dwelling vertebrates. Particularly crucial are the transition zones between the forest and the slopes, and the destruction of forests or meadows along with their fragmentation by ski slopes can significantly impact the communities of invertebrates under study (Rolando, Caprio, and Negro, 2017).

Bird populations also react similarly to the presence of ski slopes above the forest line. While natural grasslands support higher species diversity, greater diversity indices, and nesting density for birds, slopes exhibit a comparable number of species but lower bird density. Additionally, the indirect negative impact of slopes extends to surrounding habitats, which also experience a decline in bird populations (Rolando, 2005; Flousek, 2016; Rolando, Caprio, and Negro, 2017).

Furthermore, the effects of the ski industry reach beyond small mammals to other creatures that utilize the space between the soil and snow layers. Compacted snow cover significantly reduces this space, averaging just 1.2 cm, compared to an average of 8-20 cm under undisturbed snow cover, depending on the type of vegetation. Research cited in the text has shown that when the space under the snow is eliminated, the presence of two small mammal species that rely on this environment decreased by 75-80% (M. Sanecki et al., 2006).

Finally, a recent study spanning 35 years has explored the impact of winter recreation, including skiing, on sensitive alpine and subalpine ecosystems. The research indicates that negative or neutral effects on fauna tend to outweigh positive effects. This is particularly evident in Europe, where the majority of these studies were conducted. The most common negative impacts of winter recreation were observed in animals, especially birds, with fewer effects on mammals and invertebrates. These winter sports areas exhibited lower abundance and diversity of fauna compared to undisturbed areas. However, researchers note that our understanding of the life strategies of mountain organisms and their responses to human activities is still limited, and significant gaps exist in our knowledge. Moreover, observable changes in subalpine and alpine communities may only become evident after several decades (Sato, Wood, and Lindenmayer, 2013).

3.5.5 Consequences related to the production of artificial snow

Snowmaking has become a necessary component of ski resort operations, particularly in response to climate change. However, it represents a significant intervention in soil characteristics and the water balance of an area. The installation of snowmaking systems involves modifying the terrain to distribute water, installing pumping and compressor stations, and impacting previously deforested areas or snow-covered grasslands. Beyond its effect on the water balance, technical snowmaking also influences the composition of plant and animal communities (Flousek, 2016).

Commonly, it's believed that snowmaking does not harm the environment because all the water used is expected to return to the natural system, with the only difference being a slight delay. However, this perspective is flawed because the prolongation of the water cycle and its retention on the surface can result in faster losses through rapid runoff and evaporation. Research conducted in the Alps and the Atlas Mountains has revealed that nearly one-third of the water converted into technical snow disappears from the area. This loss occurs through processes like sublimation at higher altitudes, evaporation from snow-covered reservoirs, and the removal of ice crystals soon after their formation. In terms of scale, it's estimated that the total water loss in the Alps due to technical snow production is equivalent to the annual water consumption of a city with a population of 500,000. While alpine regions generally do not face issues with drinking water supply, the critical months for water availability are January and February. In the long run, the extensive use of water for snowmaking poses significant risks because it depletes water resources that act as reservoirs for winter and spring, redirecting runoff to the surface during thaw instead of allowing it to soak into the ground. This alteration disrupts the typical timing and spatial relationships between surface and groundwater, potentially leading to water scarcity issues (de Jong, Collins, and Ranzi, 2006; C. de Jong, 2007; Carmen de Jong, 2007; Flousek, 2016).

The process of technical snowmaking requires vast quantities of water and energy. To create just one cubic meter of technical snow, it typically demands 200 to 500 liters of water and 1.5 to 9 kWh of electricity. With a snow layer of about 30 cm, this translates to a consumption of 600,000 to 1,500,000 liters of water and 5,000 to 27,000 kWh of energy per hectare of downhill ski slope. These figures underscore the substantial resource utilization involved in snowmaking, and the actual consumption figures can vary depending on factors like the size of the ski area. For instance, the actual electricity consumption ranged from 0.33 to 0.60 kWh per square meter of slope in a smaller ski area like Braunwald, while larger resorts such as Davos and Scuol saw electricity consumption of 0.69 to 1.13 kWh per cubic meter of snow per square meter. Water consumption tended to be at the upper end of the estimates, amounting to 0.14 to 0.2 cubic meters per square meter for downhill runs in large ski areas (Steiger, 2010, 2012; Roux-Fouillet, Wipf, and Rixen, 2011; Flousek, 2016).

3.5.6 Disruptions caused by excessive light and noise pollution

Noise and light pollution represent significant environmental concerns associated with ski resorts and their immediate and surrounding areas. These issues are primarily linked to the day-to-day operations of ski resorts, which can include music sound systems. However, one of the main contributors to these forms of pollution is the night time activity involving snow groomers and snowmobiles responsible for maintaining ski slopes and cable transport facilities. Additionally, the production of artificial snow can generate noise levels ranging from 60 to 115 decibels (dB). It’s worth noting that efforts are underway to develop new snow-making facilities that aim to reduce this noise impact. As for light pollution, it primarily arises from the use of floodlights to illuminate downhill ski slopes for night skiing. The lighting of snow cannons and snow showers also contributes to this form of pollution (Flousek, 2016).

Although detailed monitoring of the impact of noise on animals within ski resorts is limited, we can draw indirect conclusions about the level of nighttime noise pollution from a study conducted on U.S. ski resort staff. The study found that 11% to 70% of snowmaking workers were exposed to noise levels exceeding acceptable standards, reaching between 82 and 90 dB. Night workers experienced up to 100% excess in noise standards. Interestingly, snow groomer drivers did not exceed these standards. This data indicates that nighttime noise pollution is indeed a concern in ski resorts (Radman, 2018).

In general, it is well-established that excessive noise has adverse effects on animals. It can disrupt communication among individuals of the same species, impacting mating and reproduction. It also complicates prey hunting by affecting orientation and may lead to lower fitness or increase the risk of predation by natural enemies (Francis and Barber, 2013).

Light pollution, on the other hand, significantly influences animal behavior by affecting their daily and seasonal rhythms. It can lead to issues related to reproduction, loss of direction, health problems, and more. While many studies have investigated the adverse effects of nighttime lighting on humans, this knowledge is often applicable to animals as well. For example, studies have shown that night illumination can reduce hunting success and increase predation risk in small mammals. It can also disrupt the timing of biological clocks in vertebrates and interfere with the production of the hormone melatonin, which plays a crucial role in various physiological processes in animals and has been linked to the development of malignant tumors (Rich and Longcore, 2006).

3.5.7 Impacts associated with winter activities

Recreational activities commonly indulged in at ski resorts, such as downhill and cross-country skiing, snowboarding, and ski touring, exert various influences on these environments. The compression of snow by these activities can have repercussions on the soil and vegetation. Additionally, human engagements directly impact the populations of wildlife inhabiting these areas, influencing their behavior, physiological functions, and reproductive patterns (Flousek, 2016).

3.6 Climate change adaptation in the ski industry

In their report, Scott and McBoyle (2006) provide a detailed overview of strategies that are already in use or being developed in the ski industry to adapt to changing conditions. Some of these strategies, which were relatively new at the time of the report, include:

- Artificial Snowmaking: This is the most common and important adaptation method. Ski resorts use machines to make artificial snow, extending the ski season by 55 to 120 days on average. This trend is expected to increase due to climate change. However, it has negative environmental impacts because it often involves using water from natural sources, which can harm those ecosystems. Some places limit how much water can be taken for snowmaking, and the additives used in snowmaking can be harmful to the soil, leading to opposition from environmental groups.
- Slope Development: Ski slopes can be prepared to withstand warmer temperatures. This includes tasks like removing rocks and shrubs in the summer, which reduces the amount of snow needed for skiing. Snow can also be conserved by setting aside forested areas because forests naturally collect snow and provide

shade, keeping slopes cooler. Additionally, glaciers can be protected by covering them with large plastic sheets in the summer or using snow fences. Expanding operations to north-facing slopes and higher altitudes is also becoming more important, though it can face opposition from environmental groups.

- Cloud Seeding: This method is somewhat unconventional because there's no solid scientific proof that it works. However, some ski resorts in Australia and North America, such as Vail, have been experimenting with it for years. Cloud seeding involves releasing certain molecules into the air to encourage cloud formation and increase precipitation.
- Ski Conglomerates: These are partnerships between ski resorts in different areas with varying weather conditions. The idea is that when one region experiences a poor skiing season, or even multiple bad seasons, the revenue from resorts in other regions can help offset the losses. This concept is gaining popularity in North America.
-
- Revenue Diversification: Instead of solely relying on winter skiing, some resort towns are expanding their offerings to be year-round destinations. This includes activities not dependent on snow, like dogsledding or snowmobiling, to reduce their dependence on cold weather.
- Marketing Incentives: Resorts can use marketing strategies to assure customers of a certain skiing experience, such as a specific number of open slopes for a certain amount of time during their stay. This can attract cautious travelers, but businesses need backup plans and refund policies if they can't meet these guarantees.
- Indoor Ski Halls: These facilities are independent of weather conditions and can be located far from mountains, even in places where it never freezes. They offer a way to introduce people to skiing without relying on natural snow.

These strategies aim to help ski resorts adapt to changing environmental conditions and ensure the sustainability of the industry (Scott & McBoyle, 2006).

3.6.1 The economic sustainability of snow tourism: The case of ski resorts in Austria, France, and Italy

In this study, researchers looked at the long-term economic health of a selection of ski resorts in three different countries, with a particular focus on how they can stay financially stable in the face of climate change. The authors believed that innovation is the key to ensuring these resorts can continue to thrive, and they saw money as a crucial factor in driving innovation. Essentially, they thought that the ski resorts making the most money would be the best at adapting to future environmental challenges.

The study found that the size of a ski resort is the most important factor influencing its profitability. Even though ski resorts of all sizes are currently making money, the study showed a clear connection between a resort's size and how much money it brings in. The researchers also pointed out that ski resorts are like anchor businesses. They're often the main reason people visit a certain area, and as a result, they boost the profits of other businesses in the region. This means that all ski resorts, but especially smaller ones that might be more vulnerable, should diversify their assets and work closely with their local community. By doing this, they can create an economic environment that doesn't rely so heavily on just the ski resort but instead forms a strong network of leisure businesses (Moreno-Gené, Sánchez-Pulido, Christobal-Fransi, & Daries, 2018).

3.6.2 ESPON Case Study Alpine Space

The results of the study called ESPON Climate: Climate Change and Territorial Effects on Regions and Local Economies; Annex 1 – Case Study Alpine Space suggest that mountain resorts solely reliant on winter tourism will face increasing challenges in remaining operational due to rising temperatures. In contrast, mountain resorts that emphasize summer tourism or offer attractions year-round will likely experience a growth in the number of visitors during the summer months. This is because mountainous areas tend to have cooler and more pleasant temperatures in the summer compared to lower-altitude regions, making them appealing destinations for people seeking relief from the summer heat.

Lower-lying mountain regions, however, may find their capacity for winter tourism greatly diminished, while their potential for summer tourism could be enhanced, especially if they have lakes, which are often found in lower mountain areas. Lakes are expected to become increasingly popular summer destinations, potentially replacing traditional oceanic beaches.

Additionally, the study predicts that natural disasters like floods, wildfires, and avalanches will become more frequent, but their negative impact is likely to be much greater on winter tourism compared to summer tourism (ESPON, 2011).

3.6.3 Does artificial snow production pay under future climate conditions? - A case study for a vulnerable ski area in Austria

In this particular research study, the authors examined how reliable the snowfall was in a ski area in Austria and how this related to the dependability of artificial snowmaking. They then applied these findings to a broader region in the Alps. One of their initial findings was that many earlier studies, which had assessed the impact of climate change on ski resorts, were overly pessimistic. Having provided the skiing condition, many of the previous studies neglected the widespread use of artificial snowmaking (Damm, Köberl, & Prettenthaler, 2014).

However, the study also recognized that the expenses associated with artificial snowmaking would keep increasing, and there would be fewer days suitable for making artificial snow due to changing climate patterns. This means that relying solely on snow cannons would not fully protect ski areas from the effects of climate change. The study highlighted a specific concern for ski resorts at lower elevations, as they might face challenges in remaining financially viable and could experience shorter skiing seasons. This is especially problematic if they can no longer operate in April, as this month typically sees high demand for ski tourism during the Easter holidays.

To address these challenges, the authors recommended diversifying ski resorts' offerings by focusing on activities unrelated to skiing, such as wellness services, winter hiking, and mountain biking (Damm, Köberl, & Prettenthaler, 2014).

3.6.4 Managing for climate change in the alpine ski sector

The journal article of Dowson & Scott, 2013, argues that climate change poses a greater threat to individual ski resorts rather than the entire skiing industry. In essence, while the industry as a whole will likely shrink significantly due to climate change, it will endure. Interestingly, climate change may even benefit the surviving resorts because it could lead to the closure of their competition.

Ski resorts that are relatively smaller, situated at lower altitudes, farther south, or located away from major population centers have been gradually losing their share of the market and going out of business for years, even before climate change started having major effects on the industry. Meanwhile, larger and more strategically positioned ski resorts have been able to take advantage of this situation, creating an industry that heavily favors those who are already doing well.

This trend of larger resorts prospering is expected to accelerate. However, the authors emphasize that even these advantaged resorts must invest significantly in adaptation measures to maintain their positions and avoid succumbing to the same forces that are causing smaller resorts to fail. One of the most crucial measures they recommend is for resorts to become "four-season resorts" by investing in summer tourism alongside their winter offerings.

4. Methodology

4.1 Introduction to case studies

Austria holds a significant position in the global ski industry. It ranks as the third-largest ski market in terms of the number of skier visits, following the United States and France. What's remarkable is that it boasts the highest skier visits per capita (as indicated by Vanat in 2014). The annual revenue generated from lift ticket sales amounts to approximately €1.3 billion, and the Austrian Association of Cableways estimates that ski resort customers collectively spend about €7.9 billion. This spending not only has direct economic impacts but also creates indirect and induced effects, contributing to a substantial added value of €4.3 billion (data from WKO in 2018).

Moreover, the ski tourism industry in Austria plays a pivotal role in job creation, with over 95,300 jobs being directly and indirectly supported. This represents a significant 2.65% of the total employment in Austria, according to statistics from Statistik Austria in 2018. Therefore, it is evident that ski tourism is not only vital for the regional economies of tourism-centric destinations but also exerts a substantial influence on the national economy as a whole.

In this thesis, a total of 208 ski areas in Austria have been examined. A ski area, refers to a collection of interconnected ski lifts and slopes, viewed from the perspective of the customer rather than the business entity. While there are internationally renowned extra-large ski areas like Kitzbühel and Ischgl, the majority of Austrian ski areas are relatively smaller, typically featuring less than 20 kilometers of ski slopes or a lift capacity of less than 8000 persons per hour, as indicated in Table 4.1.1.

	Base elevation (masl)	Peak elevation (masl)	Critical elevation (masl)	Share of ski slopes with snowmaking (%)	Size (km of ski slopes)	Lift capacity (persons/hour)
Min	545	1050	600	0	2.5	800
1st quartile	828	1550	1100	50	10	4765
Median	1000	1886	1400	80	19	7838
3rd quartile	1300	2200	1600	91	35	14,310
Max	2736	3440	2900	100	284	146,550

Table 4.1.1: Characteristics of Austrian ski Areas (bergfex.at, at.skiinfo.com)

Consideration of the base station elevation in Austrian ski areas becomes evident that more than half of these areas are situated below 1000 meters, with their top station elevations falling below 1900 meters. To account for ski areas with a considerable vertical range and to extend their ski season in the upper terrain, a "critical altitude" has been defined. This critical altitude represents the elevation at which each ski area can operate effectively. It is either the lowest point in the upper half of the ski area (if such a section exists), or it is the base station if no upper section is present. An upper section, in this context, signifies the ski area's capability to transport skiers from a mid-elevation point to the summit without requiring them to ski all the way down to the base station, making it possible to operate the upper elevation ski terrain independently from the lower terrain, which may lack sufficient snow coverage to reach the base station. The analysis also considers the critical snow depth threshold of 30 centimeters, which defines daily ski operations.

The adoption of snowmaking technology in Austrian ski areas has gained momentum, particularly after a series of winters in the late 1980s and early 1990s with insufficient natural snowfall (Steiger & Mayer in 2008). Presently, approximately 70% of ski slopes in Austria are equipped with snowmaking capabilities, as reported by WKO in 2018. Only about a quarter of ski areas have less than 50% of their terrain covered by snowmaking, while the majority have snowmaking capacity for more than 80% of their slopes, as shown in Table 4.1.1. This widespread implementation of snowmaking technology likely accounts for the relatively modest impact of natural snow depth on winter overnight stays in Austria, as found in a study by Falk in 2010.

The trend toward continued investments in expanding snowmaking capacity is expected to persist, as suggested by Trawoger in 2014. This implies that snowmaking will continue to be a critical aspect of the future of ski tourism in Austria.

Tourism plays a significant role in the economic landscape of Tyrol, contributing directly to approximately 15% of the region's gross domestic product (GDP), as reported by Tirol Werbung in 2010. Within the tourism sector, the winter season holds a dominant position, accounting for 60% of the annual overnight stays (MANOVA, 2009).

Tyrol's climatic conditions exhibit substantial variability in mean annual precipitation. This variation ranges from 657 millimeters in areas such as Prutz (situated at an altitude of 870 meters) to as high as 1886 millimeters in locations like Jungholz (at an altitude of 1060 meters). To assess the reliability of snow cover in the region, a widely employed guideline known as the "100-days rule" was applied to 52 climate stations. The analysis covering the period from 1981/1982 to 2000/2001, as illustrated in Figure 4.1, did not confirm the 1200-meter elevation as a consistent threshold for snow reliability. Furthermore, the considerable differences in snow reliability among stations at similar altitudes indicated that a uniform elevation criterion for snow cover could not be universally established for Tyrol. This diversity can be attributed to both large-scale factors, such as the decrease in precipitation from the northern Alps to the inner regions, and smaller-scale influences like orographic features and frequent Foehn winds, which collectively contribute to a highly variable snowfall pattern. As a result, localized climate data becomes essential for a more accurate understanding of snow conditions.

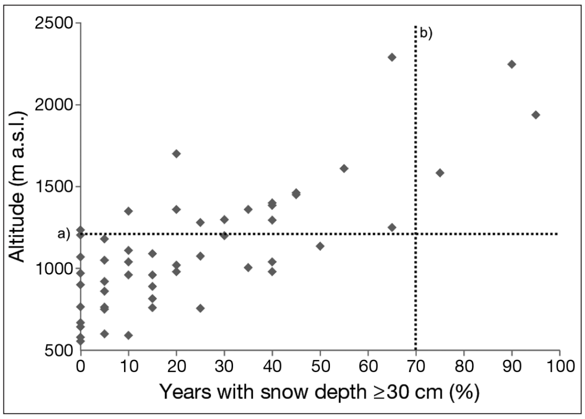


Figure 4.1. Relative number of winters with a snow depth ≥30 cm for ≥100 d, at 52 climate stations in Tyrol (1981/1982– 2000/2001). Line (a) marks 1200 m, the assumed line of snow reliability in Tyrol (Abegg et al. 2007). Line (b) marks the 100-days in 7 out of 10 winters threshold

In this thesis, three specific climate stations selected and paired with nearby ski areas to evaluate the performance of proposed climate models and assess the potential impacts of climate change. These climate stations were chosen based on their consistent data records and their location in areas with varying levels of precipitation (ranging from drier to wetter regions). The selection of ski areas was based on their mean altitudes, representing low, mid, and high-altitude ski destinations. The proximity of these ski areas to the chosen climate stations was a key consideration, as detailed in Tables 4.1.2 and 4.1.3. This strategic selection allows us to comprehensively examine the influence of climate change on Tyrol's diverse ski regions.

Ski area	Location	Elevation range (m)	Mean altitude of ski slopes (m)	No ski lifts	Distance to climate station (km)
A	St. Johann	668-1605	1100	13	1
B	Parscherkofel	903-2247	1500	5	6.5
C	Zillertal Arena	1259-2502	1900	35	0.5

Table 4.1.2. Characteristics of 3 ski areas. Letters A, B, C correspond to climate stations 1, 2, 3, respectively, in Table 4.1.3

Climate station	Location	Altitude (m)	Mean winter precipitation (mm)	Mean winter temperature (°C)	Lat. N	Long. E
1	St. Johann	756	741	0.8	47°31’	12°26’
2	Innsbruck	579	316	3.3	47°15’	11°20’
3	Gerlos	1250	426	-1.4	47°13’	12°02’

Table 4.1.3. Characteristics of 3 climate stations. Mean winter precipitation and temperature are from Nov–Apr 1981–2000. Numbers 1, 2, 3 correspond to ski areas A, B, C, respectively, in Table 4.1.2

4.2 Data preparation

To conduct this analysis, several key steps were undertaken (Figure 4.2):

1. **Data Preparation:** The initial step involved gathering meteorological data, which includes daily information on minimum and maximum temperatures, precipitation, snow depth, and snowfall. This data was sourced from the Central Institute of Meteorology and Geodynamics in Vienna, Austria. To ensure data quality, climate stations with extensive gaps exceeding 10 days per season or those lacking data within the 1981-1999 timeframe were excluded. Ultimately, a dataset was created, comprising 51 climate stations situated at altitudes ranging from 295 to 2,164 meters.
2. **Assignment of Ski Areas to Climate Stations:** Each of the 228 ski areas under examination was assigned to the nearest climate station using a proximity-based approach. In cases where the closest climate station and the ski area were separated by a significant alpine divide, which could lead to substantial climatic variations, an alternative station with a slightly greater distance but similar climate conditions was chosen.
3. **Climate Change Data:** Recognizing the uncertainties inherent in climate model data, it is advisable to employ multiple climate models driven by various

greenhouse gas emission scenarios for assessing climate change impacts. In this analysis, hypothetical warming scenarios ranging from +0.5°C to +4.0°C were employed to gauge how Austrian ski areas might respond to specific temperature increases in the future. This approach offers a static perspective, meaning it does not account for potential changes in climate variability. However, it enables direct comparisons to previous research by (Abegg et al., 2007), who used +1°C, +2°C, and +4°C warming scenarios.

4. **Weather Generator:** To apply the climate change signals to all climate stations, a stochastic weather generator called "LARS-WG5" was utilized. This generated daily time series of "synthetic" weather patterns for future scenarios. The reference period for these comparisons was set as the climatological normal period from 1961 to 1990. For climate stations with shorter time series, the warming signal was adjusted using a correction factor derived from a reference station with a longer time series that encompassed both the reference period and the available data period at the specific station.
5. **Modeling for Temperature Changes:** 15 global climate models incorporated based on three International Panel on Climate Change (IPCC) emission scenarios, namely B1, A1B, and A2. It's important to note that current greenhouse gas emissions are exceeding even the worst-case IPCC emission scenarios (A1FI), suggesting that the hypothetical warming scenarios could manifest sooner than anticipated, as observed by Allison et al., in 2009.

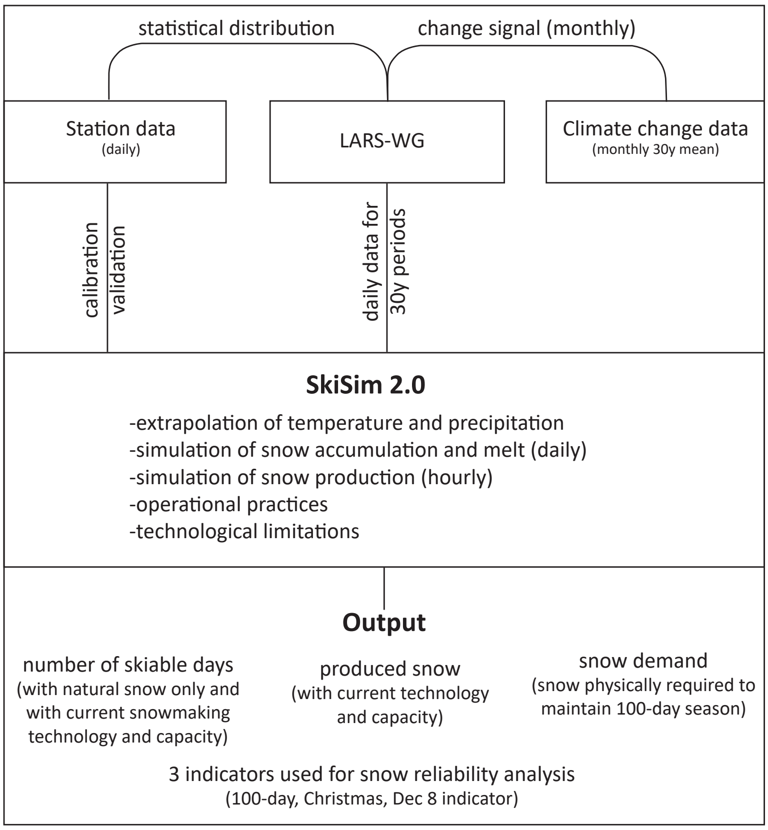


Figure 4.2. Methodological approach (Steiger, 2011)

4.2.1 SkiSim model

SkiSim is a scientific snow model that takes a comprehensive approach, considering various factors like snowmaking and the decisions involved in running ski resorts. To estimate daily snow depth accurately, the model relies on key inputs: daily minimum and maximum temperatures (in degrees Celsius) and daily precipitation amounts (in millimeters). When there's precipitation, it uses specific temperature thresholds to distinguish between solid, liquid, or mixed forms of precipitation. These thresholds are fine-tuned for each weather station by comparing the model's predictions with observed data on cumulative snowfall.

The model also considers the evolving characteristics of the snowpack. It accounts for snowpack density changes over time, representing the natural aging of the snow, and for densification during snowfall events due to the added weight on the underlying snowpack. Snow begins to melt when mean daily temperatures rise above 0 degrees Celsius. The rate of snowmelt depends on a melt factor, which represents the amount of snowwater equivalent that melts with a one-degree Celsius increase in temperature. This melt factor is adjusted for each weather station based on a comparison between modeled and observed data on the number of days with snow cover.

In this model's application, it calculates daily snow depth, which includes both natural and machine-made snow, for specific elevation bands (every 100 meters) and different aspects (north, south, west/east) of a ski area. Snow is produced under certain conditions: the date falls within the defined snowmaking season, the current snow depth is below a predefined threshold required to ensure uninterrupted ski operations, and weather conditions are suitable for snowmaking (Table 4.2.1).

To address the varying openness of ski areas and its impact on available skiing terrain (which can lead to overcrowding), the model considers the terrain days indicator. This indicator, initially introduced by Scott et al., in Ontario in 2017, is enhanced in this model by accounting for seasonal variations in demand. It distributes the winter season's total demand (measured by skier visits) across different segments, ensuring that the demand is evenly spread across days within each segment. This aspect highlights the importance of when a ski day is lost due to climate change; for instance, losing a day in early December may have less impact on the business than losing a day during the peak season.

The SkiSim2 model was used in Austria and was improved in three significant ways. First, it incorporated slope orientation by applying a correction factor for slopes facing north or south. Second, operational decisions were refined. Instead of a nationwide standard opening and closing date for the ski season, the model identified six groups of opening and closing dates based on comprehensive data from snow reports. SkiSim3 considers a ski area as open if it has a minimum of 30 centimeters of total snowpack (natural and man-made) at the specified critical altitude and falls within the operational season dates defined by the ski industry. This approach acknowledges that most ski areas do not open before mid-December due to low demand or risk considerations based on typical weather conditions. Similarly, many ski areas end their operations in spring, even with sufficient snow depth, because skiing demand drops rapidly in mid to late March. This approach enables a more realistic modeling of the total snow depth required to achieve the scheduled season closing date.

The model also takes into account variations in snowmaking capacity among different ski operators, accounting for differences in the proportion of skiing terrain equipped with snowmaking guns and the production capacity of snowmaking facilities per day. Unlike previous studies that assumed a common snowmaking capacity, this analysis obtained data on the percentage of ski terrain with snowmaking from an internet platform (at.skiinfo.com) and calibrated daily snowmaking capacity by comparing it with reported closing dates in snow reports.

Parameter	Values
Snowmaking season dates	Nov 1 - Mar 31 (non-glacier ski areas); Sept 1 - Mar 31 (glacier ski areas)
Temperature limit for snowmaking	-2°C
Minimum snow depth required for ski operation	30 cm
Density of a groomed ski slope	400 kg/m³ (Fauve, Rhyner, & Schneebeli, 2002)
Daily snowmaking capacity	1-10 cm (calibrated for each ski area)
Advanced daily snowmaking capacity	10 cm for all ski areas
Scheduled season closing	6 different categories based on ski report: Mar 19, Mar 30, Apr 9, Apr 20, May 1, May 15
Share of demand per season segment (and daily weighting factor) (Steiger, 2010)	
Early season	5% (0.098)
Christmas/New Years school holidays	30% (2.143)
Mid season	13% (0.37)
Winter break	30% (1.364)
March	15% (0.5)
April	7% (0.233)

Table 4.2.1, SkiSim modeling parameters (Steiger, 2010)

4.2.2 Sensitive assessment

The prosperity of the Alpine winter tourism industry is significantly reliant on favorable snow conditions and the capacity of ski areas to consistently provide reliable snow cover. A certain quantity of snow is essential for slope grooming, ground protection, ensuring safe operations, and offering skiers an enjoyable experience. However, both natural snowfall and the ability to artificially produce snow are expected to diminish as a consequence of climate change. This decline will, in turn, impact the snow reliability of ski areas. To assess the sensitivity of ski areas to climate change, it is essential to employ indicators that can describe potential impacts. In this context, three specific indicators are utilized: the 100-day rule, a Christmas indicator, and a season opening indicator.

The well-established 100-day rule, initially proposed by Witmer in 1986, stipulates that, for a ski area to operate successfully, a sufficient snow cover for skiing (with a snow depth of at least 30 centimeters) should persist for a minimum of 100 days per skiing season. It's important to note that the 100-day rule is not an inflexible regulation but rather a practical tool that has gained widespread acceptance among ski area operators across Europe, North America, and New Zealand, as documented in studies by Abegg et al., 2007.

The Christmas-New Year period is of particular significance in this context. It falls early in the skiing season, making it climatically vulnerable yet crucial in terms of visitor numbers and revenue. Research has shown that the share of skier visits during the Christmas-New Year period ranges from 15-20% in Canada and the USA, 25% in the canton of Graubünden, Switzerland, and as high as 30% in Tyrol, Austria. The Christmas indicator, introduced by Scott et al., in 2008, is met when a minimum snow depth of 30 centimeters is maintained throughout the Christmas holidays, typically from December 22 to January 4.

Another pivotal date in the skiing season is the season's opening. An early start signifies that the ski area is prepared for operation, driving season ticket sales and bookings for the entire winter season. In Austria, the tradition is to open many larger ski areas on December 8, a public holiday known as the Christian holy day of the Immaculate Conception, or the closest weekend to this date. Therefore, the ability to operate with a snow depth of 30 centimeters or more on December 8 is used as a third indicator in this assessment, referred to as the "8 Dec indicator."

It's worth noting that these three indicators pertain to the snow conditions at the average altitude of the ski areas. Additionally, the assumption is made that ski area operators can accommodate a certain level of variability, meaning they can compensate for "bad" years with "good" years. As a result, the indicators need to be fulfilled in 7 out of 10 years, allowing for some flexibility in meeting these criteria.

4.3 Climate data and climate change scenarios

Obtained data from climatological of 56 weather stations in Austria's central meteorological office (ZAMG) establish a baseline period covering the years 1981 to 2010. The selection of these weather stations was based on their proximity to ski areas and the availability of a comprehensive dataset, including daily minimum and maximum temperatures, precipitation, snow depth, and snowfall for the specified baseline period.

To project possible climate futures in Austria for the 21st century, climate change scenarios from the OKS15 project have been employed, as outlined in (Chimani et al.,2016). These scenarios provided monthly change values, allowing to simulate potential climate conditions in Austria. This analysis has considered thirteen climate projections, which were generated through combinations of six regional climate models (EUROCORDEX, as presented by Jacob et al., in 2014) and five global circulation models (CMIP5, in accordance with Taylor, Stouffer, and Meehl, 2011). These projections adhered to the criteria set by the Intergovernmental Panel on Climate Change (IPCC, 2019) for selecting reliable climate scenarios.

The spatial resolution of these climate scenarios was set at 12.5 kilometers, and two distinct emission pathways examined: (1) RCP 4.5, representing a moderate emission pathway consistent with successful implementation of national commitments to the Paris Climate Agreement, and (2) RCP 8.5, representing a business-as-usual pathway with limited success in reducing greenhouse gas emissions.

To streamline the results, the focus was on the ensemble mean derived from the 13 climate projections for three future time frames: the 2030s (covering 2021 to 2050), the 2050s (covering 2041 to 2070), and the 2080s (covering 2071 to 2100) for the modeling and analysis.

The findings indicate that projected warming during the winter season (December to February) across the 56 climate stations is more pronounced for minimum temperatures. For the RCP 4.5 pathway, this warming ranges from 1.3°C in the 2030s to 2.6°C in the 2080s. In the case of the RCP 8.5 pathway, the warming spans from 1.4°C in the 2030s to 4.7°C in the 2080s. In contrast, the increase in maximum temperatures is relatively lower, with a range of 1.1°C in the 2030s to 2.2°C in the 2080s for RCP 4.5, and 1.1°C in the 2030s to 4.1°C in the 2080s for RCP 8.5.

Regarding winter precipitation, it is projected to increase in both emission pathways. In the RCP 4.5 scenario, the increase is 8% in the 2030s, 9% in the 2050s, and 13% in the 2080s. In the RCP 8.5 scenario, the increase is more substantial, with 11% in the 2030s, 15% in the 2050s, and 20% in the 2080s (Steiger and Scott, 2020).

4.4 Demographic change

The demographic scenarios are constructed based on the population projections provided by Destatis in 2015 for the various federal states in Austria, as outlined in Table 4.4.1. These projections serve as the foundation for our analysis.

To refine these scenarios and account for potential variations in skier demand, additional assumptions are introduced, incorporating both optimistic and pessimistic perspectives. These assumptions take into consideration not only the effects of an aging population on skier demand but also the decreasing participation of young skiers. This decline in demand among individuals under 20 years of age is attributed to a range of factors, including the availability of alternative activities, financial constraints, or a lack of interest in winter sports, particularly among young people with a diverse cultural background.

To provide a concise summary, the pessimistic demographic scenario is a fusion of Destatis scenario G1-L1-W1 and assumption ‘a’. Conversely, the optimistic demographic scenario combines Destatis scenario G1-L1-W2 with assumption ‘b’. In both scenarios, skier demand is assumed to increase or decrease in proportion to changes in the total population. Table 4.4.2 presents the relative values representing the population development within each of these scenarios.

Assumptions	Destatis scenario G1-L1-W1	Destatis scenario G1-L1-W2
Total birth rate	1.4 (remains constant compared to today)	1.4 (remains constant compared to today)
Life expectancy	Male: 84.8 years	Male: 84.8 years
	Female: 88.8 years (moderate increase compared to today 77.7 (male) and 82.8 (female))	Female: 88.8 years (moderate increase compared to today 77.7 (male) and 82.8 (female))
Migration balance	+100,000 (gradual adjustment from 500,000 in 2014 to 100,000 in 2021 and thereafter remaining constant)	+200,000 (gradual adjustment from 500,000 in 2014 to 200,000 In 2021 and thereafter remaining constant)
Projected total population for Austria	11.4 million by 2060	12.5 million by 2060
Further assumptions	a) Population aging has no effect on demand, but demand Increases/decreases proportionately to total population. b) Population aging has an effect on demand. It is assumed that the winter sport activity decreases linearly with increasing age from 100% at an age of 60 to 0% at an age of 80 (Steiger, 2012). In addition, the participation rate of the age group < 20 years' is considered to be 80% and the total number in this cohort is multiplied by 0.8. This takes the mentioned decreasing share of young skiers into account. The demand increases/decreases proportionately to total population.	

Table 4.4.1, Demographic scenarios (Steiger, 2012; Destatis, 2015)

Parameters	Av 2014/ 15-2017/18	Pessimistic scenario (deviation from the average)		Optimistic scenario (deviation from the average)	
		2030s	2040s	2030s	2040s
Demographic change (LfStat, 2017; Destatis, 2015)	12.9 million (2017)	-26.3% first entries	-31.1% first entries	+1.6% first entries	+0.1% first entries
Number of OSDS per season (Berghammer & Schmude, 2014)	9.75	5≙-11.8% first entries	2≙ -19.3% first entries	5≙ -11.8% first entries	2≙ -19.3% first entries
Number of operating days per season (Soboll & Dingeldey, 2012)	121.5	108≙ -9.1% first entries	104≙ -11.8% first entries	119≙ -1.7% first entries	120≙ -1.0% first entries
Climate change		-20.90%	-31.10%	-13.50%	-20.30%
Total change		-47.20%	-62.20%	-11.90%	-20.20%
Results: Estimated first entries (per day)	1,510.66	796.3	570.4	1,331.60	1,206.40

Table 4.4.2, Estimated changes in first entries (per day) for the Sudelfeld ski resort (2030s and 2040s compared to the 2014/15–2017/18 average) (Berghammer and Schmude (2014); Destatis (2015); LfStat (2017); Soboll and Dingeldey (2012).

4.4 Climate change assessment approach

To ensure a consistent basis for comparing results across the study sites, certain uniform pre-conditions were established. Unlike the validation process, where individual opening and closing dates were considered, these pre-conditions were applied in the climate change assessment to create comparable potential ski season lengths. Consequently, the season lengths calculated for the climate change assessment differ from those employed in the validation process.

Since official statistics on the extent of snowmaking coverage and capacity in the ski areas were unavailable, the study assumed a 100% coverage of snowmaking. This assumption is based on interviews and findings from the survey conducted by Wolfsegger et al., 2008, which indicated that most Austrian ski areas aspire to achieve full snowmaking coverage in the future. It's worth noting that at present, approximately 75% of the ski slopes in Tyrol benefit from snowmaking, according to information from the Fachverband Seilbahnen Österreichs (Austrian Cableway Association).

To determine a representative average of the entire ski area's snow production, a weighted average of the modeled snow production was computed, taking into account the altitudinal distribution of ski slopes. This calculation involves the following formula:

Produced snow = $\Sigma^{n}_{i}={}_{1}tsnow_{i} \times \propto_{i}$, with $\propto_{i} = A_{i}/A$

In this formula, $tsnow_{i}$ represents the technically produced snow, $\propto i$ denotes the weighting factor, which is a combination of the total ski slope area (A) and the ski slope area within each specific elevation band (A_{i}), and i signifies the altitudinal band.

A potential evolution in snowmaking technology is also considered in a second variable, referred to as "snow required." If the modeled season length with the existing snowmaking technology falls short of 100 days, the required amount of additional technical snow needed to achieve a 100-day season is calculated, without imposing any temperature or capacity limitations. Notably, such temperature-independent snow production methods have already been implemented in two glacier ski areas, one in Austria (Pitztal, in 2009) and the other in Switzerland (Zermatt, in 2008).

5. Results

This thesis offers findings related to key metrics used in prior sections, specifically, season length, snow reliability, and snowmaking capacity in the context of ski operations. These results are presented to facilitate comparisons with previous assessments conducted in Austria and on a global scale. Additionally, this study introduces two new metrics for the first time in Austria.

The first new metric, termed 'terrain days' (as introduced by Scott et al. in 2017), measures the extent of available skiing terrain throughout the ski season. This metric takes into consideration variations in season length, distinguishing between terrain areas that rely on natural snowfall and those equipped with snowmaking capabilities.

The second novel metric assesses the combined impact on the performance of ski areas at the municipality level. This assessment aims to gauge the differing effects on the regional economy, considering the varying degrees of reliance on the tourism sector. This new approach allows for a more comprehensive evaluation of the economic consequences of ski operations.

5.1 Ski season length

The thesis applies a "100-days rule" to evaluate the natural snow reliability of different ski areas, primarily considering their mean altitudes. The results indicate the expected duration of snow reliability in the context of climate change scenarios. Additionally, the impact of snowmaking on the ski season duration is analyzed.

Ski area A is projected to be naturally snow reliable until the 2020s in the A1B scenario and the 2030s in the B1 scenario. With the integration of snowmaking, it can extend its operational season to the 2050s to 2070s. However, even with snowmaking, it may still experience short-term losses in skiable days (by the 2030s) ranging from 0% to 8%, medium-term losses (by the 2050s) of 9% to 24%, and long-term losses (by the 2080s) of 32% to 90%.

Ski area B is currently not naturally snow reliable due to relatively high temperatures resulting from frequent Foehn events (warm downslope winds) and dry conditions. Snowmaking can ensure a 100-day skiing season until the 2040s to 2060s. Nevertheless, it may still face short-term losses (1% to 4%), medium-term losses (10% to 29%), and long-term losses (60% to 99%).

Ski area C is naturally snow reliable until the 2060s in the A1B scenario and until the end of the century in the B1 scenario. Snowmaking can provide a sufficiently long skiing season throughout the 21st century. It may experience relatively minor short-term losses (1% to 3%), medium-term losses (5% to 8%), and long-term losses (8% to 22%).

Skiable days are expected to be lost primarily in the early season, followed by the Christmas and off-season periods (Table 5.1.1). In the 2030s and 2050s, some gains in the off-season are projected due to increased winter season precipitation and improved snowmaking, while the temperature increase remains moderate. These model runs revealed that most combinations indicated a 1°C warming for the 2011-2030 period, a 2°C warming for the 2046-2065 period, and a substantial 4°C warming by the turn of the next century.

The early season's operational days, although less financially significant, are essential for marketing purposes. Not having sufficient skiing conditions during this period can lead to hesitant bookings and reduced season pass sales, potentially damaging the destination's reputation. Given that approximately 30% of winter revenues are generated during the Christmas holidays, even slight losses in skiable days can have a substantial financial impact.

This thesis highlights the importance of ski area size as a selection criterion for skiers. Currently, 100% of skiing terrain with snowmaking is snow reliable at ski areas A and C, while at ski area B, it stands at 85%. Projections suggest that ski area A's reliability remains relatively stable until the 2030s to 2040s but experiences significant impacts afterward. Ski area B is expected to see a continuous decrease, leading to no snow-reliable skiing terrain by the 2080s. In contrast, ski area C can maintain 100% reliability until the 2060s to 2080s.

The thesis also sought to understand the threshold at which closed skiing terrain would impact demand. The threshold varies depending on factors such as ski area size and the ratio of day trippers to holiday guests. In general, an 80% threshold for open skiing terrain was considered to have minor impacts, while a 50% threshold represented major but still acceptable losses. Ski areas A and B, being relatively small and reliant on valley runs, are more sensitive to changes in snow-reliable terrain, which may cause substantial issues.

In conclusion, this thesis provides valuable insights into the evolving snow reliability of different ski areas in the face of climate change and the significance of snowmaking in mitigating potential losses in skiable days.

Ski area	**Scenario**	**Season periods**					
		1Nov–21 Dec	22 Dec–4 Jan	5 Jan–8 Feb	9 Feb–1 Mar	2–31 Mar	1–30 Apr
St. Johann (A)	Baseline	17	14	35	21	30	19
	2030 B1	14	14	35	21	30	22
	2030 A1B	8	14	35	21	30	17
	2050 B1	8	12	35	21	30	18
	2050 A1B	4	11	35	21	29	3
	2080 B1	2	8	33	21	26	2
	2080 A1B	0	0	7	5	0	0
Patscherkofel (B)	Baseline	17	14	35	21	30	19
	2030 B1	11	13	34	21	30	22
	2030 A1B	7	13	35	21	30	28
	2050 B1	3	10	33	21	30	25
	2050 A1B	3	8	32	21	27	6
	2080 B1	0	3	14	14	21	2
	2080 A1B	0	0	0	1	1	0
Zillertal Arena (C)	Baseline	36	14	35	21	30	30
	2030 B1	34	14	35	21	30	30
	2030 A1B	31	14	35	21	30	30
	2050 B1	28	14	35	21	30	30
	2050 A1B	32	14	35	21	30	29
	2080 B1	26	14	35	21	30	27
	2080 A1B	7	10	35	21	30	27
% of revenues in Tyrol (mean 2003/2004–2005/2006)		5	30	13	30	15	7

Table 5.1.1: Projected skiable days of each season period at the mean altitude, with snowmaking (Steiger, 2010).

5.2 Impacts on snow making requirements

In the baseline scenario, the weighted average of artificially produced snow stands at 45 centimeters for ski area A, with ski area B recording higher snow production at 54 centimeters due to warmer and drier conditions. In contrast, the high-altitude ski area C has the lowest snow production at 31 centimeters. To meet the anticipated season lengths, all ski areas would need to increase the volume of technically generated snow (as illustrated in Figure 5.1).

The maximum snow production, which represents the current technological limits of snowmaking, is expected to be reached in different timeframes. For ski area A, this occurs in the 2050s in the A1B scenario, with a 69% increase, and in the 2070s in the B1 scenario, with a 78% increase. Ski area B is projected to reach this maximum in the 2030s, with a 14% increase, and the 2050s, with a 15% increase. Ski area C is expected to reach its maximum in the 2080s, with an increase ranging from 16% to 112%. This increased snow production also entails a corresponding rise in water demand, necessitating more snowmaking ponds. However, this could have adverse consequences on the visual appeal of the landscape and lead to conflicts of interest. It’s important to note that as temperatures rise, the energy efficiency of current snowmaking technology decreases significantly. Producing snow near the temperature limit requires approximately six times the energy compared to production at optimal temperatures, which can result in a considerable increase in energy consumption.

If we assume the adoption of snowmaking technology with its current limits concerning the energy consumption, the study suggests a substantial overall increase in snow production would be required. Ski area A would need to increase its snow production by 167% to 330%, while ski area B would need a boost of 122% to 223% to maintain a 100-day skiing season until the end of the century. Ski area C, while relatively well-equipped with current technology, would still require a slightly higher increase in the range of 16% to 124% for certain areas. Once again, this considerable rise in water demand is likely to give rise to conflicts, and the associated increase in energy consumption raises concerns regarding climate change mitigation and sustainability considerations.

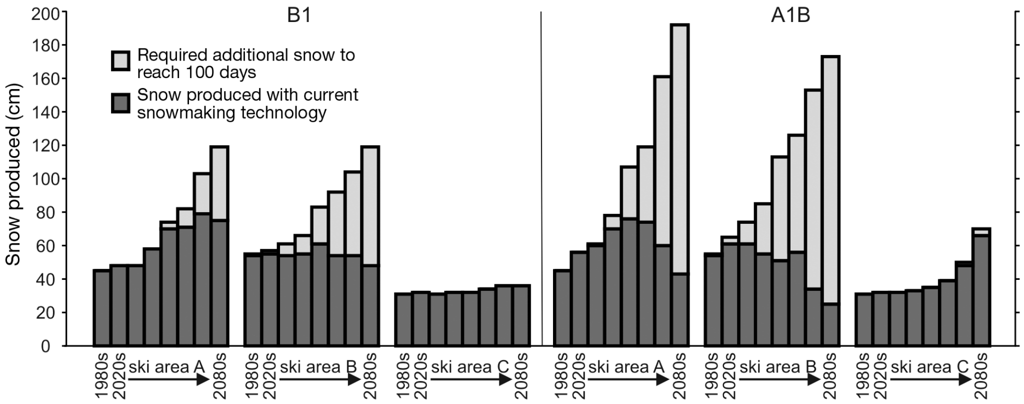


Figure 5.1, Projected snow production as a weighted average of all altitudinal bands under the B1 and A1B climate change scenarios (Steiger, 2010).

5.3 Terrain days

The analysis of reduced skiing days or decreased snow reliability does not take into account the reduced skiing terrain resulting from inadequate snow in certain sections of a ski area. This, in turn, leads to the concentration of skiers in a smaller area, potentially causing overcrowding and a decrease in skier demand. To address this issue, a terrain days indicator was introduced, initially applied by Scott and colleagues in Ontario, Canada, in 2017, to assess potential changes in market-wide capacity. In this study, the terrain day indicator has been further developed to reflect the fluctuation in demand during the ski season. This is achieved by assigning weights to available ski terrain based on the expected level of demand across six segments of the skiing season. In simpler terms, open skiing terrain during low-demand season periods (such as before Christmas or in April) is considered less important than operational terrain during high-demand season segments (such as Christmas or school holidays in February). Therefore, the financial significance of lost terrain days in the low season is less than that in the high season.

On a national scale, if the snowmaking capacity remains constant, between 6% (2030s) and 16% (2080s) of terrain days are lost in the low emission scenario, and this increases to 6% (2030s) to 46% (2080s) in the high emission future (Table 5.3.1). Even with improved snowmaking, the losses are quite similar. This might seem surprising, considering the substantial difference in snowmaking capacity. The reason for this similarity is that the initial value during the reference period, when improved snowmaking is used, is already higher than with current snowmaking. This leads to similar relative changes but at a higher absolute level.

Indicators	1981–2010	RCP 4.5			RCP 8.5		
		2030s	2050s	2080s	2030s	2050s	2080s
(A) 100-day indicator with current snowmaking	90%	80%	72%	54%	78%	52%	11%
(B) 100-day indicator with improved snowmaking (10 cm/day)	99%	93%	92%	83%	93%	80%	31%
(C) Christmas indicator with current snowmaking	84%	65%	52%	37%	63%	33%	5%
(D) Christmas indicator with improved snowmaking (10 cm/day)	98%	90%	80%	67%	92%	66%	15%

Table 5.3.1: reliability of Austrian ski resorts

Provinces like Vorarlberg and Upper Austria experience higher losses compared to other provinces due to a significant portion of their skiing terrain being situated at lower altitudes (Table 5.3.2). Additionally, Vorarlberg has a below-average proportion of ski slopes with snowmaking facilities. It's evident that climate change has a lesser impact on terrain days compared to the proportion of snow-reliable ski areas. This can be attributed to two main factors: 1) The weighting of operation days throughout the ski season, taking into account the season segments most affected, primarily the early and late parts of the season. These segments have relatively low demand, resulting in smaller weighted terrain day losses compared to projected season day losses. 2) The fact that smaller ski areas are more adversely affected by climate change due to their lower average altitude and limited snowmaking capabilities. Considering that snow reliability is a relatively broad performance indicator, these results suggest that climate change impacts may have been overestimated for some ski areas in Austria.

Province	**RCP 4.5**			**RCP 8.5**		
	2030s	2050s	2080s	2030s	2050s	2080s
Vorarlberg	—7 (—6)	—12 (—10)	—20 (—18)	—7 (—6)	—20 (—18)	—49 (—45)
Tyrol	—6 (—5)	—9 (—8)	—16 (—14)	—6 (—5)	—17 (—15)	—44 (—40)
Salzburg	—5 (—5)	—9 (—8)	—16 (—15)	—6 (—5)	—17 (—15)	—45 (—42)
Upper AT	—13 (—12)	—19 (—19)	—31 (—31)	—12 (—12)	—30 (—30)	—66 (—65)
Lower AT	—9 (—9)	—14 (—13)	—22 (—21)	—8 (—8)	—21 (—20)	—52 (—50)
Styria	—7 (—7)	—12 (—12)	—18 (—18)	—7 (—7)	—18 (—18)	—52 (—51)
Carinthia	—3 (—3)	—5 (—5)	—9 (—8)	—3 (—3)	—10 (—9)	—37 (—35)
Austria	—6 (—5)	—10 (—9)	—16 (—15)	—6 (—6)	—17 (—15)	—46 (—42)

Table 5.3.2: Decline of weighted terrain days per province with current snowmaking capacity (with improved snowmaking in brackets)

5.4 Regional economic impacts

Tourism plays a vital role in Austria, significantly contributing to the economy of numerous rural municipalities. In addition to examining business-level risks using previous indicators, it's crucial to assess potential regional economic impacts, especially in areas highly dependent on tourism. Unfortunately, data regarding the proportion of a municipality's economy represented by tourism is not readily available at the local level. To address this, "winter tourism intensity," measured by the number of winter overnight stays per resident, is used as a proxy for economic reliance on tourism.

Comparing changes in terrain days with winter tourism intensity within a 15 km road distance of 754 Austrian municipalities connected to a ski area reveals varying impacts in regions with different degrees of tourism dependence.

Table 5.4.1 presents the average change in terrain days for each winter tourism intensity class. The municipalities with the lowest winter tourism intensity, i.e., those with fewer than 50 overnight stays per resident, experience the most significant loss in ski terrain days. Conversely, the municipalities heavily reliant on winter tourism are the least affected. From a regional economic standpoint, this distribution of climate change impacts is relatively positive. It primarily impacts smaller ski areas in regions with a more significant focus on summer tourism or more diversified economies, thus reducing the overall risk. However, even a minor loss of terrain days, for instance, a 15% decrease in the high-emission scenario of the 2050s, could pose a challenge for the most tourism-dependent municipalities. This challenge arises because they would need to attract more tourists within a shorter skiing season or on smaller skiing terrains to sustain the current growth trend in winter tourism.

Tourism intensity (winter overnight stays/inhabitants)	RCP 4.5			RCP 8.5			# municipal-ities
	2030s	2050s	2080s	2030s	2050s	2080s	
<50 (low)	—12%	—17%	—26%	—12%	—26%	—60%	607
50-99 (medium)	—7%	—11%	—19%	—7%	—19%	—51%	72
100-199 (high)	—6%	—10%	—17%	—6%	—18%	—49%	49
>¼200 (very high)	—5%	—8%	—15%	—5%	—15%	—42%	26

Table 5.4.1: Decline of weighted terrain days per municipalities' tourism intensity.

The accompanying maps (Figure 5.2) unveil significant spatial patterns of climate change risks in the future. Municipalities with lower winter tourism intensity and high climate change impacts are spread across Austria. Consequently, ski areas grappling with climate change and diminishing skiing terrains represent a climate change risk in all regions. In general, climate change impacts are more pronounced in the northern half of Vorarlberg and Salzburg, as well as the eastern edge of the Alps, including southern Lower Austria and eastern Styria. These regions are strategically situated close to essential source markets in Southern Germany (Munich, Stuttgart), Eastern Austria (Vienna), and Hungary (Budapest). In contrast, the primary Alpine ridge, extending from southern Vorarlberg and Tyrol to the East, is less affected by these climate change impacts.

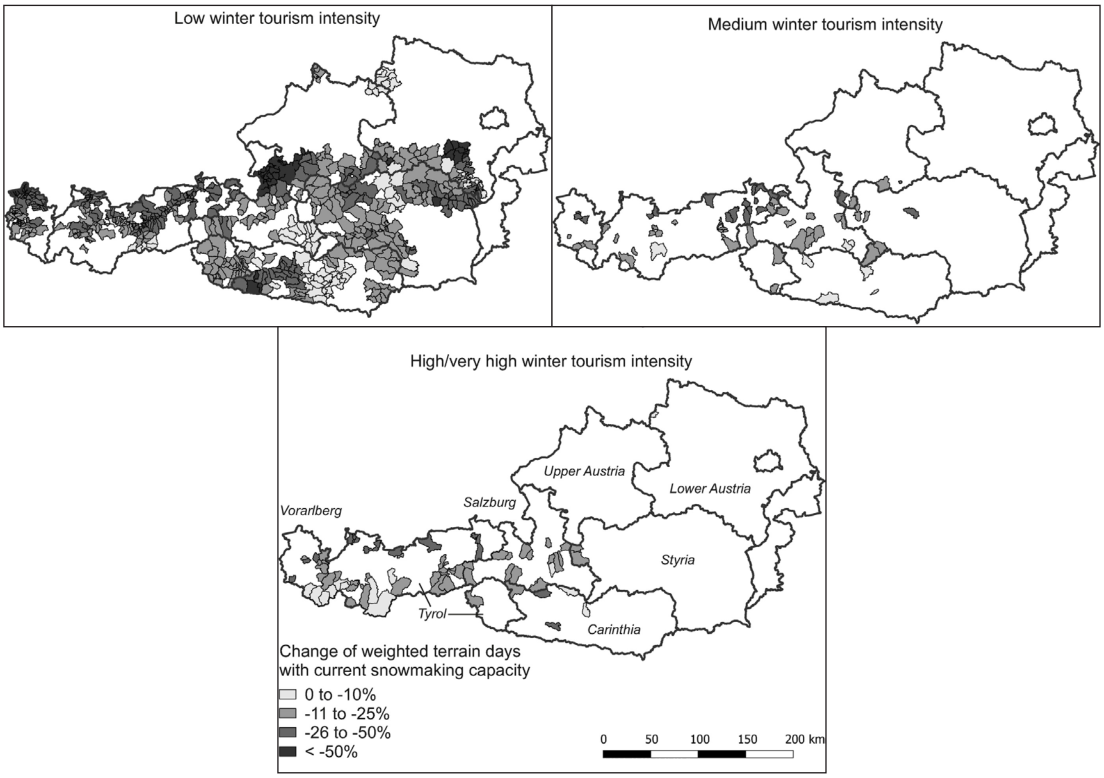


Figure 5.2: Regional economic impact of climate change with current snowmaking capacity in the 2050s RCP 8.5 scenario.

5.5 Regional economic impacts

A warmer climate has significant implications for the winter season, including an increase in the proportion of rain events. This climate shift also results in more energy available for the melting of snow. Consequently, in the future, greater quantities of machine-made snow will need to be produced to guarantee uninterrupted ski operations until the planned season conclusion. This, in turn, may necessitate a reconsideration of the traditional season schedules, as our earlier findings indicate.

If the current snowmaking capacity and terrain coverage remain unchanged, there will be a requirement to increase snow production by 22% to 26% in the 2030s and by 32% to 45% in the 2050s, under different emission scenarios (RCP 4.5 and 8.5). Notably, the quantity of snow production is somewhat lower in the high emission scenario (RCP 8.5) for the 2080s. This reduction is primarily due to the limited number of available snowmaking days, preventing the production of the additional snow required.

These increased snow production demands are directly linked to the findings presented in the season length indicators in Table 4.1.1. This means that despite the gradual shortening of the ski season and the decreasing number of snow-reliable ski areas, increasing snowmaking efforts are necessary to attain the targeted season lengths. For instance, in the 2050s high emission scenario, a 45% increase in snow production is needed to limit weighted terrain day losses to approximately 17%, as outlined in Table 5.3.2.

If snowmaking capacity is enhanced to a level where 10 centimeters of snow can be produced per day, the demand for snow production will rise by 28% to 57% in the RCP 4.5 scenario and by 33% to 73% in the RCP 8.5 scenario, as indicated in Table 5.5.1. However, it’s essential to acknowledge that despite these heightened snowmaking efforts, many ski areas are still expected to lose their snow reliability, as indicated by the 100-day rule (refer to Table 5.3.1). This suggests that the efficacy of snowmaking, in terms of ensuring a viable ski season, has its limitations and may not fully offset the broader impacts of a warming climate on ski operations.

	RCP 4.5			**RCP 8.5**		
	2030s	2050s	2080s	2030s	2050s	2080s
Current snow-making capacity	22%	32%	43%	26%	45%	40%
Improved capacity	28%	42%	57%	33%	60%	73%

Table 5.5.1: Regional economic impact of climate change with current snowmaking capacity in the 2050s RCP 8.5 scenario.

6. Discussion

The findings of this thesis reveal that the projected impacts are contingent on the specific performance indicators used. In particular, the “100-day rule,” often employed as an economic metric, tends to overstate the potential climate change risk to the Austrian ski industry. When relying on the 100-day rule, it appears that in the 2050s, under a high emission scenario (RCP 8.5), as many as 48% of ski areas may no longer be considered snow reliable. In contrast, when considering the “weighted terrain days” indicator (assuming no change in snowmaking capacity), the reduction is notably less severe at approximately 17%. This discrepancy highlights the importance of assessing the quantity of skiable terrain, which is vital for estimating system capacity and visitor experience, a point also emphasized in studies conducted in Canada.

A positive aspect of this study is that the ski areas most severely impacted are often situated in municipalities with low levels of winter tourism intensity. Consequently, the potential adverse effects on the local economy and livelihoods in the coming decades may be confined to the ski industry, rather than having a more widespread impact on the entire economies of rural valleys that heavily rely on ski tourism. However, in regions with high to very high winter tourism intensity, there may be increased demand pressure on less affected municipalities, such as those in Southern Vorarlberg or the South-West of Tyrol. These regions could potentially gain market share in what is otherwise a stagnating market. Yet, this growth might lead to issues related to overtourism, challenges in infrastructure development (e.g., road network expansion in narrow valleys), and real estate pressures due to limited available space.

To comprehensively assess the economic impacts of changing competitiveness among ski areas, future research should consider potential shifts in demand, both domestic and international.

Nonetheless, despite these relatively optimistic findings, the rising temperatures pose a compounded challenge for generating sufficient and cost-effective snow production. This is exacerbated by a reduced timeframe for snowmaking due to an increasing number of days that are too warm for efficient snow production, necessitating the production of snow in warmer and costlier conditions. Consequently, this entails escalating operational and capital costs for extending snowmaking systems. One case study in Austria revealed that lift ticket prices would need to substantially increase to maintain profitability. This signifies a potential transformation of skiing from a national sport to an activity accessible primarily to high-income individuals. Furthermore, the increased demand for snow production (ranging from 22% to 73%, as shown in Table 5.5.1) also translates to a significantly greater demand for water and energy. While water resources for snowmaking are generally available at a regional level in Austria, local constraints may arise due to geological and topographical factors that hinder proper water storage and collection.

More challenging than water availability is the escalating demand for energy. While efficiency improvements might partially offset the increasing energy consumption resulting from higher snow production volumes, the energy efficiency of current snowmaking technology is temperature-dependent and diminishes with rising temperatures. This is because different snow gun types (fan guns or air-water guns) exhibit optimal efficiency at temperatures around -14°C, which is approximately 5 to 14 times higher than at -2°C. Given that climate change is likely to reduce the number of ideal snowmaking hours and increase the hours with marginal conditions, this will also have an impact on the energy efficiency of snowmaking.

To mitigate climate change and limit global warming to a maximum of 2°C by the end of the 21st century, a substantial reduction of global greenhouse gas (GHG) emissions is essential, commencing no later than 2025. Tourism, including winter tourism, is obligated to make its own contributions to achieve this goal. The heightened energy consumption for snowmaking complicates GHG emission reduction efforts. Moreover, trends in tourism demand pose additional challenges, with tourist arrivals in municipalities within a 15 km driving distance of a ski resort having increased by 60% over the past two decades, while overnight stays have only seen a 30% increase. This can be attributed to a reduction in the length of stay, from an average of 5.8 days in 1996/97 to 4.7 days in 2015/16. In light of the likely future price increases in the Austrian ski industry, it remains uncertain if the trend of shorter stays can be reversed. More frequent periods in the winter season without natural snow, yet with good skiing conditions, could deter tourists from booking longer vacations due to uncertainty regarding skiing conditions and the absence of a "winter feeling." This underscores the need for in-depth investigations into the impact of climate change on future tourism demand.

Despite several improvements in the modeling approach and the analysis of indicators, there are certain limitations that warrant attention. While the study incorporated the most recent high-resolution climate change data for Austria, the next generation of climate change scenarios (CMIP6) and evolving climate models are expected to enhance performance, especially in regions with complex topography. In terms of the SkiSim3 model, there is a need for more data to evaluate the model's performance, especially to validate the accuracy of snow volume production. Unfortunately, data on the water consumption of snowmaking facilities in ski areas are not currently available. It has been reported that between 5% and 40% of water used for snowmaking is lost due to wind erosion and sublimation. Recent experiments conducted in the French Alps found even higher losses, ranging from 25% to 50% in the best case and from 50% to 75% in the worst case. These processes, although not considered in SkiSim3, potentially overestimated the efficiency of snowmaking in preventing losses in season lengths and terrain days. Wind, another factor not accounted for, might underestimate snowmelt under warm wind conditions.

Furthermore, snowmaking calculations in the study were based on air temperature, although snowmaking potential is also influenced by air humidity, with better conditions occurring at lower air humidity levels. Nevertheless, accurately incorporating air humidity in climate change scenarios remains a complex challenge.

Although this study incorporated more individual data related to ski area and snowmaking operations compared to previous studies, an analysis encompassing 208 ski areas still necessitates some degree of generalization, primarily due to the lack of more detailed data at the business level for such a large number of operators. Therefore, it’s crucial to exercise caution when drawing specific conclusions from these somewhat generalized results for a particular ski area. Nonetheless, the model presented here is, to the best of our knowledge, the only one that comprehensively incorporates snowmaking and has the capacity to assess multiple ski areas across various ski markets and countries. Thus, it serves as a valuable tool for better representing the operational realities of ski areas in assessments of climate change impacts.

Furthermore, the consequences of climate change are expected to have significant ramifications for the ski industry, potentially leading to the closure of ski areas that are particularly vulnerable to changing snow conditions. This could result in a gradual reduction in the number of viable ski resorts, favoring regions with more favorable climatic conditions. Such a decline in the ski sector is not an entirely novel occurrence in the Alpine region. For instance, a series of years marked by insufficient snowfall during the late 1980s and early 1990s is believed to have played a role in the permanent closure of 32 ski areas in the Alpine region (NELSAP, 2008). A substantial portion of these “lost ski areas” were small-scale operations, often family-owned and run, and in some cases, seasonal hobby businesses situated on family-owned properties. The changing snow conditions necessitated significant investments in snowmaking technology and equipment, which many small family businesses found financially unfeasible.

Considering that a number of the remaining ski areas in the Alpine region are still privately owned, and climate change is expected to exacerbate the historical challenges faced by the ski sector, it appears highly likely that this sector will continue to contract. As the probable outcome of climate change is a reduction in the number of ski operators across most regional markets, it becomes crucial to identify the specific regions and ski areas where the ski industry is most likely to contract. This information is of particular interest to various stakeholders, including the ski industry itself, investors, real estate developers, insurance companies, governments, and local communities, over the next two decades.

To move beyond business-level analysis and into the realms of the broader economy and society, more data is required to ascertain the economic significance of winter tourism for regional economies. The assumption that lost terrain days would directly translate to lost tourist spending represents an important but uncertain assumption. Similarly, the accuracy of added value calculations published by the Austrian Cable Car Association is open to question. These areas present significant avenues for future research.

6.1 Consideration of the demand-site response

The behavioral responses of individual skiers to marginal snow conditions and ski area closures play a pivotal role in determining the overall vulnerability and viability of a ski area or marketplace. In contrast to the considerable challenges and costs associated with structural and management-based adaptations currently considered by ski areas, tourists have the capacity to adjust their behavior in response to climate variability, unfavorable snow conditions, and the closure of local ski areas (as highlighted by Scott & McBoyle, 2007; Pickering, Castley, & Burtt, 2010; Gössling & Hall, 2006; Gössling, Scott, Hall, Ceron, & Dubois, 2012).

Several studies have begun to investigate how skiers adapt their behavior in the face of increasingly marginal snow conditions at ski areas. For example, König (1998) examined how skiers in Australia might respond to hypothetically poor snow conditions in the future, finding that 25% would continue skiing at the same place and frequency, 31% would ski less often, 38% would ski at other overseas locations, and six percent would cease skiing altogether. A follow-up study by Pickering et al. (2010) revealed that more skiers now indicate they would ski less often, and fewer would travel overseas to ski at more viable resorts. Similar surveys were conducted by Behringer, Buerki, and Fuhrer (2000) and Bürki (2002) at resorts in Switzerland.

Non-survey-based research, utilizing modeling and analogs, presents a less severe outlook for the future of ski area demand in changing climate conditions. For instance, Dawson, Scott, and McBoyle (2009) used a climate change analog in the US Northeast to examine the impact of unusually warm winter seasons of the past, representative of average winter conditions under different emission scenarios. Their findings indicated a decrease in visitation of just 11 and 12%, respectively. Furthermore, modeling-based studies by Fukushima et al., 2002 and Shih et al., 2009 explored the relationship between snow depth, skier visits, and ticket sales in Japan and Michigan, USA, revealing much less significant changes in skier demand during marginal winters, with reductions in the range of 7-9%.

Given the projected contraction of the ski sector, which may result in the closure of vulnerable ski areas, it becomes crucial to assess skiers' willingness to travel longer distances to access operational ski areas. Unbehaun et al., 2008 suggest that skiers in Austria find travel distances of 250-500 km acceptable for a ski holiday (i.e., not just a day trip). However, these travel thresholds can significantly vary from one region to another and certainly from one country to another, such as the differences between Europe and North America, where longer driving distances are more common.

An ironic concern associated with the anticipated contraction of ski area supply is the potential increase in transportation emissions, further contributing to climate change. Moreover, longer travel distances between major urban centers and viable ski areas raise the prospect of an overall reduction in skier participation. It remains unclear how the future demographic of skiers will evolve if existing skiers are unwilling to travel longer distances to ski, or perhaps more crucially, if new potential skiers are not introduced to skiing culture.

6.2 Operational decision-making for supply& demand impacts

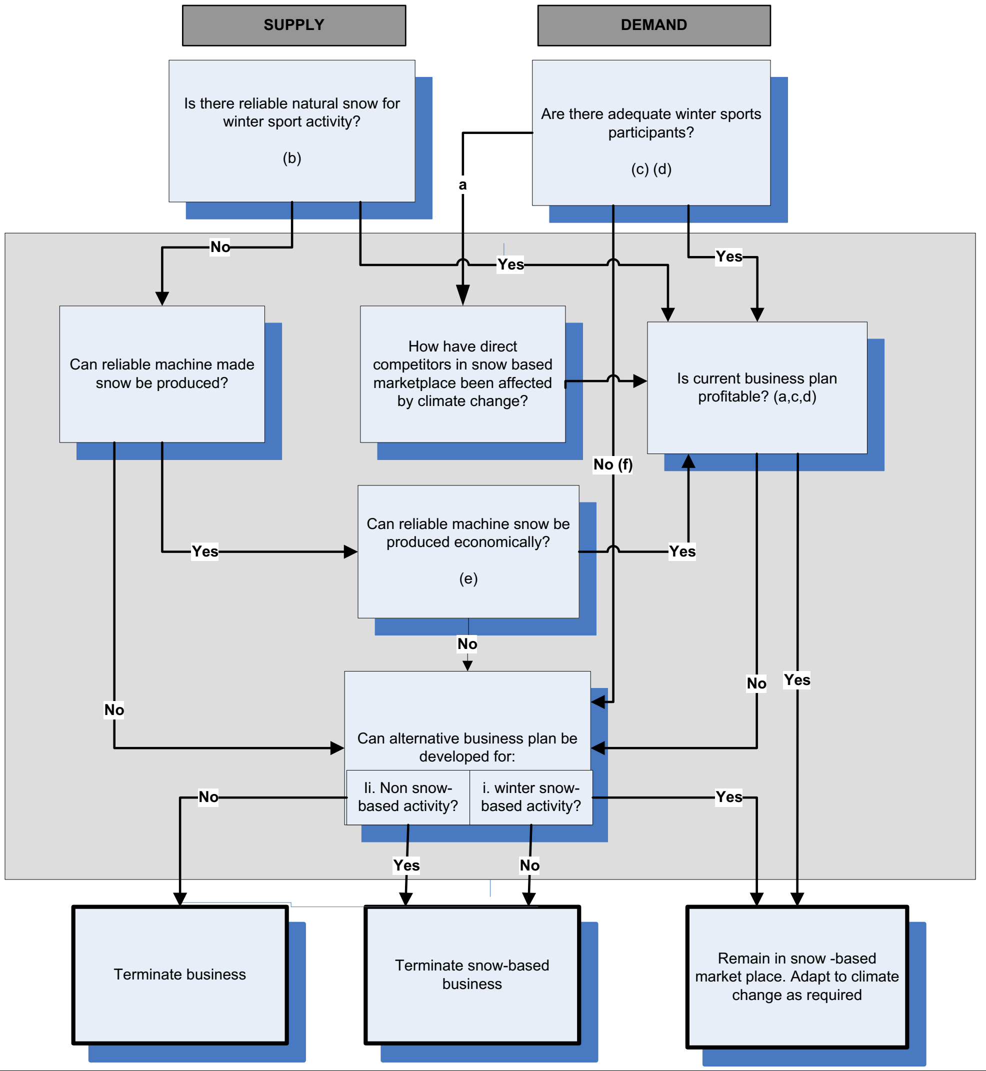
As the consequences of climate change for the ski sector are contingent on the impacts faced by competitors and the behavioral responses of skiers and snowboarders to environmental and operational alterations, ski area managers encounter a substantial challenge when attempting to gauge their expected vulnerability and plan for the future. Figure 6.1 provides a fundamental decision-making flowchart that can guide ski area managers in initiating considerations of the climate change-related decisions that necessitate immediate attention. It's of utmost importance that these managers take into account both the supply-side and demand-side ramifications of a changing climate, in addition to a contracting ski area marketplace.

Some critical questions that ski area managers need to address encompass:

- **Snow Reliability:** Is there reliable natural snow currently, and can we anticipate reliable snow in the future?
- **Snowmaking:** Can we produce adequate snow using the existing technology?
- **Participants:** Are there enough participants now, and can we expect the same in the future?
- **Costs:** What will be the costs of required adaptive strategies?
- **Technology:** Can reliable machine-made snow be produced with the available technology?
- **Competition:** How have direct competitors in snow-based businesses been impacted by climate change?
- **Adaptations:** How have competitors adapted to the current changes?
- **Profitability:** Is the current business model profitable?
- **Alternative Business Models:** Can an alternative business model be developed for either snow-based or non-snow-based activities?
- **Economic Impact:** What will be the consequences for real estate values, and how will it affect local services and environmental resources?

Simultaneously, communities that lose ski tourism operations will be obliged to devise strategies for economic diversification due to the loss of winter tourism revenues and related jobs. These communities could also face increased pressure on social services, unemployment, and a decline in real estate values. The more vulnerable ski areas will, at different junctures, need to decide whether to make substantial investments in short-to-medium-term adaptations, transition into multi-season destinations, or eventually terminate their snow-based businesses.

Significantly, climate change is just one of many factors that will shape the future of the ski industry. Other factors, including federal and state tourism policies, economic recessions, demographic changes, rising travel costs, competition with other tourism destinations, and evolving social preferences, may prove to be equally or even more significant than the direct impacts of climate change. The interplay of these multifaceted macro-scale influences necessitates a holistic comprehension to inform strategic investments, planning, and development within the ski industry over the next 10 to 20 years. Assessing the relative vulnerability of ski resorts within a regional marketplace is merely one step in the broader effort to obtain a comprehensive understanding of the complexities associated with environmental and economic changes occurring in contemporary societies.



a) Marketplace competition is likely to decline according to existing literature. If demand remains stable or dilutes proportionality less than supply, there would be a net transfer of demand throughout the remaining marketplace.
b) Are necessary 'natural' climate conditions present
c) numbers could stabilize or increase if there were increases in travel costs or emission rights
d) numbers could decrease because of changing demographics (aging and multi culturalism); social trends; climate variability; and cost
e) direct operator costs – capital investments for snowmaking systems and their upgrades; increased operating costs (energy, water, labour) of snowmaking if more snow needed at higher temperatures. Also consider indirect economic changes – changes in skier demand, marketplace, and market share.
f) examine alternative marketing plans to increase participation rates

Figure 6.1: Climate change management decision-making flowchart for ski operators (Dowson & Scott, 2013)

7. Conclusion

The thesis's results suggest that the Alp Regions ski tourism industry is unlikely to face an abrupt and devastating demise due to global warming, as some media reports have claimed in recent years. The projected impacts, while substantial and varying significantly, appear to be manageable for the majority of ski areas until at least the 2050s under a high emissions pathway (RCP 8.5) or even the 2080s in a low emissions pathway (RCP 4.5), especially when taking into account adaptive measures like additional snowmaking capacity.

Consistent with findings in North America, the losses in season length are considerably reduced when considering the full extent of current snowmaking capacity, and they are further mitigated with increased snowmaking capacity and terrain coverage—a trend that is ongoing in the Alps region. Compared to previous research for Austria, the climate risk for the ski industry remains consistent, but the impacts projected in this study are more moderate, primarily due to the improved snowmaking capacity.

The study also reveals distinct regional differences in potential impacts, influenced by factors such as snowmaking capacity and altitude. Higher impacts are concentrated in Lower Austria and the northern regions of Vorarlberg, Tyrol, and Salzburg, a pattern that aligns with past experiences during the exceptionally warm 2006/07 season, which is indicative of a RCP 4.5 2080s or RCP 8.5 2050s scenario. These regional distinctions underscore the importance of conducting climate change risk assessments at the business level.

One potential adaptation strategy to mitigate risks is the use of weather derivatives or weather insurance, although these products are seldom utilized in Austrian winter tourism. Other adaptation options include increased investments in snowmaking, expansion to higher altitudes, diversification into non-snow-based activities, or relocating investments to less vulnerable regions or alternative economic sectors. However, these adaptations may lead to increased resource demand, particularly energy and water, which could impact the industry's ecological footprint and its public image, ultimately affecting demand.

Private investors may also opt to avoid ski areas or regions with higher climate change impacts to minimize their risk. Over the years, several ski areas have permanently closed or faced financial difficulties. As a warmer future places additional pressure on governmental support or more ski areas face closure, questions about the sustainable use of public funds for potentially maladaptive measures become increasingly pertinent. Climate change, as a central issue for society, prompts decision-makers not only to safeguard their business models but also to monitor and reduce their ecological footprint in alignment with evolving societal expectations and norms.

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