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Ski tourism in a warmer world: Increased adaptation and regional economic impacts in Austria

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ABSTRACT

Climate change risk has gained considerable attention within the ski industry and its investors. Several past studies have overlooked the adaptive capacity of snowmaking and within-season demand variation and therefore overestimated climate change impacts. This study of the Austrian ski market (208 ski areas) including snowmaking found impacts are substantial and spatially highly differentiated, but nonetheless manageable (season length losses of 10–16%) for the majority of ski areas until the 2050s under a high emissions pathway (RCP 8.5) or even the 2080s in a low emission pathway (RCP 4.5). The economic impacts of reduced operations are largely concentrated in regions less dependent on tourism. Preserving this sector in high-risk areas can be considered maladaptive, but may be important to maintain demand. A sustainable end-of-century future for a high proportion of Austria's ski areas is dependent on achieving the low-emission future set out in the Paris Climate Agreement.

1. Introduction

Climate change has evolved as a major factor in the discussion of sustainable tourism development (Hall, Scott, & Gössling, 2013; UNWTO/UNEP/WMO, 2008). Projected future global warming of between 1.0 and 3.7 °C by the end of the century (compared to 1986–2005 (IPCC, 2014)) will cause a multitude of impacts on environmental and socio-economic systems that will have far-reaching consequences for tourism from the destination to global scale (Scott, Gössling, & Hall, 2012; Scott, Hall, & Gössling, 2016). Any phenomenon that will adversely affect economic growth in many regions, increase regional water and food insecurity, harm the health and displace more than a billion people, greatly increase extinction risks, increase transportation costs, and progressively threaten security is not compatible with sustainable tourism development (Scott et al., 2016). Consequently, assessing the potential impacts of a changing climate and the potential of adaptation strategies to reduce risks and enhance any related opportunities is a prerequisite for sustainable tourism and regional development.

With its direct dependence on climatic resources, winter snow-based tourism was the first tourism market examined for its climate change risk (Scott et al., 2012), and had grown to include studies in 27 countries. Steiger, Scott, Abegg, Pons, and Aall (2017) identified four phases in the literature on climate change and ski tourism. A 'pioneering phase' started in the mid-1980s with studies conducted in Canada and Australia, Switzerland and the US (Galloway, 1988; McBoyle & Wall, 1987; McBoyle, Wall, Harrison, & Quinlan, 1986), followed by the US and Switzerland in the 1990s (Abegg, 1996; König & Abegg, 1997; Lipski & McBoyle, 1991; McBoyle & Wall, 1992). In the subsequent 'growth phase' additional studies were completed in these four countries (e.g. König, 1999; Scott, McBoyle, & Mills, 2003; Scott, McBoyle, Minogue, & Mills, 2006) as well as new major ski markets like Austria (Breiling & Charamza, 1999), Japan (Fukushima, Kureha, Ozaki, Fujimori, & Harasawa, 2002), and Sweden (Moen & Fredman, 2007), as well as small markets like Scotland (Harrison, Winterbottom, & Sheppard, 1999). In the 'diversification phase' the literature grew tremendously and studies became more diversified methodologically, but also geographically (e.g. Austria: Steiger, 2012; Germany: Soboll & Dingeldey, 2012; Turkey: (Demiroglu, Turp, Ozturk, & Kurnaz, 2016; supra-regional assessments for the European Alps: Abegg, Agrawala, Crick, & de Montfalcon, 2007; and former venues of the Winter Olympic Games: Scott, Steiger, Rutty, & Johnson, 2014; Scott, Steiger, Rutty, & Fang, 2018).

Without exception, the studies that focus on climate change impacts

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on ski operations (one of five central themes identified in the review by Steiger et al., 2017) conclude that climate change represents a serious risk to the sustainability and viability of ski resorts around the globe, as the availability of natural snow will be reduced, average ski seasons will shorten and become more variable, snowmaking requirements will increase even as opportunities to make snow will decrease. As a result of changing competitiveness, the number of operating ski areas is expected to decrease in every regional market. Despite this consensus, the range of methodological approaches (for details see Steiger et al., 2017) project very different severity and timing of impacts. Scott et al. (2012), Abegg and Steiger (2017b) and Steiger et al. (2017) all point to key limitations of many studies in the extant literature that are responsible for the widely differing magnitude of impacts, including: 1) inappropriate resolution (both temporal and spatial) of weather variables used; 2) inappropriate indicators to quantify the ski industry's vulnerability; and 3) the omission or proxy representation of snowmaking, a widespread and expanding climate adaptation.

Studies in the pioneering phase only considered natural snow and often projected that the entire or at least the vast majority of ski areas would be no longer in operation by the 2050s in a high GHG emission scenario (e.g. Harrison, Kinnaird, McBoyle, Quinlan, & Wall, 1986; McBoyle & Wall, 1992). An important improvement of analyses was achieved from the 2000s onwards with studies including snowmaking, i. e. the operating reality of most ski areas, and found that this technology significantly reduced climate change impacts on season length (e.g. Scott et al., 2006; Scott, McBoyle, & Minogue, 2007; Steiger & Abegg, 2013; Steiger & Stötter, 2013) and lead to a complex set of winners and losers caused by differential impacts and altered intra- and inter-regional market competitive positions (Scott et al., 2006). Unfortunately, media representations of this topic often refer to early research that lacks snowmaking (e.g.,Bohlen, 2016). The aforementioned three major limitations can also still be found in many recent studies (Campos Rodrigues, Freire-González, González Puig, & Puig-Ventosa, 2018; Chin, Byun, Hamlet, & Cherkauer, 2018; Damm, Greuell, Landgren, & Prettenthaler, 2016; Tranos & Davoudi, 2014; Wobus et al., 2017), and as a result these studies do not represent the operating realities of most ski areas and are likely to misrepresent the climate change risk for many ski areas (Scott & Steiger, 2019). As companies are increasingly expected (or required) to disclose their physical climate risk (Task Force on Climate-related Financial Disclosures, 2018) to investors and other decision makers, such misinformation in the media and the literature is increasingly problematic.

This study builds on the work of Steiger and Abegg (2013) to advance the assessment of climate change risks to the multi-billion Euro ski tourism market in Austria in four key ways:

1) Improvements to the SkiSim ski operations model, including:
    1.1 Incorporation of ski slope orientation (i.e., north versus south facing slope) in the modeling of the snow pack for the first time;
    1.2 A more accurate representation of the current differential snowmaking capacity of individual ski areas (both percentage of terrain with snowmaking and daily capacity to make snow).
2) Using the most recent downscaled climate change scenarios available for Austria, rather than common arbitrary climate change scenarios applied to all ski areas.
3) Explore the adaptation potential of increased snowmaking capacity for the first time.
4) Assess the differential impacts on ski areas from a regional economic development perspective.

2. Methods

2.1. Study area

Austria is the third largest ski market in the world in terms of skier visits, after the US and France and has the highest number of skier visits per capita (Vanat, 2014). Annual turnover of lift ticket sales is approximately € 1.3 billion and the Austrian Association of Cableways estimates expenses of ski resort customers at € 7.9 billion (i.e. direct, indirect and induced effects) and added value generated from it at € 4.3 billion (WKO, 2018b). Over 95,300 jobs are generated directly and indirectly, representing 2.65% of jobs in Austria (Statistik Austria, 2018a; WKO, 2018b). Consequently, ski tourism is not only highly important for the regional economy of tourism intense destinations but also for the national economy.

A total of 208 ski areas are included in this study. A ski area is defined as a group of ski lifts interlinked with other lifts and/or ski slopes. We have defined ski areas spatially from the customer's point of view and not from the business view, where, in some cases, an interlinked ski area is a conglomerate of several independent companies. Despite some internationally renowned extra-large ski areas like Kitzbühel and Ischgl the majority of Austrian ski areas are much smaller, with less than 20 km of ski slopes or a lift capacity of less than 8000 persons/hour (Table 1). The base station elevation of more than half of Austrian ski areas is below 1000 m, with top station elevation below 1900m. To account for the capacity of ski areas with a large vertical range to maintain a longer ski season in the upper half of their ski terrain, we have defined a 'critical altitude' that represents partial operability of each ski area. The critical altitude was defined as either the lowest point of the upper half of the ski area, if an upper section exists, or otherwise the base station. An upper section exists if the ski area has the capacity to transport skiers from mid-elevation to the summit without having to ski all the way down to the base station elevation. In other words, the ski area can operate the upper elevation ski terrain independent of the lower elevation terrain (which may have insufficient snow to reach the base station). This is where the snow depth threshold of 30 cm that defines daily ski operations is analysed.

The diffusion of snowmaking has picked up speed after a series of snow deficient winter seasons in the late 1980s and early 1990s (Steiger & Mayer, 2008). Currently about 70% of ski slopes in Austria are equipped with snowmaking (WKO, 2018a). Only about a quarter of ski areas have less than 50% of terrain covered with snowmaking, while the majority have snowmaking capacity on more than 80% of their slopes (Table 1). This high share of ski slopes with snowmaking is likely the reason why the absolute effect of natural snow depth on winter overnight stays in Austria was found to be rather low (Falk, 2010). The trend to invest in increased snowmaking capacity is expected to continue (Trawöger, 2014) and therefore this future state of improved snowmaking capacity was included in this study.

2.2. Climate data and climate change scenarios

Climatological data for the baseline period (1981–2010) was obtained for 56 weather stations from the central meteorological office of Austria (ZAMG). Proximity to ski areas and a complete data set for daily minimum and maximum temperature, precipitation, snow depth and snow-fall over the baseline period were the selection criteria for climate stations.

Climate change scenarios of the ÖKS15 project (Chimani et al., 2016) with monthly change values were used to represent possible climate futures in Austria in the 21st century. Thirteen climate projections were available based on combinations of six regional climate models (EUROCORDEX; Jacob et al., 2014) and five global circulation models (CMIP5; Taylor, Stouffer, & Meehl, 2011) and its characteristics meet the IPCC criteria for selecting climate scenarios (IPCC, 2019). The spatial resolution of the scenarios is 12.5 km and two emission pathways were examined: (1) RCP 4.5 representative of a moderate emission pathway consistent with successful implementation of country pledges to the Paris Climate Agreement, and (2) RCP 8.5 representative of a business-*as*-usual pathway where there has been limited success to reduce greenhouse gas emissions. To provide concise results, only the ensemble mean of the 13 climate projections for the 2030s (2021–2050),

Table 1
Characteristics of Austrian ski areas.

	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

Sources: bergfex.at, at.skiinfo.com

2050s (2041–2070) and the 2080s (2071–2100) were used for modeling.

Projected warming in the winter season (December–February) averaged over the 56 climate stations is higher for minimum temperature (RCP4.5 = 1.3 °C in the 2030s to 2.6 °C in the 2080s; RCP 8.5 = 1.4 °C in the 2030s to 4.7 °C in the 2080s) than for maximum temperature (RCP4.5 = 1.1 °C in the 2030s to 2.2 °C in 2080s; RCP8.5 = 1.1 °C in the 2030s to 4.1 °C in the 2080s). Winter precipitation is projected to increase by 8% (2030s), 9% (2050s) and 13% (2080s) in RCP 4.5 and by 11% (2030s), 15% (2050s) and 20% (2080s) in RCP 8.5.

2.3. SkiSim model

Version 3 of the SkiSim model developed by Scott et al. (2003) and Steiger (2010) is used in this analysis. SkiSim is a physically-based snow model that includes snowmaking and associated operational decisions. In order to compute daily snow depth, the model requires daily minimum and maximum temperature (in °C) as well as daily amount of precipitation (in mm). In case of precipitation, two temperature thresholds are used to distinguish between solid and liquid precipitation or a mix of both. These thresholds are calibrated for each weather station by comparing modeled and observed cumulative snowfall. Snowpack density is increased over time, representing the ageing of the snow pack, and also in case of snowfall events, representing densification by more increasing weight on the underlying snowpack. Snow melt occurs at mean daily temperatures above 0 °C and is dependent on a melt factor representing the amount of snow water equivalent that is melted per 1 °C. This melt factor is calibrated for each weather station by comparing modeled and observed number of days with snow cover. For further details on the model, please see Steiger (2010).

In this application of the model, daily snow depth (total of natural and machine-made) is calculated for each 100 m elevation band and three aspects (north, south, west/east) of a ski area based on daily temperature and precipitation. Snow is produced if the following conditions are fulfilled: 1) the date lies within the snowmaking season begin-end dates set by ski areas or regulated by public authorities (Table 2); 2) current snow depth is below the industry defined threshold needed to maintain continuous ski operations until the scheduled season end in at least 90% of all years in a 30 year baseline period; and 3) climatic conditions are suitable for snowmaking (Table 2). Potential snowmaking hours per day are calculated based on a linear interpolation between daily minimum and maximum temperature.

In order to account for partially open ski areas and the resulting variability of skiing terrain (potentially leading to crowding issues), we also analyse the terrain days indicator (sum of available skiing terrain per day), which was first applied by Scott, Steiger, Rutty, Pons, and Johnson (2017) in Ontario (Canada). As a refinement to Scott et al. (2017) we also consider seasonality of demand. We used the share of total winter season demand within six season segments (derived from Steiger, 2010). The share of demand (skier visits) was then evenly distributed across each of the days within the segment, resulting in a weighting factor (Table 2) representing the share of demand on each day. It therefore matters when in the ski season a skiable day is lost due to climate change, as e.g. a lost day in early December is likely to be less relevant for the business than a lost day during the peak season.

Table 2
SkiSim modeling parameters.

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/m^3 (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)

The application of the SkiSim2 model in Austria (Steiger, 2012; Steiger & Abegg, 2013; Steiger & Stötter, 2013) was improved in three important aspects. First, slope orientation was included by applying a correction factor for the degree-day factor of ±50% for south/north oriented slopes (Hottelet, Braun, Leibundgut, & Rieg, 1993). Second, operational decisions in the model were enhanced. Instead of a nation-wide common opening and closing date for the ski season, six groups of opening and closing dates were identified from a comprehensive data set of snow reports from 2002/03 to 2015/16 (provided by Bergfex.at). In SkiSim3, a ski area is considered open if at least 30 cm of total snowpack (natural and produced snow) is available at the specified critical altitude and the day is within the operational season dates defined by the ski industry. Using industry defined dates is important, because the majority of ski areas does not open before mid-December even if snow depth would allow an earlier opening, because demand is too low in this location and/or an earlier planned season opening is considered too risky based on average climatic conditions. Many ski areas also end ski operations in spring, despite sufficient snow depth, because skiing demand declines rapidly in mid-late March. This range of dates also enables more realistic modeling of total snow depth required to achieve the scheduled season closing date. Third, snowmaking capacity is known to differ considerably between individual ski operators, both in terms of the proportion of skiing terrain equipped with snow guns as well as the production capacity of the snowmaking facilities per day. Previous studies (e.g. Steiger & Abegg, 2013) assumed common snowmaking capacity. In this analysis, the percentage of ski terrain with snowmaking was obtained from an internet platform (at.skiinfo.com). Daily snowmaking capacity was calibrated by comparing modeled season closing dates (using different daily snow production capacities between 1 and 10 cm per day with increments of 1 cm) with the closing date reported in the snow reports.

The performance of SkiSim3 was evaluated by comparing modeled versus observed (from the snow reports) season start and closing dates. The modeled season start date of the 208 ski areas was on average 3.4 days later than the observed start date as reported in the 2002/03–2009/10 period. The extreme warm 2006/07 season showed the highest model bias of −5.3 days. The modeled season end was on average 2.4 days earlier than observed, with 2006/07 again being the season with the highest deviation of 8.2 days. The modeled ski season is therefore slightly conservative at −5.8 days on average (or approximately −5% of average observed season length). This conservative bias can be explained by the decision of ski area operators to open early, when snow depth conditions may not meet their specific operational guidelines, in order to open for an extra weekend or because nearby competitors have opened. SkiSim cannot account for the variability in these types of business decisions. Similarly, the reduced model performance in the extreme warm season can be explained by the desperate situation in many ski areas that forced operators to open with less than 30 cm of snow depth, to organize large scale snow transports with trucks or helicopters, and to concentrate snowmaking on fewer slopes (Steiger, 2011). Such extraordinary measures cannot be captured in the model's operational decision rules.

3. Results

This study provides results for ski operations indicators used in previous studies (season length, snow reliability, and snowmaking volume) to enable comparisons with previous assessments in Austria and with international markets. Two new indicators are provided for the first time in Austria: (1) 'terrain days' (Scott et al., 2017) which represents the amount of available skiing terrain over the season, accounting for the different season length in terrain that relies on natural snow and that which is equipped with snowmaking; and (2) the aggregated impact on ski area performance at the municipality scale, to assess differential impacts for the regional economy based on relative dependency on the tourism economy. Each of these indicators is discussed below.

3.1. Season length

The modeled average ski season length in the reference period (1981–2010) without snowmaking was 80 days (A in Table 3). This limited ski season explains the high share ski slopes equipped with snowmaking. Season length at the critical altitude is likely to be shorter than at mean altitude as in many cases the former is considerably lower than the mean altitude (i.e., many ski areas do not have an upper section, so that the base elevation is the critical altitude). The natural ski season is further reduced under all climate change scenarios, and is reduced almost in half as early as the 2050s under the RCP 8.5 scenarios (A in Table 3).

As noted, with 70% of ski slopes already equipped with snowmaking (Table 1), natural snow conditions are not an accurate indicator of climate change risk for the majority of Austrian ski area operators. Average ski season length when current estimated snowmaking capacities are accounted for (B in Table 3) is 39 days longer in the baseline period than with natural snow only. Even with snowmaking, the average ski season was shortened substantially in future decades. Assuming that snowmaking capacities remain unchanged, the ski season is shortened by 7 (2030s) to 21 days (2080s) in the RCP 4.5 scenario and by 8 (2030s) to 58 days (2080s) in the RCP 8.5 scenario (B in Table 3). If snowmaking capacity is increased to 10 cm per day in all ski resorts (some already possess this capacity), then average ski season losses could be largely offset in the low emission scenario and delayed until after the 2050s in the high emission scenario (C in Table 3).

Regional impacts (not shown) are relatively similar on a provincial level. The province of Carinthia in Southern Austria has the least operation day losses and Upper Austria in the East has the most. But the difference in operation day losses between these two provinces is only 5 days (current snowmaking) or 5–6 days (improved snowmaking) in the 2030s, 8–10 days (or 10–14) in the 2050s and 13–17 days (or 15–29) in the 2080s.

3.2. Snow reliability

The ski area performance indicator 'snow reliability' has been defined as the ability to provide a season of at least 100 days or to ensure continuous operation during the Christmas-New Years holiday period in 7 out of 10 seasons (Abegg, 1996; Scott, Dawson, & Jones, 2008; Steiger & Abegg, 2013). Snow reliability with current snowmaking capacity of each ski area was found to be high in the baseline period, with 90% of ski resorts able to achieve seasons greater than 100-days and 84% able to open for the Christmas holiday (A and C in Table 4). Climate change will have a very visible impact on both snow reliability indicators, with a stronger impact on the Christmas holidays (declining to between 33% and 52% in the 2050s, RCP 8.5 and 4.5 respectively) because these two weeks are rather early in the ski season and thus more sensitive to climatic changes that limit early season snowmaking. The different outcome of the two emission scenarios becomes more pronounced from the 2050s onwards, with the capacity to achieve both indicators almost eliminated in the 2080s in the high emission scenario.

An increase of snowmaking capacity has a significantly positive effect on snow reliability with 80% of ski areas remaining reliable for Christmas holiday operations (+28% over current snowmaking capacity) and over 90% reliable for 100-day seasons in the 2050s low emission scenario (D in Table 4). While the majority of ski resorts are still snow reliable (67% Christmas and 83% 100-days) with increased snowmaking capacity in the low emission scenario of the 2080s, it is not sufficient to preserve snow reliability in the high emission scenario (Table 4).

From a regional perspective Carinthia has an above-average share of snow reliable ski areas today and also in all future scenarios, while Lower Austria is the most affected in terms of snow reliability. Upper Austria and Vorarlberg become similarly affected as Lower Austria in the 2050s scenarios and the 2080s RCP 4.5 scenario. Differences in the late century RCP 8.5 scenario are marginal due to the high overall impacts.

3.3. Terrain days

The analysis of reduced skiing days (season length) or snow reliability does not account for reduced skiing terrain due to a lack of snow in some parts of the ski area (i.e., the proportion of slopes at a ski area that are not equipped with snowmaking), which concentrates skiers in more limited area, causing overcrowding or reduced skier demand. The

Table 3
Modeled ski season length.

Ski season length	1981–2010	RCP 4.5			RCP 8.5		
		2030s	2050s	2080s	2030s	2050s	2080s
(A) with natural snow only	80	64	56	45	63	44	19
(B) operational relevant[a] ski season with current snowmaking	119	112	107	98	111	97	61
(C) operational relevant[a] ski season and improved snowmaking (10 cm/day)	125	121	118	112	120	111	84

[a] i.e., operating season defined by skier demand, not solely climatic potential.

Table 4

Snow reliability of Austrian ski resorts.

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%

terrain days indicator was first applied by Scott et al. (2017) in Ontario (Canada) to measure potential changes in market wide capacity. Here the terrain day indicator is further refined to reflect the intra-season variability of demand by weighting the available ski terrain with the expected level of demand across six segments of the ski season. In other words, open skiing terrain in low demand season segments (e.g. before Christmas or in April) count less than operational terrain in high demand season segments (e.g. Christmas or school holidays in February). Consequently, lost terrain days in the low season are less important financially than in the high season.

At the national scale (bottom row in Table 5), if snowmaking capacity remains unchanged, between 6% (2030s) and 16% (2080s) of terrain days are lost in the low emission scenario and 6% (2030s) to 46% (2080s) in the high emission future (Table 5). Losses with improved snowmaking are very similar. The reason for this, despite considerably different snowmaking capacity, is that the initial value in the reference period with improved snowmaking is higher than with current snowmaking, leading to similar relative changes but on a higher absolute level.

The provinces of Vorarlberg and Upper Austria have higher losses than other provinces due to a high share of skiing terrain at lower altitudes and in the case of Vorarlberg also due to a below-average share of ski slopes with snowmaking facilities. It can be clearly seen that the impact of climate change on terrain days is less than on the share of snow reliable ski areas (Table 4). This can be explained by: 1) the abovementioned demand-based weighting of operation days across the ski season. The season segments most impacted are at the beginning and the end of the season. As early and late season have only a small share of demand (see Table 2), weighted terrain day losses are smaller than projected season day losses. 2) The fact that small ski areas are more highly impacted by climate change due to their lower average altitude and lesser snowmaking capacity. Considering that snow reliability is a rather coarse performance indicator, the results suggest that climate change impacts might have been overestimated for ski areas in parts of Austria.

Table 5

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

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)

3.4. *Regional economic impacts*

Tourism is an important industry in Austria, and it is a dominant part of the economy of many rural municipalities. Thus in addition to the business level risk that has been examined using the previous indicators, it is also important to assess the potential regional economic impacts where tourism is more highly concentrated. Because no data on the proportion of the economy that tourism represents is available at the municipality level, winter tourism intensity (i.e. winter overnight stays per inhabitant) is used as a proxy for economic dependence on tourism. Comparing changes in terrain days with winter tourism intensity for the 754 Austrian municipalities within a 15 km road distance to a ski area, revealed differential impacts for tourism-intense and less tourism dependent regions.

Table 6 presents the average change in terrain days for each of the winter tourism intensity classes. Municipalities in the lowest winter tourism intensity class (<50 overnight stays per resident) have the greatest loss in ski terrain days, whereas the most winter tourism-intense municipalities are the least affected. From a regional economic perspective, this relative distribution of climate change impacts is positive, as it is predominantly smaller ski areas in regions with a stronger focus on summer tourism and/or more diverse economies that are at the greatest risk. Nevertheless, a small loss of terrain days (e.g. 15% in the high emission 2050s scenario) in the most tourism-dependent municipalities class would still be a challenge considering that more tourists will need to be attracted over fewer skiable days and/or smaller skiing terrain in order for the current growth paradigm of winter tourism to continue.

The maps (Fig. 1) reveal important spatial patterns of future climate change risks. Less winter tourism intense municipalities with high climate change impacts are distributed across Austria. As a result, ski areas struggling with climate change and declining skiing terrain represents a climate change risk in all regions. Generally, climate change impacts are higher at the northern (northern half of Vorarlberg and Salzburg) and eastern edge of the Alps (southern Lower Austria and eastern Styria) located in proximity to important source markets in Southern Germany (Munich, Stuttgart) and Eastern Austria (Vienna) and Hungary (Budapest). The main ridge of the Alps ranging from southern Vorarlberg and Tyrol to the East is less affected.

3.5. *Snowmaking*

A warmer climate means an increasing share of rain events during the winter season (Beniston, 2006) and more energy available for snowmelt. Consequently more machine-made snow will need to be produced in the future to ensure continuous ski operations until the scheduled season closing, which itself may need to evolve as the aforementioned results suggest.

If current snowmaking capacity and terrain coverage is unchanged, snow production needs to be increased by 22–26% in the 2030s and by 32–45% in the 2050s (RCP 4.5 and 8.5 respectively) (Table 7). Notably, the amount of snow production is slightly lower in the high emission (RCP 8.5) scenario for the 2080s, because insufficient snowmaking days are available to make the additional snow that is required.

These increases are directly correlated with results on season length indicators in Tables 1–4, meaning that although season length is

Table 6

Decline of weighted terrain days per municipalities' tourism intensity.

Tourism intensity (winter overnight stays/inhabitants)[a]	RCP 4.5			RCP 8.5			# municipalities
	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
>=200 (very high)	−5%	−8%	−15%	−5%	−15%	−42%	26

[a] Classification by Arnold (2014).

shortening and less ski areas remain snow reliable, snowmaking needs to be increased in order to reach these season length values. For example, in the 2050s high emission scenario, snow production needs to be increased by 45% to limit weighted terrain day losses to −17% (Table 5). If snowmaking capacity is improved to 10 cm/day, snow production will increase by 28–57% in RCP 4.5 and by 33–73% in RCP 8.5 (Table 7). Considering that despite these increases many ski areas will lose snow reliability (100-days rule, see Table 4), the suitability of snowmaking for ski areas to ensure a viable ski season is limited.

4. Discussion

The findings indicate that the severity of projected impacts depends on the performance indicators used. As indicated here and elsewhere (Steiger, 2010) the 100-day rule is a coarse economic metric, and this analysis indicates that it is likely to overestimate the climate change risk to the Austrian ski industry. When analyzing the 100-day rule 48% of ski areas are no longer snow reliable in the 2050s under a high emission scenario (RCP 8.5), while in the same climate scenario the reduction of weighted terrain days is only 17% (assuming snowmaking capacity remains unchanged). When considering the operating realities of ski area operators that the skiable terrain indicator accounts for, the impacts of climate change appear less threatening at least until the 2050s. Our results thus confirm findings from Canada where an analysis of snow reports revealed that solely using season length changes does not adequately reflect the change of quantity of skiable terrain that is so important for estimating system capacity and visitor experience (Rutty et al., 2017).

A positive finding is that the most affected ski areas are more often located in municipalities with low tourism intensity. Thus the potential negative impacts on the local economy and livelihoods over the next decades may be limited to the ski industry, rather than impacting the entire local economies of rural valleys that are highly dependent on ski tourism. When looking at regions with high/very high winter tourism intensity (Fig. 1) it becomes apparent that in order to keep domestic (local/regional) demand within Austria, there will be increased demand pressure on less affected municipalities (e.g. in Southern Vorarlberg, or South-West of Tyrol). For these regions there will be opportunities to gain market share in a generally stagnating market. Increasing tourism in already very tourism intense regions could degrade visitor experience, create overtourism conflicts, and development challenges (e.g. extension of the road network in narrow valleys, increase of number of beds in areas with already very limited buildable space, increased real estate prices). In order to better assess the economic impacts of changing competitiveness of ski areas, future research needs to include potential changes in demand (both domestic and international).

Despite these cautiously optimistic findings, rising temperatures create a compounding challenge for generating sufficient and economical snow production, because the available time for making snow is also reduced, as more days become too warm for efficient snowmaking and more snow must be made in warmer (and more costly) conditions. This means increasing operating as well as capital costs for the extension of snowmaking systems. Damm, Köberl, and Prettenthaler (2014) showed for one Austria case study that lift ticket prices would need to be increased substantially to remain profitable. The projected required increase of 3.3–5.1% annually is well above the inflation rate in the last ten years (1.89% at average, Statistik Austria, 2018b). As consequence, skiing might evolve from a national sport to an elitist activity for high-income earners. An increase of snow production by 22–73% (Table 7) also requires significantly more water and energy. While water for snowmaking in Austria is generally available at a regional level (Vanham, Fleischhacker, & Rauch, 2009), local limitations might still occur where geology and/or topography complicates proper storage and collection of water.

More challenging than water availability is the increasing energy demand. Efficiency gains might in part compensate increasing energy consumption caused by more volume of produced snow. On the other hand, the energy efficiency of current snowmaking technology is temperature-dependent and is declining with warming temperatures. Depending on the type of snow gun (fan gun or air-water gun), efficiency at an optimal temperature of −14 °C is about 5–14 times higher than at −2 °C (Olefs, Fischer, & Lang, 2010). As climate change will reduce the number of ideal snowmaking hours and increase hours with marginal conditions, climate change also affects the energy-efficiency of snowmaking. In order to limit climate change to +2 °C until the end of the 21st century, global greenhouse gas (GHG) emissions need to decline by 6% annually starting in 2025 at latest (Scott, Peeters, & Gössling, 2010). Tourism is required to make its own contribution to reach this goal. Not only increasing energy consumption of snowmaking is complicating GHG emission reduction but also trends in tourism demand: tourist arrivals in municipalities within a 15 km driving distance to a ski resort increased 60% in the last 20 years while overnight stays 'only' increased 30%, caused by a shortening of the length of stay from 5.8 days in 1996/97 to 4.7 days in 2015/16. Considering that prices are very likely to increase in the future due to high investments in the Austrian ski industry, it is uncertain if the trend of shortening length of stay can be stopped or even reversed. More frequent periods in the winter season without natural snow, but still good skiing conditions, might also prevent tourists from booking a longer holiday due to uncertainty about skiing conditions and missing 'winter feeling'. Again, this calls for a more detailed investigation of climate change impacts on demand in future research.

Despite some important improvements of the modeling approach as well as analysed indicators, some limitations need to be addressed. Although the most recent climate change data available for Austria in high resolution were used, the next generation of climate change scenarios (CMIP6) and evolving climate models will improve performance in regions with complex topography. Concerning the SkiSim3 model, more data for model evaluation is desirable, especially to assess the validity of produced snow volumes. Unfortunately, no data on water consumption of ski areas' snowmaking facilities is available to date. It is reported that 5–40% of water used for snowmaking is lost due to wind erosion and sublimation (Olefs et al., 2010). Recent experiments in four locations in the French Alps found losses to be between 25 and 50% in the best case and between 50 and 75% in the worst case (Spandre et al., 2016). These processes are not included in SkiSim3, which therefore has potentially overestimated the efficiency of snowmaking to prevent losses in season lengths and terrain days. Wind is not considered either which might underestimate snow melt under warm wind conditions. Snowmaking is calculated based on air temperature. But, snowmaking

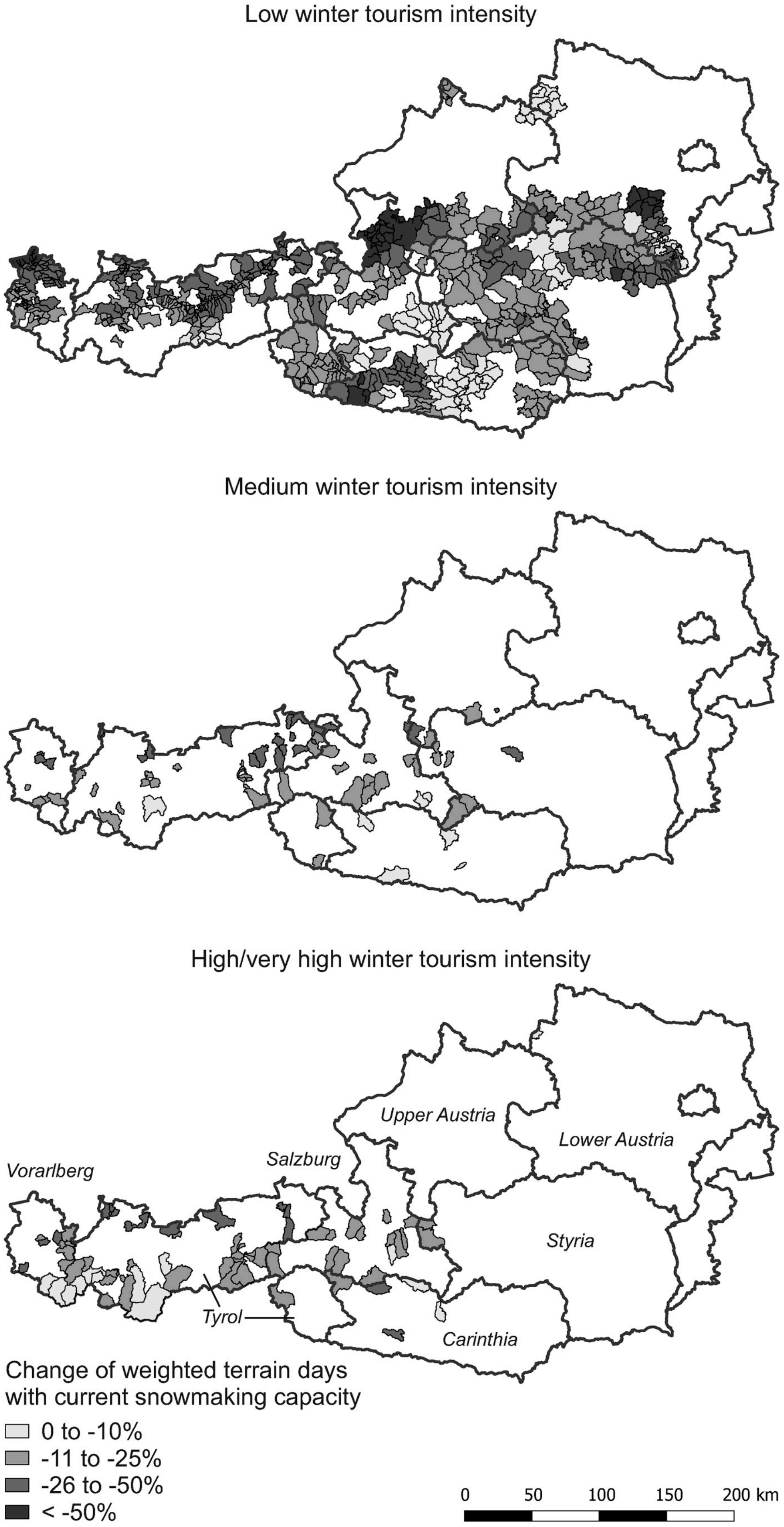

Fig. 1. Regional economic impact of climate change with current snowmaking capacity in the 2050s RCP 8.5 scenario.

Table 7
Increase in snowmaking requirements.

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

potential is also dependent on air humidity with better conditions being at lower air humidity. Nevertheless, this would also raise questions how to accurately incorporate air humidity in sufficient detail in the climate change scenarios.

Although we considered more individual data on ski area and snowmaking operations than previous studies, an analysis of 208 ski areas still requires generalizations, not least to the fact that more detailed data on a business level is not available for such a large number of operators. The results should therefore be interpreted with caution when drawing conclusions from these still generalized results for a specific ski area. Nevertheless, the presented model is the only one to our knowledge that fully incorporates snowmaking and is able to assess multiple ski areas in multiple ski markets/countries and is therefore a useful tool to better represent operating realities of ski areas in climate change impact assessments.

In order to move the analysis beyond the business level to an economic and societal perspective, more data on the economic relevance of winter tourism for the regional economy is required. Assuming that lost terrain days would directly translate to lost tourist spending, the Austrian ski businesses could lose € 221 million by the 2050s RCP 8.5 scenario and added value could decline by € 731 million. Both the validity of this assumption (see Dawson, Havitz, & Scott, 2011; Rutty et al., 2015a and Rutty et al., 2015b for behavioral adaptation of skiers) as well as the accuracy of added value calculations published by the Austrian Cable Car Association (WKO, 2018b) is uncertain, and represent important areas for future research.

5. Conclusion

The results indicate that global warming is unlikely to put an abrupt and devastating end to the Austrian ski tourism industry as claimed by some media reports in the last decade (see Abegg & Steiger, 2017b for discussion of media representation of climate change impacts on ski tourism). Overall, the projected impacts are substantial and highly differentiated, but nonetheless manageable for the majority of ski areas until the 2050s under a high emissions pathway (RCP 8.5) or even the 2080s in a low emission pathway (RCP 4.5), with the adaptive capacity of additional snowmaking capacity.

Consistent with findings in North America (Dawson & Scott, 2013; Scott et al., 2003), season length losses are considerably less when current snowmaking capacity is full accounted for and further reduced with additional snowmaking capacity (all ski areas able to produce 10 cm per day) and increased terrain coverage, which is an ongoing trend in the Alps region broadly. Compared to previous findings for Austria (Steiger & Abegg, 2013), the overarching climate risk for the ski industry is consistent, but the impacts projected in this study are smaller when accounting for improved snowmaking capacity. By accounting for aspect, individual ski area opening and closing dates, ski area snowmaking capacity, and the seasonality of demand, this analysis has better represented the realities for ski operation, and found that the impacts of climate change are anticipated to be less severe.

The results also show clear regional differences of potential impacts caused by below average snowmaking capacity and/or lower altitude. The highest impacts are found in Lower Austria and in the northern areas of the provinces of Vorarlberg, Tyrol and Salzburg. The structural and geographical pattern is consistent with experiences from the record warm 2006/07 season (Steiger, 2011), being representative of a RCP 4.5 2080s or RCP 8.5 2050s future. That consistency supports the validity of this modeling approach and the findings.

One important finding for decision makers is that climate change will increase the risk of losses and alter the competitiveness of Austrian ski areas. High regional differences illustrate the need for climate change risk assessments on the business level. One potential adaptation option to reduce the risks is weather derivatives (or weather insurance). However, it was found that using such products to offset potential losses is rarely considered by decision makers in Austrian winter tourism (Bank & Wiesner, 2009; Trawöger, 2014). Other options are more investments (e.g. into snowmaking, extension to higher terrain, etc.), a stronger focus on non-snow based alternatives or a relocation of investments to less vulnerable regions or other economic sectors. Increases in resource demand (energy and water) is likely to affect the ecological footprint of the industry. Both increasing costs and resource consumption could affect the image of this sport and will ultimately affect the demand side. As climate change is becoming more and more a central issue for our society, decision makers are advised to not only look for strategies and measures to protect their business model, but also to monitor and reduce their ecological footprint to address changing societal expectations and probably norms.

Ultimately private investors might avoid ski areas/regions with higher climate change impacts in order to minimize their risk. Between 1994 and 2011, 23 ski areas permanently closed representing 9% of ski areas and less than 2% of ski slope length and another 29 ski areas (12%) accounting for 8% of ski slopes went bankrupt, became insolvent or closed temporarily (Falk, 2013). Besides granting subsidies, public authorities have directly invested in ski areas in many cases, and sometimes even operate the ski area to keep it open (Abegg & Steiger, 2017a). In a warmer future the pressure for governmental support will increase or more ski areas will close, which raises important questions about the sustainable use of public funds for a form of (mal-?)adaptation.

Author contribution

Robert Steiger further developed the model and did all the data processing, modelling and data analysis. He drafted all sections of the manuscript.

Daniel Scott contributed to the introduction, discussion and conclusion, and reviewed the manuscript several times to improve clarity and shorten the paper.

Declaration of competing interest

None.

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