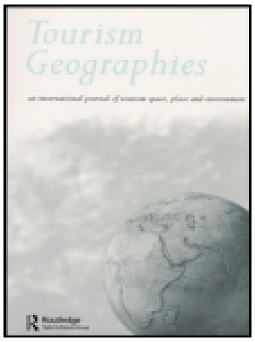

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Climate Change Impact Assessment of Ski Tourism in Tyrol

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ABSTRACT *Climate change poses a serious threat to the highly snow-dependent ski tourism industry. In this paper the potential impacts of climate change on ski areas in Tyrol (Austria, Italy) are investigated. A ski season and snowmaking simulation model 'SkiSim2' was applied to 111 ski areas. Model results suggest that all ski areas could ensure a 100-days season until the 2030s to the 2040s (high/low emission scenario) assuming a 100% snowmaking coverage and state-of-the-art snowmaking system. The Christmas holidays are a particularly sensitive season period, where already in the 2020s some ski areas do not fulfil economic thresholds. A warming greater than 3°C would force most ski areas to close their business not considering developments in snowmaking technology and economic thresholds of snowmaking costs. Regarding the snow demand to ensure a 100-days season independent of any technological limits, snow production would have to be multiplied by up to a factor of 4. It is questionable whether all ski areas will be able to afford the increasing snowmaking costs and therefore the most vulnerable regions should rethink their touristic positioning.*

KEY WORDS: Ski tourism, snowmaking, snow model, climate change, Tyrol, adaptation

Introduction

Background

> 'In fact we don't need snow, we make snow. Too much natural snow is bad for our business because it means higher costs for the grooming of slopes. The skiers only complain about natural snow pists, they want smooth slopes which we can only provide with the help of machine-made snow. It sounds absurd but the best scenario for us is less natural snow, cold temperatures for the snow production and lots of sun.' (CEO, cable car company in Tyrol/Austria, cited in Trawöger 2011)

This statement conveys the impression that the ski tourism industry has been decoupling from the natural resource snow in the recent past. It also partially contradicts

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the widely shared notion in science that winter tourism is highly dependent on climatic conditions (e.g. Abegg 1996; Elsasser & Bürki 2002; Becken & Hay 2007; UNWTO 2007) and on snow in particular as e.g. Gössling and Hall (2006) note that in 'mountainous areas, snow cover is a *conditio sine qua non* for winter sports (. . .) and many areas would lose their tourist appeal without snow' (Gössling & Hall 2006: 2). On the other hand, the winter tourism industry still is highly dependent on cool temperatures for making snow. Thus, even if the sector becomes increasingly independent of natural snow, climate warming is a serious risk as cool temperatures suitable required for snowmaking become less frequent.

In Austria, a positive correlation between snow conditions and overnight stays in ski resorts was found, except for high altitude resorts where overnight stays are negatively correlated to snow conditions of low altitude resorts (Falk 2010; Töglhofer *et al*. 2011). However, the magnitude of this impact decreased between 1972/73 and 2006/07, which can be related to an increasing use of snowmaking reducing the dependency on natural snow (Töglhofer *et al*. 2011).

The ski industry is the most studied aspect of climate change impacts on tourism with over 30 known studies in 13 countries (Scott *et al*. 2012). But snowmaking, an integral adaptation measure of the ski industry to climate variability, has been considered in only few studies, presented in the following.

Scott *et al*. (2003) were the first to incorporate snowmaking in a locally calibrated snow depth model. A further application of the SkiSim model for Québec (Canada) (Scott *et al*. 2007) and the US Northeast (Scott *et al*. 2006; Dawson & Scott 2007; Scott *et al*. 2008) revealed a moderate impact of climate change on ski season length in the first half of the 21st century and the impact is generally less than in previous studies not considering snowmaking. But the authors concluded that the required multiplication of costs for snowmaking could exceed manageable economic thresholds.

Hennessy *et al*. (2008) investigated the impact of climate change on snow conditions in Australia. In the 2020s, an increase of produced snow volume of 5–23% (low/high impact scenario) would be needed to reach the target season length and 17–62% in the 2050s. They concluded that – at least until the 2020s and with sufficient investments in snowmaking – the Australian ski industry would be able to cope with the negative impacts of climate change.

Steiger (2010) was the first in Europe to include snowmaking in a climate change impact assessment for ski areas. The Canadian SkiSim model (e.g. Scott *et al*. 2003) was adopted and applied to three ski areas in Tyrol (Austria) with differing altitude and climatic characteristics. It was found that all three ski areas could provide a 100-days season until the 2040s with a state-of-the-art snowmaking system. However it was concluded that – due to high spatial climatic differences – the transferability of results even to ski areas at similar altitude is very limited and therefore an application of the model to all ski areas in Tyrol is required.

Referring to the introducing statement, the objective of this paper is to assess if and to what extent the ski tourism industry in the Tyrol region (Austria, Italy) is affected by climate change in the 21st century. A ski season and snowmaking simulation model (SkiSim2) was applied to each of the 111 ski areas in the research area. This study is a novelty in Europe as snowmaking is considered in an analysis of individual ski areas in two provinces allowing comparisons both within a state unity and across the political border. In such a cross-country comparison of Tyrol and South Tyrol, economic and political differences, but also climatic differences north and south of the main alpine divide can be considered. Thus different spatial levels can be analysed; the local (individual ski areas), the regional and the national level. Furthermore, the results can be compared to previous studies by using established indicators.

Study Area

The Tyrol region was chosen as study area for assessing the impacts of climate change on alpine winter tourism due to:

1. a tourism sector of great economic importance in general,
2. a high dependency of rural municipalities on winter tourism, and
3. spatially highly differing climatic conditions.

The research area consists of two provinces: Tyrol (Austria) and the Autonomous Province of South Tyrol (Italy) (see Figure 1). In order to provide a better distinction of the provinces, Tyrol (Austria) is further referred to as 'NT' ('Northern Tyrol'), South Tyrol (Italy) as 'ST' and the entire research area as 'the Tyrol region'.

Climate

The climate in the northern and central part of the Tyrol region is mainly influenced by the Atlantic whereas the southern part is more influenced by the Mediterranean with the main alpine divide as a clear climatic borderline. Mean annual temperatures and temporal variability of precipitation are considerably higher south of the alpine divide. Inner alpine areas receive less precipitation than areas at the northern rim of the Alps (see Figure 1 and Table 1).

Climate variability affects ski season length and poses a risk for businesses dependent on snow. Extraordinary snow-scarce winters in ST in the 1980s cut down ski lift transports by one-third. In two climatically similar winters in the 2000s ski lift transports decreased by only 2% (Steiger 2011a). As the number of snow machines increased from 511 in 1994 to 2457 in 2009 with 75% of the ski slopes being equipped with snowmaking facilities (ASTAT 2011), snowmaking can be identified as the main reason for this reduced sensitivity to natural snow conditions. The development was similarly rapid in NT with 34% snowmaking coverage in 2002 and 75% in 2010 (WKO Tirol 2011). The extraordinary warm season 2006/07 (+3°C above the climatic mean) resulted in a decline of skier visits of 11% in NT. The impact was more pronounced at lower elevation ski areas and among small to medium ski areas,

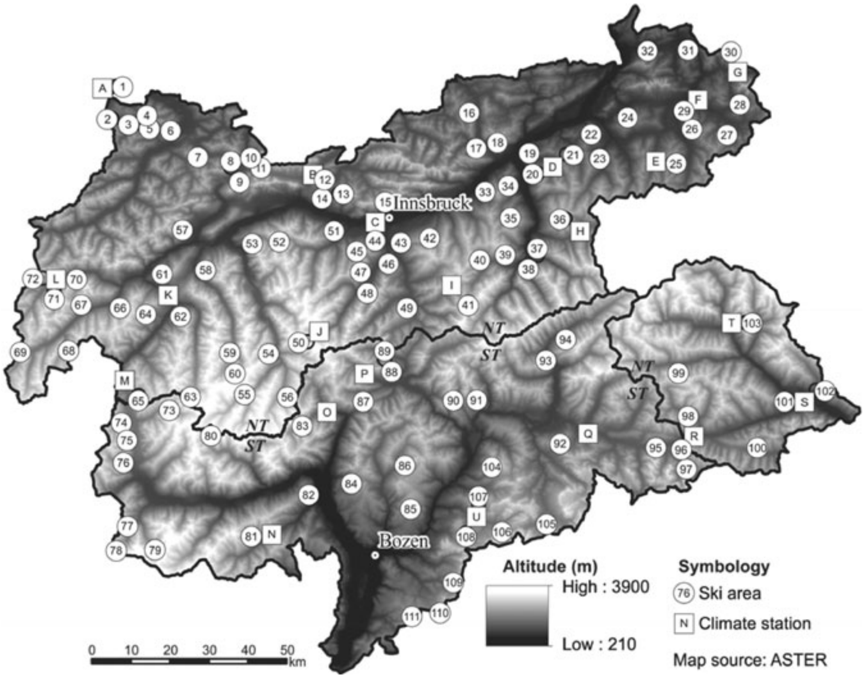

Figure 1. Climate stations used and ski areas in Tyrol. The ski areas: 1: Jungholz; 2: Schattwald; 3: Neunerköpfle; 4: Füssener Jöchl; 5: Nesselwängle; 6: Hahnenkamm; 7: Berwangertal; 8: Grubigstein; 9: Marienberg; 10: Wettersteinbahnen; 11: Ehrwalder Alm; 12: Leutasch; 13: Roßhütte; 14: Gschwandtkopf; 15: Nordkette; 16: Christlum; 17: Zwölferkopf; 18: Rofan; 19: Reitherkogel; 20: Wiedersbergerhorn; 21: Schatzberg; 22: Markbachjoch; 23: Kelchsau; 24: SkiWelt Wilder Kaiser; 25: Kitzbühel; 26: Kitzbüheler Horn; 27: Fieberbrunn; 28: Buchensteinwand; 29: St. Johann in Tirol; 30: Steinplatte; 31: Unterberghorn; 32: Zahmer Kaiser; 33: Kellerjochbahn; 34: Spieljoch; 35: Hochzillertal; 36: Zillertal Arena; 37: Gerlossteinbahn; 38: Ahorn; 39: Penken; 40: Eggalm; 41: Hintertuxer Gletscher; 42: Glungezer; 43: Patscherkofel; 44: Muttereralm; 45: Axamer Lizum; 46: Hochserles; 47: Schlick 2000; 48: Elfer Lifte; 49: Bergeralm; 50: Stubaier Gletscher; 51: Rangger Köpfl; 52: Kühtai; 53: Hochötz; 54: Sölden; 55: Vent; 56: Obergurgl - Hochgurgl; 57: Hochimst; 58: Hochzeiger; 59: Rifflsee; 60: Pitztaler Gletscher; 61: Venet; 62: Fendels; 63: Kaunertaler Gletscher; 64: Serfaus - Fiss - Ladis; 65: Nauders; 66: See; 67: Kappl; 68: Ischgl - Samnaun; 69: Galtür; 70: Pettneu; 71: St. Anton - Rendl; 72: St. Anton - Kapall; 73: Maseben; 74: Schöneben; 75: Haider Alm; 76: Watles; 77: Trafoi; 78: Stilfser Joch; 79: Sulden; 80: Schnalstaler Gletscher; 81: Schwemmalm; 82: Vigiljoch; 83: Pfelders; 84: Meran 2000; 85: Rittnerhorn; 86: Reinswald; 87: Ratschings; 88: Roßkopf; 89: Ladurns; 90: Jochtal; 91: Gitschberg; 92: Kronplatz; 93: Speikboden; 94: Klausberg; 95: Haunold; 96: Helm; 97: Rotwand - Kreuzbergpass; 98: Sillian; 99: Brunnalm; 100: Obertilliach; 101: Hochstein; 102: Zettersfeld; 103: Kals - Matrei; 104: Plose; 105: Alta Badia; 106: Gröden; 107: Seceda; 108: Seiseralm; 109: Karersee; 110: Latemar; 111: Jochgrimm. *Note:* The climate stations are listed in Table 1.

Table 1. Climate station statistics and model validation (1981–2000, Nov–Apr)

Name	Altitude (masl)	T (°C)	P (mm)	Snowcover days			Cumulative snowfall (cm)			No. of climate stations
				Obs.	Mod.	R^2	Obs.	Mod.	R^2	
Innsbruck	579	3.3	340	61.6	60.7	0.87	105.7	101.9	0.82	C
Lienz	668	1.1	325	89.3	89.4	0.78	110.8	129.9	0.77	S
St. Johann	756	0.8	690	123.9	122.9	0.90	367.1	365.9	0.85	F
Waidring	760	−0.5	637	130.8	128.8	0.88	391.8	370.2	0.84	G
Aschau	1005	0.0	576	143.6	140.0	0.82	444.9	430.8	0.78	E
Jungholz	1020	1.0	840	131.6	133.1	0.90	466.6	477.5	0.81	A
Inneralpbach	1040	0.0	491	139.4	139.1	0.71	371.9	361.4	0.86	D
Matrei i.O.	1050	0.8	294	103.1	101.4	0.77	163.5	184.2	0.94	T
Olang	1057	−1.1	202	107.7	107.5	0.76	110.8	101.0	0.80	Q
Sillian	1075	−0.2	344	118.4	117.8	0.83	211.0	222.9	0.91	R
Leutasch	1135	−0.5	574	158.0	152.0	0.74	520.6	527.1	0.91	B
Zoggl	1144	1.5	297	94.2	91.6	0.95	166.2	168.9	0.85	N
Platt	1147	2.2	430	80.7	84.2	0.42	123.8	149.2	0.57	O
St. Ulrich	1180	0.9	272	101.8	101.0	0.44	100.1	139.7	0.69	U
Gerlos	1250	−1.4	473	155.4	156.4	0.77	475.7	431.8	0.40	H
St. Anton	1298	−0.4	604	132.0	131.4	0.82	386.9	398.4	0.64	L
Ladis	1350	−0.1	309	120.4	123.9	0.72	368.7	286.7	0.83	K
Ridnaun	1350	−0.8	421	148.9	139.8	0.17	256.6	304.2	0.04	P
Nauders	1360	−0.2	271	116.2	118.8	0.60	245.2	223.0	0.73	M
Innerschmirn	1610	−1.7	426	163.4	161.3	0.62	523.6	453.1	0.86	I
Dresdner Hütte	2290	−4.0	563	211.9	210.7	0.51	746.3	816.5	0.83	J

losing between 30–40% in the average. Ski areas with higher snowmaking capacity experienced smaller impacts, but still snowmaking could not entirely prevent losses (Steiger 2011b).

Tourism

Tourism is an important source of income in the study area contributing 16.0% (NT) and 8.2% (ST) to the provincial GDPs, only considering direct effects (Lehar 2007; ASTAT 2009a). While in NT the winter season is dominant (59% of overnight stays in winter), the situation is inverted in ST (39% of overnight stays in winter). When also considering tourist expenses, which are higher (€ 137–140) in the winter season than in the summer season (€ 96–105) (ASTAT 2009b; Tirol Werbung 2011), 67% (NT) and 46% (ST) of tourist expenses are spent in the winter season. The dependency of tourism generally increases with increasing distance from the economic centres, meaning that in remote areas tourism often is at least the main, if not the only source, of income. In the district of Landeck (NT) for example, about 54% of per capita income is generated in the winter tourism sector (Breiling *et al.* 1997). Therefore, both an overview of climate change impacts on the province level as well as the regionalisation of these impacts is necessary.

Though both provinces are rather small, 36.8 million skier visits (25 million in NT and 11.8 million in ST) are remarkable compared to the leading countries the US (58 million skier visits), France (54 million) and Japan (50 million) (Vanat 2009).

Methodology

Data

Meteorological data was provided by the hydrological services of NT and ST and by the Central Institute of Meteorology and Geodynamics (‘ZAMG’). Stations were excluded from the database if (1) obvious systematical measurement errors were detected (e.g. constant snow depth over at least a week with positive daily mean temperature), (2) data gaps of more than 10 days per season occurred and (3) the location of the station has changed within the 1981–2000 period. Each ski area was assigned to the nearest of the 21 remaining climate stations (Figure 1) resulting in a mean distance from ski area to climate station of 12.7 km.

The regional climate model ‘REMO’, nested in the global ECHAM5/MPI-OM model (Roeckner *et al.* 2003; Jungclaus *et al.* 2006; Jacob *et al.* 2007) and driven by the B1 and A1B emission scenario (Nakićenović & Swart 2000) was used to produce climate change scenarios for the 21st century. The B1 scenario represents a low carbon future with moderate economic growth and higher share of renewable energy sources whereas the A1B scenario is based on rapid economic growth fossil fuels as primary energy source. Therefore the scenarios are further referred to as low (B1) and high (A1B) emission scenario. Monthly temperature and precipitation changes were derived for seven 30-year periods in decadal steps from the 2020s (2010–2039) to the 2080s (2070–2099) compared to the reference period (1971–2000). A stochastic weather generator 'LARS-WG v.5.11' (Semenov & Barrow 1997) was used to down-scale the change signals to each climate station and to produce daily data required by SkiSim2.

Digital data of ski slopes provided by the federal bureau for sports (NT) and the bureau for spatial planning (ST) were intersected with a digital elevation model to calculate the altitudinal distribution of the ski slopes per ski area.

SkiSim2

A locally calibrated semi-distributed degree-day model 'SkiSim2 was applied to model changes of ski season length and snowmaking requirements. It is an advancement of SkiSim1, which was applied to ski areas in Canada (Scott *et al.* 2003, 2007) and the US (Dawson & Scott 2007; Scott *et al.* 2006, 2008). The most important enhancements to SkiSim1 are:

- externally derived temperature lapse rates on a monthly basis for dry and wet days for each climate station instead of a uniform pre-set average winter lapse rate;
- a more complex simulation of snowmaking practices; and
- a semi-distributed model approach, calculating in 100 m altitudinal bands, producing results for the entire ski area and not for single points only (e.g. the base or the mid-point of the ski area).

Natural daily snow depth is modelled in the natural snow module, total snow depth including snowmaking is modelled in the snowmaking module. In this paper only the basic concept is presented. For further details on the procedures and equations please refer to Steiger (2010).

Natural Snow Module

Daily minimum and maximum air temperatures and precipitation are required as input variables. Additionally – for model calibration and validation – snowfall or snow depth is necessary. For snow accumulation, two temperature thresholds are calibrated for each climate station, differentiating between solid, liquid and mixed precipitation, based on the smallest difference of modelled versus measured cumulative snowfall per season. The degree-day factor is calibrated based on the smallest difference of modelled and measured snow cover days (snow depth $\geq$1 cm) per season.

A degree-day model is used for snowmelt computations, where melt (M) is defined as

$$M = ddf * T_{\text{mean}}, \quad \text{if} \quad T_{\text{pack}} = 0°\text{C}$$

where *ddf* is the degree-day factor in mm/°C/d, T_{mean} is daily mean temperature and T_{pack} is the temperature of the snowpack.

Snowmaking Module

In the snowmaking module, snow is produced on an hourly basis within the snowmaking season dates (Nov 1–Mar 31) if temperature is sufficient (≤ -5°C) and modelled snow depth is below a critical threshold. In SkiSim1, this threshold was constant over time and all altitudes. In SkiSim2 this threshold is calibrated for each 30-year period and altitudinal band separately to account for an adjustment of snowmaking practices to different climatic conditions (i.e. warmer temperatures at low altitudes, or warmer conditions in the future). The threshold is set to provide a continuous ski season until April 1 in 90% of all winters. The snowmaking capacity of 10 cm per day was adopted from the original version and – according to an interview with the leading snowmaking manufacturer in Europe – still represents a state-of-the-art snowmaking system. In order to be able to analyse the future potential of ski areas regardless of the current capacity of their snowmaking facilities, it is assumed that 100% of the skiing terrain is equipped with snowmaking facilities. Currently snow can be produced on 75% of all ski slopes (ASTAT 2011; WKO Tirol 2011) and ski area managers aim to even increase this already high snowmaking coverage (Wolfsegger *et al.* 2008).

To account for a further development of snowmaking technology, the required amount of snow to guarantee a 100-days season in the entire ski area is calculated with a second variable, regardless of climatic (temperature) and technical limitations (snowmaking capacity).

Vertical Distribution of Temperature and Precipitation

Temperature and precipitation are extrapolated to 100 m altitudinal bands. The lapse rate of precipitation was set to 3% per 100 m, representing the average in the research area (Fliri 1975). The temperature lapse rate was derived for each climate station using the nearest of eight high altitude stations (between 1545 and 2290 m). It was distinguished between dry and wet days (with precipitation <1 mm and ≥ 1 mm, respectively) to consider frequently occurring cold air pools. Temperature inversions are most frequent in the northeast, northwest and southeast with inverse temperature gradients on dry days in December and January. The lapse rate on wet days shows less regional variability, though the maximum amplitude is approximately 0.4°C/100 m.

Model Validation

Snowfall temperature and degree-day factors were calibrated for the 1981/82–1989/90 period and validated for the 1990/91–1998/99 period. The model performance for snow cover days is satisfying. All stations except 'Ridnaun' are within a 5% error range (Table 1). The mean error is ±1.7% or ±2.1 days. The mean error regarding cumulative snowfalls is higher (±10%) which can be related to greater model uncertainties due to the use of a temperature-dependent density function for fresh snow and the fact that precipitation measurements in mountainous areas are error-prone (Sevruk 1982). The R^2 values of the linear regression of modelled and observed snow cover days and cumulative snowfall is also satisfying at most of the stations (Table 1).

The SkiSim2 model results for ski season length including snowmaking were compared to real season lengths at three ski areas and revealed a difference of only ±1 operation day (Steiger 2010). An evaluation for all ski areas was not possible, as data on the snowmaking capacity and operation days of individual ski areas are not publicly available. The satisfying performance mark SkiSim2 as an appropriate tool for climate change impact assessments of the ski tourism sector.

Snow Reliability Classification Scheme

Previous studies assessed snow reliability (i.e. the climatic potential for a profitable operation of a ski area) by calculating changes of the ski season length (e.g. Scott *et al*. 2003) or by applying indicators like the 100-days rule (e.g. Abegg *et al*. 2007). Changes of ski season length are difficult to compare and interpret for 111 ski areas. Therefore, indicators relevant for ski operations are more suitable for an analysis of a high number of cases. The most common indicator for snow reliability is the 100-days rule stating that a ski area can be considered snow reliable if a continuous ski season of 100 days can be provided (e.g. Abegg *et al*. 2007). Though the required amount of snow to be able to open the ski slopes varies depending on the surface roughness, 30 cm are used as threshold for a potential operation day in SkiSim2.

The validity of this rule is limited as no information on the period when operational days are lost is given and as demand is not equally distributed over the ski season (Scott *et al*. 2008). Steiger (2010) showed that the Christmas holidays lasting for two weeks account for about 30% of winter revenues of the ski lift companies in the study area. Therefore, this economically important season period is considered in a second indicator, the Christmas indicator. A ski area is considered as snow reliable, if ski operation (snow depth ≥30 cm) can be maintained throughout the Christmas holidays in 75% of all winters (Scott *et al*. 2008). As the Christmas holidays are very sensitive to climatic changes (Steiger 2010), using the Christmas indicator results in less snow reliable ski areas. But as potential future temporal shifts of demand within the ski season could reduce the dependency on the Christmas holidays the impact on profitability might be overestimated.

Therefore the indicators were combined in a classification scheme for snow reliability also considering the share of open skiing terrain. Interviews with ski areas managers revealed that more than 20% of the skiing terrain being closed causes significant – but from a financial point of view still acceptable – losses in lift ticket sales,

Table 2. Snow reliability classification scheme

	Snow reliable skiing terrain (%)	Christmas indicator		
		≥ 80	50–79	< 50
100-days indicator	≥80	Excellent	Very good	Marginal
	50–79	Very good*	Good	Poor
	<50	Marginal*	Poor*	Very poor

*These categories remain unoccupied in the research area.

whereas more than 50% of closed terrain results in a heavy drop of demand accompanied by unprofitable operation (Steiger 2010). But due to local characteristics of the ski area (e.g. the most popular slope being the valley run) and the ratio of day-trippers and holiday guests with the last being less sensitive to snow conditions, it should be considered that these thresholds are rather crude and can differ considerably between different types of ski areas. Nine possible categories of snow reliability result from transferring these indicators to a classification scheme (Table 2).

Results

Climate Change Projections for the Tyrol Region

The REMO model results show a more intense warming in the high emission scenario with increasing regional differences towards the end of the century (Figure 2). Average temperature changes are 0.8–1.2°C (low/high emission) in the 2030s, 1.6–2.6°C in the 2050s and 2.8–4.2°C in the 2080s. From a regional perspective, this warming is stronger south of the alpine divide than north of it. Precipitation changes are slightly negative (up to −6%) for the very south and the western centre (Kaunertal, Pitztal and Oetztal) and generally positive in the rest of the Tyrol region but with high regional differences. The increase is more pronounced in the low than in the high emission scenario and changes are higher in the south (up to +32%) than in the north (Figure 3).

Impact on Snow Reliability

The 100-days and Christmas indicator. Using the established 100-days and Christmas indicators at the mean altitude of the ski areas, 99% (NT) and 100% (ST) of the ski areas are snow reliable in the baseline period (Figure 4) assuming a 100% snowmaking coverage and state-of-the-art snowmaking system. In the low emission scenario all ski areas exceed the 100-days threshold until the 2040s (NT) and the 2060s (ST). At the end of the century, 65% (NT) and 79% (ST) of the ski areas would remain snow reliable. The Christmas indicator is more sensitive as this period is rather early in the season with less natural snow and less snowmaking potential

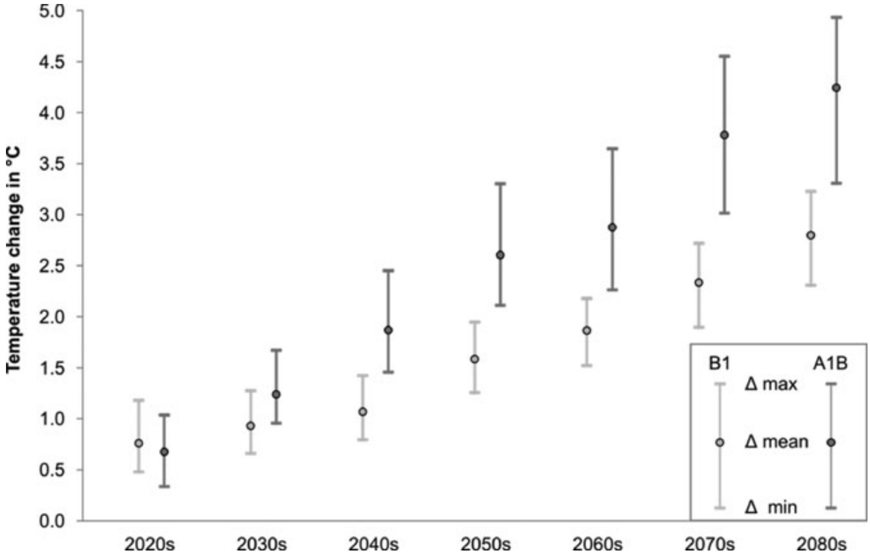

Figure 2. Regional bandwidth of winter (Nov–Apr) temperature changes in Tyrol projected for the 21st century.

than periods in the middle of the season. The share of snow reliable ski areas already will decrease in the 2020s in NT and in the 2050s in ST. At the end of the century, only 28% (NT) and 48% (ST) of the ski areas are snow reliable in the Christmas holidays.

The share of snow reliable ski areas decreases faster in the high emission scenario due to warmer conditions compared to the low emission scenario. Some ski

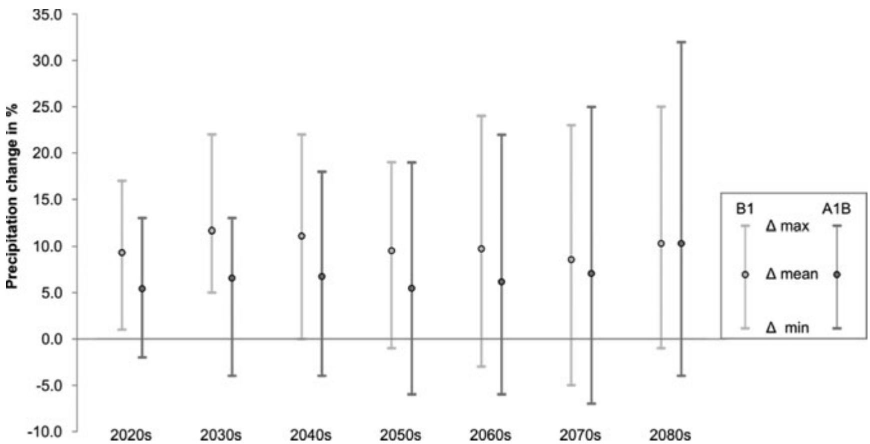

Figure 3. Regional bandwidth of winter (Nov–Apr) precipitation changes in Tyrol projected for the 21st century.

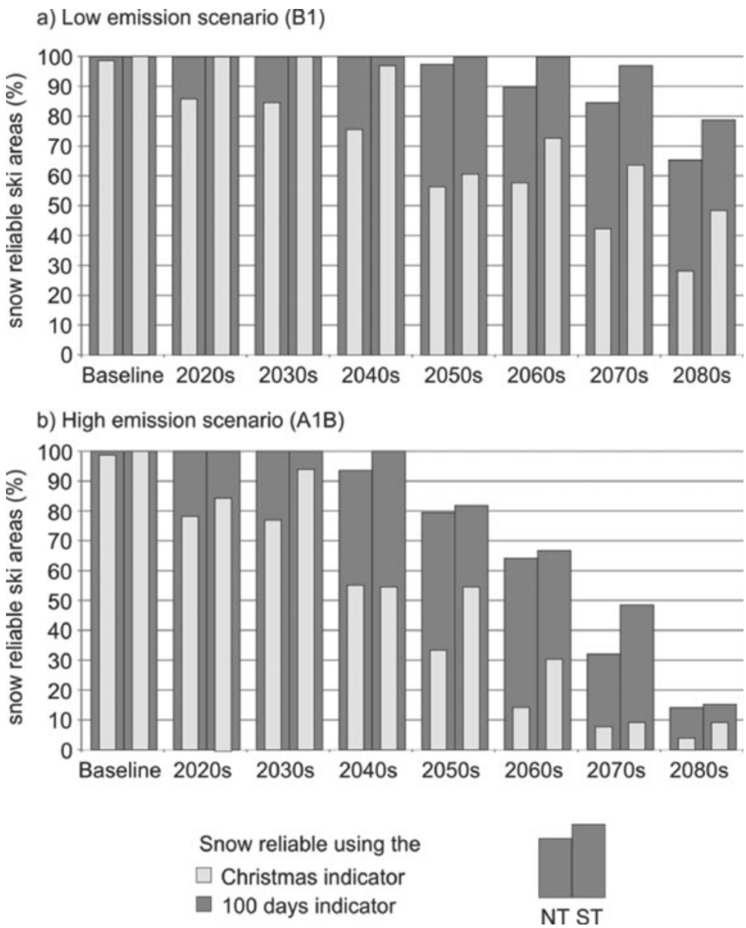

Figure 4. Share of snow reliable ski areas in the 21st century in the low (a) and high (b) emission scenario.

areas miss the 100-days threshold in the 2040s (NT) and the 2050s (ST). In the 2070s, less than half of the ski areas are snow reliable; at the end of the century only 14% (NT) and 15% (ST) remain snow reliable. Using the Christmas indicator, only half of the ski areas are snow reliable in the 2040s. At the end of the century the share decreases to 4% (NT) and 9% (ST). In general, the impact on both indicators appears to be higher on ski areas in NT (Figure 4). A warming greater than approximately 3°C would force most ski areas to close their business not considering developments in snowmaking technology and economic thresholds of snowmaking costs.

Snow Reliability Classification Scheme

Using the more detailed snow reliability classification scheme also considering the percentage of open skiing terrain, three categories remain unoccupied by ski areas (Table 2). As the Christmas indicator is more sensitive, a high share of snow reliable skiing terrain using the Christmas indicator and a low share using the 100-days indicator is mutually exclusive.

In the reference period almost all ski areas in ST are in the 'excellent' category, whereas in NT it is 'only' 78%. Ski areas affected as soon as the 2020s (not shown) and 2030s (Figure 5) are mainly located in NT, namely the northwest (Tannheim valley), the Innsbruck region and the northeast (Kitzbuehel region). In ST some ski areas in the southeast (Val Gardena) have a projected poor snow reliability. In the 2050s, snow reliability is deteriorating in the mentioned regions and also in Eastern Tyrol, the Inn valley and the centre of ST. In the 2080s low emission scenario, ski areas with good to excellent snow reliability are mainly located along the main alpine divide. In the 2080s high emission scenario, only today's glacier ski resorts remain snow reliable.

The high dependency on winter tourism in the northwest, the northeast and the southeast is problematic as these regions are among the first affected. Climate change should be considered in the strategic positioning of tourism in these regions in the upcoming 10–20 years to avoid an economic downturn. As internationally renowned ski areas are among the early losers (e.g. Kitzbuehel and Val Gardena in the Dolomites) climate change could also damage reputation of the provinces as top skiing destination. The other regions with a high dependency on winter tourism (i.e. St.Anton, Ötztal, Zillertal) are less sensitive to climatic changes as ski areas in these regions have a projected excellent to good snow reliability until the end of the century in the low emission scenario and until the 2050s in the high emission scenario. In these tourism intense regions tourism stakeholders should prepare for an increase of demand with accompanying negative impacts (e.g. overcrowding in the ski area, worsening of traffic situation, etc.).

Snowmaking Requirements

Snow production needs to be increased substantially to sustain a 100-days season (Table 3). For half of the ski areas, snow production needs to be doubled in the 2050s and tripled in the 2080s in the high emission scenario. It is questionable, if and which ski areas will be able to cope with such increasing snowmaking costs. Currently, between 10–20% of annual turnover is spent on snowmaking (including investments) in the Tyrol region with generally higher values in lower altitude ski areas (Steiger 2010).

Apart from the economic perspective, the ecological perspective needs be considered as well: an increase of snow production requires more water and energy. In order to assess the ecological impact of increasing water consumption, a water demand/supply ratio was calculated based on the required water for snowmaking

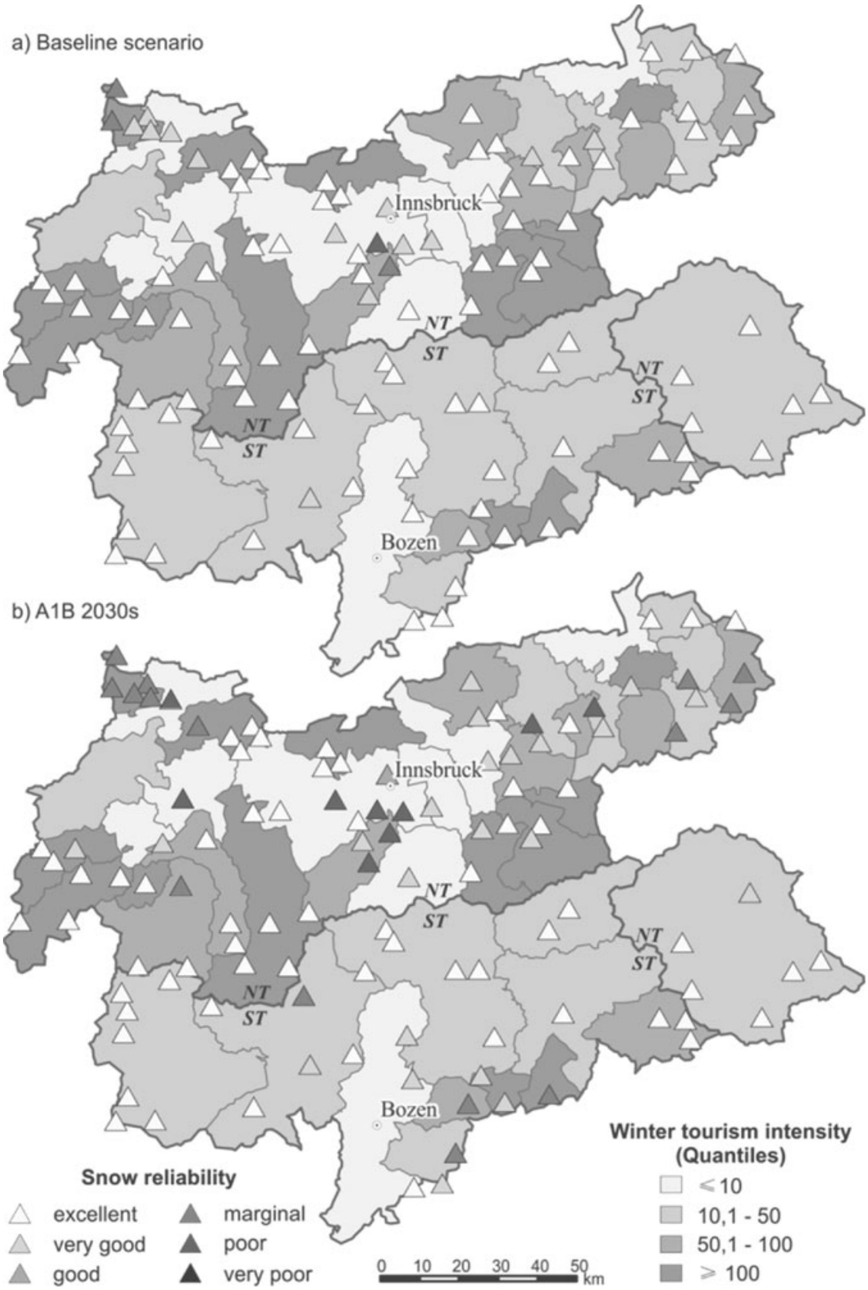

Figure 5. Snow reliability classification in the baseline period (a), the A1B 2030s scenario (b), the A1B 2050s scenario (c) and the A1B 2080s scenario (d), and winter tourism intensity per tourism board region (2010). *(Continued)*

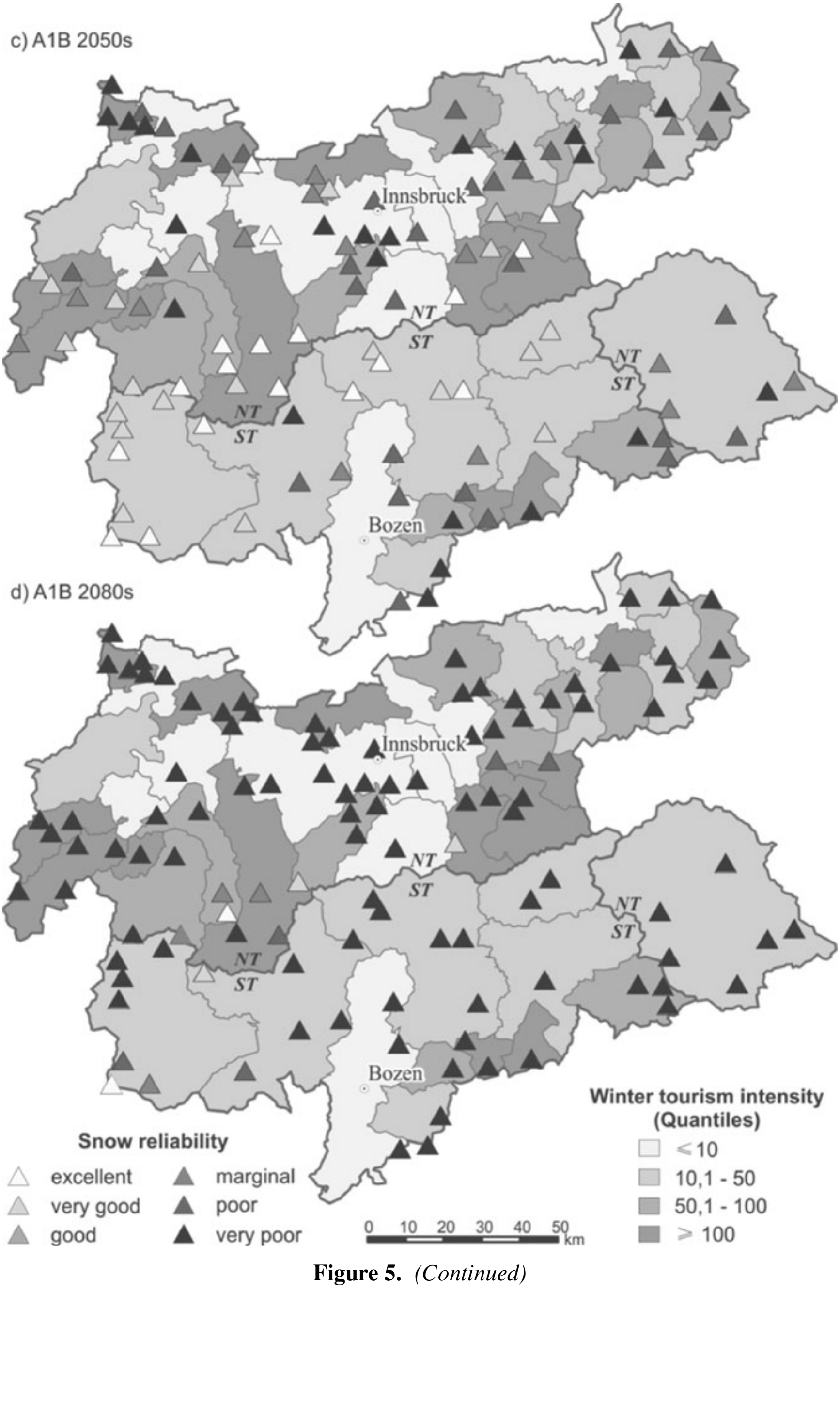

Figure 5. *(Continued)*

Table 3. Projected changes of snow demand in comparison to the present situation assuming a 100% snowmaking coverage and number of ski areas in each category

Increase of snow demand (%)	Number of ski areas ($n = 111$)					
	B1 scenario			A1B scenario		
	2030s	2050s	2080s	2030s	2050s	2080s
0–49	89	67	19	72	26	0
50–99	13	24	34	27	32	7
100–199	9	20	49	12	47	73
200–299	0	0	9	0	6	28
≥300	0	0	0	0	0	3

and the water supply provided by precipitation in the main snowmaking months (Nov–Feb). Three climate stations representing dry (Matrei i.O., 179 mm), average (Inneralpbach, 294 mm) and humid conditions (St. Johann, 433 mm) were analysed. The demand/supply ratio of the humid and the average station stays well below the ratio at the dry station in all future scenarios (Figure 6). Thus it can be interpreted that future water demand would rather be a smaller problem for regions with average to high precipitation, confirming findings of Vanham *et al*. (2009). But the projected considerable increases of water consumption at the dry station might well lead to conflicts of water usage.

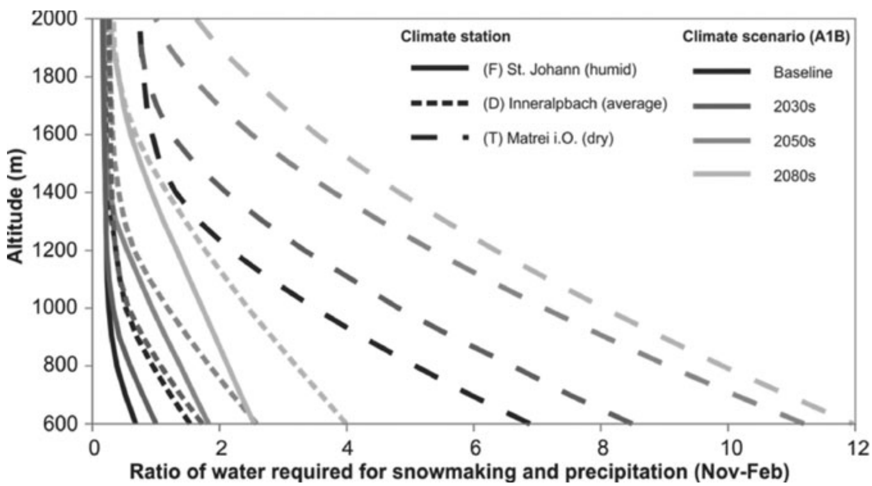

Figure 6. Ratio of water demand by snowmaking and water supply by precipitation from Nov–Feb at three climate stations in the 2030s, 2050s and 2080s A1B scenario.

The increase of energy consumption very likely will be greater than the water consumption, as the current snowmaking technology is less energy efficient at higher temperatures. Producing snow at the climatic margin requires about six times the energy than producing at optimum temperatures below −10°C (Teich *et al*. 2007). These prospects contradict the paradigm of sustainable tourism development as well as climate change mitigation goals.

Discussion

The use of established ski operation indicators allows a comparison with the international literature on climate change impacts on ski tourism from a methodological as well as from a geographical perspective. Abegg *et al*. (2007) used a statistical-empirical approach in contrast to the modelling approach of this study to apply the 100-days rule to 666 ski areas in the Alps. Several significant differences in the results can be identified:

1. Natural snow reliability is lower in the SkiSim2 calculations in most of the scenarios (Table 4). One reason might be that more climate stations and therefore more complex and heterogeneous climate conditions were considered for the present paper. Note that Abegg *et al*. (2007) used two (for the Tyrol region non-validated) altitudinal lines of snow reliability – 1200 m for NT and 1500 m for ST, whereas Steiger (2010) found that this line can vary by hundreds of meters within NT.
2. The decrease of the share of snow reliable ski areas in Abegg *et al*. (2007) is rather linear, due to the fact that the line of snow reliability rises equally in time and

Table 4. Comparison of the share of snow reliable ski areas between Abegg *et al*. (2007) and SkiSim2

		Share of snow reliable ski areas (%)			
		Abegg *et al*.	SkiSim2		
Climate scenario	Province	w/o snowmaking	w/o snowmaking	with snowmaking	Similar REMO climate scenarios
Present	NT	95	92	100	Baseline (1980s)
	ST	97	94	100	
+1°C	NT	77	86	100	+1.0 (B1 2030s)
	ST	84	73	100	
+2°C	NT	57	49	90	+1.9°C (B1 2060s)
	ST	63	55	100	
+4°C	NT	29	14	25	+3.8°C (A1B 2070s)
	ST	22	9	16	

space, whereas in SkiSim2 regional differences in climate and also in the climate change signal are considered.

3. The number of snow reliable ski areas in the 1°C and 2°C scenario is higher than in Abegg *et al*. (2007), which can be attributed to the inclusion of snowmaking in this study. However, in the 4°C scenario the share of snow reliable ski areas is lower in the SkiSim2 calculations. A likely reason is that Abegg *et al*. (2007) assumed the line of snow reliability to shift upwards by 150 m per 1°C warming which corresponds to a temperature lapse rate of 0,66°C/100 m. In SkiSim2 the temperature lapse rates are considerably lower resulting in higher temperatures and less snow reliable conditions.

Comparing the SkiSim2 results with SkiSim1 results for the US Northeast (Scott *et al*. 2008) the impact of climate change on the average ski season length appears to be less in NT/ST in the low emission scenario in the 2050s and 2080s period. The impacts in the high emission scenario 2050s period in NT/ST are similar to the US Northeast, but in the 2080s period the average shortening of the ski season is considerably higher in NT/ST than in the US Northeast although the projected climate warming in the US Northeast is higher (+5.4°C, Hayhoe *et al*. 2007).

Despite detailed results on a ski area level, several sources of uncertainty need to be addressed. Though climate models have substantially improved in the last decade, significant biases exist between climate model results and real climate data. A comparison of 16 regional climate models in the PRUDENCE project showed that in winter (Dec–Feb), REMO is warmer and wetter than the ensemble mean (Christensen & Christensen 2007). Besides, the results of climate models using different emission scenarios differ greatly. So far no estimation about the probability of any of these emission scenarios can be given.

Uncertainties exist in the SkiSim2 model as well. If current weather conditions would change significantly (e.g. more frequent westerly or northerly winds), the frequency of temperature inversions could change as well, causing a change in the temperature lapse rate. As in every model, reality is simplified in SkiSim2. As aspect is not considered, snow depth and consequently snow reliability is over- (south exposed slopes) or underestimated (north-exposed slopes). The 30 cm threshold for ski operation must be regarded as the absolute minimum, as more rugged terrain requires deeper snow depths (Abegg 1996). Finally, the SkiSim2 results represent the potential of the state-of-the-art snowmaking technology. It is assumed that snowmaking is installed on all ski slopes. Current snowmaking capacities of the ski areas or even costs and profitability of snowmaking cannot be considered as data on technical specifications of the snowmaking facilities and snowmaking costs for each ski area are not publicly available. Ski businesses could calculate the required investment and operating costs for the future based on SkiSim2 results though.

Ski tourism is not only dependent on natural snow or sufficiently cool temperatures to produce snow. The future of ski tourism is influenced by many more factors which

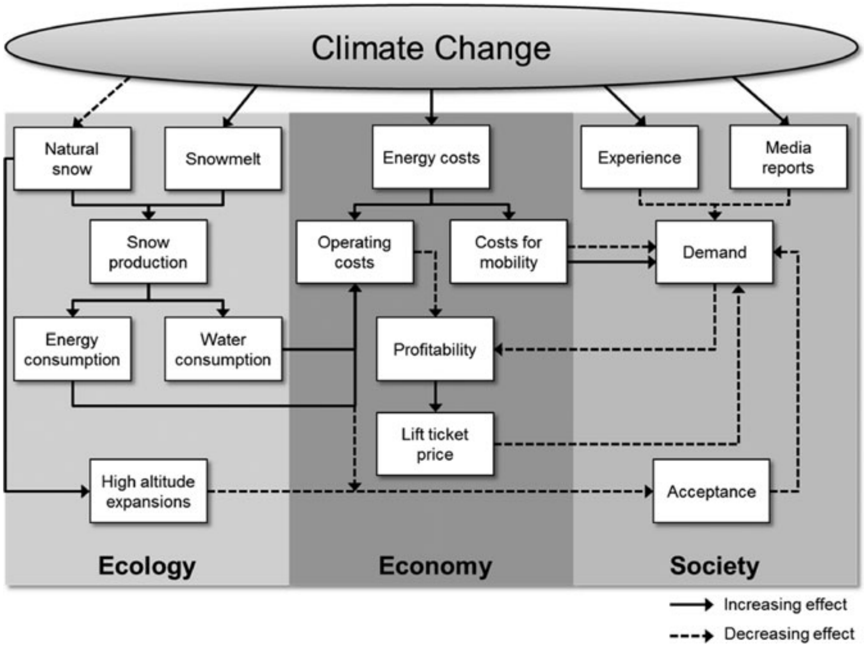

Figure 7. Three dimensions of the climate change and skiing tourism system.

can be attributed to the three dimensions of sustainability – ecology, economics and society (Figure 7). Regarding the ecologic dimension, climate change has a direct impact on natural snow and snowmelt causing an increase of technically produced snow. Energy use for snowmaking is very likely to increase disproportionately to water use, as snowmaking is less energy efficient at higher temperatures. Increasing energy consumption and CO_2 emissions to adapt to climate change in a sector highly dependent on climate is paradox. Currently about 40% of energy consumption excluding traffic in NT (Amt der Tiroler Landesregierung 2009) and 56% in ST (TIS 2010) is produced by renewables. An extension of renewable energy sources as currently discussed in NT (hydropower) and ST (wind power) is confronted with increasing social opposition. A further mechanisation of the natural/cultural landscape through a rising number of snowmaking storage ponds or high altitude expansions could cause a reduced acceptance by both residents and tourists.

Regarding the economic dimension, climate change mitigation goals are very likely to increase energy prices affecting the operating costs for ski businesses as well as the mobility costs for customers. This could reduce the tourist expenses on the one hand, but as well increase demand on the other hand, if long-distance holidays (e.g. the Caribbean) become more expensive and thus less attractive. Rising energy costs will increase operating costs in addition to the factors described in the ecologic dimension. It can be assumed that large and international ski areas with a better financial situation are more likely to be able to cope with rising costs than small to medium ski businesses with worse economic performance. International ski areas are also more likely to be able to raise lift ticket prices due to competitive advantages.

Regarding the social dimension, the development of demand is a very crucial factor if not the most important. Customers are likely to change their leisure behaviour based on experiences made in snow-scarce winter seasons. But it is unknown what occurrence-frequency of snow-scarce winter seasons would cause behavioural changes. Furthermore, the media could also play a relevant role. Ski area managers reported that the media were one of the most serious problems in the extraordinary warm season 2006/07, as it was communicated that the Alps were more or less without snow. Paradoxically, customer satisfaction benchmarks revealed a higher satisfaction than in previous years (Bergbahn Kitzbühel AG 2007).

Higher lift ticket prices might have a negative impact on demand depending on the price elasticity. A change in the tourists' attitude towards a more sustainable, less energy consuming, 'greener' tourism could be triggered by climate change mitigation policy, reducing the demand for skiing. In the end, increasing operating costs accompanied by decreasing profitability will lead to a contraction of the ski marketplace already in the near future. Thus ski tourism in its current form and spatial distribution cannot be defined as sustainable, because the added value is likely to decrease and the consumption of resources is likely to increase. Therefore, subsidies as granted in the past for snowmaking investment costs in ST or ski area extensions in NT should be critically examined. A subsidy program for alternatives to ski tourism could contribute to a more sustainable tourism development.

Several suggestions for ski areas and tourism destinations can be identified as follows. (i) Current snowmaking technology is capable of balancing climate change impacts for the next decades in most ski areas. Investing in snowmaking technology will enable ski areas to provide good skiing conditions at least within the typical investment cycles of 15–20 years. (ii) The required massive increases of produced snow volumes result in considerably higher operating costs that might exceed economic thresholds. Climate change should thus be considered in investment decisions for snowmaking. (iii) In a long-term perspective, only few destinations will still be able to offer skiing. Restructuring the regional tourism economy and redefining the tourism product portfolio needs sufficient time. Destinations that are the pioneers in climate change adaptation are likely to be the long-term winners.

Conclusion

The SkiSim2 model results for 111 ski areas in the Tyrol region suggest that all ski areas could ensure a 100-days season until the 2030s (high emission) to the 2040s (low emission scenario) assuming a 100% snowmaking coverage and state-of-the-art snowmaking system. When focusing on the economically very important Christmas holidays, stronger and earlier impacts are projected. Generally, ski areas in ST are less sensitive than ski areas in NT. A warming greater than 3°C would force most ski areas in the Tyrol region to close their business not considering developments in snowmaking technology and economic thresholds of snowmaking costs. The worsening of snow conditions in the economically very important Christmas holidays and increasing snowmaking costs are a serious medium-term threat to the ski tourism sector in the research area.

The most affected ski areas are located in the northwest, the Inn valley, the northeast and southeast. Considering also the relative importance of winter tourism, the Dolomites (SE), the Kitzbuehel region (NE) and the Tannheim valley (NW) have the highest vulnerability in the Tyrol region.

Snowmaking can alleviate climate change impacts in the next decades not considering developments in snowmaking technology and economic thresholds of snowmaking costs. As snow production would have to be multiplied by up to a factor of 4, not all ski areas will be able to afford the increasing costs of snowmaking. Increasing energy and water demand for snowmaking is in contrast to climate change mitigation goals as well as the principle of sustainable tourism development.

In the cross-country comparison NT is more vulnerable than ST. Ski areas in ST are less or later affected. The economy in ST is less dependent on tourism in general and fewer mountain communities are dependent on ski tourism. The inclusion of climate change in spatial planning and decisions on granting subsidies is strongly recommended for NT. The introductory statement and stakeholder perception studies show, that the ski tourism industry is not acting proactively and is very confident that technical solutions will be available to cope with climate change impacts (Abegg *et al*. 2008; Wolfsegger *et al*. 2008; Trawöger 2011).

For future research a sensitivity analysis using a broader range of climate models and emission scenarios should be carried out to draw best case/worst case future scenarios for the ski tourism industry. As so far no studies considering snowmaking exist for other regions of the Alps, potential changes of competitiveness cannot be assessed. Therefore it would be valuable to apply the SkiSim2 model to other regions in the Alps to identify relative winners and losers and also to be able to estimate potential spatial shifts of demand. Research on potential impacts of climate change on tourist behaviour is necessary for any economic assessment. Furthermore, it would be valuable to consider mitigation policies and their impact, for example, on energy prices and consequently on costs, lift ticket prices and tourists' mobility.

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