Current Issues in Tourism

ISSN: 1368-3500 (Print) 1747-7603 (Online) Journal homepage: https://www.tandfonline.com/loi/rcit20

A critical review of climate change risk for ski tourism

Robert Steiger, Daniel Scott, Bruno Abegg, Marc Pons & Carlo Aall

To cite this article: Robert Steiger, Daniel Scott, Bruno Abegg, Marc Pons & Carlo Aall (2019) A critical review of climate change risk for ski tourism, Current Issues in Tourism, 22:11, 1343-1379, DOI: 10.1080/13683500.2017.1410110

To link to this article: https://doi.org/10.1080/13683500.2017.1410110

© 2017 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

Published online: 08 Dec 2017.

Submit your article to this journal

Article views: 10549

View related articles

View Crossmark data

Citing articles: 41 View citing articles

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=rcit20

Current Issues in Tourism, 2019
Vol. 22, No. 11, 1343–1379, https://doi.org/10.1080/13683500.2017.1410110

A critical review of climate change risk for ski tourism

Robert Steiger[a,b*], Daniel Scott[c], Bruno Abegg[b], Marc Pons[d] and Carlo Aall[e]

[a]*Department of Public Finance, University of Innsbruck, Innsbruck, Austria;* [b]*Institute of Geography, University of Innsbruck, Innsbruck, Austria;* [c]*Department of Geography & Environmental Management, University of Waterloo, Waterloo, Canada;* [d]*Observatori de la Sostenibilitat d'Andorra, Sant Julià de Lòria, Andorra;* [e]*Vestlandsforsking, Sogndal, Norway*

(*Received 12 July 2017; accepted 19 November 2017*)

Ski tourism is a multi-billion dollar international market attracting between 300 and 350 million annual skier visits. With its strong reliance on specific climatic conditions, the ski industry is regarded as the tourism market most directly and immediately affected by climate change. A critical review of the 119 publications that have examined the climate change risk of ski tourism in 27 countries is provided. This growing and increasingly diverse literature has projected decreased reliability of slopes dependent on natural snow, increased snowmaking requirements, shortened and more variable ski seasons, a contraction in the number of operating ski areas, altered competitiveness among and within regional ski markets, and attendant implications for ski tourism employment and values of vacation property real estate values. The extent and timing of these consequences depend on the rate of climate change and the types of adaptive responses by skiers as well as ski tourism destinations and their competitors. The need to understanding differential climate risk grows as investors and financial regulators increasingly require climate risk disclosure at the destination and company scale. Key knowledge gaps to better assist ski tourism destinations to adapt to future climate risk are identified.

Keywords: ski industry; winter tourism; climate change; climate risk; adaptation; tourist behaviour

Introduction

The roots of commercial ski tourism began in early twentieth-century mountaineering, with non- or low-commercial cross-country (Nordic) skiing as the precursor to commercial down-hill (Alpine) ski tourism. As international mass tourism emerged in the 1960s and 1970s, the foundations of the contemporary ski tourism industry were established as many new ski areas were built and smaller ski areas expanded (Hudson & Hudson, 2015). Entry barriers into this market were comparably low, as ski lifts were technologically simple and cheap, and because government actively supported improved transportation access and ski tourism development as a labour-intense economic strategy in disadvantaged mountainous regions. Demand grew quickly in this era of significant economic growth and increased leisure time. This favourable market situation together with several snow abundant winters in major markets of Western Europe and North America fostered the

*Corresponding author. Email: robert.steiger@uibk.ac.at

© 2017 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (http://creativecommons.org/licenses/by-nc-nd/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way.

development of new ski areas in – from today's point of view – climatically suboptimal locations. In the 1980s and 1990s, growth in the number of ski areas and skier visits slowed and the markets matured. Intensifying competition and higher customer expectations forced ski areas to invest in comfort (e.g. high speed lifts, chair lifts, or gondolas instead of surface lifts) and to improve the reliability, quality, and season length of the snow product (e.g. slope grooming, snowmaking). These large capital investments and increased operating costs altered the market and forced many small ski areas to close. For example, the number of ski areas in the US declined from 622 in 1987–1988 to 481 in 2007–2008 (NSAA, 2017). Snow-deficient winters in the 1980s and 1990s furthered the diffusion of snowmaking and many ski areas began to diversify into four-season destinations to increase revenues and support expanded accommodations and vacation real estate. Today, ski tourism in historically leading markets has matured, with stabile (e.g. US, Canada, France) or declining demand (e.g. Switzerland, Japan) in many countries. In contrast, profound changes in the economic situation in emerging markets such as China and Eastern Europe have led to new markets with high growth rates (Vanat, 2017).

Acknowledgement that additional future climate change is unavoidable and that current emission reduction pledges are insufficient to avoid dangerous climate change (United Nations, 2016) has enhanced emphasis on understanding climate risk and accelerating adaptation among individual businesses, communities, and economic sectors, including tourism. Skiing, as a snow-dependent industry, has garnered considerable attention for its vulnerability to climate change (Scott, Hall, & Gössling, 2012). Climate change will have far-reaching consequences for many ski tourism-dependent communities, as economic alternatives are limited in (mostly) rural mountainous regions. Climate change adaptation efforts at ski destination may also exacerbate sustainability challenges – including that of tourism's increasing contribution to climate change due to increases in greenhouse gas (GHG) emissions (Aall, Hall, & Groven, 2016). With a rapidly expanding scientific literature and much speculation in the media, a number of authors (Abegg & Steiger, 2017; Scott, Hall, et al., 2012) have stressed the need for critical reflection on the state of knowledge on ski tourism climate change risk and key information gaps to advance adaptation by industry and destination communities.

This paper provides a comprehensive, critical systematic review of the climate change and skiing tourism literature. Electronic databases such as Web of Science, ScienceDirect, and Google Scholar were consulted, including papers published in peer-reviewed journals as well as books and book chapters until April 2017. While unpublished theses are not included, thesis research that has been peer-reviewed and published in journals indexed are included in the review. Review papers and books/book chapters summarizing existing knowledge without adding new evidence on climate change risk for ski tourism are also not included in the review but were consulted for screening of relevant literature. A total of 119 publications between 1986 and 2017 were identified through combinations of the following search terms: ski tourism, ski industry, snow sports, weather, climate, climate change, impact assessment, perception, and ski tourist behaviour. Most of this literature is published in English, although our international author team was able to incorporate findings from studies published in German, French, Spanish, and Norwegian.

The review is organized into two sections. First is an overview of the chronological development of the climate change and ski tourism literature and its geographic coverage. Second is a synthesis of main findings and knowledge gaps in each of the five central themes in this literature: (1) ski tourism sensitivity to weather and/or snow conditions, (2) climate change impacts on ski operations and season length, (3) ski tourists' perception and behavioural response to snow-deficient winter seasons (past and future), (4) the integrated effects of supply-side and demand-side impacts and responses to climate change (i.e. integration of themes 2 and 3) and the implications for sustainability of the ski industry, and (5) ski industry perceptions of climate change risk and their planned responses. The paper concludes with a discussion of the implications for the future development of ski tourism in an era of accelerating climate change.

Development of the ski tourism and climate change scholarship

The development of climate change and skiing tourism research can be divided in three phases (Figure 1). Scholarship on the interactions between ski tourism and climate change first appeared in the mid-1980s. The pioneering phase of 1986 to 1997 included approximately 10% of the publications in the field and began with the first climate change impact assessment studies (theme 2) in Canada and the US (Harrison, Kinnaird, McBoyle, Quinlan, & Wall, 1986; McBoyle, Wall, Harrison, & Quinlan, 1986), Australia (Galloway, 1988), and Switzerland (Abegg, 1996; Abegg, König, & Maisch, 1994). During this phase, the first sensitivity assessment (theme 1) was also published for Switzerland (Abegg & Frösch, 1994). The volume of research doubled during the 'growth phase' from 1998 to 2007 (20% of publications) and the geographic scope expanded substantially. Several new research questions and methodological advances emerged in this phase, including publications that examined tourists' behavioural response to potential climate change conditions (theme 3) (König, 1998), incorporated snowmaking as an integral adaptation to climate change (Scott, McBoyle, & Mills, 2003), and the first integrated assessment (theme 4) (Fukushima, Kureha, Ozaki, Fujimori, & Harasawa, 2002). The third decade (2008–2017) is characterized by tremendous growth in the field (70% of

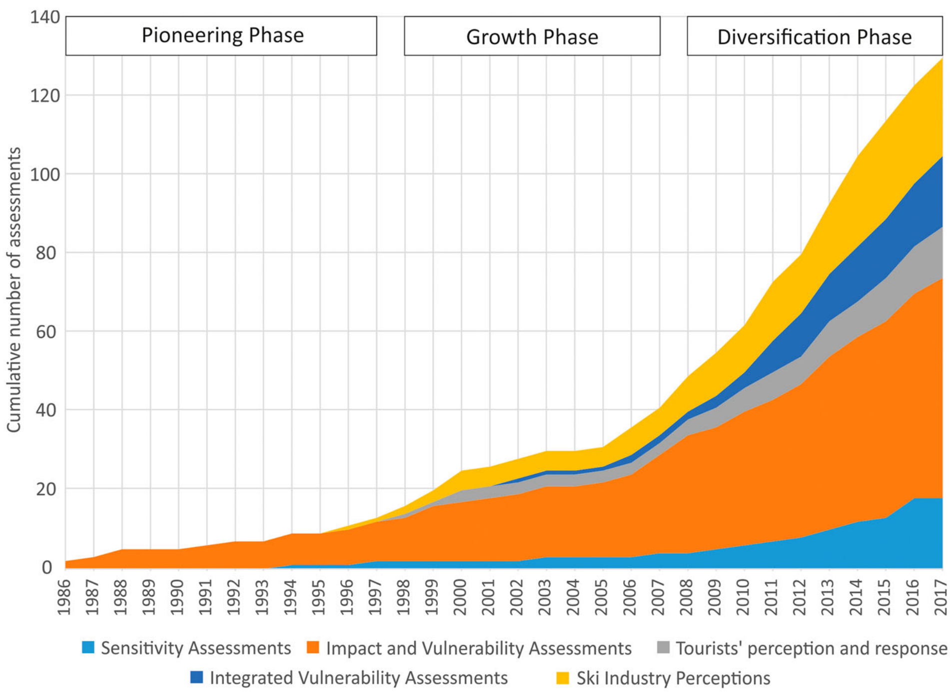

Figure 1. The evolution of peer-reviewed climate change and skiing tourism literature.

publications), increased diversification of research questions and interdisciplinary contributions, broadening geographic coverage, and increased engagement with decision-makers. Some publications contributed to more than one of our categories (e.g. König, 1998 conducted an impact assessment, a tourist survey, and stakeholder interviews). Therefore, the number of assessments is higher (130) than the number of publications (119). The large majority of assessments are climate change impact and vulnerability assessments (56 assessments or 43% of all assessments), followed by stakeholder perception studies (25), climate sensitivity analyses (18), integrated assessments (18), and skier behavioural response studies (13). New disciplinary methods were applied in several regional ski markets; however, comparisons between regional markets remain limited because of the different models and/or scenarios used (impact assessments) or indicators and research instruments employed (sensitivity assessments and skier behavioural response).

Table 1 summarizes the number of assessments in each country as well as highlights key geographic gaps, where no studies exist for countries that are in the top 10 for annual skier visits or skier visits per inhabitant. Note that some publications are assigned to more than one category (e.g. König, 1998 conducted an impact assessment, a tourist survey, and stakeholder interviews). Similarly, some studies include more than one country (e.g. Hendrikx, Zammit, Hreinsson, & Becken, 2013 in New Zealand and Australia) and such publications are listed for both countries. Therefore, the sum of publications of all countries and all categories is higher than the 119 reviewed publications. Also note that four multi-national publications are listed separately in the table, as a high number of countries are included: Abegg, Agrawala, Crick, and de Montfalcon (2007) assessing climate change impacts on ski areas in the European Alps (including France, Switzerland, Germany, Austria, and Italy) ('European Alps'); Scott, Steiger, Rutty, and Johnson (2014) modelled the impacts of climate change on 19 former host locations of the Olympic Winter Games ('Global'); while Damm, Greuell, Landgren, and Prettenthaler (2016) included 12 and Tranos and Davoudi (2014) included 32 European countries ('EU'). A more detailed listing including authors names can be found in Table A1.

The literature has expanded to include 27 countries with operating ski areas (note that Tranos & Davoudi, 2014 included several EU countries that lack snow resources for ski tourism under current climate conditions) but remains concentrated (approximately 75% of publications) in five countries: Austria, Australia, Switzerland, United States, and Canada. The highest number of publications exists for Switzerland and Austria, where the ski industry's absolute (skier visits) and relative importance (skier visits per inhabitant) (Table 1) is very high. Australia is ranked fourth in terms of number of publications, which is higher than that would be expected based on the ski industry's size and tourism relevance (20th rank in annual skier visits). This overrepresentation can be explained by a very high sensitivity to climatic changes indicated by all studies conducted for this country and the international leadership of Australian scholars in both tourism and climate change impacts and adaptation research. Other important ski markets are well represented (including the US, Canada, and Germany). Japan as the fourth largest market remains notably underrepresented, as are other major markets with very limited available research (France, Italy, Sweden, Slovakia). No country-specific studies exist for the Czech Republic, Poland, Russia, and Slovenia; countries where the ski industry is important for regional economies and winter sports culture (see skier visits/capita in Table 1). Also, China as the largest emerging market has so far not been investigated in terms of climate change implications for current or future developments. There is only one known study investigating current climate potential for skiing tourism in China (Li et al., 2016). There is also no known study for ski markets in South America. This regional imbalance of research

Table 1. Comparison of climate variability and change research in global ski tourism markets.

Region	2014 Skier Visits (SV)[a]	Rank SV[a,b]	Rank SV/ capita[a,b]	Sensitivity assessments	Number of assessments per category: Impact and vulnerability assessments	Tourists' perception and behavioural response	Integrated vulnerability assessments	Ski industry perception	Total publications
United States	57,092,127	1	18	5	10	2	3	0	***20***
France	56,226,000	2	8	3	1	0	1	1	***6***
Austria	53,155,600	3	1	4	10	1	4	3	***22***
Japan	34,432,389	4	16	0	0	0	1	0	***1***
Italy	28,100,000	5	13	0	4	0	2	1	***7***
Switzerland	26,538,264	6	3	3	12	2	1	7	***25***
Canada	18,700,400	7	11	0	9	2	3	0	***14***
Germany	14,922,000	8	19	0	7	1	3	1	***12***
Sweden	8,070,800	10	5	1	1	0	0	1	***3***
South Korea	6,531,832	12	22	0	1	0	0	0	***1***
Norway	6,390,000	13	4	0	0	1	0	0	***1***
Spain	5,677,571	14	24	0	1	0	1	0	***2***
Slovakia	5,000,000	16	7	0	0	0	1	0	***1***
Andorra	2,184,806	19	2	0	1	0	2	0	***3***
Finland	2,846,000	18	12	1	0	0	0	4	***5***
Australia	2,082,600	20	25	0	6	4	1	6	***17***
New Zealand	1,413,552	22	17	0	2	1	0	3	***6***
Bulgaria	1,200,000	26	20	0	1	0	0	0	***1***
Romania	1,200,000	27	30	0	0	0	0	1	***1***
Turkey	1,200,000	28	42	0	1	0	0	0	***1***
UK	249,311	39	47	0	2	0	0	1	***3***
EU	–	–	–	1	1	0	1	0	***3***

(*Continued*)

Table 1. Continued.

Region	2014 Skier Visits (SV)[a]	Rank SV[a,b]	Rank SV/capita[a,b]	Sensitivity assessments	Impact and vulnerability assessments	Tourists' perception and behavioural response	Integrated vulnerability assessments	Ski industry perception	Total publications
				Number of assessments per category					
Alps	–	–	–	0	1	0	0	0	***1***
Global	–	–	–	0	1	0	0	0	***1***

[a]Vanat (2014).[b]Grey shade: country in the top 10 of skier visits or skier visits per inhabitant.

is not unique to the ski tourism literature but was also identified for the whole tourism sector in the IPCC's Fifth Assessment Report (Scott, Hall, & Gössling, 2016). Major gaps were found for Asia, Eastern Europe, and South America, regions that are also identified as underrepresented in the ski tourism literature. Africa and the Middle East with major research gaps in the climate change and tourism literature (Scott et al., 2016) are no relevant markets from a ski tourism perspective.

Climate sensitivity assessments

Studies of the ski industry's sensitivity to variable weather and snow conditions have examined both ski operations and skier demand in order to understand the relevant importance of different weather variables and the consequences of extraordinary winter seasons (e.g. non-linear or threshold effects of record warm winters). Although assessing past and current climate sensitivity is an important precondition to evaluate a sector's vulnerability to future climate change, only 14% of reviewed assessments fall in this category.

Abegg and Frösch (1994) were the first to analyse the impact of snow-scarce winters at the end of the 1980s on demand in Swiss ski areas. They found that in general demand related to ski lifts (e.g. revenues, skier days, number of transported people) is more sensitive to a lack of snow than overnight stays. They reported a decline of 30% of lift passengers compared to previous seasons for the canton of Grisons/Switzerland, but with remarkable differences between individual ski areas. Low-altitude ski areas were most impacted (skier visits declined by up to 60%), whereas glacier ski areas experienced increases of demand (König & Abegg, 1997). For almost a decade, these studies were the only evidence for the industry's high sensitivity to a lack of snow.

A number of studies have investigated the relevance of different weather variables for ski demand, using regression analyses techniques and econometric models. In two studies in New England (US), a regression model including weather variables (snow depth, snow fall, temperature) and day of the week was able to explain half to two thirds of daily variation of demand (Hamilton, Brown, & Keim, 2007). Notably, demand was not only affected by weather at the ski area, but also by weather at nearby urban market areas. This finding provided some evidence of the so-called backyard-hypothesis, which the authors of this paper have repeatedly heard from ski area operators. Operators suggest that based on their experience, the lack of snow cover in major urban markets negatively impacts public perception of good snow conditions and depresses demand. The introduction of web cameras with real-time display of snow conditions on ski slopes was an industry response to this challenge. The development of social media report of 'real' snow conditions is also a response to sharing accurate information on snow conditions. Regression models for two ski areas in Michigan (US) similarly found that natural snow depth has a clear positive impact on lift ticket sales, whereas for minimum and maximum temperature, the results were inconsistent between the ski areas and peak/off-peak season, and snowfall was found to be not significant (Shih, Nicholls, & Holecek, 2009). Some evidence also exists that snowfall might be more important for demand early in the season and that demand is influenced by snow depth only up to certain threshold (Tang & Jang, 2012), as above a certain snow depth more snow does not improve skiing conditions and can impede transportation access to ski areas. The generalization of these results to other markets remains limited because each of these studies was based on only one to two ski areas.

Some larger-scale assessments followed in order to examine the sensitivity of an entire market as well as to detect differential sensitivity among types of ski areas (particularly small and large operators). Natural snow depth was found to have a significant impact on overnight stays in Austrian winter destinations (Falk, 2010; Töglhofer, Eigner, & Prettenthaler, 2011). Nevertheless, the absolute effect is rather low with a one standard deviation in the log snow depth causing an increase of overnight stays of only 1.6% (Falk, 2010). Overnight stays in higher altitude ski areas are negatively correlated to natural snow depths, meaning that in snow abundant winters, demand in higher altitude ski areas is lower due to good snow conditions in lower altitude ski areas (Töglhofer et al., 2011). The inverse occurs in snow-scarce winters, when high-elevation ski areas gain visits/stays from of the lack of snow at lower elevations. In general, the dependency of overnight stays on natural snow depth has been decreasing between 1975 and 2006 (Töglhofer et al., 2011). It is hypothesized that the massive diffusion of snowmaking has influenced this trend. On a multi-national level, Damm et al. (2016) found a significant impact of snow depth on overnight stays in 66 out of 119 analysed EU regions. A one standard deviation change of days with a snow depth of at least 30 cm caused a decline of overnight stays of up to 15% in the most sensitive regions.

Studies using skier visit data instead of overnight stays have found a significant impact of natural snow, but with varying magnitude, depending on the region and time of the year. For high-elevation ski areas in France, the impact of natural snow on demand was rather low, with a long-run elasticity of 0.034 (meaning that a 10% deviation of snow depth from a 40-year average causes a 0.34% change in skier visits) and a one standard deviation reduction of snow depth causes a 1.8% decrease in demand (Falk, 2015). In Finland, the impact of fluctuations in natural snow on skier visits decreases at higher latitudes: the short-run (year over year) elasticities of skier visits were 0.16 in the north, 0.21 in central, and 0.32 in southern Finland (Falk & Vieru, 2016), meaning that a 10% change in average snow depth to the previous season causes a 1.6–3.2% change of skier visits. This same study also found a positive impact of early snowfall. This early season temporal affect was also found in Sweden where the elasticities of lift ticket sales to snow depth are 0.14 for November and December, and 0.11 for January, and not significant for February to April (Falk & Hagsten, 2016). For summer skiing in Austria between May and September, the elasticities were found to be of similar magnitude (0.19) although the influencing weather variables differed (Falk, 2016). More generally, François, Morin, Lafaysse, and George-Marcelpoil (2014) found some correlation ($r^2 = 0.74$) between ski area elevation and share of skiing terrain with more than 100 operating days (with natural snow).

Given the importance of snow as a resource for ski tourism, some authors have investigated the relationship between snow and financial viability of ski areas. Hamilton, Rohall, Hayward, and Keim (2003) attributed the decline of ski areas in New Hampshire (US) in part to climate change, as many small-scale, low-capital investment ski areas had to close after poor snow years and the industry has contracted to larger, better capitalized, higher elevation ski areas in the northern part of the state. Beaudin and Huang (2014) concluded that reduced snowfall has significantly contributed to ski area closures between 1970 and 2007 in New England (US). For Austria on the contrary, no effect of poor snow seasons on closures could be detected (Falk, 2013).

The potential of snowmaking to reduce the industry's sensitivity to climate variability has been analysed for Switzerland and France. Gonseth (2013) showed that Swiss ski areas with 30% of ski slopes covered with snowmaking (representing the national average) have a 39% lower sensitivity of skier visits to natural snow depth compared to ski areas without snowmaking. From the empirical relationships, it was concluded that an increase of ski slopes covered with snowmaking from 30% to 50% could offset a 42% increase of natural snow variability. This positive effect of snowmaking was partly confirmed for

France, but only for higher elevation ski areas (i.e. ≥ 1770 m, the weighted average elevation of all ski lifts). Lower elevation ski areas benefit from snowmaking only in snow-poor winter seasons (Falk & Vanat, 2016).

Knowledge on the industry's sensitivity to snow has substantially increased since the early 2000s. Nevertheless, a number of limitations require further consideration. A fundamental challenge remains to identify appropriate indicators to measure ski industry sensitivity. Are overnight stays an appropriate indicator for ski tourism demand? The answer varies. Where local tourism demand is seasonally dominated by ski tourism, then nearby overnight stays is a valid proxy (acknowledging the limitation that not all overnight ski-related stays are recorded, as many skiers own vacation properties and increasingly use accommodations in the sharing-economy). However, where destination tourism products are more diversified, overnight stays have limited value as an indicator of skier visits. There can be several reasons for a weak correlation between natural snow depth and overnight stays: (1) key tourism products are not snow-dependent (e.g. city, wellness or cultural tourism); (2) tourists are resistant to shorten or cancel their trip, because of unwanted cancellation costs and limited alternate dates for their ski holiday; (3) many ski areas are highly dependent on day-trippers that are not included in overnight statistics; and (4) the chosen snow/weather variable does not sufficiently represent the necessary climatic conditions to offer the ski tourism product. Furthermore, with snowmaking, skiing can be offered even when there is no natural snow. Thus, in markets with very high implementation of snowmaking (e.g. Northeastern and Midwest US, Eastern Canada, Austria, Italy, Japan), natural snow ceased being an appropriate indicator around the turn of the twenty-first century (Scott, 2006b; Steiger & Abegg, 2017).

Another limitation is the temporal and spatial resolution of tourism data. Overnight stays are generally only available on a monthly or seasonal basis. Consequently, weather variables also need to be analysed on a monthly basis. As the length of stay is between a few days and up to one week, meteorological monthly averages only provide limited explanatory power for variations in demand, as unsuitable meteorological conditions are not sufficiently represented in a monthly average.

More knowledge on the sector's sensitivity to warm temperatures and a lack of snow is necessary to better assess its vulnerability to future climate change. A growing number of anomalously warm winters is providing more opportunities to assess differential sensitivity within and across ski tourism regions. For future studies, tourism demand data at the individual ski area resolution (e.g. revenues, skier visits) are required and will require greater collaboration between the ski industry and research community. A fundamental barrier to greater understanding of climate sensitivity in ski tourism has been the very limited willingness of ski areas to share proprietary performance data. This barrier may remain intractable unless the investment community increasingly demands independent analysis of ski industry climate risk disclosures.

Climate change impact and vulnerability assessments

The direct impact of climate change on snow resources (natural and the capacity for snowmaking) and the consequences for the ski industry has been the most widely examined question, representing 43% of the reviewed assessments on climate change and ski tourism. Despite the growing number of studies and covered regions of the world, it remains difficult to compare results due to the wide range of methodologies that have been used. These studies differ in many aspects: the meteorological variables used in the assessments; the spatial and temporal resolution of the meteorological variables;

the indicators used to interpret the impacts for the skiing tourism industry; the geographical scale of analysis; and the incorporation of adaptation measures, such as snowmaking.

The first generation of climate change impact assessment began in the mid-1980s in Ontario (Canada) (Harrison et al., 1986; McBoyle et al., 1986). These studies used a snow depth of 5 cm as the threshold to define the ski season, which – from an operational point of view – is insufficient for skiing and did not account for snowmaking. Several applications with this methodology followed for Québec (Canada) (Lamothe & Periard Consultants, 1988; McBoyle & Wall, 1987; McBoyle & Wall, 1992) and Michigan (US) (Lipski & McBoyle, 1991). Some of the investigated ski areas were projected to lose the entire ski season as early as the 2050s (see Table 2). Early work was also carried out for Australia (Galloway, 1988), analysing snow cover duration based on monthly input data. In a reapplication of Galloway's approach, using low- and high-emission scenarios for the 2030s and 2070s, only one Australian ski area was considered snow reliable in the high-emission 2030s scenario, and none in the 2070s (König, 1999).

In the mid-1990s, the first analyses in Europe were completed. Abegg et al. (1994) investigated the impact of climate change on glacier summer skiing in Switzerland by calculating changes in the altitude of the equilibrium-line (=zone where accumulation equals ablation). The study concluded that only two out of nine glacier ski resorts would be able to maintain summer skiing in the future. The first larger-scale impact study was conducted for 230 Swiss ski areas (Abegg, 1996). Using changes in altitudinal snow thresholds (shifting higher with climate change), the proportion of snow reliable ski areas in Switzerland (based upon the 100-day rule) was projected to decline from 85% in the reference period (1961–1990) to 63% in a +2°C scenario (Abegg, 1996; König & Abegg, 1997) and 44% in a +4°C scenario (Bürki, 2000; Elsasser & Bürki, 2002; Elsasser & Messerli, 2001). The same methodology was then applied to the most comprehensive climate change impact study on 666

Table 2. A comparison of projected changes of ski season length and snow reliable ski areas in the 2050s.

Region	Indicator	First generation studies (natural snow)	Second generation studies (including snowmaking)
Québec (Canada)	Reduction of season length	40–89% (McBoyle & Wall, 1987) 42–87% (Lamothe & Periard Consultants, 1988) 28–90% (McBoyle & Wall, 1992) 40–100% (Harrison et al., 1986)	32–39% (Scott et al., 2007) 32–34% (Scott et al., 2006)
Ontario (Canada)	Reduction of season length	30–100% (McBoyle et al., 1986) 35–100% (McBoyle & Wall, 1992)	36–46% (Scott et al., 2006)
Michigan (USA)	Reduction of season length	39–100% (McBoyle & Wall, 1992)	65% (Scott et al., 2006)
Tyrol (Austria)	Share of snow reliable ski areas	57% (Abegg et al., 2007)	49/90% (without/with sm) (Steiger & Stötter, 2013)
South Tyrol (Italy)	Share of snow reliable ski areas	63% (Abegg et al., 2007)	55/100% (Steiger & Stötter, 2013)

ski areas in the European Alps, which revealed considerable regional differences in the degree of climate change impacts on natural snow reliability with earlier and greater impacts at the fringe of the Alps and in the East and lower impacts towards western and inner-alpine regions (Abegg et al., 2007), (see Table 2). For Austria, similar regional patterns were found analysing statistical relationships between temperature, precipitation, and snow depth on a district level (Breiling & Charamza, 1999). Higher impacts by the 2020s were found for the East and South and by the 2050s also for the western, ski tourism intense regions (Breiling & Charamza, 1999). Like the previous studies in North America, snowmaking was not incorporated into these studies.

In the early 2000s, a second generation of studies emerged that reflected the rapid diffusion of snowmaking technology. Scott et al. (2003) were the first to include snowmaking in a vulnerability assessment initially for one ski area in Ontario (Canada). The potential impacts on ski season length were considerably lower when snowmaking was included (see Table 2), but with greatly increasing requirements for produced snow under future warmer conditions (increase of 61–342% by the 2050s). Further applications of this 'SkiSim' model were completed in other North American ski markets (Table 2 – Dawson & Scott, 2007, 2013; Scott, Dawson, & Jones, 2008; Scott, McBoyle, & Minogue, 2007; Scott, McBoyle, Minogue, & Mills, 2006). Steiger and Mayer (2008) adopted the approach of altitudinal thresholds of snow reliability (e.g. Abegg et al., 2007) and included snowmaking in their assessment for Austrian ski areas. They concluded that elevations below 1500–1600 m would not be snow reliable with a warming of 2°C.

Hennessy et al. (2008) also included snowmaking in an assessment for Australian ski areas. They followed a different approach by modelling natural snow depth and separately analysing potential snowmaking hours and the snow required to meet the gap between the target snow depth and natural snow depth. Though modelling of snowmaking potential was robust (i.e. hourly resolution and also incorporating air humidity), the separate analysis of natural snow depth and snowmaking potential does not allow for an integrated calculation of snowmelt and total snow depth. Similar non-integrated approaches were applied for Switzerland (Rixen et al., 2011), New Zealand (Hendrikx & Hreinsson, 2012, Bulgaria, and Turkey (Demiroglu, 2016; Demiroglu, Turp, Ozturk, & Kurnaz, 2016). Pons, López-Moreno, Rosas-Casals, and Jover (2015) integrated snowmaking in an assessment for the Pyrenees, but in their approach snowmaking was only active on days when total snow depth was below a 30 cm threshold. This does not represent common snowmaking practices, where season periods suitable for snowmaking are used for stockpiling the snow to be used in spring months when snowmaking conditions are unsuitable.

The SkiSim model was further developed ('SkiSim 2.0') with refined snowmaking rules to better represent operational decisions over the ski season and to produce outputs across the entire ski area elevation range (in 100 m intervals) (Steiger, 2010). Several applications followed for Austria, Italy, the US, Germany, Switzerland, and Canada (Abegg & Steiger, 2016; Abegg, Steiger, & Walser, 2015; Scott & Steiger, 2013; Scott, Steiger, Rutty, Pons, & Johnson, 2017; Steiger, 2012; Steiger & Abegg, 2013, 2015, 2017; Steiger & Stötter, 2013). A comprehensive application across the eastern part of the European Alps revealed very diverse regional impacts, with high-risk ski areas being located in Southern Germany and Eastern Austria, and low-risk ski areas in Eastern Switzerland and Northern Italy (Steiger & Abegg, 2017). The SkiSim 2.0 model was also used to assess the suitability of former Olympic Winter Games locations to host the Games again in a warmer future (Scott et al., 2014). In this application, in addition to sufficient operational snow depth, the probability of a minimum temperature of ≤0°C to account for the necessity of snow and ice surfaces to refreeze over night to provide fair and secure conditions for sports competitions was added as a second indicator. By the 2050s, the number of suitable former locations would decline from 19 to 11 (low emission scenario) or 10 (high-emission scenario). By the 2080s, only 6–10 suitable locations to host the Games would remain (Scott et al., 2014).

Scott et al. (2016b) introduced a new indicator 'terrain-days' to estimate changes in system capacity and for the first time ski areas' real snowmaking capacity was considered opposed to potential snowmaking capacity in preceding studies. The terrain-days indicator incorporates the skiable skiing terrain throughout the season. They conclude that under a 2°C Paris Agreement policy goal losses could be limited to less than 10% in the mid- and late century, whereas in a business-as-usual scenario system losses would be much higher with 28–73% (Scott et al., 2016b).

The very different magnitude of impact projected by studies that only consider natural snow (first generation) and studies that incorporate snowmaking (second generation) are remarkable. Table 2 provides a summary of results for season length losses in mid-century (~2050s) under high GHG emission scenarios. It is clear that the impact on season length was severely overestimated for North American ski areas when only natural snow resources were accounted for. Estimates of the reduction in snow reliable ski areas in two regions in the European Alps were similarly overestimated in first generation studies. Notably the share of naturally snow reliable ski areas is similar in these studies (see Table 2), although different approaches were used (Abegg et al., 2007; Steiger & Stötter, 2013).

A final dimension of climate change impacts on ski operations examined by Berghammer and Schmude (2014) is the potential change in climatic conditions comfortable for skiing. They defined an 'optimal ski day' based on precipitation, temperature, snow depth, sunshine duration, and wind speed. The calculation of optimal ski days (OSD) was limited to weekends and holidays, because these are high demand days being most important to operators. In the 2001–2010 period, investigated ski areas in Bavaria (Germany) had between 2 and 16 OSDs. The average decline of OSDs in the 2050s compared to the 2010s is between −35% and −91%. An intra-seasonal shift in the distribution of OSD towards spring months was also projected, but with such few OSD, this is uncertain.

In a globalized tourism economy, the relative vulnerability (Hopkins, Higham, & Becken, 2013) of one market compared to competing markets is relevant for assessing the competitiveness and viability of the ski tourism industry. The different methods used preclude inter-market comparisons; however, the SkiSim model has been applied to sufficient markets to enable some geographic comparison of climate change risk (Figure 2). Note that although the same SkiSim model was used in these studies, the climate change scenarios, baseline periods, as well as snowmaking rules (SkiSim1 in North America vs. SkiSim2 in Europe) differ. Only results for a high-emission 2050s scenario are shown. Season length changes are similar and moderate (<25%) for the States of Vermont, Maine, New Hampshire, Massachusetts (US), and Tyrol in Austria. Impacts in other states are considerably higher, with Pennsylvania, Connecticut, and the Canadian provinces of Québec and Ontario being between −30% and −41%, and with highest impacts in Michigan (−65%). Two snow reliability indicators are applied to the daily model results: the 100-day and the Christmas holidays indicator. A ski area is considered snow reliable if snow depth (natural and man-made) exceeds 30 cm during 100 days or during the entire Christmas-New Years holiday period respectively, in at least 7 out 10 years.

If snow reliability is considered to be necessary for viability of ski areas, then all investigated eastern US states except Vermont are projected to lose at least half of their ski areas

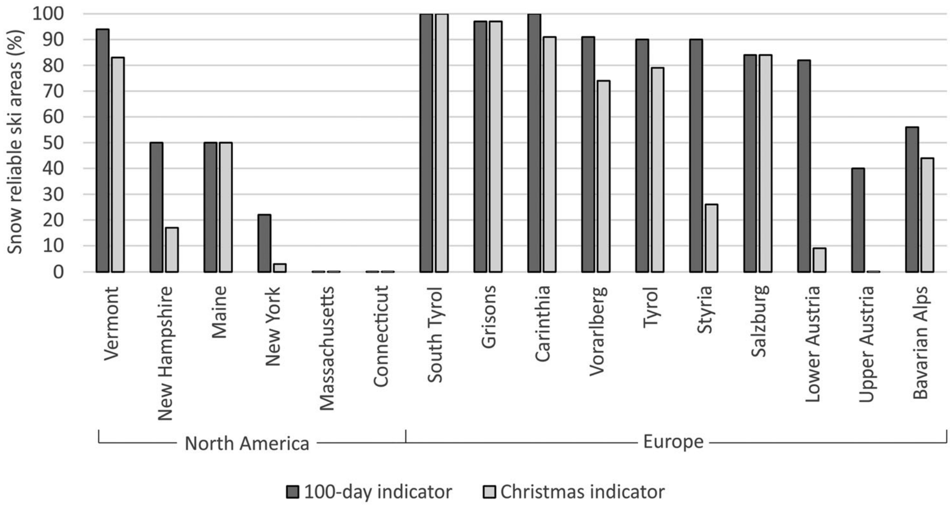

Figure 2. Share of snow reliable ski areas in North American and European regions in a 2050s high emission scenario. Source (Data from Dawson & Scott, 2013; Steiger & Abegg, 2015).

(Figure 2). In the European Alps, the picture is more positive but nevertheless diverse with regions located at the fringe of the Alps being more sensitive than western and inner-alpine regions. It is evident that the Christmas indicator is more sensitive to climatic changes than the 100-day indicator. Snowmaking needs to be increased substantially in most regions (Figure 3). Increases are highest for Ontario and Quebec (more than doubling), but many other North American and European regions would have to increase snow production by 50–100%.

Although there is a large number of supply-oriented studies (i.e. season length, snow reliability), the validity and relevance for decision-makers of many studies suffers from three important limitations. First is the inappropriate temporal and spatial resolution of climate input variables. Snow is temporally and spatially highly variable. Using monthly input data (e.g. monthly mean temperature) in physical models or in statistical relationships

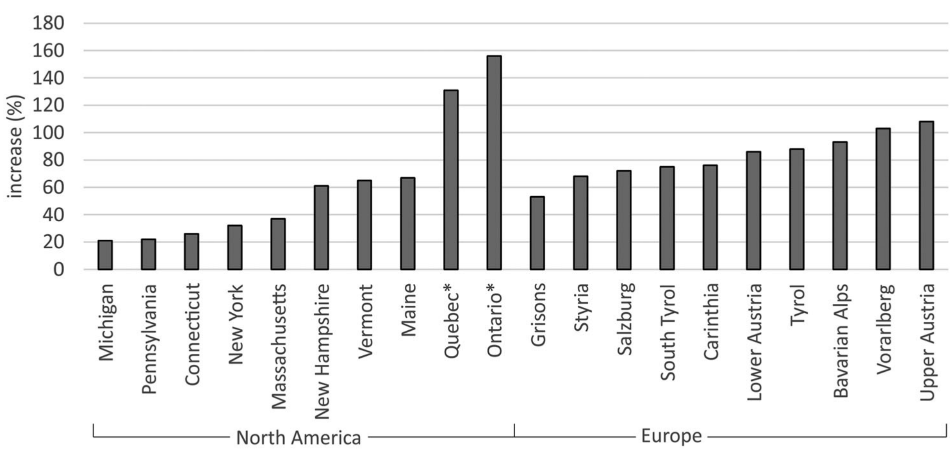

Figure 3. Required increase of produced snow to guarantee a 100-day season in a 2050s high emission scenario. Source: (Data from Scott et al., 2006, 2008; Steiger & Abegg, 2015). *Québec and Ontario based on case studies.

is insufficient to analyse potential changes of snow variables (Breiling & Charamza, 1999; Galloway, 1988; Pickering & Buckley, 2010) or snowmaking potential (Bark, Colby, & Dominguez, 2010). If the ski industry loses two or three weeks at financially critical times of the year, it makes the difference between profit and loss. Monthly scale inputs cannot capture this reality. Empirically derived altitudinal lines of snow reliability are assumed to be uniform for large areas (e.g. entire provinces; Abegg et al., 2007), but such altitudinal thresholds can vary considerably due to the climatic heterogeneity in complex alpine terrain (e.g. as shown for Tyrol (Austria) by Steiger, 2010). One particular challenge for modelling climate change impacts on ski operations is the availability of meteorological data in close vicinity to ski areas. Some studies use gridded model data to solve the problem of data availability, but introduce potentially major biases between modelled and observed weather. Endler and Matzarakis (2011), for example, report model biases of +4°C in annual mean temperature and ±20% precipitation in the Black Forest region (Germany). Such biases inevitably lead to unrealistic snow depth values and uncertainties in the validity of the analysis.

A second important limitation has been the utilization of inappropriate measures of ski industry performance. Some studies model snow cover days near ski areas (e.g. Galloway, 1988; Harrison, Winterbottom, & Johnson, 2005; Harrison, Winterbottom, & Sheppard, 1999; McBoyle et al., 1986; Sauter, Weitzenkamp, & Schneider, 2009). Although snow cover is defined differently (e.g. 1, 2.5, 5, or 10 cm of snow), none are suitable indicators for ski operations that require a snow depth of 30–75 cm (Witmer, 1986, and widespread consultations by the authors with ski area operators). Some even apply snow cover days to the '100-day rule' (Tranos & Davoudi, 2014), which is a coarse proxy for the financial viability of ski areas that has been questioned in the literature. Other hydrological indicators, such as the snow-water equivalent on the first day of April (an indicator used to estimate summer water supply) have been used to project changes in ski season (Zimmerman, O'Brady, & Hurlbutt, 2006), even though this indicator has no relevance to ski operations. Other studies have estimated season length solely on the basis of temperatures and precipitation (Heo & Lee, 2008) or on the basis of days with snowfall (Moen & Fredman, 2007), with no physical indicator of snow depth (or snowmaking requirements). Wobus et al. (2017) use natural snow threshold at the highest elevation of ski terrain to determine the season end (but either the same natural snow depth or a proxy of snowmaking hours at the base elevation to begin the season), which overestimates the length of the season for all lower elevations, particularly because this study did not physically incorporate snowmaking into the snowpack of lower elevations.

The third important limitation of many climate change impact assessments has been the omission of snowmaking. Snowmaking was first introduced in New England (US) in 1956 and became standard equipment of ski areas in several major markets in the 1980s and 1990s. Nonetheless, many studies still do not incorporate snowmaking in their modelling approaches (e.g. Endler & Matzarakis, 2011; Hendrikx et al., 2013; Uhlmann, Goyette, & Beniston, 2008). Others like Wobus et al. (2017) do not physically incorporate machine-made snow into a modelled snow pack, but rather estimate potential snowmaking hours and report a ski area as operational once a predetermined threshold has been reached. As demonstrated in the comparative studies in Table 2, when this important climate adaptation technology is neglected, climate change impacts are significantly overestimated.

These limitations need to be considered in the context of the development of the field, as scholars have developed methods to overcome limitations of pioneering work and advance the field. New research must incorporate and build on these advances to increase credibility among tourism stakeholders and other decision-makers. No longer should studies that do not reflect the current operational realities of ski areas, let alone future capacities, be acceptable.

Tourists' perception and behavioural response

Ski tourists have tremendous adaptive capacity because of their flexibility to change holiday plans at very short notice. Consequently, understanding ski tourist perceptions and responses to the impacts of climate change is essential to anticipating potential changes in ski tourism demand at the destination and regional market scale. Ski tourist behavioural adaptation can include pre-trip decisions (e.g. change destination or delay trip because of current or forecast snow conditions) or reactions to weather and snow conditions during a ski holiday (e.g. switch to snow-independent activities). Ski tourist adaptation can also occur over the long-term, as a consequence of repeated experiences with an unacceptable quantity of open skiing terrain and/or quality of snow, especially if such conditions are becoming more frequent in a warming climate. Despite the salience of understanding skier adaptive responses to accurately projecting the potential consequences of climate change for ski tourism, only 13 assessments have examined ski tourists' response to adverse or changing ski seasons and conditions. This remains an under-researched dimension of climate change and tourism research more generally (Gössling, Scott, Hall, Ceron, & Dubois, 2012; Scott, Hall, et al., 2012).

Three options are available for substituting a leisure activity if conditions for this activity are perceived to be unsuitable: spatial substitution (i.e. changing the destination), temporal substitution (i.e. when the activity is carried out at a different time, when conditions are perceived to be better than on the intended day), and activity substitution (i.e. one activity is replaced by another activity) (Iso-Ahola, 1986). The latter two options include a potential change of participation frequency (e.g. ski more often in a shorter season). The impact of these substitution patterns on a ski market differs considerably. Spatial redistribution of skiers can lead to potential winners and losers without altering the total number of skier visits within the region. Temporal substitution can result in a concentration of demand in shortening ski seasons with higher demand peaks and increased potential for crowding, but with a potential loss of total skier days if the activity frequency (e.g. weekly) remains unchanged or is even reduced. Activity substitution has the highest impact on the market, as the total number of skiers and skier days is reduced which could lead to a contraction of the ski market. The collective responses of ski tourists will differentially impact ski destinations (i.e. losses and gains in market share) (Scott et al. 2012) and have additional indirect effects in the form of changing transport patterns and volumes, which in turn could increase energy use and GHG emissions from ski tourism (i.e. 'chasing for snow') (Aall et al., 2016) or shift GHG emissions to other tourism markets (i.e. substituting a regional ski holiday for long-haul tropical sun holiday).

A number of skier adaptation studies have been carried out in Canada, the US, the European Alps, Australia, and New Zealand and it was found that the majority of respondents would alter their behaviour under scenarios of changing ski conditions and opportunities. Table 3 summarizes the key findings of these studies. However, it must be noted that comparability is limited due to the different survey designs utilized, except for two studies in Australia (König, 1998; Pickering, Castley, & Burtt, 2010) where the same questionnaire was used, and one in Switzerland (Behringer, Bürki, & Fuhrer, 2000; Bürki, 2000) where very similar questions were asked.

Spatial substitution was identified as the most frequent behaviour in all but two studies (Table 3). This is understandable as regional ski tourism markets consist of numerous ski

Table 3. Comparison of skier surveys on adaptation to climate change.

Country	Author	Spatial substitution	Activity substitution	Temporal substitution
Australia	König (1998)	63% (38% travel overseas)	6%	31%
	Pickering et al. (2010)	26% (16% travel overseas)	5%	69%
Austria	Unbehaun et al. (2008)[a]	68%	25%	39%
Austria, France, Germany	Luthe (2009)	28%	8%	64%
Canada (Ontario)	Rutty et al. (2015a)[b]	61%	3%	36%
Switzerland	Bürki (2000), Behringer et al. (2000)	49%	4%	32%
US (Northeast)	Dawson and Scott (2010)[a]	39%	46%	34%

[a]Multiple responses allowed.[b]If ski resort is closed permanently.

areas with different climate sensitivity and skiers almost always have the option to choose an alternate ski area with sufficient snow conditions. It has been demonstrated that adverse snow conditions and anomalously warm seasons can benefit some ski areas that are climatically advantaged or have greater adaptive capacity (Dawson, Scott, & McBoyle, 2009; Rutty et al., 2017; Steiger, 2011b; Töglhofer et al., 2011). The few studies that have examined the pattern of skier spatial substitution intentions reveal the importance of maintaining some capacity for intra-market spatial substitution so that ski tourism is not lost to the regional economy. For example, significant ski tourism leakage was projected for Australia, where 38% of respondents stated they would ski overseas if five winters with poor snow conditions occurred in Australia (König, 1998). Such a high rate of inter-market substitution can be explained with the small number of competitors and universally high sensitivity to climatic changes in the Australian market. Interestingly, when asked the same question 11 years later, the share that intended to shift their ski holiday overseas decreased to 16% (Pickering et al., 2010). This substantial change could have been a reaction to the global economic crisis (2008–2009). In Ontario (Canada), the majority (61%) of surveyed skiers that chose spatial substitution planned to visit five key alternative ski areas within the province (Rutty et al., 2015b). The most chosen ski resort attracted 27% of respondents, posing significant risks of crowding and diminished visitor experience. Inter-market leakage was important, with 11–15% of those selecting spatial substitution intending to visit Québec or nearby US State instead.

In addition to implications for ski area and destination competitiveness, spatial substitution would also have important implications for travel distance and associated GHG emissions. The aforementioned adaptation by Australian skiers to take ski holidays overseas (König, 1998; Pickering et al., 2010) would increase transport-related GHG emissions substantially. A web-survey of visitors to the three Norwegian alpine summer ski destinations also showed that a large share of the skiers would choose long trips by air if the summer snow conditions in Norway would be too poor (Demiroglu, Dannevig, & Aall, in press).

The intra- and inter-market pair-wise substitutions identified by Rutty et al. (2015b) increased travel distance (exclusively by car) in virtually every case.

Temporal substitution is the second-most frequent skier adaptation among the studies in Table 3. This includes skiing less frequently in response to lost opportunities of a shortened season, which would reduce annual skier visits. It can also include skiing more frequently, so as to ski the same number of days as one normally would, but doing so over shorter season. This adaptation would maintain annual skier visits, but would increase demand peaks and alter the seasonal distribution of skier visits (concentrating more visits in the more snow reliable months of January and February). Not all of the studies in Table 3 distinguished these types of temporal substitution. Rutty et al. (2015a) asked the 36% of respondents that chose temporal substitution what form this adaptation would take if their most frequently visited ski area were to close permanently, and the findings have important implications for broader market demand: 23% stated that they would reduce their number of skiing days by 25%; 43% would ski half as often as usual; and 35% would even cut their skiing days by 75%.

Activity substitution is generally chosen by a small proportion of skiers (Table 3) when respondents were asked to specify a predominant adaptation strategy, because this results in not ski the entire season or even to entirely stop skiing. Two studies report high shares of activity substitution (Dawson & Scott, 2010; Unbehaun, Pröbstl, & Haider, 2008). An explanation is likely that multiple responses were allowed in these two studies, so respondents considered activity substitution as an option they would exercise occasionally (like temporal or spatial substitution) based on circumstances of the particular trip. Potential alternatives to skiing included warm-weather activities (44%), spending more time with family or work more (21%), participating in passive indoor activities (13%), other snow-based activities (13%), and active indoor activities (9%) (Dawson & Scott, 2010).

While in early studies, respondents were asked about their intended behaviour in hypothetical future situations, more recent studies examined how individuals have responded to marginal snow conditions in the past. For example, Dawson, Havitz, and Scott (2011) referenced two recent snow-poor winter seasons (2001/2002 and 2006/2007) so that skiers were able to connect responses to a real experienced situation. It was shown that past behaviour and intended future behaviour of skiers did not differ significantly (Dawson et al., 2011; Dawson & Scott, 2010; Dawson, Scott, & Havitz, 2013) reinforcing the value of examining ski tourist responses to record warm winters as climate change analogues (see discussion in the Integrated Assessment section). A related finding by Rutty et al. (2015a) was that skiers' intended substitution behaviour differed depending on the circumstances of the ski area closure. Spatial substitution was least likely if the ski area was closed on the day the respondents were surveyed (30%), but increased if the resort would not be open until mid-season (48%) and was the greatest if the resort were to close permanently (61%). Skiers were willing to forego a day of skiing, but not half a season or give up the sport, and would increasingly look for alternate destinations.

Importantly, substitution behaviour has been found to differ substantially between tourist segments. König (1998) found different substitution behaviour of Australian skiers depending on skills: while beginners are more likely to quit skiing than intermediate or expert skiers, the latter are more likely to ski overseas. Rutty et al. (2015a) found significant differences in adaptation intentions between those with different skiing skills, age, and commitment to skiing. Expert skiers more often chose spatial substitution than respondents with lower skills, and beginner skiers are more likely to stop skiing altogether. Skiers between 50 and 64 years of age are more likely to shift the timing of their trip (temporal) instead of destination (spatial). These findings were consistent with König (1998) and similar patterns were also found among Australian skiers (Cocolas, Walters, & Ruhanen, 2016). While ski lodge/condominium owners might be the most resistant to spatial substitution, in the New England region (US) over half indicated that if the ski area where there property is located were to close, they would use the property a lot less often or sell it, with attendant implications for real estate values (Dawson & Scott, 2013).

Three important limitations need to be addressed in future skier adaptation research. One clear limitation of many existing studies has been the hypothetical scenarios presented to the respondents. König (1998), Behringer et al. (2000) and Pickering et al. (2010) used the phrase 'if the next five winters would have very little natural snow' and Unbehaun et al. (2008) used 'several snow-deficient winter seasons'. How are these scenarios to be interpreted? Does it mean that the ski season is shortened, that conditions are poor during the entire season, or that some ski areas hardly manage to open, whereas conditions in other ski areas are still sufficient? The interpretation can differ greatly between respondents depending, for example, on their skill level, past experiences, and their place of residence (only few low-altitude ski areas to choose from versus living nearby a large number of ski areas with diverse sensitivity to a lack of snow). Scenarios posed to ski tourists need to be more precisely defined to minimize the risk of misinterpretation. Asking skiers to recall their response and experiences during recent adverse conditions strengthens connections between past and intended adaptation.

A second limitation is the stated versus real behaviour gap. As the work by Dawson (Dawson et al., 2011; Dawson et al., 2013; Dawson & Scott, 2010) has shown, there is limited difference between past versus stated future behaviour. Until such time that the frequency and severity of poor ski conditions or diminished number of ski areas is sufficiently different from contemporary experience, skiers should be expected to respond to adverse winters similarly as they have. Therefore, better understanding of past behavioural adaptations, using both surveys and secondary skier visits data, is needed to better project potential future behaviour.

Third, many studies do not differentiate between tourist segments, thus assuming that one uniform ski tourist exists. As some surveys have shown (e.g. Dawson et al., 2011; Rutty et al., 2015a), the sensitivity of skiers to snow-deficient conditions differs considerably between segments. Our understanding of the role of place loyalty (including vacation property ownership) and activity involvement remains limited. Of particular interest should be how the Millennial segment behave during anomalous ski seasons, as their substitution patterns are influenced by changing car, real estate, and vacation preferences.

Fourth, none of the studies have examined the consequences of changes in ski tourism patterns for transportation patterns, which in turn will affect energy use and GHG emission intensity of ski tourism. There is a potential dual vulnerability of climate change for ski tourism, because a growing number of ski tourists will need to travel farther to find suitable ski conditions, while at the same time, transport costs are likely to increase due to tougher GHG mitigation policies. How changes in transportation costs could alter skier substitution choices in the longer-term remains an uncertainty.

Integrated vulnerability assessments

In order to fully determine the consequences of climate change for regional ski tourism markets and individual destinations, the synchronous adaptations by ski area operators as well as ski tourists in an evolving landscape of competitive destinations need to be considered. Studies that examine the interactions between evolving supply-side (i.e. shorter and more variable ski seasons, with declining number of operating ski areas) and demand-side responses (i.e. ski tourist adaptation behaviours) are the most recent category to emerge in this field of research (with 18 assessments in total).

The largest group within the integrated assessment category are climate change analogue studies. Here, the approach is to analyse how supply-side and demand-side ski industry performance indicators differ between snow-deficient (analogues for future normal conditions) and climatically normal (for the current climatology) winter seasons. Despite the increasing number of 'natural experiments' offered by record warm and snow-deficient winters, the potential of these anomalous seasons to provide insight into future average winter seasons remains under-utilized (Scott, Hall, et al., 2012).

Table 4 summarizes the demand changes observed during recent record warm winters. Where snowmaking is widely available, the reduction in skier visits is limited to approximately 10% or less, except in the Australian market. Importantly, the impact of these snow-poor winter seasons differs greatly between individual ski areas (e.g. −86% to +66% in Steiger, 2011a), with higher elevation ski areas (Pickering, 2011; Steiger, 2011a, 2011b) and large ski areas (Rutty et al., 2017; Steiger, 2011a, 2011b) found to be less sensitive. The South Tyrol region (Italy) provides evidence for the benefit of investment in snowmaking adaptation. Although the temperature anomalies in the 1988–1989 and 2006–2007 seasons were almost identical, the demand sensitivity decreased considerably as a result of massive investments in snowmaking facilities in the 1990s and 2000s (Steiger, 2011a). As indicated, the loss of skier visits during climate change analogue seasons is much less than what would be expected on the basis of some of the early skier survey

Table 4. Impacts of extraordinary warm winter seasons on supply-side and demand-side indicators.

Authors	Region	Season	Temperature anomaly[a]	Analogue for future climate change	Demand change (skier visits)	Supply change (operating days)
Scott (2006a)	Northeast (US), Ontario and Quebec (Canada)	2001–2002	+4.4°C	A1B 2040–2069	−11% (US NE) −7% (Ontario) −10% (Québec)	
Dawson et al. (2009)	Northeast (US	2001–2002	+4.4°C	A1B 2040–2069	−11.6%	−10.9 days
Steiger (2011a)	South Tyrol (Italy)	1988–1989	+2.6°C	A1B 2050s, B1 2070s	−33%	
Steiger (2011a)	South Tyrol (Italy)	2006–2007	+2.9°C	A1B 2050, B1 2070s	−2%	
Steiger (2011b)	Tyrol (Austria)	2006–2007	+3.0°C	A1B 2060s, B1 2080s	−11%	−10 days
Pickering (2011)	Australia	2006	+0.6°C, −50% precipitation	B1 2050 (only for temp!)	−38%	
Rutty et al. (2017)	Ontario (Canada)	2011–2012	+3.6°C	RCP 8.5 mid-century	−10%	−16 days

[a]Temperature difference from current climate normals (1961–1990 or 1981–2010).

results, reinforcing the need to portray realistic, and arguably historically informed, scenarios of ski operations to ski tourists in future behavioural adaptation studies.

In markets with widespread snowmaking, supply-side losses in ski season length during recent record warm winters have been limited to approximately 10–16 days (Table 4). Importantly, analogue studies also consistently found smaller losses in season length than modelling studies in the same regions. It has been postulated that the differences relate to the inability of ski operations modelling to fully account for business decisions (i.e. partial opening under even very marginal conditions because of staffing inflexibility and to provide some level of skiing to guests staying in the resort), which can lead to the overestimation of season length losses by models (Scott et al. 2012). A recent study by Rutty et al. (2017) that was able to use higher resolution daily supply-side data of individual ski areas in Ontario (Canada) provided evidence of this supposition. Although season losses from the record warm winter 2011–2012 appeared moderate (16 days, or 17%), the greatly diminished proportion of open terrain and operational chair lifts (particularly in early and late season) revealed that market-wide supply was much more significantly reduced. Furthermore, the quality of snow conditions also declined in the analogue year, with an increase of days with wet snow, machine groomed granular snow, corn snow, and spring conditions, and a sharp decline of powder snow days. The study demonstrated that solely focusing on changes of season length does not adequately reflect the change of quantity (partially open terrain) and quality (degraded snow conditions) and, therefore, possibly disguises potential negative impacts on skiing experiences and consequences for future behaviour.

Some scholars have used regression models to examine the integrated effect of climatic changes. In these studies, relationships between ski industry performance indicators and weather variables are established (see Climate Sensitivity Assessments) and then modelled under projected future climate. In Japan, a 3°C warming was projected to cause a 30% decline of skier visits, except in the northernmost Hokkaido region (Fukushima et al., 2002). Damm et al. (2016) projected that a 2°C warming and associated changes in natural snow would lead to a decline of 10.1 million ski tourism-related overnight stays in Europe. An important caveat is that neither of these studies took into account the widespread use of snowmaking in Japan and the European Alps. A regression analysis for Slovakia that did partially account for snowmaking, projected that a 1°C temperature increase would lead to a 6% loss of lift ticket sales, with much larger losses under a high-emission scenario (+3.2°C) of 19% (Demiroglu, Kučerová, & Ozcelebi, 2015). Damm, Köberl, and Prettenthaler (2014) used a detailed snow model (Hanzer, Marke, & Strasser, 2014) incorporating the location and type of each snow gun to model climate change induced changes of snowmaking costs and extrapolated skier visits based on past weather/snow and demand relationships. They concluded that nominal lift ticket prices need to be increased by 3.3–5.1% per year to remain profitable.

Steiger (2012) integrated climate change impacts on season length (including snowmaking) and demand with demographic change. To do so, potential demand losses due to a shortening of the ski season – weighting lost days according to seasonal distribution of demand – were compared to demand losses caused by ageing and decline of the population in Germany. It was found that demographic changes have a higher impact on demand in the first half of the twenty-first century, whereas climate change became the more important driver in the second half.

Another form of integrated assessment is agent-based models (ABMs), which have only recently been applied to the study of climate change and skiing. These models couple supply-side changes (e.g. ski season length) with associated demand-side adaptations (e.g. spatial substitution), with skier behaviour decision rules that are in most cases informed by skier surveys. Pons-Pons, Johnson, Rosas-Casals, Sureda, and Jover (2012) integrated a snow model incorporating snowmaking in a geo-referenced ABM for three major ski areas in Andorra to estimate potential impacts of climate change on demand and revenues. The numbers and type of tourists (e.g. day visitors vs. overnight guests) are generated randomly by the model based on real statistics derived from surveys and official statistics. In a +2°C scenario, the model projects a decrease of skiers of 14% for one ski area and 1% for the two other ski areas, because only the lower parts of the ski areas are affected. With 4°C warming, the losses would be 50% at one ski area and 20% at the other two ski areas summing up to €50 m losses per winter season (Pons-Pons et al., 2012). In the first model version, no temporal substitution of demand was considered and spatial substitution was considered only within Andorran ski resorts. Nevertheless this model approach is an important step to better incorporate economic consequences of climate change. Balbi, Giupponi, Perez, and Alberti (2013) used an ABM combined with a ski season model (SkiSim) including snowmaking to assess the most suitable future tourism strategy for a destination (Auronzo di Cadore) in the Italian Dolomites. They did not only consider climate change as influencing factor, but also four different tourism adaptation strategies, two demand scenarios and two competition scenarios. The 'beyond-snow tourism scenario' was found to produce the best results of the 12 modelled scenarios, followed by the 'alternative light-ski oriented scenario'. Pursuing the traditional ski-intensive strategy would not increase the volume of tourist nights. Climate change had negative impacts on all scenario combinations, but competition and demand were found to be more effective drivers of demand change (Balbi et al., 2013).

The first large-scale ABM in the skiing tourism context was applied for the Danube catchment area covering parts of Austria, Germany, and Switzerland (Soboll & Dingeldey, 2012; Soboll & Schmude, 2011; Soboll, Klier, & Heumann, 2012). Though both supply (use of snowmaking, permanent closing of ski areas) and demand-side reactions (temporal/spatial shifts of demand) were considered in the model setup, a number of shortcomings need to be addressed: Some important model parameters are only described in a qualitative way (e.g. 'moderate expansion of snowmaking facilities', 'overall tourism demand increases'), some fundamental rules that have a high impact on the results (e.g. the rules for spatial/temporal shifts of demand) are not described at all. Some results are not plausible, for example, when water consumption by snowmaking sharply increases around 2020 and stays constant until 2050, where a positive (more water required due to warmer conditions) or a negative trend (too warm to produce as much snow as needed) would be expected (Soboll & Schmude, 2011). Increases of tourism demand in non-snow-dependent communities are explained by (among others) 'the shift of tourism flows from southern countries' (Soboll et al., 2012, p. 154) although such international shifts of demand were not incorporated in the model. Furthermore, neither the supply-side nor the demand-side model results were evaluated with statistical data (e.g. number of operations days per ski area, impact of snow-scarce years on temporal/spatial (re)distribution of demand).

A second large-scale ABM application was conducted for the entire Pyrenean ski market (Andorra, French and Spanish Pyrenees) including activity, temporal, and spatial substitution, capturing how projected changes at local/ski resort scale can affect regional market dynamics and identifying potential winners and loser of climate change due to the differentiated level of vulnerability. Here, spatial substitution was driven by distance to ski resorts and an attractiveness index based on physical and socioeconomic characteristics of resorts. Even though the model was able to explain almost 90% of the present distribution of skiers among Pyrenean ski resorts, one limitation was the lack of specific surveys to identify the behavioural response of skiers in the Pyrenean market. The values used in the model for the behavioural dynamics of skiers were taken from surveys in other countries, increasing the uncertainty of ABM results.

The Pons et al. (2014) ABM model was further refined and coupled with the SkiSim model (Scott et al., 2017) to simulate the consequences of climate variability on the Ontario (Canada) ski market. Behavioural adaptation of skiers in Ontario was determined with a skier survey (Rutty et al., 2015a, 2015b) and integrated in the ABM (Pons et al., in press). The study also introduced the new 'climate competitiveness index' (CCI) indicator, which is a measure of the ability of a ski area to be in operation when few competitors in the regional market are open. It provides an important competitive advantage during periods of adverse weather, one that is potentially important to overcome substantial losses in season length under climate change. The CCI indicator was well correlated with lower visitation change (either negative or slightly positive) and where an ABM analysis is not feasible, the CCI was recommended as a more robust indicator of a ski area's relative climate risk and marketplace position than the '100 day rule.

Ski industry stakeholder risk perceptions

Interview and focus group-based studies of ski tourism stakeholders' awareness of climate change and their perceptions of risks, opportunities, and capacities to adapt represent 19% of reviewed assessments. While the primary focus has been on ski area operators, the perception of other ski tourism stakeholders has also been examined, including representatives from the accommodation sector, the destination management, local and regional government, and NGOs. Sample sizes typically range from 10 to 30 industry stakeholders, but occasionally larger samples capture regional perspectives (e.g. 160 in Abegg, Kolb, Sprengel, & Hoffmann, 2008) or destination resident perspectives (e.g. 400 in March, Saurí, & Llurdés, 2014).

Although the available studies differ in many respects (including regional market focus, methodology and questions employed, sample size), some common themes have emerged. A central theme has been diverse ski industry views on climate change science and perceived risk. Climate change perspectives in the ski industry differ substantially, both among ski area operators and between ski area operators and other stakeholders (i.e. accommodation sector, the destination management, local and regional government, and NGOs). The latter generally perceive climate change to be more 'real', the potential impacts more 'severe', and the adaptation capacity of the industry more 'restricted' (e.g. Hoy, Hänsel, & Matschullat, 2011; Morrison & Pickering, 2013; Trawöger, 2014).

Hopkins (2015), confirming earlier research (e.g. Abegg, 1996; Haanpää, Juhola, & Landauer, 2015; Saarinen & Tervo, 2006), found a clear distinction between risk perceptions associated with current climate variability and future climate change. Variability, including the delayed arrival of permanent snow and reduced capacities to produce snow due to high temperatures, is seen to be a current risk. Climate change, on the other hand, is perceived to be an incremental and temporally distanced threat. That 16 of the 17 warmest years in the instrumental record have occurred since 2000 (NASA, 2017) is not yet perceived to represent a changing climate.

Most stakeholders acknowledge the prospect of future climate change, however, a certain degree of scepticism remains among ski area operators (Abegg et al., 2008; Morrison & Pickering, 2013; Trawöger, 2014). Some stakeholders acknowledge climate change and expect meaningful global, but do not think local or ski industry impacts to be significant. Others contend that any recent warm winters are part of natural climate variability, often referring to the 'cyclical nature of climate' and that 'this has happened before'. The disparate positions on climate change within the ski industry are perhaps no more clearly illustrated than by the contrast between National Ski Areas Association's (US) decade long 'Keep Winter Cool' campaign to educate guests and the public, raise policy maker awareness, advocate for national GHG emission reductions and promote renewable energy, and the political donations of some ski area owners and executive to climate change denier political campaigns (Fox, 2016). Notably, the proportion of ski industry stakeholders that deny anthropogenic climate change does not appear to be substantially different than the general public in countries where the study was done. Also of importance is that where several studies have been conducted in a country, there appears to be a growing awareness over time (e.g. Morrison & Pickering, 2013; Saarinen & Tervo, 2010; Trawöger, 2014). However, there is also some evidence that stakeholder perceptions may have been influenced by the weather preceding the investigation. Several studies reporting high awareness were conducted after extraordinary warm and/or snow-poor winter seasons (e.g. Abegg et al., 2008; Bürki, 2000; Hopkins, 2015; Luthe, 2009; March et al., 2014). Saarinen and Tervo (2010) also suggest that study results are positively influenced by high media coverage prior to the investigation. First-hand experiences (e.g. snow-deficient winters, glacier retreat, and changes in the occurrence of extreme weather events) seem to play an important role in shaping perception (Abegg, 1996; Bürki, 2000; Morrison & Pickering, 2013; Saarinen & Tervo, 2010; Wyss, Abegg, & Luthe, 2014).

The gap between climate change science and ski tourism stakeholder perceptions of climate change risk can be partially explained by the industry's faith in snowmaking technology, the incompatibilities of business and climate change timelines, and the contested role of media and communication (Abegg & Steiger, 2017). In several ski tourism regions, snowmaking has been an integral part of the business for 20 years. Snowmaking is the most important adaptation to current climate variability, and most ski area operators believe that with constantly improving snowmaking techniques and continued investment, they are well prepared for climate challenges that lie ahead. Wolfsegger, Gössling, and Scott (2008), for example, found that Austrian low elevation ski area operators were highly optimistic about the long-term viability of their businesses. With further adaptation (mostly snowmaking), 82% of respondents believed they could operate their ski business for at least another 30–45 years (44% for at least another 75 years). This low-risk perception is widespread among ski area operators. More than ten years ago, Bicknell and McManus (2006, p. 397) spoke of an 'overwhelming cornucopian belief that improvements in snowmaking technology would negate the effects of climate change'. Little has changed, and strong faith in snowmaking technology is a common finding through this literature.

There is little evidence of ski area operators questioning the suitability of snowmaking as a climate change adaptation strategy (Hoy et al., 2011; Wyss et al., 2014), including the sustainability (GHG emissions and water use – e.g. de Jong, Carletti, & Previtali, 2014) and long-term effectiveness of snowmaking. There is increasing evidence that ski area operators' confidence in snowmaking might be overly optimistic. As discussed in the climate change impact section, studies that include snowmaking all reveal significant season losses for many ski areas. These analyses are limited to considerations of technical capacity and physical climatology only, and do not account for increased capital and operating costs (and attendant price increases), sustainability (including water access), or social acceptance (e.g. increasing frequency of white ribbons of snow on otherwise green mountains) that further limit the adaptive capacity offered snowmaking (Damm et al., 2014; Pickering & Buckley, 2010; Scott et al., 2007; Steiger & Abegg, 2013).

Investment in snowmaking is often not considered an adaptation to climate change, but rather a strategy to cope with current climate variability and meet changing customer expectations. However, different perspectives have been found between stakeholders with commercial interests and sport development interests. A study in Norway found a difference of perception between commercial and low-commercial stakeholders; in which representatives of the commercial ski industry (i.e. alpine resorts) were not at all concerned about climate change and explained their investment in snowmaking as purely based on an economic interest to increase the shoulder seasons. Representatives of low-commercial stakeholders (i.e. cross-country arenas close to the major cities and run by local skiing athlete clubs) stated that they were very much aware of the possible negative effects of climate change – and had installed snowmaking facilities in order to assure that children would still have the possibility to learn how to ski (Aall & Høyer, 2005). There are also instances from more than one regional market where stakeholder perception studies document ski operators' disbelief in negative impacts of climate change on snow reliability, but hypocritically use climate change as a prominent argument to legitimate the expansion of existing snowmaking capacities (e.g. Aall & Høyer, 2005; Behringer et al., 2000). In Scotland, for example, stakeholders expressed a desire to use snowmaking as a way to cope with insufficient natural snowfall, a risk which some of the same stakeholders stated was non-existent (Hopkins & Maclean, 2014).

The perception of very long time horizons associated with climate change is another barrier to anticipatory adaptation within the ski industry and among ski tourism destinations. Ski area operators adapt to season-by-season market dynamics and climate variability (e.g. weather and snow conditions during parts of each season) to survive in a highly competitive market. Industry stakeholders have expressed to the authors that short-term planning horizons dominate decisions (sub-season and next season), while mid-term planning is restricted largely to capital investments (with 10 or more depreciation periods). Long-term planning consistent with when climate change might be considered materially relevant is considered a 'luxury' (Abegg et al., 2007; Scott et al., 2007). These 'incompatibilities between business and climate change impact timelines' (Scott, Hall, et al., 2012, p. 279) have important consequences.

Climate change is regarded as an issue to be principally aware of but has a (very) low management priority (Roman, Lynch, & Dominey-Howes, 2010). Adaptation to climate variability (not future change) is predominantly incremental and reactive (short-term) rather than anticipatory and pro-active (long-term). As with the broader tourism sector (Scott, Hall, et al., 2012; Scott et al., 2016), there is limited evidence of long-term strategies to adapt to climate change, regardless of whether the competitiveness of a destination is expected to increase or decrease under climate change (Abegg et al., 2007; Scott et al., 2007; Tervo-Kankare, 2011).

In order not to diminish competitive advantage, it makes sense from a strategic business perspective not to disclose adaptation planning and to officially 'downplay any climate risk and quietly adapt or divest high-risk assets' (Scott, Gössling, & Hall, 2012, p. 223). As climate risk disclosure requirements by institutional investors and stock-markets continue to strengthen (Task Force on Climate-Related Financial Disclosure, 2016), risk assessments and adaptation strategies of publically traded companies will be increasingly required and available, so that the state of climate change adaptation among large ski conglomerates will be more clearly known by 2025.

A wide gap exists between the climate change risk perception of the ski industry and what is portrayed in the media (Abegg et al., 2008; Saarinen & Tervo, 2006; Wolfsegger et al., 2008). The media in all major ski tourism regions have repeatedly pronounced the impending doom of the ski industry (see Scott, Hall, et al., 2012 for examples). Many of these media stories have covered studies with key limitations identified in the 'impact assessment' section, and thus exaggerate the risk of climate change to the ski industry. Because the ski tourism industry is very image-sensitive, stakeholders have been very reluctant to engage in studies that will generate media coverage or government risk assessments that acknowledge climate change vulnerability and adversely influence financial institutions (e.g. lower credit access and increase borrowing costs), investors (e.g. stock prices), real estate developers and buyers, or destination image (Behringer et al., 2000; Morrison & Pickering, 2013; Scott, Gössling, et al., 2012; Trawöger, 2014). More than 10 years ago, Bicknell and McManus (2006, p. 394) found that 'rather than emphasizing their vulnerability to attract (government) assistance, these businesses emphasize their resilience in order to maintain a perception of low credit risk'. Some ski industry stakeholders have gone further to influence media coverage, labelling climate change research as 'scaremongering'. While criticisms of some studies have been warranted (Abegg & Steiger, 2017; Scott, Hall, et al., 2012) collaboration to facilitate improved information on ski tourism risk and adaptation have been limited.

Discussion and research agenda

Although ski tourism is the most studied segment of the tourism and climate change literature (Fang, Yin, & Wu, 2017), available results need to be interpreted with awareness of a range of limitations and uncertainties. In order to stimulate decision-relevant research in this field and to improve our understanding of climate change impacts on the ski tourism industry, related behavioural responses and impacts on livelihoods in mountain regions, a research agenda based on key gaps and limitations identified in the review is proposed.

Sensitivity and vulnerability assessments

One major limitation that has been criticized in many publications of the last decade (e.g. Scott et al., 2003; Scott et al., 2006; Steiger, 2010; Steiger & Stötter, 2013) is the omission of snowmaking. This is akin to modelling the impact of climate change on an irrigated crop, without the irrigation. Where snowmaking is an integral component of contemporary ski operations (or could be a major adaptation strategy), it must be accounted for because it significantly reduces sensitivity to natural snow variability, it is expected by the customer in many markets, costs, and resource consumption are increasing with climate change and this mechanization leads to paradox situations where skiing is possible in a landscape free of natural snow with unknown consequences for customer perception and satisfaction. In the view of industry stakeholders, snowmaking is also seen as insurance against climate change in the sense that technological development will solve the problem. Consequently, studies that do not incorporate snowmaking do not represent the industry's operating realities and are considered invalid by industry stakeholders.

As snowmaking capacity differs significantly between ski areas, models should be adapted to include individual snowmaking capacity. Improving snowmaking technology (e.g. automation, higher output) enabling to produce snow in rather short windows (few hours) with suitable weather conditions requires high temporal resolution (e.g. hourly) of snowmaking in the models.

Reliable results require reliable input data. This means appropriate variables (e.g. skier visits instead of overnight stays for sensitivity assessments or high quality bias corrected weather data) that are representative of climatic conditions, operating reality and demand in investigated ski areas. The ski industry's climate sensitivity is dependent on local conditions, which vary with elevation and latitude. Due to climatic heterogeneity on a macro- (e.g. maritime versus continental climate) and also meso-scale (e.g. windward and leeward locations, prevailing weather patterns), it is difficult to generalize findings to identify certain elevations and/or latitudes with higher climate resilience. The industry's sensitivity and potential climate change risk is not only dependent on climatic conditions but also on market characteristics. This includes destination reputation, demand potential, vicinity to large population centres (share of day-trippers and holiday-makers), number of competitors, and proportion of small and medium-sized enterprises versus regionally diversified ski conglomerate businesses. Adaptive capacity will vary at both the business, destination, and regional market scales (Scott et al., 2007; Steiger & Abegg, 2017).

But also the output indicators are of great relevance (e.g. number of skiable days ≥30 cm snow depth) for correct interpretation of results and for credibility to stakeholders. The use of established indicators (e.g. 100-day rule, Christmas rule, season length, CCI) is required to enable compared with previous studies. A common set of climate models and emission scenarios as the basis of vulnerability assessments would also enable inter-comparisons going forward. Even if not all models and scenarios are available in high spatial resolution (regional climate models), at least a comparison of the climate change signal to preceding studies should become standard.

Changes in multi-year average values of sectoral performance indicators are common practice in climate change assessments. Like agriculture and some other sectors, the operating reality of the ski industry and viability of the business are strongly influenced by the risk of season disruptions and economically impactful seasons. Therefore, greater focus should be put on the probability of exceeding economically damaging season disruptions (as co-defined by industry stakeholders).

Ski tourists' perception and behavioural response assessments

One major limitation of existing research in this category is the uncertain gap between intended and observed behavioural response to adverse climate and snow conditions. Winter scenarios (e.g. 'next three winters with poor snow conditions') are often imprecisely described, leaving potential for very different interpretation among respondents. The hypothetical winter/snow conditions presented to respondents need to be more precisely defined (e.g. snow conditions, altered ski season, available skiing terrain, winterly landscape), and the range of visualization techniques utilized in other fields of climate change and recreation and tourism research offer much potential in this regard. To improve comparability of results, the range of adaptive response options and consistent measurement of responses will also be important. Previous surveys have revealed considerable differences in response to poor snow conditions between tourist segments. Deeper insights into these differences in motivation and behaviour will help refine the picture of *the* ski tourist and the potential economics of ski tourism under climate change.

Integrated vulnerability assessments

The complex interrelationships of physical and socioeconomic variables at the local and regional scale necessitate advancements in integrated assessments in order to better understand the complex interactions between changing climate conditions and the supply and demand for ski tourism. Climate change analogue seasons provide valuable natural experiments to monitor real changes and adaptations taken by ski operators and tourists. ABMs are also a promising approach to simulate potential future adaptations, provided that reliable snow modelling and tourist decision rules are based on tourist responses (observed or stated) and that model performance can be evaluated with appropriate supply- and demand-side data. Of course existing limitations both in vulnerability and demand response assessments also apply for integrated assessments and need to be considered. Further work is also required to better include other industry performace variables into future integrated assessments, including transportation patterns, water or energy use, operating costs, and pricing implications. The inclusion of these factors would permit better understanding of the limits to adaptation and business viablity. For example, access to water or energy costs are potential limiting factors for future snowmaking capacity, while increase snowmaking and ski tourist adaptive responses have important implictions for the sustainability of ski tourism (i.e. have a negative effect on GHG emissions of the winter tourism industry).

Ski industry stakeholder risk perceptions

A wide range of ski tourism stakeholders will be impacted by the consequences of climate change (e.g. ski area owners and employees, destination communities, investors, real estate owners, transportation companies, tourism policy makers). These diverse stakeholders have differential interests, but all benefit from credible, decision-relevant information. Therefore, future research needs to improve credibility and also appropriate communication of results. As Scott, Gössling, et al. (2012) pointed out, there are real dangers to media misinformation and communication of flawed studies. Some European banks imposed financing restrictions on low-lying ski areas based partially on the findings of studies that did not account for current or potential future snowmaking capacity. Travel magazines and international real estate investment web sites have published articles on where to buy vacation properties to avoid the impacts of climate change, even though there was no scientific basis for such recommendations (i.e. geographic gaps, lack of inter-comparisons). As climate risk disclosure requirements expand in the financial sector (Task Force on Climate-Related Financial Disclosure, 2016), there is growing need to provide scientifically accurate information is publically available. There is an important need to also better mobilize new information by communicating to key stakeholders through appropriate industry journals or policy briefs.

A challenge moving forward remains improved engagement of tourism industry stakeholders. It has been repeatedly mentioned that ski area managers are reluctant acknowledge climate change as a challenge to their business or engage in studies of climate change vulnerability. Therefore, investigating stakeholders' perception and evaluation of the consequences of past anomalous seasons could be a more promising way of understanding their preparedness for climate changes. Few studies have attempted to explore the broader interests of destination communities, including their perceptions of climate change risk to ski tourism and associated tourism development path dependency. To date there are only few alternatives to skiing to convince tourists to go on the mountain in winter, and no alternative remotely equivalent to the revenues by skiing tourism. Missing alternatives together with high investments into snowmaking and high-speed ski lifts form a clear path dependency of ski areas. Depending on the ski area's power in a regional economy (which can be substantial in rural areas), this path dependency also influences (and in the worst case determines) the development path that a municipality or an entire valley pursues. Therefore, a better understanding of differential adaptive capacity of stakeholder groups and power structure within the region is an important field of future research.

Conclusion

The large-scale and long-term nature of climate change makes it uniquely challenging for tourism research and decision-making. While society remains at the early stages of anthropogenic climate change, our team of authors have collectively witnessed growing interest from increasingly diverse decision-makers (e.g. from institutional investors, ski area owners, grooming and snowmaking equipment companies, insurance companies, and real estate developers) for climate risk information and expert advice on the implications of climate change for individual ski areas and the ski industry as a whole. This demand will increase as the frequency of warm and snow-poor ski seasons increasingly impacts ski tourism operations and destination reputations and climate risk disclosure requirements become increasingly formalized within the financial community. Diverse stakeholders require foresight on the implications of accelerating climate change to enable effective dialogue on adaptation that will lead to a more climate-resilient and sustainable tourism sector in the mountain regions of the world.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Klima- und Energiefonds [grant number KR14AC7K11929].

References

Aall, C., Hall, M. C., & Groven, K. (2016). Tourism: Applying rebound theories and mechanisms to climate change mitigation and adaptation. In C. Aall, T. Santarius, & H. J. Walnum (Eds.), *How to improve energy and climate policies. Understanding the role of rebound effects* (pp. 209–227). London: Springer.

Aall, C., & Høyer, K. G. (2005). Tourism and climate change adaptation – the Norwegian case. In M. C. Hall & J. Higham (Eds.), *Aspects of tourism: Vol. 22. Tourism, recreation and climate change* (pp. 209–223). Clevedon: Channel View Publications.

Abegg, B. (1996). *Klimaänderung und Tourismus. Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen*. Zurich: vdf Zurich.

Abegg, B., Agrawala, S., Crick, F., & de Montfalcon, A. (2007). Climate change impacts and adaptation in winter tourism. In S. Agrawala (Ed.), *Climate change in the European Alps. Adapting winter tourism and natural hazards management* (pp. 25–60). Paris: OECD.

Abegg, B., & Frösch, R. (1994). Climate change and winter tourism: Impact on transport companies in the Swiss canton of Graubünden. In M. Beniston (Ed.), *Mountain environments in changing climates* (pp. 328–340). London: Routledge.

Abegg, B., Kolb, M., Sprengel, D., & Hoffmann, V. (2008). Klimawandel aus der Sicht der Schweizer Seilbahnunternehmer. In T. Bieger, C. Laesser, & R. Maggi (Eds.), *Jahrbuch der Schweizerischen Tourismuswirtschaft 2008* (pp. 73–83). St. Gallen: IDT-HSG.

Abegg, B., König, U., & Maisch, M. (1994). Klimaänderung und Gletscherskitourismus. *Geographica Helvetica*, *49*, 103–114.

Abegg, B., & Steiger, R. (2016). Herausforderung Klimawandel: Alpiner Skitourismus unter Anpassungsdruck. *Geographische Rundschau*, *Mai 5*, 16–21.

Abegg, B., & Steiger, R. (2017). Resilience and perceptions of problems in Alpine regions. In R. W. Butler (Ed.), *Tourism and resilience* (pp. 105–117). Wallingford: CABI Publications.

Abegg, B., Steiger, R., & Walser, R. (2015). Aktuelle und zukünftige Schneesicherheit der Skigebiete in Graubünden. In T. Bieger, P. Beritelli, & C. Laesser (Eds.), *St.Galler Schriften für Tourismus und Verkehr: Vol. 6. Schweizer Jahrbuch für Tourismus 2014–15* (pp. 1–16). Berlin: ESV.

Balbi, S., Giupponi, C., Perez, P., & Alberti, M. (2013). A spatial agent-based model for assessing strategies of adaptation to climate and tourism demand changes in an alpine tourism destination. *Environmental Modelling & Software*, *45*, 29–51. doi:10.1016/j.envsoft.2012.10.004

Bark, R. H., Colby, B. G., & Dominguez, F. (2010). Snow days? Snowmaking adaptation and the future of low latitude, high elevation skiing in Arizona, USA. *Climatic Change*, *102*, 467–491.

Beaudin, L., & Huang, J.-C. (2014). Weather conditions and outdoor recreation: A study of New England ski areas. *Ecological Economics*, *106*, 56–68. doi:10.1016/j.ecolecon.2014.07.011

Behringer, J., Bürki, R., & Fuhrer, J. (2000). Participatory integrated assessment of adaptation to climate change in Alpine tourism and mountain agriculture. *Integrated Assessment*, *1*, 331–338.

Berghammer, A., & Schmude, J. (2014). The Christmas–Easter shift: Simulating Alpine ski resorts' future development under climate change conditions using the parameter 'optimal ski day'. *Tourism Economics*, *20*(2), 323–336. doi:10.5367/te.2013.0272

Bicknell, S., & McManus, P. (2006). The canary in the coalmine: Australian ski resorts and their response to climate change. *Geographical Research*, *44*(4), 386–400.

Breiling, M., & Charamza, P. (1999). The impact of global warming on winter tourism and skiing: A regionalised model for Austrian snow conditions. *Regional Environmental Change*, *1*(1), 4–14.

Brouder, P., & Lundmark, L. (2011). Climate change in Northern Sweden: Intra-regional perceptions of vulnerability among winter-oriented tourism businesses. *Journal of Sustainable Tourism*, *19*(8), 919–933. doi:10.1080/09669582.2011.573073

Bürki, R. (2000). *Publikation der Ostschweizerischen Geographischen Gesellschaft: Vol. 6. Klimaänderung und Anpassungsprozesse im Wintertourismus*. St.Gallen: Ostschweizerische Geographische Gesellschaft.

Cocolas, N., Walters, G., & Ruhanen, L. (2016). Behavioural adaptation to climate change among winter alpine tourists: An analysis of tourist motivations and leisure substitutability. *Journal of Sustainable Tourism*, *24*(6), 846–865. doi:10.1080/09669582.2015.1088860

Damm, A., Greuell, W., Landgren, O., & Prettenthaler, F. (2016). Impacts of + 2 °C global warming on winter tourism demand in Europe. *Climate Services*. doi:10.1016/j.cliser.2016.07.003

Damm, A., Köberl, J., & Prettenthaler, F. (2014). Does artificial snow production pay under future climate conditions? – A case study for a vulnerable ski area in Austria. *Tourism Management*, *43*, 8–21. doi:10.1016/j.tourman.2014.01.009

Dawson, J., Havitz, M., & Scott, D. (2011). Behavioral adaptation of alpine skiers to climate change: Examining activity involvement and place loyalty. *Journal of Travel & Tourism Marketing*, *28*(4), 388–404. doi:10.1080/10548408.2011.571573

Dawson, J., & Scott, D. (2007). Climate change vulnerability of the Vermont ski tourism industry (USA). *Annals of Leisure Research*, *10*(3&4), 550–572.

Dawson, J., & Scott, D. (2010). Systems analysis of climate change vulnerability for the US Northeast ski sector. *Tourism and Hospitality Planning & Development*, *7*(3), 219–235.

Dawson, J., & Scott, D. (2013). Managing for climate change in the alpine ski sector. *Tourism Management*, *35*, 244–254. doi:10.1016/j.tourman.2012.07.009

Dawson, J., Scott, D., & Havitz, M. (2013). Skier demand and behavioural adaptation to climate change in the US Northeast. *Leisure/Loisir*, *37*(2), 127–143. doi:10.1080/14927713.2013.805037

Dawson, J., Scott, D., & McBoyle, G. (2009). Climate change analogue analysis of ski tourism in the Northeastern USA. *Climate Research*, *39*(1), 1–9.

de Jong, C., Carletti, G., & Previtali, F. (2014). Assessing impacts of climate change, ski slope, snow and hydraulic engineering on slope stability in ski resorts (French and Italian Alps). In G. Lollino, A. Manconi, J. Clague, W. Shan, & M. Chiarle (Eds.), *Engineering geology for society and territory. Climate change and engineering geology, chapter: 10* (pp. 51–55). Cham: Springer.

Demiroglu, O. C. (2016). Technical climate change adaptation options of the major ski resorts in Bulgaria. In B. Koulov & G. Zhelezov (Eds.), *Sustainable mountain regions: Challenges and perspectives in Southeastern Europe* (pp. 77–88). Cham: Springer.

Demiroglu, O. C., Dannevig, H., & Aall, C. (in press). Climate change acknowledgement and responses of summer (glacier) ski visitors in Norway. *Scandinavian Journal of Hospitality and Tourism*.

Demiroglu, O. C., Kučerová, J., & Ozcelebi, O. (2015). Snow reliability and climate elasticity: Case of a Slovak ski resort. *Tourism Review*, *70*(1), 1–12. doi:10.1108/TR-01-2014-0003

Demiroglu, O. C., Turp, M. T., Ozturk, T., & Kurnaz, M. L. (2016). Impact of climate change on natural snow reliability, snowmaking capacities, and wind conditions of ski resorts in

Northeast Turkey: A dynamical downscaling approach. *Atmosphere*, *7*(4), 52. doi:10.3390/atmos7040052
Dincă, A. I., Surugiu, C., Surugiu, M., & Frenţ, C. (2014). Stakeholder perspectives on climate change effects on tourism activities in the northern Romanian Carpathians: Vatra Dornei resort case study. *HUMAN GEOGRAPHIES – Journal of Studies and Research in Human Geography*, *8*(1), 27–41. doi:10.5719/hgeo
Elsasser, H., & Bürki, R. (2002). Climate change as a threat to tourism in the Alps. *Climate Research*, *20*, 253–257.
Elsasser, H., & Messerli, P. (2001). The vulnerability of the snow industry in the Swiss Alps. *Mountain Research and Development*, *21*(4), 335–339. doi:10.1659/0276-4741(2001)021[0335:TVOTSI]2.0.CO;2
Endler, C., & Matzarakis, A. (2011). Climatic potential for tourism in the Black Forest, Germany — winter season. *International Journal of Biometeorology*, *55*(3), 339–351. doi:10.1007/s00484-010-0342-0
Falk, M. (2010). A dynamic panel data analysis of snow depth and winter tourism. *Tourism Management*, *31*, 912–924.
Falk, M. (2013). A survival analysis of ski lift companies. *Tourism Management*, *36*, 377–390. doi:10.1016/j.tourman.2012.10.005
Falk, M. (2015). The demand for winter sports: Empirical evidence for the largest French ski-lift operator. *Tourism Economics*, *21*(3), 561–580. doi:10.5367/te.2013.0366
Falk, M. (2016). The stagnation of summer glacier skiing. *Tourism Analysis*, *21*(1), 117–122. doi:10.3727/108354216X14537459509053
Falk, M., & Hagsten, E. (2016). Importance of early snowfall for Swedish ski resorts: Evidence based on monthly data. *Tourism Management*, *53*, 61–73. doi:10.1016/j.tourman.2015.09.002
Falk, M., & Vanat, L. (2016). Gains from investments in snowmaking facilities. *Ecological Economics*, *130*, 339–349. doi:10.1016/j.ecolecon.2016.08.003
Falk, M., & Vieru, M. (2016). Demand for downhill skiing in subarctic climates. *Scandinavian Journal of Hospitality and Tourism*, 1–18. doi:10.1080/15022250.2016.1238780
Fang, Y., Yin, J., & Wu, B. (2017). Climate change and tourism: A scientometric analysis using CiteSpace. *Journal of Sustainable Tourism*, 1–19. doi:10.1080/09669582.2017.1329310
Fox, P. (2016, November 3). Campaign donations link ski industry leaders to climate change deniers. *Powder Magazine*. http://www.powder.com/stories/news/campaign-donations-link-ski-industry-leaders-climate-change-deniers/
François, H., Morin, S., Lafaysse, M., & George-Marcelpoil, E. (2014). Crossing numerical simulations of snow conditions with a spatially-resolved socio-economic database of ski resorts: A proof of concept in the French Alps. *Cold Regions Science and Technology*, *108*, 98–112. doi:10.1016/j.coldregions.2014.08.005
Fukushima, T., Kureha, M., Ozaki, N., Fujimori, Y., & Harasawa, H. (2002). Influences of air temperature change on leisure industries: Case study on ski activities. *Mitigation and Adaptation Strategies for Global Change*, *7*, 173–189.
Galloway, R. (1988). The potential impact of climate changes on Australian ski fields. In G. Pearman (Ed.), *Greenhouse planning for climate change* (pp. 428–437). Melbourne: CSIRO Publications.
Gonseth, C. (2013). Impact of snow variability on the Swiss winter tourism sector: Implications in an era of climate change. *Climatic Change*, *119*(2), 307–320. doi:10.1007/s10584-013-0718-3
Gössling, S., Scott, D., Hall, C. M., Ceron, J.-P., & Dubois, G. (2012). Consumer behaviour and demand response of tourists to climate change. *Annals of Tourism Research*, *39*(1), 36–58. doi:10.1016/j.annals.2011.11.002
Haanpää, S., Juhola, S., & Landauer, M. (2015). Adapting to climate change: Perceptions of vulnerability of down-hill ski area operators in Southern and Middle Finland. *Current Issues in Tourism*, *18*(10), 966–978. doi:10.1080/13683500.2014.892917
Hamilton, L. C., Brown, C., & Keim, B. D. (2007). Ski areas, weather and climate: Time series models for New England case studies. *International Journal of Climatology*, *27*, 2113–2124.
Hamilton, L. C., Rohall, D., Hayward, G., & Keim, B. D. (2003). Warming winters and New Hampshire's lost ski areas: An integrated case study. *International Journal of Sociology and Social Policy*, *23*(10), 52–73.
Hanzer, F., Marke, T., & Strasser, U. (2014). Distributed, explicit modeling of technical snow production for a ski area in the Schladming region (Austrian Alps). *Cold Regions Science and Technology*, *108*, 113–124. doi:10.1016/j.coldregions.2014.08.003

Harrison, R., Kinnaird, V., McBoyle, G., Quinlan, C., & Wall, G. (1986). Climate change and downhill skiing in Ontario. *Ontario Geographer*, *28*, 51–68.

Harrison, S. J., Winterbottom, S. J., & Johnson, R. C. (2005). Changing snow cover and winter tourism and recreation in the Scottish highlands. In M. C. Hall & J. Higham (Eds.), *Aspects of tourism: Vol. 22. Tourism, recreation and climate change* (pp. 143–154). Clevedon: Channel View Publications.

Harrison, S. J., Winterbottom, S. J., & Sheppard, C. (1999). The potential effects of climate change on the Scottish tourist industry. *Tourism Management*, *20*(2), 203–211. doi:10.1016/S0261-5177(98)00072-7

Hendrikx, J., & Hreinsson, E. (2012). The potential impact of climate change on seasonal snow in New Zealand: Part II—industry vulnerability and future snowmaking potential. *Theoretical and Applied Climatology*, *110*(4), 619–630. doi:10.1007/s00704-012-0713-z

Hendrikx, J., Zammit, C., Hreinsson, EÖ, & Becken, S. (2013). A comparative assessment of the potential impact of climate change on the ski industry in New Zealand and Australia. *Climatic Change*, 1–14. doi:10.1007/s10584-013-0741-4

Hennessy, K., Whetton, P., Walsh, K., Smith I, N., Bathols, J., Hutchinson, M., & Sharples, J. (2008). Climate change effects on snow conditions in mainland Australia and adaptation at ski resorts through snowmaking. *Climate Research*, *35*(3), 255–270.

Heo, I., & Lee, S. (2008). The impact of climate changes on ski industries in South Korea – In the case of the Yongpyong ski resort. *Journal of the Korean Geographical Society*, *43*(5), 715–727.

Hoffmann, V. H., Sprengel, D. C., Ziegler, A., Kolb, M., & Abegg, B. (2009). Determinants of corporate adaptation to climate change in winter tourism: An econometric analysis. *Global Environmental Change*, *19*(2), 256–264. doi:10.1016/j.gloenvcha.2008.12.002

Hopkins, D. (2015). The perceived risks of local climate change in Queenstown, New Zealand. *Current Issues in Tourism*, *18*(10), 947–965. doi:10.1080/13683500.2013.776022

Hopkins, Debbie. (2014). The sustainability of climate change adaptation strategies in New Zealand's ski industry: a range of stakeholder perceptions. *Journal of Sustainable Tourism*, *22*(1), 107–126. doi:10.1080/09669582.2013.804830

Hopkins, D., Higham, J. S., & Becken, S. (2013). Climate change in a regional context: Relative vulnerability in the Australasian skier market. *Regional Environmental Change*, *13*(2), 449–458. doi:10.1007/s10113-012-0352-z

Hopkins, D., & Maclean, K. (2014). Climate change perceptions and responses in Scotland's ski industry. *Tourism Geographies*, *16*(3), 400–414. doi:10.1080/14616688.2013.823457

Hoy, A., Hänsel, S., & Matschullat, J. (2011). How can winter tourism adapt to climate change in Saxony's mountains? *Regional Environmental Change*, *11*(3), 459–469. doi:10.1007/s10113-010-0155-z

Hudson, S., & Hudson, L. (2015). *Winter sports tourism: Working in winter wonderlands*. Woodeaton: Goodfellow Publishers Limited.

Iso-Ahola, S. E. (1986). A theory of substitutability of leisure behavior. *Leisure Sciences*, *8*(4), 367–389. doi:10.1080/01490408609513081

König, U. (1998). *Wirtschaftsgeographie und Raumplanung: Vol. 28. Tourism in a warmer world: Implications of climate change due to enhanced greenhouse effect for the ski industry in the Australian Alps*. Zurich: University of Zurich.

König, U. (1999). Climate change and snow tourism in Australia. *Geographica Helvetica*, *54*(3), 147–157.

König, U., & Abegg, B. (1997). Impacts of climate change on tourism in the Swiss Alps. *Journal of Sustainable Tourism*, *5*(1), 46–58.

Lamothe & Periard Consultants. (1988). *Implications of climate change for downhill skiing in Québec (88–03)*. Downsview: Meteorological Service of Canada.

Li, Y., Zhao, M., Guo, P., Zheng, J., Li, Z., Li, F., … Dong, S. (2016). Comprehensive evaluation of ski resort development conditions in northern China. *Chinese Geographical Science*, *26*(3), 401–409. doi:10.1007/s11769-016-0808-z

Lipski, S., & McBoyle, G. (1991). The impact of global warming on downhill skiing in Michigan. *East Lakes Geographer*, *26*, 37–51.

Luthe, T. (2009). *Outdoor sports and environmental science: Vol. 25. Vulnerability to global change and sustainable adaptation of ski tourism*. Cologne: DSHS Koeln.

March, H., Saurí, D., & Llurdés, J. C. (2014). Perception of the effects of climate change in winter and summer tourist areas: The Pyrenees and the Catalan and Balearic coasts, Spain. *Regional Environmental Change*, *14*(3), 1189–1201. doi:10.1007/s10113-013-0561-0

McBoyle, G., & Wall, G. (1987). The impact of CO2 – induced warming on downhill skiing in the laurentians. *Cahiers de Géographie du Québec*, *31*(82), 39–50.

McBoyle, G., & Wall, G. (1992). Great lakes skiing and climate change. In A. Gill & R. Hartmann (Eds.), *Mountain resort development* (pp. 70–81). Burnaby: Indiana University.

McBoyle, G., Wall, G., Harrison, K., & Quinlan, C. (1986). Recreation and climate change: A Canadian case study. *Ontario Geography*, *23*, 51–68.

Moen, J., & Fredman, P. (2007). Effects of climate change on alpine skiing in Sweden. *Journal of Sustainable Tourism*, *15*(4), 418–437.

Morrison, C., & Pickering, C. M. (2013). Perceptions of climate change impacts, adaptation and limits to adaption in the Australian Alps: The ski-tourism industry and key stakeholders. *Journal of Sustainable Tourism*, *21*(2), 173–191. doi:10.1080/09669582.2012.681789

NASA. (2017). NASA, NOAA data show 2016 warmest year on record globally. Retrieved from https://www.nasa.gov/press-release/nasa-noaa-data-show-2016-warmest-year-on-record-globally

NSAA. (2017). U.S. ski resorts in operation. Retrieved from http://www.nsaa.org/media/275065/Number_of_Ski_Areas_by_Season_1516.pdf

Pickering, C. (2011). Changes in demand for tourism with climate change: A case study of visitation patterns to six ski resorts in Australia. *Journal of Sustainable Tourism*, *19*(6), 767–781. doi:10.1080/09669582.2010.544741

Pickering, C. M., & Buckley, R. C. (2010). Climate response by the ski industry: The shortcomings of snowmaking for Australian resorts. *AMBIO*, *39*, 430–438. doi:10.1007/s13280-010-0039-y

Pickering, C. M., Castley, J. G., & Burtt, M. (2010). Skiing less often in a warmer world: Attitudes of tourists to climate change in an Australian ski resort. *Geographical Research*, *48*(2), 137–147. doi:10.1111/j.1745-5871.2009.00614.x

Pons, M., Johnson, P. A., Rosas, M., & Jover, E. (2014). A georeferenced agent-based model to analyze the climate change impacts on ski tourism at a regional scale. *International Journal of Geographical Information Science*, *28*(12), 2474–2494. doi:10.1080/13658816.2014.933481

Pons, M., López-Moreno, J. I., Rosas-Casals, M., & Jover, È. (2015). The vulnerability of Pyrenean ski resorts to climate-induced changes in the snowpack. *Climatic Change*, *131*(4), 591–605. doi:10.1007/s10584-015-1400-8

Pons, M., Steiger, R., Scott, D., Johnson, P., Rutty, M., & Vilella, M. (in press). Using an agent based model to assess ski tourism resilience to climate variability. *Journal of Travel Research*.

Pons-Pons, M., Johnson, P. A., Rosas-Casals, M., Sureda, B., & Jover, E. (2012). Modeling climate change effects on winter ski tourism in Andorra. *Climate Research*, *54*(3), 197–207. doi:10.3354/cr01117

Rixen, C., Teich, M., Lardelli, C., Gallati, D., Pohl, M., Pütz, M., & Bebi, P. (2011). Winter tourism and climate change in the Alps: An assessment of resource consumption, snow reliability, and future snowmaking potential. *Mountain Research and Development*, *31*(3), 229–236. http://www.bioone.org/doi/full/10.1659/MRD-JOURNAL-D-10-00112.1

Roman, C. E., Lynch, A. H., & Dominey-Howes, D. (2010). Uncovering the essence of the climate change adaptation problem—a case study of the tourism sector at Alpine Shire, Victoria, Australia. *Tourism and Hospitality Planning & Development*, *7*(3), 237–252. doi:10.1080/1479053X.2010.503049

Rutty, M., Scott, D., Johnson, P., Jover, E., Pons, M., & Steiger, R. (2015a). Behavioural adaptation of skiers to climatic variability and change in Ontario, Canada. *Journal of Outdoor Recreation and Tourism*, *11*, 13–21. doi:10.1016/j.jort.2015.07.002

Rutty, M., Scott, D., Johnson, P., Jover, E., Pons, M., & Steiger, R. (2015b). The geography of skier adaptation to adverse conditions in the Ontario ski market. *The Canadian Geographer / Le Géographe canadien*, *59*(4), 391–403. doi:10.1111/cag.12220

Rutty, M., Scott, D., Johnson, P., Pons, M., Steiger, R., & Vilella, M. (2017). Using ski industry response to climatic variability to assess climate change risk: An analogue study in Eastern Canada. *Tourism Management*, *58*, 196–204. doi:10.1016/j.tourman.2016.10.020

Saarinen, J., & Tervo, K. (2006). Perceptions and adaptation strategies of the tourism industry to climate change: The case of Finnish nature-based tourism entrepreneurs. *International Journal of Innovation and Sustainable Development*, *1*(3), 214–228.

Saarinen, J., & Tervo, K. (2010). Sustainability and emerging awareness of a changing climate: The tourism industry's knowledge and perceptions of the future of nature-based winter tourism in Finland. In C. M. Hall & J. Saarinen (Eds.), *Tourism and change in polar regions: Climate environments and experiences* (pp. 147–164). London: Routledge.

Sauter, T., Weitzenkamp, B., & Schneider, C. (2009). Spatio-temporal prediction of snow cover in the Black Forest mountain range using remote sensing and a recurrent neural network. *International Journal of Climatology*. doi:10.1002/joc.2043

Schmidt, P., Steiger, R., & Matzarakis, A. (2012). Artificial snowmaking possibilities and climate change based on regional climate modeling in the Southern Black Forest. *Meteorologische Zeitschrift*, *21*(2), 167–172. doi:10.1127/0941-2948/2012/0281

Scott, D. (2006a). Global environmental change and mountain tourism. In S. Gössling & M. C. Hall (Eds.), *Tourism and global environmental change* (pp. 54–75). London: Routledge.

Scott, D. (2006b). US ski industry adaptation to climate change: Hard, soft and policy strategies. In S. Gössling & M. C. Hall (Eds.), *Tourism and global environmental change* (pp. 262–285). London: Routledge.

Scott, D., Dawson, J., & Jones, B. (2008). Climate change vulnerability of the US Northeast winter recreation– tourism sector. *Mitigation and Adaptation Strategies for Global Change*, *13*, 577–596. doi:10.1007/s11027-007-9136-z

Scott, D., Gössling, S., & Hall, C. M. (2012). International tourism and climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *3*(3), 213–232. doi:10.1002/wcc.165

Scott, D., Hall, C. M., & Gössling, S. (2012). *Tourism and climate change. Impacts, adaptation & mitigation* (1st ed.). London: Routledge.

Scott, D., Hall, C. M., & Gössling, S. (2016). A review of the IPCC fifth assessment and implications for tourism sector climate resilience and decarbonization. *Journal of Sustainable Tourism*, *24*(1), 8–30. doi:10.1080/09669582.2015.1062021

Scott, D., McBoyle, G., & Mills, B. (2003). Climate change and the skiing industry in southern Ontario (Canada): Exploring the importance of snowmaking as a technical adaptation. *Climate Research*, *23*, 171–181.

Scott, D., McBoyle, G., & Minogue, A. (2007). Climate change and Quebec's ski industry. *Global Environmental Change*, *17*, 181–190.

Scott, D., McBoyle, G., Minogue, A., & Mills, B. (2006). Climate change and the sustainability of ski-based tourism in Eastern North America: A reassessment. *Journal of Sustainable Tourism*, *14*(4), 376–398. doi:10.2167/jost550.0

Scott, D., & Steiger, R. (2013). Vulnerability of the Ski Industry. In R. A. Pielke (Ed.), *Climate vulnerability: Understanding and addressing threats to essential resources.* (pp. 305–313). Amsterdam: Elsevier.

Scott, D., Steiger, R., Rutty, M., & Johnson, P. (2014). The future of the Olympic winter games in an era of climate change. *Current Issues in Tourism*, 1–18. doi:10.1080/13683500.2014.887664

Scott, D., Steiger, R., Rutty, M., Pons, M., & Johnson, P. (2017). The differential futures of ski tourism in Ontario (Canada) under climate change: The limits of snowmaking adaptation. *Current Issues in Tourism*. doi:10.1080/13683500.2017.1401984

Shih, C., Nicholls, S., & Holecek, D. F. (2009). Impact of weather on downhill ski lift ticket sales. *Journal of Travel Research*, *47*(3), 359–372. doi:10.1177/0047287508321207

Soboll, A., & Dingeldey, A. (2012). The future impact of climate change on Alpine winter tourism: A high-resolution simulation system in the German and Austrian Alps. *Journal of Sustainable Tourism*, *20*(1), 101–120. doi:10.1080/09669582.2011.610895

Soboll, A., Klier, T., & Heumann, S. (2012). The prospective impact of climate change on tourism and regional economic development: A simulation study for Bavaria. *Tourism Economics*, *18*(1), 139–157. doi:10.5367/te.2012.0103

Soboll, A., & Schmude, J. (2011). Simulating tourism water consumption under climate change conditions using agent-based modeling: The example of ski areas. *Annals of the Association of American Geographers*, *101*(5), 1049–1066. doi:10.1080/00045608.2011.561126

Steiger, R. (2010). The impact of climate change on ski season length and snowmaking requirements in tyrol, austria. *Climate Research*, *43*(3), 251–262.

Steiger, R. (2011a). The impact of climate change on ski touristic demand using an analogue approach. In K. Weiermair, H. Pechlahner, A. Strobl, M. Elmi, & M. Schuckert (Eds.), *Coping with global climate change: Strategies, policies and measures for the tourism industry* (pp. 247–256). Innsbruck: Innsbruck University Press.

Steiger, R. (2011b). The impact of snow scarcity on ski tourism: An analysis of the record warm season 2006/2007 in Tyrol (Austria). *Tourism Review*, *66*(3), 4–13.
Steiger, R. (2012). Scenarios for skiing tourism in Austria: Integrating demographics with an analysis of climate change. *Journal of Sustainable Tourism*, *20*(6), 867–882. doi:10.1080/09669582.2012.680464
Steiger, R., & Abegg, B. (2013). The sensitivity of Austrian ski areas to climate change. *Tourism Planning & Development*, *10*(4), 480–493. doi:10.1080/21568316.2013.804431
Steiger, R., & Abegg, B. (2015). Klimawandel und Konkurrenzfähigkeit der Skigebiete in den Ostalpen. In R. Egger & K. Luger (Eds.), *Tourismus und mobile Freizeit – Lebensformen, Trends, Herausforderungen* (pp. 319–332). Norderstedt: Books on demand.
Steiger, R., & Abegg, B. (2017). Ski areas' competitiveness in the light of climate change: Comparative analysis in the Eastern Alps. In D. Müller & M. Więckowski (Eds.), *Tourism in transition, recovering from decline and managing change*. Cham: Springer.
Steiger, R., & Mayer, M. (2008). Snowmaking and climate change. Future options for snow production in Tyrolean ski resorts. *Mountain Research and Development*, *28*(3/4), 292–298. doi:10.1659/mrd.0978
Steiger, R., & Stötter, J. (2013). Climate change impact assessment of ski tourism in Tyrol. *Tourism Geographies*, *15*(4), 577–600. doi:10.1080/14616688.2012.762539
Tang, C.-H., & Jang, S. (2012). Hedging weather risk in nature-based tourism business: An example of ski resorts. *Journal of Hospitality & Tourism Research*, *36*(2), 143–163.
Task Force on Climate-Related Financial Disclosure. (2016). Recommendations of the task force on climate-related financial disclosures. Retrieved from https://www.fsb-tcfd.org/wp-content/uploads/2016/12/16_1221_TCFD_Report_Letter.pdf
Tervo-Kankare, K. (2011). The consideration of climate change at the tourism destination level in Finland: Coordinated collaboration or talk about weather? *Tourism Planning & Development*, *8*(4), 399–414. doi:10.1080/21568316.2011.598180
Töglhofer, C., Eigner, F., & Prettenthaler, F. (2011). Impacts of snow conditions on tourism demand in Austrian ski areas. *Climate Research*, *46*(1), 1–14.
Tranos, E., & Davoudi, S. (2014). The regional impact of climate change on winter tourism in Europe. *Tourism Planning & Development*, *11*(2), 163–178. doi:10.1080/21568316.2013.864992
Trawöger, L. (2014). Convinced, ambivalent or annoyed: Tyrolean ski tourism stakeholders and their perceptions of climate change. *Tourism Management*, *40*, 338–351.
Uhlmann, B., Goyette, S., & Beniston, M. (2008). Sensitivity analysis of snow patterns in Swiss ski resorts to shifts in temperature, precipitation and humidity under conditions of climate change. *International Journal of Climatology*, *29*(8), 1048–1055. doi:10.1002/joc.1786
Unbehaun, W., Pröbstl, U., & Haider, W. (2008). Trends in winter sport tourism: Challenges for the future. *Tourism Review*, *63*(1), 36–47. doi:10.1108/16605370810861035
United Nations. (2016). United Nations treaty collection chapter XXVII environment, 7.d Paris Agreement [Paris, 12 December 2015 (C.N.92.201)]. Retrieved from https://treaties.un.org/doc/Publication/CN/2016/CN.92.2016-Eng.pdf
Vanat, L. (2014). 2014 international report on snow & mountain tourism. Retrieved from http://www.vanat.ch/RM-world-report-2014.pdf
Vanat, L. (2017). 2017 International report on snow & mountain tourism. Retrieved from http://vanat.ch/RM-world-report-2017-vanat.pdf
Witmer, U. (1986). *Geographica Bernensia: G25. Erfassung, Bearbeitung und Kartierung von Schneedaten in der Schweiz*. Bern: Institute of Geography, University of Bern.
Wobus, C., Small, E., Hosterman, E., Mills, H., Stein, D., Rissing, J., … Martinich, J. (2017). Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change Part A*, *45*, 1–14. doi:10.1016/j.gloenvcha.2017.04.006
Wolfsegger, C., Gössling, S., & Scott, D. (2008). Climate change risk appraisal in the Austrian ski industry. *Tourism Review International*, *12*(1), 13–23.
Wyss, R., Abegg, B., & Luthe, T. (2014). Perceptions of climate change in a tourism governance context. *Tourism Management Perspectives*, *11*, 69–76. doi:10.1016/j.tmp.2014.04.004
Zimmerman, G., O'Brady, C., & Hurlbutt, B. (2006). *Regional challenges of future climate change: Endless summer or business as usual?: The 2006 Colorado college state of the Rockies report card*. Colorado Springs: Colorado College.

Appendix 1

Table A1. List of reviewed literature per country and category.

Country/ region	Sensitivity assessments	Impact and vulnerability assessments	Tourists' perception and behavioural response	Integrated vulnerability assessments	Ski industry perception
Alps		Abegg et al. (2007)			
Andorra		Pons et al. (2015)		Pons-Pons et al. (2012), Pons et al. (2014)	
Australia		Galloway (1988), Hendrikx et al. (2013), Hennessy et al. (2008), König (1998), König (1999), Pickering and Buckley (2010)	Cocolas et al. (2016), Hopkins et al. (2013), König (1998), Pickering et al. (2010)	Pickering (2011)	Bicknell and McManus (2006), Hopkins et al. (2013), König (1998), König (1999), Morrison and Pickering (2013)
Austria	Falk (2010), Falk (2013), Falk (2016), Töglhofer et al. (2011)	Abegg and Steiger (2017), Berghammer and Schmude (2014), Breiling and Charamza (1999), Steiger and Mayer (2008), Steiger (2010), Steiger (2012), Steiger and Abegg (2013), Steiger and Stötter (2013), Steiger and Abegg (2015), Steiger and Abegg (2017)	Unbehaun et al. (2008)	Damm et al. (2014), Soboll and Schmude (2011), Soboll and Dingeldey (2012), Steiger (2011b)	Luthe (2009), Trawöger (2014), Wolfsegger et al. (2008)
Bulgaria		Demiroglu (2016)			
Canada		Harrison et al. (1986), Lamothe and Periard Consultants (1988), McBoyle et al. (1986), McBoyle and Wall (1987), McBoyle and Wall (1992), Scott et al. (2003), Scott et al. (2007), Scott and Steiger (2013), Scott et al. (2017)	Rutty et al. (2015a), Rutty et al. (2015b)	Pons et al. (in press), Rutty et al. (2017), Scott (2006a)	
EU	Damm et al. (2016)	Tranos and Davoudi (2014)		Damm et al. (2016)	

(*Continued*)

Table A1. Continued.

Country/ region	Sensitivity assessments	Impact and vulnerability assessments	Tourists' perception and behavioural response	Integrated vulnerability assessments	Ski industry perception
Finland	Falk and Vieru (2016)				Haanpää et al. (2015), Saarinen and Tervo (2006), Saarinen and Tervo (2010), Tervo-Kankare (2011)
France	Falk (2015), Falk and Vanat (2016), François et al. (2014)	Pons et al. (2015)		Pons et al. (2014)	Luthe (2009)
Germany		Abegg and Steiger (2017), Berghammer and Schmude (2014), Endler and Matzarakis (2011), Luthe (2009), Sauter et al. (2009), Schmidt, Steiger, and Matzarakis (2012), Steiger and Abegg (2015), Steiger and Abegg (2017)		Soboll & Schmude, 2011; Soboll & Dingeldey, 2012; Soboll et al., 2012	Hoy et al. (2011)
Italy		Abegg and Steiger (2017), Steiger and Stötter (2013), Steiger and Abegg (2015), Steiger and Abegg (2017)		Balbi et al. (2013), Steiger (2011a)	Luthe (2009)
Japan				Fukushima et al. (2002)	
New Zealand		Hendrikx and Hreinsson (2012), Hendrikx et al. (2013)	Hopkins et al. (2013)		Hopkins et al. (2013), Hopkins (2014, 2015)
Norway			Demiroglu et al. (in press)		
Romania					Dincă, Surugiu, Surugiu, and Frenţ (2014)
Slovakia				Demiroglu et al. (2016)	
Spain		Pons et al. (2015)		Pons et al. (2014)	

(*Continued*)

Table A1. Continued.

Country/ region	Sensitivity assessments	Impact and vulnerability assessments	Tourists' perception and behavioural response	Integrated vulnerability assessments	Ski industry perception
Sweden	Falk and Hagsten (2016)	Moen and Fredman (2007)			Brouder and Lundmark (2011)
Switzerland	Abegg and Frösch (1994), König and Abegg (1997), Gonseth (2013)	Abegg (1996), Abegg et al. (1994), Abegg et al. (2015), Berghammer and Schmude (2014), Bürki (2000), Elsasser and Messerli (2001), Elsasser and Bürki (2002), König and Abegg (1997), Rixen et al. (2011), Steiger and Abegg (2015), Steiger and Abegg (2017), Uhlmann et al. (2008)	Behringer et al. (2000), Bürki (2000)	Soboll and Schmude (2011)	Abegg (1996), Abegg et al. (2008), Behringer et al. (2000), Bürki (2000), Hoffmann et al. (2009), Luthe (2009), Wyss et al. (2014)
Turkey		Demiroglu et al. (2016)			
UK		Harrison et al. (1999), Harrison et al. (2005)			Hopkins and Maclean (2014)
US	Hamilton et al. (2003), Hamilton et al. (2007), Shih et al. (2009), Tang and Jang (2012), Beaudin and Huang (2014)	Bark et al. (2010), Dawson and Scott (2007), Dawson and Scott (2013), Lipski and McBoyle (1991), McBoyle and Wall (1992), Scott et al. (2006), Scott et al. (2008), Scott and Steiger (2013), Wobus et al. (2017), Zimmerman et al. (2006)	Dawson et al. (2011), Dawson et al. (2013)	Dawson et al. (2009), Dawson and Scott (2010), Scott (2006b)	
South Korea		Heo and Lee (2008)			
Global		Scott et al. (2014)			