Cover the ice or ski on grass? The dilemmas facing tourism in a deglaciating world

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Abstract

Climate change is having a world-wide impact, particularly on the cryosphere, which is experiencing rapid melting with a range of consequences for the environment and society. In many places, reduced snow and ice have implications for the experiences of visitors. This article reviews the impacts of deglaciation on glacier and ski tourism and in doing so, it brings together human and physical geography. We begin by summarising the relationships between glaciers and climate change, highlighting impacts of glacier retreat, before considering tourism in glaciated areas. We explore ways in which some locations are adapting to changing environmental conditions and examine tactics that have been used to manage the effects of deglaciation on tourism, specifically in the European Alps. Glacier conservation, snow harvesting, the production of artificial snow and modifying the range of tourist experiences all illustrate the dilemmas involved in adapting to climate change in practice.

1. Glaciers and climate change

Glaciers can be regarded as barometers of climate change, generally advancing and thickening in times of cooling and retreating and thinning when it is warmer. Over geological time, Earth has experienced cold periods when ice sheets and glaciers have been much more extensive than today and warmer periods when there has been less ice. These cold and warm periods have varied in their temporal and spatial extent, with millions of years when glaciers and ice sheets have existed – but equally, millions of years when they have not. The last 2.6 million years, a division of time known as the Quaternary Period, has been characterised by repeated advance and retreat of glaciers and ice sheets on timescales of thousands of years. The peak of the last glaciation was approximately 22,000 years ago but warming and cooling have resulted in smaller episodes of ice retreat and advance since then (for example, the 'Medieval Warm Period' and the 'Little Ice Age'). Glaciers and ice sheets currently cover approximately 10% of Earth's land surface (IPCC, 2019) and most have been retreating and thinning over the last few decades, in response to an increasingly warming climate.

Global-scale retreat of glaciers is receiving attention from scientists and the media. The pace of change is evidenced by measurements reporting striking rates of glacier retreat. For example, the Columbia ice field in Canada lost 18-28% of its area between 1919 and 2009 (Groulx et al., 2019) and Austrian glaciers lost 15% of their area from 1969-1998 (Olefs and Fischer, 2008). Glaciers in Iceland have experienced an accelerated rate of retreat over the last two decades; since 2000, the area of Iceland's glaciers has reduced by more than 600 km^2 (Phillips et al., 2014; Veðurstofa Íslands, 2018). The volume of glaciers in the Southern Alps of New Zealand has shrunk by 34% since 1977 (Salinger et al., 2014) and the complete loss of glacier Okjökull in Iceland in 2014 (Magnusson, 2019) and of Pizol Glacier in Switzerland in 2019 (Baynes, 2019) have provided us with stark examples of what lies ahead.

High mountain environments are particularly vulnerable to the rapid melting of ice and snow (IPCC, 2019) for example, by 2100 the volume of glacier ice in western Canada is predicted to shrink by 70 ± 10% relative to 2005 (Clarke et al., 2015). The IPCC (2019) suggests that areas with smaller glaciers such as the European Alps, Scandinavia, the Pyrenees and the Caucasus Mountains could lose up to 80% of their current mass by 2100. Models predict the disappearance of between a third and half of the world's mountain glacier mass over the next 100 years (IPCC, 2019).

So what do glaciers do for us and what might be the consequences of their disappearance? The retreat of glaciers and ice sheets is already affecting water security, power generation and the occurrence of natural hazards in deglaciating environments, thereby presenting challenges for society. Continued ice retreat will result in a short-term increase, followed by a long-term decrease, in glacial meltwater production affecting communities that depend on meltwater from glaciers. In the short term, we might expect floods and mudflows with increasing meltwater in glacial systems to fuel these processes, as well as the development of glacial lakes. In the longer term, there will be a reduction in the availability of potable water, water for power generation, irrigation for agriculture and ecosystem support (Vuille et al., 2018). The short-term increase in water will undoubtedly aid the filling of reservoirs, but it will also lead to their increased siltation (Fountain, 2018).

In addition to the above, snow, ice and glaciers also sustain tourism, which is crucial to the economies of some communities. But what happens to snow and ice tourism when glaciers retreat and the snow melts? How will locations adapt? Will people still visit? What are the issues for managing these environments? This article examines some of the impacts of deglaciation on the tourist industry. It introduces the idea of glacier conservation and spotlights some of the strategies that have been used to manage the effects of deglaciation on tourism, particularly focusing on the European Alps.

2. Glacier and ski tourism

Tourism is a huge industry and takes a variety of forms. 'Glacier tourism' has multiple definitions and is often described as a form of nature and/or adventure-based tourism, whereby tourists are motivated to visit glaciated environments to experience particular elements of the landscape, for example, through photography or to explore and challenge themselves within the environment by skiing, hiking and climbing (Welling et al., 2015). For the purpose of this article we define glacier tourism as tourism activities in glaciated areas (Welling et al., 2015); these activities could involve snowsports, hiking and photography. Additionally, glacier tourism can have an educational function, in which people visit glaciated environments to learn about glacier processes through fieldtrips, visits to ice caves and glacier museums. Ski tourism and associated snowsports can occur in areas where there is snow cover but no glacier. Figure 1 provides a summary of the definitions of key terms used in this article and **Figure 2** illustrates some activities involved in tourism in areas where there are glaciers and/or snow.

Term	Definition	Example activities
Glacier tourism	A complex form of adventure and/or nature-based tourism Tourism activities in glaciated areas (Welling et al., 2015, p. 643)	Visiting glaciated environments Hiking Snowsports on and near to glaciers
Ski tourism	Tourism involving skiing	Skiing Snowboarding
Last-chance tourism	Where tourists explicitly seek endangered sites or vanishing landscapes before they disappear (Lemelin et al., 2010, p. 478) Sometimes also referred to as 'last-minute tourism' (Welling et al., 2015)	Visiting glaciers before they disappear
Snowsports	Sports involving snow	Skiing Snowboarding Ice climbing Glacier hiking Skating
Pistes	Ski runs	Skiing Snowboarding
Glacier conservation	The process of delaying glacier retreat (Fischer et al., 2011)	Artificial snow production Snow harvesting Deploying glacier blankets General management of glaciated ski resorts

Figure 1: Definitions of key terms used in this article

Glacier tourism can be traced back as far as the 16th century, when pilgrims would visit glaciers as 'sites of worship, curiosity and fear' (Welling, 2014, p. 11). There is documentary evidence of scientists visiting glaciers at the end of the 17th century, which led to the development of modern glacier science in the decades that followed (Welling, 2014). Glacier tourism became popular in Iceland, Europe and New Zealand during the 19th century attracting scientists, artists and adventure tourists (Fischer et al., 2011), but it was at the start of 20th century when mountaineering became really well-established and the first ski resorts were constructed (Welling, 2014). Glacier and ski tourism became immensely popular after the Second World War and was enhanced by glaciers re-advancing during the 1970s and 1980s due to slight global cooling (Fischer et al., 2011). However, since then, most glaciers have been retreating and this has had a profound impact on glacier and ski tourism globally.

Figure 2: Some of the activities involved in tourism occurring in glaciated and snow-covered environments. Photos: Rachael Carver, Fiona Tweed and Mai Duay.

3. Impacts of deglaciation on glacier and ski tourism

As deglaciation occurs, safety and access issues become a challenge and snowfall becomes increasingly unreliable. Glaciated environments become less stable during deglaciation, leading to increased risk of rockfalls, icefalls and landslides with the potential to cause death, injury and damage to infrastructure (Tufnell, 1984; Fischer et al., 2011; Pütz et al., 2011; Purdie et al., 2015). Additionally, retreating glaciers can form large proglacial lakes which can be a source of glacier outburst floods, threating people and infrastructure (Purdie, 2013; Tweed and Carrivick, 2015). Where glaciers terminate in proglacial lakes, ice blocks can become detached or 'calve' from the ice front; ice calving has become a tourist attraction in Iceland, South America and New Zealand, but also presents challenges for safety (Purdie, 2013). Extreme weather conditions such as intense storms and high winds are becoming increasingly common in glaciated environments, further inhibiting tourism activities (Purdie et al., 2015) These hazards constrain safe access to glaciated environments, limiting tourism opportunities. For example, it is estimated that issues like these led to a 38% decrease in tourists at Jostedalsbreen National Park in Norway, between 2003 and 2009 (Welling et al., 2020). Consequently, tour operators are having to adapt their activities in order to overcome challenges associated with safety and access in deglaciating environments.

Glacier and ski tourist locations rely on snowfall; snow nourishes glaciers, eventually transforming to glacier ice chiefly by compression and alternate melting and refreezing. Glacier ice can form in as little as 5 years in low and mid-latitudes where melting accelerates the process, but it can take up to 100 years for ice to form in cold polar regions or high altitudes, where melting is scarce (Benn and Evans, 2010). Critically, snow provides the material on which many activities take place and accounts for elements of the scenic backdrop that visitors enjoy. Many locations are now experiencing later arrival of the snow season and drastic reductions in the amount of snow when that season does arrive (Parkin, 2019). This has been keenly felt in the European Alps where famous ski resorts such as Val d'Isère and Luchon Superbagneres have experienced much shorter snow seasons (Parkin, 2019; Ramming 2020).

Glacier and ski tourism form an essential part of the economy for some countries; for example, glacier and ski tourism contributes to 16.7% and 25% of employment in Iceland and the Catac region of Peru, respectively (Welling et al., 2015; Lerche, 2017). The Alpine ski industry in Europe has 35% of the world's ski resorts and sees 120 million tourists annually (Parkin, 2019; Ramming 2020). However, ski resorts are susceptible to intra and interannual climatic variability, a factor made worse by climate change and an increasing number of snow deficient winters has led to ski resorts having reduced operating periods and some closures, impacting on local, regional, and national economies (Olefs and Fischer, 2008; Fischer et al., 2011). For example, revenue from ski resorts in Japan and Austria have declined since the 1990s and 67% of Swiss ski resorts have cancelled summer skiing permanently (Mayer et al., 2018). Moreover, it has been predicted that Austria, France, Germany, Italy and Switzerland will lose between 22 and 64% of winter tourists between 2030 and 2050 (Damm et al., 2014); this amounts to a loss of US $1.9 to 2.45 billion in Switzerland (Pütz et al., 2011). Additionally, it has been projected that Switzerland's snowline could rise in altitude by 300m, resulting in

85% of Swiss ski resorts becoming snow unreliable (Koenig and Abegg, 2010). Consequently, snowsports may only be possible at ski resorts located on glaciers located at 3,000m above sea level (a.s.l.) and higher in Europe (Koenig and Abegg, 2010; Mayer et al., 2018).

Whilst deglaciation is generally having a negative effect on glacier tourism, some glaciated environments are beginning to experience a phenomenon branded 'last chance tourism' (sometimes also referred to as 'last-minute tourism)' in which tourists are motivated to visit such environments before they disappear altogether or change in character (Lemelin et al., 2010). Consequently, this has led to temporary increase in glacier tourism in some areas (Welling et al., 2015; 2020; Groux et al., 2019), but it remains unclear whether tourists will return to these sites post-environmental change. The future of glacier and ski tourism is therefore under threat.

4. Adapting to the impacts of deglaciation

Ski resorts and glaciated areas are facing some stark choices - adapt to changing conditions or lose their tourist-based economy. Some locations have already adopted some innovative strategies for maintaining their current activities or diversifying their range of visitor opportunities. The retreat of ice creates difficulties in maintaining safe access to locations of interest; access and viewing points are destined to become increasingly precarious as glaciers retreat into steeper and more unstable terrain. Popular pistes and hiking routes will require repeated monitoring and physical adjustment to account for rockfalls, icefalls, landslides and changes in watercourses, (Purdie et al., 2015), which are more likely to occur as slopes become unstable due to glacial de-buttressing and the exposure of previously frozen ground. Adaptation activities are intensive and there are environmental issues involved in continually altering routes. At some sites, it has already become risky for visitors to hike onto glaciers and alternative experiences have been developed. For example, following a major ice collapse of the Fox Glacier in the Southern Alps of New Zealand in 2012, hiking onto the glacier was deemed unsafe. To overcome this, tour operators dramatically increased the number of helicopter tours and have developed 'heli-hikes', in which helicopters deliver hikers to 'safe' parts of the glacier to walk, to enable tourists to experience the glacier (Purdie, 2013; Stewart et al., 2016). With similar challenges in Iceland, where many glaciers are becoming inaccessible due to the growth of proglacial lakes as ice melts, it is likely that aerial tours will be more widely offered as an alternative means of glacier access in the future (Lerche, 2017).

Whilst helicopter tours are an effective strategy to overcome challenges with safety and access, they carry high financial and environmental sustainability costs (Stewart et al., 2016) and they are not affordable - or desirable - for all visitors as people visit glaciers for different reasons e.g. skiing and education.

The growth of proglacial lakes as glaciers retreat has been harnessed by some as a tourist opportunity. Annual visitor numbers to Mount Cook National Park in New Zealand increased by 40% from 2015/16 to 2016/17 when visitors exceeded 800,000 and visitor numbers are predicted to reach 1.5 million by the late 2020s. The rapidly expanding proglacial lake at the Tasman Glacier in Mount Cook National Park, has attracted a great deal of interest from visitors and calving ice from the glacier edge reinforces the spectacle and excitement of the site (**Figure 3**). Boat tours have increased, with tour providers upgrading to faster and larger boats to enable tourists to get close to the calving ice front and the shorter period of winter freezing of the lake is enabling a lengthier tourist season at the site (Purdie, 2013; Purdie et al., 2020).

Figure 3: The rapidly expanding proglacial lake at Tasman Glacier, New Zealand. The debris-covered edge and surface of the ice can be seen at the foot of the mountains in the left of the image, huge moraines provide lake banks at the sides. Photo: Fiona Tweed.

Snow reliability is a major challenge for glacier and ski tourism. Ski resorts in particular have developed multiple means by which snow cover can be increased through artificial snow production, glacier conservation and snow harvesting (Olefs and Fischer, 2008; Olefs and Lehning, 2010; Fischer et al., 2011) (**Figure 4**). Artificial snow is generated by harvesting and storing meltwater and precipitation in artificial reservoirs; during winter the water is passed through snow cannons covering pistes in additional snow, thereby enabling ski resorts to operate for longer (Koenig and Abegg, 2010; Alpine Infusion, 2014; SnowTrex, 2020). Artificial snow was developed during the mid-20th century but was not widely used until the 1990s, when it became necessary due to climate change (Fischer et al., 2011).

Artificial snow is often viewed as essential to ski tourism by locals and tourists. For example, climate change led to an increase in use of artificial snow by 10-33% in Switzerland between 2000 and 2010, with 60% of Austrian and 100% of Italian pistes using it (Fischer et al., 2011; Pütz et al., 2011; Damm et al., 2014). Whilst artificial snow production is reliable, it too is facing challenges associated with climate change. Artificial snow currently cannot be produced at temperatures in excess of 1-2°C (Alpine Infusion, 2014; SnowTrex, 2020), and becomes less efficient to produce at warmer temperatures leading to an estimated 61% increase in energy costs (Damm et al., 2014); consequently artificial snow production is contributing to the very problem that it is trying to solve (Parkin, 2019). Artificial snow production is a medium-term adaption to climate change with questionable sustainability and ski resorts will need to find alternative long-term methods of adapting to climate change.

Figure 4: Management of an Alpine glacier and ski tourism site. Top left: snowcats used for placing blankets and moving snow. Top right: avalanche protection for safety and snow harvesting. Bottom left: artificial reservoir used for artificial snow production. Bottom right: snowcats placing blankets on the glacier. Photos: Rachael Carver.

If snow and ice are melting, are there other ways in which this can be reduced? Several ski resorts in the European Alps have covered glaciers in protective white blankets reducing ablation by 60%, protecting pistes and other skiing infrastructure from deglaciation. The blankets change the glacier's albedo, causing more solar radiation to be reflected thereby slowing surface melting as well as protecting snow and ice from wind erosion (Olefs and Fischer, 2008; Olefs and Lehning, 2010; Fischer et al., 2011). Teams use snowcats to roll artificial fleece blankets across the glacier surface (**Figure 4**); the blankets are then soldered together by melting the edges and are weighed down with sandbags. Blankets are placed at the start of summer and removed at the start of autumn (Stubaier Gletscher, 2011; 2020). The reduction in ice melting enables glacier-based ski resorts to operate for longer during winter and reduces the number of times ski lifts need to be re-pinned onto the ice, due to reduced ice movement (Stubaier Gletscher, 2011; 2020). Whilst this strategy is effective in maintaining glacier and ski tourism for as long as possible, it has high operating costs - some resorts invest thousands of euros per year - and it is only appropriate for resorts with year-round cover, that is at over 3,000m a.s.l. in the European Alps (Koenig and Abegg, 2010).

There has also been some success in harvesting snow and deploying it when it is needed. The snow is harvested through controlled avalanches, improving both safety and snow cover. This technique is used in conjunction with artificial snow production and glacier conservation, as excess snow is produced and harvested at the end of the ski season, and is then covered in protective blankets or wood chippings ready to be used at the start of the following season on areas of bare ice (Fischer et al., 2011; Parkin, 2019). However, like artificial snow and glacier conservation, snow harvesting is, at best, a short to medium-term adaptation to the impacts of climate change. There are strengths, weaknesses, opportunities, and threats facing glacier and ski tourism over the coming decades, as summarised in **Figure 5,** and it is crucial that resorts continue to adapt to deglaciation in the short, medium, and long-term.

SWOT analysis to assess the future of glacier tourism based on previous research:

Strengths:	Weaknesses:
• Reduced risks associated with snow and ice • Last-chance tourism temporarily increases visitors, boosting the local economy • Greater awareness of the impacts of climate change • Glacier conservation and artificial snow delay the loss of ski resorts, giving business time to adapt • Glacier ski resorts are more likely to sustain ski tourism through glacier conservation for longer	• Glaciers and ski resorts are vulnerable to climate change • As snow reliability and winter tourism decrease, local, regional and national economies will be adversely affected unless sites develop alternative tourist attractions in the future • Increased risk of hazards e.g. rockfalls, outburst floods • Methods of adapting to deglaciation including artificial snow and glacier conservation increase greenhouse gas emissions • Last-chance tourism increases greenhouse gas emissions, accelerating deglaciation
Opportunities:	**Threats:**
• Longer summer tourism season • Diversification of tourism activities including mountain biking, paragliding, grass skiing, roller skiing and festivals • Development of new tourist attractions including ice grottos, viewpoints and mountain bike parks • Creation of new hiking routes • Creation of protected areas	• Increasing temperatures could reduce/prevent artificial snow production for ski resorts • Increased operating and management costs associated with maintenance, artificial snow and glacier conservation • Insufficient water supply for artificial snow • Loss of summer snowsports • Reduction in winter tourism • Closure of ski resorts

Figure 5: A SWOT analysis of the activities involved in glacier tourism against the backdrop of deglaciation (adapted from Carver, 2020).

5. 'Undercover glaciers' - spotlight on the Stubai Glacier, Austria

Motivated by a desire to understand some of the dilemmas faced by glacier and ski tourism, field research was undertaken at the Stubai Glacier, Austria (**Figure 6**) by the lead author of this article, Rachael Carver, in the summer of 2019. This research is reported in Carver (2020). Glaciers in the Austrian Alps have retreated since the Little Ice Age (LIA), except for short periods of advance in the 1920s and 1980s and they have lost 50% of their ice as a consequence (Fischer et al., 2011). Glacier tourism in the Austrian Alps became popular at the start of the 19th century and led to the construction of ski lifts to meet growing demand (Fischer et al., 2011). However, the 1970s saw increased economic sensitivity to climate change as decreasing snow reliability led to a reduction in overnight stays during winter; by the 1990s, the impacts of poor snow reliability were being mitigated by the wide-scale production of snow (Fischer et al., 2011).

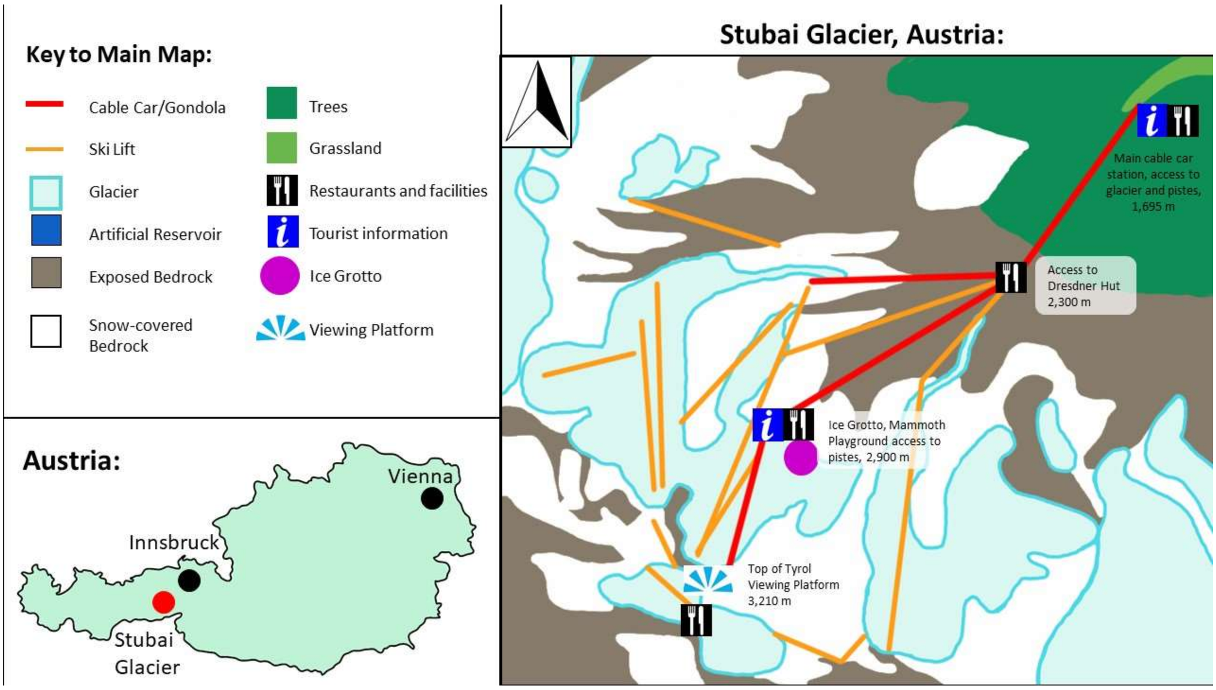

Figure 6: The Stubai Glacier, Austria, illustrating key tourist infrastructure.

Franz Senn also known as the 'Glacier Priest' introduced glacier tourism to the Stubai valley in the 19th century by taking mountaineers on guided tours of the glacier; following treks he would also take tourists to the local farmers' markets to boost the local economy. This formed the foundation for the Austrian Alpine Club that plays a fundamental role in glacier and mountain tourism in Austria today, providing a series of hikes at the Stubai Glacier (Reynolds, 2016; Reynolds, 2018). In 1969, Wintersport Tirol was set up and work began to develop the site for large-scale winter tourism. Since opening, a series of lifts and gondolas have been constructed to increase capacity and the site has become Austria's largest ski resort, covering 5 glaciers, reaching an altitude of 3,210m a.s.l. (Stubaier Gletscher, 2020). The site forms an essential part of the local economy, supporting over 80 direct jobs and indirectly supports jobs in the hospitality sector (Stubaier Gletscher, 2020); however, like several European ski resorts, the site and local economy are being affected by climate change. Consequently, the area has developed a variety of strategies to adapt.

The site uses glacier conservation to prolong winter tourism. This was first tested at the site in 2004 and 2005 and incorporated three approaches; firstly, snow compaction to reduce wind erosion; secondly, addition of water to increase glacier mass balance; and finally, protective blankets to reduce ice melting and wind erosion. Of the three approaches, it was found that covering the glacier in protective blankets was the most effective method of preserving the glacier. Consequently, glacier blankets (**Figure 7)** have been used to protect infrastructure e.g. ski lifts and pistes at Stubai since 2005 (Olefs and Fischer, 2008). The blankets are installed in June and removed in September; the process takes 8 employees three weeks and costs in excess of 90,000 Euros per year. However, the cost of the blankets is offset by the site being able to start the ski season 2-3 weeks earlier, revenue from lift passes, reduced maintenance of ski lifts and increased snow security ([reference removed for anonymity]). The site started to control avalanches in 1974, for safety, but over the last 10-20 years avalanche control has been carried out for both safety and snow harvesting for pistes (Olefs and Fischer, 2008; Stubaier Gletscher, 2020). Furthermore, the site has been using artificial snow since 1988, but has expanded its use in the twenty-first century through the construction of reservoirs and installation of additional snow cannons, maintaining ski tourism (Stubaier Gletscher, 2020). The site aims to further increase capacity for artificial snow through the construction of another reservoir and the exploration of innovative snow-making technologies in the future (Carver, 2020).

Figure 7: Glacier conservation using protective fleece blankets, Stubai Glacier, Austria. Top left: glacier blankets protecting a piste. Top right: meeting point for ‘information hour’ educating tourists about glacier conservation. Bottom left: tourists hiking across the blankets. Bottom right: ski lift protected by blankets. Photos: Rachael Carver.

Additionally, the site has developed a variety of educational resources including a tourist information office, leaflets, information boards, and a daily information hour for tourists curious about glaciers, climate change and glacier conservation, funded by the site's profits from lift pass sales. The site also opened an ice grotto in 2014 (a 150m-long tunnel which was later expanded to 200m), which became the number one summer tourist attraction in 2015, enabling tourists to explore natural features and processes within the ice (Stubaier Gletscher, 2020). To encourage families and tourists to visit the site during summer, the 'Top of Tyrol' viewing platform (3,210m), Eisgrat Playground (2,900m), Schafeljoch chapel (3,150m), and Mammoth Playground (2,900m), were opened in 2011, 2011, 2012 and 2019 respectively (Stubaier Gletscher, 2020). These developments demonstrate that the site is preparing for the transition from winter to summer tourism as snow security decreases, which may involve catering for different demographics. This transition is important considering that in 2019, continued retreat of the site resulted in one of the pistes losing the necessary slope angle for snowsports. Debris had to be deposited on top of the glacier to try to resolve the issue; this further highlights the need to develop new tourist attractions as glacier conservation and the use of artificial snow will not maintain glacier tourism indefinitely (Carver, 2020).

So, what do tourists think? And what might be the future of glacier tourism at the Stubai Glacier? In 2019, tourists who had visited the site before had noticed changes in the glacier's length (64% of visitors), thickness (50%), and cleanliness (36%), demonstrating that some tourists are aware of environmental changes occurring in deglaciating environments. Despite these environmental changes, 70% of tourists said that they would return to the site if the glaciers were not there, citing mountains, scenery and hiking opportunities as reasons. Visitors also said that they would visit to 'to witness environmental changes that have occurred' indicating there is a future for tourism in deglaciating environments, although tourists will be motivated to visit for different reasons. Whilst glacier conservation is scientifically effective, there has been little research on how it is viewed by visitors. In 2019, 90% of tourists visiting the Stubai Glacier were positive about glacier conservation, with 56% of tourists not objecting to seeing blankets on the glacier. The site has already experienced significant changes in management to overcome challenges associated with deglaciation (see **Figure 8**) and will undoubtedly witness more changes as the site transitions to a post-glaciated environment. Employees at the site envisage the site becoming a 'normal hiking area' once the glacier has retreated and they recognise the opportunity to develop new hiking routes, previously concealed beneath the glacier ([reference removed for anonymity]). Furthermore, the loss of the glacier would enable the site to develop alternative tourism activities like mountain biking and paragliding through the retrofitting of the site's infrastructure (Koenig and Abegg, 2010; Fischer et al., 2011; Rech et al., 2019); however, the site may face competition from other sites located within the Stubai Valley.

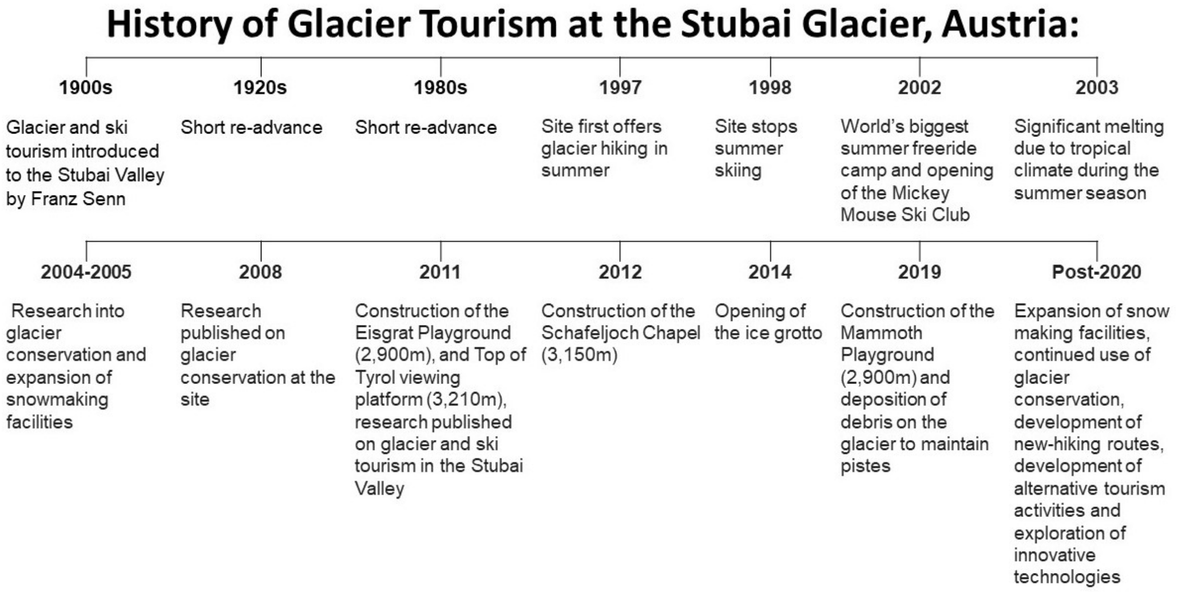

Figure 8: A summary of the history of glacier tourism, conservation and management at the Stubai Glacier, Austria.

Alternatively, the site could adopt a more radical and innovative strategy. Some ski resorts in Croatia have only one month of reliable snow each year; to overcome this challenge, they have introduced grass skiing. Grass skiers ride shorter skis with specifically designed rotating treads designed to translate skiing techniques, like calving, onto grass (Wrigglesworth, 2019). This enables ski resorts to operate year-round, prolonging the ski season without the use of artificial snow. The Stubai Glacier's lower altitude slopes could be adapted for grass skiing, providing a unique opportunity for skiers. Furthermore, the site could build on their existing educational resources, by developing an educational trail, demonstrating changes in the environment over time. This would help the site to market itself as an educational hub, attracting locals and tourists to the site through post-environmental change tourism, whereby tourists visit an environment to witness and understand environmental changes that have occurred over time (Carver, 2020).

6. The future of glacier and ski tourism

Alterations to the visual appearance of our landscape are one of the most striking results of climate change. Glacier and ski tourism is facing increasing pressure from changes which have led to reduced safety, access, issues of snow reliability and the closure of some ski resorts at lower altitudes (Rech et al., 2019). Challenges associated with changing environmental conditions have led to some resorts developing resilience through the use of helicopter trips and glacier lake tours (Purdie, 2013; Holder, 2017), artificial snow production (National Snow and Ice Data Centre, 2020), glacier conservation (Olefs and Fischer, 2011; Fischer et al., 2011; Parkin, 2019), and the development of alternative tourist attractions including grass ski resorts (Wrigglesworth, 2019). Some of the key elements of making the transition from an environment characterised by reliable snow and ice cover to a fully deglaciated environment are illustrated in **Figure 9**. Failure to overcome key challenges associated with the impacts of deglaciation will result in the loss of jobs and a decline in the local, regional and national economy for sites like the Stubai Glacier.

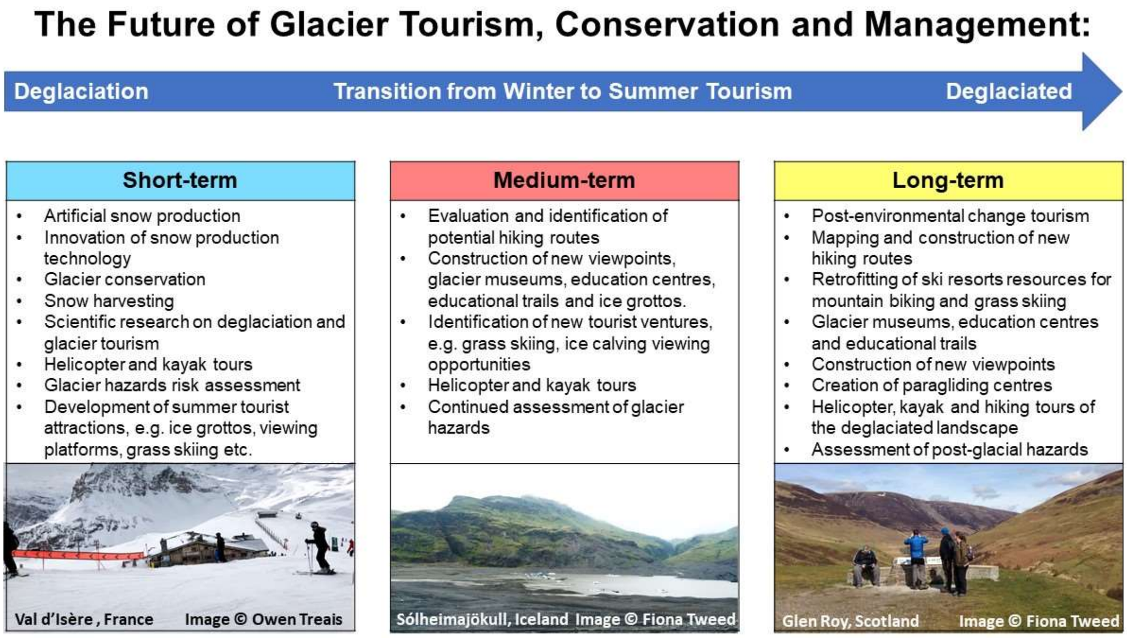

Figure 9: The future of glacier conservation, tourism and management. Photos: Owen Treais and Fiona Tweed.

The issues and examples referred to in this article highlight the difficult decisions and dilemmas involved in adapting to climate change in practice. There are real tensions involved, along with complex interdependencies. It is estimated that 95% of Italian, 70% of Austrian, 65% of French and approximately half of Swiss ski resorts are already reliant on snow machines (Parkin, 2019). However, the use of most snow and ice generation and conservation measures is caught up in loop of unsustainability, consuming energy which contributes to climate change. Forms of tourism that encourage flying are contributing to global warming, but transport habits and economic interdependencies are hard to break, even with current mounting awareness of the climate change crisis. If resorts are to survive in the long-term, they need to consider alternative visitor attractions like new hiking routes, grass ski resorts, viewing platforms and educational trails thereby providing people with opportunities to explore mountain environments in new ways.

Acknowledgements

Thank you to the staff at the Stubai Glacier, for their help and granting permission to conduct research on-site. A special thank you to Charlotte Carver, for field assistance, and to Tim and Lydia Carver for their support in planning and preparation for field work. We are grateful to Simaranjit Kaur Sangha and Gordon Walker for their comments on this article. We would also like to thank Owen Treais and Mai Duay for allowing us to use their photos. The constructive comments of an anonymous reviewer significantly improved this article.

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