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Climate Change and Utah Ski Resorts: Impacts, Perceptions, and Adaptation Strategies

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Climate change is a threat to ski resorts, the ski industry, and mountain communities that rely on ski tourism. Ski resorts may be able to mitigate some of the social and economic impacts caused by climate change with proactive adaptation strategies. Using historical weather data, future climate projections, and interviews with ski resort managers in Utah (United States), this research investigates the effects of climate change on ski resorts across the state. We examine temperature change at all resorts within the state from 1980–2018 and climate projections from 2021–2100 under different climate change scenarios (RCPs 2.6, 4.5, and 8.5). We also report on semistructured interviews with resort managers to provide insights into how resort leadership perceives the impacts of climate change, is implementing adaptation strategies, and is addressing barriers to adaptation. Many resorts in Utah are warming faster than global averages, and minimum temperatures are rising faster than maximum temperatures. By the end of the century, winter (December–March) minimum daily temperatures in Utah could warm an additional 6.0°C under the RCP 8.5 scenario near northern Utah resorts and 6.6°C near southern Utah resorts. Resort managers are concerned about shorter season lengths, shifting ski seasons, less snow cover, and poorer snow quality. Many resorts are already adapting, with the most common adaptations being snowmaking and diversifying outdoor recreation offerings (particularly during the summer and shoulder seasons). Barriers to adaptation reported by managers include financial costs, adequate water availability for snowmaking, and uncertainty about climate change projections. Climate change is already impacting Utah ski resorts, but adaptation practices can reduce the negative impacts to some degree at most resorts.

Keywords: *Utah; snowmaking; outdoor recreation; nature-based tourism; ski tourism; climate; temperature.*

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Introduction

Many mountain communities have snow-based recreational and tourism opportunities, anchored by ski resorts, that are extremely vulnerable to climate change (Gilaberte-Búrdalo et al 2014; Steiger et al 2019). Mountain communities are often at higher elevations, which are warming even faster than other environments (Pepin et al 2015; Minder et al 2018). Changes in the climate have impacted recreational aspects of mountain environments as well as the people who live there (Hock et al 2019). As the climate continues to warm and the amount of precipitation occurring as snow declines, the length of the skiing and snowboarding season is expected to get shorter and more variable (Dawson and Scott 2013). This is likely to increase the reliance on snowmaking (Scott et al 2019; Steiger and Scott 2020) and make some resorts commercially unviable (Scott et al 2006; Dawson and Scott 2013). Snow quality is also influenced by changes in temperature. For instance, snow density usually increases with higher temperatures and humidity (Meløysund et al 2007). This is important for ski resorts, as skiers prefer dryer and less dense snow, characteristics often used by resorts in their marketing campaigns. Despite its importance, snow quality is one of the lesser-studied characteristics of snowpack because of its high spatial and temporal variability (Mizukami and Perica 2008; Bormann et al 2013).

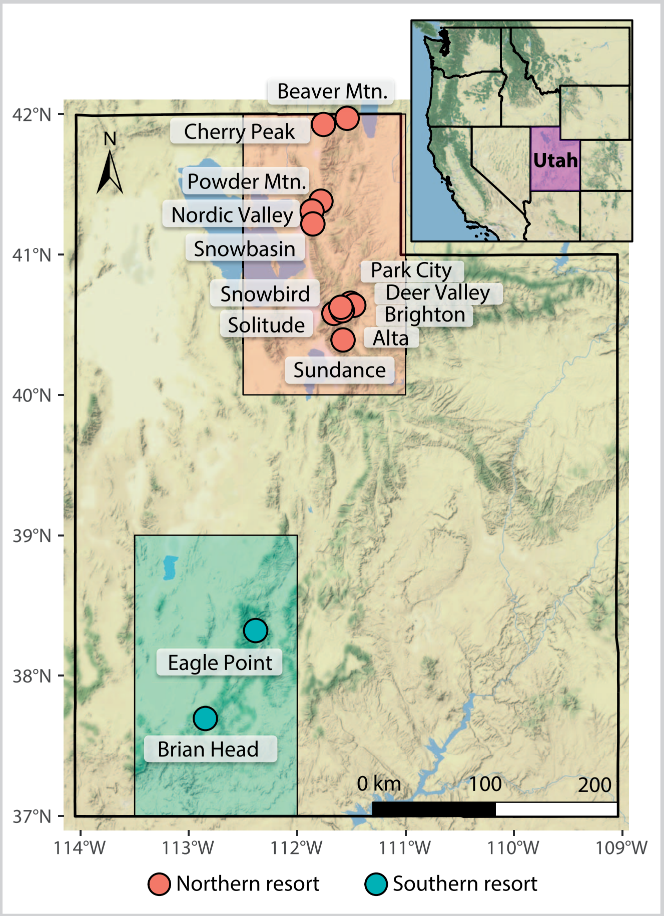
In many parts of the western United States, including the state of Utah, climate change has already decreased snowpack depths and reduced the amount of winter precipitation falling as snow (Knowles et al 2006; Safeeq et al 2016; US Environmental Protection Agency 2016; Fyfe et al 2017; Zeng et al 2018; Siler et al 2019). Despite decreased snowpack, Utah currently has a booming ski tourism industry. During the 2018–2019 season, ski tourism in Utah generated US$ 1.8 billion in economic activity and provided 5.1 million skier days (Leaver 2019). The geography and climate of Utah create storms that generate dry, low-density snowfall events; this results in deep and high-quality powder (Steenburgh 2014). Visitors cite Utah's quality of snow and snow conditions as top reasons for skiing within the state (Leaver 2018). Recent research has shown that dry, low-density snowfall events occur on fewer days in a warmer-than-average year (Rutty et al 2017). Additionally, statewide analyses have found that winters with particularly high levels of snow contributed an additional US$ 49 million to the state's economy, while low-snow years resulted in a 7% decrease in skier visits and a loss of US$ 53 million to the Utah economy (Hagenstad et al 2018). This historical variability provides a knowledge base among ski area managers that will be helpful in informing efforts to make ski areas more resilient to future warming.

Ski resorts can adapt to climate change in a variety of ways. Resort managers often perceive snowmaking to be the most important technological adaptation (Wolfsegger et al 2008; Morrison and Pickering 2013; Hopkins 2014) as it can increase season length and protect against weather variability (Scott et al 2019, 2020). Snowmaking usually requires temperatures below −5°C, although chemical additives may make snow production possible at −1°C (Scott et al 2006, 2008). Recently, snow gun manufacturers have made snow at −2°C if the humidity is low (eg SMI Snow Makers nd). Snowmaking is likely to be an increasingly less viable adaptation strategy at some resorts in the future (Scott et al 2019; Steiger and Scott 2020) because of the higher production cost at warmer temperatures (Stanchak 2002) and water availability or energy consumption concerns (Pickering and Buckley 2010; Morrison and Pickering 2013). Besides snowmaking, other adaptation strategies include moving to higher elevations, slope development, and cloud seeding (Scott and McBoyle 2007). Geographic characteristics such as slope and availability of terrain at higher elevations can drive the decision on which adaptations are most appropriate for a resort (Scott and McBoyle 2007).

Resorts can also adapt by altering their business decisions and diversifying revenue sources, joining ski conglomerates, marketing their offerings more aggressively, and sharing the cost of snowmaking with nearby resorts (Scott and McBoyle 2007; Wolfsegger et al 2008). Diversifying revenue sources most often comes through the transition from a single-season to a 4-season destination (Bicknell and McManus 2006; Morrison and Pickering 2013; Knowles 2019). This often involves adding recreational activities that are not snow dependent, such as hiking, mountain biking, wildlife viewing, or events (Knowles 2019; Sauri and Llurdés 2020). Whereas some resort managers adapt specifically because of climate change, others do so to mitigate risks and increase resilience (Hopkins and Maclean 2014; Trawöger 2014). There is less literature on potential barriers to adaptation in the ski industry. One study noted that the media's portrayal and framing of climate change may be a barrier to adaptation (eg using extreme disaster narratives) (Knowles and Scott 2021). Economic feasibility, in addition to the framing of climate change, can also be a large barrier to adaptation. In Switzerland, for example, economic feasibility is the largest barrier to adaptation in the tourism industry (Matasci et al 2014).

Ski resorts are important to local communities and economies in Utah; thus, it is critical to understand how climate change may affect the ski business and how managers are adapting to the changes across the state. With warming temperatures and increased variability in both temperatures and snowfall (Khatri and Strong 2020), the future of Utah's ski industry is uncertain. The overall goals of this research are (1) to quantify the historical and projected future temperature trends as they relate to operations at Utah ski resorts and (2) to develop an understanding of how Utah resort managers perceive adaptation strategies, barriers to adaptation, and the effects of climate change. We used historical weather data and climate projections to understand past and future temperature trends at Utah ski resorts. We also conducted interviews with resort managers to provide insights into how they perceive adaptation strategies, barriers to adaptation, and the effects of climate change.

FIGURE 1 Locations of the 14 ski resorts across Utah, United States. The 2 boxes represent areas used to explore temperature projections to 2100 (classified as northern and southern Utah).



Methods

Study sites

Study sites included all 14 ski resorts in Utah (Figure 1). Three of these resorts currently do not have the capacity to make snow, while 11 do. Base elevations range from 1646–2926 m with peak elevations ranging from 1951–3353 m. The total skiable lift-served area ranges from 0.49–29.54 km^2. Specific characteristics of each resort can be found in Table 1.

TABLE 1 Characteristics of each resort in Utah (ordered by region and elevation at the main lodge).

Resort	Utah region	Elevation at main lodge (m)	Base elevation (m)	Peak elevation (m)	Lift-served skiable area (km^2)	Snowmaking
Brighton	North	2683	2668	3200	4.25	Yes
Alta	North	2611	2600	3215	8.90	Yes
Powder Mountain	North	2521	2103	2872	11.59	No
Solitude	North	2499	2436	3197	4.86	Yes
Snowbird	North	2468	2365	3353	10.12	Yes
Beaver Mountain	North	2208	2164	2682	3.35	No
Deer Valley	North	2203	2002	2917	8.20	Yes
Park City	North	2121	2073	3048	29.54	Yes
Snowbasin	North	1952	1951	2850	12.14	Yes
Sundance	North	1851	1859	2514	1.82	Yes
Cherry Peak	North	1763	1760	2149	0.81	Yes
Nordic Valley	North	1639	1646	1951	0.49	Yes
Eagle Point	South	2933	2774	3200	2.63	No
Brian Head	South	2930	2926	3328	2.63	Yes

Note: Base elevation, peak elevation, skiable area, and snowmaking data are from Ski Utah (2018). Elevation at the main lodge was downloaded from the USGS Point Elevation Query Service using the elevatr package in R (Hollister et al 2020).

Historical data and climate projections

As the ski season is different for each resort, we acquired the opening and closing dates for each resort over 5 recent seasons (2014–2015 through 2018–2019) from resort websites, social media pages, local news outlets, and skicentral.com. This enabled us to analyze weather data within the dates that encompass a recent typical ski season at each resort. After identifying opening and closing dates for each resort in Utah over 5 recent seasons, we defined the season for each resort as the earliest opening date and the latest closing date during this period. We chose the longest recent season to represent the season length, given that historical seasons may have been longer. We included an additional 2 weeks on both ends of the season to account for the variability in operations and to account for conditions leading up to the opening of the resort each year.

To assess recent historical temperatures and snowmaking opportunities, we downloaded daily historical maximum and minimum temperatures at each resort from 1980–2019 from Daymet version 3, using the R package daymetr (Hufkens et al 2018; Thornton et al 2018). Daymet has temperature data on a 1 km grid, and we used the grid cell that contains the main lodge to represent each resort. We aggregated daily data at the seasonal level for each resort, only using days within each resort's season (as defined above). For each resort, we used daily minimum temperatures to find the proportion of the early season with a daily minimum temperature at or below −5°C, indicating favorable snowmaking conditions (Scott et al 2006, 2008). Here, we defined the early season as 2 weeks before opening through January 2. This time period contains holidays (Thanksgiving, Christmas, New Year's) that tend to see high visitation, making snowmaking critical during this period. We ran Mann–Kendall trend tests with Sen's slope on these data to identify trends in temperature from 1980–2018 (Sen 1968). We tested for statistical significance at the $\alpha \leq 0.05$ level.

To assess snow quality, we used snow water equivalent (SWE) and snow depth data from Snow Telemetry (SNOTEL) sites across the state to explore whether freshly fallen snow density has already been altered as a result of climate change (USDA NRCS nd). These data are available for individual SNOTEL stations across Utah; time periods for each sensor vary, but the data range from 1999–2018. We used the 7 stations across the state that had data for this entire period of record (station names: Tony Grove Lake, Brighton, Louis Meadow, Ben Lomond Peak, Timpanogos Divide, Midway Valley, and Big Flat). As there were only 7 stations across the state with data for this period, we analyzed the data at the state level rather than at individual resorts. All measurable snow events were identified for each selected station. We measured snow events by subtracting the start-of-day SWE values from the previous start-of-day SWE. For days with recorded changes in SWE and snow depth, the density of the snow was estimated using Equation 1.

$$\mathrm{SWE(mm)/depth(mm) = density(\%)} \qquad (1)$$

SNOTEL data reports SWE rounded to 0.254 cm (0.1 inch) and snow depth rounded to 2.54 cm (1 inch); this rounding limits precision, but is consistent over time. This density analysis was done only for freshly fallen snow at SNOTEL monitoring sites.

We used the probability of exceedance (Equation 2) to find the probability that a snow event was equal or greater to a specific density for each winter season and compared density probabilities from the 1999–2000 through 2018–2019 winters. We ranked each snow event for each selected station. The data between the 10th and 90th percentile (probability of exceedance between 0.10 and 0.90) were used for the analysis to accommodate noise due to outliers or measurement errors.

$$\text{Probability of exceedance} = \text{rank}/(1+n) \tag{2}$$

For future climate projections, we used data for Utah from 2021–2100 to explore how winter (December–March) temperature is expected to change through the 2099–2100 winter season under climate change scenarios RCP 2.6, RCP 4.5, and RCP 8.5 of the Intergovernmental Panel on Climate Change (IPCC) (van Vuuren et al 2011). RCP 2.6 represents a mitigation scenario that aims to keep warming below 2°C globally, RCP 4.5 is an intermediate scenario, and RCP 8.5 assumes high greenhouse gas emissions with little to no effort to reduce emissions (IPCC 2014). Monthly projections for the RCP scenarios between 2021–2100 were acquired using the EC-Earth general circulation model for boundary conditions (Hazeleger et al 2012) and the Rossby Centre Regional Climate ensemble model (RCA4) (Samuelsson et al 2011) through NA-CORDEX (Mearns et al 2017). This analysis is at a larger spatial scale, rather than at individual resorts, because climate projections do not currently have fine enough spatial resolutions to generate resort-specific projections. The spatial resolution of projection data is 50 km, and Figure 1 shows the 2 areas (northern and southern Utah) we used to calculate climate projections. We analyzed future projections for minimum temperature, maximum temperature, and precipitation.

We ran Mann–Kendall trend tests with Sen's slope on the winter temperature projection data for each scenario to understand the projected temperature anomalies by the 2099–2100 winter season. All analyses and visualizations were performed in R and the data and code are publicly available (Akbar et al 2021).

Key informant interviews

We conducted semistructured key informant interviews with Utah ski resort managers or senior employees (Ayres 2008). We used a mixed-methods sampling technique that included criterion sampling (ie contacting people who met our criteria for a year-round management position at any Utah ski resort) and snowball sampling to reach other people identified by interviewees as possibly helpful (Palinkas et al 2015). We contacted managers at all 14 resorts; representatives from 2 resorts declined to participate, and 4 did not respond to emails or phone calls. We interviewed 2 individuals at 1 resort and 1 individual at 7 resorts ($n = 8$ resorts; $n = 9$ interviews). These represent 1 (out of 2) resort in the southern part of the state, and 7 (out of 12) resorts in the northern part of the state.

The full interview script can be found in Appendix S1 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). Interview questions focused on background information, general questions relating to the impact of climate change, adaptation measures, barriers to adaptation, and how various climate-related scenarios would impact the resort. Most of the questions were open-ended, but 3 questions had Likert-type response scales (ie ordered categories, such as "not a barrier" to "extreme barrier"). For the questions on adaptation perceptions, some question wording was adapted from Wolfsegger et al (2008). All participants were given a copy of the questions at least 48 hours before the interview. Interviews took between 20 minutes–1 hour and were recorded if participants agreed; recorded interviews were transcribed. The Institutional Review Board at Utah State University approved this study under protocol #9773, and interviews were conducted in 2019.

Responses to open-ended questions were coded using semantic coding and coding categories (Braun and Clarke 2006; Lune and Berg 2016). We conducted a top-down thematic structural coding analysis approach in 2 rounds (Gorden 1992). Codes are defined as "tags or labels for assigning units of meaning to the descriptive or inferential information compiled during a study" (Miles and Huberman 1994: 56). Coding categories, including major and minor themes, can be found in Appendix S2 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). Interviews were coded independently by 2 authors and compared for accuracy (Lune and Berg 2016). Resulting themes and patterns were summarized and explored in the context of the literature and research questions (Attride-Stirling 2001).

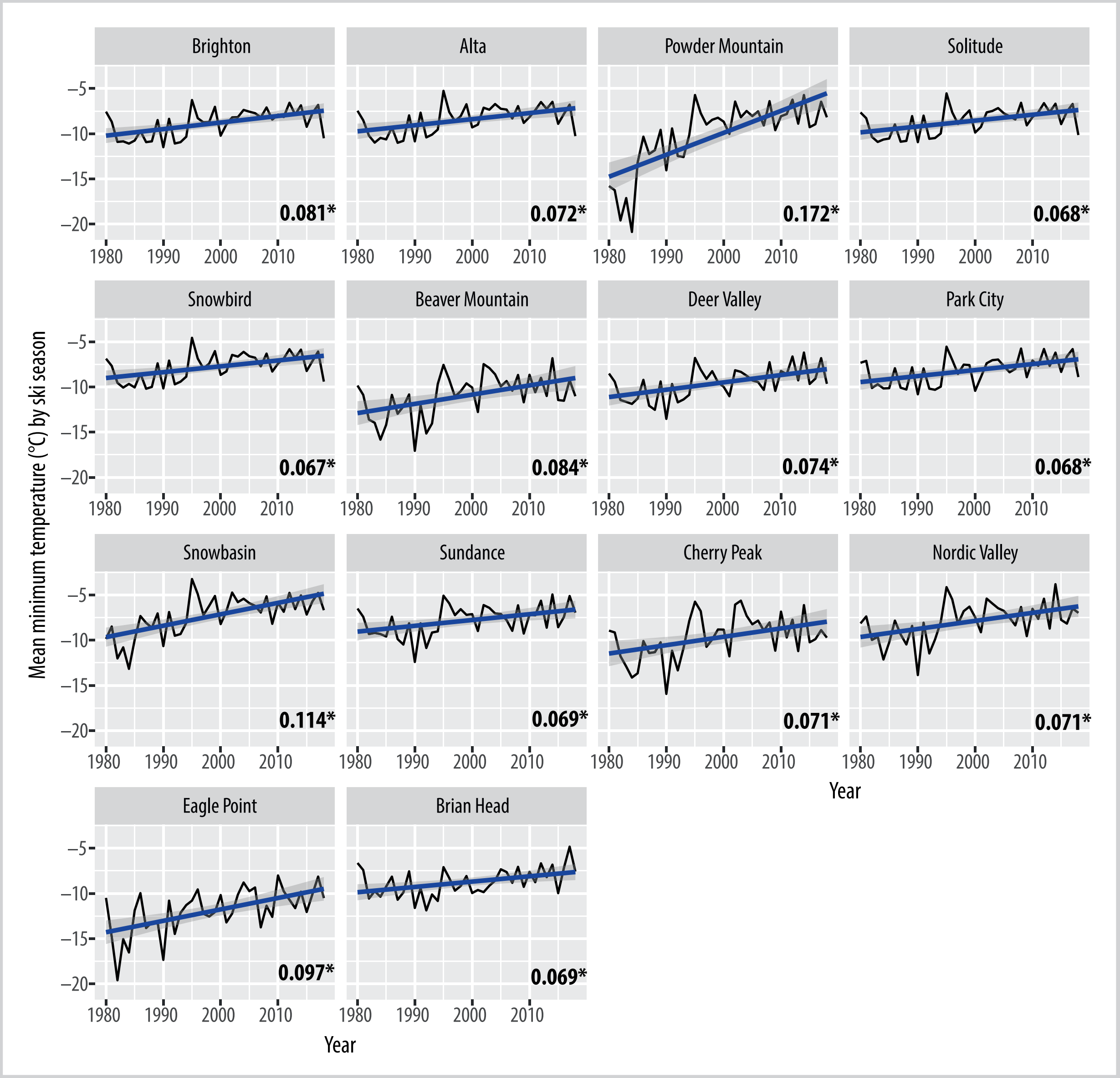
Results

Past temperature trends

Analysis of historical weather data indicates the minimum daily temperatures by ski resort season increased from 1980–2018 for all 14 resorts (Figure 2). These trends are statistically significant for all resorts at $\alpha = 0.05$, with $N = 39$ seasons (for full statistical results by resort, see Appendix S3, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). Sen's slope for these trends ranges from 0.067–0.172; these values can be interpreted as the expected annual increase (°C) in the mean minimum daily temperature over this time period during the ski season. A slope of 0.067 suggests a 2.6°C increase in minimum temperature from 1980–2018, while a slope of 0.172 suggests an increase of 6.7°C. Mean minimum daily temperature by ski resort season from 1980–2018 has been increasing faster than maximum temperature (Appendix S4, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). The increase in mean maximum daily temperature by season is statistically significant for 6 of the 14 resorts, with Sen's slope ranging from 0.039–0.106 for those that are significant (see Appendix S3, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1).

The proportion of most resorts' early/holiday season with a minimum daily temperature at or below –5°C has decreased steadily, with annual variation (Figure 3). These trends are statistically significant at 12 of the 14 resorts, with coefficients ranging from –0.003 to –0.008 (see Appendix S5, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). The 2 resorts that did not have significant trends were the 2 farthest-north resorts (Cherry Peak and Beaver Mountain). A coefficient of –0.005 indicates the proportion of the early season with daily temperatures at or below –5°C has decreased by 0.005 each season, or by 0.195 from 1980–2018. For example, if a resort had a 0.900 proportion of the early/holiday season with daily temperatures at or below –5°C during the 1980 season (eg Deer Valley), an average annual decline of 0.005 would bring

FIGURE 2 Trends in the mean minimum daily temperature (°C) by ski resort season (1980–2018). Numbers on each panel represent Sen's slope; * indicates the value is statistically significant at $\alpha \leq 0.05$.



this proportion to 0.705 by the 2018 season. Assuming an early/holiday season of 44 days, this would have dropped the snowmaking days from 40 to 31 between 1980–2018. Trends in the reduction in the proportion of days with minimum daily temperature at or below –5°C are even greater when considering the full ski season and not just the critical early/holiday period (see Appendix S6, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1).

Ski resort manager perceptions

The interviews with managers revealed varying perceptions of what constitutes a "successful season," with visitation (maintaining current numbers and increasing visitors), good-quality snow, and season pass sales all mentioned frequently. Respondents indicated that snow quality and snow quantity play a key role in a successful ski season. Resort managers reported their resort would need to be open 97–120 days each season to remain viable.

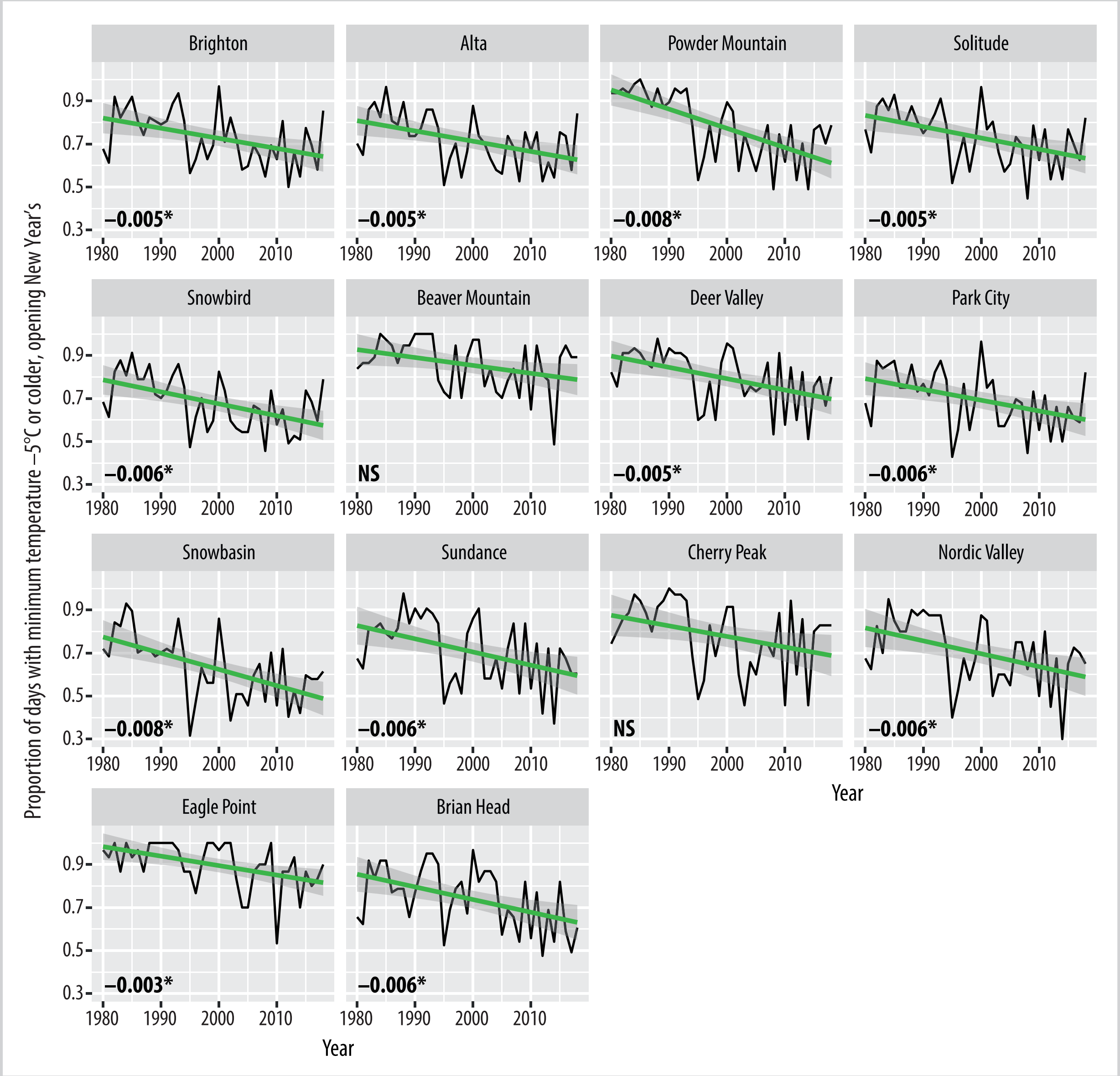
Several managers knew that increasing temperatures and shifts in snowfall patterns would affect the length of their ski season. One resort manager said:

> *Climate change will change the length of our season, the quality of our snow, causing more rain on snow events. It will impact where people will want to ski and snowboard, and it will impact the bottom line, as a shorter winter season will have, obviously, less skier days.*

A shift in the ski season and negative impacts were mentioned by another manager, who noted:

> *I've seen that we get less and less snow in November and December and we get more snow in May than we do in November and December. So, there's a shift in the pattern of when the snow actually happens. The challenge with the ski industry is that we've become accustomed to skiing between Thanksgiving and Christmas. And generally, people get out their boats and their golf clubs about mid-April, especially in this valley, in Salt Lake, where it starts to really warm up in the month of*

FIGURE 3 Trends in the proportion of days in the early season with a minimum daily temperature below –5°C by ski resort (1980–2018). The early season is defined as 2 weeks before opening (varies by resort) through January 2, to capture the holiday season. Numbers on each panel represent Sen's slope; * indicates the value is statistically significant at $\alpha \leq 0.05$.



April. But we are still expecting about a third of the actual snowfall that will fall in this watershed in April and May.

Another resort manager intimated that although high temperatures and low snowfall have happened in the past: "I would say they're becoming more frequent as far as later opening dates . . . I mean, you name it, warmer temperatures, less precipitation, we're seeing them more frequently."

Adaptation measures: We asked the resort managers to rank various adaptation measures on a scale with response options ranging from very inappropriate to very appropriate. Specific measures and their responses are in Table 2. Most resort managers indicated they have already diversified winter and all-season activities at their resort in some capacity. Seven of the 8 Utah ski resorts represented in our interviews have multiple winter activities besides skiing and snowboarding, such as snow tubing, snowshoeing, educational programming, and cross-country skiing. Activities in other seasons range from sporting activities, such as mountain biking (sometimes extensive trail systems), obstacle courses, horseback riding, and disk golfing, to events such as conferences and festivals and complementary services such as spas, restaurants, and rentals. These offerings are diversified to adapt to climate change and to help expand revenue sources alike.

Seven of the resort managers we interviewed have snowmaking at their resorts, either for most of their terrain or just to supplement critical areas. Resorts either have storage ponds for water or purchase water for snowmaking. Methods to increase snowmaking capacity are common at many resorts, as a resort manager noted that it has "been a major push in the last 10 or so years." Various methods were noted to increase snowmaking capacity at resorts. One resort manager said the resort used chemical additives, while

TABLE 2 Responses from resort managers about adaptation measures at their resort. $n = 8$ resorts.

Adaptation measure	Very inappropriate	Moderately inappropriate	Moderately appropriate	Very appropriate	Already doing
Diversifying all-season offerings	0	0	0	1	7
Snowmaking	0	1	0	0	7
Diversifying winter offerings	0	0	1	1	6
Joining ski conglomerates	0	1	1	0	6
Avoiding southern exposure of the slopes	0	1	3	1	3
Enhancing marking to intensity season	2	0	2	1	3
Increasing capacity of lifts	3	1	1	0	3
Giving up slopes that need too much snow	3	2	1	1	1
Moving to higher altitudes	5	0	0	2	1
Sharing snowmaking costs with others	4	2	0	1	1
Snowmaking with chemical additives[a)]	5	0	1	0	1

[a)] One manager did not respond to this measure.

another said the resort might consider using them in the future; others are against it. Four resort managers spoke about alternative ways to increase snowmaking efficiency at their resort, such as cooling water storage ponds before snowmaking and investing in snow gun technology. One resort manager indicated the resort did not have snowmaking capacity and did not foresee a necessity for it in the future.

Resort managers reported a variety of issues related to slope maintenance and snow coverage. Avoiding slopes that require too much snow is a consideration for many resorts; however, these areas are usually just closed for longer periods or, if they are essential, given more snowmaking capacity. Three resort managers stated that in the future they may have to close slopes for longer periods of time. Slope maintenance included clearing brush and obstacles so less snow was needed for a safe level of coverage. One resort manager reported the resort "also implemented mowing the brush, that way you can open up with minimal snow." Another manager discussed contouring the slopes so the coverage needed is equal across the skiing area.

Most resorts are as high in elevation as they can feasibly go, with lease agreements often limiting moving to higher elevations, but a few have plans to move higher. Two resort managers mentioned having higher base lodges, giving them an advantage in the future.

Barriers to adaptation: We asked the resort managers to rate potential barriers to climate change adaptations at their resort on a scale with response options ranging from *not a barrier* to *extreme barrier*. Specific barriers and managers' responses are visualized in Table 3. Resort managers face moderate to extreme barriers in financial costs to adaptation. Prioritizing the need to receive a return on investment combined with large overhead costs limits the ability of ski resorts to invest in additional adaptation methods. One manager noted, "It can be an extreme barrier because you see the potential of being able to do and adapt all these different things at once, but then you have to prioritize and it takes time." Some resorts also face additional challenges based on their size and lack of corporate backers, which limits their financial abilities to adapt.

At resorts that have snowmaking capability, water availability and temperature required to make snow were noted as major barriers to snowmaking. Some resorts own artificial water storage ponds; others receive a certain allotment from public utilities, setting a limitation on snowmaking ability. Resorts that receive water from public

TABLE 3 Responses from resort managers about barriers to adaptation at their resort. $n = 8$ resorts.

Barrier	Not a barrier	Slight barrier	Moderate barrier	Extreme barrier
Financial costs	0	1	6	1
Environmental resources	1	3	3	1
Uncertainty about short-term predictions	1	3	3	1
Uncertainty about long-term predictions	1	3	3	1
Lack of staff time to focus on this issue	2	3	1	2
Internal challenges	3	2	3	0
Lack of municipal community support	3	1	4	0

TABLE 4 Responses from resort managers about impacts of different future conditions on their resort. $n = 8$ resorts.

Scenario	No effect	Slight effect	Moderate effect	Extreme effect
Conditions of 2017–2018 being a new normal	1	2	0	5
Increase in average temperature by 3°C	1	0	3	4
20% decrease in average snowfall	1	1	3	3
Less snowfall at the start of the season	0	2	6	0
10% decrease in average snowfall	2	3	3	0
Less snowfall at the end of the season	3	4	1	0

utilities receive a reduced price because it is untreated water from natural creeks. Using water for snowmaking is considered a nonconsumptive use, although sublimation losses can be considerable (4–41%) (Reba et al 2012). Snowmaking also requires snowmaking guns, plumbing, increased electricity, and labor.

Possible scenarios: Resort managers were asked to rate the impact of possible future scenarios on a scale with response options ranging from *no impact* to *extreme impact* (Table 4). In Utah, the 2017–2018 season was a particularly warm and low-snowfall year; we specifically asked about this year given its recency.

Resorts managers had varying responses when asked about a potential decrease in snowpack. Two thought a decrease would have slight or no effect because of their annual snowfall being extremely high, with some resorts reporting over 1200 cm annually. One manager responded, “[other resort’s] average is 230 inches [585 cm] . . . but our average is 500 inches [1270 cm] plus and at 20% decrease [in snowpack] we still have got decent coverage. So, it’s a different scenario.” Some resort managers thought less snow would not affect their resort if they still had the temperature to make snow. Increases in temperatures to a level above where snowmaking is efficient would be more of an issue with one manager, who stated, “Sometimes along with less snowfall comes warmer temperatures, which doesn’t allow you to make snow.” Less snowfall at the end of the season is less of a concern than snowfall at the beginning of the season when the base is being built at the resort. According to one resort manager, short periods with less snow may not have much of an impact, but longer stretches of no snow could have a much larger impact. One manager noted: “A couple of seasons ago when a lot of ski areas couldn’t even open because there wasn’t enough snow, especially in the Northwest and the Midwest and parts of the East and stuff, we ended up getting higher skier visits.” The manager explained that, in contrast to nearby ski resorts, the manager’s resort drew visitors, as it could open many areas of the resort because of its snowmaking and grooming capabilities.

Since warmer winters with less snow are likely to become more common, we asked resort managers what the effect would be if seasons such as 2017–2018 became more common. Two managers thought there would only be a slight effect, while 5 others stated it would have an extreme effect on their resorts. However, one manager of a resort with extensive snowmaking abilities mentioned that the resort benefited that winter because it drew from other resorts that had no snow.

Snow quality and density

When asked about high-quality snow, 6 managers replied that quality snow is the cold, dry powder for which Utah is renowned; one replied “cold and copious.” One resort manager responded that quality snow depends on the skier: “Beginners may prefer different snow than a ski racer or a powder hound.” Two resort managers stated that unlike before, the focus was on coverage and long-lasting snow instead of cold, copious powder. One manager noted, “It’s now kind of like, well we’ve got enough snow to cover the rocks and the trees and stumps and it may be icy, but at least there’s enough coverage. So that’s kind of the direction now that we’re looking at.” With coverage, more of the mountain can be open and exposure of rocks and other obstacles becomes less of a risk; the season can continue for a longer period.

The density of snowfall events in Utah from 1999–2017 seems to have increased slightly (Figure 4), possibly indicating less of the cold, dry powder in recent years. However, this trend is not statistically significant for any of the percentiles shown. The trend of slightly denser snow events in the last decade is consistent across all 7 SNOTEL stations (see Appendix S7, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). Overall, resort managers felt that seasons with less high-quality snow would reduce the number of visitors and decrease user experience. A potential implication of lower-quality snow mentioned by resort managers was that fewer skiers may purchase season passes, instead buying day tickets to seek the best conditions. This approach may make resorts with high grooming/snowmaking capacity more attractive.

Climate projections

The majority of resort managers indicated an increase of 3°C would have moderate to extreme effects at their resort. Though large variability exists in the year-to-year predicted values, temperatures during winter (December–March) in Utah are likely to increase by the end of the century. Figure 5 shows the increase in minimum temperature from the 2021–2022 to the 2099–2100 winter seasons. Under the RCP 2.6 scenario, there is not a statistically significant change in winter temperature from 2021–2099 in either northern or southern Utah (Mann–Kendall trend test results in Appendix S8, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). Under RCP 4.5, the minimum

FIGURE 4 Snowfall event density in Utah from 1999–2017, by percentile. The 25th percentile indicates that 25% of the snowfall events for that year are less dense (below the point), while 75% are denser (above the point). Lines display linear trends; the trends are not statistically significant at the $\alpha \leq 0.05$ level.

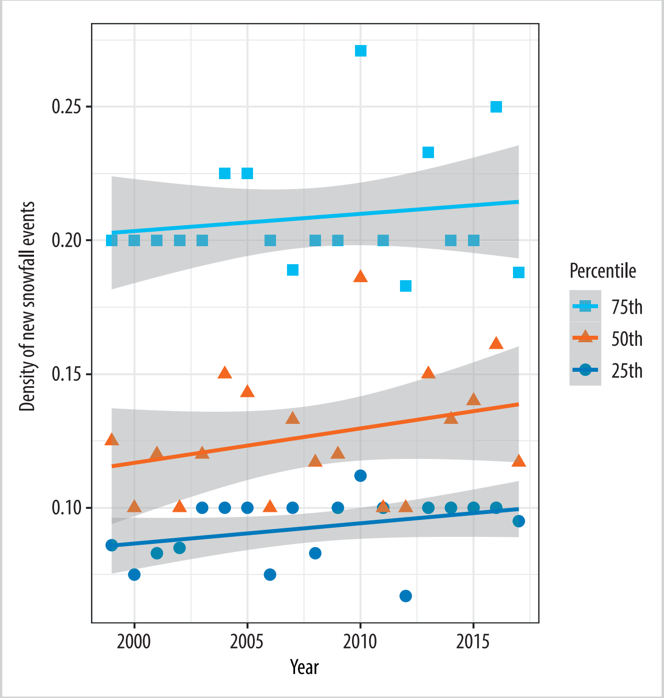
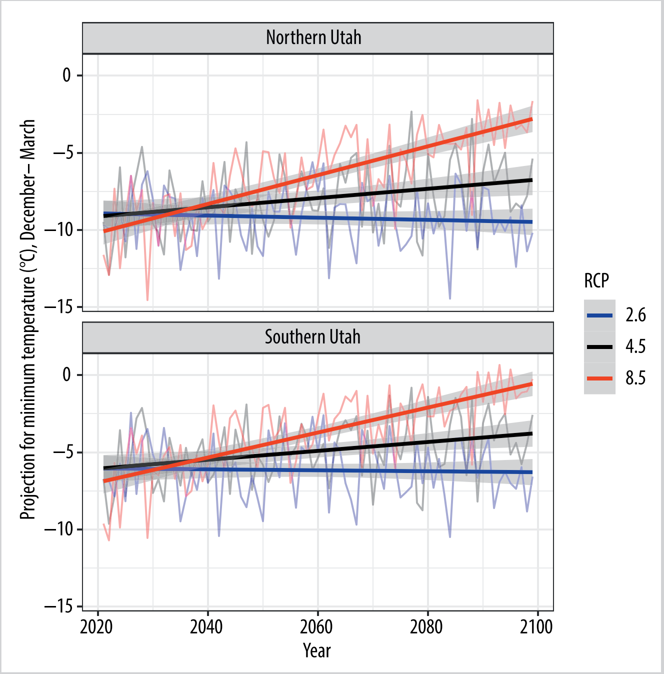


FIGURE 5 Projections for average daily winter minimum temperature for December–March, by winter season, for northern and southern Utah. Background lines represent the projections for each winter season, whereas the straight lines represent linear trends from 2021–2099.



temperature in northern Utah is projected to increase by 2.0°C in the winter from 2021–2099 (0.026°C per year), while southern Utah is expected to warm by 2.3°C (0.030°C per year). Under the RCP 8.5 scenario, winter temperatures for northern Utah are projected to increase by about 6.0°C by the end of the century (0.076°C per year), and 6.6°C in southern Utah (0.084°C per year). Given there is always uncertainty in climate projections, confidence intervals for all Sen's slopes can be found in Appendix S8 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1).

Similar trends are projected for maximum temperatures in the winter (see Appendixes S8, S9, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). Specifically, there is not a significant change in maximum temperature from 2021–2099 under RCP 2.6. Under the RCP 4.5 scenario, both northern and southern Utah are expected to warm 2.4°C by the end of the century. Under the RCP 8.5 scenario, projections show an increase in maximum temperatures of 7.3°C in northern Utah and 6.1°C in southern Utah.

It is important to note that NA-CORDEX projection data are colder than Daymet data from 2006–2018 winters, indicating actual future temperature projections may be higher (projections are about 0.9–3.0°C colder for minimum temperature and 5.1–6.5°C colder for maximum temperature; see Appendix S10, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). This does not affect the change-over-time projections (as described above), but does affect the raw projected values.

Precipitation projections indicate no substantial and consistent change in total winter (December–March) precipitation from 2021–2099 (see Appendix S11, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.S1). There is high variability in seasonal precipitation projections. However, with winter temperatures rising, we would expect that in the future, more precipitation will fall as rain, and less precipitation will fall as snow.

Discussion

Globally, average annual temperatures have risen by 1°C from preindustrial levels (IPCC 2018); Utah has warmed by about 1.5°C since 1900 (Frankson et al 2019). Ski resorts in Utah have been warming even more rapidly in the winter than the global or statewide trends. A similar trend is predicted in the future, with northern Utah expected to see 2.0°C additional warming in the winter by the end of this century under a moderate-emissions scenario (RCP 4.5), or over 6.0°C with high emissions (RCP 8.5). Although there is not a projected change in precipitation, warmer winter temperatures will cause more precipitation to fall as rain rather than snow, and there may be more variability in precipitation events (Khatri and Strong 2020). Resort managers are aware of these changes and are somewhat concerned about climate change and its impacts on their resorts. The impacts most relevant to the state's ski industry are the shortening of the winter season, the increase in temperatures, and the quantity of snow.

Utah ski resort managers are primarily concerned with how climate change will decrease season length. Shorter season length decreases visitation, a key metric for financial viability. One study found that ski resorts across the Rocky Mountain region may open around 10 days later on average under RCP 4.5 by 2050 (Wobus et al 2017). Another study concluded that season length is likely to decrease by more days at lower-elevation resorts in the western United States, and that natural ski days (ie without snowmaking) may decline by around 30 days per season across Utah resorts by 2050 under RCP 8.5 (Lackner et al 2021). Utah ski resort managers reported needing to be open for 97–120 days a season, with most stating they required over 100 days, which is a common threshold used in the literature (Koenig and Abegg 1997). Climate projections show warming temperatures decreasing the length of the ski season in Utah; this could threaten visitation and profit margins for Utah ski resorts, especially for resorts that require longer seasons to remain viable.

Visitors come from around the world to experience Utah's cold, dry powder (Leaver 2017). Consequently, maintaining the high quality and quantity of snow is important to Utah ski resort managers. Utah's low temperature and low humidity have historically accounted for low-density, good-quality snow (Roebber et al 2003; Steenburgh and Alcott 2008). Our data show a possible slight increase in snow density from 1999–2018 (but not enough data to conclude statistical significance); it is possible snow density may change more in the future. Lower-quality snow may have negative impacts on ski tourism; however, the ski resort managers we interviewed were more concerned with snow quantity and cover as opposed to quality.

Despite facing some barriers, all the resort managers we interviewed indicated that their resorts were adapting. Not all adaptations were implemented specifically because of climate change, but they will nonetheless benefit the resorts as they face climate change impacts in the future. The most common adaptations are snowmaking and diversification of offerings, similar to the most popular adaptation measures in other locations (Morrison and Pickering 2013; Sauri and Llurdés 2020). Many of Utah's resorts are experiencing success with diversification of their resorts already, and this will better prepare them to remain viable in the future.

Despite using an array of climate adaptation strategies, resort managers considered snowmaking as the primary strategy to maintain business. Many managers indicated that if temperatures remained low enough to make snow, a 20% decrease in snow quantity over a season would not have extreme effects at their resort. However, this strategy is resource and climate dependent. Although snowmaking can extend operational days in the short term, the water use and temperature constraints, as well as infrastructure and operational costs, may make this an unsustainable strategy for some areas in the long term (Hopkins 2014; Steiger et al 2019). Temperatures at or below −5°C are generally needed to make snow without additives (Scott et al 2006, 2008). However, this does not consider factors such as humidity, and previous analysis shows that snow can be made at or below a wet-bulb temperature of −2°C (Stull 2011). In any case, our analysis shows a substantial decrease in the proportion of winter season days that snowmaking was viable at Utah resorts between 1980–2018; this trend is similar to results from a ski resort in New Hampshire (United States) that also showed a decrease in snowmaking days (Wilson et al 2018). The majority of the resort managers we talked to say they would never consider using additives (particularly resorts in protected watershed areas) at their resorts; also, sometimes government policies or public resistance might not allow their use (Scott and McBoyle 2007). Overall, expenses are a moderate barrier to adaptation, particularly with snowmaking; it may be difficult to allocate sufficient financial resources to this one technological adaptation.

The adaptation practices at resorts indicate the negative effects of climate change may not impact resorts as much as the temperature trends alone may suggest. Snowmaking is unlikely to be a viable adaptation by itself, as minimum temperatures continue to rise and render fewer days where snowmaking is possible, putting more pressure on water needs and snowmaking infrastructure. As resorts diversify their offerings, they are creating a stronger platform for their success as climate change potentially accelerates.

Limitations and future research

We interviewed managers at 8 Utah resorts; the data from interviews may not be representative of all ski resorts within the state. Resort managers who agreed to participate may have been more likely to believe that climate change was real and impacted their resort. Additionally, since we were able to interview only 1 individual at most resorts, their views are not necessarily representative of the entire resort. Future research could aim to interview more employees at each resort and see how perceptions differ based on job position.

Many resorts in Utah focused on snowmaking as an important adaptation strategy. Additional research is needed to investigate future water availability, use, and rights across Utah for snowmaking. For analysis of historical water use, snowpack, and hydrological changes in Utah, see Khatri and Strong (2020). Additionally, more research on projected changes to snowfall and snowpack at Utah resorts is needed to better understand future water and snowmaking needs (eg Lackner et al 2021). Future studies could also examine how the characteristics of a resort (eg size, location, visitor profile) relate to the ability of a resort to adapt and their perceptions of barriers to adaptation. The climate and physiography of Utah are similar to those of other states in the western United States; thus, similar trends may be expected in nearby states. However, additional research is required to explore whether similar patterns would be observed in the other locations.

Conclusions

The climate in Utah will likely warm dramatically, and, according to ski resort managers, it will have moderate to extreme impacts on resort operations. The resort managers we interviewed are aware of climate change and its potential for adverse effects on their resorts. Many ski resorts in Utah have adaptations already in place, but many adaptations have related barriers that may limit their effectiveness (eg snowmaking). Climate change will continue to impact resorts and their surrounding communities in significant ways, but adaptation measures may help resorts remain viable throughout the end of this century.

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Supplemental material

APPENDIX S1 Semistructured interview script.
APPENDIX S2 Coding categories of the qualitative interviews.
APPENDIX S3 Mann–Kendall trend test results for historical temperature data for the full ski season.
APPENDIX S4 Trends in mean maximum daily temperature by ski resort season (1981–2018).
APPENDIX S5 Mann–Kendall trend test results for historical temperature data for only the early ski season (2 weeks before opening through January 2).
APPENDIX S6 Trends in the proportion of days in the full season with a minimum daily temperature below –5°C by ski resort (1980–2018).
APPENDIX S7 Snow density analysis by station.
APPENDIX S8 Mann–Kendall trend test results for change in maximum and minimum temperature under RCP 2.6, 4.5, and 8.5 climate change scenarios across northern and southern Utah.
APPENDIX S9 Projections for maximum temperatures using RCP 2.6, 4.5, and 8.5 climate change scenarios across northern and southern Utah.
APPENDIX S10 Validating the climate model: comparing temperature projection data from NA-CORDEX to Daymet data.
APPENDIX S11 Projections for precipitation using RCP 2.6, 4.5, and 8.5 climate change scenarios across northern and southern Utah.

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