Modeling Future Climate Change Risk in the California Ski Industry

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ABSTRACT

Climate change poses a significant and evolving threat to the sustainability and competitiveness of ski tourism worldwide, and California is no exception. Using historical climate data and future climate projections under low-to-high greenhouse gas emissions scenarios, this analysis estimates the changes in ski season length, snowmaking requirements, and economic viability for 19 ski resorts in California. The results indicate that under low and medium emissions scenarios, advanced snowmaking can limit mid-century season length losses to -17% and -24%, respectively, with losses increasing to -32% under high emissions scenarios. However, the three emission pathways diverge by late century, resulting in transformational impacts under high emissions scenarios, in which only a handful of ski areas can sustain financial stability. To understand the implications of these changes, the study explores the potential for intra-market redistribution of market share among ski resorts, highlighting the vulnerability of small, independent resorts. In response to the projected impacts, the paper examines adaptation and mitigation strategies employed by California ski resorts, including advanced snowmaking, year-round recreational offerings, and environmentally responsible practices. While these efforts may not completely protect the California ski industry from the impacts of climate change, they represent an important step towards increased resilience and sustainable tourism practices. The findings highlight the importance of the + 2°C Paris Agreement policy goal and a low-emission future for preserving California ski tourism. These outcomes underscore the need for ongoing research and collaboration between California ski resorts, mountain communities, and policymakers to effectively respond to the emerging challenges posed by climate change.

KEYWORDS

California ski tourism, snow reliability, season length, artificial snowmaking, adaptation

INTRODUCTION

In the past 15 years, the multi-billion-dollar ski tourism industry has matured and remained relatively stable with approximately 400 million skier visits per year (Vanat 2018). Despite the recent stability and prosperity of the global ski market, the industry is confronted with an unprecedented challenge in the form of a warming climate. Climate change is widely acknowledged as one of the most pressing global challenges of our time, and the significant threat to the ski industry is no exception. To date, it is estimated that anthropogenic emissions have caused approximately 1.1°C of warming compared to 1850 levels, and at current rates, global temperatures are expected to reach or exceed 1.5°C between 2030 and 2052 (IPCC 2014). The United Nations Intergovernmental Panel on Climate Change concluded that the consequences of anthropogenic global warming have been unprecedented and indisputable, resulting in notable impacts on both the natural and human systems (UNEP 2018). The ski tourism industry, which relies heavily on natural resources such as snow, ice, and cold temperatures, is particularly vulnerable to the risks posed by climate change.

Over 120 studies from 27 countries have investigated the effects of climate change on the ski industry, consistently forecasting that its viability, profitability, and sustainability face challenges due to decreased and unpredictable natural snow conditions, alongside rising snowmaking demands and expenses (Steiger et al. 2019). Although climate change is anticipated to influence ski destination competitiveness across all regional markets, these ramifications will manifest unevenly, as differential climate risks hinge on factors such as elevational, operational, and business model vulnerability (Dawson and Scott 2013, Rutty et al. 2015, Scott et al. 2019b, Steiger and Scott 2020). Regardless of location, ski resorts are facing significant challenges including shortened ski seasons, declining real-estate values, and reduced operational capacity, all of which will have far-reaching consequences for employment, culture, real estate, and tax revenues in tourism-dependent mountain communities (Steiger et al. 2019).

When considering the risks posed by climate change to ski resorts, America’s most populous state is certainly a market to scrutinize. However, research on the interactions between the California ski market and changing climactic conditions remains limited. Hayhoe et al. (2004) and Winton (2013) constitute the only academic research to date on the impact of climate change on the future of the California ski industry (Winton 2013). Thus, this study will examine regional climate risks of the California market using a physical snow model to simulate ski area operations. This will be done with a methodology that fully incorporates snowmaking and the new generation of climate change scenarios developed by the Coupled Model Intercomparison Project (CMIP-5 & CMIP-6) in support of the IPCC Fifth and Sixth Assessment reports (IPCC 2013, 2018).

The analysis considers early- (2030), mid- (2055), and late-century (2085), using both Shared Socioeconomic Pathways (SSP126, SSP245, SSP370, and SSP585) and Representative Concentration Pathways (RCP 2.6, 4.5, and 8.5) emission scenarios. Adhering to the standards set by Scott et al. (2021), the study incorporates these scenarios into the SkiSim2.0 model to project current and future ski season lengths, snowmaking requirements, and economic viability for 19 California ski areas (Figure 1). This approach aims to provide a more realistic representation of ski area operations and potential impacts by accounting for industry performance indicators, detailed snowmaking practices (e.g., base-layer, improvement, and emergency snowmaking), and a better altitudinal representation of ski areas (i.e., critical altitude). By projecting the effects of climate change on the California ski industry under various scenarios and timeframes, this study offers valuable information for decision-makers within the industry and destination communities, shedding light on the relative climate risks and their potential impact on regional market competitiveness and providing a robust basis for developing science-based adaptation strategies.

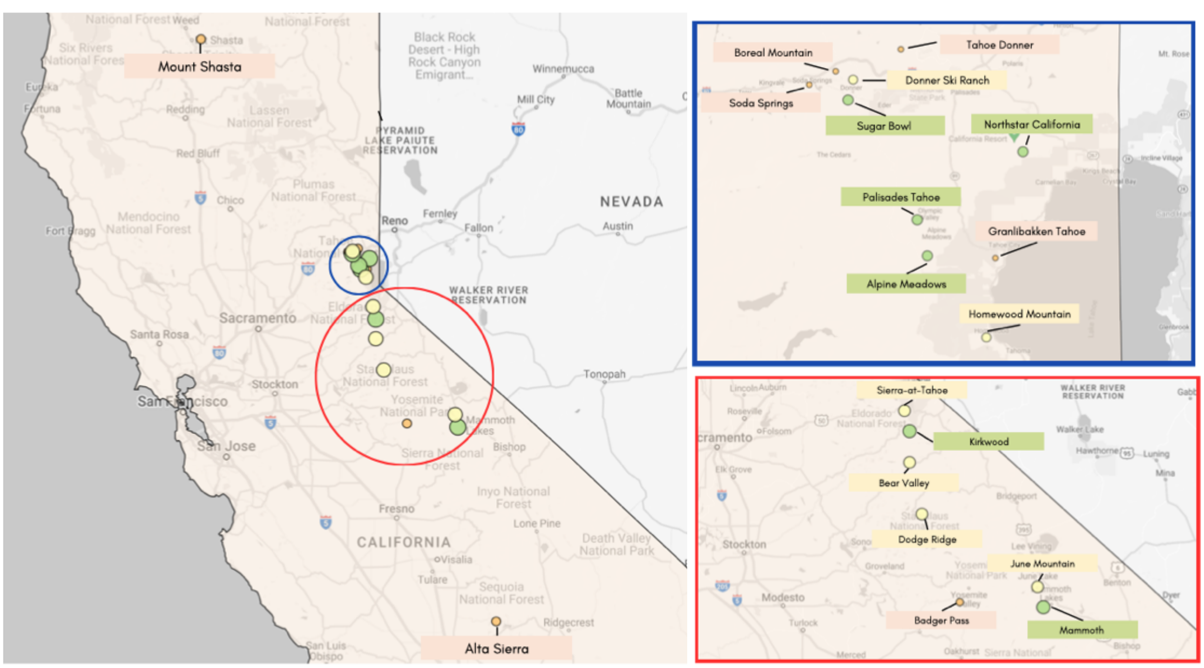


Figure 1. The 19 resorts included in the analysis.

BACKGROUND

The evolution of ski tourism

Skiing, as a culturally and historically significant activity, has not only contributed to the growth and development of the global tourism industry but also holds great importance to many individuals who enjoy the sport. The development of commercial ski tourism can be traced back to early 20th-century mountaineering, where Nordic skiing served as the precursor to the current Alpine ski tourism industry. As international mass tourism grew in the 1960s and 1970s, new ski areas were established and existing resorts expanded, aided by low entry barriers and government support for transportation and growth in mountainous regions (Hudson 2015). The market saw a surge in demand due to economic prosperity and increased leisure time, which coupled with snow-abundant winters in major Western European and North American markets, led to the development of ski areas in what are now considered climatically suboptimal locations (Steiger et al. 2019).

However, in the 1980s and 1990s, the growth in the number of ski areas and skier visits slowed as the market matured, resulting in intense competition and higher customer expectations. As a result, resorts made significant investments in snow quality via snowmaking and comfort, via the adoption of high-speed lifts, chair lifts, or gondolas instead of surface lifts (Steiger et al. 2019). These investments and increased operating costs led to the closure of many small ski areas, exemplified by the number of resorts in the US declining from 622 in 1987 to 481 in 2007 (NSAA 2017). Nowadays, ski tourism in traditionally dominant markets has reached maturity, with stable demand in countries like the US, Canada, and France or declining demand in nations such as Switzerland and Japan. Conversely, significant economic shifts in emerging markets like China and Eastern Europe have given rise to new markets experiencing high growth rates (Vanat 2018).

Incorporating snowmaking technology into climate risk assessments

As the landscape evolves, the importance of developing reliable techniques to evaluate and disclose the comparative climate hazards facing the ski sector and its associated communities increases. Critically, this necessitates the inclusion of snowmaking in the assessment of potential environmental consequences. According to Dawson and Scott (2013), the use of snowmaking technology has become ubiquitous since its inception in 1952, providing ski areas with increased resilience to unfavorable weather and climate fluctuations. As of 2019, over 90% of North American ski resorts have some snowmaking capacity (NSAA 2019).

Despite the widespread use of artificial snow, early studies attempted to assess climate risk without acknowledging the rapid diffusion of snowmaking. These studies projected immense consequences for ski resort viability (e.g. Harrison et al. 1986, Lamothe and Periard 1988) which the ski industry accurately claimed did not represent their current operational realities or capacity to adapt to cope with future climate change (Gössling and Scott 2012). Thus emerged a second generation of studies, beginning with Scott et al. (2003), that included snowmaking in vulnerability assessments. The disparity in the magnitude of impacts forecasted by studies exclusively examining natural snow (first-generation) in comparison to those incorporating snowmaking (second-generation) is striking (Table 1). For example, a first-generation study in Quebec projected mid-century season length losses of 40-89%, while a second-generation survey of the same region projected mid-century season length losses of 32-39%.

Table 1. First-generation studies (natural snow) vs. second-generation studies (including snowmaking). Projected changes in ski season length and snow-reliable ski areas in the mid-century (Source: Steiger et al. 2019)

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)

The importance of including snowmaking in vulnerability studies cannot be overstated, as the negative impact of overly dramatic predictions can be observed both within and outside the industry. Research has found that misinformation, including inaccurate representations of climate risk, can hinder the ski industry's climate responsiveness (Abegg and Steiger 2017, Knowles and

Scott 2020, Scott et al. 2012, 2019d). Exaggerated climate risk assessments can also draw media and financial sector scrutiny, potentially harming the ski industry's reputation, financial standing, and investment prospects. Nevertheless, ski resorts and their associated communities require reliable forecasts to satisfy the growing demand for climate risk disclosure from real estate markets and investors (EBRD 2018). As a result, many publicly traded ski resorts will be expected to provide accurate climate risk assessments by 2025, with independent ski resorts seeking loans or investments expected to face similar obligations soon after (Gössling and Scott 2018). Given these circumstances, the research community needs to establish robust methodologies for assessing and reporting comparative climate hazards within the ski industry and destination communities.

Climate threats to California's ski industry

With 29 ski resorts and a population of 39.35 million people, California is an unparalleled market for ski tourism. The ski industry in California sees an average of 7.5 million yearly skier visits, over 12% of the 62 million skier visits logged in American ski resorts for the 2021-2022 season. In an average snow year, this massive industry produces $1.6 billion in economic revenue and creates approximately 24,000 jobs. However, according to a 2012 study from Protect Our Winters, those numbers shrink by 1.3 million skier visits and $99 million of lost revenue in low snow years (Fox 2019). Due to compounding climatic changes, such low snow years are very likely to become more common in the region.

According to a recent report from the Governor's Office of Planning and Research, California has witnessed temperature increases of nearly 1.1° C since 1950. If emissions continue their current track, temperatures in the state could rise nearly 5° C by 2100 (Fox 2019). These temperature rises have already begun to have costly consequences for the resorts that comprise the California ski industry (Figure 2). Since 1970, Lake Tahoe's snowline has been pushed uphill by 1,200-1,500 vertical feet, and spring arrives almost three weeks earlier (Fox 2019). Furthermore, as of 2009, there was already a 10% reduction in California's snowpack, which supplies approximately one-third of all freshwater resources for the state (Winton 2013). On top of reducing natural snow levels, this shrinking snowpack may hinder ski resorts' ability to compensate with snowmaking as they will be forced to battle with agricultural, residential, and industrial players for water allocation rights (Winton 2013).

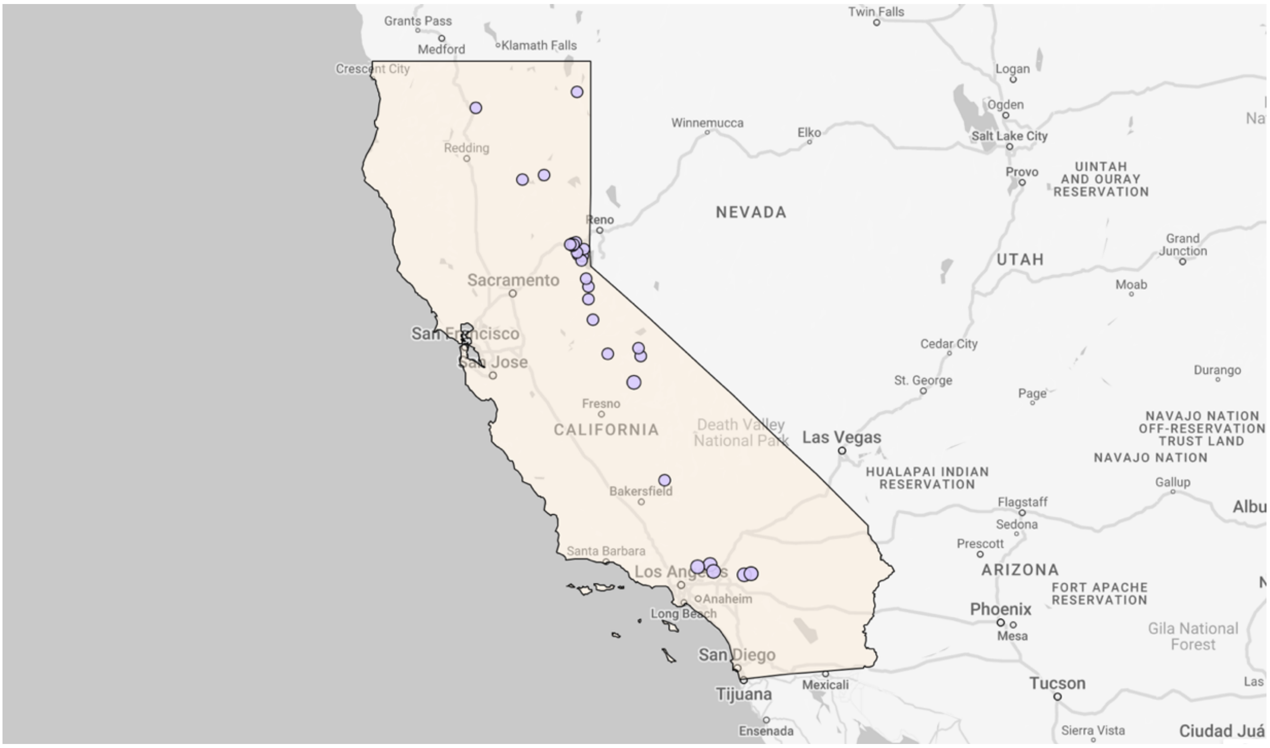


Figure 2. The 29 California ski resorts.

In addition to early springs and a rapidly retreating snowpack, California has several unique characteristics that subject ski resorts to particularly harsh climactic consequences. Variable maritime influences can bring a combination of heavy snow and heavy rain, which can wash away the product of expensive and resource-intensive snowmaking (Fox 2019). California is also infamously plagued by droughts which, in addition to decreasing snowfall, can impact snowmaking capability. While most ski resorts in the U.S. have no problem obtaining additional winter water rights, droughts in California can make non-essential water use controversial (Fox 2019). Increasingly prevalent wildfires also pose a danger to California ski resorts. In 2021, the Caldor Fire burned over 220,000 acres of land near the Tahoe Basin. Sierra at Tahoe, a 2,000-acre ski resort, was engulfed in flames. Firefighters managed to put out the blaze just before it could burn Kirkwood and Heavenly, two other massive resorts in Southern Lake Tahoe (Neville 2021). Given this complicated landscape, this study aims to use SkiSim2.0 to expand on existing research on California's evolving ski market and the risks it may face in a warming world.

METHODS

Study site selection

29 downhill ski areas were initially considered in this study. These study areas were considered for final analysis based on two metrics: (1) the presence of an adequate climate station (determined by distance to the resort, quality of data, and elevation) and (2) the size of the ski area. 10 of these sites were ultimately excluded from the analysis. Seven resorts were excluded due to excessive distance from an adequate climate station (Figure 3, depicted in purple), and three resorts were excluded due to size (Figure 3, depicted in green). Ultimately, analysis was conducted on 19 downhill ski areas represented by 6 climate stations. These ski areas exhibit diversity in size (from 70-3600 acres), geographical location (Southern, Northern, and Central CA), and ownership structure (corporations such as Vail, Powdr & Alterra, or private businesses run by venture capital firms, development companies & wealthy individuals).

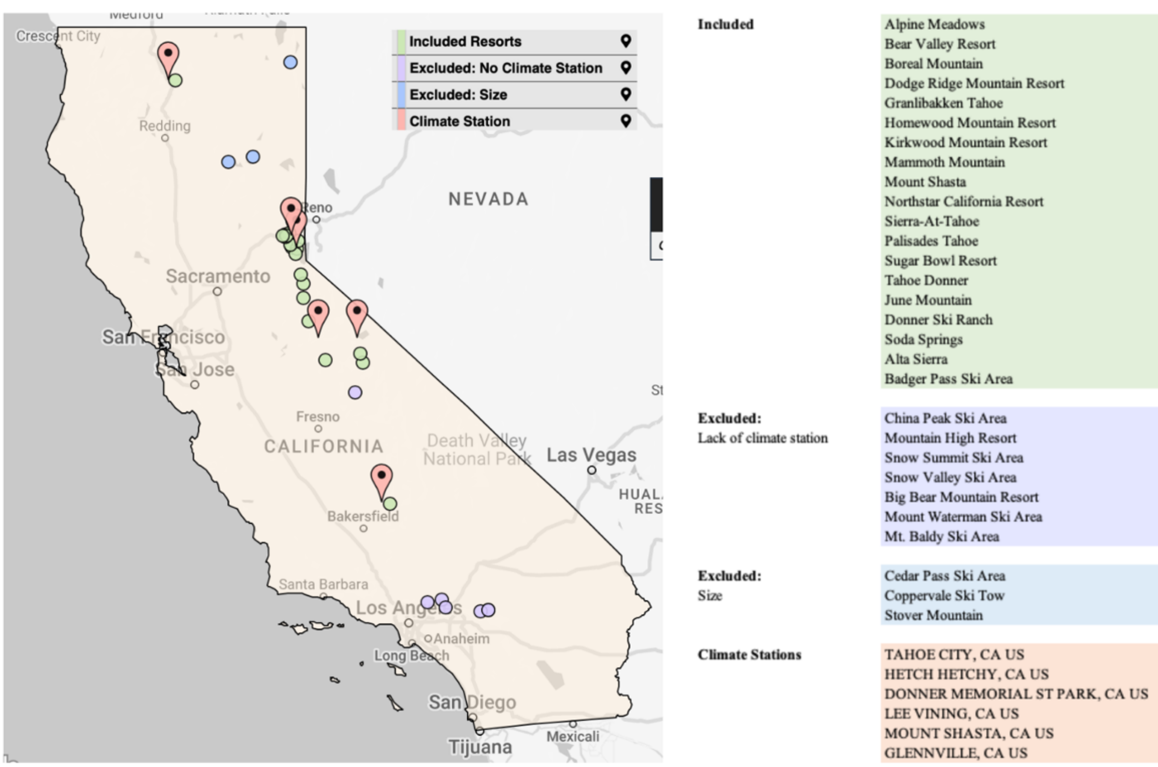


Figure 3. California ski region and ski areas included/excluded in the study. Included resorts are represented by green dots, excluded (climate station) by purple dots, excluded (size) by blue dots, and climate stations by red pins.

Size criteria

Minimum size. Resorts with ≤ 2 operational lifts as of January 2023 were not included due to unpredictable operations and overall irrelevance in the larger market (i.e., local ski tows that don't contribute significantly to the larger ski tourism economy). Three resorts (Cedar Pass Ski Tow, Coppervale Ski Tow, and Stover Mountain) were consequently omitted.

Climate station criteria

Elevation. Preferably, ski resorts and weather stations should be situated at relatively analogous altitudes. The optimal elevation difference between ski areas and climate stations would be around 500 meters or less (Winton 2013). However, the limited availability of high-altitude climate stations makes this goal challenging. While 4 selected resort-station pairs have altitudinal differences greater than 500 m, the mean and median altitudinal differences were 370 and 310 meters, respectively, indicating that elevation gaps should not have an outsized effect on the results (Table 2). Consequently, elevation was not used to omit resorts from the sample.

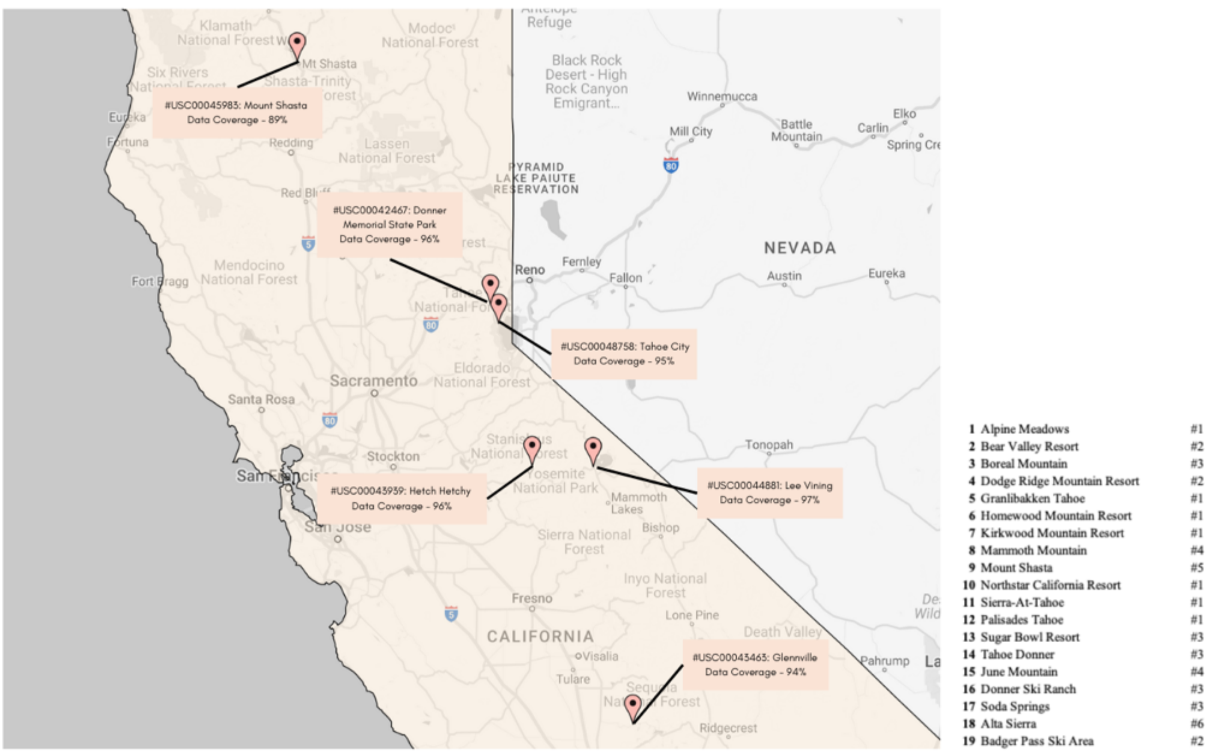
Table 2. Altitudinal difference between selected study sites and climate stations.

Station ID	Name	Climate station elevation (m)	Resort	Base Elevation (m)	Altitudinal Difference
USC00048758	Tahoe City	1898.9	Alpine Meadows	2083	184.1
			Granlibakken Tahoe	1923	24.1
			Homewood Mountain Resort	1899	0.1
			Kirkwood Mountain Resort	2377	478.1
			Northstar California Resort	1929	30.1
			Sierra-At-Tahoe	2023	124.1
			Palisades Tahoe	1890	-8.9
USC00042467	Donner Memorial	1809.6	Sugar Bowl Resort	2098	288.4
			Tahoe Donner	2057	247.4
			Donner Ski Ranch	2143	333.4
			Soda Springs	2042	232.4
			Boreal Mountain	2195	385.4
USC00043939	Hetch Hetchy	1179.6	Badger Pass Ski Area	2195	1015.4
			Bear Valley Resort	2012	832.4
			Dodge Ridge Mountain Resort	2012	832.4
USC00044881	Lee Vining	2071.7	June Mountain	2300	228.3
			Mammoth Mountain	2424	352.3
USC00045983	Mount Shasta	957.1	Alta Sierra	1981	1023.9
USC00043463	Glennville	1101.2	Mount Shasta	1676	574.8
				MEAN (m):	**367**
				MEDIAN (m):	**311**

Distance between resort and climate station. Although there is no official standard for this distance, comparable studies have cited median distances ranging from 10 to 30 km (Scott et al.

2019c, 2021). The selected climate stations were all located within 65 km of their respective resorts, with a median distance of 21 km (well within the established 10-30 km range).

Length and quality of historical climate records. Completeness of climate data was classified as records spanning from 1980 to 2010 with, ideally, gaps in daily observations for temperature and precipitation not exceeding 5%. Seven resorts were excluded due to the far geographical proximity of a climate station with a complete data set. However, two small exceptions were made: Station #5 (Mount Shasta, CA) had an 11% gap, and Station #6 (Glennville, CA) had a 6% gap. These exceptions were permitted due to their limited impact on the overall data as each station still had relatively robust climate records and was only associated with one ski resort (Mount Shasta and Alta Sierra, respectively). Overall, data were collected from 6 weather stations (Figure 4), with any gaps filled by interpolating data from other nearby weather stations.



Station #	Station ID	Name	Data Coverage	Latitude	Longitude	Elevation (m)
1	USC00048758	TAHOE CITY, CA US	95%	39.168	-120.1428	1898.9
2	USC00043939	HETCH HETCHY, CA US	96%	37.961	-119.783	1179.6
3	USC00042467	DONNER MEMORIAL, CA US	96%	39.324	-120.2331	1809.6
4	USC00044881	LEE VINING, CA US	97%	37.957	-119.1194	2071.7
5	USC00045983	MOUNT SHASTA, CA US	89%	41.322	-122.31725	1101.2
6	USC00043463	GLENNVILLE, CA US	94%	35.727	-118.7006	957.1

Figure 4. Climate station selection. Based on distance, elevation, and completeness of climate data.

Long Ashton Research Station Weather Generator (LARS-WG)

This study utilized the Long Ashton Research Station Weather Generator (LARS-WG), a stochastic weather generator, to create both baseline and future site-specific climate change scenarios. LARS-WG generates daily synthetic weather time series while retaining the characteristics of individual weather stations (Semenov et al. 1998). These synthetic time series, used in this study for both baseline and future periods, are created by calculating the distribution of dry and wet days, temperature, and solar radiation flux through statistical modeling. Although daily weather values may not match observed patterns, the synthetic year is statistically identical for the occurrence of various weather events (Semenov et al. 1998).

The LARS-WG process involves two parts: forming the baseline climate change scenarios using weather station data and forming the future climate change scenarios using CMIP models (Semenov and Stratonovitch 2010). Weather station data, including daily precipitation, maximum, and minimum temperature, were formatted for input into LARS-WG. Monthly temperature and precipitation change signals from CMIP5 and CMIP6 models were then downscaled to daily resolution at climate station locations for early- (2020-2039), mid- (2040-2069), and late-century (2070-2099) periods using LARS-WG (Semenov and Stratonovitch 2010).

LARS-WG was selected for this study due to its ability to produce site-specific daily weather data for multiple years while accounting for climate change and inter-season variability (Qian et al. 2004). It has demonstrated superior performance compared to other weather generators, particularly in simulating precipitation statistics in North America (Scott et al. 2003). This advantage made LARS-WG the ideal choice for creating accurate and reliable climate change scenarios in this study.

Climate change scenarios

The IPCC is the leading global body for the assessment of climate change, and its reports synthesize the most up-to-date climate science. CMIP, or the Coupled Model Intercomparison Project, is an international effort to assess and compare climate models, informing the IPCC's reports (Hausfather 2018). This study employs climate scenarios from the World Climate Research Programme's CMIP-5 and CMIP-6, which are developed to support the IPCC Fifth and Sixth

Assessment Reports (IPCC 2013, IPCC 2018). These climate scenarios are based on the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), which serve as inputs to the climate models and help describe possible future pathways for greenhouse gas emissions, land use changes, and other factors that influence the Earth's climate (Hausfather 2018).

In this study, a total of 16 CMIP-5 and 17 CMIP-6 general circulation models (GCMs) (Table 3) are utilized to develop ensemble projections within SkiSim2.0 for seven greenhouse gas emission scenarios: RCP 2.6, RCP 4.5, RCP 8.5, SSP126, SSP245, SSP370, and SSP585. Ensemble projections from multiple climate models are increasingly used in climate change vulnerability studies to reflect the variability of projected climate responses to future GHG emission pathways, rather than relying on the projected climate response from individual models (Hawkins & Sutton, 2009; Environment Canada, 2017). The average of RCP 2.6 & SSP 126 projections will be referred to as a low emissions future, that of RCP 4.5, SSP 245, SSP 370 a medium emissions future, and that of RCP 8.5 & SSP 585 a high emissions future.

Table 3. General circulation models (GCMs) used for CMIP5 and CMIP6 model ensembles

CMIP5	CMIP6
BCC-CSMI-I	ACCESS-CM2
CanESM2	ACCESS-ESM1-5
CCSM4	BCC-CSM2-MR
CESM1-CAM5	CAMS-CSMI-O
CNRM-CM5	CanESM5
CSIRO-Mk3-6-O	CESM2-WACCM
GISS-E2-R	EC-Earth3
IPSL-CM5A-MR	EC-Earth3-Veg
MIROC5	GFDL-ESM4
MIROC-ESM-CHEM	INM-CM5-O
MIROC-ESM	INMCM4-8
MPI-ESM-LR	IPSL-CM6A-LR
MPI-ESM-MR	MP1-ESM-1-2-HR
MRI-CGCM3	MP1-ESM-1-2-LR
NorESM1-ME	MIROC6
NorESM1-M	MRI-ESM2-O
	NorESM2-MM

The analysis is conducted for three time periods: early- (2030), mid- (2055), and late-century (2085). Late century scenarios are generally not considered relevant to tourism or business planning time horizons. However, this study includes such projections due to the importance of the long-term viability of winter sports to the identity and economies of the regional areas considered in this study.

Data collection

Weather data for this research was obtained from selected climate stations through the National Climatic Data Center (NCDC), a subsidiary of the National Oceanic Atmospheric Administration (NOAA). Specifically, temperature (mean, minimum, and maximum) and precipitation (rain and snowfall) data were gathered from NOAA for the baseline period (1981-2010). Where available, daily snow depth was obtained for calibration (7+ years for each site) and validation (7+ years for each site) of the SkiSim2.0 model.

Ski season simulation model

The first generation of the SkiSim model, SkiSim1.0, was developed and validated in Ontario, Canada (Scott et al. 2003). The initial model utilized 17 years of daily ski reports and discussions with ski industry stakeholders to quantify snowmaking capacity and operational rules, allowing for the integration of machine-made snow into a physical model of a natural snowpack. Steiger (2010) updated the model (SkiSim2.0) to reflect varying operational decisions of the ski season and to yield outputs across the elevation range of individual ski areas (in 100m intervals). These additional inputs were shown to improve the ability of SkiSim2.0 to simulate observed season lengths (as compared to SkiSim1.0), as well as provide further insight into geographical differences in ski tourism climate change risk and adaptation.

SkiSim2.0 has subsequently been applied in Austria, Italy, Germany, Switzerland, China, Norway, and provincial/state markets in the US and Canada (e.g., Fang, Steiger, and Scott 2019, Dawson and Scott 2013, Scott et al. 2019c, Steiger 2012, Steiger and Abegg 2013). It has also been applied to large-scale assessments in the European Alps (e.g. Steiger and Abegg 2018) and globally for all Winter Olympic Games locations (Scott et al. 2015, Scott et al. 2019b). SkiSim2.0 includes (1) a natural snow module, (2) a snowmaking module, and (3) an operational rules module. SkiSim2.0 is not available for public use, so all models were run by Steiger using the parameters in this paper for selected resorts. Figure 5 provides a visualization of the methodological framework of SkiSim2.0.

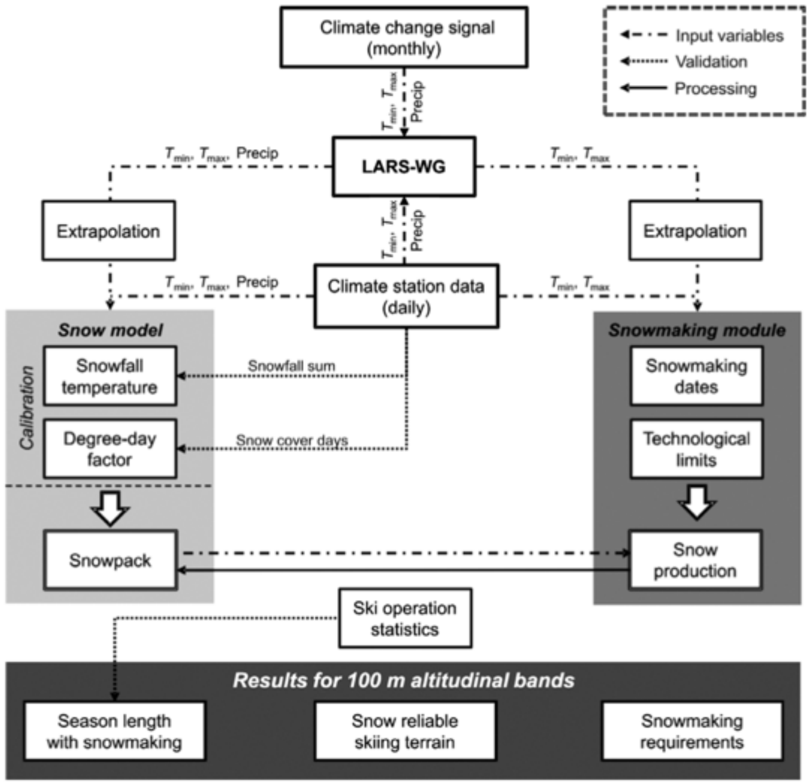


Figure 5. The methodological framework of SkiSim2.0. Source: Steiger 2010.

Natural snow module

The physical model of the natural snowpack was calibrated with observed daily snow depth data throughout the natural snow season (days with snow depth ≥ 1 cm) over the 30-year observation period (1981-2010 baseline). Snowfall and snow depth were obtained from the closest weather station to each ski area in the analysis. Daily temperature and precipitation data from these weather stations were used to simulate the natural snowpack at the analyzed elevation of each ski area. For 14 ski areas, the base elevation was used for analysis, while for the other 5 critical altitude was used (Figure 6). Critical altitude is defined as an area where lift systems allow for partial ski operations in higher altitude (hence, more snow-reliable) sections of a ski area. These areas have a considerable vertical drop and may be characterized by access via a gondola, a mid-station, or a separate system of upper mountain lifts. To adjust for the altitudinal differences between climate stations and analyzed altitudes, a generalized lapse rate for temperatures (0.65°C/100m) and precipitation (3%/100m) was employed.

Figure 6. The 5 resorts for which critical altitude was used. Mammoth Mountain, Palisades Tahoe (formerly Squaw Valley), Northstar, Bear Valley, and June Mountain have base stations at 2715 m, 2434 m, 2475 m, 2362 m, and 2650 m respectively. Critical altitude is defined as an area where lift systems allow for partial ski operation.

For each weather station observed, two important snow model parameters were calibrated: (1) precipitation typing and (2) degree-day factors. In precipitation typing, snowfall temperature is used to define a lower-end temperature threshold for 100% snow, and an upper-end temperature threshold for 100% rain. In between these two thresholds, the snow-rain ratio is linearly interpolated. The second parameter is the degree-day factor, which defines the amount of snow water equivalent (SWE) that is melted per 1°C using mean daily temperature. This parameter increases sinusoidally between December 21st and June 21st. The performance of these two calibrated parameters was investigated using the Pearson correlation coefficient. The natural snow module is calibrated by comparing the number of observed days with snow cover (snow depth threshold of 1cm) over a multi-year period with the number of modeled days with snow cover.

Snowmaking module

After the calibration of the natural snow model, SkiSim2.0 was used to simulate the ski season and identify the need for snowmaking to achieve specified operational snow depth requirements (Table 4). Daily snowmaking hours were calculated by linearly interpolating minimum and maximum temperatures to simulate the daily variation of temperature. To account for ski groomers preparing and smoothing the snow surface of slopes in study areas, a snowpack density after grooming of 400kg/m^3 is assumed (Fauve, Rhyner, and Schneebeli 2002).

Table 4. SkiSim2.0 Parameters

Module	Parameter	Value
Natural Snow Module	Natural Snow Season	snow depth ≥ 1 cm
	Temperaure lapse rate	0.65°C / 100m
	Precipitation lapse rate	3% / 100m
Snowmaking Module	Snowpack density on a ski slope	400kg/m3
	Snowmaking season dates	22 Nov - 31 Mar
	Base layer snowmaking	40 cm
Operational Rules Module	Snowmaking capacity	10 cm/ day
	Minimum snow depth for a skiable day	30 cm
	Temperature threshold for snowmaking	-5 °C
	Emergency snowmaking	-2 °C (12/15 - 1/5)

Snowmaking activity in the SkiSim2.0 model is represented in two ways: (1) early season dense base layer (40 cm) to provide a durable foundation for ski area operations and (2) additional snowmaking to respond to mid-season melts and restore snow in high traffic areas to enable continuous ski operations until season end (typically mid-April to early May in the study area). This study uses a snowmaking season of November 22nd - March 31st, derived from a review of multiple annual snow reports (NSAA 2022). It is important to note that while snowmaking stops on March 31st, if snow depth is sufficient thereafter, these days are counted as part of the operational ski season. Data on the variability of snowmaking capacity at ski areas in this study is not available. Instead, two indicators of snowmaking were utilized: PROD_SNOW, and SNOW_REQ.

Operational rules

To be consistence with previous assessments, the decision rules and capacities for the snowmaking production module are adopted from consultations with ski area managers and snowmaking crews in past studies in the US and Canada (Scott et al. 2019b, 2019c). Ski areas were recorded as closed if snow depth was less than 30 cm on any modeled day during the prescribed operating season (November 15 to April 30th). To estimate changes in the system capacity of all ski resorts in the study area to collectively accommodate current and future ski tourism demand, the 'terrain- days' indicator developed by Scott et al. (2019c) was calculated by summing the number of days skiable terrain (in acres) was operational at each ski area.

Methodological approach to SkiSim outputs

Ski area performance indicators

In this study, the SkiSim2.0 model is used to simulate indicators of ski season lengths, snowmaking requirements, and financial viability for ski areas in the region. These indicators are defined as follows:

1. **Season length.**

SKD_SM: season length (days) with natural snow and technical snow

2. **Snowmaking.**

PROD_SNOW: produced snow (cm), operational limitations
REQ_SNOW: required snow (cm), no operational limitations

3. **Economic viability.**

Econ_Viability: economic viability, defined as (1) operational during the Christmas-New Year holiday period and (2) 100-day or longer season length, both with a probability ≥ 70%.

Interpretation of SkiSim outputs

Using the metrics established in the natural snow module, snowmaking module, and operational rules module, the SkiSim model returns values for each of the 4 indicators (SKD_SM, PROD_SNOW, REQ_SNOW, and Econ_Viability), under 7 climate change scenarios (RCP 2.6, 4.5, and 8.5 & SSP126, SSP245, SSP370, and SSP585), in 3 time periods (2030s, 2050s, and 2080s) for each of the 19 included resorts.

Averaging the California market. Since data on the snowmaking capacity of individual ski resorts is not publicly available, it is difficult to tailor modeling on a site-by-site basis. Thus, a holistic perspective of the California market is taken by averaging the values of all 19 resorts.

Averaging climate change scenarios. The average value of RCP 2.6 & SSP 126 are referred to as low emissions projections, the average value of RCP 4.5, SSP 245 & SSP 370 are referred to as medium emissions projections, and the average value of RCP 8.5 & SSP 585 are referred to as high emissions projections. Visual representations of all 7 emissions pathways will be presented for context.

In sum, projections for 4 ski area indicators under 3 emissions scenarios and 3 time periods are presented (Figure 7).

		SKD_SM Season length with natural and technical snow	**PROD_SNOW** Snow produced given current limitations	**REQ_SNOW** Snow required to ensure a 100-day season	**Econ_Viability** Holiday operations, 100+ day season, ≥ 70%
Low-Emission Scenario	RCP 2.6 SSP 126	2030s	2030s	2030s	2030s
		2050s	2050s	2050s	2050s
		2080s	2080s	2080s	2080s
Medium-Emission Scenario	RCP 4.5 SSP 245 SSP 370	2030s	2030s	2030s	2030s
		2050s	2050s	2050s	2050s
		2080s	2080s	2080s	2080s
High-Emission Scenario	RCP 8.5 SSP 585	2030s	2030s	2030s	2030s
		2050s	2050s	2050s	2050s
		2080s	2080s	2080s	2080s

Figure 7. Methodology for interpreting results. Projections for 4 ski area indicators under 3 emissions scenarios and 3 time periods are presented.

RESULTS

The SkiSim model withstands tests of validity for both baseline and future projections in the 19 analyzed California ski areas. Under low (RCP 2.6, SSP 126), moderate (RCP 4.5, SSP 245, SSP 370), and high (RCP 8.5, SSP 585) emission scenarios, the model consistently points to decreased season lengths and increased snowmaking requirements throughout the California ski market. These changes are progressively more pronounced in the early, mid, and late-century scenarios. Detailed results of the impacts of projected climate change on ski operation performance indicators (ski season length, snowmaking requirements, and economic feasibility), as well as model validation, are provided below.

Model validation

As emphasized by Steiger et al. (2019) and Steiger and Scott (2020), validating model performance is essential for obtaining reliable climate change projections. Thus, it was crucial to ensure that SkiSim2.0 effectively modeled both current ski operations (represented by observed season lengths) and future ski operations (represented by an analogous record-warm season) for the selected study sites.

Validation of baseline using observed season lengths

The evaluation of SkiSim2.0's performance in the current California ski market comprised two key components. First, observed season lengths from 2013-2022 were obtained from SkiCentral.com (referred to as 'measured days'). Second, the baseline season lengths generated in SkiSim2.0 using data from LARS-WG (referred to as 'modeled days') were compared with the observed season lengths. Of the 19 resorts studied, 17 provided data to SkiCentral regularly (at least 85% of the years between 2013-2022). The average observed season length across these 17 resorts was 137 days, while the SkiSim baseline season length (natural and technical snow) was 139 days (Table 5), a disparity of just 2 days.

Table 5. Model Validation using reported season length. Comparison of SkiSim baseline season length estimates (using weather data from 1981-2010) and observed season length reported by SkiCentral.com (data available for 2013-2022 seasons)

			Resort #																		
	Source	**Average**	**249**	**250**	**251**	**253**	**254**	**255**	**256**	**257**	**260**	**261**	**262**	**265**	**266**	**267**	**268**	**272**	**273**	**279**	**282**
Projected Baseline	SkiSim (1981-2010)	141	136	156	153	123	129	127	168	154	126	176	133	172	143	143	146	148	143	70	137
Observed Baseline	SkiCentral (2013-2022)	137	156	136	155	109	115	115	143	222	94	147	136	189	139	106	111	126	123		

Similar studies have also noted that SkiSim overestimates the average season length slightly (Scott et al. 2019, 2021). This disparity is likely due to the model assuming that all ski areas have advanced snowmaking technology covering 100% of terrain. While this is not true for many resorts, information about snowmaking capacity on a site-by-site is not publicly available.

Validation of projected season length using an analogous season

To validate the performance of the model in climate change futures, the observed season length during a recent record-warm winter can serve as an analog for average conditions under mid-century climate change. This analogous season can then be compared with projected season lengths from the SkiSim model for the 2050s. During the record-warm winter of 2014–15[1], the reported ski season length was 106 days. This study projected that, for the average California resort in this study, the mid-century season length under a medium-emissions scenario would be 107 days (Table 6). The near parity of these values provides additional credence to the performance of the SkiSim model.

Table 6. Model Validation using an analogous season. Comparison of SkiSim 2050s estimates under RCP 4.5 (medium GHG emission scenario) and observed season length during an analogous warm-weather season (2014-15, reported by SkiCentral.com)

			Resort #																		
	Source	**Average**	**249**	**250**	**251**	**253**	**254**	**255**	**256**	**257**	**260**	**261**	**262**	**265**	**266**	**267**	**268**	**272**	**273**	**279**	**282**
2050s: Medium-emissions	SkiSim (2050s, RCP 4.5)	107	122	137	57	63	57	135	130	138	91	135	133	132	124	134	131	2	106	76	106
Analogous Season	SkiCentral (2014-2015)	106	130	133	156	104	64	64	130	193	28	148	93	148	107	40	98	82	84	106	

[1] In the 2014-2015 season, record-warm temperatures led to a disastrous snow year. For example, Palisades Tahoe (previously known as Squaw Valley) got 132” of snow, compared to an average of 400” (Palisades Tahoe).

Projected changes in season length under climate change

Season length plays a critical role in determining the long-term viability of a ski area. Since snowmaking is a prevalent practice, the analysis will focus on season length projections that consider both natural and technical snow, represented by the indicator SKD_SM (Table 7).

Table 7. Average ski season length (days). Projected changes in season length under the assumption of 100% snowmaking capacity.

		Low-Emission Scenario RCP 2.6, SSP 126	Medium-Emission Scenario RCP 4.5, SSP 245, SSP 370	High-Emission Scenario RCP 8.5, SSP 585
SKD_SM	**2030s**	121 (-13%)	121 (-13%)	119 (-14%)
Baseline = 139 days	**2050s**	116 (-17%)	106 (-24%)	95 (-32%)
	2080s	111 (-20%)	97 (-30%)	56 (-60%)

The average baseline (1981-2010) season length across the 19 California ski areas was 139 days. On average, early century (2030s) projections show season length losses ranging from 13-14% (a loss of 18-20 skiable days) while mid-century (2050s) projections show season length losses ranging from 17-32% (a loss of 23-44 skiable days). By late century (2080s) the pathways diverge significantly to 20%, 30%, and 60% losses in season length (or 28, 42, and 83 days) under low, medium, and high emissions scenarios, respectively (also depicted in Figure 8).

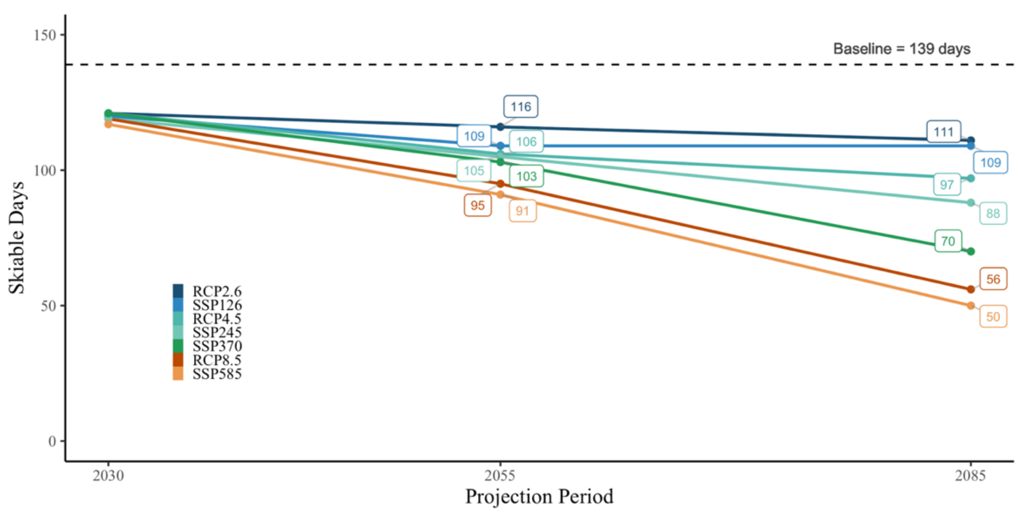


Figure 8. Season length in days with snowmaking. Shown are outcomes for the indicator SKD_SM under all 7 GHG emissions scenarios in the early, mid, and late century.

It is important to emphasize that these projected season-length losses assume that ski areas have advanced snowmaking technology covering 100% of their terrain. Without advanced snowmaking technology, season losses may be even greater, suggesting that future climate conditions in California will exceed adaptive capacity in certain resorts.

Projected snowmaking under climate change

There are two indicators of snowmaking considered in this study. The indicator PROD_SNOW represents the amount of snow produced, as limited by snowmaking rules, while REQ_SNOW represents the amount of snow produced to maintain a 100-day season, regardless of snowmaking limitations.

Produced snow

The indicator PROD_SNOW represents the amount of snow produced, as limited by snowmaking rules. Due to variability in snowmaking infrastructure, ski areas were assumed to have 100% of terrain covered by advanced snowmaking machines. Based on data available in the Ontario market (Rutty et al. 2015) ski areas can typically make 5-10cm/day over their skiable terrain.

This analysis used the upper range of advanced snowmaking (10 cm/day) assuming that ski areas will continue to invest in snowmaking capacity as climate change accelerates. As established in consultations with ski managers (Scott et al. 2003, 2019b), snowmaking in temperatures above -5°C is ideally avoided, as efficiency declines and costs substantially increase. However, one exception to this norm is seen around the economically important Christmas-New Year holiday, in which resorts may activate “emergency snowmaking”. Consequently, SkiSim2.0 activates “emergency snowmaking” between December 15th and January 5th in which snowmaking can occur at temperatures up to -2°C. Under these limitations, snow will be produced if the current combined natural and machine-made snow is insufficient to guarantee an operational ski day (>30 cm) until the end of the snowmaking season on March 31st. This projected value is represented by PROD_SNOW (Table 8).

Table 8. Produced snow (cm) over the duration of the season. Produced snow is restricted by current technological limitations.

		Low-Emission Scenario RCP 2.6, SSP 126	Medium-Emission Scenario RCP 4.5, SSP 245, SSP 370	High-Emission Scenario RCP 8.5, SSP 585
PROD_SNOW	**2030s**	108 (16%)	109 (17%)	109 (17%)
Baseline = 93 cm	**2050s**	114 (23%)	119 (28%)	120 (29%)
	2080s	116 (25%)	123 (32%)	101 (9%)

Adhering to those established operational limits, California ski areas produced an average of 93 cm of snow during the baseline period from 1981 to 2010. Projections for the early century (2030s) and mid-century (2050s) periods reveal that snowmaking increases are expected to range from 16-17% and 23-29%. In the late century (2080s) period snowmaking increases are expected to range from 25% in a low-emissions scenario, 32% in a medium-emissions scenario, and 9% in a high-emissions scenario (also depicted in Figure 9).

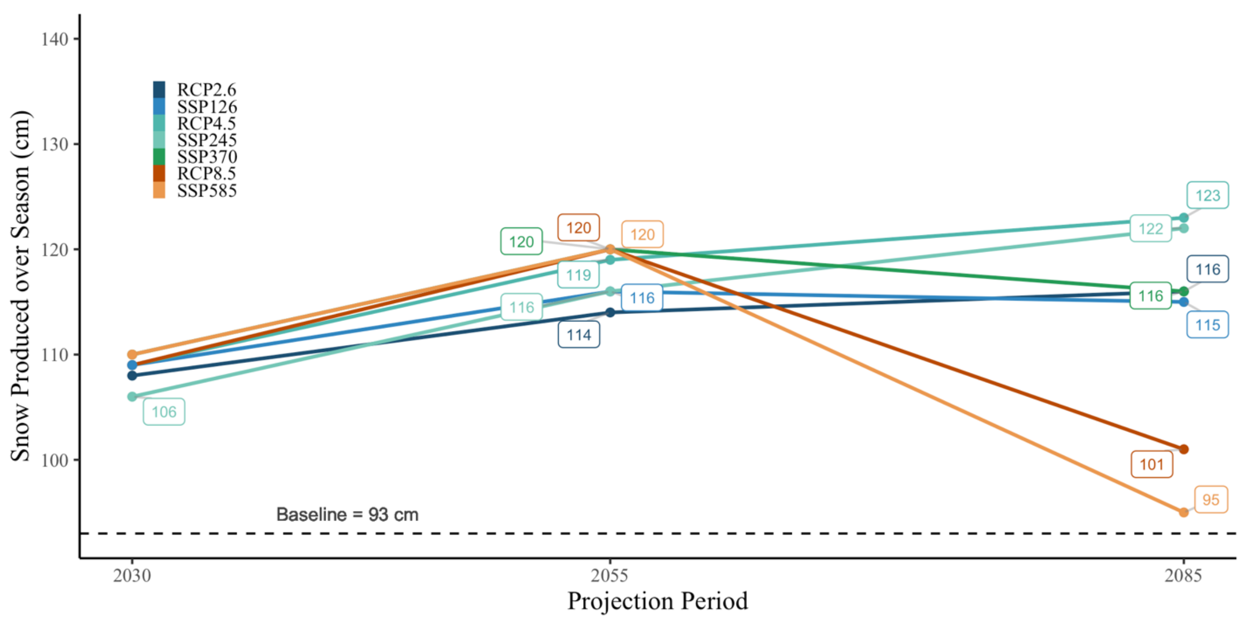


Figure 9. Snow produced over the duration of the season (cm). Shown are outcomes for the indicator PROD_SNOW under all 7 GHG emissions scenarios in the early, mid, and late-century.

It should be highlighted that the greater the increase in ambient temperatures, the less natural snow will occur. Thus, one might expect that high-emissions scenarios would see the greatest increase in PROD_SNOW. However, those same increased temperatures will also limit the ability of ski resorts to produce snow under current operational limits. For example, in the late century (2080s), this study predicts that a medium-emissions scenario would see more snowmaking than a high-emissions scenario (+32% vs. +9%), even though resorts would have a much greater need for technical snow. This decrease in snow production under scenarios where technical snow is most needed emphasizes the overall impact of global warming on the ability of resort stakeholders to operate snowmaking equipment.

Required snow

The indicator REQ_SNOW represents the amount of snow that would be required to maintain desired season length regardless of the current snowmaking restrictions (maximum of 10cm/day, minimum of -5°C) (Table 9). Ignoring these restrictions, snow will be produced if the current combined natural and machine-made snow is insufficient to guarantee an operational ski day (>30 cm) until the end of the snowmaking season on March 31st. The REQ_SNOW indicator is not employed to model season length, as it necessitates a groundbreaking technology that overcomes current operational constraints in a scientifically and economically feasible manner. Nevertheless, it provides valuable insights into the potential financial and environmental implications of such a technology, should it be developed.

Table 9. Required snow (cm) over the duration of the season. Required snow ignores limitation and represents the amount of snow needed to maintain a 100+ day season.

		Low-Emission Scenario RCP 2.6, SSP 126	Medium-Emission Scenario RCP 4.5, SSP 245, SSP 370	High-Emission Scenario RCP 8.5, SSP 585
REQ_SNOW	**2030s**	126 (66%)	127 (67%)	130 (71%)
Baseline = 76 cm	**2050s**	144 (89%)	172 (126%)	198 (161%)
	2080s	158 (108%)	199 (162%)	303 (299%)

California ski areas require an average of 76 cm of machine-made snow under current climate conditions to maintain a continuous ski season from December 15th to March 31st. However, climate projections indicate a significant increase in the required amount of snow, ranging from 66-108% in the early century, 67-162% in the mid century, and 71-299% in the late century (also depicted in Figure 10). These projections make clear that, even with unhampered snowmaking technology, ski area stakeholders would need to considerably increase technical snow production to maintain a continuous ski season under all climate scenarios and time periods.

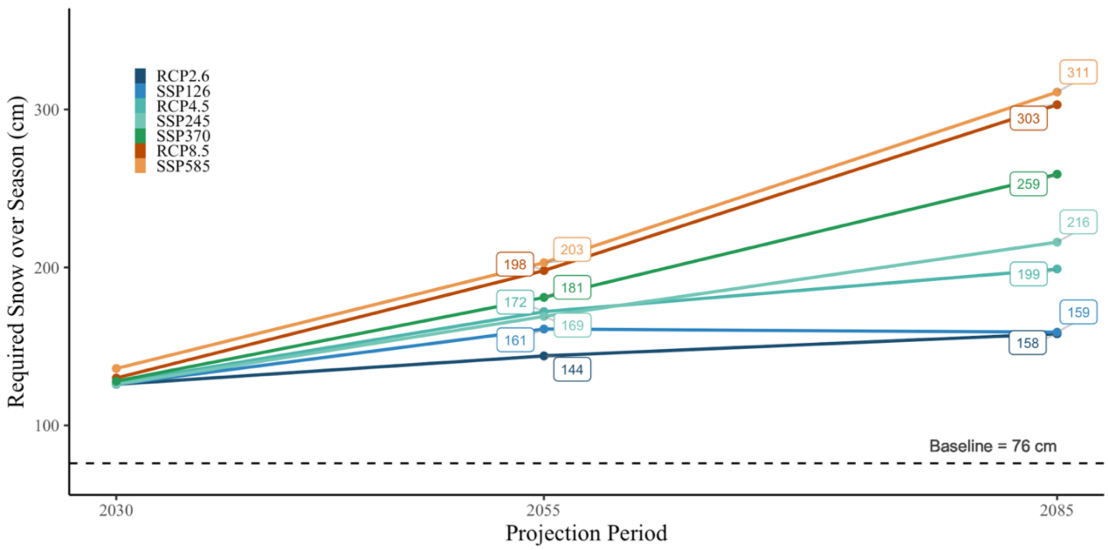


Figure 10. Snow required to maintain a 100-day season (cm). Shown are outcomes for the indicator REQ_SNOW under all 7 GHG emissions scenarios in the early, mid, and late-century.

Economic viability

To assess the economic feasibility of a ski area under different future climate scenarios, it is necessary to evaluate two fundamental indicators identified in the existing literature. Firstly, certain segments of the ski season have outsized importance in terms of skier visits and revenues, particularly the Christmas - New Year's holiday (Scott et al. 2006, 2007, 2019b, 2019c, 2019d). Thus, continuous operation during the 20 Dec – Jan 4 should be sustained for 70% of all years. Secondly, the "100-day rule", or sufficient snow cover (at least 0.3m) for at least 100 days, has been widely used in the field as a tool to assess the economic vulnerability of ski areas to climate variability (i.e. Abegg and Frosch 1994, Elsasser and Bürki 2002, Scott and McBoyle 2007). Thus, to be considered economically viable a season length of 100 days or more should be sustained in 70% of all years (Table 10).

Table 10. The number of economically viable resorts. Projected changes in economic viability for only 3 GHG emissions scenarios (RCP 2.6, 4.5, 8.5) are shown to enhance interpretability.

		Low-Emission Scenarios RCP 2.6, SSP 126	Medium-Emission Scenarios RCP 4.5, SSP 245, SSP 370	High-Emission Scenarios RCP 8.5, SSP 585
Econ_Viability	**2030s**	14 (-22%)	14 (-22%)	14 (-22%)
Baseline = 18 resorts	**2050s**	14 (-22%)	12 (-33%)	10 (-44%)
	2080s	13 (-28%)	10 (-44%)	2 (-89%)

Currently, 18 out of 19 (or 95%) resorts in this study are deemed economically viable, as they fulfill the dual economic indicators of (1) sustaining operations during the Christmas-New Year holiday period and (2) maintaining a 100-day or longer season length, both with a probability ≥ 70%. However, under low-emission scenarios, the number of economically viable ski areas in California is projected to decline to 14 by mid-century. This decline is even more pronounced under medium and high-emission scenarios, with only 12 and 10 ski areas, respectively, maintaining economic viability during the same period. By late century, the discrepancy between low- and high-emission scenarios becomes considerably more significant. Under a low emissions scenario, 13 of California's resorts are projected to remain economically viable, whereas, under a high emissions scenario, merely 2 resorts are expected to endure (also depicted in Figure 11).

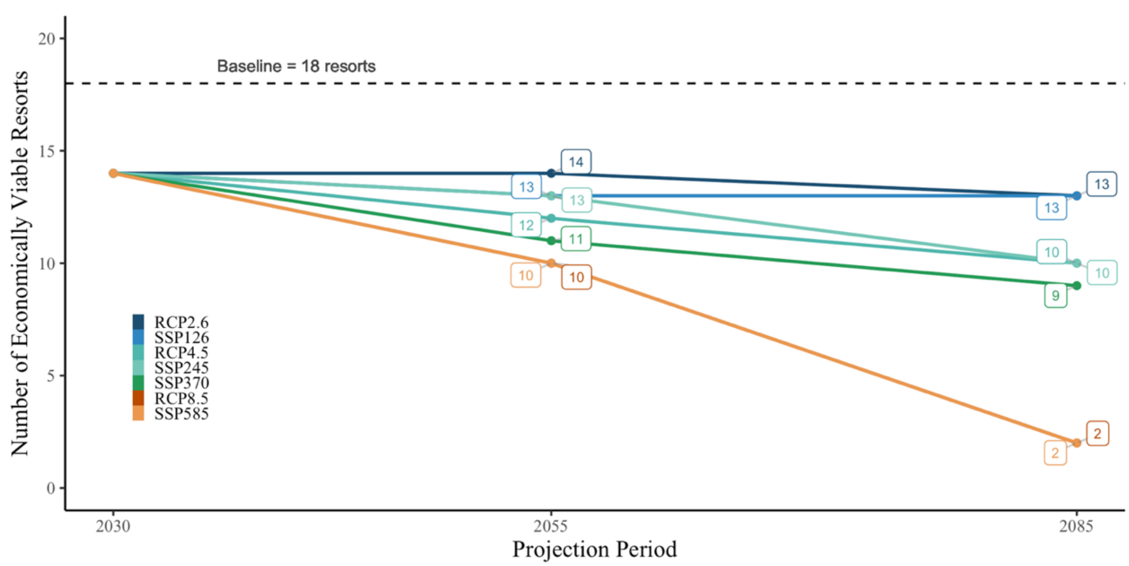


Figure 11. The number of economically viable resorts. Shown are outcomes for the indicator Econ_Viability under all 7 GHG emissions scenarios in the early, mid, and late-century.

The trends depicted in Figure 11 only take the probability of a 100-day-season and holiday operations into account. It is essential to recognize that variations in these indicators will affect individual ski areas in distinct ways, depending on factors such as:

1. Financial determinates, i.e., operating cost-revenue structure and access to capital and financial reserves,
2. Business model, i.e., public vs. private, primarily ski business vs. four-season resort, real estate development/management, etc, and
3. Other influential factors include demographics, transportation access, destination reputation, climatic resources, snowmaking capacity, and infrastructure age/efficiency (Falk 2009, Falk and Steiger 2020, Gonseth 2013).

For example, a small-medium sized enterprise (SME) with limited cash reserves and capital access may succumb to a series of poor seasons, while a ski area that is part of a multi-property conglomerate can weather poor seasons and access capital to diversify revenues. Consequently, it is crucial to note that the economic viability of many smaller ski areas in the region, which currently operate with less than 100-day season lengths, may differ from the indicators utilized in the existing literature. Unfortunately, much of this business information remains proprietary and inaccessible to researchers. Further consultation with ski areas exhibiting diverse ownership and business models is necessary to thoroughly assess this finding.

DISCUSSION

Climate change presents a continuous and evolving risk to the ski industry, with projections pointing towards shorter ski seasons, increased snowmaking requirements, and decreased economic viability in the California ski market (Figure 12). This discussion encompasses a summary of the findings, a comparison with previous studies conducted in the region, an exploration of inter- and intra-market redistribution, and an examination of current adaptation and mitigation measures.

Key findings

		SKD_SM Season length with natural and technical snow	**PROD_SNOW** Snow produced given current limitations	**REQ_SNOW** Snow required to ensure a 100-day season	**Econ_Viability** Holiday operations, 100+ day season, ≥ 70%
Low-Emission Scenario	RCP 2.6 SSP 126	2030s: -13% 2050s: -17% 2080s: -20%	2030s: +16% 2050s: +23% 2080s: +25%	2030s: +66% 2050s: +89% 2080s: +108%	2030s: -22% 2050s: -22% 2080s: -28%
Medium-Emission Scenario	RCP 4.5 SSP 245 SSP 370	2030s: -13% 2050s: -24% 2080s: -30%	2030s: +17% 2050s: +28% 2080s: +32%	2030s: +67% 2050s: +126% 2080s:+162%	2030s: -22% 2050s: -33% 2080s: -44%
High-Emission Scenario	RCP 8.5 SSP 585	2030s: -14% 2050s: -32% 2080s: -60%	2030s: +17% 2050s: +29% 2080s: +9%	2030s: +71% 2050s: +161% 2080s: +299%	2030s: -22% 2050s: -44% 2080s: -89%

Figure 12. Summary of results. Shown are outcomes for the indicators SKD_SM, PROD_SNOW, REQ_SNOW, and Econ_Viability under low, medium, and high emissions scenarios in the early, mid, and late-century.

Season length losses

This study suggests that season length losses are projected to range from 13-14% in the early century (a loss of 18-20 skiable days) and 17-32% in the mid-century (a loss of 23-44 skiable days), and 20-60% in the late century (2080s) By late century (2080s) the pathways diverge significantly to 20%, 30%, and 60% losses in season length (or 28, 42, and 83 days) under low, medium, and high emissions scenarios, respectively.

Increases in produced snow

Projections indicate that under current snowmaking limitations, production increases are expected to range from 16-17% in the early century (2030s) and 23-29% in the mid-century

(2050s). In the late century (2080s), snowmaking increases are projected to range from 25% in a low-emissions scenario, 32% in a medium-emissions scenario, to 9% in a high-emissions scenario.

Greater increases in required snow

Climate projections indicate an even more significant increase in the amount of snow required to maintain an economically viable season (100 + days & holiday operations, 70% of years), ranging from 66-108% in the early century, 67-162% in the mid-century, to 71-299% in the late century. Crucially, the technology to produce snow at this scale is not yet available.

Decline in the number of economically viable resorts

By mid-century, under low-emission scenarios, the number of viable ski areas in California is projected to decrease to 14. This decline worsens under medium and high-emission scenarios, with 12 and 10 economically viable resorts respectively. By the late century, there is a significant disparity between low and high-emission scenarios, with 13 resorts projected to be viable under low emissions compared to only 2 resorts under high emissions.

Comparative Analysis

To situate these results within the broader framework of knowledge on climate risk for the California regional market, it is necessary to compare them with findings from other relevant studies. To date, Hayhoe et al. (2004) and Winton (2013) constitute the only known academic research on the impact of future climate change on the ski industry in California.

Hayhoe et al. (2004): "Emissions pathways, climate change, and impacts on California"

In a study examining emissions pathways, climate change, and their impacts on California, Hayhoe et al. (2004) arrived at a few conclusions that align with the overarching predictions of this study. They anticipate reduced ski season length due to diminished snowpack resulting from potential climate change. The study emphasizes that the impacts are most likely to manifest during the early season.

However, Hayhoe et al. present far more pessimistic predictions than those of this study. Hayhoe et al. contend that by 2100, ski season length will be reduced by 49-103 days using the PCM model, while "under the HADCM3, similar delays occur by mid-century" for all elevations under 3000 meters above sea level (masl). Given that all California ski resorts have base areas at elevations lower than 3000 masl, the average resort is anticipated to experience season losses of 49-103 days. In contrast, this study forecasts mid-century losses of 26, 33, and 44 days under low, medium, and high emissions scenarios, respectively, which are significantly smaller than even the lowest end of Hayhoe et al.'s predictions.

The excessively pessimistic projections in Hayhoe et al.'s study can be attributed to several factors. Notably, their projections do not incorporate the use of snowmaking technology. As previously established, the use of snowmaking technology has long been widespread throughout Eastern North American ski markets, and a key finding of Scott et al. (2006) was that studies that did not include snowmaking had underestimated the current ski season length and vastly overestimated the impact of climate change. Moreover, Hayhoe et. al lack context for the reductions projected. They do not provide a quantified baseline season length from which projected reductions occur, nor do they provide a percentage reduction that would indicate the length of the remaining ski season. As an example, in their more severe projections, season length is reduced by 103 days, however, Hayhoe et al. (2004) do not indicate how many days this was reduced from nor the length of the season remaining.

In sum, the work of Hayhoe et al. (2004) provides important insight into the future of snow water equivalent (SWE) in California, as their methodology is proven in assessing this variable. However, their projections of the impact of climate change on the ski industry are overly negative and misrepresent the outlook of this industry. Based on the results of this study, it is reasonable to assert that climate change poses a significant threat to winter alpine tourism in the state, but not to the extent previously projected. This finding is important for climate risk management decisions by the ski industry, their destination communities, and institutional and real estate investors that are increasingly considering the climate risk of publicly traded companies and the tourism sector (Steiger et al. 2019).

Winton (2013): "The Impact of Climate Change on the Ski Industry in Colorado and California"

In a study of the impact of climate change on the ski industry in Colorado and California, Winton (2013) applied the SkiSim2.0 model to two Colorado ski resorts and one California resort. Although both studies employ the SkiSim2.0 model, notable distinctions in approach include:

1. **Scope.** Winton's research focused on case studies of three resorts only one of which, Palisades Tahoe (previously known as Squaw Valley), is in California, whereas this research presents a market-wide analysis of 19 ski areas in the state.
2. **Baseline data.** The studies employ different baseline periods, separated by a 20-year gap: 1961-1990 (Winton 2013) vs. 1981-2010 (Blelloch 2023).
3. **Climate change scenarios.** Winton (2013) uses 4 climate scenarios: the Goddard Institute for Space Studies B1 (GISS B1) scenario, the Canadian Centre for Climate Modeling and Analysis B1 (CCCMA B1) scenario, the Model for Interdisciplinary Research on Climate A1B (MIROC A1B) scenario, and the Institut Pierre Simon Laplace A1B (IPSL A1B) scenario. GISS B1, and CCCMA B1 are referred to as the 'least change' scenarios, while IPSL A1B, and MIROC A1B are referred to as the 'most change' scenarios. This study employs more recently updated climate scenarios from the World Climate Research Programme's CMIP-5 and CMIP-6: RCP 2.6 & SSP 126 (low emissions), RCP 4.5, SSP 245, SSP 370 (medium emissions), and RCP 8.5 & SSP 585 (high emissions).
4. **Parameters.** Winton employed derived temperature lapse rates, resulting in a shorter baseline season length due to higher extrapolated temperatures. The current study, on the other hand, models outcomes using either monthly local temperature lapse rates or the annual average lapse rate of 0.65°C/100m. Additionally, this study includes projections of economic viability, represented by the probability of both holiday operations and 100+ day seasons in greater than 70% of years.
5. **Independent variables.** Winton used altitude as an independent variable, producing 2050s projections for each of his 4 climate change scenarios at a minimum, mean, and maximum altitude. This study held altitude constant at either a base or critical altitude and explored three distinct temporal periods - early, mid, and late-century - contrasting with Winton's emphasis on the mid-century.

While these methodological differences preclude direct comparisons of the findings, it is reasonable to compare Winton's "best case" and "worst case" projections with this study's mid-century (2050s) "low emissions" and "high emissions" scenarios (Table 11). Employing this closest possible comparison of outputs between the two studies, some clear patterns of variation are evident:

Table 11. Season length with snowmaking, season length without snowmaking, and required snow production: Winton (2013) and Blelloch (2023). Approximate comparisons can be made between the "low emissions" projections in this study and the "best case"/ "mean altitude" projections in Winton (2003).

			% Change in 2050s (mid-century)	
Projections for Palisades Tahoe	**Indicator**	**Baseline**	**("best case" / "low emission")**	**("worst case" / "high emission")**
Winton 2013 *	SKD_NAT	152 days	-6%	-43%
Blelloch 2023 **	SKD_NAT	160 days	-9%	-25%
Winton 2013	SKD_SM	154 days	-2%	-16%
Blelloch 2023	SKD_SM	172 days	-14%	-17%
Winton 2013	REQ_SNOW	16 cm	22%	374%
Blelloch 2023	REQ_SNOW	22 cm	45%	223%

* In Winton 2013, projections are made for base, mean, and peak altitudinal bands. The "mean" projections are utilized for this comparison.
** In this study, generalized lapse rate for temperatures (0.65°C/100m) and precipitation (3%/100m) were utilized (see Methods for more details)

Low emissions future. Winton (2013) projects lesser impacts than the present study in the "best case"/"low emission" scenarios in 3 indicators: a change of -6% vs. -9% in ski season length with only natural snow, -2% vs. -14% in ski season length with snowmaking, and +22% vs. +45% in required snowmaking volume.

High emissions future. Winton (2013) projects higher impacts than the present study in the "worst case"/"low emissions" scenario: a change of -43% vs. -25% in ski season length with only natural snow, -16% vs. -17% in ski season length with snowmaking, and +374% vs. +223% in required snowmaking volume.

Due to such deep methodological differences, hypothesizing the reasons for these disparities in projections would be extrapolation. However, the general trends align, suggesting that both studies support similar overarching theories within this body of literature. However, the updated parameters (temperature lapse rates & climate change scenarios), more current baseline period (1961-1990 vs. 1981-2010), and broader scope (1 resort vs. 19) of the current study offer a broader picture of the long-term prospects of the California ski industry.

Inter-market redistribution: Relative climate risk within the North American ski market

Although numerous studies have been conducted across different regions worldwide, comparing results remains challenging due to the diverse methodologies employed. However, the SkiSim model has been utilized in multiple North American markets, enabling the analysis of inter-regional competition in studied US and Canadian states. Specifically, Scott et. al. 2019 (US & Canadian Northeast) and Scott et al. 2021 (US Midwest), and the present study employed the SkiSim2.0 model with variables, climate change scenarios, and snowmaking rules. This facilitates a direct comparison between the projections for the states examined in those studies and the projections for the present study (Table 12). To maintain brevity only results for medium-emission scenarios in the 2050s and 2080s are presented.

Table 12. North American SkiSim studies. Results for RCP 4.5 (medium-emission scenario) mid and late-century projections for the regions in this table are compared. Data obtained from Scott et al. 2021; Scott et al. 2019c.

Scott et al. 2021: US Midwest	Scott et al. 2019: US Northeast
Iowa	Québec
Illinois	Ontario
Indiana	New Hampshire
Michigan	Maine
Minnesota	Connecticut
Missouri	Massachusetts
Ohio	New York
South Dakota	Vermont
Wisconsin	Rhode Island
Midwest Average	Northeast Average

Season length and economic viability

Upon analysis of various SkiSim studies of North American regions, it has been observed that California ski resorts experience a reduction in season length comparable to the median (50th percentile) decrease (Figure 13a). California resorts fare even better in metrics of economic viability (an indicator that considers the likelihood of a 100-day-season and holiday operation). Under a medium emissions (RCP 4.5) scenario, 13 of the 19 surveyed resorts are expected to remain economically viable until the midcentury, with 10 retaining their viability until the late century (Figure 13b).

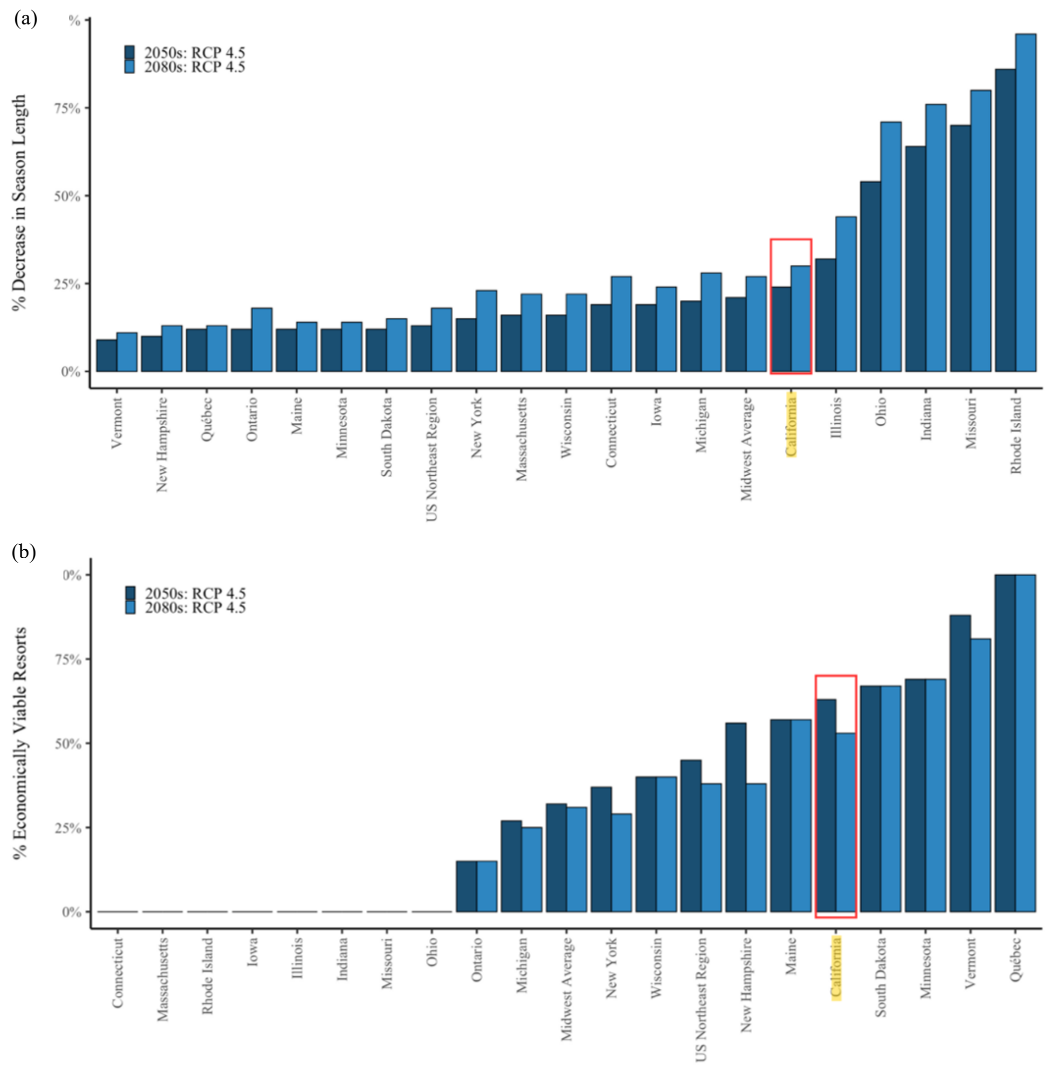


Figure 13. A comparison of projected changes in season length (a) and the number of economically viable resorts (b) across surveyed North American regions. Results shown are for RCP 4.5 (medium-emission scenario) mid and late-century projections. Data obtained from Scott et al. 2021; Scott et al. 2019c

This retention of economic sustainability places California in the 75th percentile of surveyed North American resorts. These results are undoubtedly encouraging, as it indicates that the California ski industry may not be as severely impacted as anticipated, despite the state's high climate-risk status. However, it should be noted that in *all* surveyed North American regions, researchers have concluded that the viability of the ski industry is at risk, underscoring serious concerns even for those regions that perform comparatively well (Steiger et al. 2019). Perhaps even more crucial to recognize is that achieving the medium-emissions scenario considered in this comparison is far from guaranteed. By incorporating a range of climate scenarios, this study allows for a comprehensive evaluation of potential climate impacts and mitigation options. However, it is critical to emphasize that widespread policy change is required to meet low or even medium-emissions targets (i.e., Figure 14).

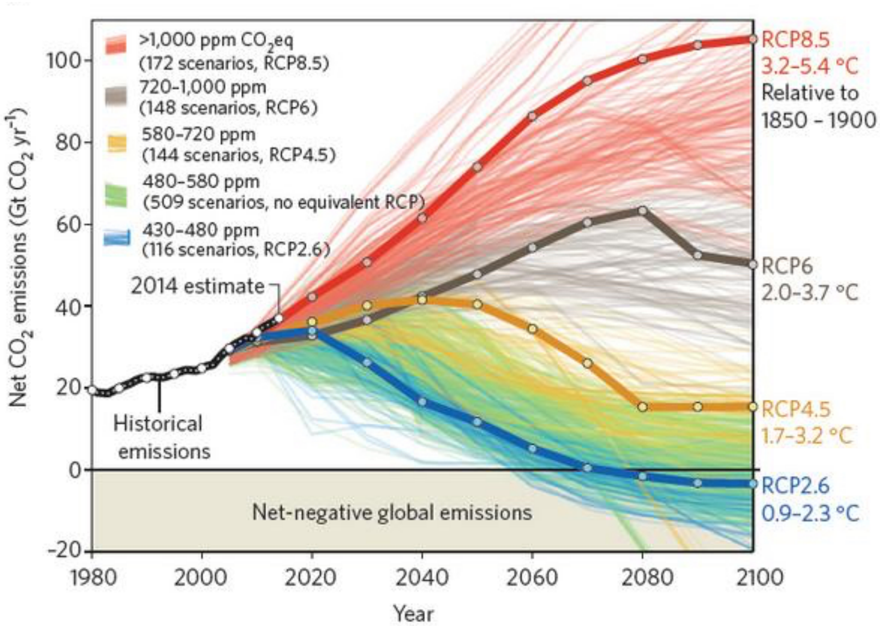


Figure 14: Emissions are currently on course for a likely temperature increase of 3.2-5.4°C above pre-industrial levels. Significant and sustained mitigation efforts are needed to maintain temperature rise below 2°C. Source: CATO Institute

Snowmaking

Snowmaking is currently the most crucial adaptation to climate variability, and many ski area operators are confident that with ongoing advancements in snowmaking techniques and sustained investment, they are well-equipped to handle the climate challenges in the future (Steiger 2019). Unsurprisingly, the direct impact of climate change on snow resources (natural and snowmaking capacity) and its consequences for the ski industry have been the primary focus of research within the literature on climate change and ski tourism. The SkiSim model predicts that California will experience relatively low increases in snowmaking needs in the 2050s, ranking in the 20th percentile compared to other states (Figure 15). However, by the 2080s, California's snowmaking requirements are projected to exceed or match those of many other states.

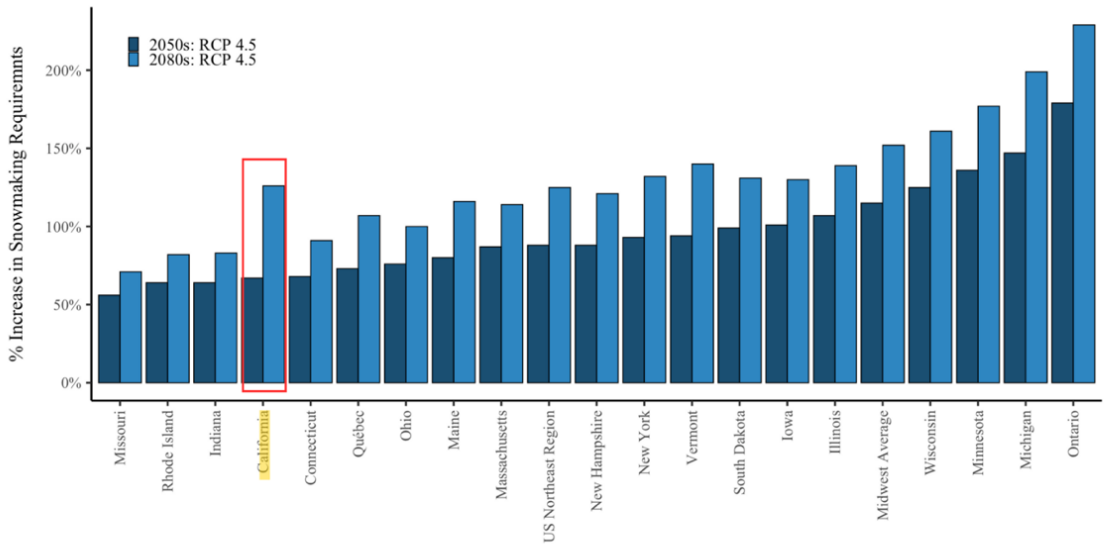


Figure 15. A comparison of projected changes in snowmaking requirements across surveyed North American regions. Results shown are for RCP 4.5 (medium-emission scenario) mid and late-century projections. Data obtained from Scott et al. 2021; Scott et al. 2019c.

Despite its effectiveness in allowing ski areas to better withstand and recover from the impact of a poor season, snowmaking is constrained by the requirement for sufficiently cold temperatures for cost-effective snow production, and hence, it has physical and economic limitations (Scott and McBoyle, 2007). Although some of these constraints will be counteracted by technological improvements that generate an increase in snowmaking capacity and allow for production at warmer temperatures (Steiger 2012), such adaptations can prove to be both financially and environmentally taxing as climate change accelerates (Rutty et al. 2015).

Fortunately, California's commitment to low-carbon grids enables increased snowmaking that keeps skier trips local and reduces emissions in the tourism system. This commitment contrasts with regions such as the Midwest, where the high carbon-intensity electricity grids make snowmaking a maladaptive solution (Scott et al. 2021). On the other hand, California is already grappling with water scarcity and water rights will continue to be one of the most contentious issues in state politics. To increase their snowmaking coverage, these resorts would need to expand their allocation rights, which is not only likely to land them in fierce competition with agricultural, residential, and industrial stakeholders but could become even more challenging in the future due to projected water supply reductions (Fox 2019).

Intra-state redistribution: Assessing relative risk within the regional market

Although California may be relatively safe from inter-state redistributions of market share, evidence from other markets suggests that intra-state redistribution may be highly likely (Pickering 2011, Rutty et al. 2015). This study produces projections for the average California ski resort, and consequently, mathematically predicting the redistribution of market share between individual resorts is beyond the scope of this paper. In general, it is challenging to generalize findings to identify specific resorts with higher climate resilience due to climatic heterogeneity at both macro and meso scales (Steiger et al. 2019). However, market characteristics, such as destination reputation, proximity to large population centers, and the number of competitors, among others, also play a significant role (Scott and McBoyle 2007, Steiger and Abegg 2018). In particular, the results of this study indicate that the size, elevation, and ownership status of resorts will be pivotal distinctions in California.

The literature has long established that smaller, lower-elevation ski areas are more vulnerable to season length and visitation losses during record-warm seasons. This vulnerability is often compounded by their exclusion from conglomerates, which places the burden of snowmaking expansion and energy costs solely on these smaller resorts (Steiger et al. 2019). Conversely, larger ski resorts situated at higher elevations may experience an increase in market share as smaller ski areas are compelled to shut down. This trend is particularly prominent if larger ski resorts are incorporated into conglomerates, which possess greater financial resources to withstand the potential impact of climate change (Scott and McBoyle 2007).

Of the 26 ski resorts in California that have two or more lifts, 14 are owned by large conglomerates (Figure 16). These conglomerates and their respective owned resorts include Alterra (Alpine Meadows, Mammoth, Palisades Tahoe, Snow Summit, Snow Valley, Big Bear), Vail (Kirkwood, NorthStar California), Invision Capital (Dodge Ridge, Mountain High, China Peak), and Powdr (Soda Springs, Boreal) (NSAA 2023). Given the established vulnerability of small, independent ski resorts, the projections presented in this study suggest that the 12 independently owned California resorts (Granlibakken, Alta Sierra, Badger Pass, Tahoe Donner, Donner Ski Ranch, Homewood, Bear Valley, Sugar Bowl, Mount Waterman, and Mount Baldy) may be forced to join conglomerates or face a high risk of closure in a warming world.

Included

Size	Resort	Ownership
Small Resort: 0-500 skiable acres 0-7000 skiers/hour	Granlibakken Tahoe	Independent
	Alta Sierra	Independent
	Badger Pass Ski Area	Independent
	Tahoe Donner	Independent
	Soda Springs	Conglomerate: Powdr
	Boreal Mountain	Conglomerate: Powdr
	Mount Shasta	Independent
Medium Resort: 500-2000 skiable acres 7000-16,000 skiers/hour	Donner Ski Ranch	Independent
	Dodge Ridge Mountain Resort	Conglomerate: Invision Capital
	Homewood Mountain Resort	Independent
	June Mountain	Conglomerate: Alterra
	Bear Valley Resort	Independent
	Sierra-At-Tahoe	Independent
Large Resort: 2000-4000 skiable acres 16,000-50,000 skiers/hour	Sugar Bowl Resort	Independent
	Kirkwood Mountain Resort	Conglomerate: Vail
	Alpine Meadows	Conglomerate: Alterra
	Northstar California Resort	Conglomerate: Vail
	Mammoth Mountain	Conglomerate: Alterra
	Palisades Tahoe	Conglomerate: Alterra

Excluded (lack of climate station)

Size	Resort	Ownership
Small Resort:	Mountain High Resort	Conglomerate: Invision Capital
	Snow Summit Ski Area	Conglomerate: Alterra
	Snow Valley Ski Area	Conglomerate: Alterra
	Mount Waterman Ski Area	Independent
	Big Bear Mountain Resort	Conglomerate: Alterra
Medium Resort:	Mt. Baldy Ski Area	Independent
	China Peak Ski Area	Conglomerate: Invision Capital

Figure 16. The size and ownership structure of 26 California resorts. Presented are the 19 resorts included in the analysis, and the 7 resorts excluded due to lack of climate data. Independently owned resorts are highlighted in red, resorts with corporate ownership structures are highlighted in green. Ownership data obtained from NSAA 2023.

Prior studies examining skier spatial substitution intentions have demonstrated the critical significance of preserving intra-market spatial substitution capacity to avoid losing ski tourism to the regional economy (König 1998, Pickering 2011, Rutty et al. 2015). In short, it is possible that only resorts that have been incorporated into larger conglomerates may survive. However, it should be emphasized that this expected redistribution of market share will not be without downstream impacts. Smaller, individually operated ski areas are a popular choice for beginner and family skiers in California. These areas, often referred to as "nursery" ski areas, play a crucial role in cultivating the next generation of skiers, and their closure could have long-term implications for future market participation (Knowles 2019, Rutty et al. 2015).

Even disregarding the fate of these small resorts, increased market share does not always translate positively for larger, more institutionalized resorts. Climate-resilient destinations may experience a significant increase in skier intensity under long-term high-emissions scenarios, potentially doubling the number of visitors per acre (Scott et al. 2021). This increase in skier intensity offers the opportunity to generate increased revenues per acre of terrain, which could potentially offset higher operational costs. Nevertheless, when crowding exceeds individual preferences, skiers may be unwilling to pay higher prices, as noted by Bausch et al. (2019).

It is important to note that the impact of climate change on ski tourism is not limited to ski resorts alone. Mountain towns, in particular, depend heavily on this industry and may face significant locational disadvantages, including limited accessibility, agricultural potential, and suitable areas for development (Steiger et al. 2019). As a result, these communities may find it difficult to develop alternative economic industries, further underscoring the impact of climate change on the regional economy (Scott et al. 2019a). Although further research is necessary to investigate market distribution in California, it is evident that adaptive capacity will differ at the business, destination, and regional market scales. Therefore, resorts and mountain communities must be prepared for both supply and demand-induced changes to ensure an effective response to these shifts.

Efforts towards resilience: Adaptation and mitigation at California ski resorts

With the consequences examined in this study already materializing, California resorts are taking measures to prepare for warmer winters. First, various ski areas throughout the state are already implementing innovative adaptation strategies. Heavenly Resort has received permits from the U.S. Forest Service to widen 12 runs near its base and remove obstacles on 11 other trails to make them safer, more enjoyable, and cheaper to cover with artificial during warm, dry years. Additionally, the resort has installed 200 high-efficiency snow guns, 20,000 feet of piping, and four pump houses, providing artificial snow coverage to over 70% of its slopes. (Cestone 2018). Heavenly's objective to enhance snowmaking efficiency is shared by numerous other resorts. Palisades Tahoe and Sugar Bowl have each allocated almost $10 million to acquire new snowmaking equipment, including snow guns that can independently adjust to weather conditions by the minute (Fox 2019).

In addition to technical innovations, many resorts are committing to four-season recreation, offering various activities and programming throughout the year. Downhill mountain biking serviced by lifts has become a natural transition for numerous ski resorts across the state. Big Bear Mountain Resort's Snow Summit Bike Park, where ski trails have been replaced with more than 100 miles of biking trails, has experienced tremendous success (Big Bear Mountain Resort). Palisades has established a “via ferrata”, or a mountain climbing route equipped with safety gear, and plans to build a mountain coaster similar to the one installed in Heavenly in 2016 (Fox 2019). Additionally, resorts are organizing microbrew festivals, zip lines, climbing walls, and outdoor movie series to attract visitors year-round (Peterson 2023). Michael Reitzell, the president of Ski California, accurately captured the drive for all-season experiences at the resort, remarking, “If we can’t turn things around, at least in the time that we need to from a climate solution standpoint … Hey, mountain biking is really fun, too.” (Fox 2019).

On top of adaptation efforts, numerous California resorts are proactively endeavoring to mitigate their climate impact. Situated three hours southeast of Lake Tahoe, the old Railroad town of Luning, Nevada houses a 50-megawatt solar array that supplies power to one-fourth of Liberty Utilities' customers, including its largest private client, Palisades Tahoe (Fox 2019). For years, the entire Olympic Valley depended on coal-fired power; however, since 2018, Palisades (and its sister resort, Alpine Meadows) have been procuring electricity from the Luning solar array. Concurrently, the resort is collaborating with Liberty and Tesla to construct a mountainside battery "microgrid" for electricity storage during periods of low demand and discharge during high demand or power outages (Fox 2019). This initiative has made these two California resorts the first in the nation to attain a 100% renewable electricity supply (Locker 2018).

Efforts to curtail emissions do not end there: Boreal Mountain recently installed 715 solar panels atop its indoor sports facility, which the resort claims will save $1.5 million in energy expenses over the next 30 years (Martin 2018). A few miles away, Soda Springs now utilizes 100% recycled water for all snowmaking endeavors. Heavenly, Northstar, and Kirkwood, as members of Vail Resorts, have adopted the company's ambitious "Epic Promise" – a commitment to eradicate all emissions and waste directed to landfills by 2030 (Martin 2018). While these efforts alone will not entirely shield California resorts from the impacts of climate change, the industry's active pursuit of adaptive measures and environmentally responsible practices undoubtedly represents a significant stride in the right direction.

LIMITATIONS

Despite the demonstrated validity of the SkiSim model in the California context, this study is subject to several limitations. Firstly, there exist inherent in modeling weather data. The standardized lapse rates for temperature and precipitation employed in this study may not be accurate for all locations, and are not actually linear, as was assumed in this study. To mitigate this, high-altitude weather stations would be needed to determine lapse rates that better reflect local climate conditions in the vicinity of ski areas. Unfortunately, these weather stations are rare and not easily accessible, making it difficult to utilize this approach in a regional, market-wide study such as this one.

Secondly, the accuracy of snowmaking predictions is constrained by the availability of data and modeling capabilities. This study employed an air temperature of -5°C as the threshold for snowmaking (and -2°C for emergency snowmaking), but snowmaking is influenced by factors such as humidity and wind. Incorporating these factors would be beneficial, but it presents a challenge in downscaling air humidity and wind speed/direction to the local level. Furthermore, the lack of publicly available information on snowmaking capacity at privately owned resorts necessitated the assumption of 100% snowmaking capacity across the market. This assumption gives ski areas in the region a tremendous benefit of the doubt: As of 2022, only 10.2% of skiable terrain in the NSAA Pacific Southwest Region (which includes California, Nevada, and Arizona) was covered by snowmaking (NSAA 2022). As a result, season length and economic viability losses may have been underestimated.

Finally, 7 of the 29 resorts considered could not be modeled with the available data due to incomplete climate station records. Notably, five of these sites are major ski destinations in the Los Angeles region (Figure 17). These Southern Californian resorts are already facing higher temperatures and more significant water rights challenges than their Northern Californian counterparts. Consequently, the results of this study may not fully account for the cumulative impact of climate change on California's ski tourism market. However, these resorts have a crucial advantage in that many are owned by large ski resort conglomerates allowing them to more easily endure grim seasons and access capital to diversify revenues.

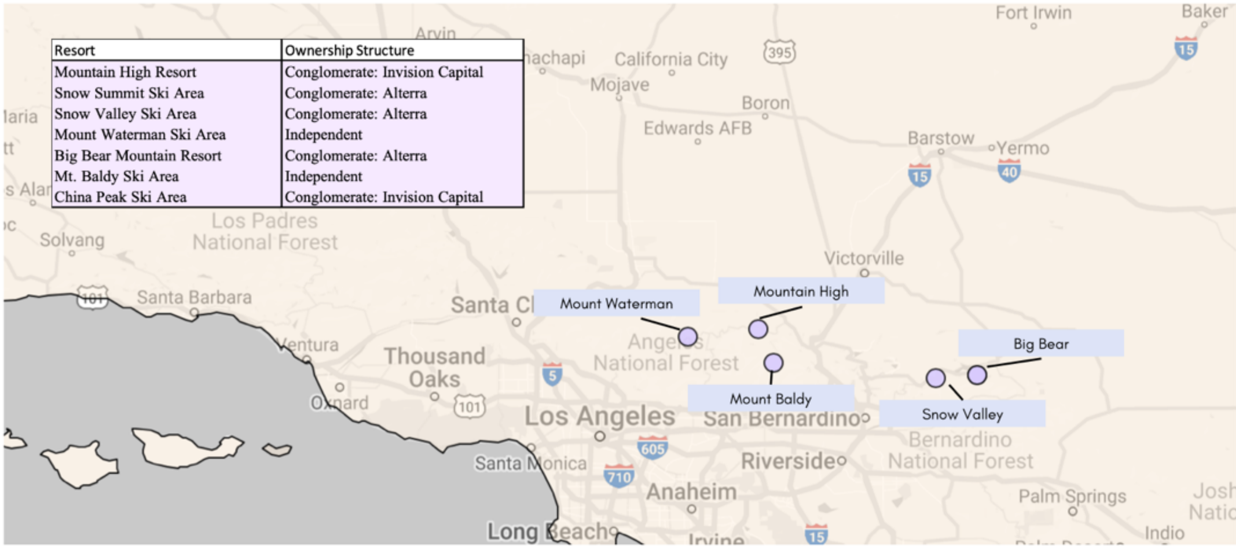


Figure 17. Ski Areas in the Los Angeles metropolitan area. Of the 7 resorts excluded due to the lack of an acceptable climate station, 5 are in this region.

CONCLUSIONS

This study constitutes the first academic attempt to present a holistic analysis of the interaction between the California ski industry and potential climate change. By projecting the impacts of climate change on the industry using up-to-date scenarios and considering different timeframes, this research offers valuable insights for industry decision-makers and local communities. It sheds light on the climate risks specific to the California region and their potential consequences for market competitiveness, providing a solid basis for developing practical adaptation strategies based on scientific evidence. A few central conclusions emerge from this paper. Firstly, the study reveals that regardless of the climate change scenario (low or high emissions), predictions indicate that (1) the average ski seasons in California's regional markets will shorten, (2) the demand for snowmaking will increase even as opportunities for it decrease, and (3) California resorts will face increasingly suffocating financial pressure.

These projected climate change impacts will not be uniform, altering intra- and inter-regional market competitiveness among California ski resorts. Although California may not face significant redistributions of market share among different states, intra-state redistribution is highly likely. Smaller, lower-elevation ski areas are more vulnerable to season length and visitation losses during warm seasons, while larger resorts situated at higher elevations may gain market share as smaller ski areas are forced to close. This trend is particularly pronounced when larger resorts are part of conglomerates and consequently have greater financial resources to withstand the potential impact of climate change. These impacts will likely reinforce the historical consolidation of the ski industry, however, both highly vulnerable and climate-resilient ski tourism destinations will need to adapt to climate change. In short, while skiers may resist the consolidation of their local mountains, it is possible that only resorts incorporated into larger conglomerates will survive, regardless of potential downstream consequences.

Lived GHG emission pathways will be the crucial determinant of the ski industry’s survival. In an emission pathway consistent with the Paris Climate Agreement (RCP 4.5), the data presented in this study suggest that by mid-century, the average California ski season will be over 30 days shorter, and six of the 19 resorts studied may have already closed. While these losses are still concerning, they do not signify the industry's end. In stark contrast, a high emission, Business-As-Usual scenario (RCP 8.5) would disrupt parts of the ski tourism market by mid-century and devastate it by late-century. In this sense, two contrasting futures for the ski industry exist, and it becomes clear that global mitigation policy will determine ski tourism’s future both in California and on a global stage.

In sum, California's ski industry should strongly promote stringent climate mitigation strategies to minimize the anticipated consequences of high emissions. Although California ski areas are undoubtedly showcasing resort-by-resort adaptation and emissions reduction initiatives, they must persist in emphasizing their responsibility to act on a broader scale. After all, if the current trajectory of emissions remains unchecked, Californians will face more pressing concerns than a mediocre Tahoe ski season.

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