CLIMATE VARIABILITY AND CHANGE: THE ECONOMIC VULNERABILITY OF THE SKIING INDUSTRY AND SURROUNDING COMMUNITIES IN ARIZONA, USA

(DRAFT DO NOT CITE WITHOUT PERMISSION OF AUTHORS)

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ABSTRACT

Climate change models predict declining snow pack, shorter and more variable snow seasons, warmer winter temperatures with increased incidence of winter snowpack melt and sublimation loss, earlier spring snowmelt, and an increase in the elevation at which seasonal snowpack can be maintained. The implications are significant for the ski industry because beginner skiers tend to learn at lower elevation 'local' ski areas [1] and these same skiers are more likely to quit if ski seasons are poor [2]. Adaptation strategies such as snowmaking can reduce climate change vulnerability [3] by increasing snow pack depth, durability and season reliability. However, snowmaking is expensive; costs, excluding capital costs, range between $500 and $4,000 per acre foot of snow depending on system efficiency [4], and crucially for the southwest snowmaking also requires large volumes of water[2] [5]. Previous research has focused on low elevation ski resorts in Europe and Canada, this paper adds to the literature by investigating the impacts of climate variability and change on low latitude, high elevation ski resorts in Arizona, USA. Arizona ski areas experience high inter-annual variability in snow reliability in terms of total snow pack, season length, and season timing. Severe winter drought conditions are common, for example in the 1983/84 and 2001/02 seasons. Such seasons, may preview longer term climate change impacts. Two case studies in Arizona, Sunrise Park and Snowbowl, highlight the opportunities and challenges of manmade snowmaking as an adaptation strategy to climate change and also to more general climate variability.

INTRODUCTION

The predictions of climate change models: less snow, reduced snow pack, and shorter and more erratic snow seasons, with more pronounced effects at lower elevation, are worrisome for ski[3] industries around the world. Less research has been done on the impacts of climate change on low latitude, high elevation ski resorts, such as those that predominate in the southwest USA. However, this research does inform this study about the likely threats and how mitigation and adaptation strategies might reduce the economic vulnerability of two Arizona ski resorts, Sunrise and Snowbowl, and their surrounding communities to climate variability and change. Of particular economic concern is the possible impact climate change will have on Sunrise which is a more marginal alpine community that is heavily dependent on winter recreation.

Assessments of climate change impacts on ski resorts have been completed in Australia [7, 2], Austria [8], Canada [9, 10], Scotland [11], Switzerland [12, 13] and the United States [14]. All these studies predict that climate change will have negative consequences for low elevation ski resorts: without adaptation strategies ski resorts will have to make a profit during a shorter season. Warming is predicted to reduce snow cover and thereby fewer days in the season will meet *minimum* operational snow base for winter sports. These thresholds vary with the sport: 10 cm for cross country skiing, 30 cm for downhill skiing and snowboarding, and >30 cm above the tree line in rocky terrain [1, 3]. Mountain managers may decide not to open their specific resort until natural and manmade snow base is deeper than these minimums. In fact Arizona's ski resorts have higher snowpack minimums than

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[2] 1 acre foot of snow = 139,222 gallons or 527,011 liters of water.

[3] We use 'ski industry/resort' as shorthand for ski and snowboard industry and 'skiers' for skiers and snowboarders.

those above: Snowbowl's snowmaking base requirement is 64 cm [15] whilst Sunrise's two snowmaking expansion plans quote a low of 36 cm to a high of 61 cm.[4] Reasons for these higher thresholds are the high elevation of the ski resorts both of which are above the tree line: elevation at Sunrise ranges from 2,836m to 3,354m and at Snowbowl from 2,805m at the base to a peak 3,506m, consequent steeper slopes, and losses in the dry interior climate [16]. Additionally it is difficult to imagine that many skiers would be satisfied with the experience of skiing on a 30 cm snow base. Possible reasons for the difference between the two sites are the steeper slopes, high wind conditions, and the suboptimal southwest-west aspect of the Humphrey's pod of ski slopes at Snowbowl. Average snow conditions are similar at both resorts. These examples illustrate that the impact of climate variability and change needs to be addressed on a site-by-site basis that takes account of snow conditions, snow requirements, and the economics of the ski enterprise.

Breiling and Charamza [1] investigated the probable impacts of climate change on the ski industry in Austria. This study is relevant for Sunrise, although Austria is located at a high latitude (47º-48º), many of its ski areas are located in small alpine communities that are dependent on winter tourism. Sunrise is just such a resort; it is located in the somewhat remote White Mountains of central eastern Arizona. The Austrian study predicts that a 2°C warming will reduce snow cover by between 47% and 79%, from a 1965-1995 baseline. The forecast reduction in skiable days is greater because of the minimum snow depth required for winter recreation. They note that even with the warming there will still be around one year in two where snow depth is within the range of the baseline data. Such increased unpredictability is highly damaging to this infrastructure-intensive industry. They posit that a 2°C warming will necessitate strong adaptation, and that the costs of increased snowmaking may make all low elevation ski resorts uneconomic thereby restricting skiing to higher elevations. They conclude that a minimum elevation of 400 m is necessary for profitable winter tourism in Austria. A similar study in the northwest USA suggests a 75 cm to 125 cm reduction in average snow depth and the movement of the mean altitude ski lift (masl in meters) from 900 masl to 1,250 masl [6].

[4] Personal communication.

Not only is the shift in masl a concern for individual ski resorts but it has implication for the wider ski industry. For example, skiing in many parts of the world is currently concentrated at low elevations with easy access to population centers. Winter recreation research has shown that these small, 'community', opportunistic ski areas are essential to the growth of the industry as they cater to novices, families, and skiers getting in shape before a longer vacation at a larger ski resort. For example, Scott, McBoyle and Mills [3] report that 45% of skiers in Toronto, the largest single market of active skiers in Canada, travel less than one hour to ski. In Arizona, Snowbowl operators estimate that day visitors account for 65.5% of total visits whilst destination (overnight) skiers make up 36.4% of total visits [15, p3-87], however, after the expansion and with more consistent operation they anticipate that the proportion of destination skiers will increase to 42% of the total [15, p3-92] . These examples confirm McBoyle and Wall's [9] insight that small regional ski areas are important in developing ski industry. Sunrise has a program that is directly growing the sport in Arizona: local under-12 year olds receive free season passes.

The timing of snowfall is crucially important to the economics of the ski industry [1]. For example, in Austria adequate snow pack over the Christmas and New Year holidays and in February is essential for a good season. In the White Mountains and Snowbowl timing is also crucial[5] and can sometimes be more important than snow abundance. For instance the 2000/01 ski season was good from a revenue perspective at Sunrise, even though snowfall was lower than average, because snow

[5] The peak days in the Arizona ski season are Christmas-New Year, Martin Luther King weekend, Tucson's Rodeo week, college and school Spring breaks, every weekend during the season, and Thanksgiving, given early snowfalls.

accumulated in October and was present over the decisive Thanksgiving and Christmas-New Year holiday season [17]. The timing of snowfall also in part determines the competitive positions of Snowbowl vis-à-vis Sunrise. For example in the 2004/05 season Snowbowl received early snow opening on November 26, whilst Sunrise was played catch up as it’s season got a slow start, only picking up after large snowfalls early in 2005.

An important concept is “snow reliability” [18]. In Switzerland the ‘reliability’ threshold is assumed to be 7 out of 10 good winter seasons, with a snow cover depth of 30-50 cm, for a minimum 100 days between December 1 and April 15. Currently, just 85% of Swiss ski resorts meet this snow reliability test. However, if, as per one climate change scenario, snow reliability were to rise to 1,500 m in the period 2030-2050, only 63% of all resorts would meet this test. The authors conclude that “climate change will lead to a new pattern of favoured and disadvantaged ski tourism regions. If all other influencing factors remain the same, ski tourism will concentrate in the high-altitude areas that are snow-reliable.” Such an outcome is not only a concern for the resorts and surrounding communities in the lower elevation preAlps but also for the ecologically sensitive Alps region where pressures to expand skiing are likely to increase.

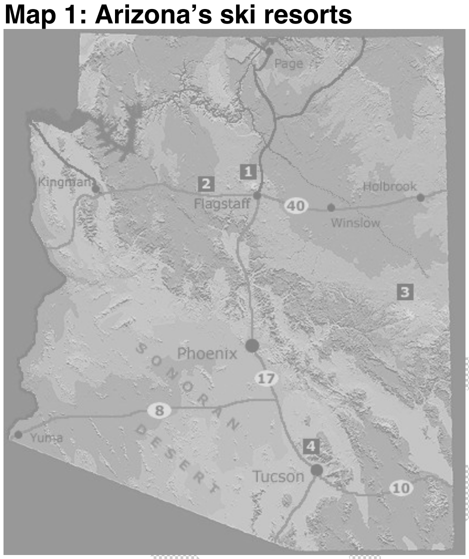
The concept of snow reliability is a good one. However, we would add one additional requirement for our study areas: the number of *consecutive* poor snowfall seasons that can be withstood. The reason for this addition is that a string of, for example three poor seasons in ten, is likely to have a greater impact on the financial viability of Sunrise and Snowbowl than three poor seasons spaced equally over a ten year period. In fact Snowbowl experienced just such a scenario and wishes to avoid a repeat of such year-on-year losses by investing in snowmaking. Before the banner 2004/05 season, Snowbowl recorded four unprofitable operating seasons (1996, 1999, 2000 and 2002) in the last eleven. The combination of poor seasons and the capital intensive nature of the industry meant that all net cumulative profits over the period were reinvested in ongoing maintenance and capital improvements [15]. Other factors are also important for reliability, such as threshold maximum temperatures and rainfall during the ski season which may hasten early ski resort closure [19]. Specific reliability or profitability thresholds are established by the mountain mangers for Sunrise and Snowbowl. However, if managers rely exclusively on natural snowfall some seasons will fall short of these thresholds. Snowmaking would enable the resorts to more consistently meet minimum operational days during the season: Snowbowl has set a goal to consistently operate 125 days per season plus or minus 15% [15, 3-112] whilst Sunrise usually operates 122 days during the season, but, in the relatively snow poor 2003/04 season only operated 100 days. Consistent operation is important both for consumers and suppliers of snow-based recreation. Many skiers would prefer to plan their skiing activity and vacations with certainty, certainty that may be absent if resorts rely on natural snow, whilst consistency allows managers to fully utilize lift, lodge, and snowmaking infrastructure and staff throughout the season.

Climate change is a long-term threat to the ski industry. Scott, McBoyle and Mills [3] argue that climate change is a “catalyst that will reinforce and accelerate the pace of structural change” in the ski industry. They note that the ski industry is increasingly two-tiered with large four-season high elevation resorts and small less profitable and less attractive low elevation resorts. However, they also argue that gradual warming will give the industry time to adapt and those with fewer constraints will, whilst those resorts that exit the industry, will do it in an actively planned manner. But, for smaller, lower elevation resorts, such as Williams and Mt. Lemmon, Arizona a couple of consecutive poor seasons combined with land ownership and water resource constraints may usher more rapid restructuring which in turn will impact local economies.

Arizona’s ski resorts

Arizona has four ski resorts, two of which are very small and therefore not discussed further, the larger two are Snowbowl which is near Flagstaff, and the largest resort, Sunrise Park near Greer. Map 1 shows the locations of all four ski resorts in the state. Table 1 summarizes ski resort statistics from Arizona's and nearby, competitor resorts. It also records mean values and the Snowbowl expansion plan data. In-state competitors are important because none of Arizona's four ski resorts are world class; they mainly cater to in-state residents. Two-thirds of Snowbowl's visitors are day trippers whilst Sunrise estimates that eighty percent of its around 200,000 annual skier visits come from in-state, with the remainder drawn from New Mexico, Southern California, and Mexico [20]. However, it is important to take a regional assessment approach [3] because a proportion of Arizona skiers can, and do travel, to other nearby resorts, particularly if snow conditions are poor in the state. Additionally, skiers from the other Four Corner states travel to Arizona if the ski conditions are good relative to their own, for example Sunrise was one of the few southwestern resorts with good snow during the 1998/99 season and benefited from large numbers of out-of-state visitors. Several factors will determine how any single ski resort fares with respect to climate variability and change: the relative impact of climate change on the resort and its competitors (a function of elevation, aspect, humidity, snow patterns, etc) and any resultant changes in intra and inter-regional skiing market share, the costs of additional snowmaking, how adaptation by skiers could alter skiing demand, and the impact of other adaptation strategies such as business diversification and weather derivatives and insurance [3].

Map 1: Arizona's ski resorts



Key: 1 = Arizona Snowbowl Ski Area, 2 = Bill Williams Ski Area, 3 = Sunrise Park Ski Resort, and 4 = Mt. Lemmon Ski Area.
Source: http://southwest-vacation-travel.net/arizona/ski-area-map.htm

Table 1: Arizona, New Mexico, and southern Colorado Ski Areas

	ARIZONA					NEW MEXICO							
	Sunrise Park	Snowbowl	Snowbowl after expansion	Williams Ski Area	Mount Lemmon Ski Valley	Angel Fire Resort	Pajarito Mountain	Red River Ski Area	Sandia Peak Ski Area	Sipapu Ski Area	Ski Apache	Ski Santa Fe Resort	**Taos Ski Valley**
Trail													
Total trails	65	32	>32	7	18	71	37	58	30	31	55	44	110
Runs (%)													
Beginner	40	37	32	30	58	31	20	32	35	20	20	20	24
Intermediate	40	42	32	50	20	48	50	38	55	50	35	40	25
Advanced	20	21	16	20	22	21	30	30	10	30	45	40	51
Longest run (km)	4.43	3.22	~4.13	1.21	2.59	5.15	1.93	4.02	4.02	2.14	3.70	4.83	9.25
Mountain													
Skiable area (ha)	324	55	83	12	28	180	113	117	81	28	304	267	524
Elevation peak (m)	3,353	3,505	3,505	2,484	2,789	3,254	3,173	3,155	3,163	2,821	3,505	3,674	3,602
Elevation base (m)	2,835	2,804	2,804	2,286	2,499	2,621	2,804	2,667	2,645	2,499	2,926	3,156	2,806
Annual snowfall (cm)	635	635	635	381	508	533	381	554	318	330	470	572	775
Snow making % of terrain	10	--	100	--	--	52	--	87	15		33	45	100
Night skiing	Yes	No	No	No	No	Yes	No	No	No	No	No	No	No
Lift													
Total lifts	10	5	9	2	3	6	6	7	7	4	11	5	12
Lift capacity (person/hr)	16,000	4,960	~7,500	850	2,000	5,770	6,500	6,720	4,500	2,900	16,500	7,800	15,500
Other													
Snowboard	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Cross-country	16 km	40 km	40km	No	No	22 km	No	No	47 km	3 km	No	No	No
Tubing	Yes		Yes	Yes				Yes	No	No	No	No	Yes

Source: www.ski-guide.com

Table 1 continued: Arizona, New Mexico and southwestern Colorado Ski Areas

	COLORADO											
	Durango Mountain Resort	Hesperus Ski Area	Telluride Ski Resort	Wolf Creek Ski Area	Silverton Mountain	Crested Butte Mountain Resort	Monarch Ski and Snowboard Area	Powderhorn Resort	Aspen Highlands	Aspen Mountain Ajax	Buttermilk	**Snowmass**
Trail												
Total trails	75	13	84	77		85	54	29	130	76	42	
Runs (%)												
Beginner	23	30	24	20		10	21	20	18		35	6
Intermediate	51	20	38	35		25	37	50	30	48	39	50
Advanced	26	30	38	25	50	8	42	15	16	26	26	12
Expert		20		20	50	57		15	36	26		32
Longest run (km)	3.22	1.68	7.40	3.22		4.18	1.61	3.54	5.63	4.83	4.83	8.53
Mountain												
Skiable area (ha)	486	32	688	647	-	428	271	206	320	272	174	1,255
Elevation p (m)	3,299	2,707	3,737	3,628	4,054	3,707	3,646	3,002	3,559	3,417	3,018	3,813
Elevation b (m)	2,680	2,469	2,659	3,139	3,170	2,858	3,289	2,499	2,451	2,422	2,399	2,470
Annual snowf (cm)	660	381	785	1181	1016	757	889	635	762	762	508	762
Snow making % of terrain	21	--	15	--		57		15	14	31	26	17
Night skiing	No	Yes	No	No	No	No	No	No	No	No	No	No
Lift												
Total lifts	11	2	16	6	1	14	5	4	4	8	9	21
Lift c (person/hr)	15,050		21,168	8,280		18,160	6,100	4,370	5,400	10,755	7,500	27,984
Other												
Snowboarding	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cross-country	No	No	30 km	6 km	No	70 km	No	No	No	65 km	No	65 km
Tubing	Yes	Yes	Yes	No	No	No	No	No	No	Yes	No	No

Source: www.ski-guide.com

Table 1 continued: Arizona, New Mexico and southwestern Colorado Ski Areas

	COLORADO							
	Sunlight Mountain Resort	Ski Cooper	Beaver Creek Resort	Breckinridge Ski Resort	Keystone Resort	Arapahoe Basin Ski Area	Copper Mountain Resort	**MEAN**
Trail								
Total trails	**67**	**26**	**146**	**146**	**116**	**69**	**125**	
Runs (%)								
Beginner	**20**	**30**	**34**	**15**	**12**	**15**	**21**	
Intermediate	**55**	**40**	**39**	**33**	**29**	**45**	**25**	
Advanced	**20**	**30**	**27**	**52**	**5**	**20**	**36**	
Expert	**5**				**54**	**20**	**18**	
Longest run (km)	**4.02**	**2.26**	**4.43**	**5.63**	**4.83**	**2.41**	**4.51**	
Mountain								
Skiable area (ha)	**190**	**162**	**658**	**894**	**753**	**198**	**985**	**341**
Elevation peak (m)	**3,016**	**3,566**	**3,487**	**3,962**	**3,719**	**3,978**	**3,753**	**3,379**
Elevation base (m)	**2,403**	**3,200**	**2,256**	**2,926**	**2,835**	**3,261**	**2,960**	**2,710**
Annual sn (cm)	**635**	**635**	**787**	**775**	**584**	**932**	**711**	**675**
Snow making % of terrain	**12**	**--**	**37**	**25**	**49**	**25**	**16**	**32**
Night skiing	**No**	**No**	**No**	**No**	**Yes**	**No**	**No**	
Lift								
Total lifts	**4**	**5**	**16**	**24**	**21**	**6**	**22**	**8**
Lift (person/hr)	**4,600**	**3,300**	**30,739**	**36,680**	**35,175**	**8,700**	**30,630**	**10,610**
Other								
Snowboarding	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Cross-country	29 km	25 km	32 km	23 km	18 km	No	No	
Tubing	No	No	No	No	No	No	Yes	

Source: www.ski-guide.com

Table 1 shows that Sunrise and Snowbowl are small resorts compared to many in the region, are average elevation, but low compared to the largest Colorado resorts, and have limited snowmaking capability compared to the average, and in particular compared to the world class Colorado and New Mexico resorts. In summary Snowbowl and Sunrise have relatively good conditions for 'local' ski resorts but have lower snow reliability as a result of lower elevation and limited snowmaking capabilities compared to the larger Four Corners resorts.

The White Mountain Apache Reservation is located in central east Arizona. It covers 6,480km^2 with elevation ranging from 1,846 m to 3,538 m. The US Department of Commerce's Economic Development Administration funded the development of skiing in the White Mountains in the 1970s. Prior to the development of the ski industry the White Mountain Apache tribe relied on summer-based businesses, such as forestry work and wildfire defense, camping, hiking and hunting. One consequence of such seasonality was that infrastructure and employees were underutilized out-of-season [17]. However, these investments have also made the tribe and surrounding communities more dependent on snow-based recreation and therefore more vulnerable to winter-based climate variability and change. Meanwhile, Snowbowl is the state's northern most ski resort. It has a good location lying 25 km north of the third largest city in the state, Flagstaff, and two hours drive from the largest city in the state, Phoenix and four hours drive from the second largest city in the state, Tucson. In contrast Sunrise is four and a half hours drive from both Phoenix and Tucson and is surrounded by small towns with small populations. However, Snowbowl is a much smaller resort than Sunrise and has some competitive disadvantages vis-à-vis Sunrise.

There are a number of competitive differences between the Sunrise and Snowbowl that offer some opportunities for Sunrise. However, it is important to note that management at Sunrise believes that a good season for Snowbowl is a good season for Sunrise because it increases interest in the sport and because many Arizona skiers ski at both resorts for variety of experience. Sunrise is located on the White Mountain Apache reservation whereas the other three resorts in the state are constrained by their location on USFS land; any plans to expand facilities must pass an environmental impact statement (EIS). Sunrise is the largest resort in Arizona and the only resort to offer night skiing, limited snowmaking, and a casino. It is also the only resort to offer on-site lodging at the 100 room Sunrise Lodge. It also has a nearby RV park. The other resorts are restricted by US Forest Service regulations that prohibit such on-site lodging.

Skier visitation data for Sunrise is not available, but, we have data on skier visitation for the state for the period 1995/96 through 2004/05 and for Snowbowl from 1981/82 through 2004/05. Using both sets of data we can calculate skier visitation at Sunrise and the two smaller resorts in the state, Williams and Mt. Lemmon. Skier visitation at these smaller resorts is minimal and therefore the remainder accounts well for Sunrise visitation. We can see from Table 2 that Snowbowl experiences large fluctuations in visitor numbers whilst visitor numbers are steadier at Sunrise. This is in part due to limited snowmaking capability at Sunrise. Nevertheless, it is interesting to note that although Sunrise is almost six times larger than Snowbowl that in good snow years skier visits are the same at both sites. This reflects the superior location of Snowbowl which is nearer large population centers.

Table 2: Arizona ski visitation and Snowbowl data

		Snowbowl		Arizona	Sunrise (Mt Lemmon, Wiliams)
Season	Snowfall, cm	Days open	Skier visitation		
1981-1982	673.1	123	63,000		
1982-1983	701.04	135	99,626		
1983-1984	193.04	64	28,913		
1984-1985	675.64	118	114,707		
1985-1986	533.4	124	105,252		
1986-1987	736.6	112	125,026		
1987-1988	462.28	92	119,259		
1988-1989	431.8	79	120,132		
1989-1990	609.6	74	99,280		
1990-1991	591.82	112	106,000		
1991-1992	914.4	134	173,000		
1992-1993	1168.4	130	181,000		
1993-1994	558.8	114	116,388		
1994-1995	657.86	122	176,778		
1995-1996	287.02	25	20,312	102,575	82,263
1996-1997	685.8	109	153,176	365,787	212,611
1997-1998	838.2	115	173,962	384,665	204,583
1998-1999	381	60	35,205	246,941	211,736
1999-2000	457.2	45	66,152	243,685	177,533
2000-2001	690.88	138	162,175	355,780	193,605
2001-2002	220.98	4	2,875	214,135	211,278
2002-2003	523.24	96	87,354	277,361	190,007
2003-2004	368.3	120	72,000	238,420	164,420
2004-2005*	1168.4	133	190,000	370,000	180,000

Source: [15, Arizona data from Kottke Survey]
*Snow and visitation data based on news reports. Season length was estimated using season start and end dates (Nov 26-April 10) minus an estimated 3 days for blizzard condition closings.

Arizona's winter precipitation variability

Arizona's climate is subject to several climate oscillations that singularly and in combination produce high inter-annual and decadal winter precipitation variability that in turn impacts snow season consistency. On an annual time scale the Pacific/North America (PNA) teleconnection and the North Atlantic Oscillation (NAO) contribute to high inter-annual precipitation variability. The PNA teleconnection relates to the position of the ridges and troughs in the polar jet stream in the upper troposphere. The PNA teleconnection describes shifts in the jet stream path in terms of positive and negative values. A positive PNA index describes the 'usual' position of the polar jet stream, with a pronounced ridge over the western US and a strong trough over the eastern US. During this typical pattern the southwest receives very little winter precipitation and this phase has been linked with winter droughts for example during 1976-1977. The strength of the positive PNA phase is also affected by the NAO. A negative NAO phase reinforces positive PNA conditions, bringing dry winters to the southwest. During a PNA negative phase Arizona receives above average winter precipitation. The important climatic oscillation that influences winter precipitation in Arizona on a decadal time scale is the El Niño Southern Oscillation (ENSO). Warm (positive) phase, El Niño conditions bring above normal winter precipitation in Arizona, for example the abundant snowfall 2004/05 season, whilst cold (negative) phase, La Niña conditions bring drier conditions. This phase is more reliably dry in Arizona than the warm phase is wet.

Longer term climate cycles, such as the Pacific Decadal Oscillation (PDO), also have a distinct impact on winter precipitation variability in Arizona. The PDO, like ENSO, has two phases, negative and positive, but unlike ENSO events which are typically limited to a year or two, the duration of the PDO cycle is around 30 years. The positive phase PDO is similar to the warm phase (El Niño) of the ENSO, whilst the negative phase PDO has similar conditions to the cool phase (La Niña) of the ENSO cycle [21]. Negative PDO conditions are associated with regional drought in the Southwest. Significantly, research has found that PDO interacts with the shorter-term ENSO cycle, enhancing or weakening La Niña and El Niño climate conditions [22]. For example, a positive PDO enhances typical El Niño conditions and weakens La Niña conditions whilst a negative PDO enhances typical La Niña conditions and weakens El Niño conditions. These interactions may be crucial to understanding winter precipitation variability in Arizona; concurrent positive PDO and warm phase ENSO cycles result in above normal winter precipitation and positive PDO cycles modulate the typical dry winter effect of the cold phase ENSO cycle.

The climate may be entering a new cold phase of the PDO cycle. Shifts in the past have occurred about every twenty to thirty years, for example there was a shift from a cold PDO to a warm PDO in around 1925, then to a cold PDO in 1947, and then to a warm PDO in 1977. The importance of such a shift is that the negative PDO weakens El Niño conditions, conditions that bring above normal winter precipitation to Arizona, and strengthens La Niña conditions, conditions that bring lower than normal winter precipitation. Furthermore, such a shift is also significant because longer term climate interactions between the positive phase of the Atlantic Multidecadal Oscillation (AMO) and the negative phase of the PDO have in the past signaled mega droughts in the southwest, such as in the 1950s [23]. Although droughts remain largely unpredictable, there is concern that the current drought in the southwest could persist due to North Atlantic warming and concurrent PDO cooling. This same combination could also signal poor snowfall conditions in the southwest.

Using data from Sunrise we tested whether the climate signals of ENSO, and the PDO modulation of ENSO on winter snowfall are detectable. The data used in the statistical analysis[6] was obtained from a snow course data station at Mt. Baldy.[7] This is the closest measuring station to Sunrise with consistent data. The snow course data recorded snow depth and SWE[8] six times per season in the period 1983-2004.

Model 1 used the 132 snow course observations and tested for the ENSO signal:

$$\text{Snow depth} = \beta_0\,\text{intercept} + \beta_1\text{ENSO} + \varepsilon \quad [1]$$

The results of the model are:
Adjusted R-squared = 0.22,
$\beta_0 = 50.88$, $t = 19.94$ and $pr>|t| = <.0001$, and
$\beta_1 = 14.30$, $t = 6.12$ and $pr>|t| = <.0001$

The results show that ENSO is a positive and significant variable in explaining the variation in snow depth at the Mt. Baldy site. Specifically, a one unit increase in the ENSO

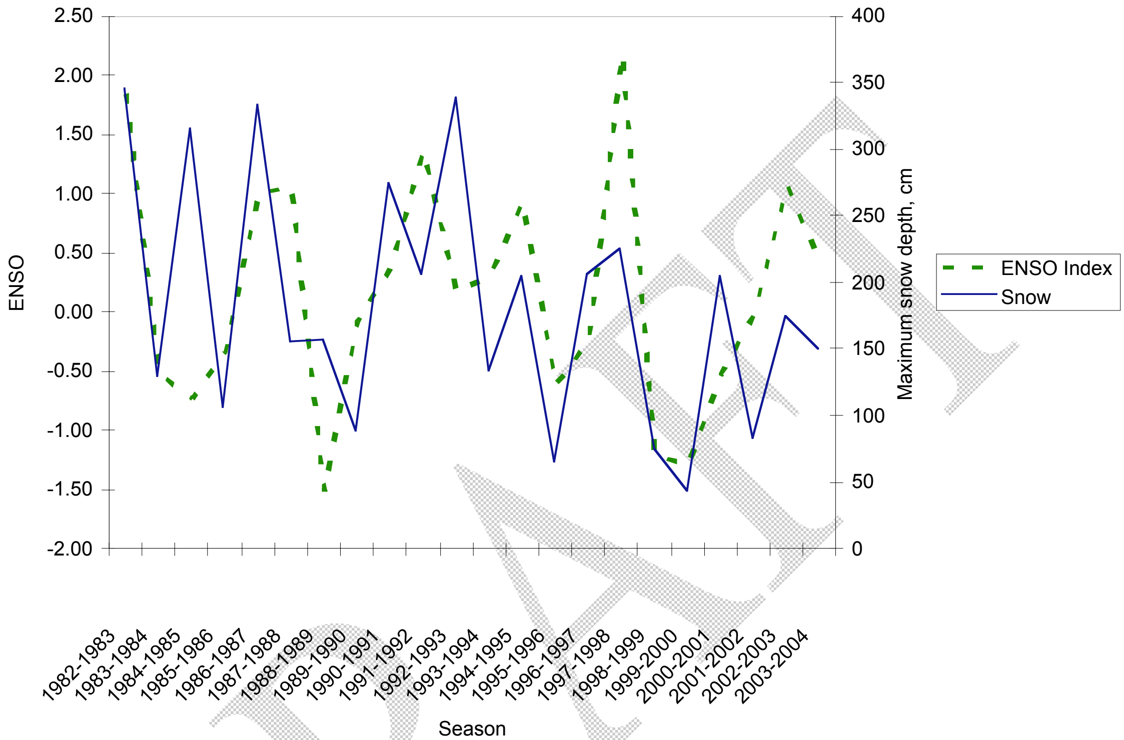
6 All the modeling was done in SAS. We used an ordinary least squares regression method and simple linear functions.

7 The Baldy Mountain SnoTel site is located at latitude 33.98, longitude 109.50 and elevation 2,782 m. This compares to Sunrise Mountain latitude 33.84, longitude 109.91 and elevation 2,836 m to 3,354 m.

8 The amount of water in snow varies and is measured by the snow water equivalent (SWE). For example, a foot of fresh, heavy, wet snow may produce 38 mm of water whereas light, powdery snow may be equivalent to just 13 mm of water.

index raises snow depth by 14.3 cm. That is at this site there is a positive correlation between El Niño and snow pack that we expected a priori. For a visual representation of this relationship Chart 1 plots snowfall data against ENSO data. The two lines move in concert that is La Niña years are correlated with lower snowfall and El Niño years with above average snowfall.

Chart 1: Mt. Baldy snowfall vs. ENSO



Next we test whether a PDO-ENSO signal could be detected in the dataset. A binary variable was created that equaled one if PDO and ENSO were simultaneously positive, and zero otherwise.

Snow depth (cm) = β_0 intercept + β_1PDO-ENSOeffect + ε [2]

The results of the model are:

adjusted R-squared = 0.12,
β_0 = 43.19, t = 12.06 and pr>ltl = <.0001
β_1 = 23.03, t = 4.26 and pr>ltl = <.0001

Model 2 shows that the PDO-ENSO effect is a positive and significant determinant of snow depth variation at the Mt. Baldy site. The results show that the combination of a positive PDO and ENSO increases snow depth by 23 cm compared to the case when this interaction is absent. This data seems to confirm that the PDO-ENSO effect is indeed an important predictor of snowfall at our site. Note also that the PDO-ENSO effect is larger than the ENSO effect alone.

The modeling was repeated using the snow course data and SWE as the dependent variable. Note that 92% of the variation in SWE in our dataset is determined by snow depth alone. These results reported that ENSO is a significant and positive determinant of SWE at the thousandth percent level. A one unit increase in the ENSO index raises SWE by 4.4 cm (t=6.19, pr>ltl=<.0001). In addition the PDO-ENSO binary variable was a positive and significant variable at the thousandth per cent level. The combination of a positive PDO and positive ENSO raised predicted SWE by 7.83 cm (t=4.84, pr>ltl=<.0001).

Snowfall variability and skier visitation

The next models ran tested whether climate variability is a significant determinant of annual snowfall, skier visitation and season length at Snowbowl (for data see Table 2). We tested models with ENSO and the PDO modulated ENSO, separately, the effects were not significant when modeled in combination. The first model tested:

SNOWFALL, cm = β_0 intercept + β_1ENSO or ENSO-PDO + ε, n=22   [3a/b]

Table 3: Snowbowl snowfall and climate oscillations

	Parameter estimate	t-value	pr>ltl	Adjusted R-squared
INTERCEPT	580.74	11.57	<.0001	0.15
ENSO	114.03	2.23	0.0372	
or				
INTERCEPT	493.54	7.78	<.0001	0.21
ENSO-PDO	249.15	2.59	0.0171	

The results show that ENSO and the modulated ENSO are positive and significant determinants of annual snowfall at Snowbowl with a five per cent confidence level. For example, in a ENSO-PDO season snowfall is 249 cm greater than when this combination is absent. The ENSO results show that a 1 unit increase in ENSO raises annual snowfall by 114 cm. These results tell us that mountain managers should take full advantage of such natural snowfall years perhaps with targeted ENSO marketing. The next model tested the effect of climate on skier visitation.

SKIER VISITS = β_0 intercept + β_1 ENSO or ENSO-PDO + ε, n=22   [4a/b]

Table 4: Snowbowl visitation and climate oscillations

	Parameter estimate	t-value	pr>ltl	Adjusted R-squared
INTERCEPT	105,609	9.94	<.0001	0.15
ENSO	23,829	2.20	0.0395	
or				
INTERCEPT	91,612	6.48	<.0001	0.12
ENSO-PDO	42,349	1.98	0.0615	

Table 4 results show that ENSO and the modulated ENSO are positive and significant determinants of skier visitation at Snowbowl. For example for each one unit increase in ENSO (warming) annual visitation rises by almost 24,000, that is El Niño years are significantly better than La Niña seasons. The last model tests whether these climate oscillations help us to explain variation in season length at Snowbowl.

DAYS_OPEN = β_0 intercept + β_1 ENSO or ENSO-PDO + ε, n=22   [5a/b]

Table 5: Snowbowl season length and climate oscillation

	Parameter estimate	t-value	pr>ltl	Adjusted R-squared
INTERCEPT	92.82	13.09	<.0001	0.19
ENSO	17.85	2.47	0.0223	
or				
INTERCEPT	82.62	8.99	<.0001	0.14
ENSO-PDO	31.08	2.15	0.0430	

The results from this model show us that season length at Snowbowl is positively affected by El Niño conditions and the ENSO-PDO effect. For example, in an El Niño-PDO year the season is 31 days longer than without this effect. All these models confirm that climate variability is indeed an important determinant of ski season outcomes at Snowbowl.

The timing of snowfall and the length of the ski season are crucial to the financial success of Arizona's ski resorts. Using Snowbowl data from the 1981/82 through 2004/05 seasons [15 and news reports for the most recent season] we modeled season days open as a function of total seasonal snowfall. The mean season length during the 23 seasons modeled was 96 days (minimum 4 days and maximum 138 days). The model tested was:

$DAYS\_OPEN = \beta_0$ intercept $+ \beta_1 SNOWFALL(cm) + \varepsilon$, n=23 [6]

Table 6: Modeling Snowbowl season length, Adjusted R-squared = 0.58

	Parameter estimate	t-value	pr>ltl	Mean
INTERCEPT	29.02	2.23	0.0370	
SNOWFALL	0.11151	5.58	<.0001	601.87

The model results show that total seasonal snowfall (cm) is a positive and significant determinant of the variation in season length. Readers should remember that Snowbowl does not have snowmaking capability and therefore this model models the importance of natural snowfall. For each 9 cm increase in snowfall during the season the season length increases by 1 day. Total snowfall is an important determinant of season length but there are other factors that were not modeled that are also important (the model only explained 58 per cent of the variation in season length), for example the number of days that meet the resorts minimum snow depth.

Using this same data we also modeled ski visitation as a function of the season length and total snowfall. Mean visitation in the 23 seasons was 110,025 (minimum 2,875 and maximum 190,000). The model tested was:

$Visits = \beta_0$ intercept $+ \beta_1 SNOWFALL(cm) + \beta_2 DAYS\_OPEN + \varepsilon$, n=23 [7]

Table 7: Modeling Snowbowl visitation, Adjusted R-squared = 0.824

	Parameter estimate	t-value	pr>ltl	Mean
INTERCEPT	-19,942	-1.46	0.1608	
SNOWFALL	109.92	3.67	0.0015	601.87
DAYS_OPEN	668.17	3.24	0.0041	96

The model results show that total seasonal snowfall (cm) and the number of days open explains 82 percent of the variation in seasonal visitors. The results show that for each additional cm of snow visitation increases by 110 visitors and each additional day open increases visitation by 668, both are significant at the one per cent level. Other factors that may be important which were not modeled are the timing of the snowfall in relation to peak visitation periods, number of days with new powder, the day of the week Christmas falls, and macro factors such as the state of the economy. We could imagine that an additional opening day that fell on the Thanksgiving weekend would raise visitation by more than the 668 skiers modeled: Snowbowl often hits peak capacity of 3,400 skiers per day on such vacation weekends. However, we do not have data on season opening dates and there is no SNOTEL site at Snowbowl to assess whether snow conditions would support early opening. The nearest SNOTEL sites are at much lower elevation and therefore not good proxies for this site. Snow course data for Snowbowl for the period 1996-2005 does exist but the data collection period is December 30 through March 31 that is it does not cover the Thanksgiving period.

Models 4 through 7 formalize what mountain managers already know: poor snowfall and a short season result in poor financial seasons. For example, low snowfall in the 1998/99 and

1999/00 seasons heralded poor revenues at Sunrise, whereas the 1997/98 and 2004/05 seasons had abundant snow and were very good revenue years. Meanwhile, at Snowbowl the 2004/05 season was snow abundant and almost record breaking whereas 2001/02 was a poor season for snowfall and ski visitation. Without snowmaking, the profitability and viability of either resort may be threatened by a series of winter drought seasons.

SNOWMAKING

Snowmaking reduces a ski operations' vulnerability to poor natural snowfall enabling resorts to operate for a longer season than if they relied on natural snowfall alone. The first study to model snowmaking as a climate adaptation strategy was Scott, McBoyle and Mills [3]. Their study in central Ontario, Canada found that climate change scenarios that double CO_2 concentrations would reduce ski seasons by a smaller 7% to 32% compared with a 40% to 100% loss predicted by McBoyle and Wall [24]. The difference between these studies is a measure of the effectiveness of snowmaking in extending seasons. Furthermore, *improved* snowmaking capabilities[9] would reduce season losses to just 1% to 21% [3]. Nevertheless, these results rely on large increases in snowmaking by the year 2080 of between 191% and 380%. Such levels of snowmaking may not be financially or environmentally viable.

Snowmaking is not viable for the snowmobiling, Nordic and cross country skiing sectors because of the huge economic and environmental barriers to snowmaking for tens or hundreds of kilometers of trails [3]. Sunrise and Snowbowl both have vulnerable cross country skiing sectors. However, without detailed information on the size of this specific market relative to the downhill skiing market, the impact of this vulnerability is unknown. Both resorts have however identified snowmaking as an adaptation strategy to climate variability for their downhill ski business.

Snowmaking can extend seasons by facilitating an earlier start and later finish than natural conditions would allow and by building up snowpack after warm or rain conditions. In these ways snowmaking enables mountain managers to achieve more consistency intra- and inter-ski seasons. The manager can then decide on the optimal season length based on costs, including projected snowmaking costs, demand, and profit margins. An example in the southwest is Beaver Mountain, Utah. Management here requires season length to be 100-105 days to realize typical industry profit margin of 6.5%-7% [6]. The assessment notes that a mere 2°C increase in temperature could reduce this resort's revenue by 20% and concludes that "location can be crucial to success. Resorts at higher elevations might not be negatively affected by projected changes in climate, and some resorts could even benefit from wet snows that help build a better snow base." Sunrise and Snowbowl are such higher elevation ski resorts, elevation that may buffer some of the negative effects of climate change.

Arizona's ski resorts are small relative to the large, commercial resorts in nearby Colorado and Utah. Sunrise currently has snowmaking capabilities for just 10% of skiable terrain. To put this in context, climate change vulnerable low elevation-high latitude ski resorts in central Ontario, Canada have snowmaking capabilities for 100% of skiable terrain [3] whilst snowmaking capabilities of 50% and higher are the norm for the top Four Corner ski resorts. Snowbowl currently has no snowmaking capability. However, its operating company has recently had its ambitious expansion plans approved; these plans incorporate snowmaking for 100% of its expanded terrain [15]. Sunrise began the process to expand its snowmaking capabilities in 2000 but the effort faded, now in 2005 it is again seeking funding to increase snowmaking capacity to improve season consistency. Water rights are a major restraint to further expansion of snowmaking beyond that approved at Snowbowl, but this constraint is not binding on the White Mountain Apache Tribe which likely has sufficient water

[9] Newer snowmaking equipment can efficiently make 15 cm of snow base per day at -2ºC compared to older equipment that makes just 10 cm snow base per day and requires lower temperatures of at most -5ºC.

supplies.[10] Sunrise would however seek Economic Development Administration assistance to help fund the upgrade.

For illustrative purposes we graphed actual snow depth and minimum snow depth thresholds to visualize when and how much snowmaking (shaded pink) might be required in a good and bad year. The graphs below show the timing and volumes of snowmaking required to meet Sunrise's 36 cm minimum snow depth over a season starting on November 20th and ending April 10th during an El Niño episode (1982/83) and a La Niña episode (1998/99). There are very limited historic climate records for Sunrise and therefore for this exercise we used daily data from the Mt. Baldy SNOTEL site. This site does not record snow depth and therefore we estimated snow depth at Sunrise using correlations between SWE data recorded at Mt. Baldy and Sunrise snow depth at the base for the 2004/05 season, for which we have some data. The graphs are therefore illustrative of snowmaking requirements rather than exact measurements of these requirements.

Chart 2 shows that during this El Niño episode snowmaking requirements would have been limited to early in this arbitrarily chosen season whereas in this La Niña episode large snowmaking requirements would have been necessary at the start and near the end of the season to maintain adequate snow depths for skiing. During a severe winter drought it may be unprofitable to make snow particularly if winter temperatures are warm causing snow losses. However, to fully address this issue the actual costs of increased snowmaking should be weighed against the expected revenue gains from increased visitation.

[10] The actual water rights of the tribe are as yet undefined. However, the White Mountain Apache Tribe has recently entered into adjudication of its water rights. This process once complete will fully define the tribes water rights.

Chart 2: Snowmaking requirements in an El Niño season, 1982/83

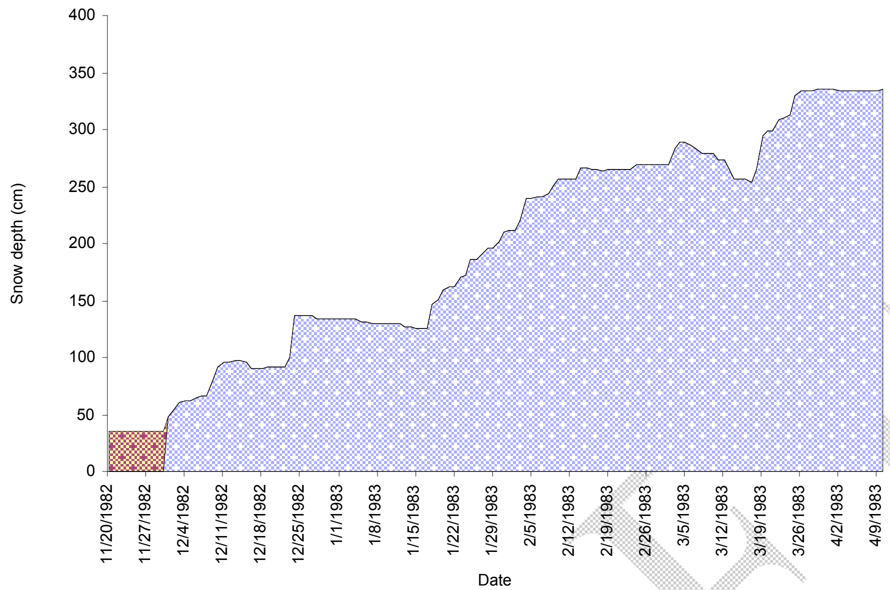
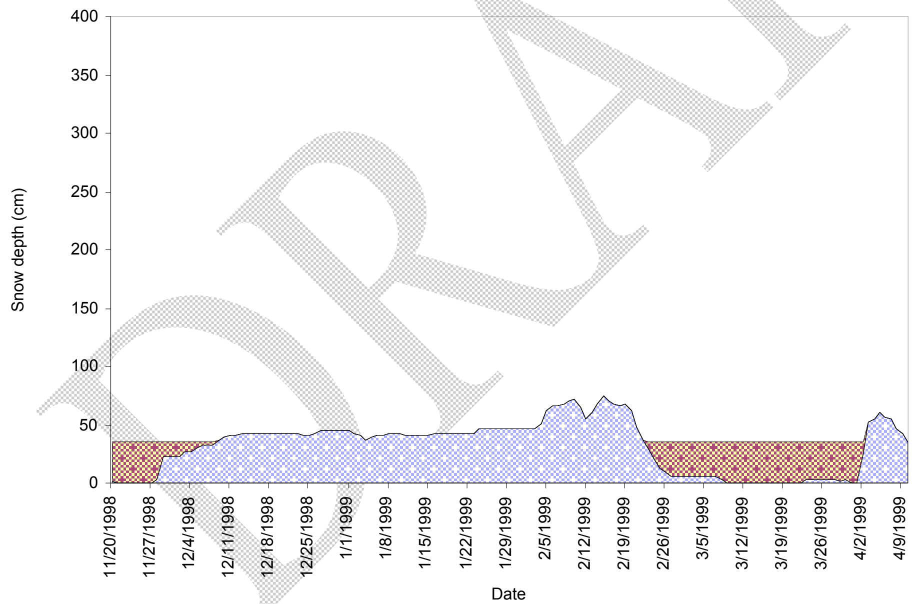


Chart 3: Snowmaking requirements in a La Niña season, 1998/99



Scott, McBoyle and Mills [3] results demonstrated the "importance of snowmaking as a climate adaptation and that the value of investments in snowmaking systems will only increase under climate change". However, they also note that ski resorts will have increased snowmaking requirements at warmer temperatures, which will increase energy requirements and costs. The authors did not address the costs and investments in equipment necessary for such extensive snowmaking and therefore it is unclear whether such increases in snowmaking would be financially viable. Investment decisions are complex: each resort needs to weigh the costs against the benefits given the likely responses of consumers, and the snow conditions at nearby competing resorts that might be superior as a result of aspect, altitude, or some other reason.

The politics and economics of snowmaking

Thirteen tribes are opposed to using reclaimed water for snowmaking on the sacred San Francisco Peaks where Snowbowl is located and environmentalists are opposed to the proposed use of scarce water resources. However, these objections were overruled in the recent EIS approval of Snowbowl's expansion and 83 ha (205 acres) of snowmaking option. Paradoxically, snowmaking investments at Snowbowl may prevent desecration of other sacred sites in the state, sites that might offer superior snow conditions than at Snowbowl and Sunrise. The proposed Snowbowl snowmaking operation requires 5.7 mn liters of water per day for 119 days between November 1 and February 28 each ski season. Snowbowl has no water rights and currently trucks in all potable water. Therefore to support snowmaking Snowbowl has signed an agreement with the City of Flagstaff that would allow for a maximum transfer of 673.8 mn liters of Grade A reclaimed wastewater per season for 5 years with possible renewal three more five year periods. The plan cites three scenarios with associated snowmaking water requirements: a dry year for the maximum 486 af (673.8 mn liters), an average year of 364 af and a wet year 243 af. To put these numbers in context an acre foot[11] of water supports on average a family of four for a year, thus, Flagstaff is giving up water that could support nearly 486 families, or other alternative economic growth activities.

Adaptation strategies such as snowmaking can reduce climate change vulnerability by increasing snow pack, durability, and season reliability. However, snowmaking is expensive; costs, excluding capital costs, range between $500 and $4,000 per acre foot (af) of snow dependent on system efficiency [4], accounting for approximately 15%-25% of total operating costs. Total costs at Snowmass, Colorado, including capital costs are as high as $5,000 af [25]. Furthermore, it may become more difficult to finance such investments. Bürki, Elasser and Abegg [18] found evidence that Swiss banks are becoming more wary of funding infrastructure investments at ski resorts lower than 1,500 m whilst ski area managers in southern Ontario, Canada now have to assess and address climate change impacts in financing negotiations with lenders [3]. Crucially for the southwest snowmaking also requires large volumes of water[12] [5]. To illustrate, a typical sized ski resort produces around 500-1,000 af of snow per season at a cost between $0.25mn-$4mn and uses between 214 af and 427 af of water per season.

Snowbowl's plans anticipate applying a base of 64 cm over the 83 ha terrain at the season start during a wet season to ensure good skiing conditions over the Thanksgiving break, one and half times in an average season and two times in a dry season, equivalent to 427 af, 640 af and 854 af of snow per season, respectively. They estimate total water demand of 243 af in a dry season, 364 af in an average season and 486 af in a wet season. Included in this total is approximately 6 af annually for toilet flushing.[13] Calculating water use per acre foot of snow from these total water requirement estimates gives us approximately 185,401 gallons of water per acre foot of snow which is one third higher than an industry estimate (see footnote 9). This difference might reflect a preference for snow with a higher snow water equivalent (wetter snow) or an estimate for losses in the low humidity environment in Arizona. If we assume a 2% inflation rate then the costs, excluding capital costs, of this snowmaking in ten years time when the investments come on-line range from $598 af to $4,780 per af of snow. Total snowmaking costs would range from $255,346 to $2.041 mn in a wet year to

[11] An acre foot = 325,851 gallons.

[12] 1 acre foot of snow = 139,222 gallons of water.

[13] Snowbowl currently trucks in 5.7 mn liters of potable water annually of which 60% is used for toilets. If we assume growth in flushing use equivalent to expected growth in visitors from an annual average 98,000 to 215,000 we arrive at 6 af for flushing annually.

$510,692 to $4.082 mn in a dry year. To put these costs in perspective Snowbowl's annual gross revenues averaged $4.525 mn in the eleven seasons from 1993/94 to 2003/04. The snowmaking proposal assumes that visits will increase to 215,000 skiers a year from the average 98,000 now, at current ticket prices[14] and assuming a 2% inflation rate, revenues in 2013/14 would be $12.1 mn (this does not include revenues from snowtubing visitors). Therefore snowmaking costs could account for between 2.1% to 16.9% of total skier revenues in a wet year and between 4.2% to 33.7% in a dry year. If we assume an industry profit of 10% snowmaking costs rise to between 2.3% to 18.7% in a wet year to between 4.7% and 37.5% in a dry year, this compares to the industry norm of between 15%-25% of total operating costs. However, all these costs are just illustrative, at temperatures higher than -2°C snowmaking is not technically viable, and even at temperatures below this threshold snowmaking may not be financially viable, as in the above example during a dry year with higher assumed snowmaking costs.

Snowmaking expansion plans for Sunrise are more modest. Management has two plans; both are restricted to increasing snow making capability for Sunrise Peak only not the two other peaks in the resort. These plans are not public and therefore approximations are used; the first more comprehensive plan anticipates increasing snow making from the current 32.4 ha to around 55 ha to a depth of 61 cm. This option would mean 100% snowmaking capability for Sunrise Peak. A second scaled down option reduces the depth of the snowpack to 41 cm and the number of trails with snowmaking, reducing the total area to around 45 ha. The timing of snowmaking in both cases is expected to be in the preseason, November through Christmas. The initial capital investments are estimated between $4 mn and $9 mn. Operating costs will depend on the efficiency of the system, the number of snowmaking applications, and the temperatures at which snow is made. To illustrate these on-going costs we assume one early season base application that would enable skiing over Thanksgiving. If we assume a five year time horizon for the snowmaking to come on-line and a 2% inflation rate then operating costs might range from $552 to $4,416 per af of snow. Therefore operating costs for the full scale plan would range between $166,000 to $1.3 mn and for the reduced plan between $80,000 to $640,000. Doubling the applications would double these estimated costs. Sunrise current revenues are between $6 mn and $8 mn a year with a profit margin of around 10 per cent. This financial picture falls short of financing the total capital costs but it would seem that the ski resort can cover the on-going costs of snow making particularly if a longer, more consistent season increases skier visits to the resort, specifically at peak times such as Thanksgiving. Sunrise can accommodate 8,000 visitors per day, if we assume an average ticket price of $30/day[15], a peak day during the season could bring in revenues of $240,000.

Although Scott, McBoyle and Mills [3] make a clear argument for the expansion of snowmaking when profitable, they do note that the success of such supply-oriented changes is dependent on the responses of consumers. A question that both Snowbowl and Sunrise need to answer before investing further in their resorts is does the demand support it? The demand for skiing is not only influenced by snow pack, but also relative snow conditions, prices at competing resorts, and the availability of other recreation activities. The Snowbowl EIS attempts to answer this question by calculating the utilization rate at the resort. This is found by dividing skier visits by total capacity. This rate averaged 64% in the period 1990-2004 peaking at 83% in 1998. They comment that US ski areas measure strong demand as a utilization rate above 40%: on this basis they conclude that there is sufficient demand in the region to support expanded ski facilities. However, research has shown that the demand for spring skiing typically "wanes before the snow pack is exhausted" [3]. A similar phenomenon has

[14] In the 2004/05 season adult full-day lift ticket prices were $42, juniors $24 and seniors $22, respectively.

[15] In the 2004/05 season adult full-day lift ticket prices were $41, juniors $24 and seniors $20.

been recorded at Sunrise and Snowbowl. For example, in the good snowfall 2004/05 season Sunrise closed the season on April 3, 2005 and Snowbowl on April 10, 2005, though both still had sufficient snow to remain open. Demand for skiing drops off in spring regardless of the snow situation and mountain managers often decide to close resorts as these last weeks are often unprofitable. Additionally, it can be difficult for resorts to keep staff so late in the season, as many are seasonal workers and move to their spring/summer employment. Marketing to skiers in the shoulder seasons is one way that Sunrise and Snowbowl can capitalize on their snowmaking investments and good late natural snowfall. In fact Sunrise resort does target this season by offering reduced lift ticket prices, $25 for adults and $15 for juniors, in the last weeks of the season. It also modifies its supply-side by closing Apache and Cyclone peaks; only Sunrise peak remains open.

These same authors note that there is little current understanding "how recreational users and tourists respond to climate variability (whether or not to participate or purchase equipment, activity substitution, use patterns, destination choice)." Some researchers have attempted to answer the question as to how different types of skiers might respond to climate change. Skier survey results from Switzerland found that during a poor season 49% of skiers would switch to a more snow-reliable resort, but more worrying for the industry, 32% of respondents said they would ski less often [18]. Only 4% of the survey respondents said that they would abandon skiing. The broader issue is the differential impact of such demand changes. It is likely that smaller ski resorts would suffer most as young skiers, day skiers, and novice skiers, their predominant clientele, are the most likely to respond negatively to poor seasons. In fact König's [18] study of skiers in Australia supports this conclusion. She found that half of all advanced skiers would travel overseas for quality snow conditions, whilst only 18% of novice skiers would, and 16% would give up skiing altogether. Therefore, a large uncertainty in any modeling of the impact of climate change on winter recreation is the response of local skiers to changes in ski season length, timing, and relative quality. Scott, McBoyle and Mills [3] argue that one scenario that would leave resorts as well off, is if skiers adjust their recreation behavior by skiing more frequently in the shorter season. A sensitivity analysis could address this uncertainty in consumer response and estimate future ski recreation demand.

Climate change and snowmaking

In order to investigate the impact of human fossil fuel use on the climate system climate researchers have developed General Circulation Models (GCM). These models replicate the complexity of climate systems and can be used to model 'what if' scenarios, such as greenhouse gas forcing, or climate change. All these models suffer from coarse resolution and as such cannot capture the influence of varied topography in the southwest nor ENSO and monsoon effects [26]. To overcome some of these limitations USGS climatologists have developed a regional simulation model, called RegCM which is nested in a GCM. The results from this regional model, which simulates a doubling of CO_2 atmospheric concentrations, are shown in the table below.

Table 8: Southwest climate change: RegCM simulation

	_ Temperature, °C	**_ Precipitation, cm**
Season	RegCM	RegCM
Winter	+4.2	-3.05
Spring	+4.2	0 to +1.52
Summer	+5	-1.52
Fall	+4.2	-1.52 to +1.52

Source: [27]

The RegCM model predicts a decline in winter precipitation in concert with higher winter temperatures [28]. Reduced snowpack and snow season length and higher spring temperatures will in turn bring forward springtime runoff, a situation likely to reduce water supplies in the snowpack-water supply dependent southwest. The simulations seem to show that climate change will herald more drought-like conditions in the southwest. However, there is a big caveat to this modeling; although the RegCM model is an improvement over GCMs it is still relatively coarse resolution, with grids 15km^2 (Sunrise resort is smaller than this grid at 3.24 km^2). Significantly, it does not account well for elevation. In the paper the researchers used RegCM to recreate current temperature and precipitation maps in the southwest to validate the model. These simulations are not particularly good at reproducing actual climate conditions in either the White Mountains region or the San Francisco Peaks; therefore we have less confidence about the magnitude of the changes reported in Table 8. However, this does not mean that warming has not already happened or that it will not happen in the future. Arizona mountain managers must prepare for warmer winter temperatures, wetter snow, and perhaps less overall or more erratic snow, and rainfall instead of snowfall on warmer winter days.

In the absence of a RegCM designed to forecast changes in snow depth and season length we instead investigate temperature data from Snowbowl [15, p3-227]. In Table 9 we arbitrarily choose a 1°C warming for each month during the ski season.

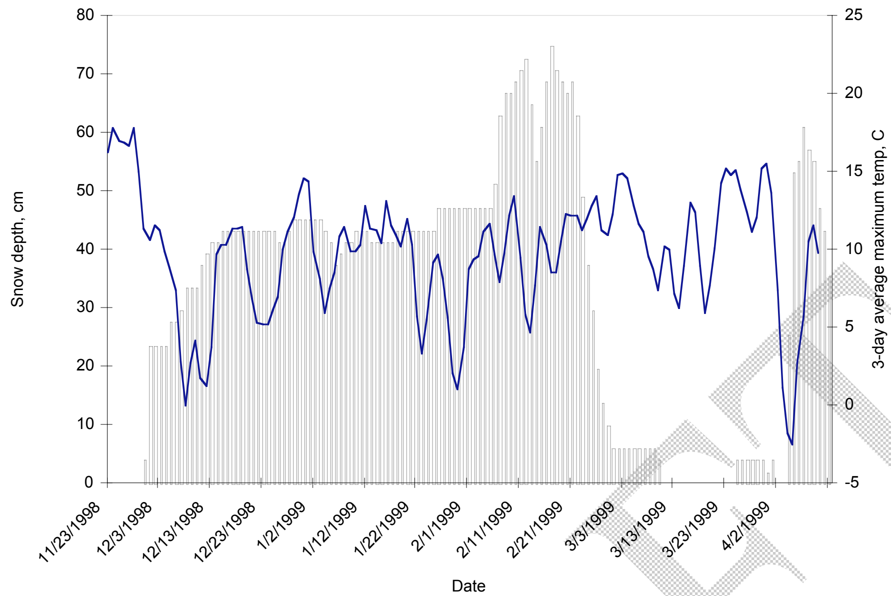
Table 9: Snowbowl winter temperatures, °C, and a climate change scenario

	1960-1990 data			1°C winter warming		
Month	**Average**	**Maximum**	**Minimum**	**Average**	**Maximum**	**Minimum**
November	-7.2	3.6	-14.4	-6.2	4.6	-13.4
December	-10.4	-0.4	-16.9	-9.4	0.6	-15.9
January	-10.2	-0.1	-17.1	-9.2	0.9	-16.1
February	-9.1	1.2	-16.1	-8.1	2.2	-15.1
March	-6.5	4.0	-14.4	-5.5	5.0	-13.4
April	-2.8	7.8	-11.6	-1.8	8.8	-10.6

The table shows that minimum temperatures even with a 1°C winter warming would still be cold enough to make snow even with less efficient snowmaking systems that require temperatures of at least -5°C compared to newer systems that operate at -2°C. However, these averages hide those days when warm systems might move through the ski resorts causing snow melt. Chart 4 shows how snow depth modeled for Mt. Baldy[16] varies with a 3-day average of the maximum temperature. The chart shows that there is some relationship between snow depth and maximum temperature: new snowfall is associated with a dip in the 3-day average whilst snow melt occurs after temperatures consistently exceed 8°C. Using this observation and the data in Table 9 snow may melt earlier in the season and higher April temperatures could shorten the season. It should be noted that the Mt. Baldy SNOTEL site is at a lower elevation than the base of both Sunrise and Snowbowl. Temperatures at both ski bases would thus be cooler as per the dry adiabatic lapse rate. Using this rate the base at Sunrise and at Snowbowl are 0.54°C and 0.23°C cooler, respectively. We are interested in the base elevations because it is here where snow tends to accumulate last and melt first. It is also an area of heavy use.

[16] Snow depth is approximated by using the following formula, snow depth = SWE*7.7.

Chart 4: Mt. Baldy snow depth and 3-day average of maximum temperatures, °C



The final impact simulated by climate change models is reduced winter precipitation. If such projections are realized Sunrise and Snowbowl may experience more winter drought-like conditions, such as currently in a La Niña year. However, other models forecast wetter snow that may actually help the ski areas as such snow makes a good base. In the absence of a model for our study areas our best approximation is that the current mix of wet, average, and dry years is likely to become more erratic and this will in turn make managing the resorts for profit more challenging, particularly, if managers rely exclusively on natural snowfall.

Note that if we had a climate change scenario for the Snowbowl region we could estimate the impact of reduced snowfall on the number of days open using Model 6 and then using the results from Model 7 we could estimate the impact on skier visitation. For example, if snowpack were forecast to decline by 45 cm (pre-snowmaking investments) Model 6 estimates that the season would be cut short by 4 days. In turn reducing season length by 4 days would reduce skier visits by an estimated 2,672. If these skiers spend $100/day economic output would decline by $267,200.

Local economic impacts

We saw that the economics of snowmaking support snowmaking at both Sunrise and Snowbowl, particularly, if the most efficient systems are installed. However, the infrastructure costs of snowmaking are high and include the building of large water reservoirs, pipelines, and purchasing snow guns, etc, and in the case of Snowbowl building a 24 km pipeline to convey wastewater to the resort. Total costs of the expansion and snowmaking are estimated at $19.77 mn; the snowmaking component is estimated to cost $8.2 mn. Sunrise estimates that its more modest snowmaking plans will cost between $4 mn and $9 mn to construct. These costs need to be weighed against the benefits arising from more consistent ski seasons. The benefits of snowmaking at either site are not confined to increased profits at the ski resort but include the local economic impacts accruing to surrounding areas as a result of skier spending. These impacts have been modeled for both resorts. Ski resorts do benefit local communities and in turn these same communities might support snowmaking investments directly or efforts to raise investment funds from the Economic Development Administration.

Snowbowl estimates that in the seasons1996/97 to 2002/03 an average 22.1 persons were employed by the ski resort on a full-time equivalent (FTE) basis, 272.4 persons year-round on a full-time seasonal basis and 204.3 persons on a part-time seasonal basis. These different types of workers add up to 172 FTE jobs. The EIS report quotes average direct expenditures of $9.79 mn per season during this same period in Coconino County. This total was calculated by multiplying the average ski visitation of 97,900 by expenditure of $100 per skier. This $100 figure is based on surveys in Colorado, Utah and at Snowbowl. It may be somewhat high considering that two-thirds of all Snowbowl's visitors are day-trippers and probably many are renting ski equipment and buying gas in Phoenix. The report goes on to estimate that total direct and indirect economic impacts in Coconino County of 232 FTE jobs and $12.08 mn in economic output (in $2003, inflation adjusted). From this data we can calculate that the multiplier used is 1.24. The expansion of Snowbowl will in turn create an estimated 232 FTE construction jobs and $21.24 mn economic output in Coconino County. At the end of the 10 year planning period when Snowbowl anticipates it will attract 215,000 visitors a year, the ski resort will directly support 332 FTE jobs and a total 564 FTE jobs in Coconino County. Economic output attributable to Snowbowl is forecast at $23.7 mn. Snowbowl also contributes to the US Forest Service through service fees and its community through property and sales taxes. These fees and taxes are forecast to rise from their baseline averages of $90,000, $36,000 and $257,000 to $193,000, $455,833 and $669,000, respectively by the 2013/14 season. The EIS calculates that winter tourism accounts for 8.6% of Flagstaff area's overall economy [15, 3-188].

In a previous study the revenues from skiing at Sunrise were estimated at between $5.1 mn to $5.95 mn [17]. Updated figures for the very good 2004/05 season are ski revenues of $8.4 mn.[17] It should be noted that these ski revenue data include ski ticket prices only. That is other spending by skiers on accommodation, food, ski equipment hire or purchase, and gas are not included in this figure. In the Snowbowl EIS [15] they estimate total expenditures of $100 per skier, if we use this figure, then direct expenditures by visitors at Sunrise and in surrounding areas in the 2004/05 season was around $20 mn. This figure does not include indirect expenditures resulting from increased income in the region. If we use the same multiplier as in the Snowbowl study we get total economic output of $24.7 mn. Note that the economic multiplier is likely to be higher for Sunrise than Snowbowl because of the larger proportion of overnight skiers.

Sunrise is one of the largest non-governmental employers in the region: employment peaks in winter months at around 518 employees, but, the FTE payroll is a much lower 198, as many jobs are seasonal. Gibson and Evans use public information on tax revenue and survey data to determine a recreation dependency ratio for the entire White Mountains region.[18] A recreation dependency ratio is the percentage of total income in the region generated by the recreation sector. The White Mountains area is not as 'developed' as Snowbowl and thus Sunrise is proportionately more important to the local community. In the White Mountains this ratio is 44%. However, this overall statistic hides variation between communities: Sunrise's dependency is 90% and nearby Greer's is 79%. They also calculate a specific winter dependency ratio. The winter dependency ratio is the percent of annual sales occurring in the winter season, defined in their study as January to March. This definition underestimates winter dependency, as in a good year a large proportion of ski visits occur during Thanksgiving and over the Christmas-New Year period. Although winter recreation is important to some communities in the region, overall this season generates just 27% of annual sales compared to the summer season's 33%, Sunrise is highly dependent on winter recreation, with a winter dependency ratio of 60%. Note that the White Mountains winter recreation dependency ratio is more than three times higher than at Snowbowl.

[17] Personal communication.

[18] This includes the off-reservation towns of Show Low, Pinetop-Lakeside, Greer, and Springerville-Eager and Sunrise and Whiteriver on the reservation.

These data show that although the ski industry in Arizona is small it is economically important to the White Mountain Apaches and also to the surrounding communities in the White Mountains and in the Flagstaff area. Importantly the ski resorts bring winter tourism and revenues that balance out peak summer-time visitation patterns.

DISCUSSION

Climate change and the increased probability of poor snowfall is likely to accelerate restructuring in the ski industry, favoring resorts at higher elevation and latitudes, and also more geographically diversified companies, and those able to afford snowmaking investments. Snowmaking not only allows resorts to adapt to shorter snow seasons predicted by climate change modeling but also provide more consistent conditions to even out the impact of more general climate variability. The economics seem to support the financial viability of such investments at Sunrise and Snowbowl, particularly when we account for local economic impacts. We found that Sunrise and its surrounding areas are more than three times more dependent than Snowbowl on winter-recreation. Nevertheless, the threat of climate change a century from now should encourage policymakers to develop a comprehensive regional development plan to ease future structural adjustment resulting from a climate that may be warmer and drier. In turn such planning may encourage mitigation efforts. Scott, McBoyle and Mills's [3] analysis of four different climate change scenarios lead them to argue that the ski industry should pursue climate mitigation in order to avoid the worst case scenario. They praise the National Ski Areas Association's Sustainable Slopes charter and the National Ski Areas Association's 'Keep Winter Cool' campaign. The industry could also be a political force for a more comprehensive national policy to reduce greenhouse gas emissions.

We have narrowly focused on the economics of snowmaking at Sunrise and Snowbowl, however, the overall impact of changing climate on these two resorts should be assessed in a larger framework that takes account of climate impacts elsewhere in the region. One possible outcome is even if ski seasons are shorter at Sunrise/Arizona, if snowfall declines are worse at Snowbowl/New Mexico, then Sunrise/Arizona might have a future, as skiers switch to Sunrise/Arizona. Such a substitution effect would be the best case scenario; although individual skiers would be displaced from their usual recreation area. However, another likely scenario is that skiing declines overall in the state and region.

The negative effects of climate variability and change on the ski industries at Sunrise and Snowbowl are still unknown. However, longer-term climate change may boost non-winter recreation and revenues. Both ski resorts have strong non-winter recreation programs. Snowbowl anticipates that its improved facilities will attract 30,000 summer visitors a year. Whilst, Sunrise generates around $1 mn in non-winter revenues from Sunrise Lake Marina, the hotel, general store, and non-skier users of chair lifts [17]. In Canada researchers investigated the impact of climate change on the length and quality of summer tourism in Canada's western mountain parks [29]. They found that tourist numbers in Calgary, Alberta would improve in every month of spring and summer under climate change scenarios. Another study investigated the changing seasonality for park visitation in the Rocky Mountain National Park, Colorado [30]. It predicted that warmer spring to fall weather would result in 193,000 to 333,540 additional visitors. In turn increased visitation would boost local economic output by between 6% and 10% and increase local employment by between 7% and 13%. Data from the White Mountains [31] records that summer recreation is the biggest contributor to the regional economy, followed second by winter recreation. A change in climate could further shift recreation visitation to the summer months, as valley residents seek respite from even higher temperatures, and also to the shoulder seasons, spring and fall, which currently account for just 20% each of annual revenue. However, Scott and McBoyle [32] caution that a change in recreation seasonality could have other implications, for example current tourism infrastructure might be inadequate to meet higher demand or additional visitation might increase environmental stress.

The White Mountain Apache Tribe Wildlife and Outdoor Recreation Division has oversight of two alternative (non-winter) income generating activities: outdoor recreation permits and the Trophy Hunting Program. This latter includes the world famous elk hunting but also the lesser-known but important pronghorn antelope, bighorn sheep, bear, mountain lion and turkey hunting seasons [33]. In 1999, these combined activities generated $600,000 profit. Such activities could help the tribe take advantage of climate change whilst reducing their economic vulnerability to climate change impacts on winter recreation.

To cope with climate variability and change we have seen the importance of snowmaking as an adaptation strategy. Another strategy that could be pursued is to extend runs into higher altitude. In Switzerland the ski industry has used climate change as an argument to extend existing runs and open new ski runs at high Alpine regions above 3,000 m against environmental concerns [18]. This seems an unlikely option at either Sunrise or Snowbowl because there are few alternatives that would be at higher elevation. However, if climate change does increase temperatures to a threshold at which it is uneconomic to make snow, we could anticipate that mountain managers might close the bottom sections of their runs and limit skiing to the higher elevation, more snow reliable terrain.

Another adaptation is to diversify risk. Large corporate ski companies such as Vail Resorts and the American Skiing Company may be less vulnerable to climate change than single resort operators because they are diversified companies, with real estate and warm-weather tourism businesses, and they are also geographically diversified, thereby reducing exposure to poor snowfall in one area [29]. Both Sunrise and Snowbowl have no real estate ventures, their location on a reservation and USFS land preclude such options. However, Sunrise does have the option to further develop on-site accommodation, for example, a new Ski in – Ski out lodge at the resort. The only onsite accommodation, Sunrise Lodge, is located 11 km from the slopes. Large companies are also better capitalized and therefore able to make investments in snowmaking. Financing snowmaking and other expansions is an obstacle for both Sunrise and Snowbowl. However, both have the support of their surrounding communities to further develop skiing in the region. Smaller operators may wish to investigate winter tourism weather derivatives market to even out good and bad seasons. A weather derivative[19] is a contract between two parties that stipulates what payment will occur as a result of the meteorological conditions that occur in the contract period. For example, the contracts could be structured to reduce weather-related risk for peak periods over Christmas and New Year.

Whilst the exact impacts of climate change are still unknown there are other actions that Sunrise and Snowbowl management could take to ensure that every good snow day at the resorts is fully utilized by skiers and profits are maximized. Management could plan activities, marketing, and hiring based on ENSO forecasts [34]: resorts could better capitalize on strong El Niño conditions, whilst, budgeting for increased snowmaking in La Niña years. Sunrise's webpage is in need of an update; a new 'public face' could better capitalize on its position as the largest ski resort in the state, its excellent spring skiing conditions, and affordable learn to ski/board packages. Both resorts could review their ski lift prices to ensure that they are not a limiting

[19] A derivative is an instrument used by companies to hedge against the risk of weather-related losses. The investor who sells a weather derivative accepts the risk by charging the buyer a premium. If nothing happens, then the investor makes a profit. However, if the weather turns bad, then the company claims the money. This is not the same as insurance, which is for low-probability events like hurricanes and tornados. In contrast, derivatives cover high-probability events like a dryer-than-expected summer. http://www.investopedia.com/terms/w/weatherderivative.asp

factor to the growth of skiing. The management may wish to introduce lower half day skiing passes to encourage opportunistic skiers and off-peak prices for mid-week, pre and late season skiing when the resorts are underutilized. Family packages could also be introduced to make the sport more affordable, this might be particularly important if snowmaking investments are realized at the resorts, because with more consistent ski seasons, families might substitute their usual vacation activities for a skiing vacation.

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