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Historical Climate Warming in the White Mountains of New Hampshire (USA): Implications for Snowmaking Water Needs at Ski Areas

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The objectives of this study were to examine changing snowmaking conditions in the New Hampshire White Mountains and how changes in snowmaking operations have compared with winter warming. We analyzed three 50-year high-quality daily temperature records representing different elevations and aspects to assess changes in snowmaking conditions during important snowmaking periods. The analysis provides context for discussing the historical relationships between temperatures, water, and snowmaking infrastructure. There was significant warming of winter temperatures over the 50-year record, notably strongest at the early portion of the snowmaking season, especially in the weeks between 1 December and 25 December. While the rates of warming were comparable on both north- and south-facing aspects, the implied reduction in days suitable for snowmaking in each period was always lowest on the north-facing aspect as the mean temperatures on this aspect were farther below the snowmaking threshold. Daily average temperatures of –2°C and –5°C were both explored as thresholds for snowmaking. The implied reduction in snowmaking opportunity during the 1 November to 25 December period using a –2°C snowmaking threshold at the north-facing site was 20%, while the implied reduction for the entire season for that site was 8.5%.This decrease in opportunity for snowmaking, especially in the economically important early season, suggests an increasing need for large volumes of water to make snow in less time, given that holiday vacations are fixed in time. Analysis of snowmaking operations at Loon Mountain Resort suggest that modern snowmaking investments there have outpaced the pressure from climate warming to date, but this has concentrated demand for water into smaller time frames.

Keywords: *Snowmaking; climate change; water; modeling; northeastern United States.*

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Introduction

Ski tourism is a significant economic engine in many mountain towns in the northeastern United States. In New Hampshire, the ski industry accounts for approximately US$ 300 million in direct spending and an additional US$ 786 million in secondary sales impact (Lee and Okrant 2014), primarily in mountain towns with seasonal, tourism-driven economies. The industry is highly dependent on climate, both for producing the conditions necessary for the activity through natural snow or snowmaking and for creating interest among potential customers, who have been shown to be less likely to take ski trips when there is no snow on the ground where they live (generally more southerly areas), regardless of the conditions at the ski areas themselves (Hamilton et al 2007; Burakowski and Magnusson 2012; Dawson et al 2013; Lee and Okrant 2014; Hagenstad et al 2018).

Snowpack presence and persistence are major factors in ski industry success, yet both have shown significant trends detrimental to the ski industry. Both the length of time snow is on the ground in a season (snowpack duration) and the maximum snowpack depth in the White Mountain region of New Hampshire have decreased over time (Campbell et al 2007; Hamburg et al 2013). This is largely due to warming winters in the region (Hamilton et al 2007; Burakowski et al 2008; Campbell et al 2010; Hamburg et al 2013), which have increased at a faster rate

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than the average annual temperatures (Campbell et al 2010; Hamburg et al 2013). Declining snowpack depth and duration have correlated with a major reduction in the number of operational ski areas in the late 20th century (Hamilton et al 2003) as well as increased adoption of and reliance on snowmaking at surviving areas (Hamilton et al 2003; Scott et al 2003). However, it is important to note that skier visits in the northeastern US region have not decreased; they have remained relatively consistent since at least the mid-1980s (NSAA 2016), although they have proven sensitive to year-to-year variability in snowfall and temperatures (Hamilton et al 2007; Hagenstad et al 2018).

Typical snowmaking systems work by using pressurized air to atomize water as it is sprayed out of nozzles at cold enough temperatures for the water to freeze. They can thus be limited by temperatures, energy, and/or water. Technological innovations in the snowmaking industry have introduced systems that dramatically cut energy costs and operate at somewhat higher temperatures (Scott et al 2003); thus, provided a resort can invest in new technology, any energy limits have been greatly reduced in recent years. The availability of water for snowmaking has been acknowledged as a factor influencing the success or failure of ski areas in New England (Hamilton et al 2003) and has been an issue of contention between some ski areas and some communities and environmental groups in the Northeast (Scott and McBoyle 2007), but water limitation can potentially affect ski area operations in a few ways. First and most simply, if a ski resort has a fixed area it needs to cover with an artificial snowpack, the thickness of the desired snowpack, typically 30–50 cm (Steiger and Mayer 2008), will roughly translate into a certain amount of water given that machine-made snowpacks have somewhat predictable density (Rixen et al 2004; Steiger and Mayer 2008). Artificial snow can only be made during adequate conditions, however, so the rate at which a resort can draw water can also be limiting if the snowmaking demand is at a higher rate than the source—in our area typically a river or stream—can provide. Many ski areas have natural or artificial reservoirs to act as a buffer and allow for rapid water withdrawals during good snowmaking conditions (Scott and McBoyle 2007). In the context of a warming climate, it is probable that a reduction in adequate snowmaking conditions will increase the pressure on water infrastructure, even if the total amount of water required by the resort remains constant.

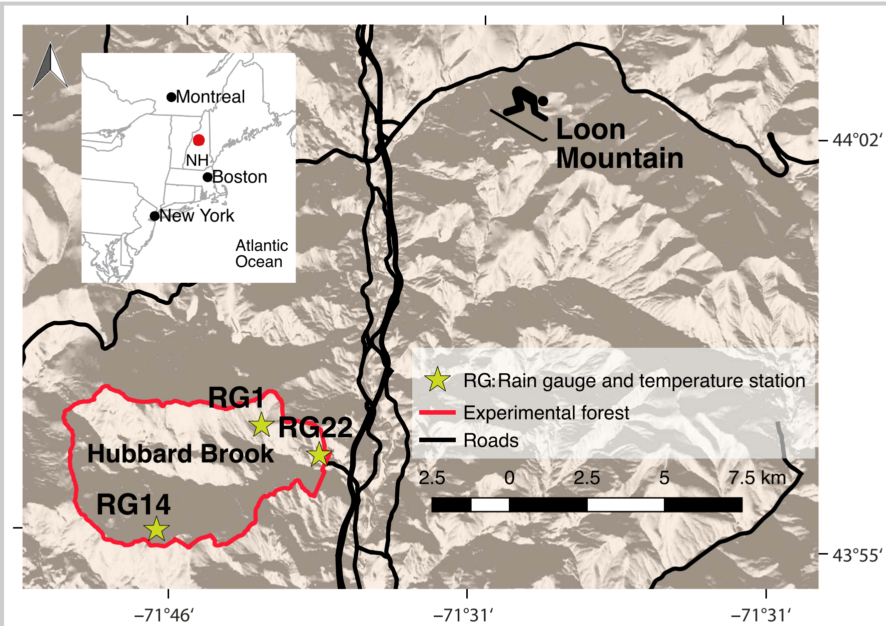
The purpose of this analysis was to interpret the winter climate warming observed over a 50-year record at the Hubbard Brook Experimental Forest (HBEF) in Woodstock, NH (Hamburg et al 2013), in terms of snowmaking time frames and conditions most relevant to the closest ski resort, Loon Mountain, located 14 km away at a comparable elevation to the HBEF record. Loon Mountain opened for skiing in 1966 and installed its first snowmaking system in the winter of 1970–1971, with top to bottom snowmaking by 1974 and steady investments of its snowmaking system beginning in the late 1980s. Most recently, it has invested heavily in both a high-efficiency snowmaking system and increased water storage and pumping capacity, addressing potential limits to operations by both energy and water. We looked at the mean daily temperature record at 3 separate weather stations over a 50-year period, noting any changes, and then interpreted this record in terms of days suitable for snowmaking as well as days where the snowpack would be exposed to thawing, given that these are operationally significant to the ski industry. We hypothesized that the documented increases of winter temperatures in general would translate into a significant reduction in snowmaking opportunities during critical times and an increased melting pressure requiring additional snowmaking. These combined would illustrate the increasing pressure faced by ski areas in our region in terms of both water resource acquisition and energy use. We paired high-quality, relatively long site-specific temperature records with information from a major nearby ski resort to provide insights into the relationship between climate warming and snowmaking adaptations. This should inform the broader discussion on projected climate warming and the potential role snowmaking will play in adaptation (Scott et al 2006; Scott and McBoyle 2007; Bark et al 2010; Steiger 2010; Dawson and Scott 2013; Wobus et al 2017).

Methods

HBEF in Woodstock, NH, is located 14 km southwest of the Loon Mountain Resort in Lincoln, NH (Figure 1). The HBEF is administered by the US Department of Agriculture (USDA) Forest Service and has a continuous hydrometeorological record from a number of weather stations distributed throughout the 3160-ha site. Three weather stations with at least 50-year records, rain gauges 1, 14, and 22, were chosen to represent a range of elevations and aspects for the region (Table 1; Figure 1). The HBEF is described in detail in other publications (see: Holmes and Likens 2016), and data are publicly available (www.hubbardbrook.org). Loon Mountain is an extra-large ski resort (15,323 vertical transport ft/h; NSAA 2016) which ranges from a base elevation of 290 m to a summit elevation of 930 m, so the temperature records at the selected HBEF rain gauges should serve as reasonable proxies for historical conditions at the mid to lower portions of the ski area (Table 1). The data we use from each site begin in January 1965 and run through December 2015.

Daily average temperatures were calculated by averaging the daily maximum temperature with the daily minimum as recorded on a Belfort hygrothermograph housed in a standard Stevenson screen, 1.5 m off the ground (Bailey et al 2003). We examined the daily average

FIGURE 1 Map of locations referred to in text. (Map by Mark Green)



temperature record in each winter season for 4 time periods deemed crucial to resort operations, 1 November to the Thanksgiving holiday (third Thursday in November), 1 November to the Christmas holiday (25 December), 1 December to the Christmas holiday, and the entirety of the typical snowmaking season, which begins as soon as suitable temperatures arrive after 1 November and runs through the end of February. These time periods were identified based on our knowledge of Loon Mountain's visitation patterns and represent an attempt to emphasize the most economically significant periods that ski areas face. For the White Mountain Region, these include opening by the Thanksgiving holiday (for the major resorts), being fully open with good conditions by the Christmas holiday, and providing good conditions for the 2-week period at the end of February, during which school vacations are typically held in the New England region (after Scott et al 2006; Frumhoff et al 2007).

Daily average temperatures were then sorted into days suitable for snowmaking and unsuitable for snowmaking, based on whether the daily average temperatures were less than or equal to −2°C (after Steiger and Mayer 2008). This threshold was determined based on our experience making snow, Steiger and Mayer (2008), and the websites of 2 leading snowgun manufacturers, HKD Snowmakers and Snow Logic, Inc., both of which cite −2.2°C as start-up temperatures for tower-mounted snowguns. However, previous literature (Scott et al 2003; Scott et al 2008; Steiger 2010) cite and use a daily average of −5.0°C as a snowmaking threshold. Therefore, to both provide consistency with previous work and to explore the sensitivity of our analysis to threshold variation, we chose 1 site, rain gauge 14, and analyzed snowmaking opportunity changes using the −5°C threshold as well. We chose rain gauge 14 because it has the most comparable aspect to Loon Mountain Resort and to 2 other nearby ski areas (although in the White Mountain region there are ski areas with snowmaking terrain facing a wide range of aspects).

TABLE 1 Location and attributes of sites referred to in the text.

Location	Coordinates	Elevation (m)	Aspect
Loon Mountain Resort	44.0564°N −71.6299°W	290 (base) to 930 (summit)	NW (primarily)
Hubbard Brook rain gauge 1	43.952121°N −71.724838°W	525	S
Hubbard Brook rain gauge 14	−71.765606°W	728	N
Hubbard Brook rain gauge 22	−71.700975°W	253	SE

TABLE 2 Changes in temperatures and snowmaking conditions for select time frames from January 1965 through December 2015 at rain gauge 1, rain gauge 14, and rain gauge 22 at the Hubbard Brook Experimental Forest.

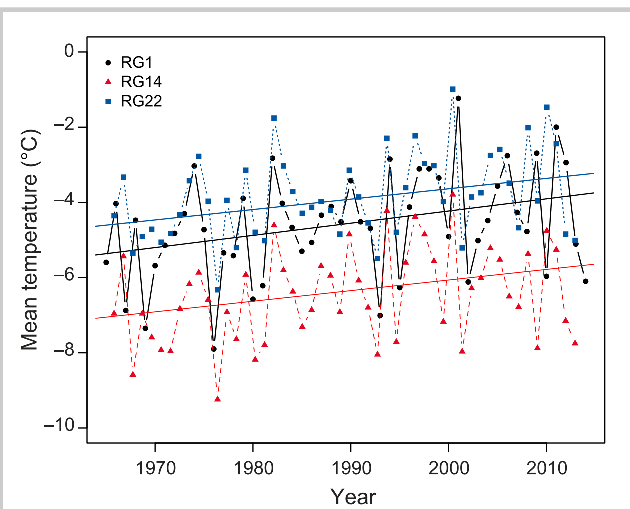
Snowmaking period	Average temperature trend (°C/decade)			Good snowmaking days trend (days/decade)		
	Gauge 1	Gauge 14	Gauge 22	Gauge 1	Gauge 14	Gauge 22
1 November to 28 Febeuary	0.3**	0.3**	0.3**	–2.7**	–1.6*	–1.9**
1 November to Thanksgiving	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
1 November to 5 December	0.4**	0.4**	0.3**	–2.0**	–1.5**	–1.7**
1 December to 25 December	0.5**	0.5**	0.5**	–1.2***	n.s.	–1.3**

n.s., not significant.
* $P \leq 0.10$; ** $P \leq 0.05$; *** $P \leq 0.01$.

The changes in total number of good snowmaking days for each time period was then analyzed for trend using the Mann-Kendall test for trends in a time series, with the slopes of any significant trend calculated using the nonparametric Sen estimate for slope (Sen 1968). Additionally, the thawing pressure trend experienced by the snowpack was analyzed by calculating a simple thawing degree-days metric, defined as the sum of all daily average temperatures above freezing (>0°C). We did not include thawing temperature trends for the time periods including November because above-freezing temperatures in November are more likely to affect ski area operations by delaying the start of snowmaking than they are to be thawing an existing manufactured snowpack. Thawing in November, therefore, would be measuring much the same operational effect as the days suitable for snowmaking analysis would.

We use snowmaking infrastructure investment history from Loon Mountain to discuss the adaptation to climatological impacts on snowmaking. In addition, we have compiled the hours per season that the snowmaking system was in operation, the total volume of water used per season to make snow as measured by a mechanical flowmeter, as well as the hectarage covered by the snowmaking system. These notes begin in the 2002–2003 season and are used to illustrate the effect that modernization of the snowmaking infrastructure has had as a climate adaptation, although we acknowledge that the motives for the snowmaking investments are more complex than simple climate adaptation. Because this period included an expansion of the terrain covered by snowmaking at Loon Mountain, the hours of snowmaking system operation as well as water volume used are discussed in the context of the total area covered by the snowmaking system (expressed in a per hectare basis).

FIGURE 2 Snowmaking season (1 November to 28 February) mean temperatures, 1965–2015. Sen slope estimates shown with solid lines.



Results

During the entire snowmaking period of interest, 1 November through 28 February, the average daily temperature warmed significantly over the 50-year record, with a slope of 0.3°C per decade at each site, or 1.5°C over the course of the record (Table 2; Figure 2). The November to Thanksgiving period showed the highest year-to-year variability and no significant change at any of the sites, while each of the other time frames (1 November to 25 December, 1 December to 25 December, and 1 November to 28 February) showed significant warming at each site (Table 2). The 1 December to 25 December period showed the most rapid warming at each site, and the rate was consistent at all 3 sites, although at the lowest site this trend was only marginally significant ($P \leq 0.10$). This represents a significant warming trend of 0.5°C per decade, or a 2.5°C warming over the course of the record (Table 2). Given the economic importance of the Christmas holiday (Scott et al 2006; Hamilton et al 2007; Scott et al 2008) this poses an obvious challenge for ski areas, although the immediacy of the problem will depend on the average temperatures at the site in general.

The scope of the operational effects, as well as the importance of individual site characteristics (such as elevation and aspect), become clearer when the temperature records are put in snowmaking terms. The 1

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TABLE 3 Comparison of 2 different snowmaking thresholds in terms of snowmaking opportunity lost to climate warming from rain gauge 14, Hubbard Brook Experimental Forest.

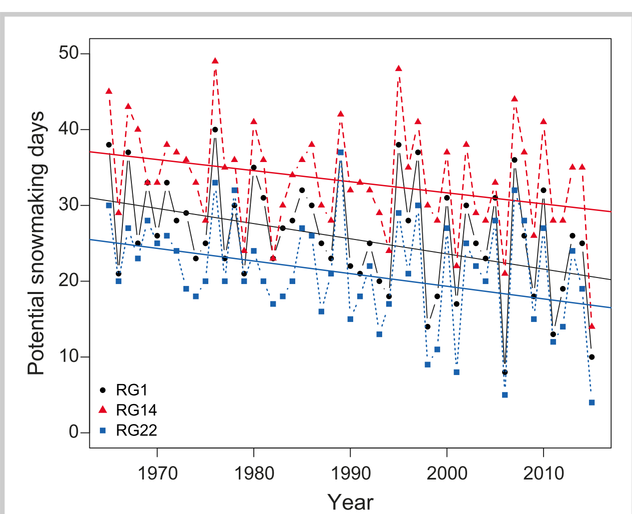
Time period	Slope of temperature change	Implied change in snowmaking days using −2°C threshold (implied % reduction)	Implied change in snowmaking days using −5°C threshold (implied % reduction)
1 November to 28 February	0.03**	−8.1* (−8.5%)	−11.25** (−15%)
1 November to Thanksgiving	n.s.	n.s.	n.s.
1 November to 25 December	0.04**	−7.3** (−20%)	−8.5** (−33%)
1 December to 25 December	0.05**	n.s.	−4.5* (−26%)

n.s., not significant.
* $P \leq 0.10$, ** $P \leq 0.05$.

to 25 December period showed consistent warming trends at each site, but the implied loss of snowmaking opportunity varied between sites, with the lowest, south-facing site showing the largest loss and the higher, north-facing site (rain gauge 14) not showing any loss in snowmaking opportunity in that time period (Table 2). We note that the 1965 calculated average temperature at that site for that period was −7.4°C, so it appears that the measured warming was not enough to cause many days to cross the snowmaking threshold of −2°C. In contrast, while the 2 lower elevation sites with southerly aspects showed comparable rates of warming, their higher average temperatures led to losses of around 6 days of good snowmaking conditions over the record in that 25-day period, or over 30% loss of opportunity. The longer pre-Christmas time period showed significant losses of snowmaking opportunity at each site (Table 2), with the north-facing site losing 7.3 days in that period for a 20% reduction in opportunity (Table 3; Figure 3).

Analysis of the whole season shows a loss of snowmaking opportunity over the record ranging from 8.1 days using rain gauge 14 to 13.6 days using rain gauge 1

FIGURE 3 Days of good snowmaking opportunity in the 1 November to 25 December time period, 1965–2015. Sen's slope shown with solid line.



(Table 2), with the bulk of the losses occurring early in the season.

Replacing the −2°C threshold with the more conservative −5°C threshold at rain gauge 14 shows a story consistent with the −2°C, but with slightly larger losses in opportunity, reflecting the colder necessary temperatures (Table 3). In each time frame analyzed, the reductions in snowmaking opportunity are larger with the more conservative threshold, but the major observation that the bulk of the warming is happening early in the season holds true. Using the −5°C threshold, 75% of the loss of opportunity during the entire snowmaking season occurs in the 1 November to 25 December time period. With the −2°C threshold it is 90%.

Despite the significant warming trends, analysis of thawing degree days did not detect significant changes in the melting pressure experienced by the snowpack. This contrasts somewhat with Hamburg et al (2013), who reported significant thawing pressure at rain gauge 1 using a December through March time frame and a 1966–2005 dataset. They did not detect any change using only January and February data. We note that our longer record includes some atypically cold winters in the early 2010s. While it is clearly warming in winter, any changes in the thawing pressure during the snowmaking season appear hard to detect and likely stronger at the tail end of the ski season and after the bulk of snowmaking has occurred.

Discussion

The warming experienced in the White Mountain region for the period of this analysis has been, on an annual basis, about 1°C (Campbell et al 2010) and closer to 1.5°C in the winter months (Campbell et al 2010). Wake et al (2014), using slightly later start and end dates (1970–2012) than Campbell et al (2010), similarly reported a higher rate of warming in winter than annually, and interestingly observed that daily minimum temperatures are consistently warming at a faster rate than daily maximums. Current projections of winter temperature warming in our region range from 0.2°C/decade to 0.8°C/decade, depending on the emission scenario and model

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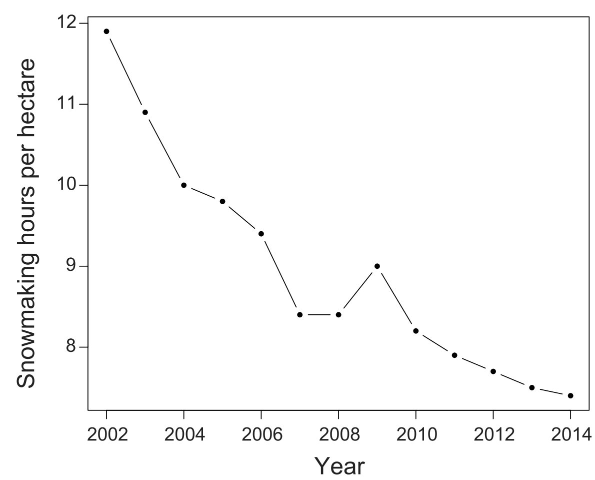
used (Campbell et al 2010). The longest snowmaking period we used indicated a historical warming of 0.3°C/ decade regardless of aspect—decidedly at the lower end of the range of predicted 21st-century change.

Our analysis demonstrates that this temperature change has already negatively affected the conditions optimal for snowmaking with state-of-the-art technologies by reducing the number of days with suitable snowmaking conditions, especially in the early season where the rate of warming was more pronounced. In a comprehensive regional analysis of the vulnerability of winter tourism in the northeastern United States, Scott et al (2008) identified 2 economic risk criteria for ski areas: the 100-day rule, where a ski area must have 100 days of operation to remain economically viable (König and Abegg 1997), and the probability of an area being open for the entire Christmas holiday (Scott et al 2008; Dawson and Scott 2013). While both risks can theoretically be mitigated through increased snowmaking, the early season warming observed in this analysis strongly suggests that addressing the second risk factor will put the greatest strain on ski areas in our region. For example, in the 2016–2017 ski season, Loon Mountain Resort operated over 100 days beyond 1 January, closing on 16 April, yet almost 25% of its tickets sales occurred before then, with over 16% occurring over the 25 December to 1 January holiday period.

In terms of the snowmaking opportunity lost to climate warming over time, the results from rain gauge 14 suggests a snowmaking season reduction at Loon Mountain over our record of between 8.1 and 11.3 days, depending on which snowmaking temperature threshold we used, or an 8.5% to 15% reduction in snowmaking opportunity (Table 3). However, improvements in snowmaking infrastructure at Loon have outpaced this pressure, as the hours of snowmaking operation per hectare have decreased by 31% from the 2002–2003 to 2004–2005 average to the 2012–2013 to 2014–2015 average (Figure 4). This reduction reflects the fact that Loon Mountain has been able to produce more snow in less time as its snowmaking infrastructure has improved, mitigating any challenges presented by the reduction in opportunity. Investments in modern snowmaking equipment have reduced peak energy demand despite increasing snowmaking acreage, and investments in pumping capacity and water storage have allowed greater volumes of water to be applied in shorter time frames, thus addressing both the potential limits of energy and water in the context of a more limiting temperature environment. For example, the average amount of water pumped per hour/hectare of operation in the last 3 seasons of the record (2012–2013, 2013–2014, and 2014–2015) was over 2.5 times higher than the average of the first 3 seasons recorded (2002–2003, 2003–2004, and 2004–2005). This water availability is met at Loon Mountain by a 272.5 million-liter storage pond, installed in 2007, which

FIGURE 4 Number of hours of snowmaking operations per season expressed per hectare of snowmaking terrain.



buffers the availability of its chief water source, the East Branch Pemigewasset River. This capacity may need to be increased if snowmaking windows continue to decrease, yet more importantly, we note that Loon Mountain is generally well-placed with regard to water access, as the site on the East Branch where Loon draws its water has over 250 km^2 of drainage area upstream. A brief survey of upstream drainage areas at other regional ski areas revealed a range of less than 1 km^2 to more than 250 km^2, with Loon Mountain having the largest in the region. These drainage areas are important because if we assume similar annual water yield per unit area (Falcone et al 2010), sites with larger drainage areas will have access to more water.

Our analysis suggests that if a ski area places a high priority on Christmas vacation snow coverage, the pressure on its water supplies has been increasing at a faster rate than an overall, season-long assessment would indicate. While existing projections of climate warming (Frumhoff et al 2007; Hayhoe et al 2007) effects on snowmaking in our region account for both the importance of the Christmas holiday (Scott et al 2006; Dawson and Scott 2013) and variety in both emissions scenarios and existing models (Scott et al 2006; Frumhoff et al 2007; Scott et al 2008), the downscaled climate models have been observed to underestimate winter warming on time scales comparable to our analysis (Hayhoe et al 2007). This is consistent with our observations of historically disproportionate warming in the early part of the snowmaking season and suggests that snowmaking requirements, and particularly demand for water, may be stronger than more general projections would indicate.

We note that our analysis emphasizes the environmental context of snowmaking by focusing on the relationships between temperature and water. We only

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generally address the broader business context in which ski areas operate by utilizing business-relevant time frames for analysis. We acknowledge that ski area operators face more challenges than just providing a surface to slide on, including the importance of natural snowfall in driving skier interest (Hamilton et al 2007; Lee and Okrant 2014). Adapting a winter climate-dependent business in the face of warming temperatures is complex (Scott and McBoyle 2007; Steiger et al 2017), with both supply-side challenges, such as season length and snow conditions, and demand-side challenges, such as customer behavioral adaptation (see Dawson et al 2013). Our study area has been fortunate to have access to both abundant water and the investment dollars required to build a state-of-the-art snowmaking system, which has allowed it to outpace pressures from increasing temperatures to date.

Pairing the long-term data with questions generated through many conversations with a local snowmaking professional has revealed a more rapid warming in the pre-Christmas holiday weeks than we would have expected from a more general, season-long analysis. This insight should be useful to other ski area operators in targeting their future snowmaking investments in the context of a warming climate. The most crucial time for snowmaking coincides with the part of the season where snowmaking opportunities are decreasing the most rapidly in our region, suggesting that investments aimed at capitalizing on shortening windows of snowmaking opportunity should be a strong consideration for ski area operations. Loon Mountain's investments in its snowmaking system have so far accomplished this, in part due to the increase in its ability to access and move large quantities of water in a shorter time. If these trends continue, the rate at which water will be used in snowmaking will increase due to the economic pressure of a more rapidly warming pre-Christmas season, even if total water used in a season were to remain relatively constant.

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