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ORIGINAL ARTICLE

Climate change vulnerability of the US Northeast winter recreation– tourism sector

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Abstract Winter recreation is an important part of the cultural identity of the Northeast United States and is a multibillion dollar contributor to the regional economy. This study examined the vulnerability of the two largest winter recreation industries, snowmobiling and alpine skiing, to four climate change scenarios for the twenty-first century. Under all scenarios, natural snow became an increasingly scarce resource. The diminished natural snow pack had a very negative impact on the snowmobile industry. As early as 2010–2039, 4 to 6 of the 15 snowmobile study areas were projected to lose more than half of the current season. Reliable snowmobile seasons (>50 days) were virtually eliminated in the region under the A1Fi scenarios by 2070–2099. The large investment in snowmaking substantially reduced the vulnerability of the ski industry and climate change posed a risk to only 4 of the 14 ski areas in 2010–2039, where average ski seasons declined below 100 days and the probability of being open for the entire Christmas–New Year's holiday declined below 75%. Conversely, by 2070–2099 only four ski study areas had not reached these same economic risk criteria. In order to minimize ski season losses, snowmaking requirements are projected to increase substantially, raising important uncertainties about water availability and cost. Climate change represents a notable threat to the winter recreation sector in the Northeast, and the potential economic ramifications for businesses and communities heavily invested in winter tourism and related real estate is sizeable.

Keywords Adaptation · Climate change · Recreation · Skiing · Snowmobiling · Tourism · Winter sports · Snowmaking

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1 Introduction

Winter sports tourism, or more specifically the skiing industry, has been repeatedly identified by government assessments as highly vulnerable to global climate change (Canada Country Study 1998; ACACIA 2000; Intergovernmental Panel on Climate Change (IPCC) 2001; US National Assessment Team 2000; World Tourism Organization 2003). Climate change studies on the ski industry have been conducted in several nations [Australia (Galloway 1988; Hennessy et al. 2003; Bicknell and McManus 2006); Austria (Breiling and Charamza 1999; Wolfsegger et al. 2008; Abegg et al. 2007); Canada (McBoyle and Wall 1987, 1992; Lamothe and Périard Consultants 1988; Scott et al. 2003, 2006, 2007; Scott and Jones 2005); France (Abegg et al. 2007); Germany (Abegg et al. 2007); Italy (Abegg et al. 2007); Japan (Fukushima et al. 2003); Switzerland (König and Abegg 1997; Elsasser and Messerli 2001; Elsasser and Bürki 2002); United States (Lipski and McBoyle 1991; Hayhoe et al. 2004; Casola et al. 2005)], each projecting negative impacts, though to varying degrees and over different time horizons.

This research literature has two very important limitations. First, climate adaptation by ski area operators has not been adequately assessed (Scott and McBoyle 2006). Only 5 of the 17 studies that have assessed the potential impact of climate change on ski operations (season length) have incorporated snowmaking (Scott et al. 2003, 2006, 2007; Scott and Jones 2005; Hennessy et al. 2003). Consequently, Scott (2005) indicated that many existing studies of the impact of climate change on ski operations may have overestimated future damages and recommended reassessments be completed in regions where snowmaking is utilized intensively. Wolfsegger et al. (2008) found snowmaking was the most preferred climate adaptation strategy by Austrian ski area managers and that the majority believed that further adaptation would allow their business to remain economically viable until at least mid-century, regardless of the magnitude of climatic change. Their findings support Scott's (2005) contention that future studies of the potential impact of climate change on skiing should anticipate the future development of snowmaking.

A second important limitation of this literature is the very limited analysis of the potential adaptive response of skiers to climate change. Behringer et al. (2000) and König (1998) surveyed skiers to examine their response to scenarios of climate change altered ski conditions in Switzerland and Australia. In both cases, about one-third of respondents indicated they would ski less often at the same locations (temporal substitution) and another third would go elsewhere (spatial substitution). Approximately 5% would stop skiing entirely. Scott (2005) used a climate change analogue approach to examine the aggregate response of skiers. When visitation during the record warm winter of 2001–2002 (which was a temperature analogue for normal winter conditions in the 2040–2069 under a higher emission scenario), was compared with the winter of 2004–2005 (which is the closest winter that is climatically representative of the 1971–2000 average), total skier visits were 7% to 11% lower in New England, Ontario, and Québec in 2001–2002. This suggests that the snow conditions provided by ski areas during this climate change analogue season were sufficient to continue to attract skiers in the region and that demand remained relatively stable despite reduced natural snow cover throughout the region. The decline in visitation was less than what was projected by the Behringer et al. (2000) and König (1998) surveys, but this finding is limited in that it only examines the impact of one poor year rather than the impact of a series of poor seasons. The analogue approach also cannot provide insight into the response of key market segments of interest to the ski industry or exactly how skiers adapted (i.e., spatial or temporal substitution of skiing activity). Further research is needed to better understand the potential behavioural response of skiers to repeated marginal winters anticipated under climate change and the role of factors such as customer loyalty.

In a North American context, another major gap in our understanding of the potential impact of climate change on winter recreation and tourism relates to the future sustainability of the economically large snowmobile industry ($27 billion – International Snowmobile Manufacturers Association 2006a). Snowmobiling relies entirely on natural snowfall because the linear nature and long distances of snowmobile trails make widespread implementation of snowmaking systems economically and logistically impractical. As a result, snowmobiling activities are highly sensitive to climate variability. As a recent example, the record warm early winter of 2005/2006 delayed the opening of many snowmobiling trails across eastern North America until late February, including Ontario (Ontario Federation of Snowmobile Clubs 2006), New York (Associated Press 2006a), and Vermont (Associated Press 2006b; Dritschilo 2006). In the only studies to examine the potential impacts of climate change on snowmobiling, Scott et al. (2002) and Scott and Jones (2006) projected the snowmobile industry could suffer large season length reductions (greater than 50%) in several regions of Canada under higher emission (A1) climate change scenarios in 2040–2069.

Previous studies of the potential impact of climate change on winter recreation and tourism in the Northeast region of the United States are highly limited. No studies on the impact of climate change on the snowmobile industry could be identified. The published (Bloomfield et al. 1997) and unpublished (Badke 1991) studies that have examined the potential impacts of climate change on the ski industry, and cited by media and non-governmental organizations (e.g., Clean Air–Cool Planet 2002), are flawed methodologically because they use unrealistic ski operation indicators and do not incorporate snowmaking, even though 75% of skiable terrain in the region was covered with snowmaking in 2004–2005 (National Ski Areas Association 2005).

This study was designed to overcome two of the aforementioned major limitations of the climate change literature on the winter recreation and tourism sector in the Northeast region of the United States. Specifically, the objectives of this study were to utilize the common set of climate change scenarios (A1Fi and B1 emission scenarios run with three Global Climate Models: the Hadley Centre Coupled Model, version 3 [HadCM3]; the Parallel Climate Model [PCM]; and the Geophysical Fluid Dynamics Model [GFDL]) developed for the Northeast Climate Impact Assessment (NECIA) (described in Hayhoe et al. 2007 and Frumhoff et al., this issue) to examine the potential impact on:

(1) the average length of the snowmobiling season and the potential change in the spatial extent of snowmobiling in the region; and,
(2) three indicators of the sustainability of the ski industry: season length, probability of being operational during the economically critical Christmas–New Year's holiday period, and snowmaking requirements.

2 The Northeast winter recreation and tourism/sector – what's at risk?

Snow-based recreation in the United States, encompassing downhill (alpine) skiing and snowboarding, cross-country (Nordic) skiing, and snowshoeing, was recently estimated to contribute an estimated $66 billion to the US economy and support approximately 556,000 jobs (Southwick Associates 2006). Just over 8% of the US population (15.5 million people) participate in these forms of snow-based recreation. The same study indicated that participation in snow-based recreation was higher (13%) in the Northeast (encompassing the states of Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) and the economic contribution to the regional economy was $4.6 billion annually.

Snowmobiling was not included in this economic assessment of snow-based recreation, but is perhaps the largest winter recreation industry in the United States, with approximately 15 million active participants that support approximately 85,000 jobs and generate an estimated $27 billion in goods and services in North America (International Snowmobile Manufacturers Association 2006a). Some of the densest snowmobile trail networks are located in Northeast, where the six states of Maine, Massachusetts, New Hampshire, New York, Pennsylvania and Vermont collectively account for 30% (approximately 40,500 miles) of all snowmobile trails in the United States (International Snowmobile Manufacturers Association 2006b). The available economic impact studies of snowmobiling in the Northeast collectively indicate the snowmobile industry is worth approximately $3 billion annually (Reiling 1998; Snowmobile Association of Massachusetts 2005; International Snowmobile Manufacturers Association 2006a). If the economic contribution of snowmobiling ($3 billion) is added to that of other snow-based recreation ($4.6 billion), the entire snow-based recreation economy in the Northeast could approach $7.6 billion annually.

3 Methods

3.1 Climate change scenarios

The six climate change scenarios used in this analysis (HadCM3, PCM, and GFDL Global Circulation Models (GCMs) each forced with two emission scenarios (Nakienovi et al. 2000): A1Fi and B1 – representing higher [970 ppm] and lower [550 ppm] emission futures, respectively), were selected by the Northeast Climate Impact Assessment team and used consistently by all sectoral analyses in this integrated regional assessment. The rationale for scenario selection, the performance of the three GCMs in the study area, and the methodological details of scenario construction (including downscaling) are described in Hayhoe et al. (2007; this issue) and Frumhoff et al. (this issue). Daily temperature, precipitation and snow depth fields were extracted from the gridded (1/8° resolution) scenarios from Hayhoe et al. (2007) and used as input into the impact analyses of the snowmobiling and skiing industries. Climate data was extracted for the climatological baseline period (1961–1990) and three future timeframes: 2010–2039, 2040–2069 and 2070–2099. Importantly, for this assessment of winter snow sports, the selected GCMs (HadCM3 and PCM) were found to somewhat underestimate recent observed warming in the winter months and the decline in snow pack in the study area and thus may also underestimate future changes in winter temperatures and snow pack under climate change scenarios.

3.2 Snow modelling

3.2.1 Snowmobile analysis

The physical resource on which snowmobiling depends is natural snow. Daily snow depth values for this analysis were derived from output of the variable infiltration capacity (VIC) model (developed by Cherkauer et al. 2003). Further details on the VIC snow model parameterization and performance in this region are available in Hayhoe et al. (2007). The

VIC model snow depth values are for the average elevation (meters above sea level [masl]) of each grid cell. Consequently, within each grid cell, the modelled snow depth may be underestimated for snowmobile trails at higher elevations or overestimated for trails at lower elevations. Data is not available on elevation of individual snowmobile trails in order to assess the extent of this source of error.

3.2.2 Ski analysis

The snow depth field from the VIC model could not be directly used for the analysis of the ski industry because it only models natural snow depth and has no capacity to integrate snowmaking. Instead, the ski operations model developed by Scott et al. (2003, 2006, 2007) was used in this analysis. The snow model within this ski operations model was trained to emulate the snow depth of the VIC model in order to provide as much consistency as possible with other sectoral studies in the NECIA that utilized VIC snow pack data. The snow model operating within the ski operations model of Scott et al. (2003, 2006, 2007) was able to emulate natural snow depth output from the VIC model reliably, with R^2 values for daily snow depth at 1 cm resolution ranging from 0.77 to 0.93 over the baseline period (1961–1990). The three study areas with the lowest R^2 values (<0.83) were areas with marginal snow cover (Connecticut, western Pennsylvania, and southwest New York), where single day precipitation events that were near the snow–rain threshold were sometimes modelled differently because of slightly different precipitation typing parameters in the two models.

The snow model used in this analysis is a physically based and locally calibrated model that is built largely on methods used to develop the *Canadian Daily Snow Depth Database* (Brown and Braaten 1999) and *Water Balance Tabulations for Canadian Climate Stations* (Johnstone and Louie 1983). Using daily temperature and precipitation inputs, the model estimates snow depth based on the calculation of three parameters: amount of precipitation that falls as snow and rain; snow accumulation; and snowmelt. Snowfall was added to the snow pack assuming a constant density of 400 kg m^{-3}. The snowmelt equation used in the model was developed by the US Army Corps of Engineers (1956).

To complete the modelling of daily snow depth at ski areas, a snowmaking module is coupled to the snow model. The technical capacities (minimum temperature at which snow can be made economically, daily snowmaking capacity) and decision rules for the snowmaking module (start/end dates, target snow pack depth to maintain) are consistent with Scott et al. (2003, 2006, 2007) and are outlined in Table 1. The snowmaking capabilities modelled represent those of an advanced snowmaking system and assumes 100% coverage of skiable terrain. It is acknowledged that not every ski area in Northeast will currently have such advanced snowmaking systems and thus, this study may underestimate the impact of climate change on some ski areas. However, with sufficient investment and adequate water supply, all ski areas could potentially develop this level of snowmaking capacity (i.e., adaptive capacity).

3.3 Recreation season and operations modelling

3.3.1 Snowmobile analysis

Recreation climatology research has endeavored to identify climatic thresholds for different recreation activities, including snowmobiling. Gates (1975) and Crowe et al. (1977) used both temperature and snow depth indicators to define a 'snowmobiling day.' For temperature, Gates (1975) defined a suitable snowmobiling day as one in which the minimum temperature was warmer than −14°C. However, adaptations in the engineering

Table 1 Ski operations model parameters

Snowmaking capacities and decision rules	
Start date	22 November (Julian day 326)[a]
End date	30 March (Julian day 90)[a]
Minimum snow base to maintain until Julian day 90	60 cm[b]
Temperature required to start snowmaking	−5°C[c]
Snowmaking capacity	10 cm/day
Power cost as percentage of total snowmaking costs	32%
Coverage of skiable terrain	100%

[a] While the start and end dates for snowmaking were based on regional averages, some ski areas attempt to open earlier and continue to make snow into late-March to extend the season.

[b] Although 30 cm is the minimum operational snow base and the climate suitability threshold used to define an operational ski day, ski areas in the region typically produce a deeper snow base (usually 50–75 cm) early in the ski season in order to have a reserve of snow in case of poor weather conditions (high temperatures, rain) later in the ski season. To emulate this management strategy, the snowmaking module was designed to maintain a 60-cm snow base until the end of March when possible (after the economically important school holiday period).

[c] While snow can be made at temperatures of approximately −1°C (with low humidity levels and special snowmaking additives like 'SnowMax'®), ski area operators and snowmaking equipment manufacturers generally identify −5°C as a threshold for efficient snowmaking.

design of snowmobiles (e.g., heated handles/control bars and footrests) and advancements in thermal clothing have meant that over the past 20 years, temperature has become a more suitable indicator of the degree of thermal comfort than a determinant of participation. The analysis of Scott et al. (2002) on the snowmobile trail condition reports and consultations with snowmobile industry stakeholders concluded that temperature was not a reliable indication of whether snowmobile trails were in operation or not.

The physical determinant of the length of the snowmobile season is natural snow and, to a lesser extent, the quality of snow conditions (e.g., icy, pooled melt water). On a daily basis throughout the winter season, snowmobile trails will be designated as 'open', 'closed', or having 'limited access', depending on natural snow conditions. Gates (1975) and Crowe et al. (1977) suggested that a minimum of 2.5 cm of snow was necessary for snowmobiling. The analysis of Scott et al. (2002) on the information available from snowmobile associations and communications with snowmobile industry stakeholders indicated that a 2.5 cm snow depth threshold was unrealistic, even for very smooth terrain. Minimum snow depths required to operate snowmobile trails vary among snowmobiling jurisdictions (e.g., New York – 8 cm (FAST 2005); Wisconsin – 10 to 15 cm (Wisconsin Department of Natural Resources 2003); Illinois – 10 cm (Lake County Forest Preserves 2005); Ontario – 15 cm (Scott et al. 2002)). Discussions with industry stakeholders suggested that a minimum snow depth of 15 cm is the favoured threshold for opening snowmobile trails with smooth terrain. Consistent with Scott et al. (2002) and Scott and Jones (2006), this analysis defined the snowmobile season length as the number of days between December 1 and March 31 with at least 15 cm of natural snow depth. Trails that require heavy grooming equipment need more than 15 cm and thus this analysis will underestimate the potential impact of climate change on some snowmobile trail systems.

3.3.2 Ski analysis

The ski operations model used for this analysis is based on the work of Scott et al. (2003, 2006, 2007) that was conducted in the nearby provinces of Ontario and Québec. The climatic criteria defining an operational ski day were adopted from Scott et al. (2003), who derived the criteria from an examination of 17 years of daily ski operations data from ski areas in Ontario and communications with ski industry stakeholders. Ski areas were assumed to close if any of the following climatic conditions occurred: snow depth less than 30 cm; maximum temperature greater than 15°C; or 2-day liquid precipitation exceeds 20 mm. It is acknowledged that these criteria may differ slightly in other ski regions; however, consultations with stakeholders from the Québec and Vermont ski industries (Bourque and Scott 2004 and Scott 2004, respectively) confirmed these criteria were generally transferable to these areas.

An important difficulty in attempting to model the length of the ski season, which is a socioeconomic system, with only climatic criteria is the inability to account for the business decision-making factors that influence ski area operations. Nonetheless, the ski operations model has been shown to perform reasonably well in comparisons of observed and modelled ski seasons. A historic record of the length of ski seasons from individual ski areas in Northeast was not available to validate the model in each of the 14 study areas selected for this analysis. Aggregated data on the average ski season is available for the Northeast ski region from the National Ski Areas Association. The average length of the most recent 15 ski seasons (1990/1991 to 2004/2005) was 124 days. The average modelled baseline ski season of the 14 study areas was 129 days. The slightly longer modelled season was expected because, as noted in Section 3.2.2, not all ski areas currently possess the advanced snowmaking capabilities assumed in the model. The difference of 5 days between the observed and modelled average regional ski season (approximately 4% difference) suggests the model performs reasonably well in the Northeast region.

3.4 Impact assessment approach and study areas

3.4.1 Snowmobile analysis

Snowmobile trail networks have varied terrain and grooming practices, which affect the depth of snow required for safe operations. Accounting for these local and trail-level variances was beyond the scope of this regional level analysis. For this analysis, it was assumed that the snowmobile trails at all study areas were relatively smooth and would only be groomed with light equipment, so that a minimum 15 cm snow depth was required for the trail to be considered operational. It is acknowledged that due to trail characteristics and microclimate features (e.g., shaded forest trail versus open terrain), the performance of the modelled season length may vary for individual trails in each study area.

Snowmobiling opportunities vary throughout Northeast due in part to differences in geography and climate. To reflect the differences in current snowmobiling seasons and the potential impacts of climate change, a total of 15 snowmobile study areas (identified as 1 to 15 in Fig. 1) were selected across the region. Each of the study areas was located where there is a high density of snowmobile trails, as determined from the websites of state snowmobile associations.

3.4.2 Ski analysis

The climate change assessment approach adopted for the ski analysis is consistent with those used by Scott et al. (2006, 2007). In order to compare the relative impact of projected climate change throughout the Northeast region, a single hypothetical ski area with identical characteristics (e.g., size, snowmaking capacities, and practices) was modelled at each study

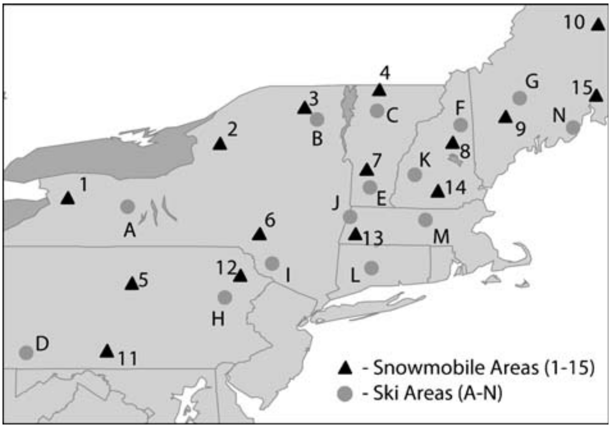

Fig. 1 Study areas

area. This approach isolates the importance of climate and projected climate change at each location, rather than assessing the relative technological (e.g., snowmaking) and business (e.g., four season operation) advantages of individual ski areas. This consistent methodology also facilitates comparisons of climate change impacts with competitors in the neighbouring ski regions of Québec and Ontario.

A total of 14 ski study areas (identified as A to N in Fig. 1) were selected to provide spatial coverage of the Northeast ski industry. For each of the 14 ski study areas, the nearby ski area(s) and the elevation range of their ski terrain are identified in Table 2. The elevation of the VIC model grid cell, from which the climate change scenarios were obtained, is also identified in Table 2. In study areas that contain multiple ski areas at different elevations, the model results would best apply to different parts of the ski terrain at each ski operation (i.e., summit or base operations). For example, the results of the North Vermont study area (area C in Fig. 1) would be representative of the base terrain of Bolton Valley Resort, Stowe Mountain Resort, and Smugglers Notch and may over-estimate the impact of climate change on their higher elevation terrain (>1,000 masl). Conversely, the model results would be representative of the summit at Cochran Ski Area and may underestimate the potential impact on this ski operation.

4 Climate change impact analysis

4.1 Snowmobile industry

The modeled average baseline (1961–1990) snowmobile season varied substantially throughout the Northeast Region and among the 15 study areas, ranged from 4 to 106 days. Long snowmobile seasons (>70 days) were found in the states of Vermont, New Hampshire, and Maine, and in the Lake Ontario snow belt of north–central New York (study areas 2, 4, 7, 8, 9, 10 and 15 in Fig. 1). Much shorter snowmobile seasons (<50 days) were found in more southern and low elevation study areas (1, 5, 6, 12, 13, 14 in Fig. 1). In the baseline period (1961–1990), the southern margin of snowmobile activity is approximately 42°N.

Table 2 Ski operations located near each ski study area

Study area (modeled snow elevation)	Ski operations	Ski terrain base (masl)	Ski terrain summit (masl)
[A] Western New York (497 masl)	Bristol Mountain	305	671
	Dry Hill Ski Area	198	290
	Swain Ski Resort	402	600
[B] Northeastern New York (692 masl)	Whiteface Mountain	372	1,417
	Titus Mountain	366	411
	Gore Mountain	457	1,097
[C] Northern Vermont (551 masl)	Bolton Valley Resort	446	960
	Stowe Mountain Resort	390	1,340
	Cochran Ski Area	152	305
	Smugglers Notch	314	1,109
[D] Eastern Pennsylvania (385 masl)	Big Boulder Ski Area	518	693
	Alpine Mountain	183	351
	Blue Mountain Ski Area	177	488
[E] Southern Vermont (568 masl)	Bromley Mountain	594	1,001
	Magic Mountain	351	869
	Stratton Mountain	571	1,181
	Mount Snow	579	1,097
[F] Northeastern New Hampshire (580 masl)	Wildcat Mountain	594	1,238
	Black Mountain	381	1,007
	Cranmore Mountain	152	518
	Attitash Resort	183	716
[G] Western Maine (573 masl)	Sugarloaf USA	432	1,291
	Saddleback Ski Area	697	1,306
	Titcomb Mountain	122	229
[H] Western Pennsylvania (662 masl)	Seven Springs Mountain	683	911
	The Springs at Laurel Mountain	579	853
	Hidden Valley Resort	701	914
	Jack Frost Ski Area	472	610
[I] Southeastern New York (383 masl)	Holiday Mountain	274	396
	Bobcat Ski Center	700	1,020
[J] Western Massachusetts (329 masl)	Bosquet Ski Area	343	572
	Jimmy Peak Mountain	381	752
	Ski Butternut	305	549
[K] Southwestern New Hampshire (449 masl)	Mount Sunapee	375	836
	Pat's Peak Ski Area	210	427
	Ragged Mountain	305	686
[L] Connecticut (145 masl)	Mount Southington Ski Area	30	160
	Powder Ridge Ski Area	76	229
[M] Eastern Massachusetts (306 masl)	Wachusett Mountain	302	611
	Ski Ward	61	125
[N] Southeastern Maine(101 masl)	Camden Snow Bowl	46	335

See Fig. 1 for the location of ski study areas (A–N).

The climate change scenarios consistently projected a trend toward shorter snowmobile seasons throughout the Northeast and a northward shift in the southern margin of snowmobiling activity. As early as 2010–2039, four of the 15 study areas are projected to lose more than 50% of their snowmobiling season under the lower (B1) emission scenario

Table 3 Modelled change in snowmobile season length

Study areas[a]	Baseline (1961–1990) (days)[b]	Lower emission scenario (B1)			Higher emission scenario (A1Fi)		
		2010–2039 (% Δ)[c]	2040–2069 (% Δ)[c]	2070–2099 (% Δ)[c]	2010–2039 (% Δ)[d]	2040–2069 (% Δ)[d]	2070–2099 (% Δ)[d]
[1] Western New York	22	−68	−85	−85	−68	−85	−92
[2] North–central New York	94	−15	−26	−39	−16	−50	−78
[3] Northeastern New York	54	−37	−46	−53	−21	−52	−73
[4] Northern Vermont	74	−30	−42	−64	−13	−38	−65
[5] North–central Pennsylvania	18	−50	−61	−61	−67	−100	−89
[6] Southeastern New York	23	−39	−61	−61	−68	−90	−94
[7] Southern Vermont	94	−23	−35	−39	−28	−56	−70
[8] Northern New Hampshire	106	−8	−18	−18	−6	−16	−39
[9] Northwestern Maine	103	−15	−21	−32	−16	−29	−53
[10] Northeastern Maine	88	−22	−25	−39	−32	−38	−61
[11] South–central Pennsylvania	4	−100	−100	−100	−67	−100	−100
[12] Eastern Pennsylvania	31	−63	−79	−75	−61	−89	−89
[13] Western Massachusetts	49	−40	−58	−61	−31	−76	−83
[14] Southern New Hampshire	45	−45	−62	−69	−62	−82	−90
[15] Southeastern Maine	73	−34	−46	−53	−44	−71	−91

[a] Study areas (1–15) are located in Fig. 1.

[b] 30-year average of six baseline scenarios (HadCM3–A1Fi, HadCM3–B1, PCM1–A1Fi, PCM1–B1, GFDL–A1Fi, GFDL–B1).

[c] 30-year average of three scenarios (HadCM3–B1, PCM1–B1, GFDL–B1).

[d] 30-year average of three scenarios (HadCM3–A1Fi, PCM1–A1Fi, GFDL–A1Fi).

% Δ: percentage change

and six locations under the higher (A1Fi) emission scenario (Table 3). Under the higher emission scenario (A1Fi) in 2040–2069, 11 of the 15 study areas were projected to lose 50% or more of the current snowmobile season, with seven study areas losing over 75% of their current season. Under the lower emission scenario (B1) only seven of the study areas lost more than 50% of their snowmobile season in the 2040–2069 period. While the proportion of study areas with short (<50 days) and long (>70 days) snowmobile seasons is approximately equal in the baseline period, by 2040–2069 only three locations are projected to still have long seasons under the lower emission (B1) scenario and two under the higher emission (A1Fi) scenario (Table 3). In 2070–2099 only northern New Hampshire and northwest Maine retain long snowmobile seasons under the lower emission (B1) scenario and under the higher emission scenario (A1Fi) a long season is no longer found at any of the study areas (Table 3).

4.2 Ski industry

Inter-annual climate variability affects various aspects of ski operations in the Northeast and has been an important driver of the massive investment in snowmaking over the past 20 years. Figure 2 demonstrates that the ski season in the Northeast ski region has varied between 101 and 146 days between 1990–1991 and 2004–2005. Figure 2 also clearly illustrates the impact of climate adaptation. As more ski areas in the region invested in

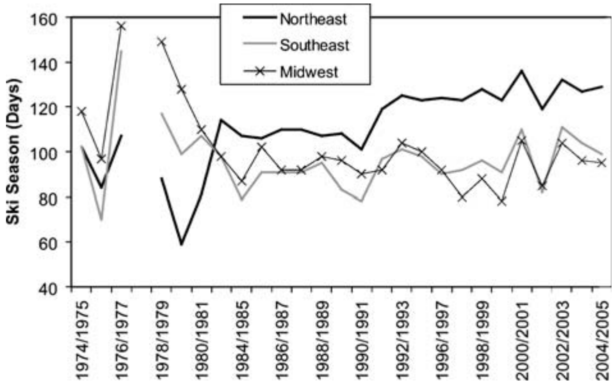

Fig. 2 Historic variability of ski seasons in Eastern US ski regions

sophisticated snowmaking systems in the 1980s and early 1990s, the average season length has increased (versus the 1980s) and has stayed above 120 days even though the 1990s were the warmest decade on record. Even during the record warm winter of 2001–2002, which was +6.5°C above the 1971–2000 average in the Northeast (National Oceanic and Atmospheric Administration 2005) and a temperature analogue for winters in 2040–2069 under a higher emission scenario, the average ski season in the Northeast was longer than all of the ski seasons prior to 1990 (Fig. 2).

The climate change scenarios consistently projected a trend toward shorter ski seasons throughout the Northeast (Table 4). Under the lower emission (B1) scenario for 2010–2039, only three study areas were projected to lose less than 10% of the ski season, while ten study areas lost 10–17% and only the Connecticut location lost more than 20%. In 2040–2069, ski season losses were not substantially higher, with only the Connecticut location projected to lose greater than 25% of its ski season. The level of climate change impact increased in the 2080s where half of the study areas were projected to lose 25% or more of their ski season.

The higher emission scenario (A1Fi) had a much greater impact on the length of ski seasons in the region, especially in 2040–2069 and beyond (Table 4). In 2040–2069, eight of the study areas were projected to lose 25% or more of their ski season. By 2070–2099 all 14 of the study areas had lost at least 25% of the ski season and half of the study areas lost 45% or more.

In order to limit ski season losses to the levels described above, snowmaking requirements were projected to increase throughout the region (Table 5). Under the lower emission (B1) scenario for 2010–2039, snowmaking requirements would increase by at least 25% at half of the study areas (Table 5). In 2070–2099, climate change had distinctly different impacts on snowmaking requirements. Five of the study areas were projected to require at least 50% more snowmaking and increases of 25 to 49% were projected for an additional four locations. The remaining five study areas were projected to make the same amount or less machine-made snow in 2070–2099 than 2040–2069 due to the inability to make snow in unsuitably warm temperatures during the early and latter part of the current ski season.

The higher emission (A1Fi) scenario had a much greater impact on snowmaking requirements (Table 5). In 2010–2039, nine of the study areas were projected to require at least 25% more machine-made snow. In 2070–2099, three study areas were projected to require over a 100% increase in machine-made snow and four other locations require at

Table 4 Modelled change in average ski season length

Study areas[a]	Baseline (1961–1990) (days)[b]	Lower emission scenario (B1)			Higher emission scenario (A1Fi)		
		2010–2039 (% Δ)[c]	2040–2069 (% Δ)[c]	2070–2099 (% Δ)[c]	2010–2039 (% Δ)[d]	2040–2069 (% Δ)[d]	2070–2099 (% Δ)[d]
[A] Western New York	113	−15	−16	−29	−13	−27	−47
[B] Northeastern New York	147	−10	−12	−18	−10	−19	−34
[C] Northern Vermont	147	−10	−12	−19	−9	−21	−37
[D] Western Pennsylvania	122	−15	−18	−29	−15	−29	−46
[E] Southern Vermont	158	−7	−11	−16	−9	−18	−33
[F] Northeastern New Hampshire	159	−8	−11	−16	−10	−19	−33
[G] Western Maine	172	−6	−8	−8	−6	−14	−25
[H] Eastern Pennsylvania	114	−15	−19	−32	−16	−30	−50
[I] Southeastern New York	108	−14	−16	−27	−16	−28	−49
[J] Western Massachusetts	130	−13	−14	−24	−14	−24	−40
[K] Southwestern New Hampshire	129	−13	−15	−24	−13	−25	−42
[L] Connecticut	100	−21	−25	−40	−23	−38	−59
[M] Eastern Massachusetts	126	−15	−17	−28	−15	−27	−45
[N] Southeastern Maine	122	−17	−17	−29	−15	−28	−48

[a] Study areas (A–N) are located in Fig. 1.

[b] 30-year average of six baseline scenarios (HadCM3–A1Fi, HadCM3–B1, PCM1–A1Fi, PCM1–B1, GFDL–A1Fi, GFDL–B1).

[c] 30-year average of three scenarios (HadCM3–B1, PCM1–B1, GFDL–B1).

[d] 30-year average of three scenarios (HadCM3–A1Fi, PCM1–A1Fi, GFDL–A1Fi).

% Δ: percentage change

50% to 99% more machine-made snow. Snowmaking was projected to decline relative to 2040–2069 in five locations (West Pennsylvania, East Pennsylvania, Southeast New York, West New York, and Connecticut) where warm temperature made it unfeasible during parts of the winter months (Table 5).

From an economic perspective, it is important to note that, exclusive of any future efficiency gains, snowmaking costs would increase more than the percentage increase in volume of machine-made snow outlined in Table 5, because snowmaking will need to take place at warmer temperatures, requiring greater energy inputs. According to data from the National Ski Areas Association (2005), snowmaking represents approximately 5–6% of total operating expenses at ski resorts in the Northeast (an average of $727,000 in 2004–2005). The projected increases in snowmaking costs will therefore be salient, especially for ski areas with greater than average snowmaking requirements or inefficient snowmaking systems.

Shortened ski seasons and increased snowmaking requirements, which could potentially reduce revenues and increase operating costs, have important implications for the economic sustainability of ski businesses in the Northeast. Only management personnel would have sufficiently detailed financial information to estimate when their enterprise may not longer be viable because of the impacts of climate change. Nonetheless, there are broad economic indicators that can be used to explore the future sustainability of ski operations in the region. One general economic indicator used in previous climate change impact

Table 5 Modelled change in average snowmaking requirements

Study areas[a]	Baseline (1961–1990) (cm)[b]	Lower emission scenario (B1)			Higher emission scenario (A1Fi)		
		2010–2039 (% Δ)[c]	2040–2069 (% Δ)[c]	2070–2099 (% Δ)[c]	2010–2039 (% Δ)[d]	2040–2069 (% Δ)[d]	2070–2099 (% Δ)[d]
[A] Western New York	199	+18	+22	+22	+11	+20	+14
[B] Northeastern New York	152	+33	+33	+55	+32	+53	+81
[C] Northern Vermont	119	+28	+33	+53	+33	+56	+89
[D] Western Pennsylvania	186	+21	+25	+24	+20	+31	+27
[E] Southern Vermont	101	+39	+39	+65	+42	+73	+108
[F] Northeastern New Hampshire	79	+29	+37	+55	+35	+68	+120
[G] Western Maine	57	+46	+58	+58	+43	+86	+155
[H] Eastern Pennsylvania	225	+11	+16	+12	0	+12	+3
[I] Southeastern New York	188	+15	+15	+15	+13	+23	+18
[J] Western Massachusetts	173	+21	+24	+37	+26	+36	+40
[K] Southwestern New Hampshire	153	+27	+3	+38	+28	+53	+56
[L] Connecticut	217	+16	+23	+14	+13	+26	+5
[M] Eastern Massachusetts	187	+25	+28	+36	+26	+38	+38
[N] Southeastern Maine	144	+32	+36	+48	+26	+48	+73

[a] Study areas (A–N) are located in Fig. 1.

[b] 30-year average of six baseline scenarios (HadCM3–A1Fi, HadCM3–B1, PCM1–A1Fi, PCM1–B1, GFDL–A1Fi, GFDL–B1).

[c] 30-year average of three scenarios (HadCM3–B1, PCM1–B1, GFDL–B1).

[d] 30-year average of three scenarios (HadCM3–A1Fi, PCM1–A1Fi, GFDL–A1Fi).

% Δ: percentage change

assessments of the ski industry in Europe is the '100-day rule' (König and Abegg 1997; Elsasser and Bürki 2002), which suggests that ski businesses require a season length of 100 days to remain profitable. Stakeholders in the North America ski industry have also referred to this general indicator of profitability (Erickson 2005). The '100-day rule' is somewhat limited as an economic indicator because it does not consider in what part of the ski season that operational days are lost (i.e., highly valuable holiday periods or parts of the season with low visitation) or the increased costs of snowmaking.

To address the limitations of the '100-day rule,' a second economic indicator was also included in this analysis. It considers whether ski areas are open for the entire Christmas–New Year's holiday (modelled as a 12-day period from 22 December to 2 January each year), which is one of the most important revenue-generating periods for ski areas in the region and the most vulnerable climatically. In the Northeast, 15–20% of skier visits occur in this holiday period (National Ski Areas Association 2005), and while other holidays later in the winter are almost as important in terms of visitation, Christmas–New Year is early in the ski season with the least opportunity to make snow if it is required. A series of consecutive years with full or partial closures during the Christmas–New Year's period could pose a risk to the profitability of some ski areas by sufficiently reducing revenues or by damaging a ski area's reputation in the marketplace. To reflect the potential impact of the Christmas–New Year's holiday closures over a series of years in close proximity, the indicator selected was when the probability of being open for the entire Christmas–New

Year's holiday dropped below 75% (i.e., when closures can be expected in 2 to 3 years in every decade).

These 2 economic impact indicators (average ski season below 100 days and less than 75% probability that a ski area would not operate for the entire Christmas–New Year's holiday period) were used to assess the relative vulnerability of the 14 study areas. The timeframe that each of the 14 study areas was projected to reach these economic impact thresholds is provided in Table 6. The four locations of Connecticut, western New York, southeastern New York, and eastern Pennsylvania reached both economic risk criteria under the higher emission (A1fi) scenario in 2010–2039 and were thus considered to be very highly vulnerable to climate change. The high vulnerability category was comprised of ski areas that reached both economic risk criteria by 2040–2069 under the higher (A1Fi) emission scenario and included: southeastern Maine, eastern Massachusetts, and western Pennsylvania. The moderate vulnerability category consisted of southwestern New Hampshire, western Massachusetts, and northern Vermont, which did not reach both economic risk criteria until 2070–2099 under the higher (A1Fi) emission scenario. The locations in the lowest vulnerability category included: southern Vermont, northeastern New Hampshire, northeastern New York, and western Maine. These four locations did not reach both of the economic impact criteria in either the lower (B1) or higher (A1Fi) emission scenarios and therefore, may represent the areas that the Northeast ski industry contracts to over the course of the twenty-first century (Table 6).

While the aforementioned changes in the average ski seasons could pose a substantial challenge to the ski industry in the Northeast, projected changes in climatic extremes and climate variability, as described by Hayhoe et al. (2007), are likely to be as important for the future of ski operations if not more so. Extremely warm winters could significantly reduce snowmaking capacity at lower lying and more southerly ski resorts in the Northeast, and have a disproportionately high impact on ski businesses in the region. The financial effect of even a single extremely poor ski season was recently demonstrated by the devastating 2004–2005 season in the US Pacific Northwest, which reduced skier visits by 76% (National Ski Areas Association 2005) and put several ski areas in "recovery mode for several years" (Goodman 2005). The impact of extreme seasons can be more pronounced on small and medium sized independent ski businesses that are not able to draw on financial reserves of a larger company (Scott 2005) and would be amplified if occurring sequentially with even marginal seasons.

Modelled changes in minimum season length at the 14 study areas are presented in Table 7. The minimum season length is reduced to well below the '100-day' threshold at ten of the study areas as early as 2010–2039 (under both lower [B1] and higher [A1Fi] emission scenarios). The higher emission scenario (A1Fi) had a much greater impact on minimum seasons in 2040–2069, when the potential for devastatingly short seasons of less than 50 days (seven weekends) was modelled at six locations. In 2070–2099, the higher emission (A1Fi) scenario with the HadCM3 model projected that winter conditions would occasionally occur where, despite advanced snowmaking systems in place, entire ski seasons would essentially be lost at seven of the study areas (i.e., seasons less than 1 month long) because temperatures would be too warm to maintain a sufficient snow base.

5 Discussion

Under all of the climate change scenarios examined, natural snow will become an increasingly scarce resource in the Northeast region, with important potential implications

Table 6 Timeframe the ski areas reached economic risk criteria[a]

Timeframe	Indicator A: Average ski season <100 days		Indicator B: <75% probability of being open the entire Christmas–New Year's holiday	
	Lower emission scenario (B1)	Higher emission scenario (A1Fi)	Lower emission scenario (B1)	Higher emission scenario (A1Fi)
1961–90 baseline	Connecticut	Connecticut	Connecticut	Connecticut East Massachusetts West Pennsylvania
2010–2039	Eastern Pennsylvania SE New York Western New York	Eastern Pennsylvania SE New York Western New York	Eastern Massachusetts Western Pennsylvania SE Maine SW New Hampshire SE New York Western New York	SE Maine SE New York SW New Hampshire Western Massachusetts Western New York Eastern Pennsylvania
2040–2069	Western Pennsylvania	Eastern Massachusetts SE Maine Western Pennsylvania	Western Massachusetts Eastern Pennsylvania	Northern Vermont NE New Hampshire NE New York
2070–2099	Eastern Massachusetts SE Maine SW New Hampshire Western Massachusetts	Northern Vermont SW New Hampshire Western Massachusetts	Northern Vermont	Southern Vermont
Criteria not reached in twenty-first century	Northern Vermont NE New Hampshire NE New York Southern Vermont Western Maine	NE New Hampshire NE New York Southern Vermont Western Maine	NE New Hampshire NE New York Southern Vermont Western Maine	Western Maine

[a] Indicates the time period when the criteria was reached in at least two of the three GCMs.

for the multi-billion dollar snow-based recreation sector in the region. The impact of the diminished natural snow pack could be devastating for the snowmobile industry and trail-based winter tourism, but would highly depend on the magnitude of future climate change and how snowmobilers and recreational trail providers (land managers and communities) adapt to new climatic regimes. The majority of the 15 locations examined in this study were projected to have marginal or non-existent snowmobile seasons in 2040–2069 under both lower (B1) and higher (A1Fi) emission scenarios. Consequently, the loss of snowmobiling

Table 7 Modelled change in minimum ski season length

Study areas[a]	Baseline (1961–1990) (days)[b]	Lower emission scenario (B1)			Higher emission scenario (A1Fi)		
		2010–2039 (days)[c]	2040–2069 (days)[c]	2070–2099 (days)[c]	2010–2039 (days)[d]	2040–2069 (days)[d]	2070–2099 (days)[d]
[A] Western New York	119	93	88	84	87	73	54
[B] Northeast New York	128	116	109	106	109	97	76
[C] Northern Vermont	99	82	78	58	83	46	33
[D] Western Pennsylvania	99	77	66	60	74	51	31
[E] Southern Vermont	127	112	103	94	107	90	71
[F] Northeastern New Hampshire	129	110	104	93	110	89	67
[G] Western Maine	117	88	87	77	98	57	48
[H] Eastern Pennsylvania	97	70	66	55	65	45	32
[I] Southeastern New York	130	108	113	101	101	88	76
[J] Western Massachusetts	90	74	63	59	72	46	30
[K] Southwestern New Hampshire	90	64	63	50	73	43	30
[L] Connecticut	69	38	34	21	43	13	8
[M] Eastern Massachusetts	99	76	71	60	77	54	39
[N] Southeastern Maine	84	67	55	47	66	30	27

[a] Study areas (A–N) are located in Fig. 1.

[b] 30-year average of six baseline scenarios (HadCM3–A1Fi, HadCM3–B1, PCM1–A1Fi, PCM1–B1, GFDL–A1Fi, GFDL–B1).

[c] 30-year average of three scenarios (HadCM3–B1, PCM1–B1, GFDL–B1).

[d] 30-year average of three scenarios (HadCM3–A1Fi, PCM1–A1Fi, GFDL–A1Fi).

activity and related tourism would appear unavoidable in the following locations if the climate change scenarios projected for 2040–2069 were realized: western New York, north–central Pennsylvania, southeastern New York, south–central Pennsylvania, eastern Pennsylvania, western Massachusetts, southern New Hampshire, and northeastern New York.

The implication of a substantial decline in nearby opportunities for snowmobile participation remains an important uncertainty. If participation remains unchanged or declines only slightly, the few locations that are projected to continue to have sufficient natural snow for snowmobiling later into the twenty-first century (north–central New York, northern Vermont, southern Vermont, northern New Hampshire, northeastern Maine, and northwestern Maine) may be in a position to market their area to winter recreation enthusiasts and potentially benefit from a change in the competitive relationships between winter recreation destinations. Further research is needed to understand the influence of distance costs and destination loyalty on changes in snowmobile patterns as well as the environmental implications of a greater concentration of snowmobile activity on the remaining trails with reliable snow conditions.

Given the projected reductions to an already short snowmobile season in much of Northeast, it is possible that snowmobilers may choose to discontinue the use of their snowmobile and adopt another type of recreational vehicle that is not limited by snow conditions (i.e., all-terrain vehicles [ATVs]) or perhaps a completely different form of recreation. Growing ATV and declining snowmobile sales in the United States over the last 5 years may provide evidence to suggest that the transition is already underway in some regions (Suthey Holler Associates 2003). If a large number of snowmobilers in the region adopt this climate adaptation strategy, there would be important implications for land managers and communities, including recreational planning and infrastructure development, to minimize the environmental impacts of trail use by ATVs. Under such a scenario, communities that developed recreational trail networks for ATVs might gain a competitive advantage over communities that continue to cater to snowmobiles.

The findings of this study suggest that the adaptive capacity offered by advanced snowmaking substantially reduces the climate change risk of the Northeast ski industry. Through to 2040–2069, only seven of the study areas examined (Connecticut, western New York, southeastern New York, western Pennsylvania, southeastern Maine, eastern Pennsylvania, and eastern Massachusetts) were projected to have average ski seasons shorter than 100 days and have a lower than 75% probability of being open for the entire Christmas–New Year's holiday period, and thus be considered at risk economically. Even under the higher emission (A1Fi) scenario for the 2070–2099, four study areas (southern Vermont, northeastern New Hampshire, northeastern New York, and western Maine) did not reach these two economic risk criteria, albeit with large increases in snowmaking requirements and the need to withstand occasional seasons as short at 75 days under new extreme conditions.

Based on this analysis, it would appear that it is not the Northeast's ski industry that is at risk to climate change but rather individual ski businesses and communities that rely on ski tourism. The probable consequence of climate change will be a continuation of the historic contraction and consolidation of the ski industry in the region observed by Hamilton et al. (2003). It will be the relative advantages of local climatic resources and the adaptive capacity by individual ski areas that determine the 'survivors' in an era of climate change. Although projected climate change would contribute to the demise of ski businesses in some parts of Northeast, it could advantage some of the ski operations that remain. Assuming that skier demand declines only to the level observed in the climate change analogue winter of 2001–2002, then ski businesses in southern Vermont, northeastern New Hampshire, northeastern New York, and western Maine would be in a position to gain market share (through lost competition) and potentially offset revenue losses due to reduced ski seasons and higher snowmaking costs.

The large increases in snowmaking requirements under climate change also raises important questions about the sustainability of this critical adaptation strategy in certain locations. Communities and environmental organizations have expressed concern about the environmental impact of water withdrawals associated with snowmaking. Under the higher emission (A1Fi) scenario, where a 50–100% increase in snowmaking was modelled at several locations, water conflicts may be heightened and access to water may be a critical constraint for future snowmaking. The economic costs of increased snowmaking (energy and water costs) were not factored into this assessment because the detailed economic information required is not publicly available, and this remains a critical uncertainty for the future profitability of ski areas in the region.

6 Conclusion

The objective of this study was to provide a broad perspective on the potential vulnerability of the Northeast winter recreation and tourism sector to climate change, by examining whether a reliable snow-based recreation product remained viable under a range of climate change scenarios. It found the snowmobiling industry was the more vulnerable of the two major winter recreation industries in the region, because of the adaptive capacity that snowmaking provides the alpine ski industry. The projected impacts of the higher emission (A1Fi) scenario were far greater, threatening the very existence of the snowmobile industry in the region and leaving only four of the 14 ski study areas able to maintain a 100-day ski season, albeit with substantially increased snowmaking requirements in most cases. An important caveat to this impact analysis is that they are conservative for several reasons. With respect to potential changes in natural snow pack, the climate models used in this assessment were found to underestimate observed winter warming and decline in snow pack, and thus may underestimate these parameters under climate change as well. Furthermore, the climate change scenarios used in this assessment represent low to medium climate sensitivity and do not represent the full range of potential climate change. The analysis of impacts on snowmobile seasons underestimates impacts on trails that use heavy grooming equipment or have rough trail surfaces and require more than a minimum 15 cm of snow. The ski season impact analysis assumes advanced snowmaking capacities that several ski areas currently do not possess.

The study focused only on the supply-side impacts of climate change and the implications for winter recreation demand remains an important area for future research if the economic implications of climate change for this important economic sector are to be fully understood. Regardless of the economic impact, the substantial reduction in winter recreation activities that help to define the cultural identity of the Northeast would represent a notable heritage loss to many of the citizens of this region.

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