POTENTIAL IMPACTS OF CLIMATE CHANGE FOR WESTERN U.S. SKI AREAS: PROJECTIONS FOR ASPEN AND PARK CITY IN THE 21st CENTURY

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ABSTRACT: We evaluate how climate change resulting from increased greenhouse gas (GHG) emissions may affect snow coverage for two case studies: Aspen Mountain and Park City Mountain in the years 2030 and 2100. Snow coverage was evaluated using the Snowmelt Runoff Model. We estimated climate changes (temperature and precipitation) using MAGICC/SCENGEN and the output from five General Circulation Models. We bracketed potential climate changes by using the relatively low, mid-range, and high GHG emissions scenarios known as B1, A1B, and A1FI.

By 2030, temperatures are estimated to increase 1.8 to 2.5°C at both Aspen Mountain and Park City Mountain. The length of the ski season is estimated to decrease by approximately 1 to 1.5 weeks at both ski areas, and the snowline is estimated at an elevation of 2,250 m, an increase of approximately 200 m from current conditions at both ski areas. In 2100, average annual temperatures are projected to increase 2.9 to 9.4°C at Aspen Mountain and 4.2 to 8.9°C at Park City Mountain. The snowline is estimated at an elevation of 2,800 to 2,900 m at both ski areas for the A1B and B1 scenarios in 2100, and 3,100 to 3,200 m for the A1FI scenario.

KEYWORDS: climate change, snow, Aspen, Park City, ski areas, General Circulation Models

1. INTRODUCTION

Potential impacts of climate change on snow has long been a concern for a variety of snow dependent industries, as snow and ice are often viewed as early indicators of a warming climate (Barry et al., 2007; Lemke et al., 2007; Armstrong and Brun, 2008). Changes to snowpack impact a range of industries from water resource management to ski area operation (Tegart et al., 1990; Watson et al., 1996; National Assessment Synthesis Team, 2000; McCarthy et al., 2001; Barry et al., 2007; Lemke et al., 2007). An increasing number of studies have investigated the potential hydrologic effects of climate change on snow (Rango and Martinec, 1997, 1999, 2000; Seidel et al., 1998; Barnett et al., 2005; Mote et al., 2005; Mote, 2006; Rango et al., 2007; and others). Similarly, a number of studies have analyzed the effects of potential climate change on ski areas and winter tourism, all of which project negative consequences for the industry (Hennessy et al., 2003; Scott et al., 2003, 2008, Forthcoming; Scott and Jones, 2005; Climate Impacts Group, 2006; Nolin and Daly, 2006; Agrawala, 2007; and others). In contrast to studies of snowmelt runoff, research on potential climate change impacts at ski areas are concerned primarily with snowpack characteristics during the snow accumulation season.

Evaluating potential changes in snow properties that are important to managing ski areas, such as snow coverage and depth, requires an approach to modeling these properties during the snow accumulation season in a changed climate. There is a need to develop easily employed and site-specific techniques for estimating potential changes in snow properties in response to future climate change scenarios. Ski area managers need to be able to address issues such as the ability to open in the early season, snow depths during the Christmas holidays, and the likelihood of ski seasons ending before the highly profitable spring break period in late March. Similarly, towns and businesses that depend on ski areas for their economic viability need very specific information on how snow properties may change in the future so as to be able to make economic adjustments.

The purpose of this study is describe a procedure for estimating spatially-distributed snow cover for ski area operating seasons using a

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physically based snow model that can incorporate the output of climate change models. Here, we present two case studies on the results of General Circulation Models (GCM) projections for three greenhouse gas (GHG) emission scenarios on snow coverage for the Aspen Mountain and Park City Mountain Resort ski areas for the years 2030 and 2100.

2. STUDY SITES

Aspen Mountain and Park City Mountain Resort lie within the Rocky Mountains in the western USA. Aspen Mountain is located in the Elk Mountains of western Colorado (Figure 1). The ski area ranges in elevation from the 2,422 m base area to the 3,418 m summit, for a total vertical rise of 996 m. Park City Mountain Resort is located in the Wasatch Mountains of north central Utah (Figure 1). The property boundary encompasses an area of 17.5 km^2, and has a vertical relief of approximately 1,067 m, from the base area at 2,100 m to the highest elevation at 3,170 m.

Figure 1: Location of Aspen Mountain and Park City Mountain Resort.

The operational season at both ski areas generally begins in mid-November and ends mid-April. The beginning of the operational season is dictated by adequate snowfall, while the end of the season is driven by a decrease in skier visits. Snow depths in early April are generally at or near their annual maximum. Meteorological data suitable for use in the Snowmelt Runoff Model (SRM) (Martinec, 1975; Martinec et al., 1994; model and documentation available at http://hydrolab.arsusda.gov/cgi-bin/srmhome) are available from several sources in and around both ski areas; including weather stations maintained by the ski areas, the Western Regional Climate Center (www.wrcc.dri.edu/index.html), highway departments, local municipalities, and Natural Resources Conservation Service SNOpack TELemetry (SNOTEL) sites. The SRM requires full-year temperature and precipitation datasets at daily time steps, but such data are not available from the ski area weather stations, which only operate during the ski season (mid-November to mid-April).

3. METHODS

3.1 Climate modeling

Future changes in GHG emissions depend on complex social, economic, and technological relationships that underlie energy use and resulting emissions. We relied on emission scenarios described by the Intergovernmental Panel on Climate Change (IPCC) in its *Special Report on Emission Scenarios* (Nakićenović et al., 2000) to develop climate scenarios for two twenty-year time periods centered on the years 2030 and 2100. The scenarios incorporate a wide range of GHG emissions and atmospheric concentrations. We used the relatively low, mid-range, and high GHG emissions scenarios known as B1, A1B, and A1FI to bracket the range of potential GHG emissions and concentrations.

Current atmospheric CO_2 concentrations are approximately 380 parts per million (ppm). In 2030, there is little divergence of GHG concentrations between scenarios, with all emission scenarios projecting approximately 450 ppm CO_2. We therefore bracketed potential climate changes in 2030 using the average of five selected GCMs, the driest model, and the wettest model. By 2100, the B1 scenario has the lowest emissions, resulting in 540 ppm of CO_2. The A1B scenario projects CO_2 concentrations (700 ppm) and temperature warming close to the middle of the projected range for 2100 described in the IPCC Fourth Assessment Report (IPCC, 2007). The A1FI scenario yields 930 ppm CO_2 by 2100. Thus, the A1FI and B1 scenarios present a stark contrast between development paths. We used 3°C as the central estimate of GCM sensitivity to GHG emissions (how much global mean temperature would increase for a doubling of CO_2) based on a recent review by Kerr (2004).

We used a dynamic downscaling approach to evaluate how changes in global GHG concentrations translate to regional climate responses. We used the model "MAGICC/SCENGEN" to project changes in temperature and precipitation across 17 GCMs, relative to the projected increase in global mean temperature (Wigley, 2004). Using relative change is preferable to averaging projected regional GCM output because using relative change avoids the problem of high sensitivity model results (Kerr, 2004) dominating the regional projections. MAGICC/SCENGEN reports changes in regional climate in 5° by 5° grid boxes (approximately 480 km on a side).

We were most interested in the GCMs that best simulate the climate over the central Rocky Mountains. In an evaluation of the ability of 17 existing GCMs to simulate current climate in western North America, Wigley (2006) concluded that the following five models performed best, and for this reason we used these GCMs in our analysis:

- CSIRO—Australia
- ECHAM3—Max Planck Institute for Meteorology, Germany
- ECHAM4—Max Planck Institute for Meteorology, Germany
- HadCM2—Hadley Model, United Kingdom Meteorological Office
- HadCM3—Hadley Model, United Kingdom Meteorological Office.

3.2 Snow modeling

We modeled snow coverage using the SRM because the required drivers are compatible with GCM outputs: air temperature and precipitation. The model is based on the concept that changes in air temperature provide an index of snowmelt. The modeled domain used in evaluating Aspen Mountain snowpack encompassed the upper portion of the Roaring Fork watershed, which drains snow melt from Aspen Mountain and other nearby ski areas. The domain was 942 km^2 in area, ranging in elevation from 2,225 m to 4,348 m. The domain was broken into seven elevation bands of approximately 305 m each. The modeled domain used in evaluating Park City Mountain Resort snowpack was the current (2008) Park City ski area property boundary area (17.5 km^2). The property boundary encompasses a vertical relief of approximately 1,067 m from the base area at 2,100 m to the highest elevation at 3,170 m. We created four elevation zones of approximately 265 m each.

The SRM accounts for winter precipitation and stores any precipitation event recognized as snow, thereby calculating the maximum snow stored for each elevation band on the user-defined winter end date. Beyond the user-defined winter end date, SRM models the melting process and the subsequent depletion of snow-covered area (SCA). To model the rate and spatial distribution of snowpack buildup during the fall and early winter months, we developed an additional module for use with the SRM. Since snowpack buildup is dictated by temperature and precipitation, we used changes in temperature to determine the change in timing at which snow begins to accumulate. We scaled the rates of change in SCA by projected changes in precipitation.

We used years for which snowfall and temperature were similar to historical average as calibration years for the SRM. Daily air temperature for the selected representative year was distributed over the defined elevation bands using a developed lapse rate (0.65°C/100 m for Aspen and 0.4°C/100 m for Park City). We imposed the projected changes in air temperature and precipitation from the GCMs on the climate data from the representative year to generate future climate scenarios.

SCA was estimated at intervals of approximately once per month using Landsat imagery from 1999–2000 and 2000–2001 for Park City Resort and Aspen Mountain, respectively. A binary classification scheme was used to classify each 30-m pixel as either snow-covered or nonsnow-covered (Klein et al., 1998; Dozier and Painter, 2004). Linear interpolation between estimated SCA values from Landsat was employed to generate the required daily SCA time series.

4. RESULTS

4.1 Projected changes in climate

Figure 2 presents estimated changes in average annual temperature for Aspen and Park City in (A) 2030 and (B) 2100 (relative to 1990) using the middle-emissions A1B scenario. Under this scenario, the average model warming by 2030 is 2.1°C in Aspen and 2.0°C in Park City, with a range of 1.8 to 2.5°C in Aspen and 1.8 to 2.2°C in Park City. By 2100 the average annual temperature for Aspen increases to 4.8°C with a range of 3.9 to 5.9°C. Park City is projected to experience more warming with an average annual temperature increase of 5.8°C and a narrower range of 5.2 to 6.2°C. There is little variance among the GCMs with respect to temperature projections.

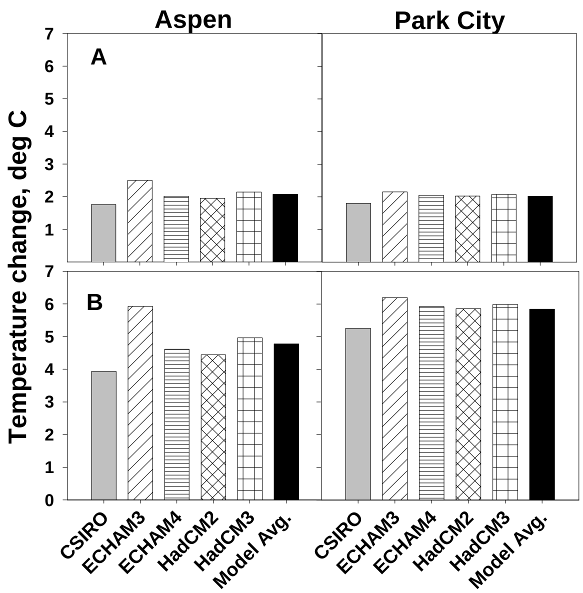

Figure 2: The projected average annual temperature changes for Aspen and Park City in (A) 2030 (B) 2100 for five GCMs for the A1B scenario. The first five bars are results for individual models within MAGICC/SCENGEN; the last bar is the model average.

Figure 3 displays the projected GCM average monthly temperature changes for (A) Aspen and (B) Park City for the B1, A1B, and A1FI scenarios in 2100. Temperature increases are larger in the summer months, with summer temperature increases about 50% greater than during the winter months for all scenarios. Projected warming under the A1FI scenario is approximately twice as much as projected under the B1 scenario. Park City is projected to experience about 1°C more warming by 2100 than Aspen for all scenarios.

For the low-emissions B1 scenario, annual average temperature is projected to increase by 3.5°C (range of 2.9 to 4.3°C) in Aspen and 4.7°C (range of 4.2 to 4.9°) in Park City. For the high-emissions A1FI scenario, annual average temperature is projected to increase by 7.6°C (range of 6.3 to 9.4°C) in Aspen and 8.4°C (range of 7.4 to 8.9°C) in Park City. As with the projections under the A1B scenario (Figure 2), there is little variance in temperature projections among the GCMs.

By contrast, there is more variance among GCMs for projections of changes in precipitation. Under the A1B scenario in 2030, all five models estimate a decrease in annual precipitation for Aspen with decreases ranging from 1% to 18% and average of 7%. Model average also projects a 7% decrease in precipitation for Park City in 2030 under A1B ranging from a 1% increase to a 16% decrease.

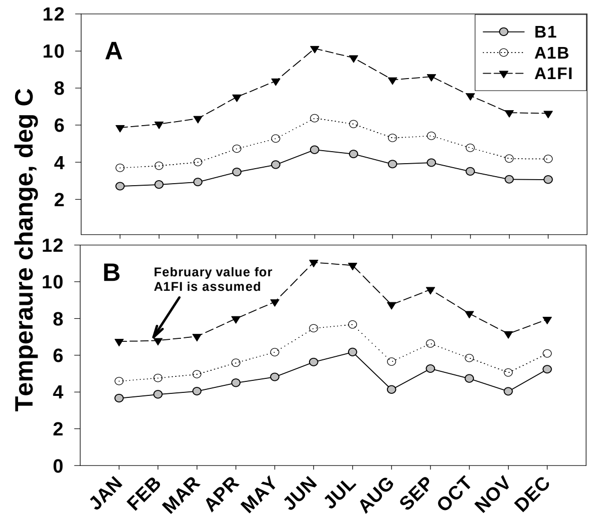

Figure 3: Projected model average monthly temperature changes in 2100 for (A) Aspen and (B) Park City.

Aspen and Park City are both projected to experience further decreases in precipitation by 2100 (Table 1). The average decrease in precipitation is projected to be smaller for Aspen and the range is greater for all scenarios. Decreases in precipitation are projected to be minor (2 to 4%) in Aspen, while annual precipitation is projected to decrease by 16 to 21% in Park City for all scenarios. All models show an increase in monthly precipitation during January and February, followed by strong declines in precipitation during April, May, and June.

	Projected change in total annual precipitation (%) in 2100		
	Average (range)		
	A1FI	A1B	B1
Aspen	-4 (-49 to 24)	-3 (-31 to 15)	-2 (-23 to 11)
Park City	-21 (-49 to 15)	-17 (-38 to 5)	-16 (-32 to 1)

Table 1: Projected changes in annual precipitation (%) for Aspen and Park City in 2100 for the A1FI, A1B, and B1 emission scenarios.

4.2 Projected changes to snowpack

We imposed the projected changes in air temperature and precipitation (Figures 2 and 3, Table 1) on the climate data from the representative years to model snowpack under future climate scenarios. Figure 4 displays projected changes in SCA relative to the selected representative year at the base area for Aspen and Park City in (A) 2030 and (B) 2100. The base area elevation zone has an area-weighted mean elevation of 2,684 m at Aspen Mountain and 2,250 m at Park City Mountain Resort.

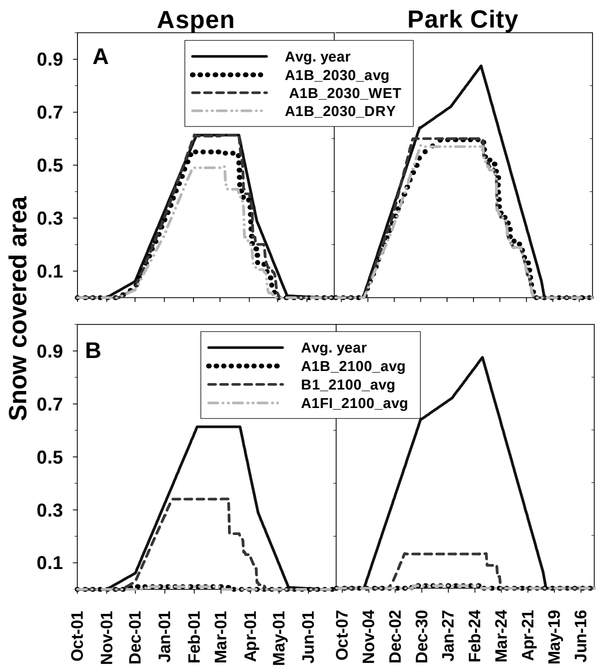

Figure 4: Projected SCA at the base areas of Aspen and Park City relative to selected representative year in (A) 2030 and (B) 2100.

Since there was little difference in SCA between emission scenarios in 2030, we compare the GCM average with the wettest and driest GCMs under the A1B scenario. Historically, the start of snowpack buildup at both ski areas begins in the first week of November. The start of snowpack buildup at the base area is delayed by approximately one week at Aspen Mountain and by three to four days at Park City Mountain Resort by 2030 [Figure 4(A)]. Snow melt at the base area historically begins in the third week of March at both ski areas. Snow melt is projected to begin four to five days earlier at Aspen Mountain and one week to 10 days earlier at Park City Mountain Resort. The snowline, defined as the elevation below which a seasonally persistent snowpack will not develop, rises about 200 m from current conditions to an elevation of approximately 2,250 m for both ski areas. This implies the snowline has moved into the lower end of the base area elevation zone at Park City Mountain by 2030.

By 2100 projected SCA suggest a very strong sensitivity to the emission scenario. The base area of both ski areas have essentially lost a skiable snowpack in all scenarios except the low-emission B1 scenario [Figure 4 (B)]. There is virtually no snow cover under the A1B and A1FI model average scenarios. Snowfall at the base area for these scenarios is projected to be infrequent or to not occur at all throughout the winter. The winter will be punctuated by frequent and sustained periods of melt. Under the B1 scenario, the snow coverage at the base area is substantially reduced, but not completely obliterated.

The start of snowpack buildup at the base area of Aspen Mountain is delayed anywhere from 1.5 weeks for the B1 scenario to 4.5 weeks for the A1FI scenario in 2100. The start of snowpack buildup at the base area of Park City Mountain Resort in 2100 is projected to begin from one to two months later than the historical start date under the B1 and A1B scenarios, respectively. For the A1FI scenario, snowpack buildup will not occur at all, and all winter precipitation will come as rain.

At Aspen Mountain, snowmelt at the base area begins 2.5 weeks earlier for the B1 scenario and 5 weeks for the A1FI scenario in 2100. At Park City Mountain resort, snowmelt at the base area will occur throughout the winter for the A1B and B1 scenarios, while all precipitation will come as rain under the A1FI scenario.

The snowline is estimated at 2,800 to 2,900 m at both ski areas for the A1B and B1 scenarios in 2100, and 3,100 to 3,200 m for the A1FI scenario. This implies that Aspen Mountain will retain skiable snow from the mid-mountain elevation and above for the A1B and B1 scenarios in 2100, while only retaining skiable snow at the top of the mountain under A1FI. For Park City Mountain Resort, skiable snow would probably exist only at the top of the mountain under the A1B and B1 scenarios, while snow will not be present at any elevation under the A1FI scenario.

5. DISCUSSION

Aspen Mountain and Park City Mountain Resort present two comparable case studies for evaluating the potential impacts of climate change on western U.S. ski areas. The warmer average temperatures in the Park City region, the lower elevation of the ski area, and the warmer and drier climate projections combine to produce greater projected losses to snowpack at Park City Mountain Resort than at Aspen Mountain. Both ski areas are projected to maintain adequate snow coverage for ski operations at all elevations through 2030. By 2100, there is strong sensitivity to the emission scenario. Park City Mountain Resort will only maintain adequate snow at the base area during mid-winter under the B1 scenario, while it will lose all its snowpack at all elevations under the A1FI scenario. Aspen mountain will not lose all its snowpack under A1FI in 2100, but the rise in snowline will confine a seasonal snowpack to the top quarter of the mountain.

Here, we have introduced a method for estimating site-specific impacts to snow coverage during the ski area operating season that can be tuned for individual ski areas. By using measured SCA from increasingly available high resolution satellite imagery, we avoid the potential pitfalls of estimating snow pack conditions with precipitation data and arbitrarily selected temperature thresholds. By relying on a physically-based model, we are able to estimate spatially-distributed snow coverage using only temperature, precipitation, and SCA data as model inputs. Requiring only these few input parameters allows us to effectively incorporate the site-specific GCM outputs for monthly climate change, where temperature and precipitation are often the only available or reliable parameters. This methodology is easily applied to other ski areas around the globe.

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