POTENTIAL IMPACTS OF CLIMATE CHANGE FOR U.S. WASTACH RANGE SKI AREAS: PROJECTIONS FOR PARK CITY MOUNTAIN RESORT IN 2030, 2050, AND 2075

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ABSTRACT: We evaluate the potential impacts to snow coverage and depth from anthropogenic climate change at Park City Mountain Resort in 2030, 2050, and 2075. Snow coverage was evaluated using the Snowmelt Runoff Model, and snow depth was estimated empirically via the relationship to snow coverage. We estimated climate changes (temperature and precipitation) using MAGICC/SCENGEN and the output from seven General Circulation Models (GCMs) from the Intergovernmental Panel on Climate Change Fourth Assessment Report. This study uses current and improved GCM output to update previous projections in Park City. We bracketed potential climate changes by using the relatively low, mid-range, and high GHG emissions scenarios: B1, A1B, and A1FI, respectively.
By 2030, temperatures are estimated to increase 1.1 to 2.1°C at Park City Mountain, and the length of the ski season is estimated to decrease by approximately one week due to earlier spring melt at the base area. In 2050, temperatures are estimated to increase 1.4 to 3.7°C, and skiing on or before Thanksgiving and after mid-March may not be possible at the ski area base. By 2075, temperatures are estimated to increase 1.9 to 6.1°C, and snowmelt is projected to occur periodically throughout the ski season. Skiing on or before Thanksgiving and after mid-March by 2075 is unlikely at the base area for all emission scenarios, and the snowline is estimated at an elevation of 2,450 m under the A1FI emission scenario, an increase of approximately 400 m from current conditions.

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

1. INTRODUCTION

The potential impacts to the cryosphere as a result of climate change have been noted as early indications of global warming (e.g., Barry et al., 2007; Lemke et al., 2007; Armstrong and Brun, 2008). Changes to snowpack in particular have implications for a range of industries from regional hydrology to 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). For example, several studies have projected negative impacts to ski areas and winter tourism as a result of potential climate change. (Galloway, 1988; König, 1998; Hennessy et al., 2003; Scott et al., 2003, 2007, 2008; Scott and Jones, 2005; AGCI, 2006; Climate Impacts Group, 2006; Nolin and Daly, 2006; Agrawala, 2007).

Research on the potential climate change impacts at ski areas is necessarily concerned with snowpack characteristics during the snow accumulation and early melt seasons, and needs to be able to evaluate issues important to managing ski areas, such as snow coverage and depth. Ski area managers are interested in knowing how early they might be able to open, how deep will the in the fall snowpack be during critical holiday periods, and when might snowmelt force premature area closings. To answer these questions, an approach to modeling snowpack properties during the operational season (generally late November through early April) is required.
The purpose of this study is to describe an easily deployed and site-specific procedure for estimating spatially-distributed snow cover for ski area operating seasons using a physically based snow model that can incorporate the output of climate change models. Here, we present a case study on the results of General Circulation Models (GCMs) projections for three greenhouse gas (GHG) emission scenarios on snow coverage for

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the Park City Mountain Resort (PCMR) for the years 2030, 2050, and 2075.

2. STUDY SITE AND CLIMATE DATA

PCMR is located in the Wasatch Range of the Rocky Mountains in Utah, USA (Figure 1). The ski area 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. The ski area operational season normally begins in mid-November and ends mid-April. The ski area opening date is dictated by adequate snowfall, and the closing date for the ski season is driven by a decrease in skier visits, despite snowpack depths reaching their annual maximum in early April.

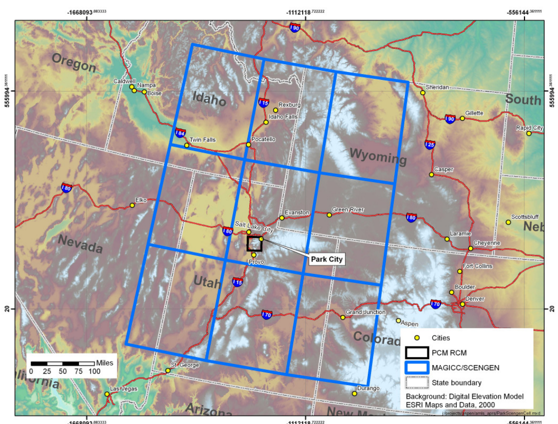

Figure 1: SCENGEN grid cell containing Park City, and the eight surrounding cells. The coordinates of the SCENGEN boxes are 37.5° to 45°N latitude and 107.5° to 115°W longitude.

We used the Snowmelt Runoff Model (SRM) (Martinec, 1975; Martinec et al., 1994; model and documentation available at http://hydrolab.arsusda.gov/cgi-bin/srmhome) in this study. The model 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. There are two sources of meteorological data for the PCMR area that meet this criteria. Full-year datasets were available from the weather station at the golf course in the town of Park City (elevation 2,080 m) and from the Thaynes Canyon U.S. Geological Survey (USGS) SNOTEL site located near the mid-mountain station in the ski area (elevation 2,813 m). The golf course station is within 23 m of the base area elevation and is approximately a quarter kilometer away, and we used data from the golf course to estimate both temperature and precipitation conditions at the bottom of PCMR. For temperatures between the base area and Thaynes Canyon and above Thaynes Canyon, we used the observed lapse rate from these two sites (0.4°C/100 m). For precipitation, we compared cumulative winter snowfall, measured in snow-water equivalent (SWE) at the Thaynes Canyon SNOTEL station and the adjacent ski area weather station (Summit station) and found that the totals matched very well. This allowed us to use precipitation data from Thaynes Canyon to represent precipitation from the mid to upper parts of PCMR.

3. METHODS

3.1 Climate modeling

Three factors are critical for modeling how Park City's climate might change:

1. Future global GHG emissions
2. How global climate will respond to increases in GHG concentrations
3. How global climate change will affect the regional climate around Park City.

Future changes in GHG emissions depend on many factors, including population growth, technology, economic growth, environmental stewardship, and government. The Intergovernmental Panel on Climate Change (IPCC) tried to capture a wide range of potential changes in GHG emissions in its *Special Report on Emission Scenarios* (SRES; Nakićenović et al., 2000). For this study, we used SRES scenarios that represent a range of potential future GHG emissions and concentrations to develop climate scenarios for three twenty-year time periods centered on the years 2030, 2050 and 2075. We used B1 as the low-end projection, A1FI as the high-end projection, and A1B as a mid-range projection.
The second critical factor affecting predictions of the effect of increasing concentrations of GHGs on climate in Park City is the rate of global temperature increase relative to the rate of atmospheric carbon dioxide (CO_2) concentration increase; called the sensitivity. The IPCC Fourth Assessment Report (AR4) (Solomon et al., 2007, p. 65) states:

> Analysis of models together with constraints from observations suggest that the equilibrium climate sensitivity is *likely* to be in the range 2°C to 4.5°C, with a

best estimate value of about 3℃. It is *very unlikely* to be less than 1.5℃. [Italics in original.]

Based on this recent review and consultations with several atmospheric scientists, we decided to use 3℃ as the estimate of sensitivity in our modeling for this project.

The third critical factor for predicting future climate at Park City is how global climate change will be manifested at the regional and local scales of Park City. 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 20 GCMs, relative to the projected increase in global mean temperature (Wigley, 2004). MAGICC/SCENGEN reports changes in regional climate in 2.5° by 2.5° grid cells (approximately 240 km on a side).

Due to the coarse spatial scale of SCENGEN grid cells, climate within a given grid box can vary substantially because of factors such as topographic relief. Thus, we used a nine-cell average (the grid cell containing Park City and the eight surrounding cells), which is generally considered a more stable estimate of site changes since results for any given grid cell are subject to more noise than a larger area surrounding the site (Figure 1).

There are numerous GCMs, and we were most interested in the models that best simulate the current climate at the global, continental, and regional scales. In an evaluation of the ability of 20 existing GCMs to simulate current climate globally, over the contiguous United States and in the Park City region, Wigley (2008) concluded that the following seven models performed best, and thus were the models we used in this study:

- CSIRO-Mk3.0 – Commonwealth Scientific and Industrial Research Organisation, Atmospheric Research, Australia
- UKMO-HadCM3 –Hadley Centre for Climate Prediction and Research/Met Office, United Kingdom Meteorological Office
- UKMO-HadGEM1 –Hadley Centre for Climate Prediction and Research/Met Office, United Kingdom Meteorological Office
- BCCR-BCM2.0 – Bjerknes Centre for Climate Research, Norway
- CNRM-CM3 – Météo-France/Centre National de Recherches Météorologiques, France
- GFDL-CM2.1 – U.S. Department of Commerce/National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory, United States
- MRI-CGCM2.3.2 – Meteorological Research Institute, Japan.

These models are described on the website for the Program for Climate Model Diagnosis and Intercomparison (PCMDI, 2008).

3.2 <u>Snow modeling</u>

We used the SRM (Martinec, 1975; Martinec et al., 1994; SRM, 2002) to examine snowpack characteristics at PCMR. The SRM is designed to predict snow coverage and snowmelt runoff patterns and is based on the fundamental concept that changes in air temperature provide an index of the net energy balance. The SRM calculates the maximum snow in storage on a defined winter end date, beyond which the SRM predicts the melting process and the subsequent reduction in snow-covered areas (SCA). We then developed an empirical relationship between SCA and snow depth to predict snow depth from modeled SCA. We use projected snow depth to determine if skiable snow will be present at different elevations at different times during the ski season. Mountain managers define skiable snow as a snowpack with a minimum natural snow depth of approximately six inches.

The spatial extent of this evaluation was the area within the current (2009) PCMR property boundary. The property boundary encompasses a vertical relief of approximately 1,067 m, and we created four elevation zones with an average elevation span of 265 m and modeled snowpack coverage separately within each of the zones (Figure 2).

The SRM requires daily estimates of SCA. We estimated SCA using high resolution Landsat images. Since obtaining high-resolution images for every year was prohibitively expensive, we selected 2000–2001 as the ski season that is reasonably representative of the historical average SCA. Precipitation and SWE at Thaynes Canyon from the October 2000 through September 2001 season were similar to average precipitation and SWE from 1971 to 2000. PCMR managers and snow safety directors agreed that the 2000–2001 season snowpack was representative of average conditions.

We used six Landsat Enhanced Thematic Mapper (ETM+) scenes from 2000 and 2001 (October 19, December 30, January 31, March 4, April 5, and May 7) to estimate SCA for the ski season. The SCA for each date was combined with digital topography to derive estimates of SCA by elevation band. To estimate SCA on all other days, we interpolated linearly between the six scene dates. A binary classification scheme was used to classify each 30-m pixel as either snow-

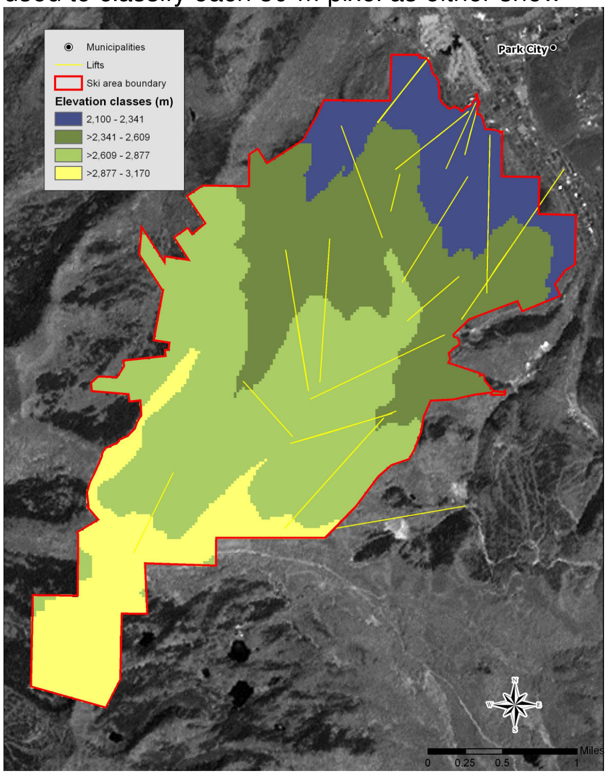

Figure 2: Spatial extent of the SRM evaluation. Colors identify the four elevation zones for which snow coverage and depth is modeled. Blue is the base area and yellow is the top of the ski area.

covered or non snow-covered (Klein et al., 1998; Dozier and Painter, 2004.)

We developed a relationship between snow depth and SCA by plotting SCA and measured snow depth in 2000–2001, collected by the area's ski patrol, for each elevation zone. As an example, Figure 3 illustrates this relationship for the base area (Zone 1) [snow depth = (0.0285 × SCA) +0.029]. Actual measured snow depth data were available from the Jupiter station at the top of the PCMR, the Summit mid-mountain station, and at the golf course near the base area elevation. These locations lie in elevation Zones 4, 3, and 1, respectively. To generate a snow depth time series to correlate to daily SCA for the mean of each elevation zone, we interpolated linearly between the three measured datasets. Since the relationship between the three measured datasets varied with date, a separate linear interpolation by elevation was conducted for each week throughout the 2000–2001 winter.

Snow depths at the golf course, and Summit and Jupiter stations are not enhanced by snowmaking, and are therefore likely to underestimate observed depths at the base area where snowmaking occurs. Thus, our approach predicts natural snowpack characteristics only. We did not evaluate the effects of augmentation with man-made snow.

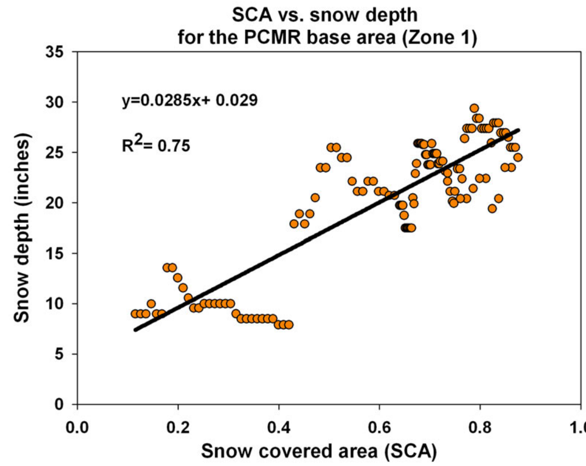

Figure 3: Example of SCA vs. snow depth relationship from the base area of PCMR for the 2000–2001 season for Zone 1.

4. RESULTS

4.1 Projected changes in climate

Figure 4 presents estimated changes in average annual temperature for Park City in 2030 (relative to 1990) using the middle-emissions A1B scenario. The first seven bars are results for individual models; the last bar is the average of the models. Under this scenario, the average model warming is 1.6°C, with a range of 1.1° to 1.9°C, and little variability across the GCMs. This pattern is consistent for all emission scenarios and years. Since the emissions scenarios do not diverge by 2030, we only report the results for A1B here.

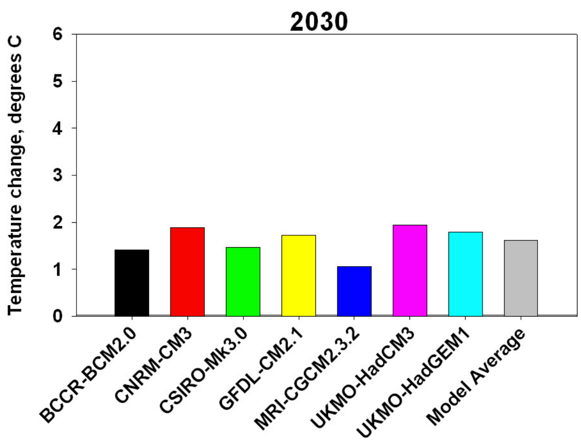

Figure 4: Estimated average annual temperature changes in Park City, predicted by seven GCMs, for the A1B emissions scenario in 2030.

Figure 5 displays the projected GCM average monthly temperature changes for Park City Bachelor for the B1, A1B, and A1FI scenarios in (A) 2050 and (B) 2075. The temperatures are projected to increase with increasing GHG emissions, and with time. Under the high GHG emissions scenario (A1FI), the annual average temperature increase in 2050 is 3.1℃, and in 2075 is 5.0℃. Under the low GHG emissions scenario (B1), the average temperature increase is 1.8℃ in 2050 and 2.8℃ in 2075. Projected warming is approximately 50% greater in the summer months than the winter months, and projected warming under the A1FI scenario is almost twice as much as that projected under the B1 scenario. As with projections under the A1B scenario in 2030 (Figure 4), there is little variance in temperature projections among the GCMs.

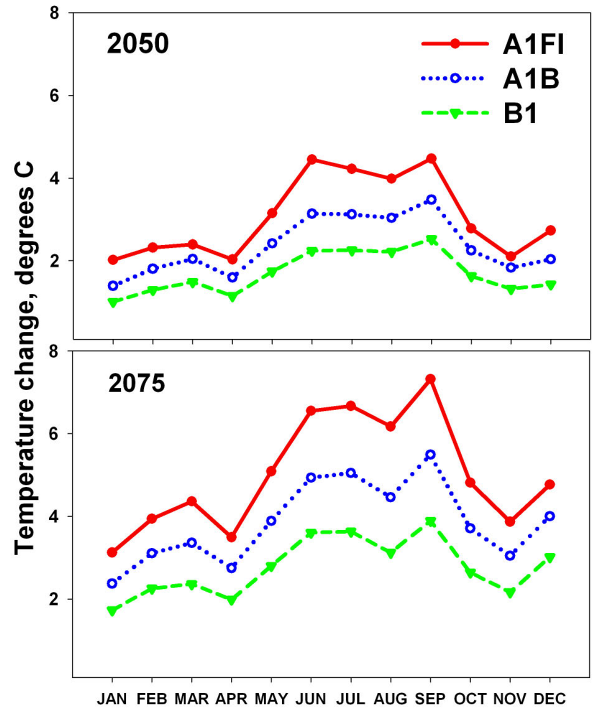

Figure 5: Projected model average monthly temperature changes in Park City for (A) 2050 and (B) 2075.

By contrast, there is more variance among GCMs for projections of changes in precipitation. Under the A1B scenario in 2030, six of the seven models estimate a decrease in annual precipitation for Park City with decreases ranging from 1% to 9% (one model shows a 4% increase in precipitation), and a model average decrease of 4%.

Park City is projected to experience similar decreases in precipitation in 2050 and 2075 (Table 1), although the range of projected changes is greater. Decreases in precipitation are projected to be minor (1 to 5%) 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 2050 and 2075		
	Average (range)		
	A1FI	**A1B**	**B1**
2050	-5 (-16 to 11)	-1 (-10 to 11)	-1 (-8 to 8)
2075	-5 (-22 to 21)	-4 (-17 to 13)	-4 (-13 to 7)

Table 1: Projected changes in annual precipitation (%) for Park City in 2050 and 2075 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 4 and 5, Table 1) on the climate data to model snowpack under future climate scenarios.

The start of snowpack buildup is defined as the date when precipitation falls as snow rather than as rain and remains as snow on the ground. Historically, the average start date of snowpack buildup at the PCMR has been November 11, based on observed historical records from the Park City golf course weather station (daily average 1988–present). Our modeling result is that the start of snowpack buildup at the PCMR base area is predicted to begin about one week later in 2030. Predicted temperatures will still allow some snowpack buildup to occur before Thanksgiving, and approximately two weeks of conditions suitable for snowmaking prior to Thanksgiving. In 2030, snow melt at the base area is predicted to begin about one week earlier than the historical melt initiation date of March 16 under the A1B scenario.

Snow depth is predicted to be slightly below historically observed depths throughout the ski season in 2030. Melt begins earlier than the historical average, as determined by predicted temperatures. The result is more reduced snow depth by spring break (March 25) due to earlier melt initiation. The earlier snowmelt date causes less than a 50% reduction is snow depth by March 25, which predicts that skiable snow will remain at the base area throughout the spring break season in 2030.

By 2050, climate change is predicted to have a substantial impact on snow coverage and snow depth at PCMR's base area, although results vary by CO_2 emissions scenario. Snowpack buildup will be delayed by 1.5 weeks under all scenarios but the high emissions A1FI. Under the A1FI scenario, snowpack buildup is delayed by a little over two weeks. Snow melt at the base area is predicted to begin one week to 12 days earlier under the low and middle emissions scenarios, and two weeks earlier under the high emissions scenarios.

For all scenarios in 2050, there will be either very little or no snow at the base area by Thanksgiving, and mid-winter snow depths will be 20% to 40% less than historically observed values. By the spring break season, snow depths are predicted to be less than ten inches under all scenarios due to an earlier onset of melt. This suggests that skiable snow is unlikely during spring break under all scenarios in 2050.

By 2075, snow conditions are predicted to be worse than in 2050, and vary more strongly with emissions scenario than in 2050. Snowpack buildup will be delayed by ten days to five and a half weeks, with the shortest delay predicted for the low emissions scenario, and the longest delay predicted under the high emission scenario. Under all emission scenarios, by 2075 the base area of PCMR will not have a skiable snowpack for Thanksgiving and spring break.

The snow line is projected to move up to approximately 2,450 m under the A1FI (high emissions) scenario, and skiable snow at the base area is unlikely for the entire ski season. Under the low and middle emission scenarios, a snowpack will eventually develop at the base area by mid-winter. Under these scenarios, snow coverage and depths at the base area will be substantially reduced (20% to 72% of historical average), but snow will not disappear completely.

Snow melt at the base area will occur periodically throughout the winter under the middle and high emissions (A1B and A1FI) scenarios. For B1 scenario, melt will occur one to two weeks earlier than the historical melt initiation date of March 16. By 2075, skiable snow may only exist at the base area during mid-winter (December through February). Snow depth seasonal maximums for the A1B and A1FI scenarios occur by February 20, and only reach 20% to 37% of the average historical maximum. By 2075, snow depths during March are substantially reduced for all scenarios to the point where skiing may no longer be possible during the spring break season.

5. DISCUSSION

PCMR presents an illustrative case study for evaluating the potential impacts of climate change on Wasatch range U.S. ski areas. PCMR is projected to maintain adequate snow coverage for ski operations at all elevations through 2030. By 2050, there is strong sensitivity to the emission scenario, and the tail ends of the ski season are projected to be problematic. By 2075, projected snow reductions are more pronounced, and suggest that skiing may only be possible during mid-winter and on the upper portions of the ski area.

Here, we have introduced a method for estimating site-specific impacts to snowpack 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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