ESTIMATING CHANGES IN CLIMATE AND SNOW QUANTITY AT THE ASPEN SKI AREA FOR THE YEARS 2030 AND 2100

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ABSTRACT

We evaluated how climate change resulting from increased greenhouse gas (GHG) emissions may affect the quantity of snow at Aspen Mountain ski area in 2030 and 2100. We modeled climate change using MAGICC/SCENGEN, and ran combinations of five general circulation models (GCMs) and three GHG emission scenarios. Snow quantity was evaluated using the Snowmelt Runoff Model, and a module developed to estimate snow quantity during the accumulation season, before snowmelt initiation. We used the five GCMs that best simulate current conditions, and three emission scenarios representing low, mid, and high emissions conditions. The date when snow starts to accumulate at the base area is delayed by six to seven days by 2030 and anywhere from 1.5 to 4.5 weeks by 2100. For mid-winter snows, a 15% increase in snowfall compensates for a 1.5°C increase in air temperature such that there was little change in snow depth. Snow depth goes to almost zero for the base area in 2100 under the medium GHG emission A1B scenario. In the high GHG emission A1F1 scenario, snow depth goes to near zero for the entire lower two-thirds of the mountain. The effect is substantially reduced under the low GHG emissions B1 scenario.

INTRODUCTION

There has long been concern regarding the potential impacts of climate change on a variety of snow dependent 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). An increasing number of hydrologic modeling studies have investigated the potential effects of climate change on snowmelt runoff volume and timing (Leavesly et al., 1992; McCabe and Hay, 1995; Rango and Martinec, 1997, 1999, 2000; Seidel et al., 1998; Barnett et al., 2005; Mote el al., 2005). Other studies have analyzed the effects of potential climate change on ski areas and winter tourism, all of which project negative consequences for the industry (Galloway, 1988; McBoyle and Wall, 1992; König, 1998; Hennessy et al., 2003; Scott et al., 2003, Forthcoming; Scott and Jones, 2005; Climate Impacts Group, 2006; Nolin and Daly, 2006). In contrast to studies of snowmelt runoff, research on potential climate change impacts at ski areas are concerned primarily with snow pack characteristics during the snow accumulation season.

Evaluating potential changes in snow properties, such as snow depth and density, that are important to managing ski areas is problematic because there is no accepted approach to modeling these properties during the accumulation season in a changed climate. In the Pacific Northwest, Nolin and Daly (2006) developed a data-driven, climatological approach of snow cover classification to reveal "at-risk" snow zones for ski areas. In Australia, Hennessy et al. (2003) developed future scenarios for ski areas using a monthly time-step based on correlations between current climate and snow depth and then updating them with future climate outputs from the CSIRO GCM. Breiling and Charmaza (1999) estimated changes in snow depth for ski areas in Austria by evaluating regional measurements of climate with snow depth and then applying a +2.0°C increase in air temperature. Scott conducted a series of studies that evaluated climate change for various GHG emission scenarios and downscaled GCM outputs, and employed a degree-day snow model, which relies on an assumed snow density and temperature and precipitation drivers, to estimate snow depth (Scott et al., 2003, Forthcoming; Scott and Jones, 2005).

There is a need to develop more easily employed and site-specific techniques for estimating potential changes in snow properties in response to future climate change scenarios. Operational managers of ski resorts need to be able to address issues such as the ability to open on Thanksgiving, top-of-mountain snow depths during the Christmas holidays, and will future ski seasons end before the highly profitable spring break period in late March?

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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 provide a procedure for estimating spatially distributed snow cover and depth for future snow accumulation seasons using a physically based snow model that can incorporate the output of climate change models. The methodology is designed to be user-friendly and easily transportable to other ski areas. Here, we present a case study on the results of GCM projections for three GHG emission scenarios on snow pack characteristics for the Aspen Mountain ski area for the 2030s and 2100s. We chose the Snowmelt Runoff Model (SRM) because it combines a physically based approach to understanding snow dynamics with climate drivers that are compatible with the output of climate models, particularly air temperature and precipitation. We update the SRM (Martinec, 1975; Martinec et al., 1994; model and documentation available at http://hydrolab.arsusda.gov/cgi-bin/srmhome) to include the snow accumulation season. Specific objectives for the Aspen Mountain ski area study are to estimate the length of the ski season, the timing of snow pack buildup and melt, and daily values of snow depth and coverage, from the bottom to the top of the mountain, for the years 2030 and 2100.

SITE DESCRIPTION

Aspen Mountain is located in Pitkin County, Colorado, USA, and lies within the Roaring Fork watershed (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. The upper third of the mountain requires 50 cm of snow depth to open for skiing. Natural snow cover is enhanced with artificial snowmaking at the base area of the mountain but not on the upper third of the mountain because of logistical and economic constraints. Lack of snow does not dictate the end of the ski season. The operational season generally ends in the second week of April because of a decrease in skier visits; snow depth at that time is generally at or near the annual maximum.

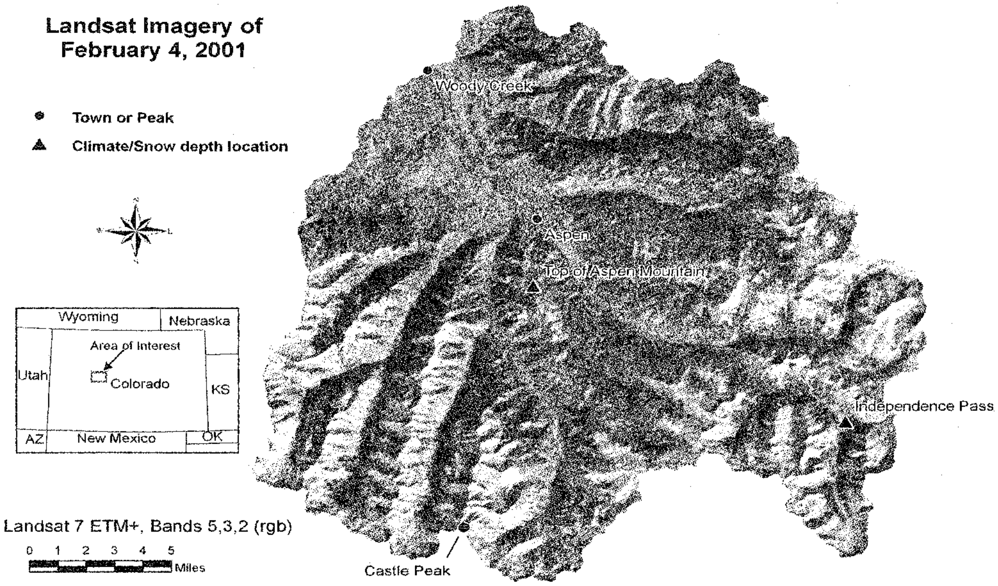

Figure 1. Location map and modeling domain centered on Aspen Ski Mountain, Landsat image.

Several sources of meteorological data exist for the Aspen area and the Roaring Fork watershed that are appropriate for the proposed modeling activities. These include a weather station at the water treatment plant in the City of Aspen (elevation 2,484 m), weather stations operated by the ski patrol at the ski area, and a Natural Resources Conservation Service SNOTEL site located at Independence Pass (elevation 3,231 m). Data from the weather station at the top of Aspen Mountain (elevation 3,355 m) is available as far back as 1968, but measurements are only made during the winter months when the ski area is operating (mid-November through mid-April). The modeling effort requires full-year datasets to drive the models, necessitating that we use data from the water treatment plant (2,484 m) or Independence Pass (3,231 m) since both locations have full-year records. Independence Pass has the closest, most reliable, complete, and representative data available, and is therefore selected as a surrogate for conditions at the upper part of Aspen Mountain. Snow depth during the ski season is measured daily at the top of Aspen Mountain (3,355 m), the mid-mountain station (3,059 m), and at the water treatment plant near the base area elevation.

METHODS

Climate Modeling

We developed scenarios for two time periods: 2030 and the 2100. The 2030s are within the "foreseeable future" and planning horizons for some industries, and the 2100s capture long-term climate change. Future changes in GHG emissions depend on many factors, including population growth, economic growth, technology, government, and society. 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* (Nakićenović et al., 2000). The scenarios result in a wide range of emissions and concentrations of GHGs.

Since likelihoods are not given by the IPCC, we use three scenarios that bracket the IPCC scenarios. A1B ends up close to the middle of the IPCC Third Assessment Report in CO_2 concentrations (700 ppm) and in the range of temperature warming by 2100 (Houghton et al., 2001). The A1F1 scenario has only slightly higher CO_2 emissions than A1B by 2030, but yields 930 ppm CO_2 by 2100. In contrast, the B1 scenario has the lowest emissions, resulting in 540 ppm of CO_2 by 2100. The A1F1 and B1 scenarios present a stark and interesting contrast between development paths. Based on a recent review by Kerr (2004) of GCM sensitivity to GHG emissions, we decided to use 3°C as the central sensitivity estimate.

We used three different approaches to evaluate how regional climate will change as GHG concentrations increases. We used the tool "MAGICC/SCENGEN" to understand the regional pattern of relative changes in temperature and precipitation across 17 GCMs (Wigley, 2004). The changes in each GCM are expressed relative to the increase in global mean temperature by the model. This pattern of relative change is preferable to simply averaging regional GCM output because it controls for differences in climate sensitivity across models; otherwise results from models having a high sensitivity would dominate. MAGICC/SCENGEN reports changes in regional climate in 5° by 5° grid boxes.

To get higher resolution estimates of changes in climate for the Aspen area, we used two additional approaches. One is the output from a regional climate model (RCM). The RCM data were provided by Dr. Ruby Leung of the Pacific Northwest Laboratory (Leung et al., 2003a, 2003b, 2004; Leung and Qian, 2005). RCMs are high-resolution climate models that are built for a region, and are "nested" within a GCM. Dr. Leung used the RCM "MM5," which has 36 km grid boxes. The model is "nested" in the Parallel Climate Model (Dai et al., 2004). At present it is not possible to run this model through 2100. Results for 2030 were not significantly different from the MAGICC/SCENGEN results and are not reported here, but are available at the Aspen Global Climate Change Institute (Lazar, 2006).

We also used statistical downscaling from GCMs, which assumes that the statistical relationship between the large-scale climate variables in a GCM and a specific location will not change with climate change. The statistical relationship is used to estimate how climate at a specific location may change consistent with the GCM projections for climate change. We used the output from the HadCM3 model (Gordon et al., 1999) and downscaled it to the SNOTEL weather station at Independence Pass. As with the RCM output, results did not diverge much from the MAGICC/SCENGEN results and are not reported here but are available at the Aspen Global Climate Change Institute (Lazar, 2006).

Tom Wigley from the National Center for Atmospheric Research analyzed how well the 17 GCM models simulated current temperature and precipitation patterns for the Earth as a whole and for western North America. The following 5 GCMs performed best for western North America and were used in our climate scenarios for this manuscript (Wigley, 2004):

- 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.

Snow Model

We used the SRM because it is designed to assess snow coverage and snowmelt runoff patterns. The model uses a temperature-index method, which is based on the concept that changes in air temperature provide an index of snowmelt. The model runs on a daily time step with drivers that are compatible with GCM outputs: air temperature and precipitation. The SRM approach thus improves on the techniques and provides a user-friendly model that Scott et al. (2003) used to investigate future changes in skiing conditions for southern Ontario in Canada. The modeled domain was 942 km^2 in area, ranging in elevation from 2,225 m to the 4,348 m summit of Castle Peak (Figure 1). The domain was broken into seven elevation bands of approximately 305 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 defined winter end date. We used the default model parameters for SRM (e.g., degree-days) developed for the nearby Rio Grande River in Colorado (Rango and Martinec, 1999), since that watershed has a similar location, areal extent, and elevation as the Aspen study area. Beyond the winter end date, SRM models the melting process and the subsequent depletion of snowcovered area (SCA). It does not, however, account for the rate and spatial distribution of snow pack buildup during the fall and early winter months. Since snow pack buildup is dictated by temperature and precipitation, we modeled this process in a module we developed as an addition to SRM. We used 2001 as a calibration year for SRM. SCA was estimated about monthly using Landsat imagery from 2001. A binary classification scheme was used to classify each 30-m pixel as either snow-covered or non snow-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.

RESULTS AND DISCUSSION

Scenarios of Climate Change

Figure 2A presents estimated changes in temperature for Aspen in 2030 and 2100 (relative to 1990) using the A1B scenario. Under this scenario, the average model warming is 2°C with a range of 1.8 to 2.5°C by 2030. There is little difference among the three scenarios in 2030 because there is little divergence in CO_2 amounts. By 2100 the average annual temperature increases by 4.8°C with a range of 4 to 6°C. Figure 2B presents the estimated changes in precipitation for the same scenario. All five models estimate a decrease in annual precipitation for Aspen by 2030. The decreases range from 1% to 18%, and average 7%. The average decrease in precipitation is smaller by 2100, 3%, and the range is greater. The wettest model estimates a 15% increase in annual precipitation, while the driest has a 31% decrease. Thus, in contrast to modeled temperature, there is much more variance among the GCMs for precipitation changes. This pattern of consistent warming throughout the 21st century, along with variable precipitation patterns, is consistent with climate projections for mountain areas in Europe (Beniston, 2006), Australia (Hennessey et al., 2003), and Canada (Scott et al., 2003).

Figure 3 displays the average of monthly temperature and precipitation changes for the B1, A1B, and A1F1 scenarios in 2100. Temperature increases occur primarily in the summer months, with summer temperature increases about 50% greater than during the winter months. All models show an increase in monthly precipitation during January and February, followed by strong declines in precipitation during April, May, and June.

SRM Model Development

Daily air temperature for 2001 was distributed over the seven elevation bands using a lapse rate developed between the climate station located at the city of Aspen and the SNOTEL site at Independence Pass. There was a significant relationship between daily air temperature measured at the city of Aspen and at the Independence Pass SNOTEL site ($y = 1.06x+6.86$, $R^2 = 0.97$, $n = 365$, $p << 0.001$) (Figure 4). The resulting lapse rate was 0.65°C/100 m. Average daily air temperatures for both locations drop below 0°C in the second week of November, and rise above 0°C by the end of April. At Independence Pass, mid-winter air temperatures decreased to near -20°C.

Next, a relationship for snowfall amounts between Independence Pass and Aspen Mountain was determined so that we could estimate snowfall amounts at Aspen Mountain during the non-operating season when the ski patrol was not active. Snowfall was highly correlated between the two sites, with an R^2 of 0.98 ($y = 1.06x + 1.28$, $n = 169$, $p << 0.001$). We scaled daily measurements of snowfall from Independence Pass to Aspen Mountain using this regression equation.

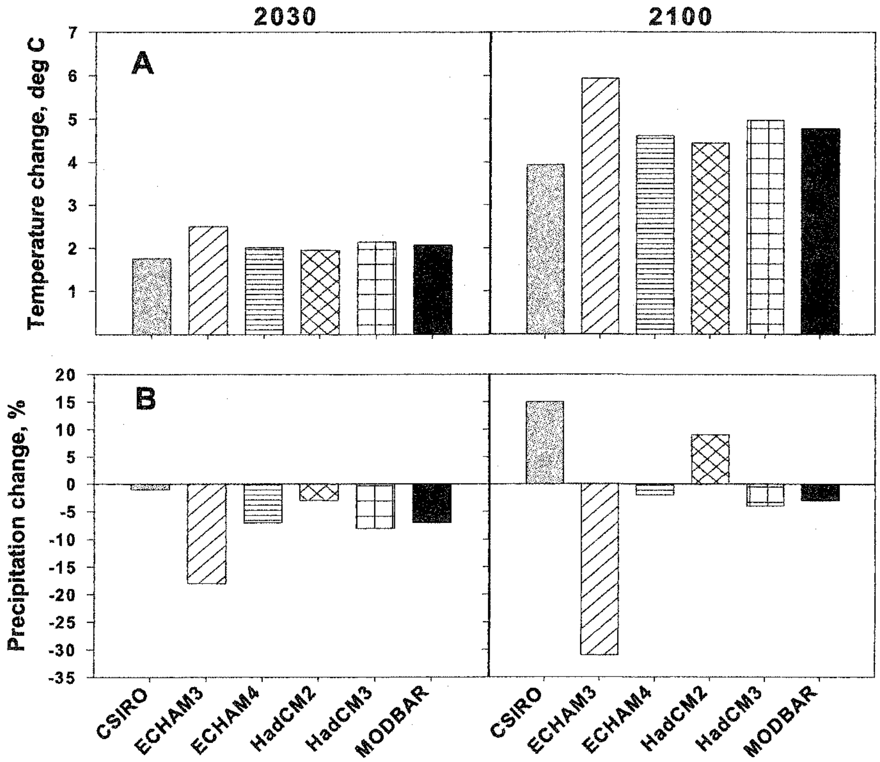

Figure 2. The projected annual changes in (A) temperature and (B) precipitation for the five GCMs for the A1B scenario. The first five bars are results for individual models within MAGICC/SCENGEN; the last bar is the model average.

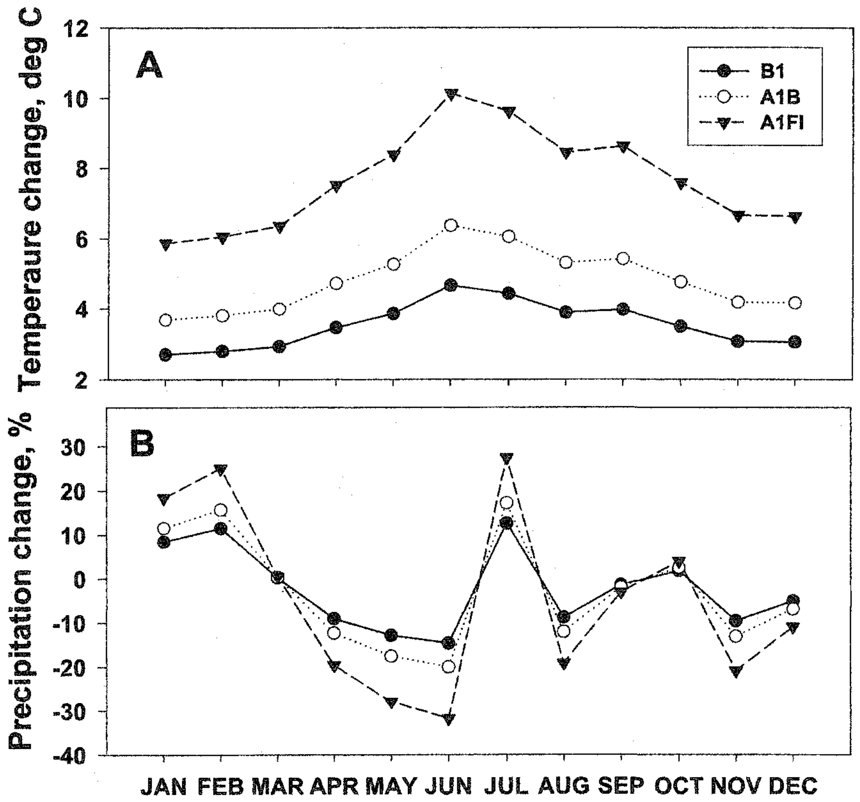

Figure 3. Average monthly changes in (A) temperature and (B) precipitation by GCM emission scenarios for 2100.

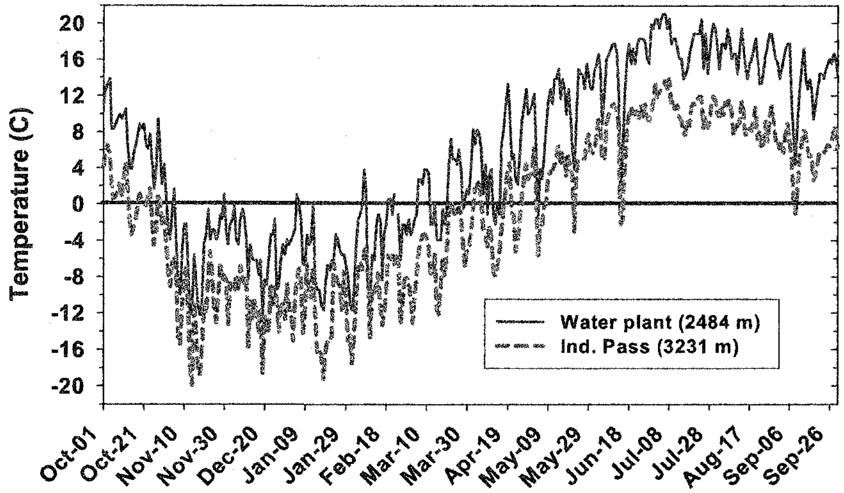

Figure 4. Average daily air temperature in 2001 measured at the Aspen water treatment plant and the SNOTEL site at Independence Pass. Note that air temperatures for both locations in 2100 drop below 0°C in the second week of November and rise above 0°C by the end of April, defining the snow accumulation season for that year.

Next, SCA in each elevation band in 2001 estimated from Landsat images was converted to snow depths using the relationship between SCA and measured snow depths collected by the ski patrol at the area base, mid-mountain, and top-of-mountain. The simple linear regression shows a significant relationship with SCA ($y = 0.01x - 0.2$, $R2 = 0.83$, $n = 169$; Figure 5). To generate a snow depth time series for the other elevation zones, we employed linear interpolation between the three measured datasets. Since the relationship between the three measured datasets varied with date, a separate linear interpolation was conducted for each week throughout the winter. Evaluation of the estimated snow depths was accomplished by comparing modeled snow depth to measured 2001 snow depths that were not used for the SCA-snow depth linear regression, and to the historical average (1968-2005) snow depths for matching dates.

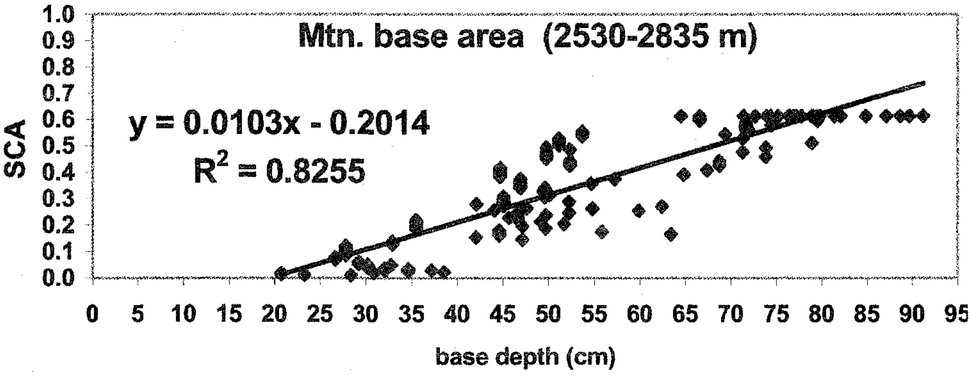

Figure 5. SCA vs. snow depth for elevation zone 2 near the base of Aspen Mountain.

Climate Scenario: SCA

The modeled SCA results at Aspen Mountain's base area for 2030 are illustrated in Figure 6 and for 2100 in Figure 7. For both years we compare projected SCA areas to measured values from 2001. For 2030, since there was little difference in SCA between A1B, B1, and A1F1 scenarios, we compare A1B_AVG with the wettest and driest A1B scenarios. The date when snow starts to accumulate at the base area is pushed back by approximately one week for all three of these scenarios. The A1B_WET scenario recovers and reaches the same SCA as 2001. However, the A1B_DRY scenario at maximum SCA is only about 70% of 2001 and begins losing SCA several weeks earlier than in 2001. There appears to be a larger impact of the scenarios at the top of mountain (Figure 6B). Accumulation of snow is delayed almost a month. Neither the wet nor dry scenarios recover to the same SCA as 2001. The top of the mountain has historically received October precipitation in the form of snow. In 2030, October precipitation falls as rain. The delay in the start of the snow accumulation season at the top of the mountain results in less SCA throughout the ski season.

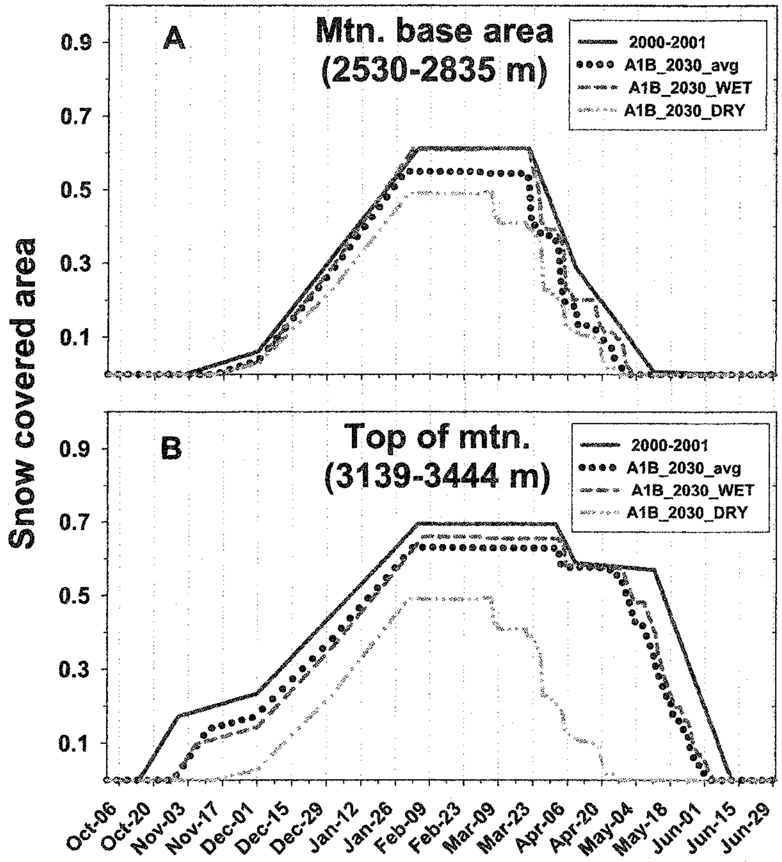

Figure 6. SCA in 2030 for the A1B emission scenario for the model average, the wettest, and driest model output at the (A) base area (elevation zone 2), and (B) top of mountain (elevation zone 4).

In contrast to 2030, in 2100 there is a large difference in SCA depending on the GCM scenarios (Figure 7A). There is virtually no snow cover under the A1B and A1F1 scenarios at the base of the mountain. Under the B1 scenario, about 50% of the snow cover is lost compared to 2001. The conditions at the mid-mountain elevations (2,835-3,139 m) show much less sensitivity to the A1B and B1 scenarios than the base area, but substantial sensitivity to the A1F1 scenario. The cooler temperatures at this higher elevation insulate the snow pack from potential warming enough to maintain a seasonal snow pack in all but the A1F1 high emissions scenario (Figure 7B). The critical elevation line where seasonal snow no longer accumulates has moved from approximately 2,286 m in 2030 to approximately 2,835 m for the A1B and B1 scenarios, and up to 3,139 m for the A1F1 scenario. These results imply that skiable snow would exist from the mid-mountain and above for the A1B and B1 scenarios, but not for the A1F1 scenario.

Climate Scenario: Snow Depth

In 2030, snow begins accumulating under all scenarios within a week of the average accumulation start date of November 8. By Thanksgiving, snow depth is within 20% of the average depth (Figure 8).This condition allows for some snow pack buildup to occur before Thanksgiving (third week of November), and provides two weeks of conditions suitable for snowmaking. Snowmelt at the base area initiates four to five days earlier than the historical melt initiation date of March 26, implying that skiable snow will exist at the base area throughout the mid to late March spring break season in 2030. The A1B_AVG and A1B_DRY scenarios, characterized by moderate warming and reduced winter precipitation, result in reduced maximum snow depths (Figure 8), and a more rapid melting. The A1B_WET scenario, characterized by moderate warming and increased precipitation, illustrate that a 15% increase in winter precipitation can compensate for an approximate 1.5°C winter warming, such that there is no significant change from current conditions. This result is consistent with Scott et al. (2003) and Siedel et al. (1998). Snow depth in 2030 during mid to late March showed a 7 to 25% decline in the base area, with small decreases near the top of the mountain. However, the onset of the spring avalanche cycle (melt initiation) started four to five days earlier in all model runs.

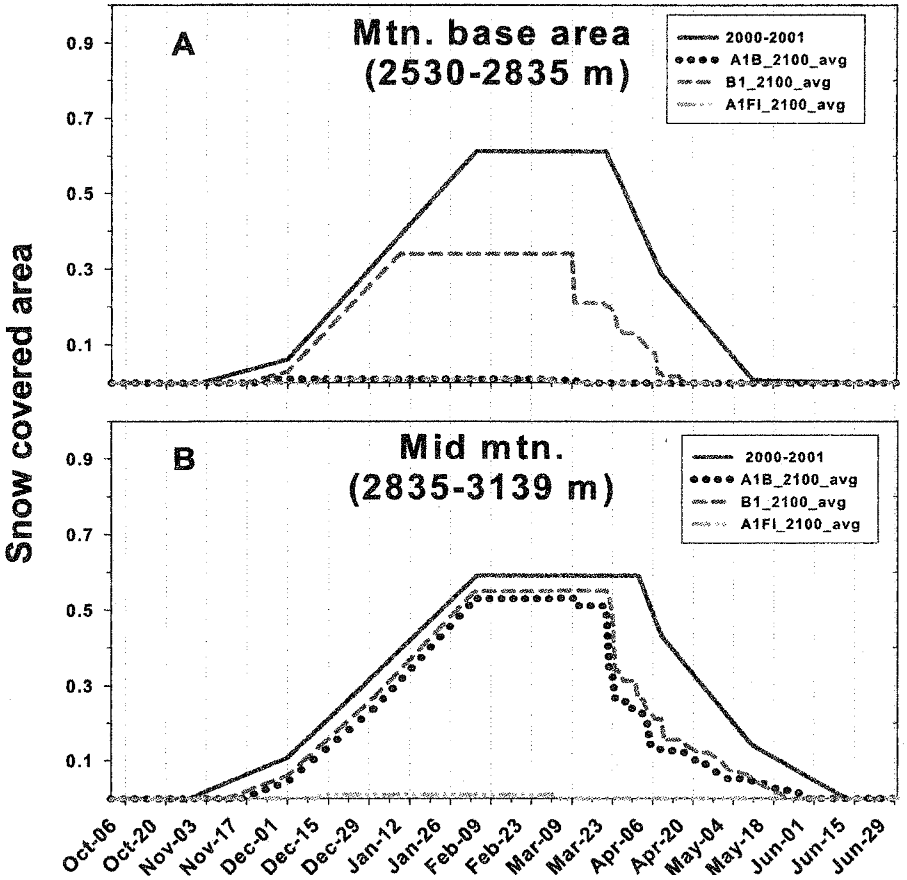

Figure 7. SCA in 2100 for the A1B, A1F1 and B1 emission scenarios for the model average, the wettest, and driest model output at the (A) base area (elevation zone 2), and (B) lower mid-mountain (elevation zone 3).

All model runs show skiable snow for all elevations on Aspen Mountain in 2030, but by 2100 this is only true for the B1 scenario. Figure 8 illustrates how significantly base area snow depths are affected by 2100. It should be noted that the very low snow depths for the A1B and A1F1 scenarios are at their winter maximum by December 20, and begin melting by early February. This is a substantial departure from historical patterns, where maximum snow depth is not usually reached until March. The start of snow pack buildup at the base area of Aspen Mountain begins anywhere from 1.5 to 4.5 weeks later in future climate scenarios for 2100, as compared to historical start date of November 8. Snowmelt at the base area initiates 2.5 to 5 weeks earlier than the historical melt initiation date of March 26. Results for the A1B scenario for 2100 indicate that a persistent snow pack will only exist for the upper two-thirds of the mountain. For the A1F1 scenario, persistent snow coverage is confined to only the top third of the mountain. Snow depth goes to almost zero for the base area in 2100 under the A1B emission scenario. In the A1F1 scenario, snow depth goes to near zero for the entire lower two-thirds of the mountain. The effect is substantially reduced under the low emissions B1 scenario. In the A1B scenario, even in 2100 with a 4 to 5°C increase in air temperature, there is little change in overall snow depth in the elevation bands from 2,896 m to the top of the mountain, compared to current levels. This is true from 3,139 m and above for the high emission A1F1 scenario, which shows a more substantial 6 to 7°C warming.

Somewhat surprisingly, these modeled climate scenarios for 2030 show little change in the amount of snow-covered area and snow depth on Aspen Mountain. The small changes in SCA and snow depth anticipated by the climate models in 2030 can be met with operational changes in snowmaking, similar to the findings of Scott et al. (2003). The potential need for additional snowmaking in 2030 does pose the question of where the additional water will come from. Note that in 2030, there is much less snow in the elevation zone below the base of Aspen Mountain (Lazar, 2006). Snowline in 2030 is moving upwards.

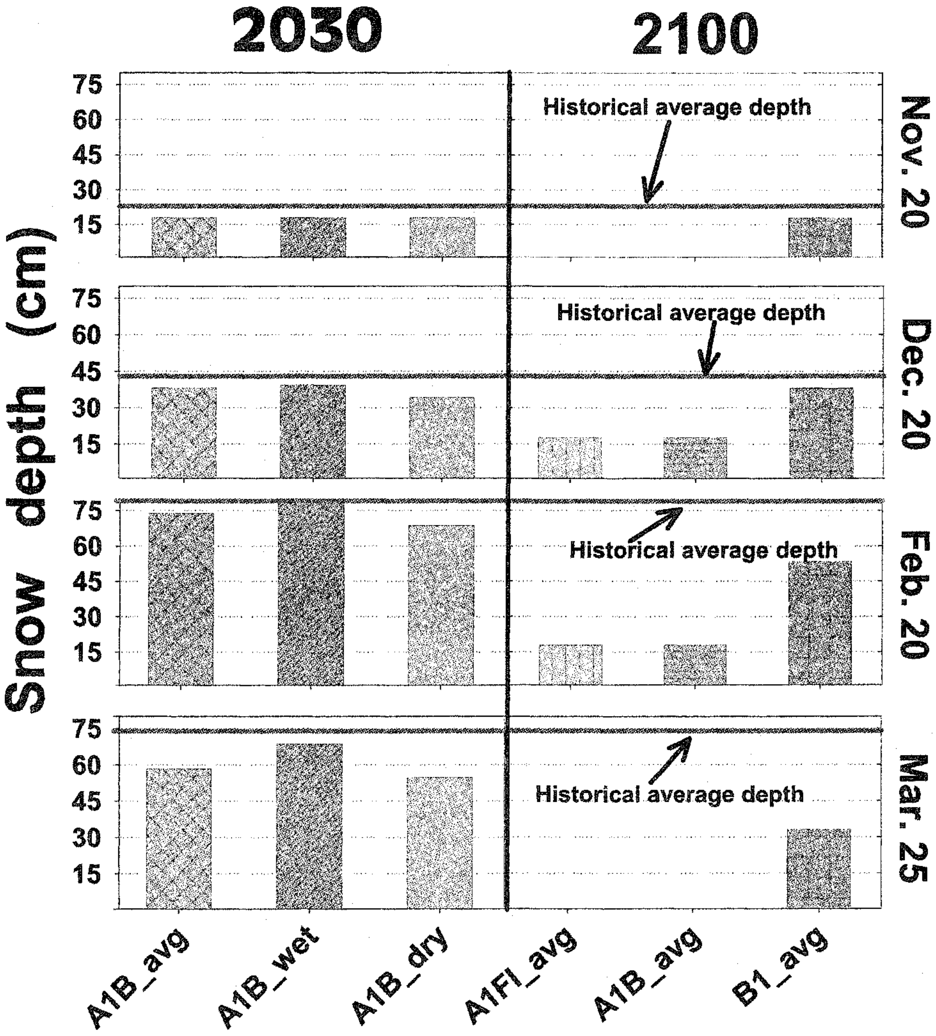

Figure 8. Zone 2 (Ski area base) estimated snow depths.

The GCM scenarios for 2100 suggest a very strong sensitivity to the amount of GHG emissions. Snow depth goes to almost zero for the base area in 2100 under the medium GHG emission A1B scenario. In the high GHG emission A1F1 scenario, snow depth goes to near zero for the entire lower two-thirds of the mountain.

There is limited, if any, ability to make snow for these two climate scenarios because air temperatures during the winter will be near or above 0°C. The effect is substantially reduced under the low GHG emissions B1 scenario. The B1 scenario suggests that there will be operational snow on Aspen Mountain in 2100. Moreover, the decrease in natural snow depth at the base of the mountain under the B1 scenario could be compensated for by snowmaking.

Thus, the operational status of Aspen Ski Mountain in the next 100 years will be a direct result of the amount of carbon dioxide released over that time span. Under the high-carbon A1F1 scenario, most likely there will not be enough snow for the ski area to operate.

CONCLUSIONS

Here, we have introduced a method for estimating site-specific impacts to snow quantity during the snow accumulation 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 and depth 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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