CLIMATE CHANGE IN WESTERN SKI AREAS:
TIMING OF WET AVALANCHES IN ASPEN SKI AREA IN THE YEARS 2030 AND 2100

Brian Lazar[1] and Mark Williams[2]
[1] Stratus Consulting Inc., Boulder, Colorado and American Institute of Avalanche Research and Education, Gunnison, Colorado
[2] Department of Geography and Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado

ABSTRACT

We evaluate how climate change resulting from increased greenhouse gas emissions may affect the timing of wet avalanches at Aspen Mountain in the years 2030 and 2100. Snow quantity was evaluated using the SRM, and we determined the timing of wet avalanche activity by examining changes to historical average temperatures. Climate changes were evaluated using MAGICC/SCENGEN and the output from five GCMs, based on which GCMs best simulate present climate patterns. The climate change estimates were run using the relatively low, mid-range, and high greenhouse gas emissions scenarios: B1, A1B, and A1FI. We then bracketed potential climate changes by using the mean of the five models, a warm-wet model projection (HadCM2), and a warm-dry model projection (ECHAM3). We define wet slab avalanches as likely to occur when average daily temperature exceeds 0°C and investigate three scenarios: first day when daily average temperature exceeds 0°C, first period of three consecutive days when average temperature exceeds 0°C, and the day after which average temperature remains greater than 0°C. We focus on the top of the mountain and the base area for the years 2030 and 2100. By 2030 at the top of Aspen Mountain, wet avalanches are likely to occur between two and 19 days earlier than historical averages, with little difference across the GCMs. In 2100, the A1B and B1 scenarios show that wet avalanches at the top of the mountain start 16 to 27 days earlier. In contrast, the A1FI scenario shows wet avalanches occurring 41 to 45 days earlier. This same pattern is evident at the base area, with wet avalanches likely to occur six to 22 days earlier by 2030, and little variance in the GCMs; 22 to 37 days earlier for the A1B and B1 emission scenarios; and 57 to 65 days earlier for the A1FI scenario.

KEYWORDS: climate change, wet avalanches, Aspen, ski areas, GCM

1. INTRODUCTION

Wet snow avalanches are a major safety concern for ski areas in all parts of the world. Although the accuracy of weather and avalanche forecasts is increasing, wet snow conditions continue to pose a difficult hazard management problem for snow safety managers (CAIC, 2005). Springtime is a critical period for the Rocky Mountains of North America, during which ski areas generate a large percentage of their annual revenue (Gosnell et al., 2006). This period is characterized by increasing air temperatures that cause the snowpack to transition from dry snow to wet snow. Ultimately, a transition from a stable wet snowpack to wet and avalanche-prone snowpack occurs. The timing and spatial variability of this transition can be particularly difficult to pinpoint, and is further complicated by the difficulty in controlling wet avalanche release with conventional means such as explosives (Armstrong and Fues, 1976; Romig et al., 2004). Nevertheless, it is important for ski area managers to estimate when snow stability conditions turn from stable to dangerous to determine when particular ski slopes need to be closed for safety reasons and to allow them to gauge the financial implications of such closings.

Various forecasting approaches have been employed in an effort to develop better methods for estimating avalanche hazards (La Chapelle, 1979; Bovis, 1977; Salaway, 1979; Buser, 1983; Roeger et al., 2001; and others). Wet avalanche release is a complicated phenomenon involving energy balance components such as short and long-wave radiation, surface albedo, and latent and sensible heat transfers. Despite this complexity, it is widely accepted that air temperature consistently plays a critical role in determining when slopes become susceptible to wet avalanche releases (McClung and Schaerer, 1993; Roeger et al., 2001; Vojtek, 2002; and others). While previous studies have investigated

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[*] *Corresponding author address*: Brian Lazar, Stratus Consulting Inc., Boulder, CO 80302;
tel: 303-381-8000; fax: 303-381-8200;
email: blazar@stratusconsulting.com.

the predictive value of weather data for forecasting avalanches (Jamieson et al., 2001; Roeger et al., 2001; Vojtek, 2002), they have focused on short-term (24 hours to several days) forecasting horizons.

The aim of this study is to provide a procedure for estimating spatially and temporally distributed temperature and wet avalanche hazard for future ski 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 using climate values from General Circulation Model (GCM) projections for three greenhouse gas (GHG) emission scenarios to evaluate the likelihood of wet avalanche releases on the Aspen Mountain ski area during the 2030s and 2100s.

We chose the Snowmelt Runoff Model (SRM) (Martinec, 1975; Martinec et al., 1994; model and documentation available at http://hydrolab.arsusda.gov/cgi-bin/srmhome) to determine the presence or absence of snow at various elevations and dates 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 have shown that this approach appears to work well in forecasting future snow depths for Aspen Mountain (Lazar et al., 2006). The effect of air temperature on the likelihood of wet avalanches is estimated by focusing on three scenarios: the first day when daily average temperature exceeds 0°C, the first period of three consecutive days when average temperature exceeds 0°C, and the day after which average temperature remains greater than 0°C.

2. STUDY SITE

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. Lack of snow does not currently 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.

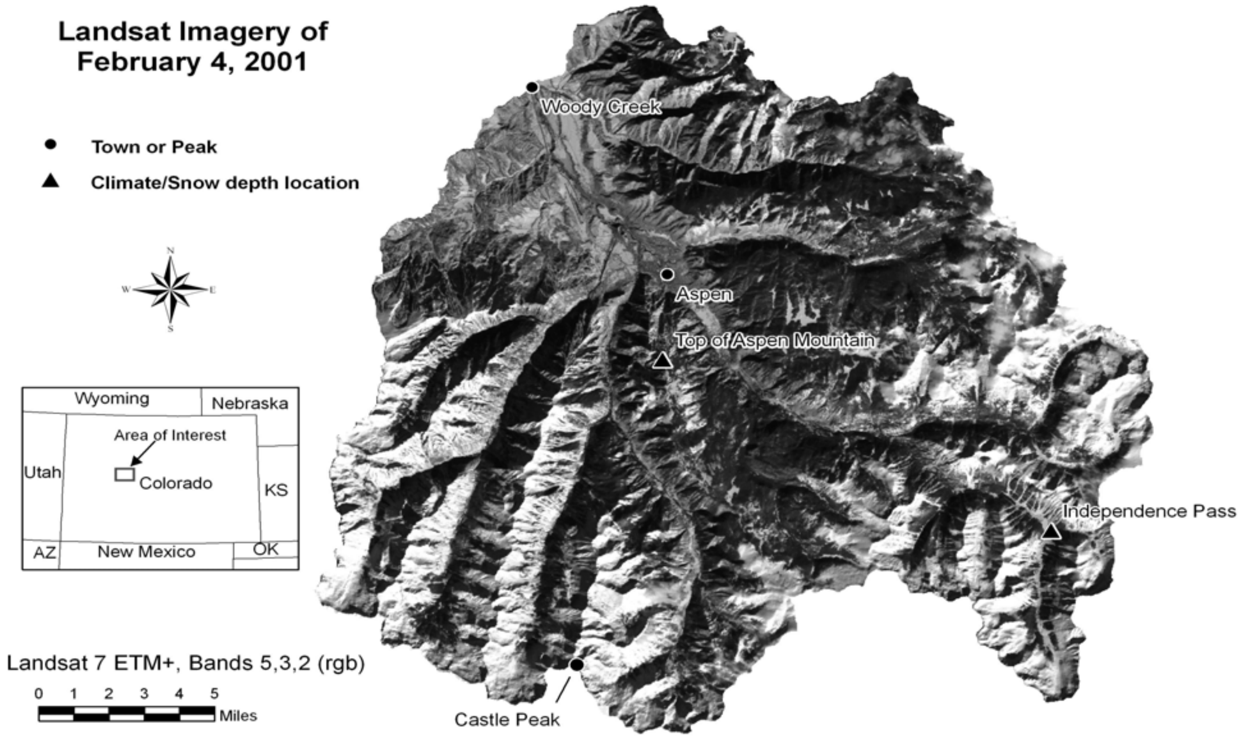

Figure 1: Location map and modeling domain centered on Aspen Ski Mountain, Landsat image.

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) are 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 was 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.

3. METHODS

3.1 Climate modeling

We developed scenarios for two time periods: 2030 and 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. By 2100, the A1B scenario projects CO_2 concentrations (700 ppm) and temperature warming close to the middle of the range described in the IPCC Third Assessment Report (Houghton et al., 2001). The A1FI 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 A1FI 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 model "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, MM5) (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. The RCM "MM5" 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 they are available at the Aspen Global Climate Change Institute (Katzenberger and Crandall, 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 (Katzenberger and Crandall, 2006).

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 five 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.

3.2 Snow modeling

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 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 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 snow-covered area (SCA). We used 2001 as a calibration year for SRM. SCA was estimated approximately once per month using Landsat imagery from 2001. 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 Climate change scenarios

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. 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 warming throughout the 21st century, along with variable precipitation patterns, is consistent with climate projections for mountain areas in Europe (Beniston, 2006), Australia (Hennessy et al., 2003), and Canada (Scott et al., 2003).

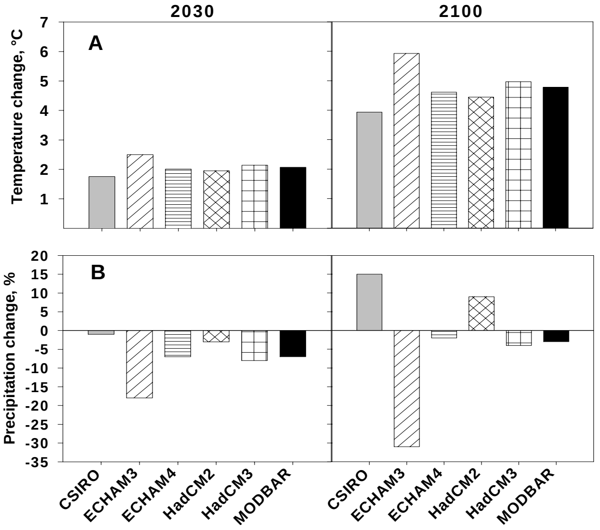

Figure 2: The projected annual changes in (A) temperature and (B) precipitation for the five GCMs for the A1B scenario. The first five bars are results for individual models within MAGICC/SCENGEN; the last bar is the model average.

Figure 3 displays the average of monthly temperature and precipitation changes for the B1, A1B, and A1FI 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. There is little difference among the three scenarios in 2030 because there is little divergence in CO_2 amounts. Therefore, projections for 2030 are not presented here.

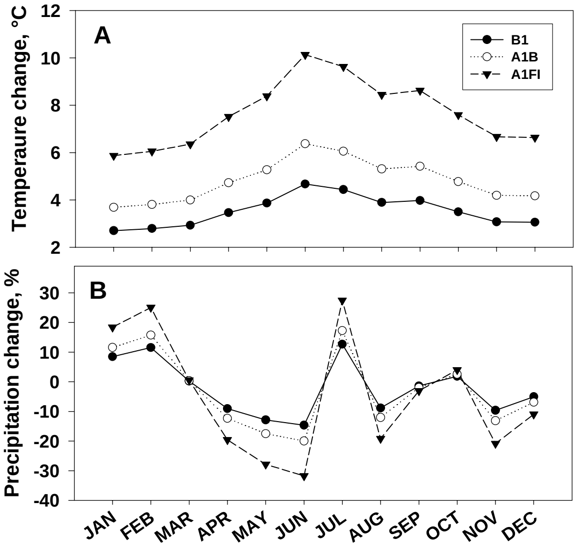

Figure 3: Average monthly changes in (A) temperature and (B) precipitation by GCM emission scenarios for 2100.

4.2 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.

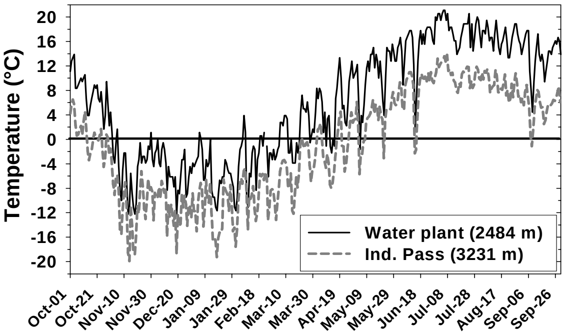

Figure 4: Average daily air temperature in 2001 measured at the Aspen water treatment plant and the SNOTEL site at Independence Pass.

Next, a relationship between snowfall amounts for 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.

SRM was used to determine whether or not snow was present to avalanche during the time periods when defined critical temperature conditions were achieved.

4.3 Timing of wet avalanches

We imposed the projected changes in air temperature (Figures 2 and 3) on the historical average temperature (1968-2005) (Figure 5) for each elevation zone on Aspen Mountain. Figure 6 illustrates the results of the three defined scenarios used to quantify the likelihood of temperature-induced wet avalanche release for the top of Aspen Mountain. By 2030 at the top of Aspen Mountain, wet avalanches are likely to occur between two and 19 days earlier than historical averages, with little difference across the GCMs. The A1B_wet scenario projects wet avalanches occurring two to 12 days earlier, while the A1B_dry scenario projects wet avalanches occurring 12 to 19 days earlier. The scenario defined as the first period of three consecutive days when average temperature exceeds 0°C projects the largest departure from historical average dates.

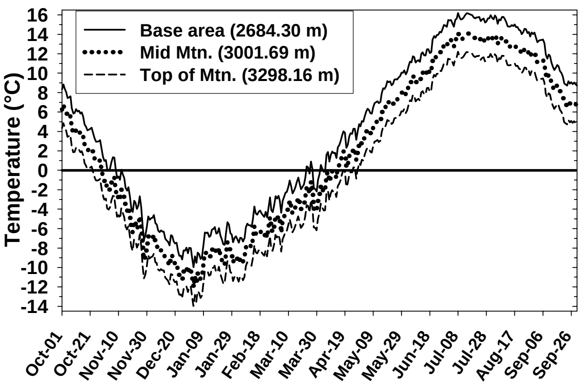

Figure 5: Historical average (1968-2005) daily average temperatures for the base area, mid-mountain, and top of the mountain on Aspen Mountain. The expressed values are the hypsometric mean elevations (in meters) of each elevation zone.

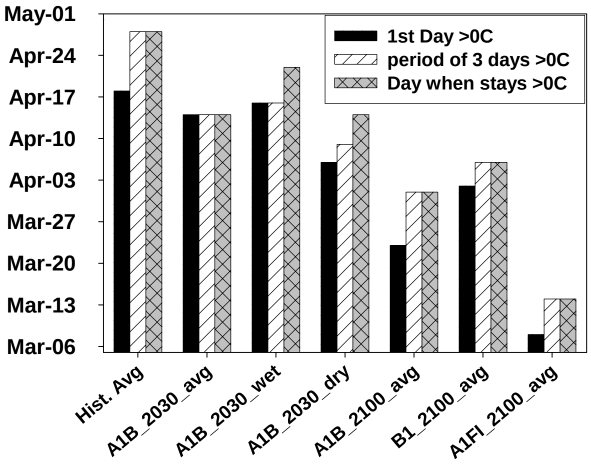

Figure 6: The dates at which wet avalanche releases become likely at the top of Aspen Mountain, as determined by three defined temperature scenarios.

In 2100, the occurrence of wet avalanches at the top of the mountain varies strongly with CO_2 emission scenarios. The A1B scenario shows that wet avalanches at the top of the mountain start 25 to 27 days earlier than historical averages, while the B1 scenario projects a shift to 16 to 22 days earlier. In contrast, the A1FI scenario shows wet avalanches occurring 41 to 45 days earlier.

This same pattern is evident at the base area, with wet avalanches generally likely to occur six to 22 days earlier by 2030, and little variance in the GCMs (Figure 7). Similar to the top of the mountain results, the scenario defined as the first period of three consecutive days when average temperature exceeds 0°C projects the largest departure from historical average dates, with the A1B_dry scenario projecting the largest shift in timing. By 2100, wet avalanches are likely to occur 22 to 36 days earlier for the B1 emission scenario, 31 to 37 days earlier for the A1B scenario, and 57 to 65 days earlier for the A1FI scenario.

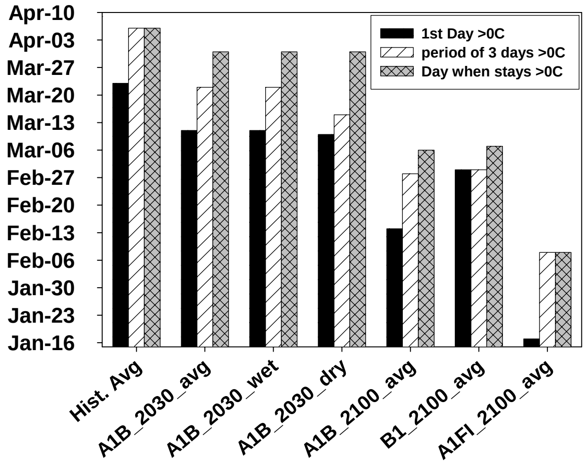

Figure 7: The dates at which wet avalanche releases become likely at the base area of Aspen Mountain, as determined by three defined temperature scenarios.

5. DISCUSSION

Results indicate that wet avalanche hazards will continue to be a concern for ski area operations throughout the remainder of the 21st century, regardless of the emission scenario. Despite the projected increases in air temperature, snow cover will still persist, on at least some portions of the ski area, well into the spring skiing season. The extent of spring snow coverage on Aspen Mountain varies with emission scenario. The entire elevation range is likely to be snow-covered under the low emission B1 scenario, while only the top third will retain spring snow under the high emission A1FI scenario. The timing of wet avalanche initiation will shift to earlier dates and may force ski area managers to close certain portions of their available terrain before snow coverage would otherwise dictate. This could have substantial economic impacts for ski areas that rely heavily on spring skiing revenue.

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