POTENTIAL CHANGES IN THE FREQUENCY OF RAIN-ON-SNOW EVENTS FOR U.S. CASCADES SKI AREAS AS A RESULT OF CLIMATE CHANGE: PROJECTIONS FOR MT BACHELOR, OREGON IN THE 21ST CENTURY

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ABSTRACT: We evaluate how climate change resulting from increased greenhouse gas (GHG) emissions may affect the frequency of rain-on-snow events at Mt. Bachelor in the years 2030, 2075 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 ten 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.
Temperatures at Mt. Bachelor are estimated to increase 0.8 to 1.7°C by 2030, 1.6 to 5.6°C by 2075, and 1.9 to 7.4°C by 2100. The snowline is estimated to rise above the base area elevation (1,671m) to an elevation of 2,000 m under the A1FI scenario in 2075. In 2100, the snowline is estimated at an elevation of 2,400 m under the A1B scenario and 2,800 m under A1FI. The total number of rain-on-snow events during the ski area operating season is expected to increase a day or two by 2030, and up to seven days by 2075. By 2100, the loss of snowpack reduces the projected number of rain-on-snow events, but the ratio of rain to snow events continues to increase. For any time period and elevation in which a snowpack exists, the frequency of rain-on-snow events is projected to increase by 1.5 to 2.5 times, compared to the same time period under current conditions.

KEYWORDS: climate change, rain-on-snow, avalanches, Mt. Bachelor, ski areas, Cascades

1. INTRODUCTION

Rain is not the desired form of precipitation for ski areas. Not only is the length of ski season shortened when fall and spring precipitation comes as rain rather than snow, but rain events that occur after the snowpack has begun developing have particularly negative consequences for ski area operations. These events are referred to as rain-on-snow events. Rain, by definition, is warmer than the snowpack it is falling onto. The release of latent heat from rain-on-snow events can greatly accelerate the settlement and melt of the snowpack (McClung and Schaerer, 2006; Armstrong and Brun, 2008). Thin early season snowpacks can be completely obliterated by even light to moderate rain-on-snow events. With more mature snowpacks, light to moderate rain-on-snow events can cause substantial reductions in snowpack depth while severe and prolonged events can completely eliminate even deeper (> 1 m) snowpacks.

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Additionally, rain adds substantial and rapid load to existing snowpacks, and breaks bonds between snowpack layers and individual snow grains, thereby increasing the avalanche hazard for ski area slopes (McClung and Schaerer, 2006.)
The avalanche problem is further complicated by the difficulty in controlling wet avalanche releases with conventional means such as explosives (Armstrong and Fues, 1976; Romig et al., 2004). For these reasons, knowing when, how many, and at what elevations rain-on-snow events are likely to occur is important planning information for mountain managers.
The aim of this study is to describe a procedure for estimating spatially and temporally distributed rain-on-snow events for future ski seasons using a physically based snow model that can incorporate the output of climate change models. This methodology is designed to be user-friendly and easily transportable to other ski areas. This case study used climate values from ten General Circulation Models (GCMs) projections for three greenhouse gas (GHG) emissions scenarios to evaluate the likelihood of rain-on-snow events on the Mt. Bachelor ski area during the 2030s, 2070s, and 2100s.

2. STUDY SITE

Mt. Bachelor is located within the Cascade Mountains in Oregon, USA (see Figure 1). The ski area ranges in elevation from the 1,671 m base area to the 2,761 m summit, for a total vertical rise of 1,090 m. The property boundary encompasses 33.8 km^2. The operational season generally begins in mid-November and ends mid-May. The beginning of the operational season is dictated by adequate snowfall, while the end of the season is driven by a decrease in both snowpack and skier visits. Snow depths in early April are generally at or near their annual maximum.

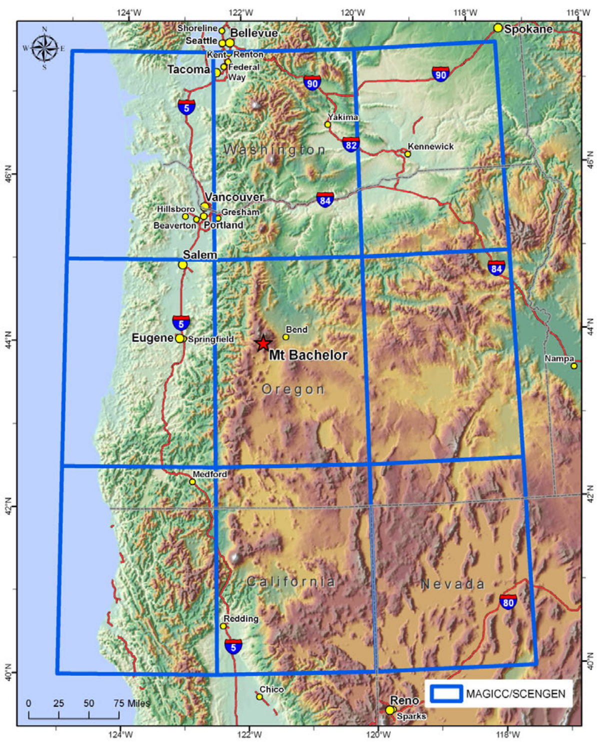

Figure 1: Location of Mt. Bachelor and the SCENGEN grid boxes containing Mt. Bachelor. The coordinates of the boxes are 40° to 47.5°N latitude and 117.5° to 125°W longitude.

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 the ski areas; including weather stations maintained by the ski area, the Three Creeks Meadow Natural Resources Conservation Service SNOpack TELemetry (SNOTEL) site located approximately 16 km to the NNE of the Mt. Bachelor base area, the Oregon Department of Transportation weather station at Wanoga Butte, located a few kilometers down the road from the ski area, and the University of Washington Summit weather station, located at the summit of Mt. Bachelor.

3. METHODS

3.1 Climate modeling

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 three 20-year time periods centered on the years 2030, 2075, 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 carbon dioxide (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 only report projections for the middle A1B scenario in 2030. The emission scenarios begin to diverge in 2050, and 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 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). 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 2.5° × 2.5° grid boxes (approximately 240 km on a side). The SCENGEN grid boxes around Mt. Bachelor

are shown in Figure 1. In reality, climate within a grid box can vary substantially because of topographic relief. SCENGEN does not capture climatic differences within grid boxes. The values for the grid cell containing Mt. Bachelor are calculated as the average of the given grid cell, and the eight surrounding cells. The nine-cell (7.5° × 7.5°) area average is generally considered a more stable estimate of site changes since results for an individual grid cell are subject to more noise than a larger area surrounding the site.
We were most interested in models that simulate well the current climate over the contiguous United States, because they will best project future climate response in the United States. In an evaluation of the ability of 20 existing GCMs to simulate current climate over the contiguous United States, Wigley (2008) concluded that the following ten models performed best, and for this reason we used these GCMs in our analysis:

- CCSM3 – National Center for Atmospheric Research, USA
- CGCM3.1 (T47) – Canadian Centre for Climate Modelling & Analysis, Canada
- ECHO-G – Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group, Germany/Korea
- GFDL-CM2.0 – U.S. Dept. of Commerce/ NOAA/Geophysical Fluid Dynamics Laboratory, USA
- GFDL-CM2.1 – U.S. Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA
- MIROC3.2 (medres) – Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan
- ECHAM5/MPI-OM – Max Planck Institute for Meteorology, Germany
- MRI-CGCM2.3.2 – Meteorological Research Institute, Japan
- UKMO-HadCM3 – Hadley Centre for Climate Prediction and Research/Met Office, United Kingdom
- UKMO-HadGEM – Hadley Centre for Climate Prediction and Research/Met Office, United Kingdom.

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

3.2 Snow modeling

We chose the SRM (Martinec, 1975; Martinec et al., 1994) to determine the presence or absence of snow at various elevations and dates, 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 the net energy balance.
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 (1999–2000 ski season) was distributed over the elevation range of the ski area using a developed lapse rate (0.4°C/100 m). We imposed the projected changes in air temperature from the GCMs on the climate data from the representative year to generate future climate scenarios.
The SRM requires daily estimate of snow-covered area (SCA) We used eight Landsat (ETM+ and TM) scenes from 1999 and 2000 (October 2, November 3, December 21, March 10, April 11, May 21, June 14, and August 17) to estimate SCA for the ski season. The SCA for each date was combined with digital topography to derive estimates of SCA by elevation. To estimate SCA on all other days, we interpolated linearly between the eight scene dates. 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.)
To project the change in frequency of rain-on-snow events, we compared projected snow cover at various elevations to historical occurrence of rain-on-snow events. Mt. Bachelor currently experiences rain-on-snow events during the ski area operating season. Mountain managers report that the elevation range from the base area to just above mid-mountain at 2,400 m experiences four to six rain-on-snow events per ski season. Rain-on-snow events extend to the summit elevation of 2,761 m one to two times per ski season. We evaluated the number of days the daily average temperature is projected to be above freezing, compared to the historically average number of days, to estimate the number of rain-on-snow events for the future climate scenarios, described in Section 3.1. We scaled the historic number of rain-on-snow-events by the percentage increases in the number days above freezing during the ski season to project the future number of rain-on snow events in 2030, 2075, and 2100.

4. RESULTS

4.1 Projected changes in temperature

Figure 2 presents estimated changes in average annual temperature for Mt. Bachelor in 2030 (relative to 1990) using the middle-emissions A1B scenario. The first ten bars are results for individual models; the last bar is the average of the models. Under this scenario, the average model warming is 1.3℃, with a range of 0.8° to 1.7℃, and little variability across the GCMs. This pattern is consistent for all emission scenarios and years.

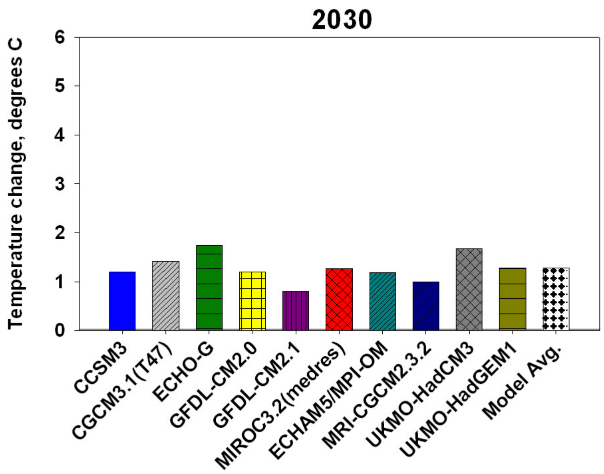

Figure 2: The projected average annual temperature changes for Mt. Bachelor in 2020 for ten GCMs for the A1B scenario. The first ten bars are results for individual models within MAGICC/SCENGEN; the last bar is the model average.

Figure 3 displays the projected GCM average monthly temperature changes for Mt. Bachelor for the B1, A1B, and A1FI scenarios in (A) 2075 and (B) 2100. 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 2075 is 4.1℃, and in 2100 is 5.5℃. Under the low GHG emissions scenario (B1), the average temperature increase is 2.4℃ in 2075 and 2.7℃ in 2100. The largest temperature increases are projected for the summer months, while the smallest increases are projected for the winter months. This is the case for all three emissions scenarios

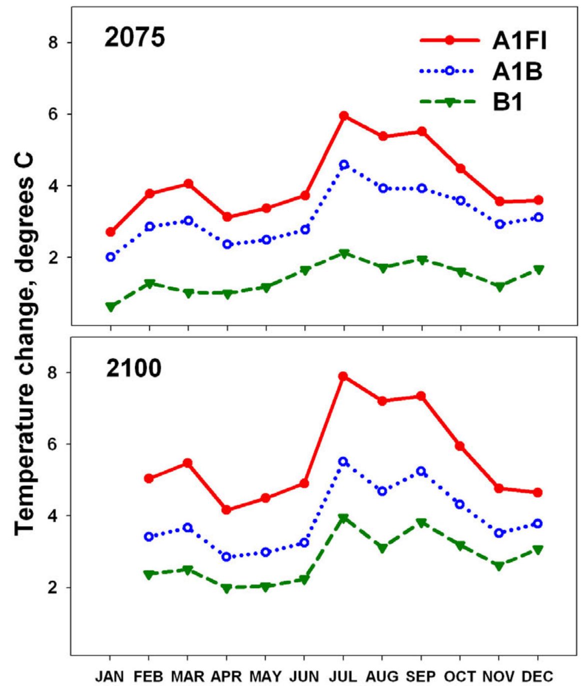

Figure 3: Projected model average monthly temperature changes in Mt. Bachelor for (A) 2075 and (B) 2100.

4.2 Projected changes to snowpack

We imposed the projected changes in air temperature (Figures 2 and 3) on the temperature data from the representative years to project the number of rain-on-snow events under future climate scenarios. Important to this estimate is whether there will be snow coverage at particular elevations. An examination of projected temperatures indicates that the snowline, defined as the elevation below which a seasonally persistent snowpack will not develop, is estimated to rise above the base area elevation (1,671m) to an elevation of 2,000 m under the A1FI scenario in 2075. In 2100, the snowline is estimated at an elevation of 2,400 m under the A1B scenario and 2,800 m under A1FI.

In 2030, the number of rain-on-snow events during the operating season at the mid-mountain elevation (approximately 2,200 m) is projected to increase by approximately one day (from the current four to six days per season) for all scenarios. The frequency of rain-on-snow events at the summit of Mt. Bachelor (2,761 m) is projected to remain unchanged from the current frequency of one to two days per season for all scenarios in 2030.

In 2075, the number of rain-on-snow events per ski season extending to the mid-mountain elevation is projected to increase by approximately five to seven days for A1B and four to six days for B1. While the number of precipitation events that come as rain as opposed to snow is projected to increase under the A1FI scenario, there is projected to be no rain-on-snow events for the lower half of Mt. Bachelor since a snowpack is not projected to develop at these elevations in 2075. The number of rain-on-snow events per ski season extending to the summit elevation is projected to increase by approximately two to three days for A1FI, one to two days for A1B, and one day for the B1 scenario.

In 2100, the dramatic decrease in the duration, or the complete loss, of snow coverage will reduce the total number of rain-on-snow events during the historical ski area operating season for all scenarios. The ratio of rain to snow events, however, will continue to increase. This implies the number of rain-on-snow events will increase for any given time period in which snowpack is present, compared to the same time period under historic conditions. For any time period or elevation in which a snowpack exists, the frequency of rain-on-snow events is projected to increase by 2.5 times for A1B and two times for B1. We project no rain-on-snow events for the A1FI, since a snowpack is not projected to develop at any time or elevation on Mt. Bachelor in 2100 under this scenario.

5. DISCUSSION

Mt. Bachelor provides a case study indicative the potential changes in the frequency of rain-on-snow events for ski areas in the U.S. Cascades. The change in rain-on-snow event frequency is sensitive to both the emission scenario and the time.

Here, we have introduced a method for estimating the frequency of rain-on-snow events during the ski area operating season that can be catered 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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