NOTES AND CORRESPONDENCE

Mapping "At Risk" Snow in the Pacific Northwest

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ABSTRACT

One of the most visible and widely felt impacts of climate warming is the change (mostly loss) of low-elevation snow cover in the midlatitudes. Snow cover that accumulates at temperatures close to the ice-water phase transition is at greater risk to climate warming than cold climate snowpacks because it affects both precipitation phase and ablation rates. This study maps areas in the Pacific Northwest region of the United States that are potentially at risk of converting from a snow-dominated to a rain-dominated winter precipitation regime, under a climate-warming scenario. A data-driven, climatological approach of snow cover classification is used to reveal these "at risk" snow zones and also to examine the relative frequency of warm winters for the region. For a rain versus snow temperature threshold of 0°C the at-risk snow class covers an area of about 9200 km^2 in the Pacific Northwest region and represents approximately 6.5 km^3 of water. Many areas of the Pacific Northwest would see an increase in the number of warm winters, but the impacts would likely be concentrated in the Cascade and Olympic Ranges. A number of lower-elevation ski areas could experience negative impacts because of the shift from winter snows to winter rains. The results of this study point to the potential for using existing datasets to better understand the potential impacts of climate warming.

1. Introduction

One of the most visible and widely felt impacts of climate warming is the change (mostly loss) of low-elevation snow cover in the midlatitudes. Temperature trends in the northwestern United States show a warming of 1°–2°C since the middle of the last century and related declines in snow cover (Karl et al. 1993; Lettenmaier et al. 1994). Changes in snow cover are particularly pronounced in the Pacific Northwest region of the United States. Using measurements of 1 April snow water equivalent (SWE) dating back to 1950, Mote et al. (2005) noted that the Pacific Northwest has experienced the largest declines in snowpacks in the western United States. This change can be primarily attributed to an increase in winter temperatures (Mote 2003; Mote et al. 2005). Phenological shifts of earlier blossoming as well as earlier spring snowmelt are further evidence of

a winter warming trend in the region (Cayan et al. 2001). Stewart et al. (2004, 2005) examined discharge data from 1948 to 2000 and found a 9–11-day earlier snowmelt runoff in the Pacific Northwest that they attributed to an increase in winter temperatures. It is important to recognize that all of the trend analyses discussed above were limited to the latter half of the twentieth century, because data were generally insufficient before about 1950. Given that climatic conditions within this 50-yr period exhibited complex and nonlinear variations over various time scales, it is unclear how representative the reported trends would be for different time periods, both past and future.

Climate impacts on snow hydrology are important throughout the western United States, but Pacific Northwest water budgets are particularly sensitive because total annual precipitation is highly concentrated in the winter months. Furthermore, snow cover that accumulates at temperatures near 0°C is at greater risk to climate warming than cold climate snowpacks because temperature affects both precipitation phase (snow versus rain) and the rate of snowpack ablation. Warmer winter temperatures will lead to more of the

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precipitation falling as rain than as snow and earlier snowmelt. Changes in such climatologically sensitive winter precipitation can impact management strategies for reservoir storage and hydropower generation, the frequency of rain-on-snow floods, and winter recreation.

Climate models are in general agreement that temperatures will continue to rise over the next century. Future climate scenarios show continued rising winter temperatures in the Pacific Northwest with estimates ranging from 0.2° to 0.6°C decade^{-1} (Mote et al. 2003). As we endeavor to gauge the potential consequences of climate change we need to understand the impacts not only on a regional scale but also on watershed scales. For many applications, climate model output is too coarse and even the downscaled hydrologic simulations are at resolutions no finer than 10 km (Mote et al. 2005). Furthermore, the projected temperature changes would not be uniform from year to year and need to be understood in the context of the relative frequency of warmer winters.

With this in mind, the goals of this investigation are to

1) map areas of seasonal snow cover in the Pacific Northwest that are at risk of converting to a rainfall-dominated winter precipitation regime under projected climate warming, and
2) quantify the current and projected relative frequencies of warm winters in the Pacific Northwest.

The data and methodology used are described in section 2. Section 3 describes and discusses the results from the decision tree classification, the relative frequency analysis, and implications for ski resorts in the region. Results are summarized in section 4.

2. Data and methodology

a. Justification for using a snow classification approach

A climatologically based classification of seasonal snow covers provides a physically based and widely applicable means of characterizing snow classes. Sturm et al. (1995) developed a snow classification system that uses temperature, precipitation, and wind speed as the relevant climate parameters for discriminating snow classes. Values of temperature and precipitation are easily obtained but accurate wind speed data are generally not available and therefore they used vegetation type as a proxy for wind speed. Sturm et al. reasoned that the presence or absence of trees determined whether or not an area is a low or high wind environment. It is well established that wind speeds typically decrease as vegetation density increases (Pomeroy and

Gray 1995; Sturm et al. 2001; Walker et al. 2001; Essery and Pomeroy 2004). For instance, wind speed is the factor that distinguishes between the "taiga" (boreal forest; wind speeds of less than 0.2 m s^{-1}) and "tundra" (low tussocks; wind speeds of 2–5 m s^{-1}) snow classes. Validation of this classification system showed that these three variables related closely to the physical properties of the snowpack. This original classification was produced globally at 0.5° × 0.5° resolution.

Aside from producing maps of snow cover classes, a climatologically based snow cover classification system can also be used to explore how changes in climate might alter the distribution of snow classes. Of particular interest in the Pacific Northwest is the distribution of maritime snow, that is, areas with high snowfall but relatively warm winter temperatures. Within the classification of Sturm et al., maritime snow falls into a winter precipitation regime of greater than 2 mm day^{-1} and high winter temperatures (near 0°C). For this class, wind speed is not a relevant parameter because it does not significantly influence snowpack physical properties such as density and depth.

Using climate data to classify snow cover types provides an additional advantage in that it allows one to test the impacts of projected temperature change on Pacific Northwest snow packs. By imposing projected changes in temperature on the climate data, one can examine the potential effects of climate change at higher resolution. In this study, we use a projected climate change of +2.0°C, well within the projected range of increase of 1.5°–3.2°C by the year 2040 for the Pacific Northwest (Mote et al. 2003). The Pacific Northwest region as defined in this study includes the states of Oregon, Washington, Idaho, and western Montana (Fig. 1). Below, we describe the datasets, decision tree classification method, and a frequency analysis used to better understand possible changes in interannual variability.

b. Precipitation and temperature data

We extend the work of Sturm et al. by using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly et al. 1994, 2002; http://www.ocs.oregonstate.edu/prism/). This is a widely used, high quality, topographically sensitive dataset of precipitation and temperature with a grid resolution of 2.5 min (4 km), two orders of magnitude higher spatial resolution than the original snow classification.

We used historical monthly averages of mean temperature and precipitation for December, January, and February from 1971 to 2000. PRISM provides values for mean monthly maximum temperature (T_{max}) and
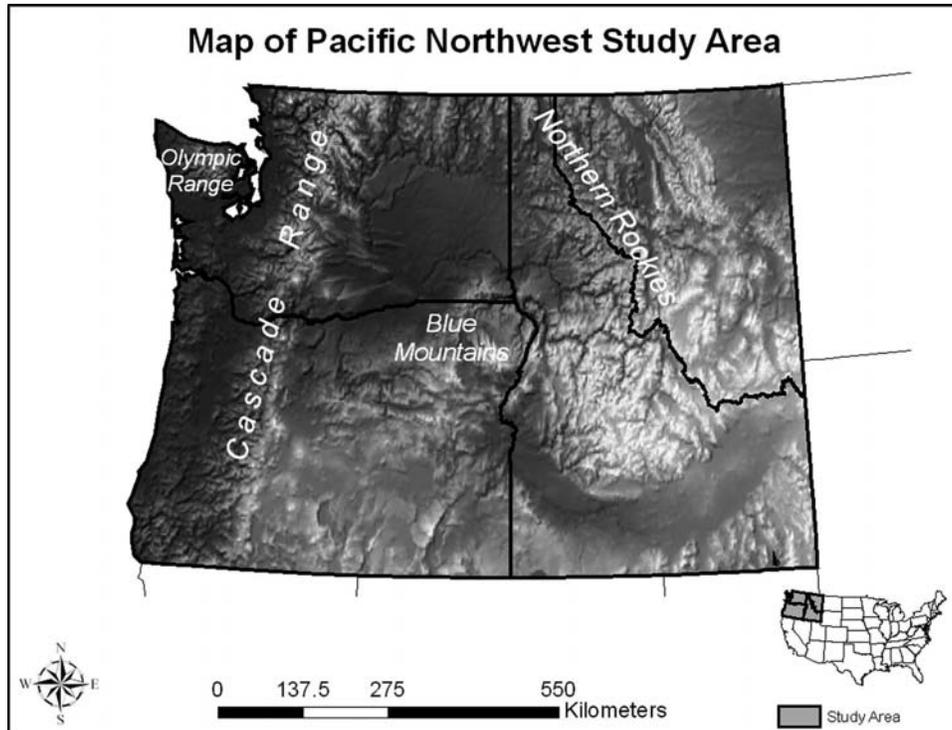
FIG. 1. Shaded relief locator map of the Pacific Northwest region used in this study.

mean monthly minimum temperature (T_{min}) and from this we computed the monthly mean temperature (T_{mean}), where $T_{mean} = (T_{min} + T_{max})/2$.

c. Vegetation cover data

Since 2000, global maps of vegetation cover fraction have been produced using data from the Moderate Resolution Imaging Spectroradiometer (MODIS; Hansen et al. 2003). These vegetation cover fraction maps provide measures of percent tree cover for each 500-m grid cell and have been aggregated to the 4-km PRISM resolution. For inferring high wind versus low wind snow environments, tree cover fraction is preferred over biome maps, which provide no information on forest density. For completeness we have produced a full snow cover classification that includes temperature, precipitation, and wind speed.

d. Decision tree classification and thresholds

The new seasonal snow cover classification can be readily applied using a decision tree approach: a binary classification system that assigns classes based on whether the snow exists in a cold or warm climate, a wet or dry climate, and a windy or calm climate. The structure of the decision tree is shown in Fig. 2 and the threshold values are listed in Table 1.

To discriminate whether a grid cell is considered to have any accumulation of seasonal snow, it must have a mean monthly temperature of less than or equal to a selected temperature threshold for each of the core winter months [December–February (DJF)]. This is the rain versus snow threshold temperature and for individual storms is not a constant value and depends on a variety of complex factors. Snow can fall at temperatures above 0°C such as when a cold precipitating layer lies above a warmer surface layer. In this case, latent heat exchange caused by the melting snowflakes near the ground will lead to cooling of the lower layer (other factors aside). Conversely, rain can fall at temperatures below 0°C such as when a warmer precipitating layer lies above a stable cold layer at the surface. This freezing rain phenomenon is a self-limiting process because latent heat is released, warming the cold layer to 0°C (Lackmann et al. 2002). In this study, we use monthly mean temperatures in which these transitory threshold phenomena should average out. However, to address the inherent uncertainty in selecting a single value, we perform our analysis using a range of rain versus snow temperature threshold values from −2.0 to 2.0°C.

For the high versus low winter precipitation threshold, we use the Sturm et al. value of 2 mm day^{-1} for each of the three core winter months. This allowed us to
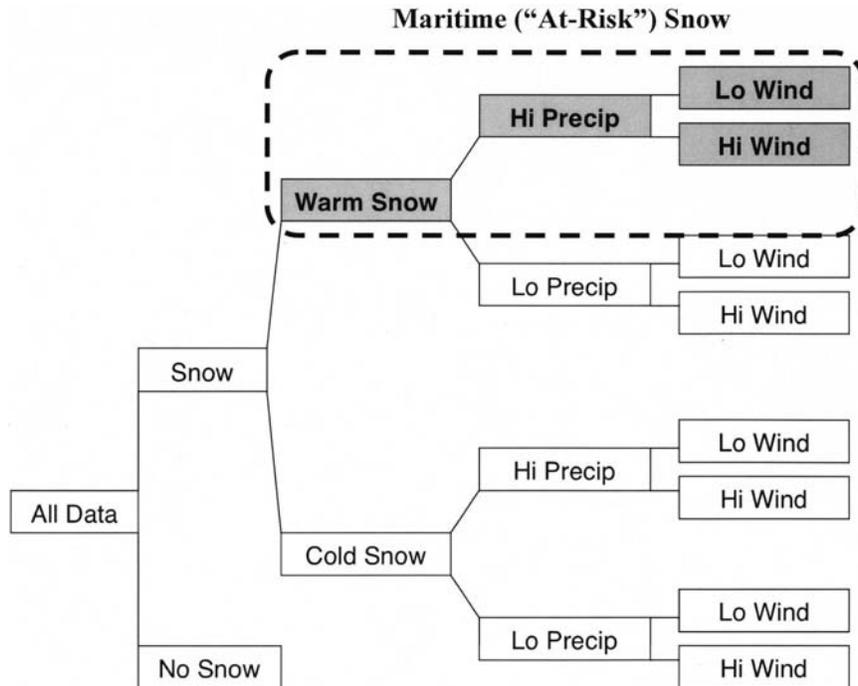
Maritime ("At-Risk") Snow

FIG. 2. The decision tree structure used in the snow cover classification.

map areas where winter precipitation is significant. In the Pacific Northwest, the majority of precipitation falls during the winter and we are mainly concerned with changes in seasonal snow in areas where there is significant precipitation. A change in seasonal snow in a region of high winter precipitation and low summer precipitation is far more important than such a change in a drier climate or one that has more of a balance of winter and summer precipitation.

There is no clear evidence on the density of vegetation that is required to establish a low wind environment. Therefore, for this study, the threshold value is arbitrarily set at a forest cover density of 35%.

e. Relative frequency analysis

The impact of climate warming should be recognized within the context of climate variability. Indeed, year-to-year variability in average winter temperature is typically larger than the temperature changes projected by climate models. Therefore, we include an analysis of the relative frequency of warm winters and use that as a guide to estimate the increased frequency of warm winters in a projected climate-warming scenario.

Relative frequency is defined as the number of times (N') an event occurs within a number of N trials and it is empirically similar to probability. Thus, the relative frequency of an event is N'/N. For the 30-yr time series (1971–2000), we compute the average winter temperature over the DJF period for each winter. Gridded time series data were again obtained from the PRISM datasets (http://www.ocs.oregonstate.edu/prism/). For each grid cell, we compute the relative frequency of winters with a mean temperature less than a specified temperature threshold ($0°$, $-0.5°$, $-1.0°$, $1.5°$, $-2.0°C$). This approach allows us to examine the spatial variability of winter temperatures over the region and the number of warm winters for a range of temperature threshold values under the $2°C$ projected climate-warming scenario.

TABLE 1. Threshold values used in the decision tree classifier.

Criteria	Threshold
Rain vs snow	DJF $T_{mean} \leq -2.0°C$ to $2.0°C$ in $0.5°$ increments
Cold snow vs warm snow climate	Rain vs snow threshold minus $2°C$
High vs low winter precipitation climate	DJF $P_{mean} \geq 2$ mm day^{-1}
Low wind vs high wind climate	Tree cover fraction $\geq 35\%$

Snow Classification
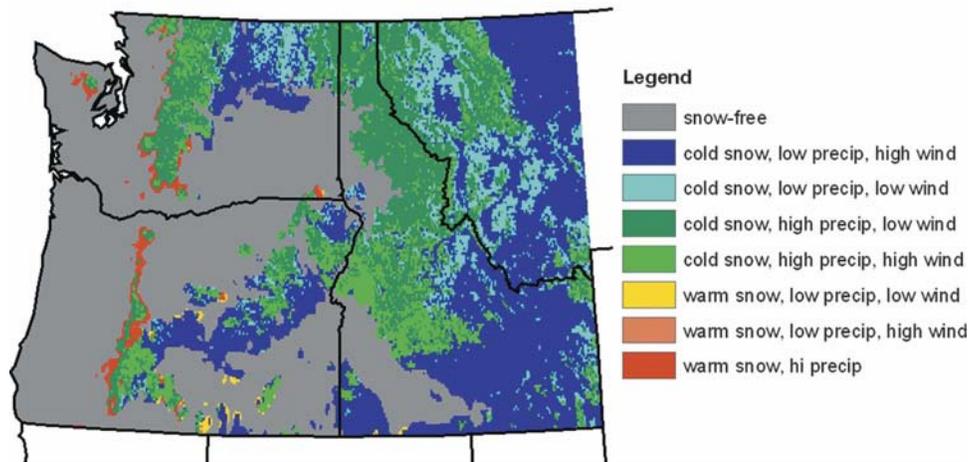

FIG. 3. Snow cover classification using a rain–snow threshold of 0°C. At-risk snow is shown in red.

3. Results and discussion

a. Snow cover classification

The decision tree classifier was implemented using the various thresholds listed in Table 1. Figure 3 shows the results of the snow cover classification for a rain versus snow temperature threshold of 0°C. Shown in red is the area of snow cover representing that which is currently maritime snow with an average winter temperature less than 0°C but exceeding −2.0°C. This snow class represents the area that, for a projected warming of 2.0°C, would convert from predominantly snowfall to predominantly rainfall. The total area represented by this snow class is 9200 km². To consider this in terms of snow water equivalent, we assume an annual average peak SWE of 68.4 cm for this snow area. This is a mean value computed from the climatological mean peak SWE values (1971–2000) of 11 snow-pack telemetry (SNOTEL) sites that fall within the area covered by this snow class. For this temperature threshold, the total volume of water represented by this snow class is roughly 6.5 km³. Results for the other temperature threshold values are shown in Fig. 4. We see that the area of the at-risk snow cover class ranges from a minimum of 6080 km² for a rain versus snow temperature threshold of 2.0°C to a maximum of 10 832 km² for a rain versus snow threshold of −0.5°C. Figure 4 also shows that the area of the at-risk snow cover class comprises less than 2.5% of all snow cover in the region. However, at-risk snow is disproportionately concentrated in the Cascade Range. Using the 0°C threshold case as an example, 51% of all at-risk snow in the Pacific Northwest is in the Oregon Cascades, and 21.8%

of all snow-covered area in the Oregon Cascades falls into the at-risk snow class. By comparison, 12.5% of all snow-covered area in the Washington Cascades is in the at-risk category. The Olympic Range is another mountain region with a large proportion, 61%, of its snow-covered area in the at-risk class.

b. Relative frequency analysis and potential impacts on the ski industry

Figure 5 shows the spatial variability of the relative frequency of winters with mean temperatures below 0°C. As expected, the mountain regions have a much higher frequency of winters with a mean temperature below 0°C than do lower elevations. Figure 5 also shows the ski areas in the region and, while most of them are outside the at-risk snow class, a number of them are negatively impacted by the projected warming. Using the 30-yr temperature record, we compute the relative frequency of warm winters. Even for those ski areas that are outside the at-risk snow class, there would be an increase in the frequency of warm winters. In Table 2 we have listed 20 ski areas in the Pacific Northwest that would experience a significant number of warm winters (defined as having a relative frequency greater than 0.3 for the mean DJF temperature exceeding −2°C) under a climate-warming scenario. The location of each ski area corresponds to the center of the grid cell in which the main lodge is located. In some cases, the elevation of the PRISM grid cell was significantly higher or lower than the base elevation of the ski area. If the elevation difference between the PRISM data and the base elevation of the ski area exceeded 100 m, a search was performed within a radius of three
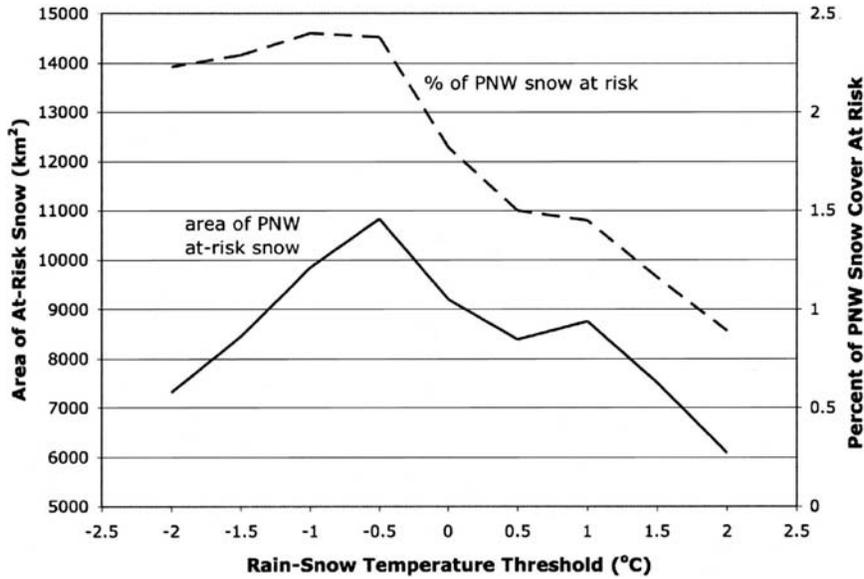
FIG. 4. Total area of at-risk snow in the Pacific Northwest study area and the percent of total snow-covered area comprised by the at-risk class for the different rain vs snow temperature thresholds.

grid cells to locate the cell with the closest match to the ski area elevation. Given that temperature is strongly influenced by elevation, and that there are uncertainties in the ski area location and digital elevation model (DEM) terrain representation, selecting a nearby grid cell with the closest elevation is likely to give a more accurate result than selecting the grid cell with the closest geographic coordinates.

There are a number of relevant questions to consider when assessing the potential impacts of climate change on the ski resorts. These include the following. How will the projected changes described earlier affect ski

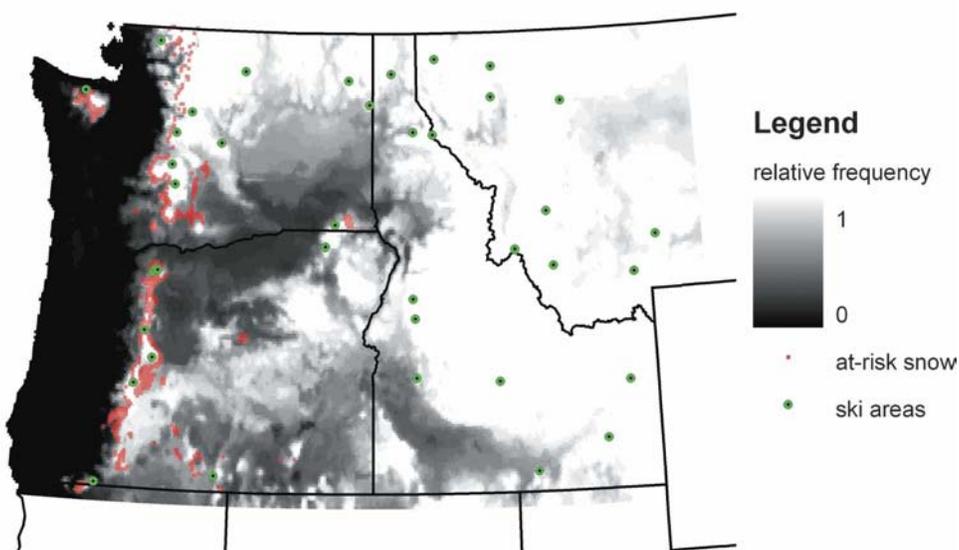## Relative Frequency of Mean DJF Temperature Less Than 0°C

FIG. 5. Relative frequency of winters with a mean DJF temperature less than 0.0°C with the at-risk snow cover class shown in red and ski areas indicated by the green dots.

TABLE 2. List of Pacific Northwest ski areas that are projected to experience a significant increase in the relative frequency of warm winters for a range of temperature thresholds.

Ski areas by region	Base elevation (m)	Relative frequency of winters with a mean DJF temperature exceeding				
		−2.0°C	−1.5°C	−1.0°C	−0.5°C	0.0°C
Oregon Cascades						
Timberline	1509	0.43	0.30	0.13	0.10	0.07
Mt. Hood Meadows	1379	0.47	0.40	0.23	0.13	0.07
Mt. Hood Ski Bowl	1082	0.73	0.63	0.63	0.53	0.30
Cooper Spur	1219	0.73	0.67	0.63	0.57	0.40
Hoodoo	1423	0.67	0.57	0.43	0.27	0.07
Mt. Bachelor	1920	0.33	0.13	0.07	0.00	0.00
Willamette Pass	1561	0.67	0.50	0.37	0.27	0.03
Warner Canyon	1606	0.63	0.60	0.50	0.33	0.20
Mt. Ashland	1935	0.40	0.40	0.27	0.17	0.07
Eastern Oregon and Washington						
Spout Springs	1478	0.40	0.30	0.17	0.00	0.00
Mount Spokane	1164	0.57	0.53	0.50	0.33	0.27
Bluewood	1385	0.53	0.40	0.33	0.27	0.03
Washington Cascades						
Mt. Baker	1082	0.33	0.13	0.03	0.03	0.03
Mission Ridge	1393	0.37	0.27	0.17	0.07	0.07
Crystal Mountain	1341	0.47	0.27	0.13	0.03	0.00
White Pass	1372	0.47	0.30	0.20	0.07	0.00
The Summit at Snoqualmie	866	0.57	0.53	0.43	0.33	0.27
Stevens Pass	1238	0.37	0.27	0.10	0.03	0.03
Olympic Range						
Hurricane Ridge	1463	0.77	0.63	0.57	0.43	0.33

areas at different elevations and at different latitudes? How would an increase in the frequency of warm winters influence the number of skier days for particular ski areas? How would climate warming affect the length and quality of the ski season? One might also consider whether climate warming would have indirect but undesirable impacts such as an increase in the frequency of forest fires in resort areas. An economic assessment of these impacts is beyond the scope of this research, but this points to the need for further study of such potential impacts.

Clearly this approach does not address potential changes in atmospheric circulation patterns, patterns of year-to-year persistence, or the effects of individual cold storms that may occur within an otherwise warm winter. However, it does provide a rough idea of the projected change in the number of warmer winters for the region.

4. Conclusions

A climatological approach to snow cover classification reveals not only patterns of snow cover but also an area of winter precipitation and relatively warm snow temperatures that would be at risk of converting to rainfall under a projected 2°C winter warming. While the impacts depend on the rain versus snow temperature threshold that is used, they are not insubstantial. For a rain versus snow temperature threshold of 0°C, the "at risk" snow class covers an area of about 9200 km^2 and represents approximately 6.5 km^3 of water, equivalent to about one-third the volume of Crater Lake, Oregon. While the fraction of total snow cover represented by this at-risk class is small overall, it is concentrated in the western mountains of the study area, particularly the Cascade and Olympic Ranges. This at-risk area of snow cover is not well sampled by existing SNOTEL or snow course sites and would benefit from additional, regular measurements.

Examination of the relative frequency of warm winters shows that in many parts of the Cascade Range the number of warm winters is likely to increase significantly though not uniformly over the Pacific Northwest region. Socioeconomic impacts would include an increase in the number of warm winters affecting ski resorts, especially those at lower elevations where the temperatures are generally warmer. Additional impacts of these changes would likely be felt in reduced mountain-front recharge of groundwater and hence summer low-flow levels in streams and rivers of the region.

The results of this data-driven approach point to the potential for using existing datasets to better interpret potential impacts of climate model output. Furthermore, such an approach can help point the way for

additional high spatial resolution modeling activities for watershed-level analysis and simulations that would allow estimates of projected changes in the frequencies of warm versus cold winters.

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