A COMPLEX RELATIONSHIP: SIERRA NEVADA BIGHORN SHEEP AND SNOW

Edward Bair[1*], Karl Rittger[2], Tom Stephenson[3], Dani Berger[4], Kezia Manlove[5], Huilin Huang[5], Yun Qian[5], Carrie Vuyovich[6]

[1] *Leidos, Reston VA, USA*
[2] *University of Colorado, Boulder CO, USA*
[3] *California Department of Fish and Wildlife, Bishop CA, USA*
[4] *Utah State University, Logan UT, USA*
[5] *Pacific Northwest National Laboratory, Richland WA, USA*
[6] *National Aeronautics and Space Administration, Greenbelt MD, USA*

ABSTRACT: Sierra Nevada bighorn sheep are an endangered species who inhabit avalanche-prone areas of the central and southern parts of the range. Due to severe winters, disease, and predation, the animals almost became extinct with only 100 individuals left in 1995. Through conservation efforts, including those of the California Department of Fish and Wildlife's Bighorn Sheep Recovery Program, the population grew to 600 in 2015, but record snow in 2023, combined with increased mountain lion predation, have reduced the current population to 350. The sheep have a complex relationship with snow, as it is the main source of water for their forage, yet 73 dead sheep have been found in avalanche debris over the past 14 years, with up 12 deaths from a single avalanche. To better understand how the sheep interact with snow and avalanches, simulations were run for our current (1990-2020) and future (2050-2080) climate under a pseudo warming scenario, a downscaling method for coarse spatial resolution climate projections. For the current climate, daily timespace cubes of avalanche hazard covering the past 20 years across the range were built. The cubes use hazard forecasts from the Sierra Avalanche Center, snow depth, as well as terrain slope and canopy cover. Snow depth estimates are from 2 km Weather Research Forecast model output. Current climate avalanche hazard was then applied to the diminished snowpack under warming to estimate future avalanche hazard. Results suggest that avalanches will continue to cause fatalities for the bighorn sheep in a warmer climate and, if the number of extremely wet events increases as predicted, avalanche fatality rates may increase.

KEYWORDS: avalanche, snow, sheep, climate change, remote sensing.

1. INTRODUCTION

Prior to the 19th century, there were around 1,000 Sierra Nevada bighorn sheep living on the east side of the Sierra Nevada USA from Olancha Peak to Sonora Pass (U.S. Fish and Wildlife Service, 2007) (Figure 1).

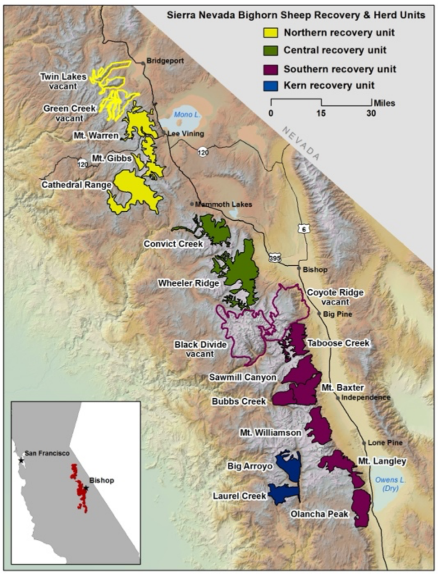

Figure 1: Sierra Nevada Bighorn Sheep Recovery & Herd Units. Image courtesy of the California Department of Fish and Wildlife Bighorn Sheep Recovery Program (https://wildlife.ca.gov/).

The California Gold Rush in 1849 saw thousands of settlers move to the east side of the Sierra Nevada and marked the beginning of the decline of the bighorn population. Bighorn sheep were commonly hunted for food. For example, a menu from the ghost town Bodie, which once had about 8000 people , proudly offers "mountain sheep" meat (Wehausen, 1988). Along with the hunting, domestic sheep herding–which numbered in the hundreds of thousands across the Sierra Nevada–caused overgrazing and disease that further reduced the bighorn population. By the late 1970s, only about 250 individuals were left. Through conservation efforts, including those of the California Department of Fish and Wildlife's Bighorn Sheep Recovery Program, the population grew to 600 in 2015, but record snow in 2023, combined with increased mountain lion predation, have reduced the current population to 350 (Figure 2).

The Sierra Nevada bighorn sheep have a complex relationship with snow. The snow is beneficial to the animals in that there is a positive relationship with wet years and survival, which improves the availability of forage, especially in the fall. Yet, snow avalanche hazard is a significant predictor of sheep mortality (Conner et al., 2018). In this study, we aim to better understand how the sheep interact with snow and avalanches and model how that interaction will change in a future climate.

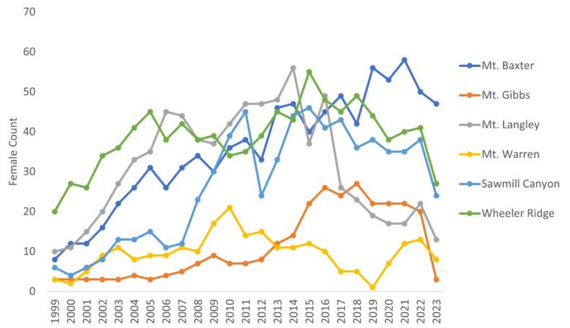

Figure 2: Significant bighorn deaths from the winter of 2023 with 50% ewe mortality. Image courtesy of the California Department of Fish and Wildlife Bighorn Sheep Recovery Program (https://wildlife.ca.gov/).

2. METHODS

Simulations were run for a current (1990-2020) and future (2050-2080) climate under a pseudo warming scenario, a downscaling method for climate projections (e.g., Liu et al., 2017). For the current climate, a coupled weather-aerosol-snow model was used (Zhao et al., 2014). The weather model is the Weather Research and Forecasting Model v3.9.1 (WRF). In a pseudo warming scenario, the differences between a current and future climate are computed.

$$\Delta CMIP5_{RCP8.5} = CMIP5_{RCP8.5} - CMIP5_{current} \quad (1)$$

Then these differences can be added to standard forcings

$$WRF_{input} = MERRA2 + \Delta CMIP5_{RCP8.5} \quad (2)$$

The WRF_{input} are inputs for the coupled weather-aerosol-snow model, MERRA2 is a forcing dataset (Gelaro et al., 2017), the $\Delta CMIP5_{RCP8.5}$ is the difference between current ($CMIP5_{current}$) and future ($CMIP5_{RCP8.5}$) climate runs of the Coupled Model Intercomparison Project Phase 5 (CMIP5). The RCP8.5 refers to the Representative Consensus Pathway 8.5 W/m^2, a high emissions future scenario.

Three candidates water years were used: 2013, 2018, and 2019, corresponding to dry (47% of 1 Apr mean snow water equivalent-SWE statewide) , dry (51% of 1 Apr mean SWE), and wet (161% of 1 Apr mean SWE) years. For the current climate, daily timespace cubes of avalanche hazard across the Sierra Nevada were created.

For each of the analog years, the daily Sierra Avalanche Center danger ratings (1-Low, 2-Moderate, 3-Considerable, 4-High, 5-Extreme) were used and scaled 0-1, i.e., Low is 0, Extreme is 1. Days without ratings were assumed 1-Low. The scaled index is called the $avalanche_{danger}$.

A snow terrain index ($snow_{terrain}$), also 0-1, was created as follows. The fraction of 30-60° slopes (slopes where avalanches are most common) was computed for each 2 km pixel by upscaling a 1/3rd arc sec terrain slope computed from the USGS 3DEP digital elevation model. Canopy cover from the National Land Cover database was used. The $snow_{terrain}$ was set to 0 for areas with ≤ 300 mm of snow depth (a threshold avalanche formation depth from the WRF model) or ≥ 45 percent canopy cover. For other areas, an evenly-weighted hazard $avalanche_{hazard}$ was computed as

$$avalanche_{hazard} = (avalanche_{danger} + snow_{terrain})/2 * 100 \quad (3)$$

3. RESULTS AND DISCUSSION

A histogram of avalanche fatalities by month shows that the majority of fatalities occurred in January and March (Figure 3). From reading the Sierra Avalanche Center bulletins, these are periods with significant dry snow avalanche activity in the Sierra, suggesting that dry snow avalanches during winter storms cause more deaths than wet snow avalanches in the spring.

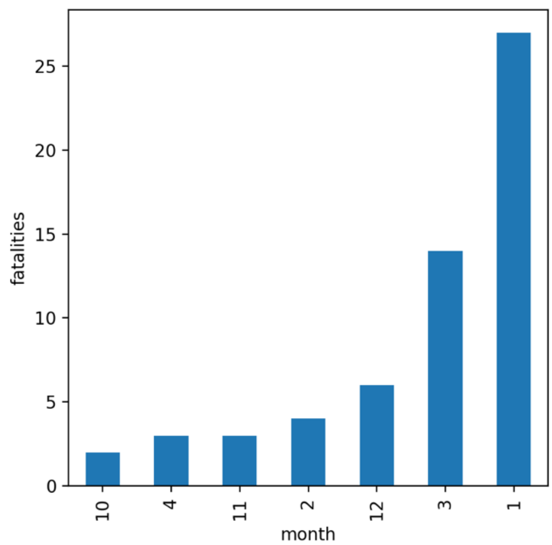

Figure 3: Bighorn avalanche fatalities by month, 2011-2023. Some avalanche deaths from water year 2023 are missing.

There were only 7 bighorn avalanche fatalities in water year 2019, the wet year. Water years 2013 and 2018, the two dry years, did not have any recorded fatalities. The absence of any avalanche fatalities in 2013 and 2018 is noteworthy as the frequency of both droughts and wet years is expected to increase in California, with the increase in wet years dominating, including a more than 3-fold increase in events equivalent to the Great Flood of 1862 (Swain et al., 2018). Thus the wet water year 2019 and its warming analog (pseudo global warming – PGW) are shown (Figures 4-7).

Comparing the current and future avalanche hazard shows the most dramatic differences in the northern

Sierra, i.e., north of 38° latitude, on the western side, and in the spring (Figures 4-7).

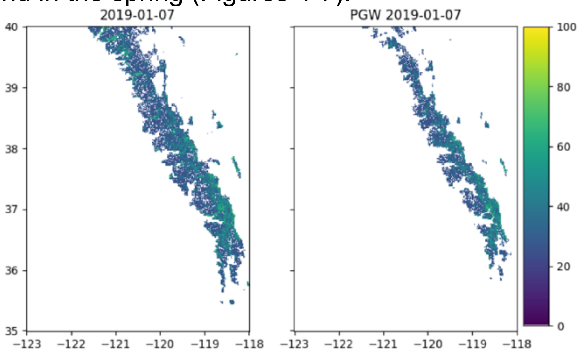

Figure 4: Avalanche hazard index for 7 Jan 2019 (left) and the same date with pseudo warming applied (right).

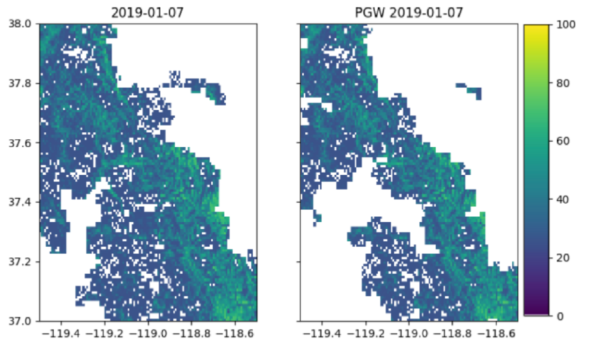

Figure 5: Magnified avalanche hazard index around the Mammoth Lakes area for 7 Jan 2019 (left) and the same date with pseudo warming applied (right).

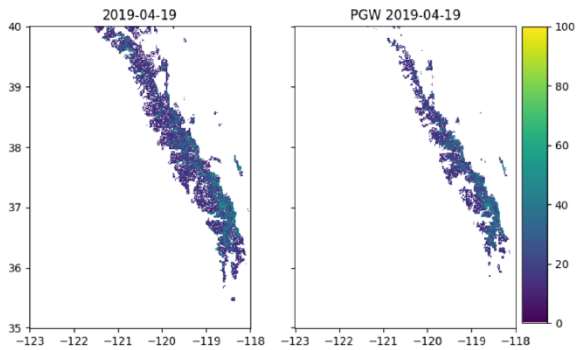

Figure 6: Avalanche hazard index for 19 Apr 2019 (left) and the same date with pseudo warming applied (right).

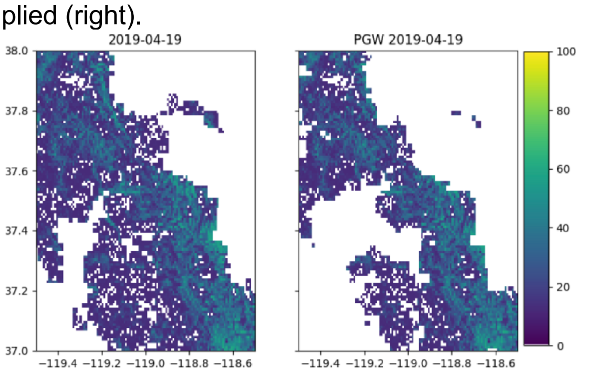

Figure 7: Magnified avalanche hazard index around the Mammoth Lakes area for 19 Apr 2019 (left) and the same date with pseudo warming applied (right).

These trends are consistent with the lower elevations and snow-to-rain transition under warming in these regions, however they are not part of the bighorn habitat (Figure 1). There are reductions in avalanche hazard due to a snow cover loss in bighorn habitat under the pseudo warming scenario, but they are less noticeable. To better understand if these reductions affect bighorn sheep fatalities, the confirmed avalanche death dates were transformed into day of year and plotted against the time series of the avalanche hazard under the current climate and with the pseudo warming for water year 2019 (e.g., Figure 8).

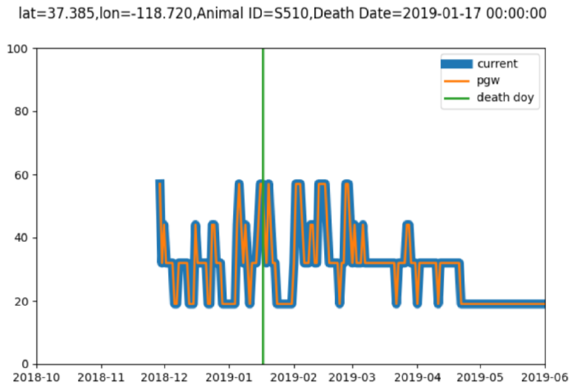

Figure 8: Time series of avalanche hazard for a given pixel nearest to the animal's avalanche death location. The death day of year is shown in green (death doy), the current climate hazard shown in blue (current), and the future climate hazard shown in orange (pgw).

This day of year transformation is used to visualize when avalanche fatalities might occur in a future climate, while acknowledging the scarcity of avalanche deaths for years at a time. This approach is imperfect as each year is different in terms of snow depth. For example, there were only 7 fatalities in water year 2019, but all 7 of the 2019 fatalities occurred on days with elevated avalanche hazard in both the current and future climate, suggesting that the model performed well in 2019 and that the fatalities would remain unchanged in a future climate, at least for the 2019 pseudo warming year. Of the 59 fatalities with complete information, 7 occurred on days of the year with zero avalanche hazard for both the current climate and under warming. For the remaining 52 fatalities, 31 occurred on days of the year with elevated current and future climate avalanche hazard. The other 21 fatalities occurred on days with elevated avalanche hazard in the current climate but zero avalanche hazard in a future climate. These results suggest that the majority of avalanche deaths would also have taken place in a warmer climate, but with considerable uncertainty.

4. CONCLUSION

Results show that avalanches are a significant cause of mortality for bighorn sheep in the current climate and suggest that they will continue to be a significant cause of mortality in a future climate. The high elevation of the bighorn habitat and timing of the avalanches (most frequent months for fatalities are January and March) suggest that snow avalanches will continue to threaten sheep. Research suggesting that the frequency of wet events (e.g., atmospheric rivers) will increase under warming is supported by the modeling efforts here which show SWE increases at the highest elevations of the Sierra in a warmer climate. Given that most of the fatalities occur during and immediately after winter storms, a warmer climate could even lead to increases in the avalanche fatality rate for bighorn sheep.

5. ACKNOWLEDGEMENT

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