PROJECTED IMPACT OF CLIMATE WARMING ON AVALANCHE ACTIVITY AT TWO SITES IN THE SWISS ALPS

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ABSTRACT: Climate change strongly affects the seasonal snow cover in mountainous areas worldwide. Warming-induced changes of snowfall and snow cover are expected to influence the frequency and type of snow avalanches, but research on the effect of climate change on avalanches is scarce. To investigate the effect of climate change on avalanche activity in the region of Davos, Switzerland, we simulated snow stratigraphy until the end of the 21st century using downscaled climate projections for two automatic weather stations at 2147 m a.s.l. and 2540 m a.s.l. Projections were based on eight different climate model chains and three different emission scenarios and snow stratigraphy was simulated with the snow cover model SNOWPACK. We interpreted simulated snow stratigraphy in terms of wet- and dry-snow instability using two recently developed random forest models. Results suggest that, depending on the emission scenario, dry-snow instability expressed as avalanche days will on average decrease by 20 to 60% until the end of the century compared to the reference period (1991-2020). Wet-snow instability, on the other hand, will slightly increase, by up to 20% for the higher-elevation site, and decrease by up to 50% for the lower-elevation site. Detailed analysis of the monthly changes of avalanche activity revealed a shift of wet-snow instability to earlier winter months. Overall, our results contribute to a better understanding of the influence of climate warming on avalanche activity which is crucial to revisit long-standing avalanche risk mitigation strategies.

KEYWORDS: climate change, snow avalanches, climate projections, snow stratigraphy

1. INTRODUCTION

It is now well established that climate change has a profound impact on the seasonal snow cover in mountain regions around the world (Hock et al., 2019). Numerous studies have quantified the decline of the seasonal snow cover resulting from a warming-induced shift from solid to liquid precipitation and an earlier onset of snowmelt. Predicting the impact of climate change on avalanche activity, yet, has remained a challenge due to the intricate interplay of weather, terrain, and snowpack characteristics.

The influence of climate change on avalanches can be either assessed by analyzing long-term observational records of past avalanche activity or by using climate scenarios to obtain projections of future activity. Available studies analyzing historical avalanche data series suggest that increasing temperatures have contributed to a reduction in both the number and size of avalanches (Teich et al., 2012; Eckert et al., 2013; Giacona et al., 2021; Peitzsch et al., 2021;) particularly at lower elevations. Additionally, a rise in the proportion of wet-snow avalanches has been reported (Naaim et al., 2016; Pielmeier et al., 2013). Regarding changes at higher elevations, some studies suggested an increase in dry-snow avalanche activity resulting from a warming-related intensification of heavy snowfall events (Lavigne et al., 2015) or from a higher prevalence of wet-snow conditions (Ballesteros-Cánovas et al., 2018). Overall, the findings of studies focusing on future snow stability were not conclusive (Castebrunet et al., 2014; Katsuyama et al., 2022; Lazar and Williams, 2008), in part because they did not account for detailed snow stratigraphy, did not distinguish between dry- and wet-snow avalanche activity or relied on a simple stability index, which cannot reliably predict avalanches (Jamieson et al., 2007; Mayer et al., 2023). Predicting the influence of climate warming on future avalanche activity is however crucial with respect to the potential adjustment of long-standing avalanche risk mitigation strategies.

Here, we project future changes of natural avalanche activity at two sites in the Swiss Alps up to the end of the 21st century considering eight different climates model chains and three different emission scenarios. To assess avalanche activity, we use two recently developed classification models, which distinguish between avalanche days (AvDs) and non-avalanche days based on simulated snow stratigraphy and meteorological data. The predicted trends are discussed in light of the potential consequences for avalanche risk management.

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2. METHODS

2.1 Sites

We modeled future changes in avalanche activity at two automatic weather stations (AWS) of the IMIS network used in operational avalanche forecasting in Switzerland (Lehning et al., 1999). The two AWS, Weissfluhjoch (WFJ2; 2540 m a.s.l.) and Madrisa (KLO2; 2147 m a.s.l.), are in the region of Davos in the Eastern Swiss Alps about 10 km apart.

2.2 Climate projections

To obtain climate projections of meteorological variables at the location of the two AWS, we used eight different climate model chains from the EURO-CORDEX ensemble (Jacob et al., 2014) which were each available under three different emission scenarios (Representative Concentration Pathways, RCP2.6, RCP4.5 and RCP8.5). Climate projections of meteorological data for the time span 1990 to 2099 were obtained by a statistical spatial transfer of the Swiss CH2018 climate change scenarios (CH2018, 2018) to the location of the two AWS, combining univariate (Rajczak et al., 2016) and multivariate (Cannon, 2018) quantile mapping. To downscale the climate change scenarios to an hourly resolution, we applied the MEteoroLOgical observation time series DISaggregation Tool (MELODIST) library (Förster et al., 2016).

2.3 Snow cover simulations

By driving the one-dimensional snow cover model SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a; Lehning et al., 2002b) with the hourly downscaled climate data, we obtained climate projections of snow stratigraphy from 1 September 1990 to 31 May 2099. This involved calculating the full energy balance at the snow-atmosphere boundary (Neumann boundary condition). Incoming longwave radiation, which was not available in the downscaled climate data, was obtained using the parametrization of Carmona et al. (2014). The flow of liquid water through the snow cover was simulated based on a bucket scheme approach (Bartelt and Lehning, 2002).

2.4 Assessment of avalanche activity

To classify daily dry- and wet-snow avalanche activity (AvD vs. non-AvD) based on the climate projections of the meteorological and snow stratigraphy data, we applied two recently developed classification models (Hendrick et al., 2023; Mayer et al., 2023) which provide probabilities for dry- and wet-snow avalanche activity in the vicinity of an AWS. For the assessment of dry-snow avalanche probability, we used a model that combines the simulated three-day sum of new snow with information on potential weak layers in the simulated snow stratigraphy indicated by a random forest model (Mayer et al., 2022) with the simulated three-day sum of new snow (model "combi" in Mayer et al., 2023). Here, a day was classified as a dry-snow AvD if the probability for an AvD indicated by the dry-snow avalanche model exceeded 0.5 and the simulated snow depth was at least 40 cm. Wet-snow avalanche activity was assessed with the random forest model described in Hendrick et al. (2023). We classified a day as a wet-snow AvD if the probability for an AvD indicated by this model was larger than 0.5 and the simulated snow depth on this day was at least 40 cm. Both dry- and wet-snow avalanche activity models were validated with observed avalanche activity data in previous studies (Hendrick et al., 2023; Mayer et al., 2023).

Using this model chain of climate scenarios, SNOWPACK, and avalanche activity models, every day from December to May (DJFMAM) for the winter seasons 1990/91 to 2098/99 was classified as AvD or non-AvD with respect to dry- and wet-snow conditions at both sites and for all 24 combinations of climate models and RCP scenarios. In our analysis of projected changes in avalanche activity we particularly compared seasonal numbers of AvDs averaged over a 30-year period at the end of the century (2069/70-2098/99; EOC) to mean seasonal numbers computed for a 30-year reference period (1990/91-2019/20; REF).

3. RESULTS

Avalanche activity by the end of the 21st century as indicated by our model chain will substantially differ from avalanche activity in the reference period (Fig. 1). The projected multi-model median of the seasonal number of dry-snow AvDs shows a significant reduction towards the EOC, with relative changes of 20-60% for both stations KLO2 and WFJ2 (Fig. 1a,c). The largest declines are observed under the RCP8.5 emission scenario. For the REF period, the seasonal number of dry-snow AvDs ranges around 23 and 30 for KLO2 and WFJ2, respectively. At the EOC and under RCP8.5, in contrast, the seasonal number of dry-snow AvDs at these stations reduces to only 9 and 14 AvDs, respectively. While the eight ensemble members show considerable variation, the majority of members project a statistically significant decline in dry-snow avalanche activity by the EOC for all emission scenarios and both stations.

Projected changes in wet-snow avalanche activity, on the other hand, differ between the stations (Fig. 1b,d). For the WFJ2 station, the multi-model median number of wet-snow AvDs (REF period: ~23 AvDs) is projected to slightly increase by 10-

20% (or 2-4 AvDs) under RCP2.6 and RCP4.5 by the EOC. Under RCP8.5, the projected number of wet-snow AvDs at the EOC is roughly similar to the count of wet-snow AvDs in the REF period. While not shown in Fig. 1, an increase of wet-snow AvDs for RCP8.5 by around 20% is also observed until mid-century, followed by a subsequent decrease. For the lower-elevation station KLO2 (REF period: 23 wet-snow AvDs), wet-snow activity is projected to decrease, with most pronounced changes towards the EOC and for the RCP8.5 scenario, with a decrease by up to 50%. Projections also indicate a shift in the seasonal distribution of wet-snow AvDs (not shown). For the WFJ2 station and the REF period, wet-snow avalanche activity between December and February (DJF) is mostly close to zero and rapidly increases in March, peaking towards the end of the season. For the EOC, in contrast, projections under RCP8.5 indicate 2-4 wet-snow AvDs/month at WFJ2 for the DJF period. In April and May, in contrast, there is an overall decrease in wet-snow avalanche activity compared to REF and wet-snow avalanche activity will thus peak earlier in the season at the WFJ2. For the KLO2 station, projected changes in the seasonality of wet-snow avalanche activity are similar, albeit less pronounced, as for this station, the estimated monthly wet-snow activity during the REF period already amounts to 1-3 AvDs/months for the DJF months.

4. DISCUSSION AND CONCLUSION

We quantified 21st century changes in avalanche activity at two sites in the region of Davos, Switzerland, considering three different emission scenarios and by using a model chain of climate projections, SNOWPACK and avalanche activity models. Projections show that, depending on the emission scenario, dry-snow instability expressed as AvDs will on average decrease by 20% to 60% until the EOC compared to the REF period. Wet-snow activity, on the other hand, will increase towards the mid-century, by as much as 20%, and then level off or return to similar levels as during the REF period for the station at 2540 m a.s.l. For the lower station at 2147 m a.s.l., in contrast, wet-snow activity will decrease by as much as 50%. Our findings align with existing research, showing

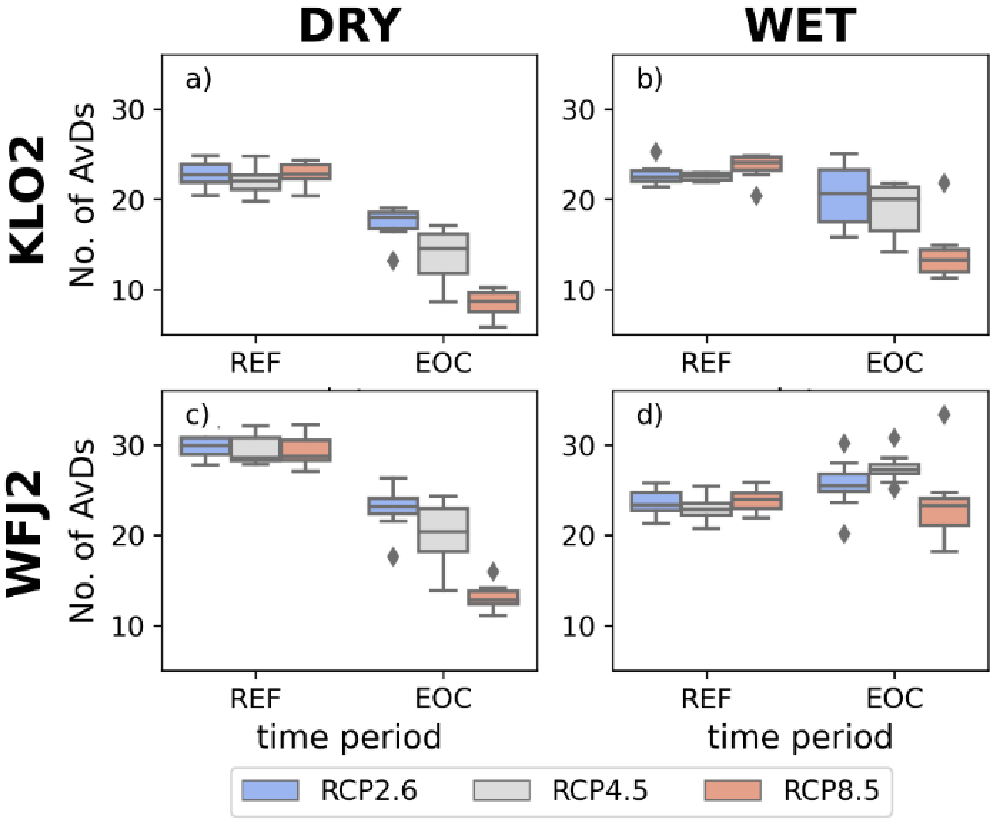

Figure 1: Simulated mean seasonal number of dry-snow AvDs (a,c) and wet-snow AvDs (b,d) for the two stations KLO2 (2147 m a.s.l, upper row) and WFJ2 (2540 m a.s.l, lower row) for the two time periods REF (1991-2020) and EOC (2070-2099). Coloring of the boxes refers to the three different emission scenarios. The box and whiskers show the variability within the eight climate ensemble members, where the line indicates the median, the box extends from the first to the third quartile, whiskers show the range of observed values that fall within 1.5 times the interquartile range above the 3rd and below the 1st quartile, and the black diamonds show outliers.

a substantial decrease in avalanche occurrences particularly at lower-elevation mountain ranges (Castebrunet et al., 2014; Giacona et al., 2021), and a shift of wet-snow activity to earlier winter months (Castebrunet et al., 2014; Lazar and Williams, 2008; Reuter et al., 2022). The projected increase in wet-snow AvDs at the WFJ2 station only partially offsets the decrease in dry-snow AvDs at this site. Thus, overall avalanche activity is projected to decrease for both stations.

Projected changes in snow stratigraphy provide a consistent rationale for the anticipated shifts in both dry- and wet-snow avalanche occurrences, beyond a decline in solid precipitation and snow depth. Our simulations indicate an increasing proportion of melt forms and melt-freeze crusts in the DJF snowpack towards the EOC at the expense of a decreasing proportion of persistent grain types. With increasing temperatures, new snow is thus less likely to fall on a snowpack containing persistent weak layers, resulting in fewer dry-snow avalanches. On the contrary, the high prevalence of melt forms and melt-freeze crusts during the DJF months results from more frequent melting and rain-on-snow events.

While the model chain applied in our study captures changes in mean avalanche activity in terms of the mean seasonal number of avalanche days, it does not account for changes in avalanche size. Yet, the projected decrease in snow depths and increased frequency of wetting events suggest that less snow will be present along the avalanche path. This will potentially lead to a decrease in avalanche runout distances, which previous studies also suggested based on historical avalanche records (Eckert et al., 2013).

The anticipated changes in avalanche activity may require a re-evaluation of existing avalanche risk mitigation strategies. With the decline in dry-snow avalanche occurrences and the potential decrease in avalanche runout, it may be necessary to reassess hazard mapping procedures. In this context, more research is needed to investigate changes in extreme avalanche activity. This would particularly require dynamical downscaling methods to more accurately project changes in extreme precipitation events in mountainous regions (e.g., Schär et al., 2020). Furthermore, our projections indicate potential challenges for avalanche forecasting as patterns of avalanche activity change and wet-snow avalanches during peak-winter season (DJF) become more frequent. With this regard, automated avalanche prediction models, such as the ones utilized in this study or other recent alternatives (e.g., Pérez-Guillén et al., 2022; Viallon-Galinier et al., 2023), will gain heightened importance.

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