A MULTI-STEP AVALANCHE RISK FRAMEWORK FOR THE QUANTIFICATION OF CLIMATE CHANGE IMPACTS ON LARGE SCALE AVALANCHE HAZARD

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ABSTRACT: Specific impacts of climate change on snow avalanche risk for inhabited areas are largely unknown and call for further investigation. Numerous studies suggest that expected increasing temperatures and changes in precipitation could have significant effects on the release and flow characteristics of snow avalanches. To assess the possible consequences of potential changes in snow accumulation and temperature and their subsequent impact on avalanche hazard and risk, we introduce a comprehensive framework for modelling avalanche risk at large scale, incorporating climate change scenarios. By applying a down-scaling procedure, we processed data from the CH2018 Swiss climate change scenarios within the extreme RCP8.5 emission scenario considering six different climate model chains. This data set is used to simulate potential snowcovers of 100 future winters for each of the selected model chain with the physical snowcover model SNOWPACK. Return period scenarios with future avalanche fracture depths are defined for the mid (2060) and end of the century (2085) by applying methods of extreme value statistics. Within these periods, potential future snowcover temperatures are analyzed and compared. The changed parameters serve as input for the research version of the established avalanche simulation software RAMMS. Generated large scale hazard indication maps are combined with the probabilistic risk assessment platform CLIMADA. The output are spatially explicit hazard and risk maps that illustrate possible climate change effects on avalanche risk and allow the quantification of potential future changes. Avalanche risk maps can illustrate the potential effects of climate change on snow avalanches, thus serving as a foundation for assessing future risk assessment and effective strategies to address climate change-related objectives.

Keywords: Climate Change, Avalanche, Risk Assessment, SNOWPACK, RAMMS, Climada, Risk Maps

1. INTRODUCTION

In the last decades, the decrease in mean snow depth and the spatial extent and duration of snow cover has been recorded in various regions worldwide and numerous authors relate these changes to the increasing temperatures and the changing precipitation patterns as consequence of the ongoing climate change (Marty, 2008; Marty and Blanchet, 2012; Morán-Tejeda et al., 2013; Bellaire et al., 2016; Marty et al., 2017; Kotlarski et al., 2023; Eckert et al., 2024). Practitioners pose the question on how snow avalanche hazard and the risk to buildings and infrastructure such as traffic or energy supply might be affected by changing temperature and precipitation patterns. The formation and the dynamics of avalanches depend on a complex interplay of terrain, vegetation, regional and local meteorological disposition as well as the actual weather situation and the spatial distribution of height and stability of the snowpack (Schweizer et al., 2003). How climate change effects this complex interplay is the subject of ongoing research, but the influence on future hazard and resulting risk has not been understood so far. In 2018, the Swiss climate scenarios CH2018 were published, illustrating the impacts of climate change on Switzerland until the end of the 21st century (CH2018, 2018). The scenarios predict warmer winters, a decrease in snow depth in general, fewer new snow days, and a rise of the zero-degree line. However, an answer on how these changes affect the formation of snow avalanches, the hazard and the resulting risk to building and infrastructure is not provided by the CH2018-scenarios. In response to these questions, we present a first basic approach to assess and quantify the potential future impact of climate change on snowpack development, the spatial distribution of snow avalanche hazard and thereby provide a first basis for estimating the future risk in alpine regions. We present elements of the framework and some results of an example in a case study region in central Switzerland, which are described in greater detail in (Ortner et al., 2023a,b,c).

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2. METHODS

The framework consists of a multi-step procedure, see Fig.1 using the climate scenarios CH2018 as

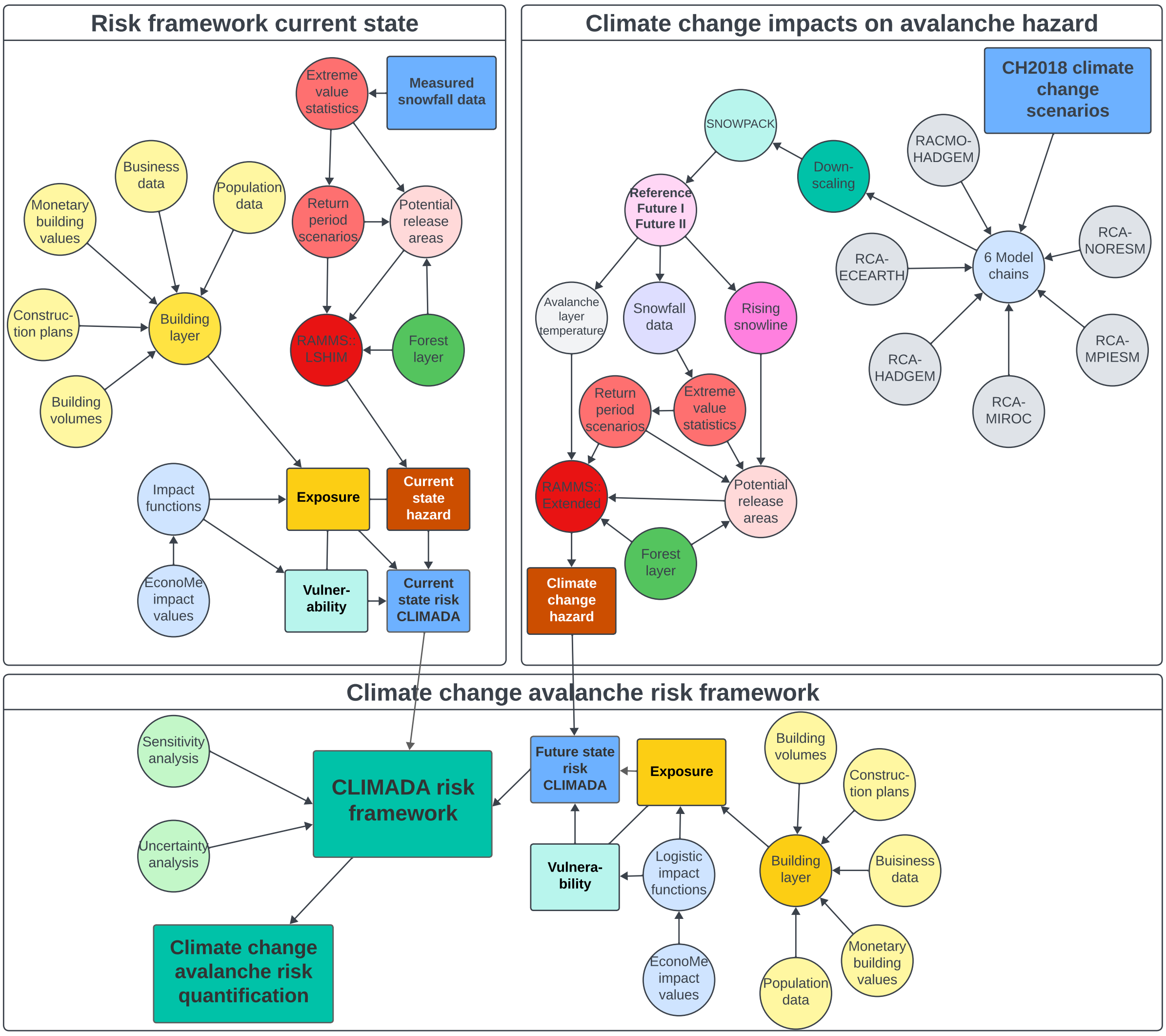

Figure 1: Structure of the multi-step framework for large-scale hazard and risk mapping considering climate change impacts

primary input for obtaining spatially explicit risk indication maps. As a first step, we decided on using the Representative Concentration Pathway RCP 8.5 and selected six model chains (GCM-RCM pairs) out of over 30 model chains that we think are best suited to represent the development of temperature and precipitation during the winter months. In the next step, we use the grided data of CH2018-scenarios with a daily resolution and downscaled it to temperature, precipitation, humidity, wind and radiation data for a specific single station at an hourly resolution using approaches of Hanzer et al. (2020) and Michel et al. (2021). This dataset served as input for the physical snow cover model SNOWPACK (Lehning et al., 1998) simulating snow covers for in total 100 years of the coming century, for three time frames: a reference time frame representing the current state (1997 – 2022) , one centered 2060 in the middle of the century (2048 – 2073, denoted “Future I” hereafter) and one centered 2085 at the end of the century (2073 – 2098, denoted “Future II” hereafter). For each of these time frames, SNOWPACK delivered the snow accumulation in three days (“ΔHS3D” hereafter) as input for the numerical avalanche simulations and the temperature of the snowpack. The rise of the snowline was considered to represent a threshold below which no avalanches release can be expected. The snow line rise, based on the CH2018-scenarios was assumed to be 1525 m a.s.l. for Future I and 1875 m a.s.l. for Future II, compared to 1000 m a.s.l. for the reference period (Ortner et al., 2023c). Potential release areas were automatically identified and classified in four sizes from large (>60 000 m^3) to tiny (< 5 000 m^3), using an approach developed by Bühler et al. (2018, 2022). With these components as input, we use the extended research version RAMMS::EXTENDED to simulate the spatial distribution and the runout of avalanches for three scenarios (30-, 100-, 300y return period) in the reference period and for the two future states Future I and II. RAMMS::EXTENDED allows to adapt snow temperature and thereby to consider changing flow regimes that come along with rising temperatures (Glaus et al., 2023). The resulting avalanche hazard indication maps show the spatial distribution of simulated snow avalanches and the impact of changing temperature and precipitation patterns on the run-out and avalanche pressure. These hazard indication maps were used as an input to the probabilistic risk framework CLIMADA (Aznar-Siguan and Bresch, 2019; Kropf et al., 2021), to estimate risk and to create maps that indicate the modelled avalanche risk expressed as expected annual impact in Swiss Francs [CHF] for individual objects. By this, the maps allow a comparison of the spatial distribution of quantified avalanche risk for the reference period with the two future states Future I+II.

3. RESULTS AND DISCUSSION

When a mean snow accumulation (ΔHS3D) over all climate scenario model chains, is considered, the risk in the case study region decreases continuously towards the end of the century (see Fig.3). The overall risk (accumulated over the entire region) shows an average aggregated annual impact of 2.46 million CHF/year in the reference period, which decreases to 1.57 million CHF/year in Future I, and to 0.61 million CHF/year in Future II. As the risk maps in Fig.2 show, impact patterns of affected objects remain almost similar near Wassen and Gurtnellen. However, they change dramatically on the northeast slopes of Altdorf. This can be explained by the assumed rise of the snow line, below which precipitation is expected to be rain and above to be snow. In areas where avalanches start at high elevations and flow down to the valley bottom in channels, modelled changes of risk are only small. At low lying areas, risk is significantly decreasing due to the assumed rising snowline and reduced avalanche release. We have also considered scenarios that take into account extreme snowfall increase or extreme snowfall decrease. The picture changes completely, with model chains that produce either a minimum or a maximum snow accumulation and strong changes of snow temperature. A scenario of increasing snow accumulation leads to significantly higher risk in Future I and to the contrary with decreasing snow accumulation. For Future II in the end of the century it is different, here strongly increasing snow accumulation does not lead to an increased risk, and decreasing snow accumulation leads to a drastically decreasing risk. The reason for this is the assumed rise of the snowline up to high elevations and an increase in avalanche temperature. The need for further research is identified here in order to better assess how the snow line actually will develop in detail with climate change. We have only made assumptions in our approaches. Regardless of the chosen model chain, a general trend towards warmer snowpack temperatures in future could be also observed. All results are discussed in great detail in Ortner et al. (2023a,b,c).

4. CONCLUSIONS

The combination of a framework for large-scale hazard indication mapping (RAMMS::LSHIM), coupled with climate scenarios that take effects of climate change into account, in combination with the probabilistic risk platform CLIMADA, closes a gap between large-scale hazard modelling and climate risk assessment at a large scale. The developed framework allows to test and quantify the effect of various input scenarios. Such scenarios could be the changing protective function of mitigation measures or socio-economic developments such as an increase or decrease in the number of buildings and exposed persons, as well as an increase or decrease in traffic frequency. Hence, this framework can contribute to the decision-making process by helping to identify locations at which a detailed risk assessments might be appropriate. It is the first time that a hazard (indication) mapping has been performed for a large scale using temporally high resolution data based on climate scenarios. It, allows for an estimation of the change of the spatial extent of avalanches and their impact pressures, based on modelled assumptions of the changed snowfall, snow temperature and rising snow line. In future, with this new framework, the effects of changed input parameters such more precise precipitation data that might come along with a new generation of climate models could be tested. Further it would allow to test the effect of forest disturbances that are expected with rising temperatures and decreasing precipitation. Our new framework can thus support a decision-making process for the future adaptation to climate change.

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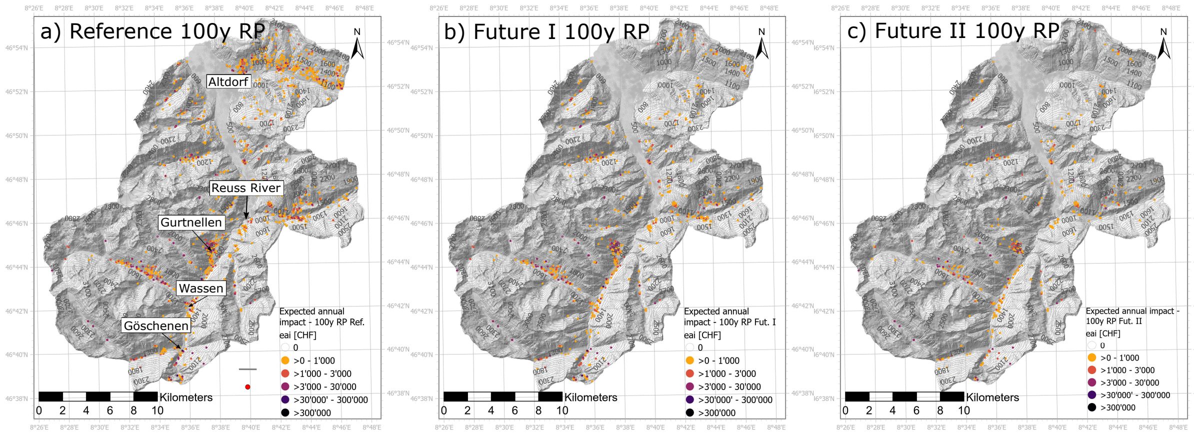

Figure 2: Risk maps showing the expected annual impact in Swiss Franks [CHF/Year] in the case study region for the Reference Period, Future I and Future II (Ortner et al., 2023b).

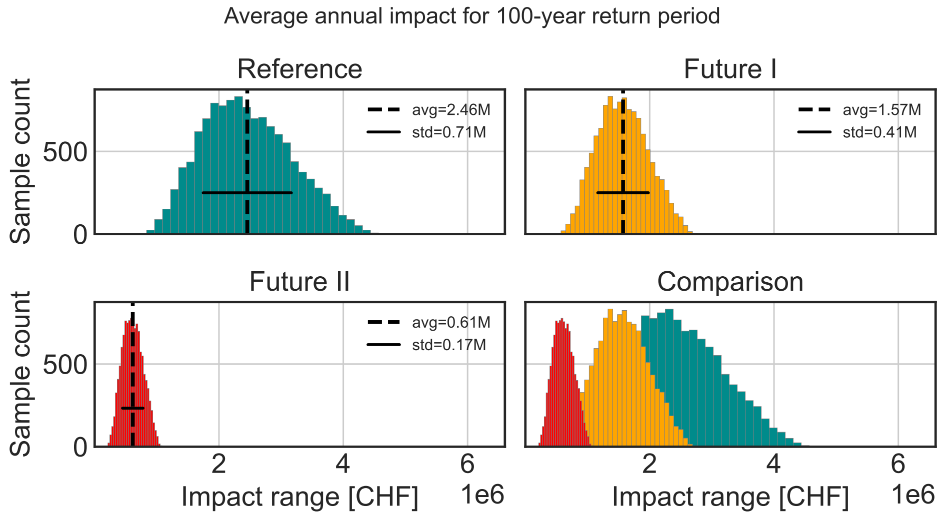

Figure 3: Histogram of the range of the calculated average annual impact (potential risk) in CHF within the two future time frames compared with the reference period considering a mean snow accumulation over the six model chains

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