ON THE IDENTIFICATION OF SLOPES SUSCEPTIBLE TO GLIDE SNOW AVALANCHES BY DEVELOPING A REGIONAL SPATIAL SNOW GLIDE MODEL

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ABSTRACT: Glide snow avalanche activity is expected to increase in the future due to climate change. Half of the fatal avalanches on traffic routes in Switzerland between 2001 and 2021 can be attributed to glide snow avalanches. Currently used tools to assess the glide snow avalanche hazard demand thorough data collection and/or intensive field work on the scale of a single slope. Meaning that glide snow avalanche hazard assessment on a regional level by an engineering office is either expensive or neglected. This paper presents a spatial snow glide model (SSGM) applicable on a regional scale, that is capable of indicating slopes that are susceptible to glide snow avalanches by incorporating a digital elevation model and a landscape model. Both datasets are openly available throughout the European alps and other regions. The validation of this model with mapped glide snow avalanches indicated probabilities of detection (POD) of up to 90%. The model provides a first assessment and can act as a basis when doing regional glide snow avalanche hazard assessments.

KEYWORDS: glide snow avalanche, snow gliding, spatial model.

1. INTRODUCTION

Gliding and creeping of snow as well as glide snow avalanches are natural hazards gaining importance not only within the scientific community but also among professionals in local municipality-based avalanche committees, ski patrollers as well as with safety officers for railroad operations (Etter et al. 2011, Techel et al. 2013). The database registering deadly avalanche incidents in Switzerland by the Swiss avalanche research institute (SLF 2022) lists eight deadly incidents on traffic routes (streets, ski slopes etc.) in the past twenty years (01.10.2001 – 30.09.2021). According to the accident reports in the winter reviews, four out of these eight incidents were caused by glide snow avalanches (Etter et al. 2008, Etter et al. 2011, Techel et al. 2013, Winkler et al. 2018, Zweifel et al. 2019). The importance of glide snow avalanches in such settings is expected to increase in the future due to climate change, which could be creating conditions favorable towards the disposition and release of glide snow avalanches (Maggioni et al. 2019). So far, typical avalanche mitigation techniques such as the use of explosives to trigger avalanches did not prove to be a reliable technique applicable to this kind of avalanche. As a consequence the mitigation work mainly focused on the erection of structural barriers preventing the snow from gliding and creeping down slope (Leuenberger 2003). In order to identify these areas where such (expensive) structures should be erected two workflows are already established. (1) By Margreth (2013) which follows a checklist assigning points to different factors (e.g. ground roughness, slope type, soil humidity etc.) that influence the susceptibility of the slope to glide snow avalanches. After a certain threshold of these summed up points is reached this single slope is declared a possible release area for glide snow avalanches. (2) The model by Leitinger et al. (2008) analyses six different properties of a slope in order to estimate a possible snow glide distance in mm for a slope. Factors for this are for example the presence of forests, the winter precipitation sum (Dec - Mar) as well as the static friction coefficient measured on sight. Both of these techniques demand intensive and time consuming field work for each slope that is analyzed. This makes these approaches burdensome when applied on a regional scale. As a result of that, this work attempted to create a model that is applicable on a regional level, is less time consuming and demands as little input data as possible in order to identify slopes that are susceptible to glide snow avalanches.

2. METHODS

As a basis for the development of this spatial snow glide mode (SSGM), georeferenced datasets from the authorities of the Cantons of Bern, Grisons and Valais are used. In these datasets all avalanche mitigation measures are stored, however, for this study only mitigation structures that specifically focus on glide snow avalanches were considered. Including wooden tripods, berm steps and ground impalements, while excluding snow bridges, remote avalanche control systems and others. Although also snow bridges can be used to prevent glide snow avalanches the amount of work to analyze every single purpose of avalanche mitigation structure would have gone beyond the scope of this study. Due to different formats in the shapefiles of the point, line and polygon data needed to be homogenized. Resulting in a standardized dataset consisting of 1164 polygons of glide snow mitigation structures projects, which covered 917'637 m^2. Each polygon representing a glide snow mitigation structures project was analyzed after its mean elevation, mean slope angle and the mean aspect, using a digital elevation model with a spatial resolution of 2 m (Swisstopo 2021).

The developed SSGM builds on a semi-probabilistic part and a deterministic part. The insights gained with this glide snow mitigation structures analysis constructs the basis of the semi-probabilistic part. For this the normalized probability density function of each polygon characteristic (mean elevation, mean slope angle and mean aspect) was calculated (fig. 1) and summed up resulting in the term SSGMp (eq. 1).

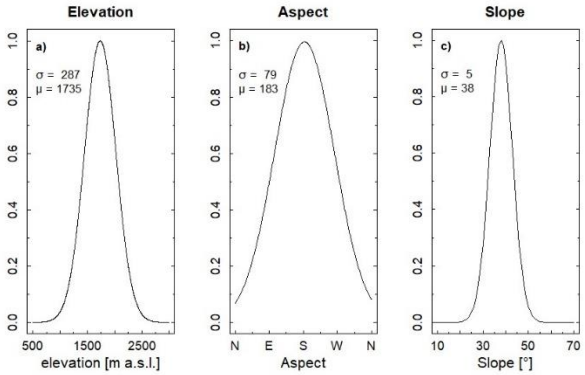


Figure 1: Normalized probability density functions for elevation, aspect and slope angle. With μ signifying the mean of the normalized probability density function and σ standing for one standard deviation.

The deterministic part is strongly influenced by the findings of Leitinger et al. (2008). They introduced a binary exclusion of slopes that are not possible release zones for glide snow avalanches due to their characteristics, based on a literature review. These include the following surface characteristics: x_1 the presence of forests, x_2 a 10 m buffer around single trees, x_3 high friction surfaces and x_4 glaciers (eq. 1). These exclusion areas can be extracted from the publicly available dataset SwissTLM3D (Swisstopo 2021b). The surface classes “rock”, “loose rock”, “unconsolidated rock” and “loose unconsolidated rock” in the SwissTLM3D are interpreted as high friction surfaces that prevent the snow from gliding down slope and will therefore be excluded from the SSGM as possible slopes susceptible to glide snow avalanches. Additionally, a 10 m radius around single trees will also be excluded from the SSGM due to the fact that single trees standing closer than 20 m together can prevent snow from gliding (Höller 2001).

$$SSGM = \left(\frac{\frac{1}{\sqrt{2\pi*287}} e^{-\frac{(x_e-1735)^2}{2*287^2}}}{0.001387849} + \frac{\frac{1}{\sqrt{2\pi*79}} e^{-\frac{(x_a-183)^2}{2*79^2}}}{0.005071437} + \frac{\frac{1}{\sqrt{2\pi*5}} e^{-\frac{(x_s-38)^2}{2*5^2}}}{0.07992912} \right) * x_1 * x_2 * x_3 * x_4 \qquad (1)$$

The SSGM resulting through combining the semi-probabilistic and deterministic part (eq. 1). This equation can now be applied to a DEM and a landscape model (e.g. the SwissTLM3D). This results in values ranging from 0 (low susceptibility to glide snow avalanches) up to 3 (high susceptibility to glide snow avalanches).

As a validation dataset the database of the SLF (2023) was used. Within this database 10’048 glide snow avalanche in the cantons of Bern, Grisons and Valais are stored as point data. The first glide snow avalanche is from 1941 while the last glide snow avalanche is from spring 2023. The mapping has been done by the SLF’s researchers, professional observers, other experts as well as by recreational enthusiast. These points, each indicating a glide snow avalanche, were buffered with a radius of 10 m. From within this 10 m radius the maximum SSGM value was extracted. In the cases where the maximum SSGM value met or exceeded 1.8 the glide snow avalanches were marked as a true positive. If the maximum value was <1.8 it was seen as a false negative. To calculate the probability of detection (POD) the true positives were divided by the sum of observations (true positives + false negatives).

3. RESULTS AND DISCUSSION

In figure 2 the result of applying the equation of the SSGM to a DEM and a landscape model can be seen. The area seen on the map is the Dorfberg in Davos (Switzerland), a well-known glide snow avalanches slope. The blue stars indicate mapped glide snow avalanches from the SLF database which contains 257 glide snow avalanches. The orange to purple shading indicate the calculated SSGM, where the threshold of 1.8 was exceeded. This threshold was exceeded for 243 (94.6%) glide snow avalanches in the database of the SLF. Meaning these areas were correctly identified as glide snow avalanche release areas. Three (1.1%) were classified with a value of zero indicating that the model does exclude these areas as possible glide snow release areas. And eleven (4.3%) showed values between zero and 1.8. Additionally, areas where avalanche mitigation structures were erected (fig. 2 green polygons, lines or points) were also identified by the SSGM to be susceptible to glide snow avalanches.

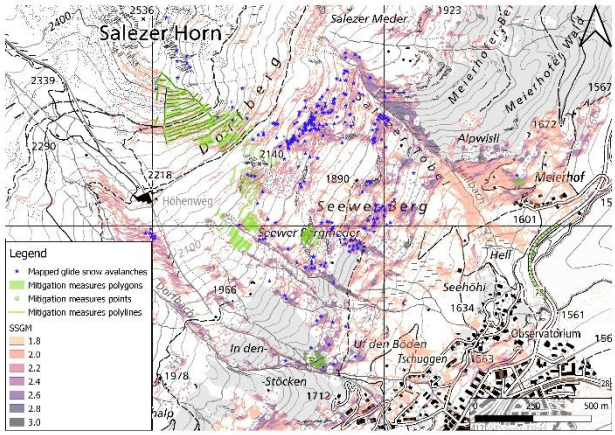


Figure 2: Map of the Dorfberg in Davos (Switzerland). Blue stars indicated mapped glide snow avalanches from the SLF database (SLF 2023). Green lines, points and polygons indicate avalanche mitigation structures such as wooden tripods and snow bridges. The colored shading indicates the result by the SSGM, the darker the colors the higher the susceptibility to glides snow avalanches. Basemap: Swisstopo (2021a).

When applying the SSGM to the Cantons of Bern, Grisons and Valais the calculated POD is 0.747. The POD for the Canton of Bern by itself is 0.905, for the Canton of Grisons it is 0.769 and for the Canton of Valais it is 0.569 (Tab. 1). The better performance of the SSGM in the Cantons of Bern and Grisons could be explained due to the amount of glide snow mitigation structures projects mapped in these two Cantons compared to the Canton of Valais.

Table 1: Calculated PODs and amount of glide snow mitigation structures considered in this study.

	Bern	Grisons	Valais	All three
POD	0.905	0.769	0.569	0.747
# glide snow mitigation structures	477	426	261	1164

In the Canton of Bern 477 and in the Canton of Grisons 426 glide snow mitigation structures projects were mapped. While in the Canton of Valais almost half the amount, 261 were mapped. As a consequence the model tends to better illustrate the glide snow avalanche problematic in the Cantons of Bern and Grisons. Additionally, when looking at the elevation part of the SSGM in figure 1a, it becomes clear that the SSGM is indicating a raster cell above 2500 m a.s.l. to be less susceptible to glide snow avalanches in terms of its elevation. The Canton of Valais has a higher mean elevation compared to the Cantons of Bern and Grisons, resulting in a diminished performance of the SSGM in such areas. Furthermore the validation dataset itself must be treated with caution, although the first glide snow avalanche in this dataset is from 1941, 97.5% of these mapped glide snow avalanches occurred between 2016 and 2023 (Fig. 3).

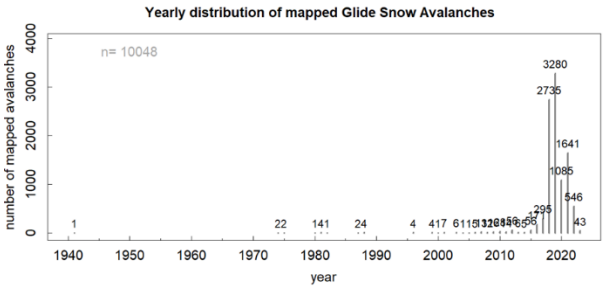


Figure 3: Mapped glide snow avalanches in the SLF database (SLF 2021). Although the amount of mapped glide snow avalanches is impressive and is an extremely valuable database, this graph indicates the limitations of it to be used as a validation dataset in this study.

Resulting in the realization that not all slopes that are susceptible to glide snow avalanches are depicted in this dataset. To emphasize this incompleteness of the validation dataset a picture published by Bebi and Ulrich (2008) shows the Dorfberg in 1945 where at least 19 glide snow avalanches are visible (fig. 4).

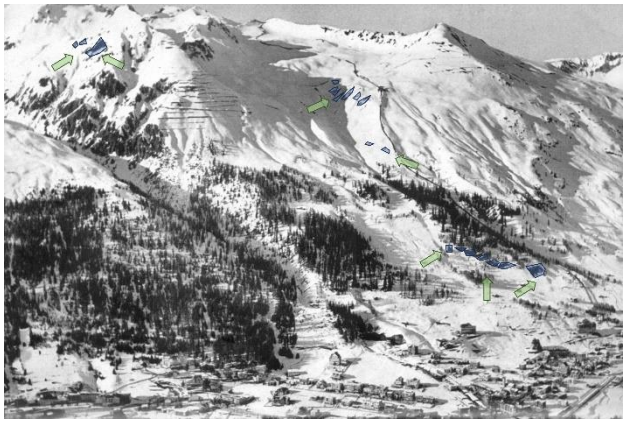


Figure 4: Picture of the Dorfberg from 1945 extracted from Bebi and Ulrich (2008). Dark blue polygons indicated areas with glide snow avalanches visible.

However, in the validation dataset not a single glide snow avalanche was mapped during this winter. When looking at the slopes indicating glide snow avalanches, these slopes have all been identified by the SSGM to be susceptible to glide snow avalanches (values ≥1,8), underlining the correct functioning of the model (fig. 5). Due to the fact that the validation dataset is not complete, a probability of false detections (POFD) is not feasible to calculate.

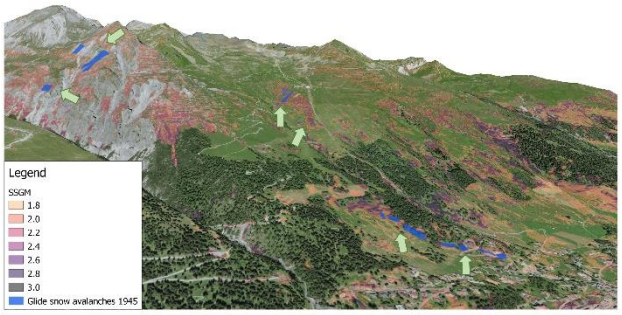


Figure 5: Pseudo-3D map from the Dorfberg with a similar viewing angle than the one from Bebi and Ulrich (2008). The dark blue polygons indicate the glide snow avalanches seen in the picture from 1945 while the shading indicate the results from the SSGM. The SSGM has been able to indicate these areas as being susceptible to glide snow avalanches.

As an additional measure to test the model, the SSGM was also applied to the Canton of Uri (Switzerland), an area that has not been taken into account during the development of the model. By applying the same validation method as with the other Cantons, a POD of 0.853 for the Canton of Uri has been achieved.

4. CONCLUSION

The aim of this study was to develop a model with the capability to identify slopes susceptible to glide snow avalanches on a large regional scale without intensive field work or detailed data. The validation process indicated that this goal has been met and that the SSGM is a tool ready to be applied by engineering offices or any other hazard assessing entity. Nevertheless, expert knowledge for the interpretation of the produced results is still demanded. Especially, since a POFD could not be determinded in a meaningful way, resulting in the possibility that the model is indicating too many slopes being susceptible to glide snow avalanches. Consequently, the SSGM is intended to be used as a first assessment and basis to start from when evaluating the glide snow avalanche hazard on a regional scale. Additionally, since the elevation parametere is excluding any slope above 2500 m a.s.l. or below 750 m a.s.l. it is only applicable within this elevation band. However, when applying the same workflow with glide snow mitigation structures data from a different area the resulting formula could still be applicable.

The POD of 0.853 for the Canton of Uri indicates, that the model is not limited to the three Cantons on which's data it is developed on but also on areas that share similar climatological and topographic characteristics, for example the European Alps. However, testing the applicability of the SSGM's methodology to another region such as Norway for example, where similar data is available could be done in a later phase. Furthermore, additional development of this SSGM will be not focused on the incorporation of more detailed geospatial data. One reason for this is the goal of having a workflow that is broadly applicable to many areas. The second reason being the lack of knowledge about the processes leading to glide snow avalanches themselves. Incorporating more formulas or parameters without understanding well enough the basic triggering processes about glide snow avalanches is little helpful for a glide snow model.

A probable further application for the SSGM could be to investigate the impact of climate change on the occurrence of glide snow avalanches. The report by the NCCS (2018) expects a rise in the zero-degrees Celsius temperature line of 400-650 m in Switzerland by the year 2060 compared to the period of 1981 to 2010. This upward shift could be incorporated into the SSGM by moving the elevation curve in figure 1a by 400-650 m upwards and then applying it to a DEM. This could be especially helpful in identifying slopes that are newly susceptible to glide snow avalanches due to climate change. This could help authorities or engineering offices to estimate areas where mitigation measures must be applied in the future.

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