ABSTRACT: AvalMap is a complex, multi-layer snowpack and avalanche hazard model with a basic idea of spatially and temporally modelling the evolution of snowpack and giving an estimate to avalanche hazard. Beside calculating the most important snowpack parameters: layer height, density, grain size, sphericity and dendricity by modelling the processes taking place in the snowpack: settlement, melt, metamorphism, weak layer formation and transport by wind for unlimited number of layers, it also gives an estimate of the avalanche hazard for each pixel based on the actual snowpack, terrain, weather and vegetation parameters. It uses a number of basic weather and snowpack data from meteorological stations, a digital elevation model and land cover as input. AvalMap has modular structure and is built up of 5 modules: weather, snowpack, terrain, land cover and avalanche danger. The weather module calculates and extrapolates the important weather parameters from measured point meteorological data. The snowpack module extrapolates the measured snow data based on the previously calculated meteorological maps and models their evolution by using physical or empirical based equations. The terrain module delineates the potential avalanche paths from slope and plan curvature. The vegetation module defines the relation of land cover and snowpack height. The avalanche danger module calculates the strength of bonding between each layer and defines the effect of the current and past weather situation on avalanche hazard. The final outcome of the model, the avalanche danger map is produced by combining these latter two with the result of the terrain and land cover modules.

KEYWORDS: AvalMap, snowpack, multi-layer, model, avalanche hazard

1. INTRODUCTION

Traditional avalanche forecasting is still the most reliable and used way to predict avalanches. However, with the increasing quality and quantity of data and computational capacity available, we can build better and better models to simulate the evolution of the snowpack and give predictions about the time and location of avalanches. The use of GIS allows us to model the spatial variability of the snowpack and identify the most avalanche prone times and areas. Although the modelled results still have their limitations, an assessment of avalanche hazard, visualized on a map, could already provide useful extra information for professionals and decision makers. The objective of this study is to introduce our complex, multi-layer snowpack and avalanche hazard model, AvalMap, that was created with such an aim in sight.

2. STUDY AREA

The study site is located in the central part of the Low-Tatras mountain range in Slovakia, which is a popular skiing area with east to west oriented, long, grassy, ridge with an average height of 2000 meters. The north facing slopes are steep, rocky, the south facing ones are rather gentle sloping.

3. METHODS

The model AvalMap has modular structure and is built up of 5 modules: weather, snowpack, terrain, land cover and avalanche risk modules (see Figure 1). The latter one uses the results of the previous modules. The weather module calculates the important weather parameters based on measured point meteorological data. The snowpack module extrapolates the measured snow data based on the meteorological maps and models their evolution by using physical or empirical based equations. The terrain module delineates the potential avalanche paths from slope and plan curvature. The vegetation module defines the relation of land cover and snowpack height. The avalanche hazard module calculates the strength of bonding between each layer and chooses the lowest bonding strength for each pixel. It also defines the effect of the current and past weather situation on avalanche hazard. The final outcome of the model, the avalanche hazard map is produced by combining these two with the result of the terrain and land cover modules, showing the spatial distribution of avalanche hazard for the actual day.

3.1 Weather module

The weather module extrapolates the measured point meteorological data to the whole modelled area. The measured parameters are: minimum and maximum air temperature, minimum and maximum snow surface temperature, wind speed and wind direction. The input data used for the extrapolation process are DEM, aspect, slope, solar radiation, cloudiness and land cover.
Figure 1: Flowchart of AvalMap
Air temperature is the most important factor in calculating snow melt, snow crystal metamorphism and snow settlement. As no general, physical based equation about the spatial extrapolation of the temperature measurements were found in the literature, I used multiply linear regression for the extrapolation of the 5 point temperature data, using elevation and solar radiation for clear sky as independent variables, thus getting different equations for each day.

Extrapolation of the snow surface temperature is done from a single point, using the same equation as for the air temperature, but in this case, using solar radiation for the cloudiness of the actual day instead of radiation for clear skies.

For the wind extrapolation the wind modification effect of terrain on both macro and micro scale were combined. The macro scale is calculated by using a method developed at Purdue University, USA (ASCE 2010) with the modification of an empirical constant. For the micro scale part, a set of equations by Liston et al. (2007) is used, modified to take the turbulence effect into account. The wind direction altering effect of terrain on both macro and micro scale were combined. The macro scale is calculated by using a wind profile, to threshold shear velocity, calculated by the logarithmic ratio of shear velocity, calculated by the logarithmic wind profile, to threshold shear velocity, calculated by an equation from Kind (1981), which is based on shear and threshold shear velocity. The difference of the fluxes are calculated for each pixel from the direction of the wind, to determine the amount of snow that could actually be carried away or deposited. Sublimation and densification in the carried snow are also considered. The amount of snow actually transported, depends on the temperature, height and density of the available snow layers. For the determination of the spatial distribution of wind deposited snow, the deposition areas indicated by the difference of fluxes, the distance from the ridges and the time the air spends at each pixel by the given wind speed are calculated.

In the snow metamorphism submodule, the shape of the snow crystals is characterised by dendricity and sphericity. Empirical equations, based on the research results of Brun et al. (1989) are used to describe the change of these. For the description of grain size, empirical equations of Marbouty (1980) are used. The equations are mainly built up from the temperature gradient of the snowpack and the temperature of the given layer.

Weak layers are identified in the form of surface hoar and ice layers based on methods by McCuling et al. (1999) and COMET (2010), combined with our own empirical data. Depth hoar is taken into account in the snow metamorphism submodule.

3.2 Snowpack module

The snowpack module defines the most important characteristics of the snowpack by modelling the following processes: snow melt, snow settlement, snow transport by wind, snow crystal metamorphism and the formation of weak layers. The module produces snow layer height and density, grain size, grain dendricity and sphericity and ice and surface hoar rasters. Each snowfall or wind deposited snow, exceeding the height of 3 cm, creates a new layer with the above characteristics. These layers, which represent the features of the snow layers above each other, change according to the input weather and terrain parameters, simulating the temporal and spatial changes of the real snowpack.

For snowmelt modelling, we used the method from Walter et al. (2005) and Debele et al. (2009), calculating the energy balance of the snowpack. AvalMap’s snowpack module only calculates the snowmelt, if the energy balance of the snowpack is positive and the snow surface temperature is 0°C.

The settlement of snow is calculated based on the research done by Flerchinger & Saxton (1989) and McConkey (1992). As the old snow/new snow transition in these equations was not smooth and the results did not match with the results of other researchers, the settlement was too fast, the equations were modified based on the results of Steinkogler’s (2009) study.

Snow transport by wind mainly depends on the ratio of shear velocity, calculated by the logarithmic wind profile, to threshold shear velocity, calculated by a method modified from Liston et al. (2007). Flux, the potential carrying capacity of the wind, is calculated by an equation from Kind (1981), which is based on shear and threshold shear velocity. The difference of the fluxes are calculated for each pixel from the direction of the wind, to determine the amount of snow that could actually be carried away or deposited. Sublimation and densification in the carried snow are also considered. The amount of snow actually transported, depends on the temperature, height and density of the available snow layers. For the determination of the spatial distribution of wind deposited snow, the deposition areas indicated by the difference of fluxes, the distance from the ridges and the time the air spends at each pixel by the given wind speed are calculated.

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3.3 Terrain module

The effect of terrain on avalanche hazard is calculated by creating a variable from the horizontal curvature of the slope and the slope angle. The higher this value the higher the avalanche hazard, as the model already takes into account the reduced snow accumulation on steep slopes.

3.4 Land cover module

The land cover module, based on supervised classification of Landsat images and terrain factors, delineates the areas where the snow is able to slide by taking the anchoring effect of vegetation into account. Classes of land cover were unified based on their average height and a snowpack height limit was ordered to them. If the snowpack exceeds this limit, avalanches can slide, otherwise avalanche hazard is considered zero at the final hazard map.

3.5 Avalanche hazard module

Based on the results of the weather and snowpack modules, the avalanche risk module determines the strength of the bonding between the snow layers. From these values the model takes the highest value (weakest bonding) and determines the effects of weather parameters on avalanche risk in numbers.
Based on these two dynamic factors, and the terrain and land cover parameters, a map representing the avalanche risk according to the terrain, weather, snowpack and land cover conditions is created.

Bonding between two layers rasters are created when new layers are formed either through snowfall or wind deposition. It depends on temperature of snow surface and new snow, temperature change during snowfall, sphericity of upper layer, thickness of wind deposited snow layer, snowfall on surface hoar and on ice layer and depth hoar McClung et al. (1999).

AvalMap calculates the weather related avalanche risk from temperature change, high temperature, high incoming radiation, melting, mass of the new snow layers, and rain, based on McClung et al. (1999) and COMET (2010).

The final avalanche hazard raster is calculated by first normalizing the terrain hazard, the avalanche risk due to weather and the risk due to bonding strength to the same interval, and then multiplying them. Then this is further multiplied by the 1/0 value of the snowpack related land cover module

4. RESULTS AND DISCUSSION

Validation of the results was done by comparing the traditional snow profiles (2 profiles each week at different locations) with the results of the submodules at the date and location of the profiles. The comparison was quite challenging because of the differences in the parameters of the two methods.

The model shows good results in the following submodules: snow settlement, snow transport by wind, dendricity, terrain hazard, bonding related avalanche risk, weather related avalanche risk

The results show some errors in the following cases, so the submodules of these need to be improved: snow melt (about 30-60% overpredicted, especially on the southern sides), grain size and sphericity. At the moment energy balance equations are run for each layer. This is probably the cause of the overcalculated snow melt.

The results were also validated by studying the temporal change of snow layer heights at a chosen location, representing snow melt, snow settlement and snow transport by wind (Figure 2). The increase in height is the most intense on lee areas, if new snowfall and snow deposition by wind happens at the same day (arrow 1, 2). Significant winds deposit snow on lee areas and carry snow away from luv areas (arrow 3, 4). The density of freshly fallen, low-density layers increase quickly, especially if the temperature is high and new snow layers are formed by snowfall or are blown onto the former ones by wind, showing the results of snow settlement. The effect of snowmelt can best be seen in the time of spring warm weather (arrow 5).

Figure 2: Temporal distribution of snow layer heights at Chopok for the season 2009/2010. Bands of different colors show the heights of snow layers, red line shows the snow surface temperature.

Spatial distribution of the results was not validated due to the lack of validation data, but the results were studied if they “looked good”, like in case wind redistribution (Figure 3). Here, one can see that the northern wind carried away the snow from most of the luv sides and deposited it on the southern, lee sides, especially behind the ridges and in culois.

Figure 3: Snowpack height in case of 50 cm starting snowpack height and wind of 14.8 m/s and 10°at the peak station Chopok.

The final outcome of the model, the avalanche hazard was validated both spatially and temporally. The spatial distribution of the avalanche hazard values shows good matching with the active avalanche paths on the day of avalanches (Figure 4.). It also indicates high avalanche hazard in other avalanche paths with similar parameters, where no avalanches occurred.

The temporal distribution of the avalanche hazard was validated by first calculating an average of the avalanche hazard for the upper, grassy areas, and drawing it against the official avalanche forecast and the date of avalanches. The modelled curve well follows official forecast and defines the date of avalanches by peaks or sudden rising trends (Figure 5.). However, in some cases the model indicates high avalanche risk when there were no avalanches.
5. CONCLUSION AND FUTURE PLANS

AvalMap already shows promising results, however due to the complexity of the problem further improvements are already in progress in order to make the results even more accurate. In this new version of the code the following changes will be implemented: (1) the energy balance equations will be limited to the upper few cms in case of energy from the Sun and the lowest few cms in case of energy from the Earth to prevent the too fast melting. (2) The settlement equations will be changed in a way that the density of the layers can not only increase, but in case of high temperature gradients, decrease as well. (3) Grain size equations will be modified to speed up grain size change and different equations for wet snow will be used. (4) The calculation method for sphericity will be changed so the increase of sphericity will be slower. (5) Input data will be used as it comes from AWS (automatic weather stations), so no data preprocessing will be necessary. With these improvements we hope to achieve that the model can provide to be a useful tool in the future for avalanche professionals, providing an easy to understand numerical and visual aid in their decision making process.

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