CAN SCENARIO-BASED AVALANCHE DYNAMICS CALCULATIONS HELP IN THE DECISION MAKING PROCESS FOR ROAD CLOSURES?

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ABSTRACT: Temporary prevention measures such as closures and evacuation of endangered areas are important elements of the integral avalanche protection approach. They require assessing the avalanche hazard, which usually involves analyzing snow and weather data, avalanche occurrence and snowpack conditions in combination with local knowledge and experience. Predicting a probable avalanche runout is a main goal of such an evaluation. Combining avalanche dynamics calculations with (modelled) snow cover data along the path may help predicting avalanche runout. With recent advances in avalanche flow modelling, e.g. snow temperature dependent entrainment processes, this approach seems feasible. We chose the well-documented Salezertobel avalanche path (Davos, Switzerland) for an initial case study. We apply scenario-based avalanche dynamics calculations using different release and entrainment conditions (fracture depth, location and number of release areas, entrainment depth and snow temperature) to predict the potential runout. The simulation results vary strongly for the different scenarios, yet are plausible. They exemplarily show how the different variations in model input affect the runout distance. Further variations must be studied, e.g. different sizes of the release area, before a support tool for avalanche control services may become useful.

KEYWORDS: Avalanche dynamic, hazard evaluation, road closure.

1. INTRODUCTION

Knowing when to close a road is a difficult problem for many avalanche control services, especially when snow conditions are non-extreme. The main problem is to forecast avalanche runout distance under the given meteorological and snow cover conditions. It is often difficult to judge at what fracture depth d_0 a critical situation will arise. It is likewise difficult to assess how snow cover properties will affect avalanche flow. Moreover, snow conditions are almost never measured in the release area and along the track. Instead, study plot measurements, often from valley bottoms, are extrapolated to derive threshold values indicating a critical situation (e.g., Schweizer et al., 2009).

Avalanche runout is typically calculated with avalanche dynamics models in the context of hazard mapping where extreme scenarios with return periods of 30 to 300 years are considered (e.g., Bründl and Margreth, 2015). However, for scenarios with return periods of a few years, which typically need to be considered by avalanche control services when deciding on temporary preventive measures, it is unclear whether avalanche dynamics simulations can provide useful information since snow cover conditions must be considered. However, recent advances in process understanding and model development now allow considering snow temperature and its effect on snow entrainment (Vera Valero et al., 2015). In addition, snow cover simulation results have been linked with avalanche dynamics calculations to predict wet-snow avalanche runout (Vera Valero et al., 2018).

Our aim is therefore to perform avalanche dynamics calculations with the extended RAMMS model to identify how the snow and weather conditions affect avalanche runout. We chose the well-documented Salezertobel avalanche (Davos Switzerland) as an initial case study.

2. STUDY SITE

The Salezer avalanche path in Davos has been analyzed by Föhn and Meister (1982) and Schweizer et al. (2009). Between 1950 and 2018 avalanches are well-documented. Avalanches release at 2500 m asl and descend 940 m (vertical), reaching the main road to Davos at 1560 m asl. The return period of an avalanche reaching the road is about 5 years (Schweizer et al., 2009). Since 1984 the road is protected by an avalanche shed, but a winter hiking trail runs parallel to the shed and a parking lot is located directly below it. Snow entrainment and secondary avalanche releases are possible producing a wide range of runout distances. Out of 13 large avalanches to the road, 10 occured with new snow sums of >55 cm in Davos at 1560 m, mostly during a 2- to 4-day snowfall period. Of these, 5 avalanches started with a sum of new snow height >75 cm. Conversely, at least one avalanche hitting the road occurred with only

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Table 1: Fracture depths d_0 were determined according to the so-called guideline method (Burkard and Salm, 1992). It begins with measured new snow heights and modifies these values according to elevation, wind-blown snow and slope angle.

	Scenario 1 (cm)	Scenario 2 (cm)	Scenario 3 (cm)
New snow height at Davos 1560 m	40	60	80
Correction for elevation difference 1560 m → 2500 m	85	105	125
Correction for slope angle: cos(28°)	75	93	110
Including wind-blown snow (+ 15 – 25 cm)	90	110	135
Correction for 40°-slope (0.60)	54	66	81
Fracture depth d_0 for aval. calculations (best estimate)	**50**	**60**	**80**

40 cm of new snow. Schweizer et al. (2009) found a critical sum of new snow height between 55-60 cm as a good indication that an avalanche might reach the road. Critical new snow amounts should be considered as a first guess and always be adapted to the actual situation (Stoffel and Schweizer, 2008).

3. METHODS

The RAMMS model (Christen et al., 2010) with extensions for fluidization of the avalanche core (Buser and Bartelt, 2009; Buser and Bartelt, 2015), powder cloud formation (Bartelt et al., 2016) and thermal energy fluxes (Vera Valero et al., 2018; Vera Valero et al., 2015) was used to simulate the scenarios. The entrainment model is described in detail by Bartelt et al. (2018, this issue).

The scenarios combine three fracture depth (50 cm, 60 cm and 80 cm) with two different entrainment gradients and two temperature conditions (warm, cold). In addition, we considered also secondary avalanche releases. These results in a total of 24 scenarios, 8 for each fracture depth.

3.1 Avalanche release areas

A terrain slope angle analysis was used to define a primary release area at 2500 m and two secondary release areas at 2150 m. All terrain with slope between 30° and 50° was considered in the terrain analysis. The primary release area is a 39° slope (63,000 m^2). The secondary release areas are approximately 36° steep, each with an area of 50,000 m^2. Only the fracture depth d_0 varied in the simulation scenarios; the location and size of all three release areas did not change.

3.2 Fracture depth d_0 and entrainment conditions

In the following we make an assumption to define the fracture depth d_0 in the avalanche release area based on new snow amounts in Davos. The procedure of Table 1 is also used generally to define d_0 for avalanche dynamic calculations in Switzerland (Burkard and Salm, 1992), except that in the so-called guideline method the snow depth increase is considered instead of the new snow height. The result of this analysis was to define three fracture depths d_0 = 50 cm, d_0 = 60 cm and d_0 = 80 cm. These depths were also used to define the entrainment conditions. The snow entrainment depth d_Σ was set to these values at 2500 m. Two snow depth gradients were then used to reduce the snow depth with elevation: a "deep" snow cover with a small gradient (1 cm/100 m elevation change) and a "shallow" snow cover with a larger gradient (10 cm/100 m elevation change). The density of the eroded snow layer was ρ_Σ = 150 kg/m^3 for cold conditions and ρ_Σ = 200 kg/m^3 for warm conditions. We then specified two possible temperature regimes (cold, $T_\Sigma \leq$ -5°C and warm, T_Σ = -2°C). We do not consider wet flow regimes.

4. MODEL RESULTS

The discussion of the model results is divided into the three fracture depth scenarios, d_0 = 50 cm, d_0 = 60 cm and d_0 = 80 cm. A scenario is termed *critical* when the simulated avalanche reaches the road; a scenario is *non-critical* when the avalanche stops before reaching the road. In many cases only the simulated powder cloud reaches the road. This case is considered *critical* if the cloud has a pressure above 0.1 kPa.

4.1 Fracture depth d_0 = 50 cm

The simulations revealed only one critical scenario: when the avalanche entrains a deep, cold snow cover and triggers secondary releases (Fig. 1). All other scenarios are non-critical.

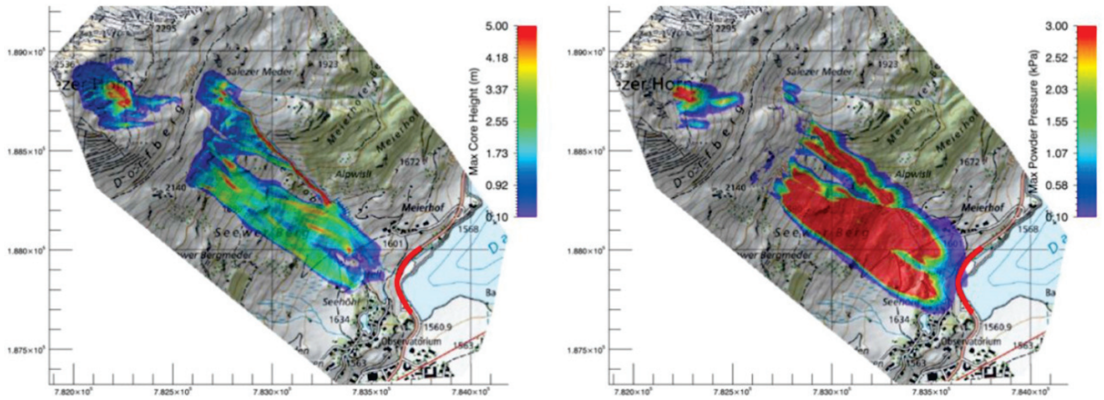

Figure 1: *Critical* scenario for fracture depth d_0 = 50 cm. The powder cloud of the avalanche reaches the road only when it entrains a cold, deep snow cover. The avalanche core stops before the road. Secondary releases are necessary. The figures depict the core height (left) and powder cloud impact pressures (right). The extent of the cloud is greater, but exerts pressures less than 0.1 kPa. The red line marks the road and the shed.

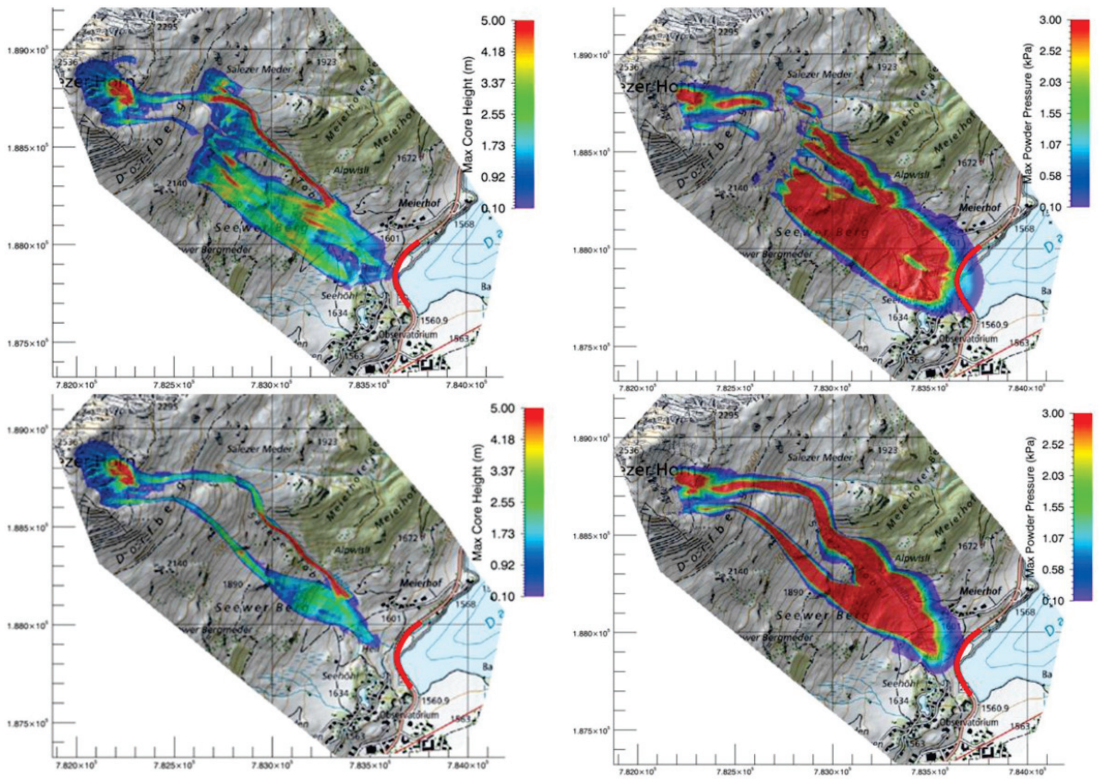

Figure 2: *Critical* scenario for d_0 = 60 cm. The powder cloud reaches the road when it entrains a cold, deep snow cover. With secondary releases both the avalanche core and cloud reach the road (top panel); without secondary releases only the cloud reaches the road (bottom panel).

4.2 Fracture depth d_0 = 60 cm

The simulations revealed two *critical* scenarios (Fig. 2): The powder cloud reaches the road when it entrains a cold, deep snow cover. With secondary releases both the avalanche core and cloud reach the road; without secondary releases only the cloud reaches the road. Two *non-critical* scenarios are shown in Fig. 3.

4.3 Fracture depth d_0 = 80 cm

We found only two *non-critical* simulations for the d_0 = 80 cm scenarios (Fig. 4). The first is the warm, shallow snow cover scenario. In this case the simulated avalanche core stopped 220 m above the road. The second is the warm, deep snow cover scenario. Both scenarios had no secondary releases. All other scenarios are *critical* but differ in the runout distance and lateral extent of the core and powder cloud (Fig. 5).

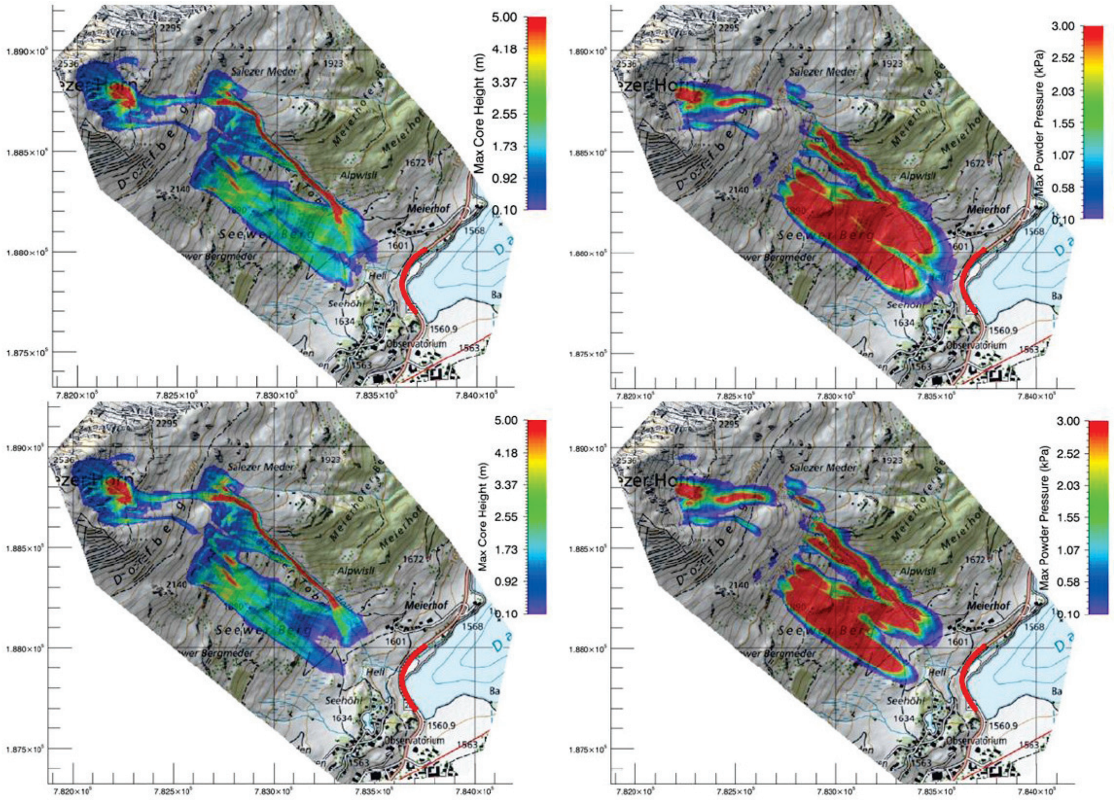

Figure 3: Examples of non-critical simulations for the d_0 = 60 cm scenario. Top: Warm, deep snow conditions, including secondary releases. Bottom: Cold, shallow snow cover, including secondary releases. Both scenarios stopped above the road (including powder cloud).

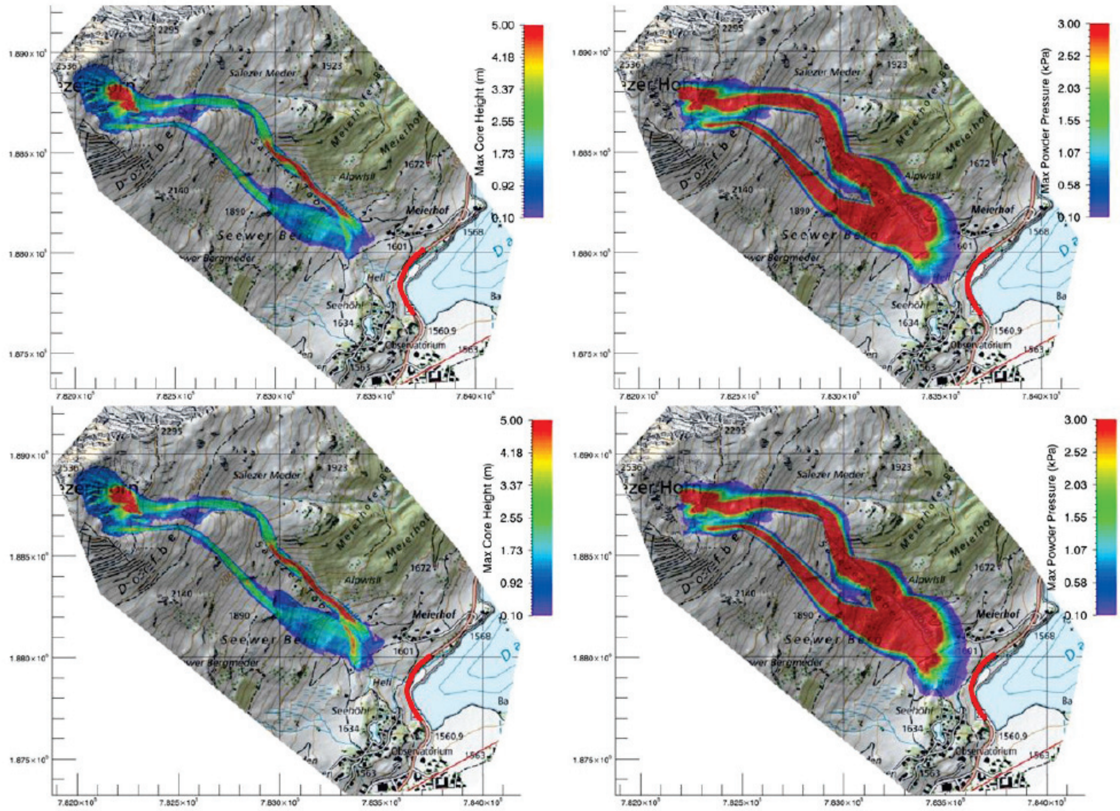

Figure 4: Non-critical simulations for the d_0 = 80 cm scenario. Avalanches stop above the road for warm snow covers (for both deep and shallow snow covers). Secondary releases make the warm, deep snow cover scenario critical.

5. DISCUSSION AND CONCLUSIONS

The calculated avalanche runout is strongly influenced by the selection of release depth d_0 and the release areas (with/without sec. release areas), entrainment and snow temperature (Table 2). The different scenarios of avalanche runout appear plausible. The calculations with a release depth d_0 = 50 cm indicate that a powder avalanche will reach the road only under extreme conditions (cold, much snow entrainment, secondary releases). The calculations with d_0 = 60 cm show also that both cold conditions and avalanche mass growth by entrainment are required for avalanches hitting the road. For the d_0 = 80 cm only two scenarios were evaluated as non-critical (warm conditions, no secondary release, little or much snow entrainment). The possibility of secondary releases will therefore cause the evaluation to move from *non-critical* to *critical*.

We emphasize that the fracture depth d_0 is the average value of the whole release area (observed crown heights can be larger). Moreover, estimating the fracture depth d_0 from flat field measurements (e.g. automatic weather stations) may contain considerable uncertainty.

We only considered a limited number of scenarios. Further scenarios should include the variation of the following parameters. At present we considered only the release of new snow. How the additional release of old snow layers can be introduced into the procedure should be evaluated. The old snow cover should also be considered for snow entrainment, as presently only new snow was eroded. Finally, variations of the starting zone size should also be studied in a next step.

Once many more different simulations exist a probabilistic forecast could become possible – as is common today in weather forecasting. However, how to interpret this kind of forecasts in decisions when lives are at stake is far from straightforward. Moreover, the use of scenario-based avalanche dynamics calculations requires avalanche control services to approximately identify snow cover conditions and avalanche flow regime, which might not always be possible. In the future, numerical snow cover modeling might provide this input (Vera Valero et al. 2018). Finally, a model chain linking a numerical weather prediction model to a snow cover model to provide input for avalanche dynamics calculations would in principal allow assessing the avalanche hazard due to large avalanches based on currently prevailing snow and weather conditions, also called dynamic hazard mapping.

REFERENCES

Bartelt, P., Christen, M., Bühler, Y., Caviezel, A. and Buser, O., 2018. Snow entrainment: Avalanche interaction with an erodible substrate, Proceedings ISSW 2018. International Snow Science Workshop, Innsbruck, Austria, 7-12 October 2018.

Bartelt, P., Buser, O., Vera Valero, C. and Bühler, Y., 2016. Configurational energy and the formation of mixed flowing/powder snow and ice avalanches. Ann. Glaciol., 57(71): 179-188.

Bründl, M. and Margreth, S., 2015. Integrative risk management: The example of snow avalanches. In: W. Haeberli and C. Whiteman (Editors), Snow and Ice-Related Hazards, Risks and Disasters. Hazards and Disaster Series. Elsevier, Amsterdam, Netherlands, pp. 263-301.

Burkard, A. and Salm, B., 1992. Die Bestimmung der mittleren Anrissmächtigkeit d_0 zur Berechnung von Fliesslawinen. Eidg. Institut für Schnee- und Lawinenforschung, Interner Bericht Nr. 668: 16 pp.

Buser, O. and Bartelt, P., 2009. Production and decay of random kinetic energy in granular snow avalanches. J. Glaciol., 55(189): 3-12.

Buser, O. and Bartelt, P., 2015. An energy-based method to calculate streamwise density variations in snow avalanches. J. Glaciol., 61(227): 563-575.

Christen, M., Kowalski, J. and Bartelt, P., 2010. RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. Cold Reg. Sci. Technol., 63(1-2): 1-14.

Föhn, P. and Meister, R., 1982. Determination of avalanche magnitude and frequency by direct observations and/or with aid of indirect snowcover data, Proceedings IUFRO/FAO colloquium on research on small torrential watersheds (incl. avalanches), Grenoble, France, June 1981. Mitteilungen der forstlichen Bundesversuchs-anstalt, Vienna, Austria, Vol. 144, pp. 207-228.

Schweizer, J., Mitterer, C. and Stoffel, L., 2009. On forecasting large and infrequent snow avalanches. Cold Reg. Sci. Technol., 59(2-3): 234-241.

Stoffel, L. and Schweizer, J., 2008. Guidelines for avalanche control services: organization, hazard assessment and documentation – an example from Switzerland. In: C. Campbell, S. Conger and P. Haegeli (Editors), Proceedings ISSW 2008. International Snow Science Workshop, Whistler, Canada, 21-27 September 2008, pp. 483-489.

Vera Valero, C., Wever, N., Christen, M. and Bartelt, P., 2018. Modeling the influence of snow cover temperature and water content on wet-snow avalanche runout. Nat. Hazards Earth Syst. Sci., 18(3): 869-887.

Vera Valero, C., Wikstroem, J., K., Bühler, Y. and Bartelt, P., 2015. Release temperature, snow cover entrainment and the thermal flow regime of snow avalanches. J. Glaciol., 61(225): 173-184.

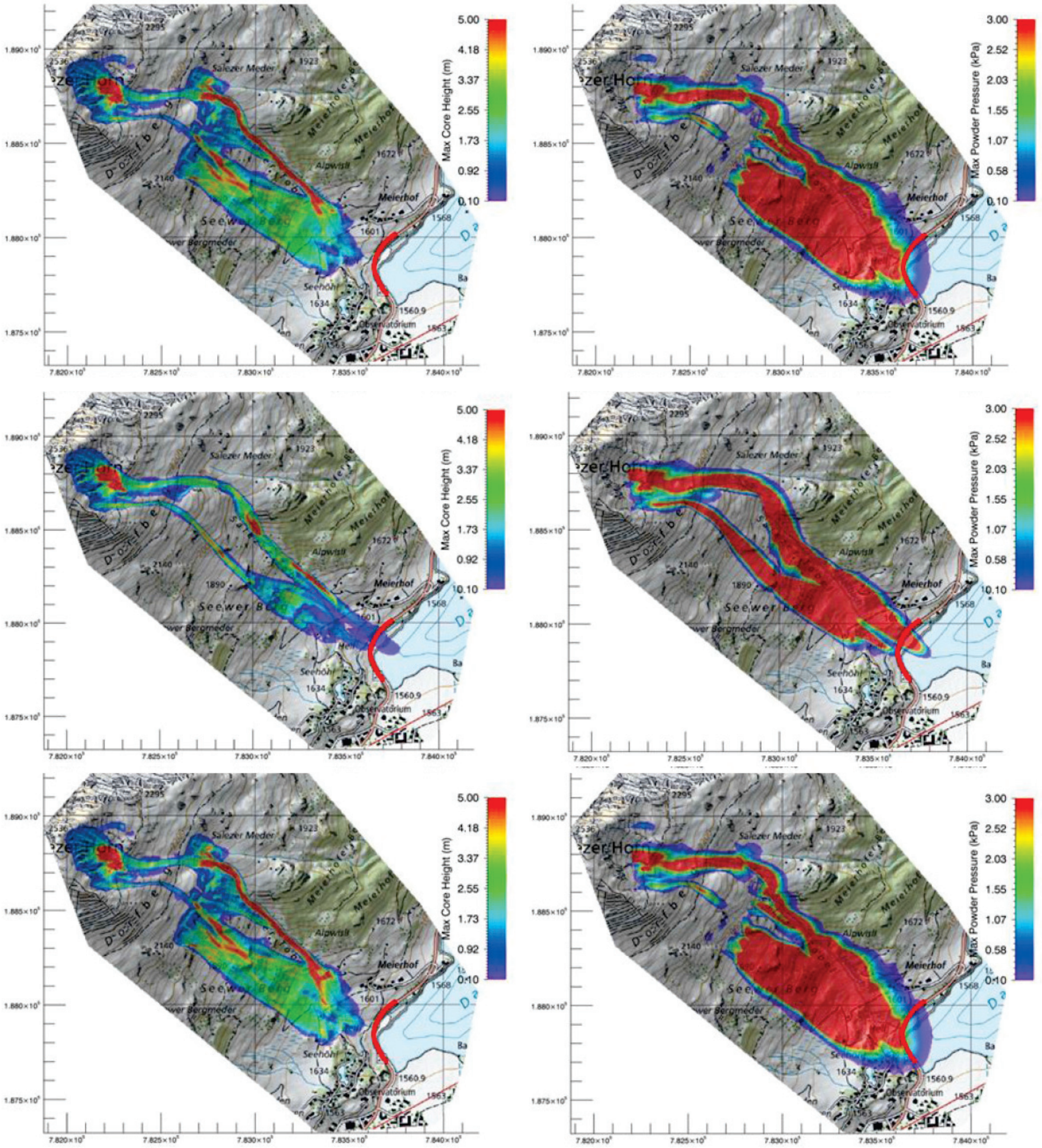

Figure 5: Examples of critical simulations for the d_0 = 80 cm scenario. Top: warm, shallow snow cover including secondary releases. Middle: cold, shallow snow cover, without secondary releases. Bottom: warm, deep snow cover, including secondary releases.

Table 2: Overview of the evaluated scenarios according to the simulations. Red = *critical* avalanche situation for the road. Green = *non-critical* avalanche situation for the road.

New snow height at Davos	Fracture depth d_0	Release areas	Deep snow cover		Shallow snow cover	
			Cold	warm	cold	warm
approx. 40 cm	50 cm	Top+sec. areas				
		Top				
approx. 60 cm	60 cm	Top+sec. areas				
		Top				
approx. 80 cm	80 cm	Top+sec. areas				
		Top				