Response to Reviewer #1 Author: Cesar Vera Valero
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Response to Reviewer # 1

We sincerely thank reviewer # 1 for his helpful suggestions to improve the quality of the paper. The reviewer has suggested the following points to improve:

Reviewer: As is also pointed out in the Abstract of this manuscript, the wet snow avalanches are getting more important as the global warming is in progress. Based on this background, in this manuscript, the authors applied the avalanche model developed in Switzerland for the wet snow avalanches broke out in Chilean Andes. However, I do have got a feeling that it is nothing more than that. Thus I unfortunately came to the conclusion that this manuscript is not matured yet for the publication. Particularly, no new findings are specified in the discussion part.

Response: The paper presents several new findings:

1. The new model accounts for a) the initial temperature and temperature rise due to dissipation and entrainment of warm snow b) meltwater production and c) lubrication. Clearly, the model is not yet finished because it uses only mean values and empirical relations, but the inclusion of these effects is a step forward in avalanche modelling.

2. The simulated avalanches have very small release volumes and are dominated by entrainment processes. This is a particular feature of wet, point release avalanches in Chile and elsewhere. It is presently unknown how well avalanche dynamics models can simulate small avalanches.

3. If accurate information of the snowcover is available (temperature, density, water content) then it is possible to simulate these small point release avalanches. This is, in our opinion, both novel and surprising.

Reviewer: Although the RAMMS already has had established reputation, I am not sure the wet snow version of the model utilized in this simulation also has enough power to reproduce the wet snow avalanches in a high accuracy. I am wondering that all the specific processes related to the wet snow avalanches, such as the liquid water production, its effect on the fluidization of snow, further, the lubricant effect on the basal and turbulent frictions, are all taken into account precisely and verified satisfactory with the real avalanches. Are the equations of 6 and 7 in page 5 accurate enough to describe the phenomena in nature? Even though it is the case, description of the model is too short and, thus, it is hard to recognize even the principle. Perhaps all the procedures are mentioned in the reference line by line, but more explanations are essential. Otherwise, all the reader will be frustrated.

Response: We agree with the reviewer that the explanations about specific wet snow avalanche features were brief in the first manuscript. We have rewritten the whole model section (see below at the rewritten section in this letter). It was not the aim of the current manuscript to review the current RAMMS model (Vera et al., 2015). The goal of this paper was to do exactly what the reviewer recommends: demonstrate the model can reproduce documented avalanche events. We gladly rewrote the modeling section, so the reader will not become frustrated.

Reviewer: Actually, the model outputs the physical properties of the wet snow avalanches and its development along the path. Then, the temperatures, water production, avalanche flowing volume and the ratio to the initial ones are introduced in figures 7 to 9. However, mostly no data were obtained for the four exemplified avalanches to verify the simulation, except for the run-out distances and the roughly estimated volumes of debris. Thus, all the simulation outputs shown in figures 7 to 9 are merely illustrating a meaningless row of numbers. How do you determine the initial snow depth on the avalanche track?

Response: The quantitative information is much better than casual observations. We have (1) meteo-information from nearby automatic weather stations (2) GPS measurements for mass balance/entrainment (3) snowpits in the release zone and deposition zones (4) measurements of deposits (width, runout, height, granulometry). The quantitative information that is missing are avalanche flow velocities. In the paper we included a new figure (fig 2) with the GPS points taken during the field campaigns and we clarified the methods used to perform these measurements . In two of the avalanches the terrain was too steep and too dangerous to enter. However, measurements of deposition heights and perimeter were performed in the runout zone; entrainment depths were measured. Refrozen melt forms on the sliding surface were identified. Furthermore, low quality videos of the event were used to constrain the flow velocities.

Snow depth erosion was measured in a few points at the release area and in the avalanche path for the case studies BN-1 and LGW-2 (see in the current manuscript section 'Initial and boundary conditions: point release areas') For the cases CCHN-3 and CG-1 the highly alpine terrain and the mine regulations prevent us to reach the release area although we performed measurements at the very low part of the avalanche track and on accessible slopes. The erosion depths were estimated from these direct measurements, SNOWPACK was used to calculated the snow temperature, density and water content. Nonetheless, the reviewer is completely right about the lack of field measurements during the time the avalanche occurs concerning flowing temperature and melt water production (the road was closed at the time the avalanches occurred, and currently it is not possible to get data from snow flowing temperature and water content even in real scale avalanche test sites). Since this field campaigns were performed on a industrial mining road it was not possible to perform direct measurements when the avalanche occurs. We amend the paper by including the data available about the snow cover at the release areas and in the run outs (added into the table 2 and in 'Initial and boundary conditions: point release areas' section). We believe this will better support one of the key conclusions of the paper: the model was able to simulate run out distances and volumes at the deposits when constrained with additional input data (temperature, snow density, water content). Additionally, using different temperature/water content inputs in the release area, the avalanche simulations stopped immediately without developing into a wet snow avalanche. In accordance with the reviewers suggestions, we emphasize this point in the discussions (see the rewritten Discussion section below). We cannot ensure that the calculated velocities are correct in all cases, but at least in one case we have video information. In summary, we did our best to gather as much relevant information as possible. Often, however, safety concerns prevented us from obtaining more detailed information. We agree with the reviewer that more work is necessary about the relations between friction, fluidization and lubrication processes with snow temperature and water content, at the moment only the empirical relationships published in (Vera, 2015) are used.

Reviewer: : It looks far from uniform according to the figures in the manuscript strongly depending on the topography. As you see, the re-distribution of snow by the wind will be the key issue. Needless to say, initial snow depth distribution gives the strong effect not only on the basal friction but on the erosion mass. I wonder the authors introduced ARPS as well as SNOWPACK models, and utilized to estimate the initial snow depth distribution. If it is not included in the initial condition, the following calculation sounds meaningless.

Response: As the reviewer points out the wind can certainly be a strong point in case of dry cold slab avalanches. But the cases simulated in the current manuscript were completely wet, warm snow. The fact that the wind redistributes the snow cover has nothing to do with the amount of snow was eroded on those four cases. The eroded snow was measured and did not reach more than 40 cm in all cases. Perhaps the fact that 2-3 days before the avalanches, snowfall occurred might lead the reviewer to think that wind is important. In our case we give the model the erosion depth as an input, so the total snow depth wind affected or not is not important for us.

Reviewer: : As you see, snow properties, such as dry or wet, are far from satisfactory. Further, although this article sets on the focus on the point release avalanches, consequently, no specific differences were found among four avalanches and the point release does not give distinctive effect on the avalanche dynamics. So I am not sure the title of this manuscript is suitable or it still has room for improvement. Well, to say the least, the approach introduced here may be useful for the practitioners. However, the descriptions of the avalanche releasing mechanism, that is much more direct and necessary information for them, is not involved in this manuscript. That sounds very inconsistent.

Response: Yes, the goal of this paper is provide practitioners with a tool to help them predict the runout of small avalanches, which is vital for mining operations. Our goal was not to discuss possible release mechanism, rather to answer the question: if the avalanche goes, how far will it go? This is for the mining operations a central question. A paper concerning the mechanics of wet snow avalanche release is outside the scope of this paper. The title was chosen to suggest that only wet point release snow avalanches were simulated. Maybe Simulating wet snow point release avalanches fits better. We agree with the reviewer there is room for improvement.

Reviewer: Since the SNOWPACK model is utilized in this approach, authors must be able to issue the warning from this aspect as well. Thus, I have an impression that this manuscript will be fairly well if it is submitted as something like a short note. However, if the authors are willing to submit the article as a scientific paper, the quality needs to be improved much more to make it worthy of. In particular, discussion part should be expanded further.

Response: Initially the manuscript was written with one unique Discussions and Conclusions section. The editor in a minor revision kindly asked us to split this part in two, according to the Journal guidelines. We tried to keep the manuscript short and concise. We wanted to present how wet snow point release avalanches can be simulated but considering the reviewer enquiry we agree on extend the discussion part giving more explanations of the model strong and weak points, (see the rewritten sections below).

Comments by lines:

Reviewer: Is there a specific reason why 2m grid size was set in the simulation in spite the 1m resolution of DEM was available?

Response: It was a mistake on the text the available DEM resolution is 2 m. It has been corrected now in the manuscript.

Reviewer: : In this model only the wet snow were eroded and not the dry ones. Although it looks quite rough assumption, is this reasonable and verified with the four avalanches here or previously?

Response: The eroded snow was measured in the field when possible (BN-1 , LGW-2) when not (CCHN-3 and CG-1) from accessible slopes and SNOWPACK simulations (Page 13 lines 24-25 from the current manuscript). The field observations showed that only wet snow was eroded and not dry snow and this how we simulated them.

Reviewer: Table 2: It looks like the simulation parameters shown in Table 2 seem to be set arbitrarily not physically, such as Cohesion C. Please describe the reason how each values were chosen.

Response : We measured cohesion values in our experimental chute (Bartelt et al., 2015); these values were used in the simulations. We have added an explanation in the discussion concerning the selection of each model parameter.

Reviewer: Further, I am a bit anxious whether the depth-averaged shallow water equation model is able to describe the avalanche motion precisely on the steep clip as is shown in the figures

Response : Yes, we are concerned too. Shallow water theory is based on mild slope changes. However, in the case of this paper the cliffs are not completely vertical and they are rather short. The shallow water approximation does not appear to be too bad, yet we have no direct measurements to assess the error (if any) we are making. However depth-averaged shallow water equations have been extensively used [Christen et al., 2010, Sampl et al., 2004, Sheridan et al., 2005, Mergili et al., 2012] in avalanches modeling.

Rewritten sections included in the reviewed manuscript

Rewritten modeling section:

To model wet snow avalanches in general three-dimensional terrain we extend the depth-averaged model equations of [Christen et al., 2010] to include streamwise density variations [Buser and Bartelt, 2015] and thermal effects [Vera et al., 2015]. In this model avalanche flow is described by nine state variables:

$$\mathbf{U}_\Phi = (M_\Phi, M_\Phi u_\Phi, M_\Phi v_\Phi, Rh_\Phi, Eh_\Phi, h_\Phi, M_\Phi w_\Phi, N_K, M_w)^T. \quad (1)$$

M_Φ denotes the total mass (per unit area) of the avalanche core, including both snow and meltwater. The meltwater mass is tracked separately and denoted M_w. When M_w=0, the avalanche is termed 'dry'; 'wet' flows occur when $M_w > 0$. The mass of water is always bonded to the moving snow which is moving in the slope parallel direction with velocity $=(u_\Phi\ ,\ v_\Phi)^T$. The flow height of the avalanche is designated h_Φ. The model equations can be conveniently written as a vector equation:

$$\frac{\partial \mathbf{U}_\Phi}{\partial t} + \frac{\partial \boldsymbol{\Phi}_x}{\partial x} + \frac{\partial \boldsymbol{\Phi}_y}{\partial y} = \mathbf{G}_\Phi \tag{2}$$

where the flux components ($\boldsymbol{\Phi}_x$, $\boldsymbol{\Phi}_y$) are:

$$\boldsymbol{\Phi}_x = \begin{pmatrix} M_\Phi u_\Phi \\ M_\Phi u_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\ M_\Phi u_\Phi v_\Phi \\ R h_\Phi u_\Phi \\ E h_\Phi u_\Phi \\ h_\Phi u_\Phi \\ M_\Phi w_\Phi u_\Phi \\ N_K u_\Phi \\ M_w u_\Phi \end{pmatrix}, \ \boldsymbol{\Phi}_y = \begin{pmatrix} M_\Phi v_\Phi \\ M_\Phi u_\Phi v_\Phi \\ M_\Phi v_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\ R h_\Phi v_\Phi \\ E h_\Phi v_\Phi \\ h_\Phi v_\Phi \\ M_\Phi w_\Phi v_\Phi \\ N_K v_\Phi \\ M_w v_\Phi \end{pmatrix} \tag{3}$$

and

$$\mathbf{G}_\Phi = \begin{pmatrix} \dot{M}_{\Sigma\to\Phi} \\ G_x - S_{\Phi x} \\ G_y - S_{\Phi y} \\ \dot{P} \\ \dot{Q} + \dot{Q}_{\Sigma\to\Phi} + \dot{Q}_w \\ w_\Phi \\ N_K \\ 2\gamma\dot{P} - 2N w_\Phi / h_\Phi \\ \dot{M}_{\Sigma\to w} + \dot{M}_w \end{pmatrix}. \tag{4}$$

The mathematical description of mountain terrain is defined using a horizontal X-Y coordinate system. The elevation $Z(X, Y)$ is specified for each (X, Y) coordinate pair. We introduce a local surface (x, y, z) coordinate system with the directions x and y parallel to the metric geographic coordinates X and Y. The grid of geographic coordinates defines inclined planes with known orientation; the z-direction is defined perpendicular to the local x-y plane. The flowing avalanche is driven by the gravitational acceleration in the tangential directions $\mathbf{G} = (G_x, G_y) = (M_\Phi g_x, M_\Phi g_y)$. The acceleration in the slope perpendicular direction is denoted g' and is composed of gravity g, dispersive N_K [Buser and Bartelt, 2015] and centripetal accelerations f, [Fischer et al., 2012]. The total normal stress at the base of the avalanche is given by $N = M_\Phi g'$.

$$g' = g + N_K + f \tag{5}$$

The model extension includes the explicit calculation of the depth-averaged free mechanical energy R [Bartelt et al., 2006, Buser and Bartelt, 2009]. The mechanical free energy of the avalanche is partitioned into two parts, see [Buser and Bartelt, 2015]

$$R = R_K + R_V \tag{6}$$

where R_K is the kinetic energy associated with random particle movements and R_V is the potential or configurational energy associated with expansion of the avalanche core, defined by the height h_Φ. Shearing in the avalanche core induces particle interactions that create a dispersive pressure N_K at the basal boundary which leads to fluidization of the avalanche core and streamwise variations of avalanche flow density, ρ_Φ. The production of free mechanical energy $\dot{P}$ is given by an equation containing two model parameters: the production parameter α and the decay parameter β, see [Buser and Bartelt, 2009]

$$\dot{P} = \alpha \left[\mathbf{S}_{\Phi} \cdot \mathbf{u}_{\Phi} \right] - \beta R_K h_{\Phi}. \tag{7}$$

The production parameter α defines the generation of free mechanical energy from the shear work rate $[\mathbf{S}_{\Phi} \cdot \mathbf{u}_{\Phi}]$; the parameter β defines the decrease of the kinetic part R_K by inelastic interactions. In this model formulation the basal boundary plays a prominant role because particle motions in the slope-perpendicular motion are inhibited and reflected back into the flow. The basal boundary converts the production of random kinetic energy into an energy flux that changes the z-location of particles and therefore the potential energy and particle configuration within the avalanche core. The energy flux associated with the configurational changes is denoted $\dot{P}_V$ and given by

$$\dot{P}_V = \gamma \dot{P}. \tag{8}$$

The parameter γ therefore determines the magnitude of the dilitation of the flow volume under a shearing action. When $\gamma = 0$ there is no volume expansion by shearing. Therefore, the model formulation we apply allows the simulation of both disperse and dense avalanche flow types. In this paper we are primarily concerned with dense, plug-like wet snow avalanche movements ($R_V \approx 0$); however, as we shall see in the case studies, even wet flows fluidize in steep, rough terrain ($R_V > 0$, $\gamma > 0$). The production α, decay β parameters, which control the degree of the flow dilitation will be discussed in the next section when discussing wet snow avalanche flow rheology. The model extension also includes the explicit calculation of the depth-averaged avalanche temperature T [Vera et al., 2015]. The temperature T is related to the internal heat energy E by the specific heat capacity of snow c

$$E = \rho_{\Phi} c T. \tag{9}$$

The avalanche temperature is governed by (1) the initial temperature of the snow T_0, (2) dissipation of kinetic energy by shearing $\dot{Q}$, as well as (3) thermal energy input from entrained snow $\dot{Q}_{\Sigma \to \Phi}$ and (4) latent heat effects from phase changes $\dot{Q}_w$ (meltwater production), see [Vera et al., 2015]. Dissipation is the part of the shear work not going to free mechanical energy in addition to the inelastic interactions between particles (decay of random kinetic energy, R_K)

$$\dot{Q} = (1 - \alpha) \left[\mathbf{S}_{\Phi} \cdot \mathbf{u}_{\Phi} \right] + \beta R_K h_{\Phi}. \tag{10}$$

The model equations are solved using the same numerical schemes outlined in [Christen et al., 2010].

0.1 Entrainment of warm, moist snow

We treat the entrainment of warm, moist snow as a fully plastic collision between the avalanche core Φ and snow cover Σ. Snow with temperature T_{Σ} is entrained at the rate $\dot{M}_{\Sigma \to \Phi}$. The entrained snow is initially at rest, but after the collision with the avalanche all the entrained mass is moving with the avalanche velocity $\mathbf{u}_{\mathbf{\Phi}}$ (definition of plastic collision). If the entrained snow is moist, water mass, in addition to the snow mass, is entrained at the rate $\dot{M}_{\Sigma \to w}$. The water mass is always at temperature $T_w = 0^{\circ}$ C. The total entrainment rate is defined by the (1) density of the snowcover ρ_{Σ}, (2) the dimensionless erodibility coefficient κ and (3) the avalanche velocity, [Christen et al., 2010]:

$$\dot{M}_{\Sigma \to \Phi} = \rho_{\Sigma} \kappa \left\| \mathbf{u}_{\Phi} \right\| \tag{11}$$

The entrained water mass is found from the volumetric water content of the undisturbed snow-cover, θ_w:

$$\dot{M}_{\Sigma\to w} = \theta_w \dot{M}_{\Sigma\to\Phi}. \tag{12}$$

The thermal energy entrained by the avalanche is therefore

$$\dot{Q}_{\Sigma\to\Phi} = [(1-\theta_w)c_\Sigma T_\Sigma + \theta_w c_w T_w]\,\dot{M}_{\Sigma\to\Phi} + \frac{1}{2}\dot{M}_{\Sigma\to\Phi}\,\|\mathbf{u}_\Phi\|^2 . \tag{13}$$

where c_Σ is the mass heat capacity of dry snow and c_w is the mass heat capacity of water. The last term in this equation represents the heat produced during the plastic collision. In this entrainment model no random kinetic energy is generated during the entrainment process because of the entrainment process is considered completely inelastic.

0.2 Wet snow avalanche flow rheology

Wet snow avalanches are regarded as dense granular flows in the frictional flow regime [Bozhinskiy and Losev, 19 Measured velocity profiles exhibit pronounced visco-plastic like character and are often modelled with a Bingham-type flow rheology [Dent and Lang, 1983, Dent et al., 1998, Bartelt et al., 2005, Kern et al., 2009]. Granules in wet-avalanche flows are large, heavy and poorly sorted in comparison to granules in dry avalanches [Jomelli and Bertran, 2001, Bartelt and McArdell, 2009]. Sintered particle agglomerates and levee constructions with steep vertical shear planes are found in wet snow avalanche deposits, indicating that cohesive processes are an important element of wet snow avalanche rheology [Bartelt et al., 2012c, Bartelt et al., 2015]. To model wet snow avalanche flow we apply a Voellmy rheology with cohesion. Frictional resistance is given by a Voellmy-type shear stress $\mathbf{S}_\Phi = (S_{\Phi x}, S_{\Phi y})$, containing Coulomb stress S_μ (coefficient μ) and velocity dependent stress S_ξ (coefficient ξ):

$$\mathbf{S}_\Phi = \frac{\mathbf{u}_\Phi}{\|\mathbf{u}\|_\Phi}\left[S_\mu + S_\xi\right]. \tag{14}$$

For wet snow avalanche flow, the Coulomb shear stress is modified to include the cohesion, parameterized by the coefficient N_0, see [Bartelt et al., 2015]:

$$S_\mu = \mu(R_V)N - [1-\mu(R_V)]\,N_0 \exp\left[-\frac{N}{N_0}\right] + [1.0-\mu(R_V)]\,N_0. \tag{15}$$

Note that when N_0=0 and the standard Coulomb friction of the Voellmy model is retrieved: $S_\mu = \mu(R_V)N$. Experiments with flowing snow have identified cohesion values for wet snow to be as low as $N_0 = 100$ Pa, but never exceeding $N_0 = 2000$ Pa [Bartelt et al., 2015]. The speed dependent stress of the Voellmy friction model is

$$S_\xi = \rho_\Phi g \frac{\|\mathbf{u}\|_\Phi{}^2}{\xi(R_V)}. \tag{16}$$

We define the functional dependency of the friction parameters (μ, ξ) on the configurational energy R_V and cohesion N_0 as

$$\mu(R_V) = \mu_d \exp\left[-\frac{R_V}{N_0 + R_0}\right] \tag{17}$$

and

$$\xi(R_V) = \xi_d \exp\left[\frac{R_V}{N_0 + R_0}\right]. \tag{18}$$

With this frictional model μ_d and ξ_d are the static friction coefficients associated with dry, non-fluidized flowing snow, R_V=0. The parameter R_0 defines the decrease in shear stress with increasing fluidization (lower flow density), see [Bartelt et al., 2012a]. Snow temperature and wetness have a strong influence on the mechanical properties of snow and therefore the amount of free mechanical energy in the avalanche. The primary difference between wet and dry flows is the production and dissipation of free mechanical energy, which controls the fluidization of the avalanche core. When the avalanche snow contains some free water, the hardness of the granules decreases [Voytokskiy, 1977], and they can be plastically deformed and sculptured into well-rounded forms [Bozhinskiy and Losev, 1998]. We model this effect by using production coefficients $\alpha \geq 0.05$ and large free mechanical energy decay coefficients $\beta = 1.0$ for wet snow. This ensures that only in very rough and steep terrain is fluidization of the wet avalanche core possible.

0.3 Meltwater production and lubrication

In wet snow avalanche flow, we must consider two additional physical processes: (1) the production of meltwater $\dot{M}_w$ and (2) the decrease of Coulomb shear stress because of meltwater lubrication. Meltwater production is considered as a constraint on the flow temperature of the avalanche: the mean flow temperature T can never exceed the melting temperature of ice T_m = 273° K. The energy for the phase change is given by the latent heat L

$$\dot{Q}_w = L\dot{M}_w \tag{19}$$

under the thermal constraint that within a time increment Δt

$$\int_0^{\Delta t} \dot{Q}_w dt = M_\Phi c(T - T_m) \qquad \text{for} \qquad T > T_m. \tag{20}$$

Of course, when the flow temperature of the avalanche does not exceed the melting temperature, no latent heat is produced $\dot{Q}_w = 0$. The length of the time increment is defined by the numerical time integration scheme of the vector equations. Because we employ a depth-averaged model to calculate the bulk avalanche temperature T we have no information to define the depth in the avalanche flow core where melting occurs. The dissipation rate $\dot{Q}_w$ depends on the internal shear distribution, which can be concentrated at the bottom surface of the avalanche, or distributed uniformly over the entire avalanche flow height. The spatial concentration of meltwater will therefore determine how the meltwater lubricates the flow. To account for the spatial distribution of meltwater in a depth-averaged model, we use the following two-parameter lubrication function to replace the dry Coulomb friction coefficient μ_d,

$$\mu(h_w, R_V) = \mu_s + (\mu_d - \mu_s)\exp\left[-\frac{h_w}{h_m}\right]. \tag{21}$$

The amount of meltwater in the avalanche core is characterized by the height h_w defined with respect to the density of water $M_w = \rho_w h_w$. This height (measured from the avalanche running surface) is compared to the height h_m, representing the height where the meltwater is concentrated. We approximate the height h_m using measured shear layers of wet avalanche flows which show 0.01 m $\leq h_m \leq$ 0.1 m, see [Dent and Lang, 1983, Dent et al., 1998, Bartelt et al., 2005, Kern et al., 2009]. The parameter μ_s defines the Coulomb friction when the layer h_0 is saturated, $h_w \approx h_m$. We take $\mu_s = 0.12$. This ensures that dense, non-fluidized wet snow avalanches will not stop on slopes greater than 9° when they contain fully saturaled lubrication layers, $\mu(h_w, R_V) \approx 0.15$ for $h_w = h_m$.

0.4 Initial and boundary conditions: point release areas

The initial release volume V_0 is calculated by estimating a release area A_0 and a mean fracture depth h_0. This is somewhat difficult for point release avalanches because the area is reduced to a single point with no surface area. In this work, point release avalanches are specified by defining a small triangular shaped release area where the upper apex of the triangle is located at the point release. The triangle together with the fracture height defines the initial release volume .

Fracture depth, erosion depths, surface eroded and snow properties along the avalanche paths were estimated from snow cover observations and meteorological data. The Codelco Andina mine has automatic weather stations which provide air temperature, snow surface temperature, pressure, wind, precipitation and radiation measurements. The meteorological data was used to run SNOWPACK simulations [Bartelt , 2002, Lehning et al., 2002] to define the release temperature, density and initial snowcover water content. Coupled with the field studies performed by the winter operation crew, provides accurate snow cover information. The distance between the chosen automatic weather station and the avalanches paths varies between 0.5 km and almost 4.0 km. The release areas in the case studies were between 3085 and 3600 m.a.s.l.; the used weather station is located at 3570 m.a.s.l. The small elevation difference between the release zones and the automatic weather station ensures accuracy in snow and meteorological data. However, snow surface temperature and surface energy fluxes might be influenced by the slope exposition. SNOWPACK allows the user to generate virtual slopes, specifying slope angle and exposition and coupling the measured meteorological and snow data to the virtual slopes [Bartelt , 2002, Lehning et al., 2002]. Meteorological data from the winter operation building at the valley bottom (Lagunitas building 2700 m.a.s.l.) is available. Thus, it was possible to estimate the precipitation and temperature gradients existing between the weather station location and the winter operation building and therefore to estimate the snow cover conditions along the selected avalanche paths. To estimate the fracture and erosion depths for each case study we considered field work measurements and the data provide from the automatic weather stations and the SNOWPACK simulations. The remaining snow input parameters are snow temperature, snow water content and snow density. These were specified directly using SNOWPACK simulations using the meteorological and snow data collected from the automatic weather station.

Rewritten Discussion

Many existing avalanche dynamics models widely used in practice (e.g. [Christen et al., 2010, Sampl et al., 2004, Sheridan et al., 2005, Mergili et al., 2012]) do not include the role thermal temperature, fluidization or snow wetness in their mechanical description of avalanche motion. As such, wide ranging flow parameters are required to model avalanche runout and danger. These models therefore cannot be applied to forecast how avalanche activity will disrupt mining operations because they cannot take into account measured and observed snow conditions. Road closure is associated with severe financial costs and avalanche forecasters must deliver runout warnings based on daily, perhaps hourly, meteorological information.

To address this problem we developed a depth-averaged avalanche dynamics model that separates the properties of flowing snow from the specification of initial and boundary conditions, which can be supplied by avalanche forecasters using a combination of weather stations and snowcover modelling. The avalanche model requires input parameters for snow temperature, density and water content in the release area and along the avalanche path. The temperature data provided by the automatic weather stations can be assumed to be reliable at the altitude and exposition where the weather stations are located. However, the difference in altitude and exposition of the four different cases studies requires a method to extrapolate temperature from the point locations of the automatic weather stations to the entire slope. For this purpose we applied the SNOWPACK model on virtual slopes matching the expositions with the studied slopes. When it was possible to enter the slopes we used hand measurements of validate the SNOWPACK model predictions for temperature and density.

As the SNOWPACK simulations predicted isothermal snowcover at T=0° for the snow depth affected by the avalanches, the entrained snow temperature was set to zero degrees in all four cases studies. This approach could not be followed with the modelled snowcover water content which has no limiting value in an isothermal snowcover. Although SNOWPACK was used to predict snow water content [Wever et al., 2014] it was difficult to measure and validate the distribution of snow water content at lower altitudes and different expositions. For example, in the case CG-1 the snowfall was preceded by rain making it difficult to calculate the snowcover water content which depends on the variability of the rainfall.

The position of all release zones was obtained from the eyewitness reports and post-event surveys. Entrainment depths for the simulations were also obtained from field studies and event documentation. In the examples LGW-2 and BN-1 the erosion depths where measured along the path in several points. Because the avalanches disrupted road traffic, road clearance crews could estimate deposition depths allowing good estimates of avalanche mass balance. The temperature, snow density and water content of the eroded mass are the key input information to predict accurate avalanche deposition volumes and runout distances. The release mass does not play an important role apart from defining the location of release and the triggering the whole subsequent process.

The four examples contain mountain rock faces with well defined flow channels (CG-1, CCHN-3) as well as open slopes (BN-1, LGW-2). At release the avalanche mass spreads depending on the terrain features. In two of the four case studies, avalanche spreading is inhibited by the steep sidewalls of mountain gullies, a function of the topographic properties of the mountain. The remaining two examples are open slopes where the spreading angle is larger. Avalanche movement is therefore not only controlled by the hydrothermal state of the snow, but also by the slope geometry. High resolution digital elevation models that accurately represent mountain ravines and channels are thus necessary to apply avalanche dynamics models to simulate small avalanches, [Bühler et al., 2011].

The avalanche model simulates both fluidization and lubrication processes. This requires introducing depth-averaged equations for thermal energy [Vera et al., 2015], mechanical free energy [Buser and Bartelt, 2015] and meltwater [Vera et al., 2015]. The degree of fluidization characterizes the avalanche flow regime: dry snow avalanches being associated with more fluidized, less dense flows (mixed flowing/powder avalanches) and wet avalanches being associated with less fluidized, dense flows. The degree of fluidization is controlled by parameters governing the production and decay of free mechanical energy R (α, β and γ [Buser and Bartelt, 2015]). The production parameter α is made dependent on terrain roughness and is independent of the avalanche temperature and moisture content. Highly plastic, wet particle interactions quickly dissipate any free mechanical energy leading to dense flows that can only fluidize in steep, rough slopes. We model this process by increasing the dissipation parameter β for warm, wet avalanches. This produces dense flows in the frictional flow regime. In the four case studies the flow density in the runout zone is close to the deposition density $\rho_\Phi = 450$ kg/m^3, whereas in the steep track sections the flow density is somewhat lower $\rho_\Phi = 300$ kg/m^3. Important is that the same model formulation is used for both dry and wet avalanches and fluidization is controlled by a combination of terrain (production of free mechanical energy) and wet snow granule properties (dissipation of free mechanical energy). A single model parameter β controls the degree of fluidization. An important model assumption is that entrainment of moist wet snow is a completely dissipative process which does not introduce additional free mechanical energy into the avalanche core.

Therefore, our results indicate that fluidization cannot be responsible for long runout distances of wet avalanches. Snow chute experiments with wet snow, showing that cohesive interactions in the avalanche core further hinder fluidization [Bartelt et al., 2015], provide more evidence that wet snow avalanche mobility is strongly linked to the temperature and moisture dependent mechanical properties of wet snow [Voytokskiy, 1977]. To investigate this hypothesis, we postulate that temperature and lubrication effects lead to a significant reduction of the Coulomb part of the Voellmy friction. A two parameter empirical relation between water content and friction μ was devised. A problem with depth-averaged models is that the distribution of meltwater in the avalanche height cannot be predicted from depth-averaged calculations of avalanche flow temperature, which depends on the slope perpendicular shear profile in the avalanche core. We assume that meltwater is concentrated in a shear layer of height h_m. When this layer becomes saturated with meltwater, Coulomb friction is reduced to a sliding value of μ_s, which we take, for now, to be constant μ_s=0.12. This value was selected based on our observations of wet snow avalanche runout in Switzerland. The layer height was set to h_m= 0.01 m, indicating that shearing in wet avalanche flows is concentrated in a thin basal layer. This is in agreement with velocity profile measurements of wet avalanche flows [Dent et al., 1998, Kern et al., 2009].

The model calculates the depth-averaged flow temperature from initiation to runout. In the four case studies the avalanche reached the melting point of snow-ice immediately after release due to the warm initial conditions. The entrainment of warm, moist snow enhanced the lubrication process. The decrease of Coulomb friction due to lubrication effects was essential for the point release avalanches to develop into long-running wet snow avalanches. For practical applications it is important that lubrication processes due to the (1) initial snow water content, (2) snow melting by frictional dissipation and (3) heat energy of entrained snow must all be taken into account. The method used to simulate the avalanche point release requires defining a small triangular area. The ratio between the eroded snow volume and the initial snow volume is between 20 to 60 for the four case studies we studied in this paper. The initial area used to simulate the avalanche release does not affect the final run-out, velocity and avalanche deposit calculations. The model results emphasize that complete information of the snow cover is necessary to achieve accurate representations of the events. The model is sensible to variations in the initial snow cover conditions (temperature and water content). For example, when colder snow is specified at release, the simulated avalanches stop immediately after release and do not reach the valley bottom. Given accurate initial conditions the model was able to back calculate runout distances, flow perimeters and avalanche volumes. Therefore, with this model formulation, it is only possible to obtain realistic runout predictions with accurate snow cover data. The application of the avalanche dynamics model should be restricted to cases where accurate data is available.

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