Modelling Wet Snow Avalanches with Thermal Effects, Snowcover Entrainment and Lubricated Sliding

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Abstract

Snow avalanches are dangerous, gravity-driven geophysical flows. They consist of a fast-moving mass of snow clods that are formed when the snow-cover is set in motion. Immediately after release, the snowcover breaks up into blocks of diverse sizes which become increasingly rounded by frictional interactions in the core of the avalanche. The primary problem in avalanche dynamics is to physically describe the motion of the churning particle ensemble. Due to the great number of particles, however, the motion of the particle ensemble must still be mathematically described using continuum theories of moving fluids. The ensemble properties of the continuum are defined by the sum of all the frictional interactions between particles and between particles and the ground. The myriad particle interactions are far from simple, but inevitably must be considered in continuum models in order to accurately describe and simulate avalanche flows. This is particularly true for wet snow avalanches where the temperature of the particles is near to the melting point of ice and considerable meltwater can be present in the porous ice-matrix of the clods of flowing snow. The high snow temperature and the presence of meltwater define the mechanical response of the avalanche mass under gravity. Thus, the micro-scale interactions between particles lead to different macroscopic avalanche regimes and therefore different avalanche velocities and runout distances.

In this dissertation we develop a continuum model for avalanche flow accounting for the temperature and moisture content of the moving snow. We first extend existing continuum theories to consider the mechanical energy dissipated by moist particle interactions. We must consider two temperatures: the true thermal temperature and the so-called “granular” temperature, which is associated with random particle movements within the granular ensemble. The model extension therefore requires an internal energy equation to calculate the mean flow temperature as well as an equation to track the kinetic energy of random particle motions. Meltwater produced from frictional heating can be quantified. A third mass conservation equation, however, is necessary to track the meltwater trapped in the pore space of the particles. Knowing this quantity allows us to understand how moist particles damp the granular temperature and to postulate lubrication functions that simulate wet snow sliding. With this approach we can simulate dense, viscous-type flows typically associated with wet snow avalanches.

The additional source of heat and meltwater is from snowcover entrainment.
Avalanches can start from cold snow slabs but entrain warm snow at lower elevations. Often this snow is wet, either from rain or intense thermal heating. To apply the proposed model to solve practical avalanche problems therefore requires the specification of the snowcover temperature, density and moisture content along the avalanche path. A set of documented case studies is used to test the model by reproducing measured runout distances and area covered by the avalanche deposits. Long avalanche runout is possible depending on the initial and boundary conditions of a specific problem. We performed a sensitivity analysis to demonstrate how runout distances and inundated areas can vary as a function of the initial and boundary conditions such as temperature, moisture content, and density of the snowcover. In a final application we fed the model with simulated snowcover data derived from actual meteorological measurements to forecast wet snow avalanche runout in an operational environment. We demonstrate using sensitivity analysis why the specification of boundary conditions leads to great model uncertainties. This work is a first step towards the application of avalanche dynamics models as operational tools to assess the current wet snow avalanche risk.

Key words: wet snow, avalanche modeling, natural hazards, numerical simulation
Zusammenfassung


In dieser Dissertation leiten wir ein Kontinuum-Modell für Lawinen her, welches die Temperatur und den Feuchtigkeitsgehalt des sich bewegenden Schnees miteinbezieht. Wir erweitern existierende Kontinuumstheorien um die mechanische Energie zu berücksichtigen, welche durch die Interaktion von feuchten Partikeln verbraucht wird. Hierbei müssen wir zwei Temperaturen berücksichtigen: Einerseits die wahre thermische Temperatur und andererseits die sogenannte ”granulare” Temperatur, welche mit den zufälligen Partikelbewegungen innerhalb des granularen Ensembles assoziiert ist. Die Modellerweiterung bedarf daher einer Gleichung zur Beschreibung der inneren Energie, die es ermöglicht die durchschnittliche Fliesstemperatur der Lawine zu bestimmen, sowie einer Gleichung um die kinetische Energie der zufälligen Partikelbewegungen nachzu vollziehen. Die Schmelzwassermenge, welche durch Reibungswärme entsteht, kann somit quantifiziert werden. Eine dritte Massenerhaltungsgleichung ist dennoch nötig um das Schmelzwasser zu verfolgen, welches sich in den Hohlräumen der Partikel
befindet. Diese Gleichung liefert das Verständnis wie feuchte Partikel die granulare Temperatur senken und ermöglicht es eine Reibungsfunktion zu postulieren, welche die Bewegung von Nassschnee beschreibt. Mit diesem Modell ist es schliesslich möglich dichte, zähfließende Prozesse welche bei Nassschneelawinen auftereten zu simulieren.


Stichwörter: Nassschnee, Lawinenmodellierung, Naturgefahren, Numerische Modellierung
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Chapter 1

Introduction

1.1 Motivation

Between the years 2000 and 2010 avalanche engineering in Switzerland underwent a fundamental transition: In 2000 the Swiss Federal Institute of Snow and Avalanche Research (SLF) introduced a computer based model to perform avalanche dynamics calculations. The AVAL-1D program [Christen et al., 2002], largely based on the well-known Voellmy model, replaced hand calculation methods traditionally used in avalanche mitigation problems. The new computer model was used extensively in Switzerland to predict avalanche runout and therefore to zone land into safe and hazardous avalanche terrain. AVAL-1D was well-liked by practitioners, but was restricted to a one-dimensional mountain profiles (Fig. 1.1). This restriction was removed when the SLF introduced the quasi three-dimensional avalanche dynamics program RAMMS in 2010, (Christen et al. [2010], Fig.1.2).

RAMMS exploited many new developments of computer technology: computer performance, graphical visualization and increased user-friendliness. Advances in remote sensing technology could be exploited to produce high resolution terrain models, the essential requirement for numerical calculations. Because RAMMS allowed engineers to solve avalanche problems in complex three-dimensional terrain, it quickly replaced AVAL-1D as the standard calculation tool in practice, (see Fig. 1.2).

Despite this progress, the underlying physics of the RAMMS model did not change substantially from the Voellmy approach. This was in part advantageous, because the new computer-based calculations largely confirmed to simple hand calculations. Therefore, the large number of hazard maps created between 1970 and 2000 remained valid and required no re-calculation. On the other hand, a clear inadequacy of the Voellmy model became apparent: actual avalanche events could not be modeled without significant
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Figure 1.1: Example of a velocity calculation with a point mass model (AVAL-1D) using a one-dimensional profile. The top panel depicts the one-dimensional mountain profile together with the calculated velocity. The bottom panel displays the track width. The model Aval-1D was extensively used by practitioners from 2000 to 2010 to perform runout calculations.

changes to the model parameters. The model could be used to predict extreme runout distances and velocities of “generic” avalanches, but only when calibrated extreme avalanche parameters were applied.

The selection of appropriate flow parameters, the “parameter problem”, was always the central problem in avalanche dynamics calculations [Buser and Frutiger, 1980]. The problem became more acute from 2010 onwards because high precision laser scanning was being increasingly used to document avalanche deposition fields [Bühler et al., 2009]. It became easier to compare three-dimensional model results with accurate three-dimensional field measurements. (Since 2015 drones are applied to document avalanches [Vera Valero et al., 2016, Bühler et al., 2016].) It became increasingly obvious that the standard Voellmy model could not reproduce avalanche events, even those captured at the full scale Swiss Vallée de la Sionne test site. The Voellmy model was designed to simulate the velocity and inundation area of large, primarily dry, flowing avalanches [Gruber and Bartelt, 2007]. The model over-predicts runout for smaller events, and does not account for specific snow conditions, including wet snow [Dreier et al., 2014]. It is difficult to simulate the measured deposition heights with the Voellmy model, even when entrainment processes are included in the model formulation [Sovilla et al., 2006]. The introduction of the RAMMS model had another important side-effect: Between 2010 and 2015 avalanche engineers had become
1.1. Motivation

Figure 1.2: Example of a flow height calculation using the RAMMS model in three-dimensional terrain. Calculations require an accurate digital terrain model. From 2010 onwards avalanche calculations in Switzerland were performed using three-dimensional models.
increasingly interested in applying models to hazard problems involving small and more frequent avalanches, especially for problems involving road and ski-run safety [Dreier et al., 2014].

Such problems cannot be solved using standard approaches with Voellmy-type models using “calibrated” parameters. The simulation of non-extreme events requires more physics-based models. It necessarily involves the problem of temperature dependent snow rheology [Bozhinskiy and Losev, 1998], how to model snow entrainment [Sovilla et al., 2006, Naaim et al., 2004] and the problem of avalanche flow in forests [Feistl et al., 2015]. It had become clear from the increased application of computer models that the Voellmy model was no longer adequate to meet all, or even specific, demands of avalanche engineering practice.

The scientific goals of this dissertation were formulating in view of the developments in avalanche modelling from 2010 onwards. The primary need arising from engineering practice is to extend the application range of computer-based modeling beyond the limit of extreme, dry avalanches. Extreme events can be adequately represented by the standard Voellmy model using calibrated friction parameters. The underlying research question became how can a physics-based model of avalanche flow be constructed such that the wide-range of avalanche motion (including small, frequent and wet events) could be accurately simulated? Such a model would find wide application in avalanche engineering, especially to handle engineering problems outside the realm of the Voellmy approximation. This question necessarily involves the application of friction parameters that depend on the physical state of snow such as temperature, moisture content, density and microstructure. The drawback of this approach is that avalanche dynamics calculations would need accurate initial and boundary conditions, such as the spatial variability of snowcover conditions along the entire avalanche path could be simulated. Therefore, a secondary question arose: how can the initial and boundary conditions be prescribed to allow the application of more physics-based models? These are the two primary research questions posed in this dissertation.

1.2 Snow avalanches as geophysical flows

Although snow avalanche modeling has a young history (the first models appeared in the 1930s, see [Salm, 2004], the material snow has long fascinated scientists. Aristotle (384–322 BC) was probably the first thinker to discuss snow, defining snow as an unnatural form of water in his Meterologica, [Taub, 2013]. Aristotle believed that snow is defined by its transformation from solid to liquid water and used snow to demonstrate that materials
cannot only be defined by their existing state, but also by changes and transformations. Thus, Aristotle did not believe the material snow violated the ancient Greek division of all materials into the four classical elements (earth, water, air and fire). Aristotle’s ancient concept of snow is in many ways modern, because it stresses the idea that transformations are central to understanding snow (and avalanches).

Several early historical references also described snow avalanches. The best known are the Greek geographer *Strabon* (63-23 BC) who wrote, “.. ice avalanches which often carry away with them whole tourist parties and throw them into the abyss. For numerous are the layers lying one above the other. The snow develops layer by layer to ice and the uppermost detaches from time to time before it has been molten by the sun”. The historian *Livius* (59 BC-14 AD) [Hutter, 1996] documented Hannibals crossing of the Alps in 218 BC writing, “The snow cover was caused to glide down by the weight of men and animals.” The science of snow flows, however, could only be understood after Newton’s *Principia* was published in 1687. Interestingly, Newton used snow to describe the process of densification, using the compression of snow to distinguish between volume and mass, this immediately before introducing his three fundamental laws of mechanics (*Principia*, 1687).

### 1.2.1 Avalanche dynamics modelling

Newton not only discussed snow in his *Principia*; he also solved one of the first avalanche dynamics problems posed by the Swiss mathematician John Bernoulli in 1697. Bernoulli postulated the question what is the shape of an avalanche track, such that an object will descend a fixed distance in the shortest amount of time, the so-called Brachistochrone problem (see Fig.1.5a and [Wanner, 1988]). The solution of this problem (a cycloid) considers the object to be a lumped mass and requires specifying the force of gravity tangential to the avalanche track. Thus, “lumped mass” models, albeit without friction, were clearly known to the scientific community by 1700, principally to Newton who supposedly solved Bernoulli’s problem in an evening. It is exactly this problem, finding an appropriate friction model to describe avalanche flow, left unanswered by Newton and Bernoulli, that has made the avalanche problem so difficult to solve.

[Voellmy, 1955] was one of the first to develop a frictional relationship for modeling avalanche flows using lumped mass models. Voellmy combined a Coulomb friction and a velocity dependent squared (or hydraulic) resistance to define the overall flow resistance $S$ to the driving force of gravity $g$ (see Fig.1.5b). The Voellmy model can be directly stated as,

$$S = S_\mu + S_\xi = \mu N + \rho g U^2 / \xi$$

where $\mu$ is the friction coefficient, $N$ is the normal force (weight of avalanche),
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Figure 1.3: Example of flowing dry avalanche at Vallée de la Sionne avalanche test site. Source: KEYSTONE.

\[ \rho \text{ the flow density; } U \text{ the velocity of the flow and } \zeta \text{ the "turbulent" friction.} \]

Voellmy maintained that avalanche runout was controlled by the Coulomb parameter \( \mu \), while the terminal avalanche velocity was given by the parameter \( \zeta \). The turbulent friction limits the terminal velocity of the avalanche to a finite value, even on long steep slopes. This behavior has been observed in snow avalanches, e.g. [Turnbull and McElwaine, 2007]. The Voellmy model was later modified by Salm [Salm, 1966], who partitioned the avalanche track into three segments – the starting zone, the transition or acceleration zone and the runout zone (see Fig.1.5b). In each track segment the Voellmy model was applied. Salm formalized the Voellmy model such that it could be applied in avalanche practice.

More important than the practical impact of the work of Voellmy, however, is that many of Voellmy’s ideas foreshadowed concepts that are very actual, particularly for this work. Firstly, Voellmy supposed there was an essential difference between dry and wet/moist avalanches. Although the Voellmy model is general and can be used to simulate all avalanche types, Voellmy maintained that dry and wet avalanches were governed by different mechanical processes, [Voellmy, 1955] Figs. (see Fig. 1.3, 1.4). Voellmy believed that
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Figure 1.4: Example of wet snow avalanche deposits at Codelco Andina mine. Source: P. Cerda Codelco-Andina.

(a) Brachistochrone problem formulated by J. Bernoulli
(b) Voellmy-Salm avalanche model path description. Courtesy S. Margreth

Figure 1.5: Graphical description of two early ‘avalanche’ models

fluidization governed the mobility of dry avalanches, whereas meltwater lubrication was responsible for the long reach of wet snow avalanches. In both cases the Coulomb parameter \( \mu \) was reduced. Secondly, Voellmy modeled an avalanche as a rigid block described by a point mass, although he clearly stated that this was an over-simplification. Avalanche motion he claimed, is dominated by surges and fluctuations; that is, avalanche flow is basically non-steady and cannot be described by a uniform velocity.

The strongest feature of the Voellmy model is both its simplicity and ap-
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Satisfactory runout and maximal flow speeds can be obtained for a wide range of different avalanche types and sizes by changing only two parameters. This simplicity is the reason why the Voellmy model remains in use until this day. However, the many attempts to find optimal set of friction parameters conclude that a large uncertainty exists [Ancey, 2005, Eckert et al., 2007, 2008, Gauer et al., 2009]. Recently [Naaim et al., 2013] simulated 735 avalanches in order to find friction parameters which best match the measured run out distances. An important result of this work is that a relation between the static coefficient $\mu$ and the existing snowcover conditions (temperature and liquid water content) was found. The work of Naaim suggests that the problem of parameter calibration in the Voellmy model is strongly linked to snowcover conditions.

After Voellmy several models continued along the lines of a center of mass approach, such as the PCM model [Perla et al., 1980]. The PCM model was an improvement because the slope was not divided into three segments, rather defined by a two-dimensional avalanche path. The PCM model used only one friction parameter, the Coulomb friction $\mu$. Both the Voellmy and PCM lumped mass models were used until the year 2000 because they provided engineers with the two main quantities needed in a hazard analysis: the terminal velocity and the avalanche runout distance.

The problem, however, with lumped mass models is that they assume a rigid avalanche body. Internal shearing and deformations are not considered during flow. Therefore, they are not able to accurately represent avalanche deposition patterns, lateral spreading or spatial and temporal velocity variations within the avalanche. This is a severe deficiency, especially when trying to model actual avalanche features, not only terminal velocity and runout distance.

New models of avalanche flow were subsequently developed that tracked the avalanche from initiation to runout. In these models, the avalanche is allowed to deform and is no-longer a rigid body of fixed geometry. We loosely classify these models into three categories:

1. Hydraulic, free surface, open channel models

Hydraulic models are based on the equations of Saint-Venant and are often employed to simulate avalanche motion in two (mountain profile) or three-dimensional terrain, [Weiyan, 1992]. The geometry of the flow is characterized by a free upper surface and, for numerical solutions, a piecewise linear discretization of the bottom surface. The equations assume incompressibility (and therefore constant flow density). The mass and momentum equations can be written concisely in
vector form,
\[
\frac{\partial \mathbf{U}_\Phi}{\partial t} + \frac{\partial \Phi_x}{\partial x} + \frac{\partial \Phi_y}{\partial y} = \mathbf{G}_\Phi. \tag{1.1}
\]

A model formulation with three state variables results:
\[
\mathbf{U}_\Phi = (M_\Phi, M_\Phi u_\Phi, M_\Phi v_\Phi)^T. \tag{1.2}
\]

Where $M_\Phi$ denotes the mass per unit of area and $u_\Phi$ and $v_\Phi$ the velocity components parallel to the slope. The flux components ($\Phi_x, \Phi_y$) are:
\[
\Phi_x = \left( \frac{M_\Phi u_\Phi}{M_\Phi u_\Phi + \frac{1}{2} M_\Phi g h_\Phi} \right), \quad \Phi_y = \left( \frac{M_\Phi v_\Phi}{M_\Phi u_\Phi + \frac{1}{2} M_\Phi g h_\Phi} \right). \tag{1.3}
\]

Where $g$ is the gravity acceleration and $h_\Phi$ the flow height. The source terms $\mathbf{G}_\Phi$ are
\[
\mathbf{G}_\Phi = \begin{pmatrix} 0 \\ G_x - S_x \\ G_y - S_y \end{pmatrix}, \tag{1.4}
\]

where $G_x$ and $G_y$ are the gravitational components parallel to the slope and $S_x$ and $S_y$ are the corresponding friction components. The Voellmy model (Eq. 1) can be used to define the friction components $S_x$ and $S_y$. It is common to solve the system of equations using the flow height $h_\Phi$ instead of mass $M_\Phi$ using the incompressibility assumption and $M_\Phi = \rho_\Phi h_\Phi$.

As such, the avalanching material is modeled as a homogeneous continuum, described by the flow height and mean flow velocity. Gravity is the primary force driving the flow which is counteracting by the frictional forces concentrated between the rigid bed and flow at the bottom of the avalanche. Velocity components are in the slope-parallel direction; in the perpendicular direction the pressure distribution is hydrostatic.

Different frictional models can be implemented within the framework of depth-averaged, shallow water hydrodynamics. The four primary models for snow are: (a) Voellmy type [Voellmy, 1955], (b) Savage-Hutter [Savage and Hutter, 1989] (c) NIS [Norem et al., 1989], and (d) Bingham bi-viscous [Dent and Lang, 1983]. The common feature of all these models is the application of a Coulomb-type friction at the sliding surface. Savage-Hutter is similar to the Voellmy model in that uniform velocity profiles are typically assumed (although this condition can be relaxed). Savage-Hutter, theory, however, differs from Voellmy
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as it contains no velocity dependent friction. The effect of flow dilatations/contractions are modeled using the soil mechanics concept of active-passive pressure. Active-passive pressure accounts for the longitudinal straining in the avalanche body and improves the simulation of avalanche flow depths, [Pudasaini and Hutter, 2007]. The Savage-Hutter model reproduces the motion of small scale granular flows on inclined planes. However, when the model tries to simulate real case snow avalanche flow problems arise with the estimation of bed friction parameters as well as the discretisation of the topography, the estimation of the moving mass considering no snow entrainment, which may be present, in some instances to a large extent, [Hutter et al., 2005]. These problems, however, are common to all avalanche dynamics models.

The remaining two models, NIS [Norem et al., 1989] and Bingham [Dent and Lang, 1983], start by assuming a specific velocity distribution in the depth. The NIS model is based on the continuum theory of Criminale-Eriksen-Filby, leading to frictional terms strongly dependent on both the effective pressure and shear deformation rate. The model is general in that the shear stress is described as some power $n$ of the shear rate, allowing the simulation of viscous Bingham type flows, (power $n=1$) or Bagnold-type collisional flows (power $n=2$). Comparison between Voellmy-type and NIS models on real case studies are contained in [Norem et al., 1989, Bartelt et al., 1999, Sovilla et al., 2006]. Finally, there is a wealth of experimental evidence showing that avalanches, especially wet/moist avalanches, exhibit Bingham type velocity profiles containing a bottom shear layer and a uniform plug flow [Dent et al., 1998, Kern et al., 2009, Nishimura and Maeno, 1987]. Voellmy models this behavior by collapsing the shear layer to the ground; whereas Bingham type model explicitly model the finite height of the shear and plug layers. This leads to a model containing a normal stress independent yield stress (governing the height of the non-yield flow plug) and a viscous resistance linearly dependent on the shear gradient. The yield stress dependency leads to models which reproduce observed avalanche phenomena, such as flow surges [Bartelt et al., 1999].

2. Continuum kinetic theories and granular models

Kinetic theories and granular avalanche dynamics models supplement the governing field equations of mass and momentum conservation with (a) constitutive theories based on particle properties (size, shape, restitution, etc) and collisional particle interactions and/or (b) additional field equations describing the energies associated with random
particle movements, often termed particle fluctuations or granular temperature [Jenkins and Richman, 1986, Jenkins and Savage, 1983].

A large number of avalanche models have been developed to model flows of dry granular material, see the review paper of [Goldhirsch, 2003]. Here we concentrate on models that have been explicitly developed and applied for snow avalanches. Although the NIS model contained no granular temperature equation, the constitutive parameters are based on shear experiments with granular materials and then modified for snow. With this approach, micro-mechanical properties of the particles are upscaled to macro-mechanical constitutive constants. The resulting constitutive model can be implemented with the framework of hydraulic approaches. Kinetic or granular theories attempt to include some of the micro-mechanical parameters. An early example was the granular model of [Hutter and Szidarovsky, 1986], based largely on early work of [Jenkins and Savage, 1983]. This model, especially designed for snow avalanches, used both a constitutive formulation with micro-parameters (particle size and restitution) in addition to a granular temperature equation. Another early granular snow model was proposed by [Gubler, 1987] who was able to qualitatively connect actual velocity measurements on snow avalanches to the fluctuation energy of snow clods. An important result of [Gubler, 1987] is the identification of two flow regimes: a sliding (non-fluidized) regime with little fluctuation energy and a partially fluidized regime with large fluctuation energy, primarily at the avalanche front.

In the more recent work of [Bartelt et al., 2006] and [Buser and Bartelt, 2009] the fluctuation energy (termed random kinetic energy) was implemented via thermodynamic arguments by splitting the dissipative work into two parts, (1) the production of thermal heat and (2) production of fluctuation energy. They also showed that the production of random kinetic energy, but also “configurational” energy [Bartelt et al., 2016], closely linked to the local potential energy of the avalanche core. This method was used to mathematically describe the expansion of the avalanche core and the intake of air (Fig.1.6). Basically, the incompressibility assumption of hydraulic and early granular models, was no longer necessary. This theory leads to highly non-uniform flows, far from steady-state, with streamwise variations in flow density [Buser and Bartelt, 2015]. The authors use this modeling approach to simulate both the formation of powder snow avalanches [Bartelt et al., 2016] and the motion of wet flows [Vera Valero et al., 2015].

3. Discrete particle methods

Using too the assumption of discrete particles the Discrete Element Method (DEM) is a direct simulation method where every single par-
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![Diagram of avalanche dynamics](image)

Figure 1.6: Advanced avalanche dynamics models divide the flow into a granular core (denoted $\Phi$) surrounded by a powder cloud (denoted $\Pi$). The granular core can consist of different "configurations" – dense, disperse or dilute.

Particle is followed and its interactions with the other particles are computed. The model solves explicitly the momentum equation for a fixed number of particles. The collisions between particles are assume to be elastic or plastic with a corresponding restitution coefficient. The method has shown good results but limited to a small number of particles [Thompson and Grest, 1991], extrapolate the method to a real-size flows is still hardly feasible, [Pudasaini and Hutter, 2007]. Such simulations can hardly hold real case problems involving millions of particles in which the interactions between them are far from simple. However these simulations provide useful hints in the formulation of continuum theories [Campbell, 1990, Savage, 1983].

1.2.2 Modelling wet snow avalanches

Both hydraulic and granular flow models have concentrated on understanding the fluidization process of dry flows that lead to long runout. Hydraulic models, in particular the NIS model of Norem, account for this process by selecting resistance parameters that reflect the state of the fluidized flow region. For example, the relationship between shear rate and shear resistance is governed by a power law characterizing the dispersive interactions of the granules. Savage-Hutter type formulations have been extensively calibrated
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for dry granular materials [Savage and Hutter, 1989]. The granular models of [Bartelt et al., 2006] account explicitly for the energy fluxes required to change the particle configuration during fluidization. These are improvements over the standard Voellmy model which uses calibrated parameters, reflecting the fluidized regime. Because the flow parameters are constant in the Voellmy model, flow regime transitions cannot be modeled.

Little attention has been given to the motion of wet snow avalanches. Voellmy recognized early that the motion of fluidized avalanches, typically accompanied by a powder cloud, differed strongly from the motion of wet flows [Voellmy, 1955]. Voellmy surmised that the physical mechanism governing dry flows was fluidization, whereas lubrication was the dominating physical mechanism governing the runout of wet flows, see Table 1.1. The problem of modeling wet snows was not urgent, because hazard maps were focused on the extreme scenario corresponding to a fast, long-running dry (powder-) snow avalanche. This view has shifted for three reasons:

1. Climate change scenarios: Global warming suggest an increase of wet snow avalanche activity, see [Castebrunet et al., 2014, Eckert et al., 2009, Beniston, 2003, McClung, 2013]. Many authors argue that climate change will increase wet snow avalanche cycles and therefore the threat of wet snow avalanches will increase. Even without climate change, wet snow avalanches are a dominant threat in many regions in the world (Alaska, Russia, Japan, Chile, Norway, Iceland)

2. Operational forecasts: Avalanche dynamics modeling has been based on extreme case studies, driven by maximum snowfall amounts. However, road safety and ski-area managers increasingly require more detailed estimates of avalanche activity, depending on the actual meteorological conditions, including stability of warm moist snowcover. These new applications (including several discussed in the following) require operational estimates of avalanche runout, often involving no new snowfall. To model these conditions a wet snow avalanche model for small frequent avalanches is required. Some authors consider wet snow gliding will be a new hazard, that must be included in the hazard maps. For example [Margreth, 2013] states ‘As some of these events happened in areas not usually exposed to avalanches, the question arises as to whether avalanche risk maps should be updated to take this ‘new’ threat into account’. A recent review of the wet snow gliding problem is found in [Ancey and Bain, 2015].

3. Voellmy’s hypothesis: The hypothesis of Voellmy is unanswered. The granular flow models appear to resolve the question of how fluidization controls the motion of dry avalanches. The motion of wet snow avalanches, however, remains unknown: all observations and exper-
1. Introduction

Experimental results indicate dense, viscous-type flows with only partial fluidization [Kern et al., 2009, Nishimura and Maeno, 1987]. The question then arises what physical mechanism is controlling the motion of wet flows such that long runout distances can be attained?

The main feature of wet snow avalanches is a truism: they contain higher liquid water content in comparison to dry avalanches. Liquid water content [McClung and Schaerer, 2006] is used to distinguish between dry and wet flows. To model wet snow avalanches, we must go beyond this simple definition and quantify the two main sources of water. These were identified in the recent paper of [Vera Valero et al., 2015]: meltwater due to frictional heating and water within the undisturbed snowcover. Moreover, water contained in the snowcover is both an initial condition (defining the water content at release) and a boundary condition (defining the water added to the avalanche by entrainment). To account for all these processes a wet snow avalanche model must therefore address:

- Thermal energy of the avalanche (temperature of the flowing snow). A first step is to solve the non-uniform, non-steady, thermal energy equation for the avalanche flow temperature considering the fluxes of mechanical, random and internal (thermal) energies. This requires modeling sources of thermal energy, which depend on the snowcover boundary conditions [Vera Valero et al., 2015]. Moreover, the absolute flow temperature of the avalanche is controlled by the slab and snowcover (entrainment) temperature and therefore the topography of the avalanche path: length, elevation drop and steepness.

- Constitutive relations. The temperature of snow granules controls their fluctuation and therefore the configuration (form) of the avalanche, [Buser and Bartelt, 2009, Bartelt and Buser, 2011]. Colder snow granules are related to elastic collisions whereas warmer granules are related to plastic, dissipative collisions, leading to dense, viscous-type flows [Issler and Gauer, 2008]. Free water lubricates the sliding surface of the granular interactions and decreases the friction. A closure relationship is therefore needed to account the influence of water content on frictional processes on sliding surfaces. Presently, it is not clear how to introduce temperature dependence into constitutive relationships.

- Phase Changes. Because of the frictional heating, snow melting occurs. A phase change constrain is needed to calculate the amount of liquid water produced. Because this will depend on when enough frictional heat is generated, meltwater content will depend on the initial conditions as well as the form of the avalanche track.

- The meltwater travels with the speed of the granules. The water is transported with the speed of the flow. Therefore, it is not needed to
1.2. Snow avalanches as geophysical flows

consider momentum interchange between the solid and liquid phases. However, it is necessary to include a water transport equation to trace the water content within the snow flow in space and time.

Table 1.1: Characteristic parameters of main cases of avalanche flows, [Hutter, 1996, Pudasaini and Hutter, 2007]

<table>
<thead>
<tr>
<th></th>
<th>Wet avalanche</th>
<th>Dry-Mixed avalanche</th>
<th>Powder Avalanche</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical velocity</td>
<td>5-20 m s(^{-1})</td>
<td>30-60 m s(^{-1})</td>
<td>70-100 m s(^{-1})</td>
</tr>
<tr>
<td>Flow height</td>
<td>1-5 m</td>
<td>1-5 m</td>
<td>50-100 m</td>
</tr>
<tr>
<td>Density</td>
<td>300-600 kg m(^{-3})</td>
<td>100-300 kg m(^{-3})</td>
<td>1-5 kg m(^{-3})</td>
</tr>
<tr>
<td>Flow regime</td>
<td>Frictional</td>
<td>Frictional-Collisional</td>
<td>Turbidity Current</td>
</tr>
</tbody>
</table>

1.2.3 Scope of dissertation

Snow avalanches remain a threat to human activities in mountainous regions. Presently the personal and material damage caused by avalanches in inhabited mountain areas is estimated to be 58 Mio Swiss francs per year in Switzerland, [Wegmann et al., 2007]. The affected activities are related with transportation routes in alpine regions (railways, roads, pipelines, etc), working activities (mining, construction), human settlements (mountain towns, ski resorts, etc) and recreational activities (mountaineering, skiing, outdoor sports). In the last years there is a trend showing an increase in accidents while practicing outdoor winter sports [Techel et al., 2016]. Conversely, the number of accidents along transportation routes or in inhabited areas is seemingly decreasing. This trend may be due to improvements in avalanche knowledge, avalanche risk awareness and in avalanche protection strategies, [Rudolf-Miklau et al., 2014]. Nevertheless accidents caused by snow avalanches have regularly occurred and remains a strong motivator to understand dynamics of snow avalanche motion.

This work explores possible solutions to two actual problems in avalanche science:

- We construct an avalanche dynamics model specifically to simulate the motion of wet snow flows. The model predicts the spatial and temporal development of the mean avalanche temperature as a function of initial conditions, frictional dissipation and snowcover entrainment. Phase changes are included to predict the production and transport of meltwater. We test the Voellmy hypothesis that significant meltwater production and water entrainment can lead to far-reaching and dangerous avalanche runout and quantify under which snowcover conditions
1. Introduction

This can occur.

- We address the longstanding problem of the specification of initial and boundary conditions. Avalanche science does not lend itself to analytical solutions with differentiable functions of few parameters. Avalanches can be described by well-posed systems of differential equations [Naaim et al., 2002, Christen et al., 2010, Sampl and Zwinger, 2004]. However, the constitutive behavior of snow coupled with uncertain initial and boundary conditions make numerical solutions necessary. This work will follow the path outlined by [Naaim et al., 2013] and apply a physics-based wet snow avalanche model using friction parameters which are given by detailed snowcover modeling [Wever et al., 2016]. Friction parameters will be not tuned but fixed within the framework of empirical functions parameterized by density, temperature and liquid water content.

The region where we test and apply the avalanche model and specification of initial snowcover conditions is primarily in the Andina copper mine located in the central Andes 100 km North of Santiago de Chile and the Davos region in the Swiss alps. The copper mine is served by a 35 km long industrial road threatened by 148 avalanche paths. Mine activities are often interrupted by avalanche danger, specifically small and frequent avalanches, and requires new methods to evaluate avalanche risk in order to minimize road closures. The mine is an ideal location to develop a wet snow avalanche model because of warm temperatures and closeness to the Pacific ocean. The avalanche expert M. Atwater (author of *The Avalanche Hunters*, 1968) worked for the Andina mine between 1965-1968 and wrote in his *Operations manual – snow and avalanche, 1965,*” ... high temperature, winter rain, warm wind (chinook) release avalanches by lubrication and overloading” ... “release avalanches even in fair weather....”

No dissertation in the topic of avalanche dynamics is complete without considerable field verification. Field documentation of spontaneous avalanche events has improved dramatically over the past few years. Hand-held GPS devices, geo-referencing tools for photographs, drones with cameras and smart-phone videos can all be used to document events. When this information is coupled with snowpit measurements and high-resolution terrain models (that are now more readily available) avalanche engineers have considerable information including: (1) the location of the starting zone and fracture height, (2) flow paths, (3) where and how much snow the avalanche entrained and (4) the spatial extent and height of the avalanche depositions. Videos can be used to document the flow regime e.g. existence of a powder cloud or motion of wet flow fingers. In some cases videos can be used to estimate the flow velocity of the avalanche at different points along the
1.3 Summary of contents

The present dissertation is structured in five chapters and three appendixes. In the introduction, Chapter 1, we provide a motivation for the wet snow avalanche problem and literature survey. A brief summary of the different avalanche models and various numerical approaches is included. The scope of the work is defined.

Chapter 2 reworks the contents of the paper [Vera Valero et al., 2015] published in the Journal of Glaciology. This chapter presents an extensive overview of the physical processes we include in the wet snow avalanche model. A system of differential equations is derived that includes the effect of temperature, meltwater production (phase changes) and meltwater lubrication. The chapter contains a set of theoretical and real test simulations using the new model. This helps the reader understand both the potential and limitations of the mathematical development.

In Chapter 3 the model is applied to predict avalanche runout in an operational environment. Specifically, to forecast when will avalanches cross the industrial road of the Codelco Andina mine in the central Andes in Chile. This chapter is based on the publication [Vera Valero et al., 2016]. The initial and boundary conditions of the model are extracted from snowcover simulations forced with measured meteorological data. The results obtained show that the model can be driven by accurate snowcover information without using extensive parameter tuning.

In Chapter 4 the model is used to simulate an additional set of well documented medium to large sized wet snow avalanches. The initial and boundary conditions were extracted again from snowcover simulations performed with the detailed physics based SNOWPACK. The simulations were forced with measured meteorological data. The calculation results were then compared to the results obtained using the existing Voellmy-Salm model commonly used in avalanche practice. The new model extension clearly outperformed the classical Voellmy-Salm method, by improving both the calculated run out distances and area covered by the deposits. An additional sensitivity analysis was performed. The different case studies were repeated using combinations of initial and boundary conditions corresponding to wet avalanche track. Although field documentation cannot replace full-scale experiments at instrumented test sites, they offer a wider range of data concerning terrain characteristics, mass balance, avalanche size and snowcover conditions.
1. Introduction

snow avalanche days. On average the better results were obtained using the simulated snowcover and boundary conditions. However, the model is sensitive to changes in initial and boundary conditions. The extensive simulation results are included in the Appendixes.

The thesis conclusions and outlook are presented in Chapter 5. This chapter synthesizes the findings obtained in the previous chapters and gives an outlook and defines the further steps that are needed.

The second of the Appendixes contains the work published at [Wever et al., 2016], where the author of this thesis is co-author. This piece of work is particularly important in this thesis because shows the importance of water ponding within the snowcover in wet snow avalanche prediction and a technique to estimate the fracture and erosion depth in the input of wet snow avalanche simulations. This technique was extensively used in Chapters 3 and 4 of this dissertation.
1.4 List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c)</td>
<td>J kg(^{-1}) K(^{-1})</td>
<td>specific heat</td>
</tr>
<tr>
<td>(c_a)</td>
<td>J kg(^{-1}) K(^{-1})</td>
<td>specific heat of air</td>
</tr>
<tr>
<td>(c_i)</td>
<td>J kg(^{-1}) K(^{-1})</td>
<td>specific heat of ice</td>
</tr>
<tr>
<td>(c_w)</td>
<td>J kg(^{-1}) K(^{-1})</td>
<td>specific heat of water</td>
</tr>
<tr>
<td>(E_{\Phi})</td>
<td>kg m(^{-1})s(^{-2})</td>
<td>flowing core thermal energy</td>
</tr>
<tr>
<td>(f_z)</td>
<td>m s(^{-2})</td>
<td>centripetal acceleration</td>
</tr>
<tr>
<td>(g)</td>
<td>m s(^{-2})</td>
<td>gravitational acceleration</td>
</tr>
<tr>
<td>(g')</td>
<td>m s(^{-2})</td>
<td>sum of gravitational and centripetal acceleration</td>
</tr>
<tr>
<td>(g_x)</td>
<td>m s(^{-2})</td>
<td>‘x’ component gravitational acceleration in local coordinates</td>
</tr>
<tr>
<td>(g_y)</td>
<td>m s(^{-2})</td>
<td>‘y’ component gravitational acceleration in local coordinates</td>
</tr>
<tr>
<td>(g_z)</td>
<td>m s(^{-2})</td>
<td>‘z’ component gravitational acceleration in local coordinates</td>
</tr>
<tr>
<td>(h_{\Phi})</td>
<td>m</td>
<td>avalanche flowing core height</td>
</tr>
<tr>
<td>(h_w)</td>
<td>m</td>
<td>avalanche core water content</td>
</tr>
<tr>
<td>(K)</td>
<td>kg m(^{-2})s(^{-2})</td>
<td>kinetic energy</td>
</tr>
<tr>
<td>(L)</td>
<td>J kg(^{-1})m(^{-3})</td>
<td>latent heat of fusion of ice</td>
</tr>
<tr>
<td>(M_{\Phi})</td>
<td>kg m(^{-2})</td>
<td>flowing mass</td>
</tr>
<tr>
<td>(M_{\Sigma \rightarrow \Phi})</td>
<td>kg m(^{-2})</td>
<td>entrained snow mass</td>
</tr>
<tr>
<td>(M_{\Sigma \rightarrow w})</td>
<td>kg m(^{-2})</td>
<td>entrained water mass</td>
</tr>
<tr>
<td>(N)</td>
<td>kg m s(^{-2})</td>
<td>total reaction force from the ground</td>
</tr>
<tr>
<td>(N_g)</td>
<td>kg m s(^{-2})</td>
<td>reaction force from the ground due to gravity</td>
</tr>
<tr>
<td>(N_f)</td>
<td>kg m s(^{-2})</td>
<td>reaction force from the ground due to centrifugal forces</td>
</tr>
<tr>
<td>(Q_{\Sigma \rightarrow \Phi})</td>
<td>kg m(^2)s(^{-2})</td>
<td>thermal energy entrained</td>
</tr>
<tr>
<td>(R_{\Phi})</td>
<td>kg m(^{-1})s(^{-2})</td>
<td>flowing core random kinetic energy [Buser and Bartelt, 2009]</td>
</tr>
<tr>
<td>(R_0)</td>
<td>kg m(^{-1})s(^{-2})</td>
<td>activation energy for fluidization [Buser and Bartelt, 2009]</td>
</tr>
<tr>
<td>(S_{\Phi})</td>
<td>kg m s(^{-2})</td>
<td>avalanche core friction force</td>
</tr>
<tr>
<td>(S_{\Phi x})</td>
<td>kg m s(^{-2})</td>
<td>‘x’ component of the friction force</td>
</tr>
<tr>
<td>(S_{\Phi y})</td>
<td>kg m s(^{-2})</td>
<td>‘y’ component of the friction force</td>
</tr>
<tr>
<td>(T_0)</td>
<td>K</td>
<td>snow temperature at the release</td>
</tr>
<tr>
<td>(T_m)</td>
<td>K</td>
<td>melting temperature of ice/snow</td>
</tr>
<tr>
<td>(T_{\Phi})</td>
<td>K</td>
<td>flowing core temperature</td>
</tr>
<tr>
<td>(T_{\Sigma})</td>
<td>K</td>
<td>entrainment layer temperature</td>
</tr>
<tr>
<td>(t)</td>
<td>s</td>
<td>time</td>
</tr>
<tr>
<td>(u_{\Phi})</td>
<td>m s(^{-1})</td>
<td>‘x’ component of the avalanche core velocity</td>
</tr>
<tr>
<td>(u_{\Phi})</td>
<td>m s(^{-1})</td>
<td>avalanche core velocity</td>
</tr>
<tr>
<td>(U_{\Phi})</td>
<td>–</td>
<td>state variable vector</td>
</tr>
<tr>
<td>(v_{\Phi})</td>
<td>m s(^{-1})</td>
<td>‘y’ component of the avalanche core velocity</td>
</tr>
<tr>
<td>(V_{\Phi})</td>
<td>m(^3)</td>
<td>avalanche core volume</td>
</tr>
<tr>
<td>(W_{\Phi})</td>
<td>kg m(^{-2})s(^{-2})</td>
<td>work dissipated by friction forces and plastic granular collisions</td>
</tr>
<tr>
<td>(x)</td>
<td>m</td>
<td>local coordinate in the ‘x’ direction</td>
</tr>
<tr>
<td>(y)</td>
<td>m</td>
<td>local coordinate in the ‘y’ direction</td>
</tr>
<tr>
<td>(a)</td>
<td>–</td>
<td>random kinetic energy generate parameter</td>
</tr>
</tbody>
</table>
### List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>$s^{-1}$</td>
<td>random kinetic energy decay parameter</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>–</td>
<td>erodibility [Christen et al., 2010]</td>
</tr>
<tr>
<td>$\theta_a$</td>
<td>$m^3 m^{-3}$</td>
<td>air volume fraction at the entrainment layer</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>$m^3 m^{-3}$</td>
<td>ice volume fraction at the entrainment layer</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>$m^3 m^{-3}$</td>
<td>water volume fraction at the entrainment layer</td>
</tr>
<tr>
<td>$\mu$</td>
<td>–</td>
<td>friction coefficient</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>–</td>
<td>dry snow friction coefficient</td>
</tr>
<tr>
<td>$\mu_d$</td>
<td>–</td>
<td>fluidize snow friction parameter</td>
</tr>
<tr>
<td>$\mu_w$</td>
<td>–</td>
<td>minimum wet snow friction parameter</td>
</tr>
<tr>
<td>$\rho_\Phi$</td>
<td>$kg \ m^{-3}$</td>
<td>density of the flowing avalanche core</td>
</tr>
<tr>
<td>$\rho_\Sigma$</td>
<td>$kg \ m^{-3}$</td>
<td>density of the entrainment layer</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>$kg \ m^{-3}$</td>
<td>density of air</td>
</tr>
<tr>
<td>$\rho_i$</td>
<td>$kg \ m^{-3}$</td>
<td>density of ice</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>$kg \ m^{-3}$</td>
<td>density of water</td>
</tr>
<tr>
<td>$\xi$</td>
<td>$m \ s^{-2}$</td>
<td>turbulent or viscous fluidize snow friction coefficient</td>
</tr>
<tr>
<td>$\xi_0$</td>
<td>$m \ s^{-2}$</td>
<td>turbulent or viscous non-fluidize snow friction coefficient</td>
</tr>
</tbody>
</table>
Chapter 2

Release Temperature, Snowcover Entrainment and the Thermal Flow Regime of Snow Avalanches

Summary

To demonstrate how snowcover release and entrainment temperature influence avalanche runout we develop an avalanche dynamics model that accounts for the thermal heat energy of flowing snow. Temperature defines the mechanical properties of snow and therefore the avalanche flow regime. We show that the avalanche flow regime depends primarily on the temperature of the snow mass in the starting zone as well as the density and temperature of the entrained snowcover which define the influx of heat energy. Avalanche temperature, however, not only depends on the initial and boundary conditions, but also on the path dependent frictional processes that increase internal heat energy. We account for two processes: (1) frictional shearing in the slope-parallel flow direction and (2) dissipation of random fluctuation energy by inelastic granular interactions. In avalanche flow, nonlinear irreversible processes are coupled with variable initial and boundary conditions that lead to transitions in flow regime. Snow avalanches thus exhibit a wide variety of flow behaviour with variations in snowcover temperature.¹

2.1 Introduction

The purpose of this chapter is to introduce snow temperature as an independent field variable in avalanche dynamics calculations. Snow tempera-

¹This chapter includes contents which were published in Vera Valero, C., Bühler, Y., Wikstroem Jones, K. and Bartelt, P. Release Temperature, Snowcover Entrainment and the Thermal Flow Regime of Snow Avalanches. Journal of Glaciology, 2015, 61(225), 173-184
2. Wet snow avalanche model

Figure 2.1: The deposition field of the Gatschiefer avalanche that released on the 26th of April 2008, Klosters, Switzerland. A cold, dry snow slab released. However, the avalanche entrained warm moist snow in the transition and runout zones leading to the formation of a heavy wet snow avalanche. Snow temperature controlled the avalanche flow regime.

Temperature defines the mechanical properties of flowing snow [Voytkovskiy, 1977, Bozhinskiy and Losev, 1998] and therefore the avalanche flow regime [Gauer et al., 2008, Issler and Gauer, 2008]. Dense, wet snow avalanches form from moist snow at warm temperatures (Fig. 2.1); mixed flowing/powder avalanches form from dry snow at cold temperatures. Wet snow avalanches exhibit pronounced visco-plastic type flow behaviour in contrast to the dispersive granular motion of dry snow avalanches which are often accompanied by a powder cloud of suspended ice-dust. The important role of snow temperature in controlling avalanche runout was recently highlighted in [Naaim et al., 2013]. An understanding of how snow temperature controls the mechanics of avalanche motion is key to predicting how different snow conditions influence avalanche flow regime, runout and deposition [Steinkogler et al., 2014]. Temperature $T$ is related to the internal heat energy $E$ of the avalanche, which is a function of the dissipative processes [Miller et al., 2003, Bartelt et al., 2005]. In this work we will consider the
temperature to describe the total specific internal energy $E$ of the avalanche completely; that is, for now we will not consider such effects as the potential energy of microscopic bonding forces including cohesion [Rowlinson, 2002]. In this case the total energy balance of the avalanche requires all potential energy from the initial fall height to be dissipated to heat. However, dissipative processes, such as frictional work, are extensive path functions and therefore require a precise definition of how they are created and where they work [Bejan, 1997]. Conventional avalanche dynamics models consider only the heat generated from the slope-parallel frictional shear work [Pudasaini and Hutter, 2007]. In addition we consider the dissipation of the kinetic energy associated with granular fluctuations [Bartelt et al., 2006]. Because the dissipation rate of each mechanism is controlled by a different process, the spatial distribution of temperature varies within the avalanche. When the snow flowing temperature exceeds the ice melting temperature the production of meltwater lowers the friction at the basal gliding surface [Colbeck, 1992]. Therefore, we must also consider phase changes in the model.

However, calculating the rate at which the avalanche transforms potential energy into heat is only one component of the total energy balance. The thermal flow regime of an avalanche is determined by the initial temperature of the starting mass at the release as well as the temperature of the entrained snowcover, (Fig. 2.2). Snowcover temperature profiles can vary, ranging from isothermal distributions to strong temperature gradients in depth [Bozhinskiy and Losev, 1998, McClung and Schaerer, 2006]. The combination of (1) variable release temperature, (2) snowcover temperature that varies with track elevation and depth and (3) the path-dependent evolution of different dissipative processes allows snow avalanches to exhibit a wide range of flow behaviour. The path dependent processes are a function of the avalanche terrain. In this chapter we develop an avalanche dynamics model that accounts for release temperature as well as the influx of thermal energy with snow entrainment. The model facilitates the study of different dissipative mechanisms because it accounts not only for shearing but also the dissipation of the fluctuation energy associated with random particle movements within the avalanche core. We use the model to study four case studies. The question emerges under what snow conditions the calculated temperature rise is large enough to induce meltwater production and the lubrication of sliding surfaces, leading to longer avalanche runouts. We also demonstrate how the spatial distribution of temperature and meltwater can affect avalanche deposition patterns, for example the formation of levees [Bartelt et al., 2012b].
2. Wet snow avalanche model

Figure 2.2: Definition of model domain and coordinate system [Christen et al., 2010]. The starting zone has the initial temperature $T_0$. The snowcover temperature is $T_{\Sigma}$. The avalanche temperature $T_{\Phi}$ increases from the release temperature $T_0$ as a function of the dissipative processes and entrainment. The avalanche core $\Phi$ entrains snow from the snowcover $\Sigma$ at the rate $M_{\Sigma \rightarrow \Phi}$. 

\[ Z(X,Y) \]

\[ Z = 0 \]

\[ \Phi \]

\[ \Sigma \]

\[ T_0 \]

\[ T_{\Sigma} \]

\[ T_{\Phi} \]

\[ \dot{M}_{\Sigma \rightarrow \Phi} \]
2.2 Model Equations

We extend the equations for avalanche flow derived by [Christen et al., 2010] to account for temperature effects. The general system of four differential equations describes the volume, mass, momentum and energy balances of a representative flow volume \( V_\Phi \) (Figs. 2.2 and 2.3). The mathematical description of the mountain terrain is defined using a horizontal \( X-Y \) coordinate system. The elevation \( Z(X,Y) \) is specified for each \((X,Y)\) coordinate pair, typically using digital elevation models with a resolution of one to ten meters. We introduce a local surface \((x,y,z)\) coordinate system with the directions \( x \) and \( y \) parallel to the metric geographic coordinates \( X \) and \( Y \), (Fig. 2.2). The directions \( x \) and \( y \) are the slope parallel directions while the \( z \)-direction is oriented perpendicular to the local \( x-y \) plane.

The equations written in vector form are [Christen et al., 2010]:

\[
\frac{\partial U_\Phi}{\partial t} + \frac{\partial \Phi_x}{\partial x} + \frac{\partial \Phi_y}{\partial y} = G_\Phi \tag{2.1}
\]

A model formulation with four state variables results in:

\[
U_\Phi = (M_\Phi, M_\Phi u_\Phi, M_\Phi v_\Phi, R_\Phi h_\Phi)^T. \tag{2.2}
\]

The flux components \((\Phi_x, \Phi_y)\) are:

\[
\Phi_x = \begin{pmatrix}
M_\Phi u_\Phi \\
M_\Phi u_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\
M_\Phi u_\Phi v_\Phi \\
R_\Phi h_\Phi u_\Phi
\end{pmatrix}, \quad \Phi_y = \begin{pmatrix}
M_\Phi v_\Phi \\
M_\Phi u_\Phi v_\Phi \\
M_\Phi v_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\
R_\Phi h_\Phi v_\Phi
\end{pmatrix}. \tag{2.3}
\]

The source terms \( G_\Phi \) are:

\[
G_\Phi = \begin{pmatrix}
M_\Sigma \to \Phi \\
G_x - S_{\Phi x} \\
G_y - S_{\Phi y} \\
\alpha W_\Phi - \beta R_\Phi h_\Phi
\end{pmatrix}. \tag{2.4}
\]

The velocities \( u_\Phi \) and \( v_\Phi \) are defined in the \( x \) and \( y \) directions, parallel to the topographic slope (Fig. 2.2). The components of \( U_\Phi \) include the mass \( M_\Phi \) per unit area and the avalanche momentum in the directions parallel to the slope, \( M_\Phi u_\Phi \) and \( M_\Phi v_\Phi \), respectively. The remaining state variable is the non-directional kinetic energy associated with the granular velocity fluctuations, \( R_\Phi \) [Bartelt et al., 2006]. The flow height of the core is \( h_\Phi \). The flowing avalanche is driven by the gravitational acceleration in the tangential directions \( G = (G_x, G_y)^T = (M_\Phi g_x, M_\Phi g_y)^T \). The total normal pressure \( N \)
at the base of the avalanche is given by the weight per unit area $N_g$ and the centripetal pressure $N_f$ [Fischer et al., 2012]

$$N = N_g + N_f. \tag{2.5}$$

The total slope-perpendicular acceleration of the flow column is therefore the sum of the slope-perpendicular component of gravity $g_z$ and centripetal acceleration $f_z$:

$$g' = g_z + f_z. \tag{2.6}$$

The total normal pressure is therefore $N = M_{\Phi} g'$. The term $M_{\Sigma \rightarrow \Phi}$ represents the snow influx by entrainment. This term becomes especially important as the mass influx is associated with a corresponding influx of heat energy defined by the snowcover temperature. It will be discussed in the next section. Frictional resistance is given by the Voellmy-type shear stress $S_{\Phi} = (S_{\Phi x}, S_{\Phi y})^T$, with

$$S_{\Phi} = \frac{u_{\Phi}}{||u_{\Phi}||} \left[ \mu(R_{\Phi})N + \rho_{\Phi}g' \frac{||u_{\Phi}||^2}{\xi(R_{\Phi})} \right]; \tag{2.7}$$

that is, the shear stress is a function of the avalanche velocity $u_{\Phi}$, fluctuation energy $R_{\Phi}$ and total pressure $N$ in the $z$-direction. We define the functional dependency of the friction parameters ($\mu$, $\xi$) on $R$ as:

$$\mu(R_{\Phi}) = \mu_0 \exp \left( -\frac{R_{\Phi}}{R_0} \right) \tag{2.8}$$

and

$$\xi(R_{\Phi}) = \xi_0 \exp \left( \frac{R_{\Phi}}{R_0} \right). \tag{2.9}$$

With this frictional model $\mu_0$ and $\xi_0$ are the friction coefficients associated with the volume and therefore the non-fluidized state, $R_{\Phi}=0$. The model parameter $R_0$ defines the activation energy that is required to fluidize the core [Bartelt et al., 2012c].

### 2.3 Thermal Heat Production and Melting

#### 2.3.1 Frictional and Collisional Dissipation

The frictional work rate (dissipation rate) is

$$\dot{W}_{\Phi} = S_{\Phi} \cdot u_{\Phi}. \tag{2.10}$$

Frictional work is required to produce both the fluctuation energy $R_{\Phi}$ and internal heat energy $E_{\Phi}$, see [Bartelt et al., 2006]. As fluctuation energy is produced according to

$$\frac{D(R_{\Phi} h_{\Phi})}{Dt} = \alpha \dot{W}_{\Phi} - \beta R_{\Phi} h_{\Phi}, \tag{2.11}$$
2.3. Thermal Heat Production and Melting

Thermal heat energy is generated according to

\[
\frac{D(E_{\Phi}h_{\Phi})}{Dt} = (1 - \alpha)W_{\Phi} + \beta R_{\Phi}h_{\Phi}. \tag{2.12}
\]

We consider no loss of heat energy by conductive boundary fluxes or radiation. The avalanche stops before cooling processes are relevant [Miller et al., 2003]. Therefore, we consider only thermal heat advection during avalanche motion and do not model diffusive heat transfer within the avalanche flow. For the time scale of the avalanche diffusive processes are small as Peclet numbers are \( Pe >> 1 \) [Incropera and DeWitt, 2002]. Energy conservation requires

\[
\dot{W}_{\Phi} = \frac{D(R_{\Phi}h_{\Phi})}{Dt} + \frac{D(E_{\Phi}h_{\Phi})}{Dt}. \tag{2.13}
\]

Moreover, the frictional work rate \( \dot{W}_{\Phi} \) is split into two parts. One part is dissipated immediately to heat \( E \) while the second part becomes fluctuation energy \( R_{\Phi} \). The splitting fulfills the condition that the sum of the change in kinetic energy \( K \), the change in random kinetic energy \( R_{\Phi} \) and heat energy \( E_{\Phi} \) is equal to the work done by gravity \( W_{\Phi}^g \):

\[
\dot{K} + \frac{D(R_{\Phi}h_{\Phi})}{Dt} + \frac{D(E_{\Phi}h_{\Phi})}{Dt} = \dot{W}_{\Phi}^g. \tag{2.14}
\]

The model parameter \( \alpha \) describes the production rate of random energy from the shear work \( \dot{W}_{\Phi} \). When \( \alpha = 0 \), all frictional shear work is dissipated immediately to heat. No intermediate fluctuation energy can exist in the avalanche. When \( \alpha > 0 \), fluctuation energy is produced from the shear work, but inelastic interactions between snow granules (shearing, collisions, rubbing), cause the fluctuation energy to decay to heat at the rate \( \beta \) [Buser and Bartelt, 2009]. All fluctuation energy created within the avalanche will eventually decay to heat. The model parameters \((1-\alpha)\) and \( \beta \) therefore define the relative production of heat by internal shearing and decay of fluctuation energy, respectively. Typical values of \( \alpha \) are \( \alpha \approx 0.1 \), meaning that 90 percent of thermal energy is generated by shear and only 10 percent by collisional interactions between snow granules.

The temperature \( T_{\Phi} \) is a measure of the internal heat energy \( E_{\Phi} \) contained within the representative volume \( V_{\Phi} \). This volume is defined between the basal boundary and the avalanche top surface given by the flow height \( h_{\Phi} \) with flow density \( \rho_{\Phi} \). The flow volume contains snow in the form of particulate mass and air. The particulate mass is in the form of snow granules and other snowcover fragments that are produced during the release slab break-up and the churning motion of the avalanche core. The flow density of the volume \( \rho_{\Phi} \) is

\[
\rho_{\Phi} = \theta_{\Phi}^i \rho_i + \theta_{\Phi}^a \rho_a + \theta_{\Phi}^w \rho_w \tag{2.15}
\]
2. Wet snow avalanche model

We consider the thermal energy balance within a representative flow volume $V$ in the avalanche core. The height of the core is $h_\Phi$.

where $\theta_i^\Phi$, $\theta_a^\Phi$ and $\theta_w^\Phi$ are the volumetric fractions of ice, air and water (in the avalanche core), respectively. The ratio between internal heat energy $E_\Phi$ and temperature $T_\Phi$ is given by

$$\frac{E_\Phi}{T_\Phi} = \rho_\Phi c_\Phi$$  \hspace{1cm} (2.16)

where $c_\Phi$ is the specific heat capacity of the volume mass (J kg$^{-1}$ K$^{-1}$)

$$c_\Phi = \theta_i^\Phi c_i + \theta_a^\Phi c_a + \theta_w^\Phi c_w$$  \hspace{1cm} (2.17)

where $c_i$ (2110 J kg$^{-1}$ K$^{-1}$), $c_a$ (1012 J kg$^{-1}$ K$^{-1}$) and $c_w$ (4180 J kg$^{-1}$ K$^{-1}$) are the specific heat capacity of ice, air and water respectively [Armstrong and Brun, 2008].

2.3.2 Temperature and entrainment of warm, moist snow

We treat the entrainment of warm, moist snow as a fully plastic collision between the avalanche core $\Phi$ and snow cover $\Sigma$. By definition of a plastic collision, entrained snow is initially at rest, but after the collision with the avalanche all the entrained mass is moving with the avalanche velocity $u_\Phi$. A layer of snow with height $l_\Sigma$, density $\rho_\Sigma$ and temperature $T_\Sigma$ is entrained at the rate $\dot{M}_{\Sigma \rightarrow \Phi}$ (Fig. 2.3). If the entrained snow is moist, in addition to the snow mass, water mass is entrained at the rate $\dot{M}_{\Sigma \rightarrow w}$. The entrained mass
2.3. Thermal Heat Production and Melting

is composed of ice (superscript \( i \)), water (superscript \( w \)) and air (superscript \( a \)),

\[
\dot{M}_{\Sigma \rightarrow \Phi} = \rho_{\Sigma} \dot{l}_{\Sigma} = \rho_i \dot{l}_i + \rho_w \dot{l}_w + \rho_a \dot{l}_a. \tag{2.18}
\]

The snowcover erosion rate \( \dot{l}_{\Sigma} \) is defined by the dimensionless erodibility coefficient \( \kappa \) [Christen et al., 2010],

\[
\dot{l}_{\Sigma} = \kappa \| u_\Phi \|. \tag{2.19}
\]

The wet and dry components of the snowcover are entrained at the same rate, proportional to the volumetric components of the snow layer

\[
\dot{l}_i = \theta_i \dot{l}_{\Sigma} \quad \dot{l}_w = \theta_w \dot{l}_{\Sigma} \quad \dot{l}_a = \theta_a \dot{l}_{\Sigma} \tag{2.20}
\]

where \( \theta \) is the volumetric component of ice, water and air, \( \theta_i = \dot{l}_i / \dot{l}_{\Sigma} \), etc.

The total snow mass that is entrained is

\[
\dot{M}_{\Sigma \rightarrow \Phi} = \rho_{\Sigma} \kappa \| u_\Phi \|. \tag{2.21}
\]

The entrained water mass is therefore,

\[
\dot{M}_{\Sigma \rightarrow w} = \theta_w \dot{M}_{\Sigma \rightarrow \Phi}. \tag{2.22}
\]

The thermal energy entrained during the mass intake is

\[
\dot{Q}_{\Sigma \rightarrow \Phi} = \left[ \theta_i c_i + \theta_w c_w + \theta_a c_a + \frac{1}{2} \frac{\| u_\Phi \|^2}{T_{\Sigma}} \right] \dot{M}_{\Sigma \rightarrow \Phi} T_{\Sigma} \tag{2.23}
\]

When the snow layer contains water \( \theta_w > 0 \), then the temperature of the entire layer is set to \( T_{\Sigma} = 0^\circ \text{C} \). Equation 2.23 takes into account the production of heat energy during the plastic collision. In this entrainment model no random kinetic energy is generated because the entrainment process is considered a perfectly plastic collision.

2.3.3 Wet snow avalanche flow rheology

Wet snow avalanches are regarded as dense granular flows in the frictional flow regime [Voellmy, 1955, Bozhinskiy and Losev, 1998]. Measured velocity profiles exhibit pronounced visco-plastic like character and are often modelled with a Bingham-type flow rheology [Dent and Lang, 1980, Norem et al., 1987, 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., 2012a, 2015].
To model wet snow avalanche flow we extend ideas first suggested by [Voellmy, 1955] and adopted in the Swiss guidelines on avalanche calculation [Salm et al., 1990, Salm, 1993]. Voellmy proposed a frictional resistance $S_\Phi = (S_{\Phi x}, S_{\Phi y})$ consisting of both a Coulomb friction $S_\mu$ (coefficient $\mu$) and a velocity dependent stress $S_\xi$ (coefficient $\xi$):

$$S_\Phi = \frac{u_\Phi}{\|u_\Phi\|} \left[ S_\mu + S_\xi \right]. \quad (2.24)$$

Voellmy maintained that the Coulomb friction term decreased to zero $S_\mu \to 0$ for two extreme avalanche flow regimes: powder snow avalanches and wet snow avalanches. In these cases, avalanche velocity was determined purely by the velocity dependent stress $S_\xi$. This is given by

$$S_\xi = \rho_\Phi g \frac{\|u_\Phi\|^2}{\xi}. \quad (2.25)$$

The Coulomb friction term was neglected for powder avalanche flow because of the dispersive, fluidized character of the avalanche core. In wet snow avalanche flow, the decrease of Coulomb shear stress is due to meltwater lubrication. To model the decrease in friction from either dispersion or meltwater lubrication we make the Coulomb stress dependant on the random kinetic energy $R_\Phi$ and meltwater water content $h_w$.

$$S_\mu = \mu(R_\Phi, h_w) N \quad (2.26)$$

to arrive at a general friction law, valid for both dry and wet avalanche flows. This relation will model the decrease in friction when the avalanche is highly fluidized and when the water content reaches a sufficient amount that lubrication cannot be neglected.

Because we employ a depth-averaged model to calculate the bulk avalanche temperature $T_\Phi$ we have no information to define the depth in the avalanche flow core where melting occurs. The dissipation rate depends on the internal shear distribution, which can be concentrated at the bottom surface of the avalanche, or distributed 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 standard Coulomb friction coefficient $\mu$

$$\mu(R_\Phi, h_w) = \mu_w + (\mu_d - \mu_w) \exp \left[ -\frac{h_w}{h_s} \right]. \quad (2.27)$$

where $\mu_d$ is the dry Voellmy friction coefficient, $\mu_w$ is the limit value of lubricated friction (Voellmy assumed this value to be $\mu_w = 0$ in the limiting case) and $h_s$ is a scaling factor describing the height of the shear layer where
2.3. Thermal Heat Production and Melting

Figure 2.4: Voellmy plot showing the dependence of the friction parameter $\mu$ with random kinetic energy $R_\Phi$ and water content $h_w$ according to Eq.(2.27), $S_\mu \to 0$. Non-fluidized wet snow avalanches will not stop on slopes steeper than $9^\circ$ when they contain fully saturated lubrication layers, $\mu(R_\Phi, h_w) \approx 0.15$ for $h_w = h_m$ and $R_\Phi \approx 0$.

Meltwater is concentrated (Fig. 2.4). The dry friction $\mu_d$ depends on the avalanche configuration,

$$\mu_d = \mu_0 \exp \left[ -\frac{R_\Phi}{R_0} \right]$$

where $\mu_0$ is the dry Coulomb friction associated with the flow of the co-volume, which we take to be $\mu_0 = 0.55$, see [Buser and Bartelt, 2015]. The parameter $R_0$ defines the activation energy for fluidization, which is a function of the particle cohesion [Bartelt et al., 2015].

Meltwater production is considered as a constraint on the flow temperature of the avalanche: the mean flow temperature $T_\Phi$ can never exceed the melting temperature of ice $T_m = 273.15 \, K$. The energy for the phase change is given by the latent heat $L$

$$\dot{Q}_m = L \dot{M}_m$$

under the thermal constraint such that within a time increment $\Delta t$

$$\int_0^{\Delta t} \dot{Q}_m \, dt = M_\Phi c(T_\Phi - T_m) \quad \text{for} \quad T > T_m.$$
2. Wet snow avalanche model

When the flow temperature of the avalanche does not exceed the melting temperature, no latent heat is produced, $\dot{Q}_m = 0$. When the flow temperature of the avalanche exceeds the melting temperature, the energy associated with the difference is used to drive the phase change instead of raising the temperature (Eq. 2.30). Thus, the temperature never exceeds the melting temperature $T_m$ (Fig. 2.5). This procedure is dependent on the size of the time step, which controls the magnitude of the imbalance between $T_\Phi$ and $T_m$. The length of the time increment is defined by the numerical time integration scheme of the vector equations.

The mass of meltwater in the avalanche core $M_w$ is characterized by the height $h_w$ defined by the density of water $M_w = \rho_w h_w$. This height, measured from the avalanche running surface, is compared to the height $h_s$. We approximate the height $h_s$ using measured shear layers of wet avalanche flows which show $0.01 \, \text{m} \leq h_s \leq 0.10 \, \text{m}$, see [Dent and Lang, 1983, Dent et al., 1998, Bartelt et al., 2005, Kern et al., 2009]. When the water content reaches the height $h_w$ compared to the shear layer height $h_s$ the friction function $\mu(R_\Phi, h_w)$ decreases according to Eq. 2.27 (see Fig. 2.5)

The parameter $\mu_s$ defines the Coulomb friction when the layer $h_s$ is saturated, $h_w \approx h_s$. We take $\mu_w = 0.12$. This ensures that dense, non-fluidized wet snow avalanches will continue to flow on slopes steeper $7^\circ$ when they contain fully saturated lubrication layers.

### 2.3.4 Wet snow avalanche model summary

The thermal energy equation Eq. 2.12 and meltwater production and transport equations Eq. 2.30 can be added to the general system of model equations Eqs. 2.3. It is convenient for numerical solutions to write these equa-
tions in compact matrix form,
\[
\frac{\partial U_\Phi}{\partial t} + \frac{\partial \Phi_x}{\partial x} + \frac{\partial \Phi_y}{\partial y} = G_\Phi. \tag{2.31}
\]

A model formulation with six state variables results:
\[
U_\Phi = (M_\Phi, M_\Phi u_\Phi, M_\Phi v_\Phi, R_\Phi h_\Phi, E_\Phi h_\Phi, M_w)^T. \tag{2.32}
\]

The flux components \((\Phi_x, \Phi_y)\) are:
\[
\Phi_x = \begin{pmatrix} M_\Phi u_\Phi \\ M_\Phi u_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\ M_\Phi u_\Phi v_\Phi \\ R_\Phi h_\Phi u_\Phi \\ E_\Phi h_\Phi u_\Phi \\ M_w u_\Phi \end{pmatrix}, \quad \Phi_y = \begin{pmatrix} M_\Phi v_\Phi \\ M_\Phi v_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\ M_\Phi u_\Phi v_\Phi \\ R_\Phi h_\Phi v_\Phi \\ E_\Phi h_\Phi v_\Phi \\ M_w v_\Phi \end{pmatrix}. \tag{2.33}
\]

The source terms \(G_\Phi\) are
\[
G_\Phi = \begin{pmatrix} \dot{M}_{\Sigma \rightarrow \Phi} \\ G_x - S_{\Phi x} \\ G_y - S_{\Phi y} \\ \alpha \dot{W}_\Phi - \beta R_\Phi h_\Phi \\ (1 - \alpha) \dot{W}_\Phi + \beta R_\Phi h_\Phi + \dot{E}_{\Sigma \rightarrow \Phi} h_\Phi - \dot{M}_m L_f \\ \dot{M}_m + \dot{M}_{\Sigma \rightarrow w} \end{pmatrix}. \tag{2.34}
\]

The mass \(M_\Phi\) contains both the ice mass of the flowing snow as well as the meltwater \(M_w\). Therefore, there is no momentum exchange between the snow ice and liquid phases. The model was applied to simulate four case studies. The equations are solved using the same numerical schemes outlined in [Christen et al., 2010].

2.4 Model Calculations

2.4.1 Temperature entrainment calculations on an inclined plane

To investigate the relationship between release temperature \(T_0\), entrainment temperature \(T_\Sigma\) and slope angle, we applied the model to simulate avalanche flows on an infinite inclined plane, Fig. 2.6. The simulation series allowed us to investigate model results without considering variations in natural terrain. The slope angle was varied to produce different frictional dissipation rates in the avalanche core. We performed three sets of simulations: (1) identical released mass at the same initial temperature with no entrained snow at three different slope angles, (2) identical released mass at the same slope angle with four different initial temperatures and (3) identical mass released
at identical temperature and slope angle entraining snow at two different
temperatures, see Table 2.4.1. The grid size and friction parameters were
kept constant to allow a comparison between the simulation results. In all
three case studies the release depth was set to \( h_0 = 1 \) m; release density \( \rho_0 = 300 \) kg m\(^{-3}\). When entrainment was specified, the entrainment height and
density was also kept constant, \( h_\Sigma = 0.20 \) m and \( \rho_\Sigma = 300 \) kg m\(^{-3}\).

The increase of the snow flowing temperature \( T_\Phi \) for flows at different slope
angles with no entrained mass show that the model correctly dissipates en-
ergy proportional to the vertical height drop (the total change in potential
energy); that is, there is no influence on the slope angle on dissipation rate
for constant friction parameters, (Fig. 2.7). The total temperature rise is
constant for the same vertical drop, but the flows on the steeper slope reach
the final temperature faster, (higher slope angle leads to faster speed and
faster warming but the total energy dissipated is always proportional to the
vertical drop, therefore the final dissipated energy will be the same). The
example simulation on a 25\(^\circ\) slope angle stopped before reaching \( T_\Phi = 0^\circ\).
With no entrainment the avalanche stopped flowing after two hundred me-
ters of vertical drop (Fig. 2.7).

In the next series of numerical experiments, we held the slope angle of the
plane constant (\( \phi = 35^\circ \)) but varied the release temperature \( T_0 \) and the en-
trained mass temperature \( T_\Sigma \), (Fig. 2.8). We investigated four release tem-
peratures \( T_0 = -2, -4, -6, -8 \) \(^\circ\)C. For the case with no entrainment, the rise
in avalanche temperature with vertical drop is constant, indicating the con-
stant dissipation rate, (Fig. 2.8). When entrainment is included \( T_\Sigma = 0^\circ\)C
and \( T_\Sigma = -2^\circ\)C, the temperature rise with vertical drop is no longer constant.
In fact, the slope of the temperature rise increases with relative difference
between the release temperature and entrainment temperature. Although
the influx of heat energy is the same, the averaging procedure leads to a
slightly higher warming rate for colder release zone temperatures. In com-
parison to frictional heating, entrainment appears to be a more effective way
to increase the average temperature of the avalanche for this case with this
amount of mass released. Higher entrainment temperatures lead to higher
warming rates (Fig. 2.8b). An avalanche that starts as a cold slab can reach
high temperatures quickly by entraining warm snow. In this case study the
rise in temperature without entrainment was approximately +1\(^\circ\)C per 200 m
of vertical drop. When entraining snow at \( T_\Sigma = 0^\circ\)C we find the rise in tem-
perature to approximately +2\(^\circ\)C per 100 m of vertical drop; that is, almost
four times higher than the case without entrainment.
2.4. Model Calculations

Figure 2.6: Three series of simulations where carried on an infinitely long inclined plane, see Table 2.4.1. The slope angle $\phi$, release temperature $T_0$ and entrained snow temperature $T_\Sigma$ varied in the simulation. The output displays the maximum calculated temperatures when the flow stops.

Table 2.1: Summary of input and simulation parameters for the numerical experiments on an infinite inclined plane, (Fig. 2.6).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Slope angle Simulations 1</th>
<th>Release $T_0$ Simulations 2</th>
<th>Entrainment $T_\Sigma$ Simulations 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid size</td>
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<td>2 m</td>
<td>2 m</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>$\xi_0$</td>
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<td>1300 ms$^{-2}$</td>
<td>1300 ms$^{-2}$</td>
</tr>
<tr>
<td>$\alpha$</td>
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<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>$\beta$</td>
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<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$V_0$</td>
<td>326 m$^3$</td>
<td>326 m$^3$</td>
<td>326 m$^3$</td>
</tr>
<tr>
<td>$h_0$</td>
<td>1 m</td>
<td>1 m</td>
<td>1 m</td>
</tr>
<tr>
<td>$\rho_\Sigma$</td>
<td>No erosion</td>
<td>300 kg m$^{-3}$</td>
<td>300 kg m$^{-3}$</td>
</tr>
<tr>
<td>$h_\Sigma$</td>
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<td>no erosion</td>
<td>0.20 m</td>
</tr>
<tr>
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<td>-2, -4, -6, -8 °C</td>
<td>-2, -4, -6, -8 °C</td>
</tr>
<tr>
<td>$T_\Sigma$</td>
<td>No erosion</td>
<td>No erosion</td>
<td>0, -2 °C</td>
</tr>
<tr>
<td>Slope Angle</td>
<td>25°, 30°, 35°</td>
<td>35°</td>
<td>35°</td>
</tr>
</tbody>
</table>
2. Wet snow avalanche model

Figure 2.7: Temperature calculations performed on the incline plane with identical mass and initial temperature but with three different slope angles 25°, 30°, and 35° and no entrained mass. Note that temperature gradient with vertical drop is the same for the three cases. However, the example calculated with 25° did stop before reaching zero degrees, whereas the other two cases reached zero degrees after dissipating the same amount of potential energy (around 380 vertical meters).

2.4.2 Gatschiefer and Salezer avalanches.

The Gatschiefer (Klosters, Switzerland) and Salezer (Davos, Switzerland) avalanches occurred spontaneously on the afternoon of April 23rd, 2008. Both avalanches started as dry-slab avalanches and ended as wet snow avalanches. They are well-documented events as aerial laser scanning of the release and deposition zones was performed. Aerial photographs helped delineate the exact extent of the release zones. Furthermore, it was possible to enter the runout zones several hours after release to investigate depositional features [Bartelt and McArdell, 2009, Bartelt et al., 2012b]. Temperatures at the time of release could be determined from a local weather station that are located less than a kilometer away from the starting zones. The stations measured both air and snow surface temperatures. The Gatschiefer avalanche was fortunately recorded by chance by a passing bus driver; therefore, front velocities could be estimated by video analysis, see (http://www.youtube.com/watch?v=kgY43LZ8o94).

The Gatschiefer avalanche started from two main release areas, (Fig. 2.9). The first area was large (141,000 m²) and located at an elevation of 2200m. The fracture crown extended 250 m along the mountain crest. The second release area was smaller (21,000 m²) and located at an elevation of 2100 m. The entire snowcover released from both areas. From laser scan measurements
2.4. Model Calculations

Figure 2.8: Temperature calculations performed on the incline plane with identical slope angle, 35° and identical initial mass but varying the temperature of the released mass. a) Different released temperatures from $-2^\circ C$ to $-8^\circ C$ entraining snow of $0^\circ C$ (dashed line) and with no entrainment (solid line). Note that with no entrainment the avalanche stops before reaching $0^\circ C$, but entraining snow of $0^\circ C$ the avalanches reached the melting point after different vertical drops depending on the initial temperature. b) Different released temperatures from $-2^\circ C$ to $-8^\circ C$ entraining snow of $0^\circ C$ (dashed line) and $-2^\circ C$ (solid line). The varying slope angles of the lines in the graph are results of the relative temperature differences between released and entrained snow.

the mean fracture height of the large area was estimated to be 2.5 m. The fracture height of the secondary release zone was determined to be 1.6 m. Immediately below the upper release zone the avalanche deposited 194,000 m³ of snow on a terrain terrace, (Fig. 2.9). Assuming a release density of 300 kg m⁻³ and a deposition density of 500 kg m⁻³ the deposited mass in this region corresponds to 83 percent of the total release mass. Thus, 192,100 m³ (57,630 tons) of snow continued down into the track from both release areas. From the laser scanning measurements, the estimated volume of the lower deposit was 153,000m³. Assuming a deposit density of 500 kg m⁻³, the mass of the deposit was over 77,000 tons. Thus, the avalanche increased in mass by 18,870 tons. Assuming a potential erosion area of 280,000 m², this corresponds to an average entrainment depth of $h_\Sigma = 0.17$ m (of snow with a density of 400 kg m⁻³), [Sovilla et al., 2012].

The mean snowcover temperature of the release zones ($T_0 = -1 ^\circ C$) was esti-
2. Wet snow avalanche model

estimated from snow surface temperature measurements from weather station in the neighbouring area, less than 200 m distant from the starting zone. We estimated the temperature of the snow at lower elevations to be warmer, $T_\Sigma = 0^\circ C$, (see Table 2.2). The avalanche event was simulated using the data from the laser scan and weather station as initial values for release heights and temperature. It was possible to simulate the snow deposited on the terrain terrace. The total volume that reached the valley bottom is in good agreement with the laser scan measurements. The simulation results indicate that the flow temperature of the avalanche reaches $T_\Phi = 0^\circ C$ after descending 200 m of vertical elevation, (Fig. 2.10). After 300 meters of vertical drop the entire flowing mass is at $T_\Phi = 0^\circ C$ and considerable melting occurs. Meltwater contents reached 10 mm m$^{-2}$, $h_w = 0.01$ m, (Fig.2.11 and Fig.2.13). Snow that departed from the primary release area and was deposited on the upper terrace did not reach the melting point. A large amount of snow stopped before the avalanche reached the melting temperature. There is good agreement between the measured and simulated extent and height of the avalanche deposits in the runout zone. The avalanche did not fluidize and flowed as a dense flowing avalanche at a speed of 5 m s$^{-1}$ in the runout zone. The deposition occurred in two waves. The measured velocities from video recordings was estimated to be 5 m s$^{-1}$, in agreement with the calculations, (Fig.2.11). At the end of the runout the entire snow mass within the avalanche is at zero degrees, (Fig.2.10). We performed an additional simulation setting $T_0 = T_\Sigma = -5^\circ C$. The avalanche stopped completely on the upper plateau and did not reach the runout zone.

The Salezer avalanche was also characterized by multiple releases, probably triggered at the same time, (Fig.2.13). In comparison to Gatschiefer, the release zones are located at a higher elevation, between 2400 m and 2200 m and the mean release temperatures are slightly lower, $T_0 = -2 ^\circ C$. Observations revealed full-depth fracture planes. Laser scanning measurements outside of the avalanche path estimated the snowcover depth before the avalanche to be on average 0.9 m. This value was used to determine the avalanche fracture height. The temperature of the snowcover was determined from the weather station in the neighbouring area (Weissflujoch, Davos), $T_\Sigma = 0 ^\circ C$. The estimated release volume is approximately 67,000 m$^3$. The measurements revealed that 35,750 m$^3$ of snow was deposited in the runout zone. Thus, 31,250 m$^3$ of snow was deposited at the upper terrace. Assuming a density of 300 kg m$^{-3}$ for the release zone and 400 kg m$^{-3}$ for the deposition zone, the avalanche entrained an additional 3,575 tons of snow. Because the potential entrainment area is approximately 120,000 m$^2$, the average entrainment depth is $h_\Sigma = 0.10$ m. Most of the Salezer avalanche path is located in a narrow gully. Entrainment volumes were subsequently smaller than in the Gatschiefer case study.

This event is interesting because frictional heating, not entrainment, is the
2.4. Model Calculations

Figure 2.9: Gatschiefer avalanche a) Avalanche release area and and upper avalanche track. b) Closer view from the release areas and deposit no. 1. A large part of the initial released area was deposited at the deposit no. 1 [Sovilla et al., 2012].

Figure 2.10: (a) Gatschiefer avalanche and (b) Salezer avalanche snow temperature calculations. In both cases the model predicted the avalanche began producing meltwater only a few meters of vertical drop. Both avalanches flowed at $0^\circ$ C until the final deposition.
Figure 2.11: a) Gatschiefer avalanche maximum calculated velocity. The calculated maximum velocities agree with the observed front velocities from the video recording [Sovilla et al., 2012]. b) Calculated meltwater production. The model predicts the maximum meltwater production at the point of maximum velocity.
Table 2.2: Summary of input and simulation parameters for the avalanche simulations at the different case studies. 1) Gastschiefer Avalanche 2) Salezer Avalanche

<table>
<thead>
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<th>Salezer, Switzerland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid size</td>
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<td>5 m</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>$\xi_0$</td>
<td>1300 ms$^{-2}$</td>
<td>1300 ms$^{-2}$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>$V_0$</td>
<td>93800 m$^3$</td>
<td>64900 m$^3$</td>
</tr>
<tr>
<td>$h_0$</td>
<td>1.5 m</td>
<td>0.9 m</td>
</tr>
<tr>
<td>$\rho_\Sigma$</td>
<td>400 kg m$^{-3}$</td>
<td>400 kg m$^{-3}$</td>
</tr>
<tr>
<td>$l_\Sigma$</td>
<td>0.17 m</td>
<td>0.10 m</td>
</tr>
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<td>$T_0$</td>
<td>-1 °C</td>
<td>-2 °C</td>
</tr>
<tr>
<td>$T_\Sigma$</td>
<td>0 °C</td>
<td>0 °C</td>
</tr>
</tbody>
</table>

primary heating mechanism. As in the case of the Gatschiefer avalanche, the Salezer avalanche quickly reached the melting temperature in the upper regions of the flow path, (Fig. 2.10). The model predicts that considerable melting occurred before the avalanche exited the narrow gully and stopped on the 18° degree runout zone, see (Fig. 2.12 and Fig. 2.14). The avalanche fluidized only in the upper regions of the path where the slopes were steep ($\alpha = 0.08$, $\beta = 1.0$ s$^{-1}$, see Table 2.2). In the runout zone the flow velocities were smaller than 2 m/s (Fig. 2.14).

2.4.3 Andina Copper Mine, Chile

The Andina copper mine is located 100 km to the North-East of Santiago de Chile in the 'Cajon del Rio Blanco' valley in Chile. The mine is at the end of the North-South oriented valley 35 km long. The valley entrance is located at 1700 m and the mine is situated at its end on a glacial bed at 4200 m. Since the valley is north-south oriented, the avalanche paths start at slopes with East or West facing aspect. The avalanche paths start mostly on an open slope at high altitudes (from 3200 to 4500 m) and become channelized through rough terrain until they reach the valley bottom, endangering the mine service road. From km. 21 to km. 28 the valley becomes narrower and all the avalanche paths jeopardize the mine service road. Due to the maritime climate of the region, most of the avalanches contain warm, moist snow. Avalanche sizes range from mid-sized ($V=20,000$ to $30,000$ m$^3$ Fig. 2.15) to very large, catastrophic avalanches ($V>100,000$ m$^3$) that can reach lower elevations. The mid-sized avalanches can occur several times per winter after significant snowfalls.
2. Wet snow avalanche model

On the 9\textsuperscript{th} of September, 2013, a wet snow avalanche released at 14:00 hours at 3245 m after two days of intense thermal cycling (Fig. 2.15). An automatic weather station located 300 m above the release area measured an air temperature of 7\textdegree C at release. Furthermore, the snow surface temperature was 0\textdegree C for the three hours before the release. The avalanche started as a point release below a rock band and eroded the uppermost snow layer and spread across the slope while flowing down reaching a width of 150 m at the runout (Fig. 2.15). The erosion depth of 30 cm was measured in the field the day after the avalanche released. This value coincides with the snow layer saturated with water observed from snow pit measurements performed four hours before the avalanche occurred at 14:00. The runout reached the valley bottom and stopped at a mine service road. The mean height of the deposits was 1.5 m.

Figure 2.12: (a) Salezer avalanche and (b) Gatschiefer avalanche calculated meltwater profile. Both profiles are positioned at the middle of the avalanche flow.
2.4. Model Calculations

Figure 2.13: a) Aerial image from the Salezer avalanche 23\textsuperscript{th} of April, 2008 (Davos). Release occurred between 2200 and 2400 m. The avalanche flowed through a gully with a shallow snowcover b) Closer view of the avalanche deposits in the runout zone. Photo Wilhem (2008).

Figure 2.14: (a) Salezer avalanche maximum calculated velocity . (b) Calculated meltwater production. The maximum meltwater production occurred in the gully.
Figure 2.15: Image from the avalanche occurred at km 28 at the Andina mine in ‘Cajon del Rio Blanco’ valley, Chile on the 9th of September, 2013. The avalanche started as a point release below a rock band and eroded the warmer uppermost snowcover reaching a mine service road. Photo Vera, SLF. The calculated model velocity reached 18 m/s at the steepest track segment.
2.4. Model Calculations

We simulated the avalanche by specifying a triangular shaped release area of 900 m$^2$ and 30 cm of entrainment depth, reproducing the observed avalanche starting conditions. The starting mass had a temperature of $T_0 = 0$°C, (see Table 2.3). The model predicted correctly the deposition and runout on the mine access road, (Fig. 2.15). Since the initial snow temperature was $T_0 = 0$°C, flowing snow began to melt immediately (Fig. 2.16), producing meltwater which was transported with the flow. The meltwater production reached a total of 1.5 mm m$^{-2}$ (Fig. 2.16). The maximum calculated speed of 18 m s$^{-1}$ agrees with the field observations made by the winter operation crew at the road (Fig. 2.15).

2.4.4 Bird Hill, South Central Alaska

Bird Hill is a 3.2 km long ridge, on average 1000 m and south-south east facing, between Girdwood and Bird Point along the Turnagain Arm in south central Alaska. The steepest sections are in the upper elevations above 700 m (up to 70°), which translates into, on average, 30° slopes continuing to sea level (Fig. 2.17). The Seward Highway and the Alaska Railroad are situated on a narrow strip of land between the terminus of the slope and the ocean. The ridge consists of approximately 25 topographically similar avalanche paths. Avalanches frequently hit the highway and the railroad, counting for 24% of all the avalanches reported by the Seward Highway Avalanche Program between 1979 and 2013. At Bird Hill, small to medium-sized avalanches (up to $\approx 0.5$ m fracture height, $< 50 000$ m$^3$ release volume) have historically exhibited surprisingly long runout distances and debris piles on the highway and the railroad, indicating significant snow entrain-
2. Wet snow avalanche model

Figure 2.17: Avalanche calculations in Whiskey no. 934, Alaska. Release is situated at 1000 m.a.s.l and finishes on the coast line. The left column ((a), (c), (e)) shows the flow height, velocity and temperature calculations for an example calculated with $T_0 = -2°C$ and $T_Σ = -1°C$. On the right column ((b), (d), (f)) are shown the same calculations but modifying the release temperature and the entrainment temperature to $T_0 = -4°C$ and $T_Σ = -4°C$. Note the difference in runout distance and velocity between both simulations after modifying the initial temperature conditions.
2.4. Model Calculations

Figure 2.18: (a) Calculated erosion rate with $T_0 = -2^\circ C$ and $T_\Sigma = -1^\circ C$ and (b) meltwater production in Whiskey no. 934 avalanche. Note that the meltwater production occurs after 200 hundred meters of vertical drop (800 m.a.s.l.), which coincides with the highest calculated velocity (Fig. 2.17) and the highest entrainment rate.

Figure 2.19: Meltwater calculations in Whiskey no. 934 for an example calculated with $T_0 = -2^\circ C$ and $T_\Sigma = -1^\circ C$. In black the meltwater produced along the track. In red the same meltwater produced and also transported with the advection velocity of the avalanche (Eq.2.33).
2. Wet snow avalanche model

Figure 2.20: Entrainment mass for the two examples: $T_0 = -2^\circ C$ and $T_\Sigma = -1^\circ C$ in black line and $T_0 = -4^\circ C$ and $T_\Sigma = -4^\circ C$ in red line. The first avalanche continued flowing at mid-elevation and entrained warm snow until the end of the slope (Fig. 2.17). The second avalanche with colder snow stopped earlier before reaching the melting point, (Fig. 2.17).

Coastal south central Alaska’s maritime snow climate is characterized by large snow storms and strong winds, most often due to a dominant low pressure system over the Gulf of Alaska [Hendrikx et al., 2013] that is in its strongest phase in January [Mock, 1996]. Air temperatures as high as $+10^\circ C$ are possible as a result of occasional warm, downslope winds that move westward through the Turnagain Arm [Mock, 1996].

A set of hypothetical avalanches were modelled in the avalanche path named Whiskey no. 934 at Bird Hill to compare avalanche runout distances resulting from variable snowcover temperatures. A release volume of approximately 10,300 m$^3$ (fracture height 0.5 m) was simulated with release snow temperature from $T_0 = -4^\circ C$ to $-1^\circ C$. The entrainment height was 0.25 m and simulations with snow temperatures $T_\Sigma =0^\circ C$, $-0.5^\circ C$, $-1^\circ C$, $-2^\circ C$ and $-4^\circ C$ were performed, (see Table 2.3).

The avalanches consistently accelerated in the upper steep section of the path and decelerated around 600 m, where the slope lessens to $\approx 30^\circ$. The avalanches continued flowing below this point with different flow characteristics depending on the temperature of the entrained snow. $T_0 = T_\Sigma = -4^\circ C$ resulted in an avalanche that stopped early (Fig. 2.17d). However, simulating a theoretical avalanche with $T_0 = -2^\circ C$ and $T_\Sigma = -1^\circ C$ reached the road at the bottom of the slope, with speeds close to 18 m/s and flow heights of 2 meters (Fig. 2.17a and c). The warmer example entrained snow close to the melting point, the snow temperature reaches zero degrees after less than two hundred meters of vertical drop, (Fig.2.17e) and starts producing meltwater. The meltwater decreases the friction (Eq. 2.27). The combined effect
2.5 Discussion and Conclusions

Table 2.3: Summary of input and simulation parameters for the avalanche simulations at the different case studies. 1) Andina mine, Chile 2) Bird Hill, Alaska

<table>
<thead>
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<th>Bird Hill, Alaska</th>
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<td>$\mu$</td>
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<td>350 kg m$^{-3}$</td>
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<tr>
<td>$T_\Sigma$</td>
<td>0 °C</td>
<td>0, 0.5, -2, -4, °C</td>
</tr>
</tbody>
</table>

of decreasing friction and entraining warm snow increases the avalanche runout. The snow temperature of entrained snow determined the elevation for where this process occurs, (Fig. 2.18). When the initial release snow temperature is warm and the avalanche encounters even warmer snow temperatures at mid-elevation, entrainment is facilitated and the avalanche is capable of increasing its mass significantly (Fig. 2.20). Any combination of warmer release temperature and entrainment temperature than the one showed in Fig. 2.17 will result with an avalanche reaching the bottom of the slope. Although meltwater is produced in the transition zone (Fig. 2.19), it is advected with the flow, and the meltwater content reaches high values at the bottom of the slope in the deposition zone. In this case study, meltwater advection (Eq. 2.33) appears to be an important transport mechanism to describe the mobility of avalanches in the runout zone.

2.5 Discussion and Conclusions

In this chapter we have extended an existing avalanche dynamics model to calculate the flow temperature and meltwater production within the avalanche core. The model includes two dissipative processes that lead to a rise in avalanche temperature. It can be used with a wide range of initial snow release and snow entrainment conditions. The model allows us to simulate wet snow avalanches and dry snow avalanches separately, but also allows us to study the case of an avalanche starting as a dry-cold avalanche and transforming into a wet snow avalanche because it entrains warm moist snow along the avalanche path.
We draw three main conclusions from our analysis and applications:

1. The temperature rise from frictional heating has the magnitude of degrees. The exact amount will depend on the size of the avalanche and distance the avalanche travels. This modest temperature rise is significant only when the release temperature \( T_0 \) is close to zero degrees or slightly lower. Only then can sufficient meltwater be produced to lubricate the motion of the avalanche. Avalanches that start in cold conditions (e.g. \( T_0 < -5 \, ^\circ \text{C} \)) and entrain cold snow (e.g. \( T_\Sigma < -2 \, ^\circ \text{C} \)) will not change phase under most topographic conditions.

2. Snow entrainment is the dominating process that controls the avalanche temperature and therefore flow regime. Warm, dense snow can quickly change the thermal flow regime of the avalanche, even when the starting temperatures are cold (for example \( T_0 < -5 \, ^\circ \text{C} \)). Long-running wet snow avalanches are possible when warm, moist snow can be entrained. For example, the likelihood of an avalanche hitting the highway in the Alaska and Chile case studies should not only be linked to the amount of erodible snow at mid-elevation, but also to the temperature and density of the snowcover that potentially can be entrained. Warming of the snow surface as a result of strong solar radiation or a sudden increase of air temperatures is worth close attention for more accurate forecasts of avalanche runout. Rain on snow, a common occurrence in maritime regions, introduces both heat and meltwater into the snowcover and therefore has a strong influence on avalanche flow regime.

3. When the avalanche reaches \( T_\Phi = T_m \), meltwater production depends on the dissipation rate. The dissipation rates are generally the highest in the main body of the avalanche where flow heights and speeds are large. They decrease towards the lateral edges of the flow. Meltwater therefore accumulates in the avalanche interior behind the avalanche front. The spatial variation of temperature and meltwater production therefore explains several features of avalanche deposits, such as location of glide planes with refrozen surfaces. These are often located upslope of the avalanche front between levee sidewalls [Bartelt et al., 2012b]. Meltwater lubrication therefore assists the formation of levees that are a common feature of wet snow avalanche flows.

Currently the model does not take into account the distribution of temperature in the z slope perpendicular direction. In the future it might be necessary to model this temperature distribution, for example when modelling lubrication processes at the basal boundary. However, at present, the streamwise variations in temperature in the slope-parallel directions are of primary interest. We find significant variations in both width and flow length of the avalanche. This creates spatial variations in flow temperature. The impor-
tance of this result is that experimental investigations with snow avalanches should be able to measure these variations at a particular location in time. This would make the application of thermal cameras a useful addition to other videogrammetric measurements. If it is possible to measure the thermal initial and boundary conditions, it might even be possible to reconstruct snow entrainment rates from measured temperature histories. Our results reveal that measured temperatures would contribute to a better understanding of other point measurements (pressure, velocity) because temperature is a path-dependent variable that contains much of the avalanche history. The prerequisite for such an analysis is a physical model that accounts for the complex nature of dissipative processes in snow avalanches. Our driving conjecture is that these processes are not only linked to friction in the slope-parallel direction, but also to the heat produced by granular interactions in the avalanche core. Each of these processes has a different dissipation rate and depends on the avalanche flow regime.

Another problem is apparent in our calculations. We applied a phenomenological rule relating the meltwater content to the frictional parameter $\mu$, (Eq.2.27). This rule allows us to fit the measured runout and deposition heights of the wet snow avalanches we have observed in four field studies. Our basic postulate is that the total meltwater content per square meter of flow area is a good proxy for the reduction of flow friction and the lubrication of the basal surface. We do not have to account for detailed distributions in the $z$-direction of the avalanche but assume that lubricated sliding on the basal surface is the dominant frictional mechanism controlling the runout of wet snow avalanches. The entire meltwater is collapsed down onto the flow area, as is common with depth-averaged models. Shear is concentrated at the basal layer where frictional heating is large and meltwater production high. We model a plug-like flow behaviour, see [Nishimura and Maeno, 1987, Dent and Lang, 1980, Dent et al., 1998, Kern et al., 2009].
Chapter 3

Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

Summary

Mining activities in cold regions are vulnerable to snow avalanches. Unlike operational facilities, which can be constructed in secure locations outside the reach of avalanches, access roads are often susceptible to being cut, leading to mine closures and significant financial losses. In this chapter we discuss the application of avalanche runout modelling to predict the operational risk to mining roads, a longstanding problem for mines in high-altitude, snowy regions. We study the 35 km long road located in the “Cajon del Rio Blanco” valley in the central Andes which is operated by the Codelco Andina copper mine. In winter and early spring this road is threatened by over 100 avalanche paths. If the release and snowcover conditions can be accurately specified, we find that avalanche dynamics modelling is able to represent runout and safe traffic zones could be identified. We apply a detailed, physics based snowcover model to predict snow temperature, density and moisture content in three-dimensional terrain. This information is used to determine the initial and boundary conditions of the avalanche dynamics model. Of particular importance is the assessment of the current snow conditions along the avalanche tracks which define the mass and thermal energy entrainment rates and therefore the possibility of avalanche growth and long runout distances.¹

¹This chapter includes contents which were published in Vera Valero, C., Wever, N., Bühler, Y., Stoffel, L. Margreth, S. and Bartelt, P. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine in the central Andes. Natural Hazards and Earth System Sciences, 2016, 2016, 1-41
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

3.1 Introduction

High-altitude mining activities are frequently disrupted by snow avalanches. Historically, three of the most severe avalanche disasters ever recorded have destroyed mining settlements. On December 5th, 1935, a large avalanche released from Mount Iukspor and destroyed wooden buildings constructed to house workers of a Soviet apatite mine in the Khibiny mountains. The avalanche killed 89 people [Bruno, 2013]. On the 8th of August, 1944, the Teniente copper mine in the central Andes was struck by a catastrophic avalanche, killing more than 100 workers in the Sewell mining camp [Ver-gara and Baros, 2002, Gallardo, 2003]. The worst mining avalanche disaster occurred on February 9th, 1945, when an avalanche buried the living quarters of the coal mine October on Sakhalin island, killing 131 people [Podol-skiy et al., 2014]. The avalanche disasters in the Khibinys and Sakhalin are of great historical importance since they motivated avalanche studies in the former Soviet Union [Bruno, 2013].

Nowadays the majority of mine workers do not live in mining camps close to the operation areas. Mines are operated in shifts where a large number of workers are transported in and out of the primary excavation areas. The main risk from avalanches occurs during shift changes when miners are exposed to avalanche danger on access roads. The miners are transported in long bus convoys containing many vehicles and therefore are at great risk. During high avalanche risk periods the access roads must be closed; causing significant financial losses because mine operations and shift changes are disrupted.

For this reason large mines have well-trained avalanche winter operation crews who are responsible for road management. The winter operation crews must make closure decisions often well in advance of avalanche activity in order to plan the next operational shift. Safety experts therefore require methods to assess avalanche danger. They use automatic weather stations and have some data on the current snowcover conditions, including snowpit measurements. However, unlike avalanche forecasters in ski regions, the primary question avalanche experts in mines must answer is directly related to road traffic; that is, can avalanches reach the road? A secondary question then arises: if the road is buried by an avalanche, how quickly can it be cleared and reopened? Safety crews can position clearing equipment in different locations according to where they expect the largest avalanche deposits in order to open the roads as quickly as possible, minimizing the operational disruption. These questions involve both the problem of snowcover stability and the problem of expected avalanche runout.

In this chapter we discuss the use of avalanche dynamics models that use initial input data defined by current snowcover conditions. At this stage of the investigation, the goal is to determine the quality of the dynamic modeling
3.1. Introduction

to accurately and consistently predict avalanche runout, and not yet, if ever, to define real time hazard maps. Our goal is to identify how accurate initial conditions must be defined (snow release height, temperature and moisture content) in order to make reliable runout predictions. Model comparison to observations is a first step to integrating avalanche dynamics calculations in an operational environment. The problem is of great interest, because it requires the simulation of small, frequent avalanches, a task which is increasingly arising in engineering offices, but one that represents a large change in the application of traditional avalanche dynamics models.

Recent advances in snow avalanche dynamics research make this work possible. For one, the mean avalanche temperature has been introduced as an independent state variable in avalanche calculations [Vera Valero et al., 2015]. Avalanche temperature is controlled by the temperature of the snow at release as well as by the temperature of the snow entrained along the path. Moreover, not only is mass entrained, but also its thermal energy. Although it is well-known that avalanche flow regime is a function of snow temperature, (see e.g. [Bozhinskiy and Losev, 1998, Gauer et al., 2008, Issler and Gauer, 2008, Steinkogler et al., 2014]), it is only recently that a statistical correlation between temperature and avalanche runout has been established [Naaim et al., 2013]. Modelling how the temperature affects avalanche runout requires postulating temperature dependent functions for avalanche friction. The long runout distances of wet avalanches suggest a decrease in Coulomb friction induced by lubricated gliding at the basal boundary which controls the reach of the avalanche. Experimental field measurements indicate wet snow flows exhibit slower, plug-like velocity profiles where shearing is concentrated at the avalanche base [Dent et al., 1998, Kern et al., 2009]. Isothermal, moist snow is typically associated with dense flows in the frictional flow regime indicating that velocity fluctuations are strongly damped with increasing snow temperature [Buser and Bartelt, 2015]. This serves to concentrate the dissipation within a thin shear layer located at the base of the avalanche, concentrating the frictional heating (and therefore the meltwater production) at the running surface [Miller et al., 2003]. Another effect is the increase of snow cohesion with increasing temperature [Voytkovskiy, 1977], further preventing the fluidization of the avalanche core and the transition to fluidized flow regimes [Bozhinskiy and Losev, 1998, Bartelt et al., 2015].

To demonstrate how initial and boundary conditions control avalanche flow, we simulate several avalanches documented during three winter field campaigns at the “Cajón del rio Blanco” Valley of the Codelco Andina mine situated 100 kilometers North East from Santiago in the Chilean Andes. This region is well-known for wet snow avalanche activity [Gallardo, 2003, McClung, 2013]. The terrain is represented using a 2m high resolution DEM
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

(digital elevation model). To model the observed avalanches, we employ an avalanche dynamics model described in the previous chapter. To estimate the snowcover conditions at the avalanche release and erosion areas, numerical snow cover simulations using the detailed, physics based SNOWPACK model were used [Bartelt and Lehning, 2002, Lehning et al., 2002], driven by meteorological data from automatic weather stations over a period of five winter seasons. The SNOWPACK model results were validated with field measurements (snow pits) performed by the winter operation crew. An additional problem is the danger arising from small point releases, often containing only 100 m$^3$ of mass but which can develop in dangerous bigger avalanches when entrain enough snow. Avalanche growth by entrainment is therefore critical to model runout and the final deposition volume.

The results indicate that avalanche runout forecasting applications might be possible in the near future if accurate snow cover information, coupled with high resolution terrain models, can be used to drive avalanche dynamics calculations. Such tools could significantly support the existing expertise and know-how of mine road safety crews.

3.1.1 Initial and boundary conditions

The Codelco Andina mine operates three automatic weather stations that measure air temperature, snow surface temperature, air pressure, wind speed, precipitation and incoming/reflected short wave radiation, see Fig. 2.1. The distance between the closest weather station and the avalanche paths varies between 0.5 km and almost 4.0 km. The meteorological data are used to run SNOWPACK simulations [Bartelt and Lehning, 2002, Lehning et al., 2002] that estimates the snow temperature, density and initial water content in the release zone ($T_0$, $\rho_0$, $\theta_{w0}$) and snowcover ($T_\Sigma$, $\rho_\Sigma$, $\theta_{w\Sigma}$). Snow pits are dug by the winter operation crew at regular intervals to supplement and validate the measured/simulated snowcover data.

The release areas in the case studies are located between 3085 m and 3600 m; the weather station used here to drive the SNOWPACK simulations is located at 3520 m. The small elevation difference between the release zones and the weather station provides sufficient accuracy in snow and meteorological data. However, surface energy fluxes are influenced by the slope exposition. To get representative simulations for potential avalanche release zones, virtual slope angles of 35° are used, shortwave radiation measured at the meteorological station as well as snowfall amounts are reprojected onto these slopes, taking into account slope angle and aspect [Lehning and Fierz, 2008b]. Meteorological data from the winter operation building at the valley bottom (Lagunitas 2720 m, see Fig. 2.1) are also available. Thus, it was possible to estimate the precipitation and temperature gradients existing between the weather station location and the winter operation building.
3.1. Introduction

Figure 3.1: Two and three-dimensional visualizations of a segment of the 35 km long mining road located in the “Cajon del Rio Blanco” valley in the central Andes, Chile. The figure depicts the location of the five avalanche (CCHN-3 Caleta Chica North, CG-1 Cobalto, LGW-2 Lagunitas West, BN-1 Barriga North and CV-1 Canaleta East) tracks in relation to the road and the location of two weather stations used to drive the SNOWPACK model. One weather station is located at the ‘Lagunitas’ operation center at the valley bottom (2700 m). The automatic weather station is located at an elevation of 3520 m. Picture obtained from Google Earth Pro.
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

at the valley bottom and therefore infer the snow cover conditions along the selected avalanche paths. To estimate the fracture and erosion depths for each case study we considered SNOWPACK simulations using Richards equation for liquid water flow [Wever et al., 2014], which is able to reproduce the accumulation of liquid water at microstructural transitions inside the snowpack [Wever et al., 2015]. Therefore we identify the interface below water accumulations as fracture points [Kattelman, 1984, Mitterer et al., 2011a, Takeuchi and Hirashima, 2013]. Subsequently, the simulations provide fracture depth, average snow density, temperature and liquid water content of the slab, which extends from the depth of the maximum liquid water content to the snow surface, [Wever et al., 2016]. The SNOWPACK estimations are validated with field measurements when the access is possible.

The initial avalanche release volume $V_0$ is calculated by estimating a release area $A_0$ and a mean fracture depth $h_0$. Point release avalanches are specified by defining a small triangular shaped release area where the upper apex of the triangle is located at the release point. The triangular area together with the fracture height defines the initial release volume. This procedure is used only a to start the model and the initial volume used $V_0$ is not related with the physical process occurred when a point release avalanche releases. The location of the release areas is based on observed releases for a particular track. This information has been collected and documented by the road safety crew.

The fracture $h_0$ heights and erosion layers $l_{\Sigma}$ are estimated using the method showed at [Wever et al., 2016]. The road management crew studies the SNOWPACK results to identify layers where meltwater accumulates. This can be at the bottom of the snowpack, leading to full depth avalanche releases, or it can be at an interface between two snow layers. The mean snow temperature, density and moisture content of the release zone and erosion layers are defined from the simulation data after the fracture and erosion depths have been defined. At present the procedure is not automatized to allow the safety crew to explore different release and erosion scenarios.

3.2 Case studies

The “Cajón del rio Blanco” valley contains over 100 avalanche tracks. In the following we investigate five documented events that represent avalanche activity in the mine. The avalanches are designated: CCHN-3 Caleta Chica North, CG-1 Cobalto, LGW-2 Lagunitas West, BN-1 Barriga North and CV-1 Canaleta East (Fig. 3.1). The first four cases are spontaneous point release wet avalanches that released in periods of high temperature (isother-
Figure 3.2: Erosion-deposition measurements in the LGW-2 (a), BN-1 (b) avalanches and (c) CV-1. The yellow dots in (a) and (b) correspond to GPS measurements, see Table 3.1. For the CV-1 avalanche (c) the erosion-deposition area was determined by a drone flight. The blue polygons show the erosion areas. The white polygons show the area where the avalanche was still eroding and already depositing mass (less than 1 meter deposits height). The red polygons inside the white polygon show the main deposit areas where the accumulations were higher than 1 meter. The measured deposit areas (red) were 7935 m$^2$ for LGW-2, 3726 m$^2$ for BN-1 and 7373 m$^2$ for CV-1.

These particular avalanches were selected because they reached the main industrial roads, endangering workers or interrupting mine logistics and communication. The avalanches were subsequently well documented by the winter operation crew. The fifth avalanche also reached the road and was documented by an observation drone providing better runout, deposition and spreading data. This avalanche released as a slab and entrained moist, warm snow. In all five cases high-resolution digital elevation models, 2m resolution, of the terrain are available.

For the five case studies field measurements were carried out. The field measurements consisted of: GPS measurements (see Table 3.1) and manual measurements of the avalanche deposit heights along several transects perpendicular to the main flow direction (see Fig. 3.2). For the BN-1 and LGW-2 cases it was possible to reach the release area and measure the amount of snowcover eroded by the avalanche. Erosion measurements were conducted using a marked depth probe along the avalanche path (see Fig. 3.2 and Table 3.1). Due to the steep terrain and mine regulations those measurements could not be performed for the CCHN-3 and CG-1 cases near the release areas. Erosion height measurements could only be carried out in and im-
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

Table 3.1: Summary of the GPS measurements by the Codelco Andina winter operation crew and the author. The measurements were taken with a GARMIN Etrex vista HCx device with an accuracy of ±2-5 m. Erosion depth measurements were taken at the erosion areas together with the GPS points, (see Fig. 3.2)

<table>
<thead>
<tr>
<th>Deposit Outline</th>
<th>Erosion area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude</td>
</tr>
<tr>
<td>BN-1</td>
<td>-33.081576</td>
</tr>
<tr>
<td>LGW-2</td>
<td>-33.081576</td>
</tr>
<tr>
<td>BN-1 LGW-2</td>
<td>-33.082093</td>
</tr>
<tr>
<td></td>
<td>37 cm</td>
</tr>
<tr>
<td></td>
<td>-33.082047</td>
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<tr>
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<td>32 cm</td>
</tr>
<tr>
<td></td>
<td>-33.084367</td>
</tr>
<tr>
<td></td>
<td>32 cm</td>
</tr>
<tr>
<td></td>
<td>-33.084933</td>
</tr>
<tr>
<td></td>
<td>29 cm</td>
</tr>
<tr>
<td></td>
<td>-33.087569</td>
</tr>
<tr>
<td></td>
<td>32 cm</td>
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<td>-33.087569</td>
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<td>-33.087569</td>
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<tr>
<td></td>
<td>32 cm</td>
</tr>
</tbody>
</table>

Immediately above the main deposition area. For the CV-1 avalanche aerial photography is available from a drone flight, (Fig. 3.2c).

The measured meteorological data was used to drive the SNOWPACK simulations. Since the time of release of all avalanche events is known, the simulated snowcover data at the time of avalanche release was used to determine the input values, Figs. 3.3, 3.4, 3.5, 3.6, 3.7 [Weyer et al., 2016].

3.2.1 Caleta Chica North, CCHN-3

The CCHN-3 is a long, narrow and steep avalanche path that starts at a ridge located at an elevation of 3685 m (Fig. 3.3). The path contains a steep gully that includes track segments with steep inclinations of more than 60 degrees. The avalanche path ends directly above the industrial road at 2700 m. Although the gully is narrow, the avalanche collects enough snow to endanger the industrial road due to the long distance between the release zone and the deposition area.

On the 14th of August 2013 around 17:30 a point release avalanche started at the top of the avalanche path reaching the industrial road with a final volume of 2500 m$^3$ (estimated by the winter operation crew, see Fig. 3.6a. On the 12th of August 0.15 m of new snow was measured at 3500 m. A 24 hour period of cloudy weather followed the snowfall. The 14th of August was the first clear sky day after the snow fall from the 12th of August. The air temperature at the estimated release time was 3.7 °C at 3550 m.

3.2.2 Cobalito, CG-1

The CG-1 avalanche path is located 2 km to the north (see Fig. 3.1) of the CCHN-3 track with similar west exposition. The track starts at 3465 m and ends at the industrial road at 2450 m (Fig. 3.4). The release is located at a steep inclination located below a ridge. The track is channelized between
3.2. Case studies

Figure 3.3: (a) CCHN-3 avalanche picture taken from the helicopter the day after the release. The point release was on the top of the steep gully on a rock face. The avalanche crossed the industrial road. (b) Calculated maximum flow height, red polygon denotes the measured GPS contour at the deposits. The model correctly estimated the runout distance and the height of the avalanche deposits. Lower panel depicts the results of the SNOWPACK simulations, liquid water content, density and temperature, black color at the temperature plot denotes snow at 0°C with liquid water content greater than zero. The red line denotes the time of release.
two vertical rock pillars. The gully between the pillars has an inclination between 50 and 60 degrees for the first 500 vertical meters of drop. The track becomes progressively flatter (about 40-45 degrees) and wider. For the last 300 m of elevation drop the gully is between 50 to 70 meters wide and the avalanche can entrain large amounts of snow. The deposition area is located on a cone shaped debris fan above the industrial road (see Fig. 3.4). The surface of the debris fan contains large blocks.

On the 7th of September, 2013 at 17:30 hours a point release avalanche started from the upper part of the gully, eroding the upper new snow layer. The avalanche reached the valley bottom stopping a few meters above the industrial road (see Fig. 3.4). The volume of the deposits was estimated to be approximately 7000 m$^3$. On the 6th of September a 24 hour storm left 0.40 m new snow at 3500 m. At 2720 m the storm began as a rainfall, placing 7 mm of water in the snowcover. At higher elevations above 2720 m, the rain turned to snow depositing 0.10 m of moist new snow on the wet snowcover. At 2400 m only rain was measured. The winter operation crew made two snow profiles at the morning of the 7th of August and estimated that the rain reached 2900 m, above this elevation all precipitation fell as snow.

### 3.2.3 Lagunitas West, LGW-2

The LGW-2 avalanche path starts at 3250 m below a rock band and continues over an open slope with 40-45 degree inclination (Fig. 3.5). The track contains two five meters drops over rock bands before it gets progressively flatter, reaching an inclination of 30-35 degrees. The track finishes at 2800 m at the industrial road with a 25 degree inclination (Fig. 3.1).

At 14:30 hours on the 9th of September, 2013 a point avalanche released below the upper rock band reaching a secondary industrial road. The 9th of September was the first clear sky day after the three day storm and cloudy weather that started on the 6th of September. The air temperature at the release time was 8.3 °C at 2720 m.

### 3.2.4 Barriga North, BN-1

The BN-1 avalanche path starts directly in front of the winter operation building at 3100 m (Fig. 3.6). The release area has a southern exposition and is situated below a wide ridge with 40-45 degrees slope angle. Below the release zone, the avalanche path flattens and twists, the track becoming exposed to the west. The avalanche path ends on an industrial road at 2775 m.
3.2. Case studies

Figure 3.4: (a) Avalanche path **CG-1**. Image taken from the helicopter the day after the release. The avalanche started at 3465 m but stopped eroding snow at 2900 m. The avalanche reached the valley bottom flowing over a scree surface. (b) Calculated maximum flow height. The model predicts the observed runout distance, avalanche outline and deposition volume, red polygon denotes the measured GPS contour at the deposits. Lower panel depicts the results of the SNOWPACK simulations: liquid water content, density and temperature, black color at the temperature plot denotes snow at 0°C with liquid water content greater than zero. The red line denotes the time of release.
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

Figure 3.5: (a) Picture of the BN-1 avalanche taken from the Lagunitas operation center some minutes after the event. The avalanche crossed the road depositing on average 2 m of snow on the road. The top left inset provides a closer view of the point release. (b) Calculated maximum flow heights, red polygon denotes the measured GPS contour at the deposits. The model accurately simulated the avalanche spreading angle including the change in trajectory half way down the avalanche path. On the top left the calculated release area is shown in red. Lower panel depicts the results of the SNOWPACK simulations: liquid water content, density and temperature, black color at the temperature plot denotes snow at 0°C with liquid water content greater than zero. The red line denotes the time of release.
3.3 Simulation results

At 17:30 hours on the 9th of September 2013, three hours after the LGW-2 release, a point avalanche released below the ridge. The avalanche eroded new snow in the flat area, passed the channel turn and reached the access road. The winter operation crew estimated the maximum avalanche deposits to be approximately 3.5 m in height; 2 m on average. The air temperature at the release time was 7.8 °C. The avalanche was observed by mine staff members. Low quality video recordings from mobile phones are available.

3.2.5 Canaleta East, CV-1

The CV-1 is a steep avalanche path that has two main sections (Fig. 3.7). The starting point is a 40 degrees steep rock band which accumulates snow transported by north westerly winds. Below the rock band appears a 20 meter high cliff that leads to a steep and narrow 50 meter long gully. The avalanche path finally opens onto a graveled 40-42 degrees steep fan. The fan is located directly above the industrial road.

On the 19th of October 2015 at 18:15 hours a wet slab released from the rock band 200 meters above the industrial road. The avalanche flowed over the cliff and then into the gully, eroding the remaining snow cover. The snow on the fan was also eroded. The avalanche stopped after crossing the industrial road leaving about 10000 m$^3$ of mass in the deposits. Between the 13-14th of October, 97 cm of new snow were measured at Lagunitas operations center (400 meters away from the avalanche path). After the snow fall between the 16th and 18th of October air temperatures between 6°C to 9°C were measured. In the last three hours before the release three millimeters of rain were measured in Lagunitas.

3.3 Simulation results

The primary goal of the case study simulations is to reproduce avalanche runout using the measured and simulated snowcover initial ($h_0$, $V_0$, $\rho_0$, $T_0$, $\theta_w^0$) and boundary ($h_\Sigma$, $V_\Sigma$, $\rho_\Sigma$, $T_\Sigma$, $\theta_w^\Sigma$) conditions, friction parameters were not allowed to vary from one case study to the next. The selected friction parameters are presented in Table 3.2. All simulations were performed on a 2m x 2m digital elevation model. The terrain model was obtained using 2m laser scanning measurements performed in 2011 and 2013. The calculation domains contained up to 25000 cells, but calculation times were less than 20 minutes on a standard PC.
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

Figure 3.6: (a) Avalanche LGW-2 picture taken from the valley bottom. The avalanche released below a rock band and spread over the slope flowing over two rock bands before reaching a secondary road at the valley bottom. Top left shows a closer view from the release point. (b) Calculated maximum flow heights. The model correctly predicted the formation of three avalanche arms and therefore an accurate modeling of the avalanche outline, red polygon denotes the measured GPS contour at the deposits. On the top left a closer view with the calculated release area (in red) is shown. Lower panel depicts the results of the SNOWPACK simulations: liquid water content, density and temperature, black color at the temperature plot denotes snow at 0°C with liquid water content greater than zero. The red line denotes the time of release.
3.3. Simulation results

Figure 3.7: (a) Picture of the CV-1 avalanche taken from helicopter after the release. The slab was on the top the steep gully on a rock face. The avalanche crossed the industrial road leaving up to six meters of snow on the road. (b) Calculated maximum flow heights, red polygon denotes the measured GPS contour at the deposits. The avalanche deposits area and release area were photographed by a drone three days after the avalanche occurred (inset). Lower panel depicts the results of the SNOWPACK simulations: liquid water content, density and temperature, black color at the temperature plot denotes snow at 0°C with liquid water content greater than zero. The red line denotes the time of release.
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

Table 3.2: Summary of input simulation parameters for the five calculation examples.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BN-1</th>
<th>LGW-2</th>
<th>CG-1</th>
<th>CCHN-3</th>
<th>CV-1</th>
</tr>
</thead>
<tbody>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$\mu_0$ (-)</td>
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<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>$\mu_w$ (-)</td>
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<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
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</tr>
<tr>
<td>$\xi_0$ (m s$^2$)</td>
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<td>1300</td>
<td>1300</td>
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<td>1300</td>
</tr>
<tr>
<td>$\alpha$ (-)</td>
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<td>0.07</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>$\beta$ (1/s)</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$R_0$ (kJ/m$^3$)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$h_s$ (m)</td>
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<tr>
<td>$\kappa$ (-)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

3.3.1 Runout, flow width and deposition

Figs. 3.3, 3.4, 3.5, 3.6 and 3.7 depict the calculated maximum flow height and runout. Photographs of the real events are provided in the figures to allow a direct comparison. In all five case studies the avalanches start on steep slopes. Flow paths were all correctly modeled, including the location where the avalanche cut the road. Calculated runout distances are in good agreement with the GPS measurements made by the road operation teams. Three flow fingers developed in the LGW-2 avalanche were all reproduced by the model, Fig. 3.5. No channel break-outs were observed or calculated for the channelized avalanches CG-1 and CCHN-3. In both cases, the avalanches followed a steep, deep and twisted channel. All calculations were made with the same model parameters with the exception of the generate parameter $\alpha$, which depends on the avalanche track steepness and changing curvature and twists. In the BN-1 and LGW-2 avalanches it was required to use a slightly lower production value ($\alpha$) for the random kinetic energy, $\alpha = 0.07$ (in comparison to $\alpha = 0.08$ for the other case studies), see Table 3.2.

Not only was it possible to reconstruct the avalanche runout, but also the avalanche flow width (Fig. 3.8). For example, the measured width of the BN-1 avalanche depositions on the road at 2750 m elevation was 82 m; the calculated width was 90 m. The measured width of the CV-1 avalanche was 132 m at 2720 m (drone measurements); the calculated width 139 m. That is, the model predicted somewhat larger deposition widths indicating a slight spreading before stopping, especially for the three open slope avalanches BN-1, LGW-2 and CV-1. Fig 3.8 compares the observed maximum deposition heights with the calculated deposition heights at the road. In the case study CCHN-3 the calculated deposition heights are lower than the maximum observed heights because the avalanche ran over old 2 m high avalanche depositions, which are not included in the simulations. If the
height of the old deposits is added to the simulation results, a good agreement between calculated and observed deposition heights is achieved.

### 3.3.2 Avalanche temperature and meltwater production

Calculated avalanche temperatures are shown in Fig. 3.9. In the five case studies the calculated temperature of the flowing snow $T_\Phi$ reached the snow melting temperature $T_m=0^\circ$. This indicates that frictional dissipation produced meltwater over considerable distances along the avalanche path, for all five case studies. Avalanches that started with release temperature below $T_0 < 0^\circ$C (CG-1 and CV-1) quickly reached the melting temperature. Total meltwater produced, at a specific point on the avalanche track, reached peak values of $3 \text{ mm m}^{-2}$. Once produced, meltwater is advected with the speed of the avalanche, leading to regions in the flow where meltwater accumulates. Meltwater accumulations can be as high as $60 \text{ mm m}^{-2}$, see Figs. 3.10 and 3.13. The advected meltwater accumulations determine the value of Coulomb friction, see Fig. 3.10, which is a function of both the configurational energy and the amount of meltwater.

### 3.3.3 Avalanche velocity and fluidization

Figure 3.15 depicts the maximum velocity calculations of the BN-1 and LGW-2 case studies. The flow velocities of the avalanches did not exceed $15 \text{ m s}^{-1}$; the maximum calculated velocities in the runout zone never exceed $10 \text{ m s}^{-1}$. Avalanche velocities could be roughly estimated using the mobile phone video recordings. The velocity measurements (about $10 \text{ m s}^{-1}$) coincide with these predictions. Unfortunately the recordings are not accurate enough to perform a more precise analysis.

For such steep terrain, higher velocities are to be expected. However, the avalanches did not fluidize completely. The avalanches remained in a frictional flow regime with relatively high flow densities, $\rho_\Phi \approx 300 \text{ kg m}^{-3}$, see Fig. 3.13. At the point of maximum flow velocity ($15 \text{ m s}^{-1}$), the BN-1 avalanche had a minimum flow density of $\rho_\Phi = 305 \text{ kg m}^{-3}$. Similarly, at the point of maximum flow velocity ($18 \text{ m s}^{-1}$), the LGW-2 avalanche had a minimum flow density of $\rho_\Phi = 302 \text{ kg m}^{-3}$. In the runout zone the minimum flow densities were on the order of $\rho_\Phi = 450-480 \text{ kg m}^{-3}$. This value is very close to the final deposition density of $\rho_\Phi = 500 \text{ kg m}^{-3}$. The maximum configurational energies reached 80-100 kJ/m$^2$, see Fig. 3.10.

### 3.3.4 Entrainment

The numerical results underscore the important role of snow entrainment. The increase in avalanche volume from release to deposition for four case studies is depicted in Fig. 3.11. The initial release volumes $V_0$ are defined at
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

Figure 3.8: Observed (left column) and calculated avalanche deposits (right column) on the road: (a) CCHN-3, (b) CG-1 (c) LGW-2 (d) BN-1 and (e) CV-1. The outline and maximum height of the deposits were measured by the winter operation crew with a hand-held GPS device. The red lines in the plots depict the observed width and maximum height of the avalanche deposits.
3.3. Simulation results

Figure 3.9: Calculated temperature (red) and meltwater production (black). (a) CCHN-3, (b) CG-1, (c) LGW-2, (d) BN-1 and (e) CV-1. The avalanche temperatures are close to $T_\Phi = 0^\circ C$ from initiation to release. Frictional dissipation therefore led to a quick production of meltwater. The model predicted up to 3 mm m$^{-2}$ of meltwater. The grey shadow in the background indicates the elevation profile along the avalanche track.
3. MODELLING WET SNOW AVALANCHE RUNOUT TO ASSESS ROAD SAFETY AT A HIGH-ALTITUDE MINE

Figure 3.10: Friction coefficient $\mu$ (blue), total liquid water content LWC (black) and total random kinetic energy $R$ (red): (a) CCHN-3, (b) CG-1 (c) LGW-2 (d) BN-1 and (e) CV-1. Friction $\mu$ decreases with increasing LWC and random kinetic energy $R$. The grey shadow in the background indicates the elevation profile along the avalanche track.
3.4. Discussion

For all point release case studies the initial volume $V_0 < 300 \text{ m}^3$. The final calculated deposition volumes $V_\Phi$ are $V_\Phi \approx 8700 \text{ m}^3$ for the BN-1 and $V_\Phi \approx 10000 \text{ m}^3$ for the LGW-2 case studies. In the remaining two examples CCHN-3 and CG-1 the avalanches did not entrain snow after the track midpoint. In these two examples there was no snow cover below 2900 m (see Figs. 3.3 and 3.4). The growth indexes for these avalanches are smaller, but nonetheless large. The calculated growth indexes (Fig. 3.11b) reach values between $V_\Phi / V_0 \approx 20$ and 90 indicating that entrainment processes are controlling the avalanche size. These indexes are calculated using the initial release procedure explain on the introduction, so the initial volume at the release is not representative of the real point release, however these grow indexes are certainly representative of the main role of snow entrainment in these avalanches.

The two case studies with entrainment measurements (BN-1 and LGW-2) are particularly important. Dividing the calculated deposition volumes by the area measured by the winter operation crew (see Fig. 3.2b) we found $h_\Phi \approx 2.4 \text{ m}$ deposit height in the BN-1 case study and $h_\Phi \approx 1.3 \text{ m}$ in the LGW-2 case study. These results roughly agree with the field volume measurements, $h_\Phi \approx 3 \text{ m}$ and $h_\Phi \approx 2 \text{ m}$, respectively.

3.4 Discussion

The simulation results rely on accurate initial conditions (release volume, location and snow temperature, density and liquid water content) and boundary conditions (track roughness, snowcover depth, snow density, temperature and liquid water content) and not in changing the model parameters for wet snow (which we kept constant). The model predicts dense flows with high flow density, congruent with observations of wet snow avalanche motion. Fluidization can occur in steep and rough terrain; however, runout is controlled by meltwater lubrication and therefore the changing material properties of snow as it becomes warmer and wetter. This implies that snowcover conditions temperature, density and moisture content, which control the hydrothermal state of the flowing snow, must be included in the model formulation.

As the SNOWPACK simulations predicts isothermal snowcover at $T_\Sigma = 0^\circ$ for the snow depth affected by the avalanches, the entrained snow temperature was set to zero degrees in all five case studies, see Table 1. This approach could not be followed with the modeled snowcover water content which has no limiting value in an isothermal snowcover. Although SNOWPACK was used to predict snow water content [Wever et al., 2015], 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
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

Figure 3.11: (a) Avalanche flowing volume calculations. Flat curves indicate the time when the avalanches stopped entraining snow, (cases CG-1 and CCHN-3). Entrainment is the the main source of mass. (b) Avalanche growth index: Ratio between the avalanche flow volume $V_Φ$ and the initial release volume $V_0$ over time. In four of five case studies the ratio between the final volume and the initial simulated released volume is between $20 \leq V_0/V_Φ \leq 90$, using as initial release the procedure described above.

The snowfall was preceded by rain making it difficult to calculate the snow water content which depends on the variability of the rainfall.

The positions of all release zones were obtained from the eyewitness reports and post-event surveys. Entrainment depths for the simulations were also obtained from field measurements and event documentation. In the examples LGW-2 and BN-1 the erosion depths where measured along the path in several points (Fig. 3.2). Because the avalanches disrupted road traffic, the winter operation crew 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. In the case of point releases, the release mass does not play an important role (Fig. 3.11) apart from defining the location of release and the triggering of the whole subsequent process.

The five examples contain mountain rock faces with well defined flow channels (CG-1, CCHN-3) as well as open slopes (BN-1 and LGW-2) or a mix
3.4. Discussion

Figure 3.12: Comparison between avalanche run out distance using cold ($T_0 = -10^\circ$C, blue line) and warm snow ($T_0 = 0^\circ$C, red line) for the (a) LGW-2, (b) BN-1 and (c) CCHN-3 case studies. Warm snow leads to more frictional melting and longer avalanche runout.

of them, CV-1. At release the avalanche mass spreads depending on the terrain features. In two of the five case studies, avalanche spreading is inhibited by the steep sidewalls of mountain gullies, a function of the topographic properties of the mountain. The remaining three examples are more open slopes where the spreading angle is larger. The spreading angle was accurately reproduced in all three case studies. Small avalanches are extremely sensitive to small topographic features therefore high resolution digital elevation models that accurately represent mountain ravines and channels are thus necessary to apply more detailed 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 Valero et al., 2015], mechanical free energy [Buser and Bartelt, 2015] and meltwater [Vera Valero 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 ($\alpha$ and $\beta$) governing the production and decay of free mechanical energy $R$ [Buser and Bartelt, 2015]. The production parameter $\alpha$ is made dependent on terrain roughness, in this work the values used correspond to the 7-8% (see Table 3.2) of the work done by the friction at the bottom surface. 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 $\beta$ to 1.0 for warm, wet avalanches, [Buser and Bartelt, 2015]. 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$^{-3}$ (see Fig. 3.13). Important is that the same model formulation is used for both dry and wet avalanches.
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

and fluidization is controlled by a combination of terrain (production of free mechanical energy) and wet snow granule properties, (dissipation of free mechanical energy). 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 [Voytkovskiy, 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 $\mu$ 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 whose height is in the order of magnitude of $h_m$. When this layer becomes saturated with meltwater, Coulomb friction is reduced to a sliding value of $\mu_s$, which we take, for now, to be constant $\mu_s = 0.12$. This value was selected based on our observations of wet snow avalanche flowing in slopes not flatter than $7^\circ$, (tan $7^\circ = 0.12$). The layer height was set to $h_m = 0.1$ m, indicating that shearing in wet avalanche flows is concentrated in a basal layer, (see Fig. 2.4). This is in agreement with velocity profile measurements of wet avalanche flows [Dent et al., 1998, Kern et al., 2009, Nishimura and Maeno, 1987]. The snow water content values obtained in the simulation results varied between 10-50 mm m$^{-2}$. Spreading such amount of water within the shear layer ($\approx h_s$) leads to water concentrations volume higher than 15% of volume water content. With such water concentration this avalanche layer is above the so-called capillary regime [Mitarai and Nori, 2006] where the interstitial water pressure is higher than air pressure and therefore lubrication occurs. Spreading the same amount of water content obtained in the model in a hypothetical larger shear layer ($h_s \approx 1$m) leads to a lower water concentration and therefore to a higher $\mu$ which prevents the avalanche to reach the measured run out (see Fig. 3.14).

The model calculates the depth-averaged flow temperature from initiation to runout. In the five 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. This is shown in Fig. 3.12. We made two calculations for the LGW-2, BN-1 and CCHN-3 avalanches. In the first calculation we set the release
3.4. Discussion

Figure 3.13: Total calculated meltwater and flow density for the LGW-2 and BN-1 avalanches. (a) Total meltwater in LGW-2 avalanche. (b) Flow density LGW-2. (c) Total meltwater in BN-1 avalanche. (d) Flow density BN-1. In steep track sections the avalanche fluidized slightly (flow density $\rho_{\Phi} = 350$ kg/m$^3$). In the runout zones the avalanche densified. Deposition densities are $\rho_{\Phi} = 500$ kg/m$^3$. 
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

Figure 3.14: Case study **LGW-2** simulated with (a) and without (b) lubrication effects. Without lubrication several flow arms (that were observed) are not reproduced.

Figure 3.15: Calculated maximum velocities of the **BN-1** avalanche (a) and of the **LGW-2** avalanche (b). Max. flow velocities reached about 15 m s\(^{-1}\).
3.5 Conclusions

The method used to simulate the avalanche point release requires defining a small triangular area. The ratio between the final snow volume and the used initial snow volume is between 20 to 90 for the four point releases 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 outlines and avalanche volumes. Therefore, with this model formulation, it is only possible to obtain realistic runout predictions with accurate snow cover data.

3.5 Conclusions

For mining companies road closure is associated with severe financial costs and winter operation crews must deliver runout warnings based on daily, perhaps hourly, meteorological information. Many existing avalanche dynamics models widely used in practice, (e.g. [Christen et al., 2010, Sampl and Zwinger, 2004, Sheridan et al., 2005, Mergili et al., 2012, Naaim et al., 2002]), do not include the role thermal temperature, fluidization or snow liquid water content in their mechanical description of avalanche motion. As such, wide ranging flow parameters are required to model avalanche runout and velocity. These models therefore cannot be applied to predict how avalanche activity will disrupt mining operations because they cannot take into account current measured and observed snow conditions.

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 winter operation crews using a combination of weather stations and snowcover modeling. The avalanche model requires input parameters for fracture depth, snow temperature, snow density and water content in the release area and
3. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine

along the avalanche path. The meteorological data provided by the automatic weather stations is representative at the altitude where the weather stations are located. However, the difference in altitude and exposition of the five different cases studies requires a method to extrapolate temperature, snowcover depth and liquid water content 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 traditional snow profiles measurements performed by the winter operation crew to validate the SNOWPACK model predictions for temperature, density and water content.

Avalanche dynamics models have been traditionally applied to simulate large, dry, slab release avalanches. The starting volumes of such avalanches are typically larger than $V_0 > 50,000 \text{ m}^3$. The primary application is to prepare avalanche hazard maps which are based on extreme events with long return periods or back calculate occurred case studies. In this paper avalanche release mass was modeled using small triangular shaped release zones containing less than $V_0 \approx 100 \text{ m}^3$ of snow. The application of an avalanche dynamics model to simulate small, point release avalanches is novel and poses many new challenges. Five preconditions for the simulation of such small avalanche events are:

1. The availability of high resolution digital terrain models
2. Information concerning the location of the release zone
3. Simulation of snow entrainment to model avalanche growth
4. Reliable snowcover information, including snow density, temperature and liquid water content
5. Reliable parameter values linking mechanical properties to snow temperature (e.g. dissipation, dry and wet Coulomb friction $\mu_0$ and $\mu_w$, etc.)

This information is seldom available in its entirety. Although we can imagine the development of tools linking release zone delineation, snowcover modeling with avalanche dynamics simulations in the near future, their application will remain restricted to regions of similar climate and terrain where they can be thoroughly tested and applied by expert users. The application of this system was tested for three winter seasons in the Andina mine (Chile). The encouraging results motivated us to test the operational application. Simulations coupled with accurate and continually updated snow cover and meteorological information is required to predict avalanche run outs and deposition volumes. The model does not provide any indication whether the avalanche is going to release or not, but if the avalanche releases
the model gives a good indication of the potential run out distances and deposition volumes.

Finally, a primary goal of this work is to develop a model that allows small and frequent events to be analyzed by comparison model computations to field measurements. It is no longer necessary to wait for rare and extreme events as the model parameters are defined as material constants which depend not on avalanche size, but snow temperature and moisture content. As more data can be obtained from field observations it should be possible to further refine the constitutive formulations for meltwater lubrication and snowcover entrainment. We have proposed simple relations for obviously complex processes that clearly need further testing. Alternative formulations are possible. More small, frequent avalanches should be studied and documented for this purpose.
Chapter 4

Initial and Boundary Conditions for Wet Snow Avalanche Modelling

Summary

In the previous two chapters a wet snow avalanche model was developed and applied to simulate several case studies. We found that the inclusion of additional physical processes (entrainment, meltwater production and frictional lubrication) can improve model performance. However, another problem arises: how to choose appropriate initial and boundary conditions for a specific model application? The snowcover temperature and moisture content needs to be defined in the release zone and along the track. At present, statistical methods combined with expert judgment are typically used to address this problem.

In this chapter we test a different approach: in addition to expert judgment, we use meteorological measurements to drive a detailed physics based snowcover model (SNOWPACK). The model results are used to define the initial and boundary conditions of twelve well-documented wet snow avalanches. We simulate the case studies using two approaches: (1) using the extended wet snow avalanche model presented on the first two chapters and (2) using the standard Swiss Guideline Voellmy-Salm (VS) model. We thus investigate a long-standing question in avalanche dynamics: can physics-based models improve avalanche mitigation, or, must we continue to use empirical, but well-calibrated, methods because they provide more conservative (safer) results?

This question can only be answered when we have some way to objectively compare simulation results. To achieve this, we use a contingency table analysis in addition to calculation runout distances. A contingency table provides us with a way to compare the predicted areas covered by avalanche deposits. Not only is absolute runout distance important, but also the degree
the runout is under- or overestimated by the model as well as correctly assessing areas covered by the avalanche.

4.1 Introduction

In this chapter we use modeled snowcover information to establish the initial and boundary conditions of avalanche dynamics calculations. For all case studies, snow cover information is derived from detailed physics based snowcover model simulations using SNOWPACK [Bartelt and Lehnning, 2002, Lehning et al., 2002]. It is important to note that avalanche friction parameters are not tuned, but are fixed within the framework of empirical functions parameterized by density, temperature and moisture content [Vera Valero et al., 2015, 2016]. Our goal is to obtain accurate runout and deposits area predictions without ad-hoc modifications to avalanche friction parameters. Instead of parameter optimization, we specify snow depth, density, temperature and moisture content in both release and entrainment zones as input data for the model. This information defines the thermal flow regime of the avalanche and therefore the primary physical mechanism governing avalanche mobility – either, fluidization (dry avalanches) or lubrication (wet avalanches).

We apply two numerical avalanche dynamics models (see Table 4.1): (1) The standard Voellmy-Salm (VS) model with friction parameters given by the Swiss avalanche guidelines [Salm et al., 1990] and (2) the fluidization/lubrication model of [Vera Valero et al., 2015, 2016]. Both models are used to simulate 12 documented avalanche events with different grid resolutions. Field measurements from the 12 case studies area available (see Table 4.2.1), including measurements from airborne laser-scans, drones and photography and hand-held GPS devices. To determine how the models perform we compare the area covered by the simulations at the deposits with the deposits area measured at the field and the simulated runout distance with the measured avalanche runouts. The correspondence of observed deposits and calculated deposits is checked using a dichotomous contingency table, (see Table 4.2) that splits the terrain in four different classes: hits, misses, false alarms and correct negatives.

Additionally a sensitivity study with the extended model is performed by interchanging the initial and boundary conditions of the twelve case studies. The same contingency analysis and runout comparison is performed with the results obtained from the sensitivity analysis. This establishes the fact that the initial and boundary conditions are the control of the model results for a particular terrain.
### 4.2 Methods

The analysis consists of four steps (see Fig. 4.1):

1. Selection of avalanche events
2. Simulation of snowcover conditions using measured weather data as input
3. Simulation of avalanches using initial conditions defined by snowcover conditions
4. Contingency table analysis to define the statistical score of avalanche runout calculation

Each step is defined in the sections below.

#### 4.2.1 Avalanche events

The data set includes twelve wet snow avalanches that occurred in the Swiss Alps and in the Chilean central Andes between 2008 and 2015. The avalanches were selected for three reasons: (1) the avalanche was located in the vicinity of an automatic weather station (henceforth AWS), (2) the release area and the area inundated by the avalanche were measured either by hand held GPS, drone or aerial laser scanning and (3) a high resolution digital elevation model (i.e. 2m or higher) is available to simulate the terrain. This information is summarized in Table 4.2.1. The avalanche release volumes varied between 7000 m³ and 330,000 m³. Most avalanches released from a wet snowcover and entrained additional wet snow. However, in three events (Grengiols, Braemabuhl Verbauung, Gatschiefer) the avalanche released as a dry slab at subzero temperatures, but entrained warm, moist snow at lower elevations. The release, transit and deposit zone of ten of the twelve case studies were additional photographed from a helicopter. The two remaining avalanches (Drusatscha and Braemabuhl 2013) were photographed by the authors from the deposition zone.

Table 4.1: Voellmy-Salm and Extended models main features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Voellmy-Salm RAMMS</th>
<th>RAMMS Extended wet snow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erodibility</td>
<td>No</td>
<td>Erodibility [Christen et al., 2010]</td>
</tr>
<tr>
<td>Temperature</td>
<td>No</td>
<td>Depth-averaged temperature [Vera Valero et al., 2015, 2016]</td>
</tr>
<tr>
<td>Meltwater</td>
<td>No</td>
<td>Phase change and entrainment [Vera Valero et al., 2015, 2016]</td>
</tr>
<tr>
<td>Fluidization</td>
<td>No</td>
<td>RKE and streamwise density variations [Buser and Bartelt, 2009, 2015]</td>
</tr>
<tr>
<td>Lubrication</td>
<td>No</td>
<td>$\mu$ function of the LWC [Vera Valero et al., 2015, 2016]</td>
</tr>
<tr>
<td>Friction</td>
<td>(Swiss guidelines) $\mu$ and $\xi$ constant</td>
<td>$\mu$ and $\xi$ function of LWC and RKE [Vera Valero et al., 2015, 2016]</td>
</tr>
</tbody>
</table>
4. Initial and boundary conditions

Table 4.2: Case study, date and estimated time of occurrence, (AWS) automatic weather station and virtual slope used at the top and at valley bottom for the release zone and deposits area, type of field measurement and altitude of the release and of the deposits in m.a.s.l.

<table>
<thead>
<tr>
<th>Avalanche</th>
<th>Date/Hour</th>
<th>Meteostations Top/Valley (Altitude AWS m.)</th>
<th>Measurements</th>
<th>Altitude release/Deposits (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gruenbodeli</td>
<td>23.04.2008 ≈ 14h00m</td>
<td>KLOS-NE (2140)/ SLF2 (1550)</td>
<td>Laser scan</td>
<td>1900/1600</td>
</tr>
<tr>
<td>Salez</td>
<td>23.04.2008 15h00m</td>
<td>WFJ2-W (2560)/ SLF2 (1550)</td>
<td>Laser scan</td>
<td>2400/1700</td>
</tr>
<tr>
<td>Gasteinflieger</td>
<td>23.04.2008 16h00m</td>
<td>KLOS-N (2180)/ SLF2 (1550)</td>
<td>Laser scan</td>
<td>2400/1200</td>
</tr>
<tr>
<td>Braemuhlbühl 2013</td>
<td>18.04.2013 15h00m</td>
<td>WFJ2-NE (2560)/ SLF2 (1550)</td>
<td>Laser scan</td>
<td>2200/1600</td>
</tr>
<tr>
<td>Drausstschluech</td>
<td>15.04.2013 17h00m</td>
<td>WFJ2-W (2560)/ SLF2 (1550)</td>
<td>Laser scan</td>
<td>2200/1700</td>
</tr>
<tr>
<td>MO4 Andina Chile</td>
<td>15.10.2013 18h15m</td>
<td>CAND5-SE (3520)/ Lagunias (2790)</td>
<td>Ortophoto</td>
<td>3700/1200</td>
</tr>
<tr>
<td>Grengsiales</td>
<td>26.12.2013 13h00m</td>
<td>GOMS-NE (2450)/ Estimated</td>
<td>GPS profile</td>
<td>2500/1400</td>
</tr>
<tr>
<td>Verbeu Marignous</td>
<td>13.03.2014 17h00m</td>
<td>ATT2-W (2545)/ Estimated</td>
<td>GPS profile</td>
<td>2400/1700</td>
</tr>
<tr>
<td>Verbeu La Comb</td>
<td>13.03.2014 17h00m</td>
<td>ATT2-NE (2545)/ Estimated</td>
<td>GPS profile</td>
<td>2200/1600</td>
</tr>
<tr>
<td>Braemuhlbühl verbarrung</td>
<td>04.04.2015 12h00m</td>
<td>WFJ2-NE (2560)/ SLF2 (1550)</td>
<td>GPS profile</td>
<td>2200/1600</td>
</tr>
<tr>
<td>Braemuhlbühl Wödi</td>
<td>04.04.2015 14h00m</td>
<td>WFJ2-NE (2560)/ SLF2 (1550)</td>
<td>Drone photogrametry</td>
<td>2200/1600</td>
</tr>
<tr>
<td>CV-1 Andina Chile</td>
<td>19.10.2015 17h00m</td>
<td>CAND5-E (3520)/ Lagunias (2790)</td>
<td>Drone photogrametry</td>
<td>2700/2500</td>
</tr>
</tbody>
</table>

The measurements from the release areas and deposits outlines are summarized in the Appendix A.

4.2.2 Snowpack simulations, initial and boundary conditions

The data provided by the automatic weather stations allows us to run detailed, physics based snowcover simulations. We apply the SNOWPACK model [Bartelt and Lehning, 2002, Lehning et al., 2002, Wever et al., 2014] in a similar setup as the snow-height driven simulations in Wever et al. [2015, 2016]. Because SNOWPACK is a one-dimensional model we must transfer point simulation results to the slope in order to apply a three-dimensional avalanche dynamics model. The horizontal distance between release zone and meteorological station varied between 200 m (the nearest) and 2200 m (the farthest). More important than the linear distance is the difference in altitude. The small elevation difference between the release zones and the weather stations, (see Table 4.2.1), provides the sufficient conditions to apply snowcover models to estimate the initial and boundary conditions of the case studies, [Vera Valero et al., 2016, Wever et al., 2016].

To determine the initial temperature and moisture content of the snowcover requires an accurate modeling of the surface energy fluxes (sensible and latent heat exchanges, incoming short and longwave radiation) which are influenced by the slope exposition. We account for exposition effects on surface energy fluxes using the virtual slope concept proposed by [Lehning and Fierz, 2008b], which was found to provide accurate slope simulations that correspond with wet snow avalanche activity, [Wever et al., 2016, Vera Valero et al., 2016]. We obtain snowcover layering, temperature, density and liquid water content in the release zones using virtual slope angles of 35°. The real slope angles of the release zones varied between 32° and 45°. Shortwave radiation measured at the AWS as well as snowfall amounts are re-projected onto these slopes, taking into account the exposition of the slope, [Lehning and Fierz, 2008b].
To model the snowcover at lower elevations in the transit and runout zones we use meteorological data measured at the valley bottom. This information provides us with the snow temperature, snow height, density and liquid water content at lower elevations. In eight of the twelve case studies the snowcover in the avalanche model can be considered as a single homogeneous layer while for the remaining case studies, the snowcover was best modeled as a two layer system consisting of old wet snow covered by dry new snow, see Table 4.2.6. The elevation dependent properties of the snowcover along the avalanche path were determined by constructing a linear gradient between the upper and lower meteorological stations. This procedure could be applied for the case studies that occurred near Davos (seven case studies) and the cases in Chile (two cases).

For the remaining case studies (Verbier Mont Rogneux, Verbier Ba Combe, Grengiols, see Table 4.2.1) we estimated snowcover conditions along the avalanche track by applying a negative linear gradient of one third of snowcover height per 1000 meters of altitude. This rule provides gradients of snowcover depth of 2 cm to 6 cm per 100 meters of elevation (see Table 4.2.6). This method is in agreement with the Swiss Hydrological atlas, [Spreafico et al., 1992]. In these special cases, the snow temperature, density and liquid water content were kept constant to the values estimated by the SNOWPACK model at the release altitude. In case of avalanches with new snow on top of the wet old snowcover we consider the new snow amount measured at the AWS and estimate a decreasing linear gradient of new snow depth with altitude.

4.2.3 Dynamic modeling

We apply two different numerical models to simulate the set of case studies. Both dynamical avalanche models are integrated into the RAMMS snow avalanche software package. The first model is based on the extended avalanche dynamics equations presented in chapter 2 and 3 and recently published, see [Vera Valero et al., 2015, 2016]; the second avalanche model is the numerical Voellmy-Salm model used in RAMMS following the Swiss guidelines [Salm et al., 1990, Christen et al., 2010] and outlined in [Gruber and Bartelt, 2007]. The two different models are compared Table 4.1.

In the calculations we are primarily concerned with the initial and boundary conditions, which are given by the snowcover model simulations; the release area is given by the field measurements. The fracture depth is defined by the location of the highest water accumulation within the snowcover [Wever et al., 2016] as was previously suggested by [Vera Valero et al., 2016]. Once the fracture depth is known we set the snow density, snow temperature and
liquid water values as the mean values over the slab which extends from the location of the maximum liquid water to the snow surface. We take the values at the estimated time of avalanche release. These values are shown in Tables 4.2.6 and 4.2.6. The amount of erodible snow along the path is estimated calculating a gradient between the snowcover conditions at the release and the conditions at the valley bottom. The erosion model used is described by [Christen et al., 2010, Bartelt et al., 2012c].

Once the initial and boundary conditions were found, the first set of simulations using the extended model were performed. As input parameters the model uses the release area (measured), the snowcover initial conditions (calculated) and a set of friction and avalanche parameters. The avalanche parameters were found by [Buser and Bartelt, 2009, Vera Valero et al., 2015, Buser and Bartelt, 2015]. These parameters were kept constant for all 12 case studies as in [Vera Valero et al., 2016]. The fluidization parameter $\alpha$ (see [Bartelt et al., 2006, Vera Valero et al., 2016]), was fixed to a set value based on the terrain characteristics for each avalanche path. Once this parameter was fixed it was not tuned for the remaining set of simulations.

To perform standard Voellmy-Salm snow avalanche simulations following the Swiss guidelines [Salm et al., 1990] it is necessary to include the entire avalanche mass within the release volume. The guidelines do not consider entrainment along the avalanche path and therefore erosion was not considered in the Voellmy-Salm simulations. This procedure was adopted to follow as closely as possible the Swiss guideline procedures for avalanche calculations and allows a comparison between models which consider entrainment conditions (extended model) and models which employ calibrated parameters (Voellmy-Salm). The avalanche mass of the release area was estimated from the final mass (released plus eroded) calculated using the extended model. The total mass calculated in the extended model is concentrated in the measured release area. With this approach a higher release depth is obtained, in comparison to model calculations with entrainment. This method ensures that the total mass in both simulations is similar. The Swiss guidelines provides the user a set of friction parameters to use depending on the avalanche size and avalanche return period. Those friction parameters correspond to extreme, fast moving, dry-flowing avalanches which have longer runouts than wet ones. For the 12 case studies the friction parameters used were the correspondent to 'Small' avalanches and return period of 10 or 30 years. This parameter combination led to the overall best fit to observations. The calculations were performed with the same terrain and grid resolution.
4.2. Methods

Simulation results:
avalanche deposits and run out

Meteorological Conditions (high and low altitude)

Initial and boundary conditions

Avalanche dynamics model (RAMMS)

Detailed point snowcover simulations (SNOWPACK)

Altitude gradient

Release areas

Deposit area

Figure 4.1: Flow diagram showing the method process

4.2.4 Contingency table analysis for deposition area

The results obtained with the two models are compared through a statistical contingency table analysis. We compare the area covered by the avalanche
4. Initial and boundary conditions

Figure 4.2: Method to construct the contingency table, based on measured deposits outline (a), which is then combined with the simulated deposits area (b) to identify hits (blue), false alarm (red), misses (yellow) and correct negatives (no colour, map only) (c).

<table>
<thead>
<tr>
<th>Forecasted</th>
<th>Yes</th>
<th>No</th>
<th>Total forecasted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>hits</td>
<td>false alarms</td>
<td>forecasted yes</td>
</tr>
<tr>
<td>No</td>
<td>misses</td>
<td>correct negatives</td>
<td>forecasted no</td>
</tr>
<tr>
<td>Total</td>
<td>observed yes</td>
<td>observed no</td>
<td>TOTAL</td>
</tr>
</tbody>
</table>

Table 4.2: Mathematical definition of the statistics scores: probability of detection (POD), false alarm rate (FAR), Equitable threat score (ETS) and Hanssen Kuijpers or true statistic score skill score (HKS)

\[ FAR = \frac{\text{false alarms}}{\text{hits + false alarms}} \]
\[ POD = \frac{\text{hits}}{\text{hits + misses}} \]
\[ HKS = \frac{\text{hits}}{\text{hits + misses} - \text{false alarms + correct negatives}} \]
\[ ETS = \frac{\text{hits - hits}_{random}}{\text{hits + misses + false alarms - hits}_{random}} \]

Where \( \text{hits}_{random} = \frac{(\text{hits + misses})(\text{hits + false alarms})}{\text{total}} \)

Table 4.3: Mathematical definition of the statistics scores: probability of detection (POD), false alarm rate (FAR), Equitable threat score (ETS) and Hanssen Kuijpers or true statistic score skill score (HKS)

deposits calculated with both models with the deposits area measured for each case study. The terrain is divided in square cells which correspond with the calculation cells used in the avalanche simulations (see Fig.4.2 (a) and (b)). For each cell we check whether the cell was covered by the observed avalanche deposits or not and whether the cell was covered by the avalanche simulation once the simulation stops or not. A cell will be considered as covered by the avalanche simulations only if the calculated flow height with the mass at rest is more than 20 cm corresponding approximately to two granules diameter [Bartelt and McArdell, 2009]. The correspondence of observed deposits and calculated deposits is checked using a dichotomous contingency table (see Table 4.2), that split the terrain in four different classes: hits, misses, false alarm and correct negatives (see Fig. 4.2(c)). Computing the amount of cells for each class allows to calculate different metrics to judge how both models perform. In this study the probability of detection (POD), false alarm rate (FAR), equitable threat score (ETS) and Hanssen-Kuijpers skill score or true statistic score (HKS) (see table 4.3) are calculated [Wood-
4.2. Methods

Figure 4.3: Run-out distance calculation procedure. From each calculation cell at the release area the line of steepest descend is calculated. The intersection of the lowest part of the avalanche deposits with the longest calculated (red dot) define the avalanche runout. The same procedure is repeated with the simulation results. The distance measured on the steepest line between the two intersection points is defined as the runout calculation error.

cocker, 1976]. For POD, ETS and HKS a score of 1 would mean a perfect score, in the case of FAR a score of 0 would indicate the perfect score.

4.2.5 Avalanche runout

Parallel to the contingency analysis study, runout studies are conducted. The runout distance was calculated from the difference in meters between the maximum distance reached by the avalanche measurement and the avalanche simulation calculated over the line of steepest descend for each avalanche path in a DEM smoothed to a resolution of 20 m (see Fig. 4.3). The line of steepest descend was chosen as the longest line of steepest descend among all the possible ones departing from the depicted release area for each avalanche path.
4. Initial and boundary conditions

4.2.6 Influence of initial conditions on avalanche runout: sensitivity study

To investigate how initial conditions influenced the avalanche runout and area covered by the deposits we performed 432 simulations on the 12 avalanche tracks where we interchanged the initial and boundary conditions from the 12 different initial and boundary conditions: from each of the 12 case studies we performed 3 different sets of simulations (3x12x12). As a sensitivity analysis we determined the difference between the observed and simulated runout as a function of the initial and eroded temperature, initial moisture content, fracture depth and snow density. Avalanche runout was defined as the reach of the avalanche on the line of steepest descent.

The sensitivity of the model to changes in the snowcover conditions was additionally evaluated. For this purpose the same contingency analysis was performed for three different simulation sets constructed by varying the initial and boundary conditions for each avalanche path used in this study.

The three sets of simulations were constructed as follows:

1. Twelve simulations for each avalanche path interchanging the initial and boundary conditions (fracture and erosion depth, snow temperature, density and liquid water content at the erosion and at the release) for the twelve different avalanches, obtaining thereby a set of 144 simulations.

2. A second set of simulations was performed by using the snow temperature and liquid water content that was simulated by the snowcover model for that track. However, we varied the release and erosion depths and the snow density of the twelve different case studies. This set contains another 144 simulations and is used to verify the model sensibility to changes in avalanche mass at the release and at the erosion.

3. A third set of simulations is constructed by keeping the snow depths and snow densities constant. The remaining conditions (i.e., temperature and liquid water content) were taken from the 12 case studies, leading to another set of 144 simulations.

In total 432 simulations were performed for the entire sensitivity analysis, thirty six per each of the twelve avalanche paths.
4.3 Results

The contingency table analysis is used to explore the following questions:

1. Is it possible to drive guideline-type avalanche dynamics calculations with initial and boundary conditions derived from snowcover modeling? Does the application of physics-based models improve the area covered by avalanche deposits and runout distances?

2. How sensitive are the simulated deposit areas and runout distances to released mass and snowcover properties?

3. What role does the calculation grid resolution play in the simulated areas covered by the deposits and runout distances?

4.3.1 Comparing Guideline-VS and Extended wet Snow Avalanche Models

The 12 avalanche events were simulated using the guideline-VS model [Salm et al., 1990] and the Extended wet snow avalanche model. Recall that the guideline friction parameters were used for wet snow avalanches and best overall fit to the observed inundation areas was found using the classification small and frequent return period of 10 to 30 years. The extended model used the fracture and entrainment depths derived from the snowcover mod-
4. Initial and boundary conditions

ing. Bulk snow temperature and moisture contents were determined by layer averaging of the fracture depth. The contingency table analysis for deposition areas and runout distances are shown in Fig. 4.4.

A comparison between the guideline-VS and the extended wet snow avalanche model reveals that the extended model obtains significantly better results than the guideline-VS model. The probability of detection (POD) in conjunction with false alarm rate (FAR) scores achieved by the extended model improve the results by more than 0.15 points (see Fig. 4.4). The equitable threat score (ETS) achieved by the extended model improves the guideline procedure by more than 0.1 points (4.4). Additionally, the Hanssen and Kuipers or true skill score (HKS) reached by the extended model improves by 0.19 points in comparison to the HKS reached by the guideline model. Therefore, the extended model statistically outperforms the guideline procedure in all four contingency metrics. The fact that the difference in ETS score between the extended model and guideline procedure is higher than the difference in HKS score shows that the HKS score is weighted toward detection, and thus POD, when the area covered by the deposit of an avalanche is small compared to calculation domain (i.e., hitting pixels with the avalanche deposits becomes a rare event). In contrast, the ETS penalizes both misses and false alarms and therefore, guideline simulations which overran the measured deposit area have increased FAR, and a stronger reduction in ETS scores in comparison to HKS (see Appendix A).

The difference in performance between guideline-VS and extended wet snow avalanche model simulations differ per avalanche path (see Fig. 4.4). The guideline-VS procedure has particular difficulties with tracks containing a smooth transition between the acceleration and deposition zones. These avalanche paths have a long distance where the steepness is getting progressively flatter (i.e. Braemabuhl, Mont Rogneux, Ba Combe and Drusatcha, see Table 4.2.1 and Appendix A). In contrast, the guideline-VS model does much better on avalanche paths with a sharp transition between the acceleration and runout zones (Gruenbodeli, Salezer and Gatschiefer). In the examples where the slope angle changes smoothly the guideline calculations systematically overran the measured deposits (Braemabuhl, Wildi, Mont Rogneux, Ba Combe). Thus, the guideline-VS does achieve good scores on detection (POD) but is at the same time exhibiting a high false alarm rate (FAR).

The extended model performs equally well on both types of slope and is able to reproduce runout distances on slopes with gradual transition to the runout zone. In the case of Grengiols (Fig. A.9) the runout distance is somewhat underestimated; however, this was found to be caused by the uncertainty of the elevation of the snowfall limit. This is an important result since it indicates that the snowcover modeling must be able to accurately predict
4.3. Results

Figure 4.4: Comparison of the statistical results from the extended model (black) and the guidelines-VS model (blue), for POD (a), FAR (b), ETS (c) and HKS (d).

the snowline elevation.

4.3.2 Sensitivity analysis

The scores of contingency table analysis reveal that the extended wet snow model that utilizes the modeled initial and boundary conditions can outperform a model based on calibrated guideline friction parameters. The primary result of the preceding section is that guideline-based avalanche dynamics models with extreme friction parameters will have difficulty reconstructing individual case studies and that they are not easily linked to snowcover conditions. The next step is to check how sensitive the extended model is to changes in the modeled initial and boundary conditions.

Role of initial conditions

To demonstrate the role of initial conditions we simulated the 12 case studies using the initial conditions of all the other case studies, performing a total of 144 simulations. The initial conditions consist of fracture depth, snow density, temperature and liquid water content. For example, we simulated the Ba Combe case study with the initial conditions from the other 11 case studies.
4. Initial and boundary conditions

Fig.4.5 depicts the results of the 144 simulations. In these plots, the red dots indicate the simulations performed with the SNOWPACK modeled initial conditions belonging to the specific avalanche path; the small black dots represent the remaining combinations of 11 simulations. The large open circle represents the average of the 11 variations.

The first result obtained from the simulations is that the score difference varies more than 0.2 statistical points for every avalanche path and indicator (POD, FAR, ETS and HKS scores). This result indicates a large variability of the model with different initial conditions. The POD scores using the “right” initial conditions are generally higher, than using those from the other case studies. Furthermore, the false alarm (FAR) rate is lower. The average of the four statistical indicators calculated with the real initial and boundary conditions (red line at Fig. 4.5) outperformed in every case the ones calculated with the interchanged initial and boundary conditions. However, for some single cases, particular simulations with initial conditions from another avalanche path outperformed the one calculated with the real initial conditions. However, the simulation with the original initial condition is mostly among the simulations with the highest ETS or HKS and for the initial conditions from the other case studies, it is not a-priori clear which one will perform best. Also the average scores over all 12 cases is better for the corresponding initial conditions than for the other initial conditions. A last important observation is that the spread of scores provided by the initial conditions from the other avalanche paths for most individual case studies exceeds the spread of scores for all 12 simulations with the corresponding initial conditions.

Again, for the longer avalanche with a smooth transition to the runout zone (Gatschiefer, Drusatcha, Grengiols, Verbier Mont Rogneux and Braemabuhl), the scores varied up to 0.5 points in comparison to avalanche paths where the transition is marked by an abrupt change in slope angle (MO-4 and CV-1 and Gruenbodeli). Thus, long avalanche tracks with a smooth transition to the runout zone, are more sensitive to changes in initial conditions and benefit most from a correct initialization using SNOWPACK simulations.

Role of snowcover mass and density

The initial conditions include both mass/density and temperature/water content. To quantify the relative importance of initial mass versus initial snowpack properties, we performed another set of 144 simulations where only the mass varied, both the fracture mass and entrainment depths. The results of the contingency table analysis are depicted in Fig.4.6. The results are similar to the first sensitivity analysis where the entire set of initial and boundary conditions were varied. This suggests that the selection of the ini-
4.3. Results

Figure 4.5: Sensitivity study simulating every avalanche path with the 12 different initial and boundary conditions calculated from the 12 case studies. The red dot denotes the simulation performed with the initial and boundary conditions calculated for this avalanche path. The open black circle denotes the average of the 12 results. In this plot for every avalanche path fracture and erosion depth, temperature, density and liquid water content at the release and along the avalanche path (erosion) are varied.

tial and boundary conditions for mass is more important than the definition of temperature/liquid water content. For wet snow avalanches, this implies that the layers where meltwater accumulates in the release zone must be identified accurately as this defines the height of the fracture slab and therefore the release mass. A small variation in the fracture depth would lead to a large variability in the predicted avalanche runout. This is a problematic result because it indicates the critical role of fracture depth as an input parameter in avalanche simulations.

Role of snowcover temperature and water content

Fig. 4.7 displays the results of the other set of 144 extended wet snow avalanche model simulations where the temperature and liquid water content in the release and entrainment zones were varied. The mass (release and eroded) was defined by the snowcover simulations driven by the meteorological data for each case study. We find the results are less sensitive to changes in temperature and liquid water content than to mass. This is due to the fact that only wet snow avalanches were considered and the temperature range did not vary outside the wet snow regime. Variations are
4. Initial and boundary conditions

Figure 4.6: The plot repeats the same procedure than the plot above but in this case the sensitivity to different avalanche mass (fracture depth and density) is showed. For every avalanche path 12 different fracture depth, released density erosion depths and eroded density are varied, keeping the liquid water content and snow temperature constant to the calculated for this avalanche case study.

primarily due to variations in liquid water content. This too, is a sensible result because moisture contents in the 12 case studies varied only between 0% and 5%, see Table 4.2.6. However, the variations are less pronounced than those caused by mass changes. The variation was strongest on long avalanche tracks with a smooth transition to runout zone, once again indicating that this path geometry is especially sensitive to any changes in the initial conditions.

4.3.3 Varying calculation grid size

Contingency tables scores for the extended model could depend on the selection of the grid resolution. This would imply that the constant set of friction parameters of the extended wet model is based on a particular cell size. We subsequently repeated the simulations using three different grid sizes: 3mx3m, 5mx5m and 10mx10m. The influence on the contingency scores is depicted in Figs. 4.8 and 4.9 for 10 m and 5m respectively.

A similar analysis was performed by [Bühler et al., 2011]; however without a statistical score and only on a limited number of case studies. The qualitative results of that study indicate that a courser resolution smooths out
4.3. Results

Figure 4.7: The plot repeats the same procedure than the plot above but in this case the sensitivity to different snow temperature and liquid water content is checked. For every avalanche path 12 different snow temperature and liquid water content conditions at the erosion and at the release are varied, keeping the release and eroded depth and density constant to the calculated for this avalanche case study.

...the terrain, causing the extended wet model simulations to overflow the calculated deposit areas. Due to overflowing the measured deposit areas, the POD score increases by almost 0.1 statistical points in average in comparison with the 3m resolution simulations. The coarser simulations are highly penalized in the FAR false alarm rate indicator, showing a drop of 0.2 statistical points on average in comparison with the finer resolution. The statistical scores (ETS and HKS) were positively influenced by the increase in hit rate, but this was compensated by the even larger increase in false alarms. The ETS score is severely penalized, dropping the statistical score by 0.15 points for the coarser simulations (10m) in comparison to finer simulations (3m). Even though the HKS score is more weighted to the number of hits, it likewise decreased, but by a smaller amount. The increase in false alarms was so large that it mostly compensated the improvement obtained by an increase in the number of hits.

The same analysis was repeated using 5m resolution. In this case, the results do not differ greatly from the ones obtained with 3m resolution. The 5m resolution overall statistics (see Fig.4.9) are close to or even equal (in the case of the HKS score, see Fig.4.5), to the results obtained by the 3m resolution simulations. Nevertheless the 5m meter resolution simulations obtained higher...
4. Initial and boundary conditions

POD score than the 3m resolution but also a higher FAR. This pattern was already observed in the comparison between 3m and 10m; however, in this case the difference is much lower. In the other two statistical indicators ETS and HKS even more similar results are obtained. The ETS score (see Fig.4.9) is slightly lower in the 5m resolution than in the 3m, however both obtained the same score in the HKS indicator. The results obtained in the ETS and HKS indicators show the same tendency observed in the comparison between 3m and 10m. Coarser resolutions lead to overflowing and obtaining more hits but also in more false alarms, which penalize the overall score. Nevertheless, in the case of 3m and 5m, it is necessary to compare avalanche path by avalanche path and to check which resolution suits better with each avalanche path. Narrow steep gullies with pronounced topographic features (Ba Combe, MO-4, CV-1 in Chile) require higher resolution than open slopes (Drusatscha, Mont Rogneux, Wildi, Gatschiefer).

A secondary result in this analysis, is that independent of the grid resolution there was a large variability of the model results by varying the initial and boundary conditions. The variability found for 3m, 5m and 10m cell size was similar for all case studies and for all statistical indicators.

4.3.4 Runout analysis study

In this section, we repeat the analysis by considering only one scalar value, the runout distance. The runout study was performed for the three sets of 144 simulations interchanging the initial and boundary conditions as described in the previous section. The 12 simulations performed with the modeled initial conditions and extended are depicted in red dots, the runout calculations for the guidelines-VS are depicted in blue dots. The absolute error in runout distance from the extended is about 3 times smaller than those predicted by the guidelines-VS model (see Fig. 4.10). This difference was larger on those paths were the transition to the deposition zone was smoother, Drusatscha, Braemabuhl, Mont Rogneux, Ba Combe, Gatschiefer. On those paths where this transition is more pronounced the calculated runout distances were closer (e.g., Gruenbodeli, MO-4, CV-1, see Fig. 4.10).

The analysis was repeated using two different coarser resolutions 10 m and 5 m cell size, (light blue and black dots respectively, Fig. 4.10). In the case of 10 meters resolution, the model overruns all the measured runout distances. The average error between simulated and measured runout increases from around 49 m with a 3 m resolution to 70 m with 10 m resolution. Only in the Gruenbodeli case study, where the runout area is confined, the 10 m resolution runout distance is simulated better than the 3m runout simulation.
4.4. Discussion

The results obtained performing the sensitivity analysis confirmed the results achieved in the previous contingency analysis. The extended model is sensitive to changes in the initial and boundary conditions. Those changes are more important on those avalanche paths where the transition to the runout is smooth. On those paths, changes in the initial and boundary conditions lead to deviations of hundreds of meters on runouts calculations, Gatschiefer, Drusatscha, Mont Rogneux, Ba Combe, Fig. 4.11.

As was shown in the contingency analysis, the runout calculations were more sensible to changes in mass than in changes in snowcover conditions (temperature and liquid water content). Varying the mass in the release and erosion doubles the absolute error obtained by varying only snow temperature and liquid water content (see Fig. 4.11).

### 4.4 Discussion

Our analysis is limited to evaluating runout distances and deposition areas for the 12 case studies. Other important avalanche variables, such as speed,
4. Initial and boundary conditions

Figure 4.9: Sensitivity study simulating every avalanche path with the 12 different initial and boundary conditions calculated from the 12 case studies repeating the analysis done at 4.5 but with a simulation resolution (grid size) of 5 m for the 144 simulations. The red dot denotes the simulation performed with the initial and boundary conditions calculated for this avalanche path. The open circle denotes the average of the 12 results. In this plot for every avalanche path fracture and erosion depth, temperature, density and liquid water content at the release and along the avalanche path (erosion) are varied.

dynamic flow heights and impact pressures are not considered in the analysis, although they are crucial in many aspects of assessing avalanche risks. Thus, we are considering only one primary component of the avalanche flow problem: calculating the area covered by the avalanche deposits. We circumvent the lack of flow data by considering well-documented case avalanche case studies in a single flow regime (wet) with return periods of approximately 10 to 30 years. An advantage of this approach is that we consider more than one track geometry, allowing us to draw conclusions about the application of snowcover models and avalanche dynamics calculations in different terrain. This is important because our analysis reveals that the interplay between track geometry and mass are the decisive components in the estimation of runout and inundated area. This is a well-known and general result of all geophysical mass movements [Hutter, 1996].

The starting mass was specified by performing snowcover simulations to determine the fracture depth, density, temperature and water content of the release zone. The snowcover simulations were driven by measured meteorol-
4.4. Discussion

Figure 4.10: Runout error plot comparing guideline-VS runout calculations (blue dots), Extended wet snow model calculations (red dots) and extended runout calculations with 5m and 10 m model resolution (black dots and light blue dots respectively). Some dots are overlapped by other dots. The legend shows the absolute average simulation error for each set of simulations.

Logical data from stations near the release zone. The spatial extent of the release was known from observations and/or measurements. Having accurate information where the avalanche released contributes much to the goodness of the statistical scores. Knowing the location of the release zone and a DEM of the avalanche track predetermines the flow path of the avalanche in the simulations, making a contingency table analysis useful. The model has one parameter $\alpha$ [Buser and Bartelt, 2009], which depends on the avalanche path and still has to be chosen by the avalanche expert. Therefore the application will demand experience in terrain and modeling of avalanches by the avalanche expert, even though the range of $\alpha$ is well-constrained [Vera Valero et al., 2016].

An advantage of the contingency table analysis is that it can be used to identify tracks where there will be a large variability in runout depending on the initial conditions. Our analysis of the simulations revealed a large variability in predicted runout for tracks with flat terraces and gradual slope transitions to the runout zone. Here, we showed that the results are very sensitive to the specification of mass in the release and entrainment zones. On these tracks, an underestimation of fracture depth of only 10cm could lead to significant runout shortening and underestimation of the affected area. However, the initial and boundary conditions estimated from snowcover modeling have

\begin{footnotesize}
\begin{tabular}{l}
3m*: 49 m \\
5m: 44 m \\
10m: 72 m \\
VS: 158 m
\end{tabular}
\end{footnotesize}
4. Initial and boundary conditions

Figure 4.11: Difference between simulated and measured runout distance for the extended wet snow model simulations with the corresponding initial conditions (red dots) and for the sensitivity study simulations (black dots), the average of which is depicted as an open circle, for (upper panel) varying both snow mass (fracture depth and density) and snow properties (temperature and liquid water content), (middle panel) varying snow mass only and (lower panel) varying snow properties only. The red and black lines show the average absolute error in meters of the whole set of simulations (sensitivity and real simulations) to the runout distance measured in the field.
demonstrated a good accuracy in the overall results, the red dots on Figs. 4.5, 4.6 and 4.7 show on average better statistical scores than the black dots calculated with the variations. This result suggests statistically that initial conditions derived from snowcover modeling improve randomly chosen initial conditions derived from a set of wet snow avalanche days. Once again, although the coupling between the snowcover modeling and avalanche dynamics calculations can be automatized, the sensitivity analysis suggests that a mistake in the mass estimation can lead to entirely wrong results. We emphasize that we come to this conclusion even though we restricted our attention to a single avalanche flow regime. Nonetheless, the coupling of snowcover models and avalanche simulations could provide avalanche services with more information to make a risk assessment. Using avalanche dynamics models in this way, differs from traditional avalanche calculations, which are based on extreme conditions, with no link to particular snowcover or meteorological conditions.

The extended wet model performs better than the guideline-VS model in all statistical scores, HKS, ETS, POD and FAR (see Fig. 4.4). The guideline procedures are designed to model extreme, dry flowing avalanches, not particular avalanche events. However, the guideline model achieved in some cases high contingency table scores, despite the application on non extreme, wet snow avalanches. The guideline-VS model was forced using friction coefficients calibrated by Salm et al. [1990]. It was necessary to use the friction coefficients corresponding to smaller avalanche sizes in order to achieve a good correspondence between measurements and simulations. For all case studies, the friction coefficients chosen correspond to size ‘Small’ and a return period of 10 to 30 years. The guideline-VS model had to be manipulated by an expert user to get the best results. For example, the extended model was first applied to determine the mass-balance of the event, which was then used to establish the initial conditions (i.e., released plus eroded mass) of the guideline-VS model. Another disadvantage of the guideline model is that first a calibration of the friction parameters is required to obtain reasonable contingency table scores. Both steps are not required in the extended model applications, because the friction parameters are determined as a known function of snowcover conditions. Moreover, the connection between friction and initial starting mass for the guidelines-VS model were derived from the extended wet snow model calculations. The guideline-VS model really cannot exploit the automated weather measurements, and additional procedures are required to make the guidelines calculations.

Because we considered only wet snow avalanches, the range of snow temperature was rather narrow and close to zero. The water content varied between 1% and 5%, which is a typical range of bulk liquid water content for slopes
Initial and boundary conditions

The vertical liquid water distribution typically exhibited a thin layer with high liquid water content located near layer boundaries (capillary barriers), which supports the assumption in the avalanche model that the liquid water is concentrated at the sliding surface. The results of the snowcover simulations were visually inspected to determine the avalanche fracture depth (following Wever et al. [2016]). This depth could be verified by the observations of the actual release zone. The bulk liquid water content of the slab above the maximum liquid water content was used to initialize the simulations. In general, the statistical scores of the contingency table analysis did not change much as a function of the water content. However, changing water content in some cases led to a large difference in simulated inundation area and runout distance. These cases are associated with terrain characteristics and its influence on the rate of meltwater production as well as the liquid water content of the eroded snow. For example, the Grengiols, and Mont Rogneux avalanche case studies stopped on a flat zone when the initial liquid water was reduced below the simulated SNOWPACK value. This indicates that underestimated liquid water content can lead to spurious runout shortening. In general, however, variations of mass (i.e., fracture and erosion depths together with snow density) produced larger variations in the final simulation results (see Fig. 4.5, 4.6 and 4.7). The mass variations in the sensitivity analysis were broad, see Table 4.2.1. Therefore, using this set of case studies with only wet snow avalanche cases, the model is more sensitive to changes in avalanche mass than in snowcover conditions (LWC and snow temperature).

The statistical scores of the contingency table analysis are dependent on the grid resolution of the avalanche dynamics calculations. The 10m resolution appears to be far too coarse for the avalanche sizes of the case study examples. The contingency scores of the 3m and 5m resolutions are similar. However, the 3m runout calculations show a trend to slightly shorter runout distances. The statistical scores of the 3m resolution are overall better than the 5m resolution because the 3m scores were not penalized by excess runout and therefore obtained fewer false alarms. The 5m resolution clearly achieved the best results for open slopes with gradual transition zones. A 3m resolution might still be necessary when the track contains narrow gulies, bare ground or shallow snowcovers where terrain features, including the presence of blocky scree, can play an important role. Deposition patterns of the smaller events could clearly be better represented by the finer 3m resolution.

4.5 Conclusions

In this chapter we used the physics based snowcover model SNOWPACK to establish the initial conditions for avalanche dynamics calculations. We re-
stricted our attention to avalanches in one flow regime (wet) where the depth and spatial extent of the avalanche release area was known. We used a contingency table analysis to statistically evaluate how well avalanche dynamics models can predict deposition area and runout distances. Although we can demonstrate that physics based models improve the statistical scores, we note that on certain track geometries the results of the avalanche dynamics calculations are extremely sensitive to the specification of the correct starting conditions, particularly fracture and entrainment depths. These tracks contain flat track segments below the release zone and gradual transition zones leading towards the avalanche runout zone. In these cases, underestimating fracture heights and entrainment depths can lead to significant underprediction of avalanche runout distances. The problem appears not to be with the quality of the avalanche dynamics simulations, but illustrates that for these cases it is crucial that numerical snowcover models accurately predict the state of the snowpack from data measured from automatic weather stations.

The model chain could be applied in regions where considerable experience and knowledge of local snowcover variability and avalanche history exist. As these conditions change from year to year, a complete cadaster of documented events is still invaluable. There are cases where these conditions are fulfilled (see [Vera Valero et al., 2016]). In these situations the model chain can support decisions on a deterministic basis and provide decision makers with a valuable source of information about current avalanche risks.
Chapter 5

Conclusions and Outlook

Overview

Avalanche dynamics models are traditionally used to calculate extreme scenarios involving dry, fast moving avalanches. These catastrophic avalanches are associated with unstable layers in cold snowcovers. In this dissertation we model the motion of both frequent and extreme wet snow avalanches. We show how warm temperatures and the presence of water can prevent the fluidization of the avalanche core, leading to heavy, dense flows, that can nonetheless reach considerable runout distances. We assume that meltwater lubrication at the base of the avalanche is the primary process governing wet snow avalanche runout. However, because we develop the model within the general framework of granular physics, mixed-type avalanche forms can be simulated by changing the initial and boundary conditions along the avalanche track. Empirical relationships are used that cover the entire range of avalanche temperature. Moreover, if the initial conditions correspond to a dry cold avalanche the parameters will correspond to a dry avalanche; if the initial conditions correspond to a wet snow avalanche the parameters will correspond to a wet avalanche. We therefore show that excessive parameter tuning is not needed if and only if the initial and boundary conditions can be accurately specified.

Dry snow avalanche models are based on the solution of depth-averaged mass, momentum and random energy (granular temperature) equations [Christen et al., 2010]. To model wet snow avalanches we extended the initial set of four differential equations with a (1) thermal energy equation and (2) a liquid water transport equation. This allows us to investigate how frictional dissipation can raise the avalanche flow temperature to the point where meltwater can be produced. Another important source of meltwater is the entrainment of moist snow. Together, these processes (dissipation and entrainment) control the temperature and moisture of the avalanche and therefore the thermal flow regime (dry, wet). With these modifications to the
5. Conclusions and Outlook

standard dry model, we find that avalanche flow is remarkably dependent on the terrain profile and snowcover conditions. How this result can be exploited to improve practical avalanche dynamics needs further clarification, involving case-by-case analysis of well documented events.

Snowcover simulations with SNOWPACK are only possible at points were automatic weather stations measure the meteorological input data. The concept of ‘virtual slope’ is used to extrapolate the snowcover conditions from the measurement point to other locations on the slope. However, the natural variability of the terrain and local meteorological conditions make it difficult to extrapolate data from the automatic weather station to distant release areas and erosion zones. We could not quantify the possible error related to the density of the measurement stations. Given the current computer capacity it would be possible to use Alpine3D simulations to calculate the snow conditions at a finer scale.

A major caveat of this work is the application/modification of a Voellmy-type relationship governing avalanche flow friction. We applied a Voellmy relationship in order to ensure compatibility with many foregoing avalanche calculations. This allows a comparison between existing models and new approaches. In fact, the new approaches and existing models are exactly equal when all energy is dissipated to heat, and no random fluctuation energy is produced. That is, the existing Voellmy model is a particular subset of a more general model. The Voellmy model remains the model of choice of avalanche engineers, despite its relatively old age (60 years). However, it does require the use of empirical functions that link snow properties (temperature, moisture) to two friction parameters ($\mu, \xi$). Until more experimental evidence can be gained concerning the nature of snow-on-snow basal friction, the Voellmy-model will most likely remain the work horse of avalanche dynamics calculations.

5.1 Research Questions: Answered and Unanswered

The dissertation highlighted several of the central questions in avalanche dynamics and the role of numerical modeling. An underlying research question evolved: How can a physics-based model of avalanche flow be constructed such that the wide-range of avalanche motion (including small, frequent and wet events) can be accurately simulated?

The answer to this question is that snow temperature, wetness, flow density, velocity fluctuations are not constant within the flow, neither in time nor space. Avalanches are highly non-steady phenomena, where assumptions of steadiness and homogeneity cannot be reasonably supposed. We attacked the problem of streamwise variations of temperature, wetness, density and velocity fluctuations. This procedure allows us to model a wide
range of avalanche motion, including both dry and wet flows. However, depth-variations could not be resolved. Therefore, the model physics is based on mean, depth-averaged values that are locally produced and transported within the flow. Spatial and temporal variations can be modeled (e.g. concentration of turbulent energy at the avalanche front, or concentration of liquid water content in the interior of the flow). Physics-based models therefore provide insights into the formation of powder snow avalanches [Bartelt et al., 2016], or the formation of deposition levees in the runout zone [Bartelt et al., 2012b], a common feature of wet snow avalanches.

Of course, the primary problem with the streamwise approach is that empirical relationships are still required to link mean variables to frictional processes, because information is lost over the avalanche flow depth. We concentrate shearing processes at the base of the avalanches, and therefore cannot predict the real distribution (height) of meltwater in the flow. Many experiments measuring internal shear profiles [Dent et al., 1998, Kern et al., 2009, Nishimura and Maeno, 1987] suggest that this assumption is acceptable, but it might not be applicable in general. For example, when snow is entrained into the avalanche we assume a homogeneous mixing of avalanche snow and snowcover. Thus the moisture content and temperature of the snowcover is distributed instantaneously throughout the avalanche flow depth. This can only be a rough approximation of reality.

The application of a physics-based model leads to many secondary questions. For instance, How must the initial and boundary conditions of physics based models be prescribed?

Our answer is to rely on snowcover modeling. The development of detailed physics-based snowcover models in three-dimensional terrain [Lehnig et al., 2006, Vionnet et al., 2012] enables the use of pointwise automatic weather stations. However, snowcover variability and local climate effects cannot be well represented by snowcover models forced with meteorological data from a limited number of measurement points. In future we expect a much wider proliferation of automatic weather stations. Denser networks of sensors will exist which could deliver more accurate snowcover data from larger and remote areas in real time. Nonetheless linking two process models – one for the snowcover and the other for avalanche calculations is not straightforward- Extensive experience for each avalanche path is still much needed to identify the input dimensions of the release zones. Every avalanche path has its own local conditions in terms of wind exposure, ground surface, exposition, etc. The avalanche expert should gather this information together with the snowcover data coming from the snowcover simulation and build the input and boundary conditions for the simulation. In this work we have demonstrated statistically that the snowcover models can provide an accurate estimation of initial and boundary conditions, but
5. Conclusions and Outlook

much work is still needed to identify the limitations of this approach.

Previous studies have noted that fixed friction parameters in a Voellmy type model are not able to represent the spatial and temporal variations of flow height and velocity [Gruber and Bartelt, 2007]. Calibration tests show that the parameter variability is due to both terrain features as well as snow properties [Fischer et al., 2015, Ancey, 2005, Naaim et al., 2013]. Models with fixed parameters are therefore not able to simulate avalanche flow regime transitions. Here, we replace model parameters with physical relationships governed by fixed parameters which are a function of snow properties. The result of this approach is that it is possible to simulate a wider range in avalanche behavior, including different avalanche sizes, different avalanche tracks and, most importantly, both dry and wet snow avalanches.

The development of snow avalanche models driven by parameters defined by the current snow conditions opens a new perspective in avalanche risk assessment. Is it possible to simulate an avalanche that can happen now? Is it possible to depict ‘dynamic’ avalanche hazard maps which get updated every time we get new snowcover conditions? Models able to simulate wider range of avalanche types can be called ‘operational’ because they can be used to ascertain the threat to roads or ski runs daily exposed to avalanche threats.

5.2 Outlook

The presented work does not pretend to be a substitute for the expert judgment of an experienced avalanche engineer. The chain of snowcover and avalanche dynamics models provides these experts with up-to-date information of the avalanche risk at a specific avalanche path or even entire region. It bundles information within the framework of results from physical models driven by actual meteorological measurements. It is the task of the avalanche experts to use the modeling results appropriately. Once the model chain has been extensively tested, the experts operating it will have certain level of experience, and the level of confidence will increase for specific avalanche paths. The model chain, however, will remain only one tool more to assess avalanche risk. Increasing computing power coupled with accurate meteorological data means that more snowcover data is available. This work is then a first step on the direct use of snowcover measurements to define the initial conditions of an avalanche dynamics model. This first step can open new doors like direct assessment of avalanche risk in an operational basis. To directly couple snowcover models with avalanche dynamics models opens new possibilities in avalanche risk assessment.

Thus, the primary work in future must concentrate on raising the confidence level of the model chain, starting from the automatic weather stations and
ending with the avalanche dynamics calculations. To increase the accuracy/applicability of the model chain requires:

- **Improved methods to delineate the location and size of avalanche release zones.** Several recent works have addressed this problem [Bühler et al., 2013, Dreier et al., 2014, Veitinger et al., 2015]. These works are driven by the fact that the definition of the release area is the critical input and a small error can result in poor estimation of avalanche runout. It is unlikely that this procedure can be automatized without directly involving the avalanche experts at a particular site. Different strategies exist to infer the release area, even for a well-documented avalanche path. Nonetheless even for ‘regular’ snowcover conditions, the spatial variability of the snowpack or unexpected mechanical loads (e.g. wind) or local conditions can lead to an ’unexpected’ release sizes. A particular problem will be transferring delineation procedures from one region or terrain to another.

- **Improved snow entrainment models.** The entrainment calculations in this work are based on so-called collisional entrainment theories [Christen et al., 2010, Vera Valero et al., 2016]. These models assume that the flux of intake snow is proportional to the mean avalanche speed. (The proportionality constant is the dimensionless parameter κ, termed the erodibility). Because the speed of the intake of snow is moving at the speed of the avalanche at the end of the collisional interaction, the entrainment process can be considered to be completely plastic. A collisional description of entrainment does not resolve the issue how much snow is collected, only the functional dependency on avalanche speed. The height of the snow layer eroded by the avalanche still needs to be specified by the avalanche expert. In this work we use the snowcover model simulations to infer what is the amount of erodible snow (mass, density, moisture content) for every avalanche case by case [Wever et al., 2016]. The snow cover models now provide information on snow quality (grain-size, shape and bonding) which are important to define entrainment rates.

- **Improved parametrization of ground roughness.** In granular avalanche models, ground roughness partitions the frictional work rate into heat and random kinetic energy [Bartelt et al., 2006]. Thus, ground roughness plays an important role in avalanche dynamics because it leads to fluidized or dense avalanche cores [Huang et al., 2009], thus collisional or frictional flow regimes [Ancey and Evesque, 2000]. Within the framework of this dissertation, it was impossible to quantify the partitioning coefficient for a particular terrain which appears to depend on the height of the non-entrainable snowcover, snow temperature and terrain ruggedness. Thus, this parameter had to be varied, especially
5. Conclusions and Outlook

in the steep, rugged slopes of the Chilean Andes. Clearly, more work must be invested in this area, before the model chain can be used extensively as an operational tool.

- More experimental data from wet snow avalanche tests. This thesis relied heavily, almost exclusively, on measured inundation areas and deposition heights of wet snow avalanches. We used measured wet snow velocity profiles to qualitatively construct a lubrication function, in which shearing and therefore meltwater production, is concentrated in a layer located near the running surface. Videos of the wet snow events were used to constrain the avalanche velocity. To improve existing wet snow avalanche models in the near future, additional measurements are required. These include measuring the evolution of the moisture content from the release to the runout zone. Therefore moisture profiles must be made at several different locations along the avalanche track. At these same locations, it would be necessary to measure avalanche velocity and density. This is only possible with great financial expense and at a fully equipped avalanche test site containing several masts at different locations in the avalanche runout zone.

Finally, we emphasize that this dissertation was completed at a time when avalanche engineers are confronted with a change in climate. The wet snow avalanche model will be helpful in quantifying how climate change will affect snow avalanche runout [Eckert et al., 2009, 2010]. The same model framework could be used to simulate slush flows [Hestnes, 1998]. A slush flow model is possible within the same model formulation, but will require additional modifications. Quite possibly it might be necessary to include the liquid phase in the model formulation. The wet snow avalanche model, assumes that the granules are surrounded by air. Furthermore the liquid water is attached to the granules and therefore the granules and water are transported at the same speed. Such assumptions can no longer be made for slush flows. Modeling slush flows will need additional constitutive relationships including the momentum exchange between the granules and the free liquid water. Empirical relations must be extended beyond the range of bonded water, assumed in this dissertation.
Appendix A

The following appendix shows the run out calculations performed with the VS guideline model and with the extended-VS model for the 12 case studies used in the chapter IV. For each figure the measured released (orange polygon) and deposits (violet polygon) areas are shown too.

![Figure A.1: Gatschiefer Davos](image)

(a) Extended simulation  
(b) Voellmy Salm simulation

Figure A.1: Gatschiefer Davos
A. Appendix A

Figure A.2: Ba Combe Verbier

(a) Extended simulation

(b) Voellmy Salm simulation
Figure A.3: Mont Rogneux Verbier

(a) Extended simulation

(b) Voellmy Salm simulation
Figure A.4: Gruenbodeli Davos
Figure A.5: Salezer Davos

(a) Extended simulation

(b) Voellmy Salm simulation
A. Appendix A

Figure A.6: Braemabuhl Verbauung Davos

(a) Extended simulation

(b) Voellmy Salm simulation
Figure A.7: Wildi Davos
A. Appendix A

Figure A.8: Drusatscha Davos

(a) Extended simulation

(b) Voellmy Salm simulation
Figure A.9: Grengiols
A. Appendix A

Figure A.10: Codelco Andina MO-4

(a) Extended simulation

(b) Voellmy Salm simulation
Figure A.11: Codelco Andina CV-1
Appendix B

The following appendix shows the run out sensitivity analysis calculations performed with the extended-VS model for the 12 case studies used in the chapter IV. The upper plot in each figure correspond to the 12 simulations performed interchanging all the initial and boundary conditions: fracture and erosion depth, density, snow temperature and liquid water content for the 12 case studies. The middle plot correspond to simulations where the initial mass conditions were interchanged: fracture and erosion depth plus density are interchange among the 12 case studies. The lower plot correspond to simulations where the initial snowcover conditions were interchanged: snowcover temperature and liquid water content for the 12 case studies. For each figure the measured released and deposits areas are shown in two polygons, orange and green respectively.

Figure B.1: Gatschiefer Davos
Figure B.2: Gruenbodeli Davos
Figure B.3: Salezer Davos
Figure B.4: Drusatscha Davos
Figure B.5: Codelco Andina Chile MO-4
Figure B.6: Grengiols
Figure B.7: Mont Rogneux Verbier
Figure B.8: Ba Combe Verbier
Figure B.9: Braemabuhl Verbauung Davos
Figure B.10: Wildi Davos
Appendix C

Assessing wet snow avalanche activity using detailed physics based snowpack simulations

Water accumulating on microstructural transitions inside a snowpack is often considered a prerequisite for wet snow avalanches. Recent advances in numerical snowpack modeling allow for an explicit simulation of this process. We analyze detailed snowpack simulations driven by meteorological stations in three different climate regimes (Alps, Central Andes and Pyrenees), with accompanying wet snow avalanche activity observations. Predicting wet snow avalanche activity based on whether modeled water accumulations inside the snowpack locally exceed 5 – 6% volumetric liquid water content is providing a higher prediction skill than using thresholds for daily mean air temperature, or the daily sum of the positive snow energy balance. Additionally, the depth of the maximum water accumulation in the simulations showed a significant correlation with observed avalanche size. Direct output from detailed snow cover models thereby are able to provide a better regional assessment of dangerous slope aspects and potential avalanche size than traditional methods.1

C.1 Introduction

In mountainous regions, wet snow avalanches pose a serious threat to society and infrastructure. The wetness of the released snow contributes to dense flows and lubrication at the base of the flow can occasionally cause long runout distances [Naaim et al., 2013]. There is an increasing demand for forecasting wet snow avalanche activity (e.g., Zischg et al. [2005], Mitterer

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et al. [2013]). Lazar and Williams [2008] have shown that global warming may cause a shift of wet snow avalanche activity into the operational ski season of ski resorts. Also the proportion of wet snow avalanches as compared to dry snow avalanches may increase in the future [Martin et al., 2001, Pielmeier et al., 2013, Castebrunet et al., 2014], although regionally, historical trends were found to be opposite [Bellaire et al., 2016].

Most studies addressing the predictability of wet snow avalanches use statistical methods to relate meteorological conditions or the snowpack energy balance to wet snow avalanche activity [Romig et al., 2004, Zischg et al., 2005, Jomelli et al., 2007, Baggi and Schweizer, 2009, Peitzsch et al., 2012, Mitterer and Schweizer, 2013, Helbig et al., 2015]. Although a significant positive energy balance of the snowpack is often required to predict wet snow avalanche activity, calculating the snow energy balance only is often not sufficient. The thermal state of the snowpack is also important, i.e., wetting of an initially below freezing snowpack is more critical for snowpack stability than additional melt occurring in a ripe snowpack [Armstrong, 1976, Durand et al., 1999, Techel et al., 2011, Mitterer and Schweizer, 2013].

Ultimately, the wet snow avalanche formation process is governed by liquid water flow processes in snow. A prominent characteristic of water flow in snow is ponding at capillary barriers caused by transitions in grain size, grain shape or density [Wakahama, 1975, Marsh and Woo, 1984, Conway and Benedict, 1994, Waldner et al., 2004]. The water ponding process is generally considered to be an important factor in wet snow avalanche formation (e.g., Kattelmann [1984], Fierz and Föhn [1994], Mitterer et al. [2011b], Takeuchi and Hirashima [2013]) and the presence of capillary barriers has been statistically linked to wet snow avalanche activity [Baggi and Schweizer, 2009]. Based on field experiments, it is generally considered that snow strength is strongly reduced once volumetric liquid water content (LWC) exceeds 5 – 7% [Brun and Rey, 1987, Bhutiyani, 1996, Yamanoi and Endo, 2002, Ito et al., 2012]. As the typical LWC of snow in the absence of gradients in capillary suction is below this value [Coléou and Lesaffre, 1998, Heilig et al., 2015], ponding inside the snow cover seems to be an important prerequisite to reduce the stability of a wet snowpack. In recent laboratory experiments, LWC in layers adjacent to capillary barriers was found to peak around 33% [Avanzi et al., 2015].

Recent improvements in the simulation of liquid water flow in the numerical SNOWPACK model [Bartelt and Lehning, 2002, Lehning et al., 2002,b] by using Richards equation [Hirashima et al., 2010, Wever et al., 2014] allow for the direct simulation of ponding conditions inside the snowpack [Hirashima et al., 2014, Wever et al., 2015, Avanzi et al., 2015]. This study aims to investigate whether the occurrence of ponding at layer interfaces inside the snowpack can be related to wet snow avalanche activity. An advantage
of using physics based models is that they ideally do not require site-specific calibration. This is tested for by analyzing data from three different climate regimes: the Swiss Alps, the Spanish Pyrenees and the Chilean Central Andes.

C.2 Data and methods

C.2.1 Meteorological Forcing Data and Simulation Set-up

Meteorological forcing data to drive the SNOWPACK model was collected from three measurement sites, located in three different mountain ranges with varying climatological regimes. The Weissfluhjoch (WFJ) measurement site is located at 2540 m a.s.l. in the Swiss Alps (46.83°N, 9.81°E) and is equipped with high quality instruments [WSL Institute for Snow and Avalanche Research SLF, 2015-09-29]. We consider here the period October 2001-July 2015, corresponding to the period for which consistent avalanche activity data is available. The Codelco-Andina mine is located 100 km north-east of Santiago in the Chilean Central Andes. We use data from the automatic weather station Laguna Angela (LAG, 33.03°S, 70.28°W, 3550 m a.s.l.), operated by the mine, for the period January 2010 to December 2015. Finally, the avalanche warning service of Val d’Aran in the Spanish Pyrenees operates the Comalada (COM) meteorological station (42.71°N, 0.94°E, 2075 m a.s.l.), from which we use data between October 2012 and June 2015. At all three stations, air temperature, relative humidity, wind speed, incoming shortwave radiation and snow height are measured. At WFJ and LAG, additionally reflected shortwave radiation is measured. For WFJ, this allows us to drive the SNOWPACK model with measured snow albedo. The absence of ventilation or heating of the incoming shortwave radiation sensor at LAG to prevent riming or snow piling up, made us decide to use the reflected shortwave radiation sensor in combination with parametrized albedo to determine net shortwave radiation. At COM, net shortwave radiation is determined using the incoming shortwave radiation sensor and the parametrized albedo. Furthermore, in contrast to the WFJ site, at LAG and COM the sensors for air temperature and relative humidity are not ventilated, and there are no incoming longwave radiation measurements. For these two stations, the incoming longwave radiation is parametrized using air temperature, relative humidity and cloudiness [Omstedt, 1990], where cloudiness is estimated from measured shortwave radiation [Bavay and Egger, 2014]. WFJ is additionally equipped with a heated rain gauge, enabling also an estimation of the occurrence of rainfall events for this site.

The physics based snow cover model SNOWPACK was used to simulate the temporal evolution of the snowpack at the meteorological stations. Liquid water flow in snow was solved using Richards equation (RE), which was
found to improve several aspects (e.g., percolation time) of the simulation of liquid water flow in snow [Wever et al., 2014, 2015]. Furthermore, the simulations with RE reproduced accumulations of liquid water at microstructural transitions inside the snowpack [Wever et al., 2015]. These arise from variable water retention curves, currently parametrized depending on grain size and density [Yamaguchi et al., 2012] and gradients in hydraulic conductivity. The layer thickness of snowpack layers in the SNOWPACK model is variable due to variations in snow settling, but typically is around 2 cm. Here, the hydraulic conductivity at the interface nodes is calculated with the geometric mean [Wever et al., 2015], which is able to reproduce the LWC values of around 33% at microstructural transitions inside the snowpack, as observed in laboratory experiments [Avanzi et al., 2015].

As the stations are located on flat sites, they cannot be regarded as representative for avalanche release zones in steep slopes. For this reason, four main virtual slopes [Lehning and Fierz, 2008a] were used with a north, east, south and west aspect and a slope angle of 35° (similar to Mitterer and Schweizer [2013]). For WFJ, four additional virtual slopes (north-east, south-east, south-west and north-west) were used for the direct comparison with aspects used in avalanche activity reports. Direct shortwave radiation as measured at the flat measurement site was projected on those virtual slopes. Snow height measurements were used to determine snowfall at the flat field, which was subsequently projected on the virtual slopes. The analysis is limited to the period with a snowpack at the flat measurement site, as otherwise, the meteorological measurements are not representative for slopes that are still snow-covered.

C.2.2 Wet Snow Avalanche Activity Data

Wet snow avalanche activity within a maximum distance of approximately 25 km from WFJ has been derived from daily reports by trained observers for the period October 2001 to July 2015. Avalanches are considered wet when the snow in the release area is wet. The reports may concern a single avalanche, but more often summarize daily activity by reporting the number of avalanches, subdivided into the five Canadian size classes [McClung and Schaeerer, 2006]. Additionally, the lowest and highest release elevation are provided in steps of 200 m when reporting multiple avalanches and a single release elevation when a single avalanche is reported. Observers also indicate the slope aspects in which wet snow avalanche activity is observed, subdivided into 8 aspects. To match the avalanche activity with the simulations for the WFJ measurement site, we selected avalanche reports of wet snow avalanches with either the lowest or highest reported release elevation between 2200 and 2800 m a.s.l. This selection procedure results in a 14 season total of 213 avalanche days and 2979 days with no wet avalanches re-
C.2. Data and methods

ported. When analyzing individual slope aspects, we require both the lowest and the highest release elevation to lie in this elevation band. An avalanche activity index (AAI) is then computed by weighting the number and size of the reported avalanches, using weights 0.01, 0.1, 1.0 and 10.0 for each very small, small, medium and large avalanche, respectively [Schweizer et al., 1998].

The dedicated avalanche service at the Codelco-Andina mine in Chile monitors avalanche activity in an area of about 70 km², particularly for avalanche paths that may potentially pose a threat to the infrastructure or the access roads of the mine. Small avalanches in non-threatening slopes are not necessarily getting reported. Totaled over 6 seasons (2010-2015), the dataset consists of 943 non-avalanche days and 50 avalanche days. Due to the limited number of observed avalanches, we did not apply an additional criterion for release elevation.

The avalanche warning service of Val d’Aran in Spain also records avalanche activity within approximately 20 km distance from the COM measurement site by mapping the avalanche paths and documenting the type of avalanche. Using the ASTER Global Digital Elevation Model [METI/NASA/USGS, 2009], the elevational range of occurred wet snow avalanches was determined. The upper one-third of the avalanche outline was considered the release area and only avalanches where the middle of the release area was between 1675 and 2475 m a.s.l. were considered. For the three winter seasons in the dataset (2013-2015), this selection procedure results in 496 non-avalanche days and 28 avalanche days.

C.2.3 Methods

To synthesize useful information from the numerical snowpack simulations, we analyze the daily sum of positive surface energy balance of the snowpack, determined at each model time step of 15 minutes (similar to Mitterer and Schweizer [2013]) as well as the highest LWC found in any of the snowpack layers in the simulations (henceforth denoted as maximum local LWC). From the meteorological measurements, the daily mean air temperature was taken into consideration as an example of a prediction method that does not require the use of a snowpack model. We consider the strategy of predicting wet snow avalanche days based on the exceedance of a threshold in these three variables in one or more of the four virtual north, east, south and west slopes.

The correspondence of predicted and observed wet snow avalanche activity is investigated using dichotomous contingency tables, where both the observations and the simulations can indicate either a wet snow avalanche day or a non-wet snow avalanche day. The Hanssen-Kuipers skill score (HKS, Hanssen and Kuipers [1965]) is considered a suitable metric to judge overall
performance of the dichotomous predictions, without requiring equalizing
the number of events and non-events [Woodcock, 1976]. We also calculate
the probability of detection (POD), defined as the number of correctly pre-
dicted avalanche days divided by the total number of observed avalanche
days, the probability of null events (PON), defined as the number of cor-
rectly predicted non-avalanche days divided by the number of observed
non-avalanche days, the false alarm ratio (FAR), defined as the number of
days predicted as an avalanche day which was not observed as one, di-
vided by the total number of predicted avalanche days and the accuracy
(ACC), defined as the total number of correctly predicted avalanche and
non-avalanche days, divided by the total number of days [Doswell et al.,
1990].

We determined the prediction thresholds for avalanche or non-avalanche
days for each of the variables separately as those that provide the highest
HKS. This calibration is performed with the seven even years from WFJ,
using the other seven uneven years for validation. Further validation is
performed by a comparison with the simulations and wet snow avalanche
data from the Central Andes and Pyrenees. The expression for the standard
delegation as derived by Hanssen and Kuipers [1965] is used as an indication
of the accuracy of the HKS [Woodcock, 1976].

C.3 Results and Discussion

Figure C.1 displays the evolution of the snow height, daily sum of posi-
tive energy balance, maximum local LWC and wet snow avalanche activity
during the 7 calibration snow seasons at WFJ. The snow height is the av-
erage value over all main four slope aspects, whereas the other variables
are the daily maximum values found in either one of those slope aspects.
The snow season at WFJ typically consists of a cold winter period, where
the snow melt is concentrated in south facing (sunny) slopes, followed by
a melt period in spring with snow melt occurring in all slope aspects. The
peak in wet snow avalanche activity is often found shortly before or after
the maximum snow height is reached and is accompanied by peaks in both
the daily sum of positive energy balance as well as the maximum local LWC
inside the snowpack. However, while the energy balance increases towards
the end of the melt season, driven by an increase in air temperature and
incoming solar radiation towards the summer season, avalanche activity is
decreasing. In contrast, the maximum local LWC found inside the snowpack
is peaking during periods of wet snow avalanche activity and declining after-
wards, a pattern which visually seems to be in closer correspondence with
the avalanche observations.

Peaks in maximum local LWC in the simulations often coincide with the first
C.3. Results and Discussion

Figure C.1: Running mean (7 days) of snow height, daily sum of positive energy balance (EB), daily maximum local LWC and the logarithm of the daily wet snow avalanche activity index (AAI), averaged (snow height) or maximum value over four simulated aspects (North, East, South and West slope), for the 7 calibration years for WFJ, Switzerland. Each variable is standardized using its maximum value over the complete period. The upper part of the graph in each row shows the relative position of the maximum local LWC inside the snowpack for values > 1% LWC, ranging from 0 to 1 for the bottom and top of the snowpack respectively, separated into north and south facing slopes.

wetting as a result of the combined effect of ponding on capillary barriers and a strong gradient in hydraulic conductivity over the barrier. Later in the melt season, when the snowpack is also moist below the capillary barrier, the gradient in hydraulic conductivity is reduced, weakening the strength of the capillary barrier. These model simulations thereby seems to be congruent with the notion that the first wetting of the snowpack is particularly dangerous [Durand et al., 1999, Techel et al., 2011]. A few peaks in maximum local LWC do not correspond to periods with wet snow avalanche activity (for example in 2002 and 2006), which seems to particularly occur in south facing slopes when the maximum local LWC content is found close to the snow surface (see Figure C.1).

In Figure C.2, the distributions of daily mean air temperature, daily sum of positive energy balance and the maximum local LWC are shown for WFJ, LAG and COM, separated into days on which wet snow avalanches were
C. Assessing wet snow avalanche activity using detailed physics based snowpack simulations

observed and days without reports of wet snow avalanche activity. The Kolmogorov-Smirnov test showed that for all three variables, the distributions differ significantly (p < 0.05) between avalanche and non-avalanche days for WFJ and LAG. For COM, only the maximum local LWC distribution differs significantly between avalanche and non-avalanche days. For all three sites, the Kolmogorov-Smirnov test statistic is larger for the maximum local LWC than for the daily sum of positive energy balance or the daily mean air temperature. The Mann-Whitney-Wilcoxon test yields similar results, also indicating that for COM, only the median of maximum local LWC is significantly different (p < 0.05) on avalanche and non-avalanche days, whereas for WFJ and LAG all three variables have a significantly different median (p < 0.05). The test statistic is again highest for maximum local LWC, indicating that of the three variables studied here, the maximum local LWC seems most suited for separating avalanche from non-avalanche days.

For the area surrounding WFJ, the long and detailed dataset enables a separation into individual slope aspects. Figure C.3 shows the distributions of the daily sum of positive energy balance and the maximum local LWC as a function of slope aspect, separated into days with and without wet snow avalanche activity reports for the particular slope aspect. A clear dependence of the daily sum of positive energy balance with slope aspect is found for days with observed wet snow avalanche activity. This can be attributed to the aspect dependence of incoming shortwave radiation. In contrast, the median of the maximum local LWC varies between 5 and 7% and only a weak dependence with slope aspect is present.

We now consider the prediction strategy for wet snow avalanche activity based on whether the chosen prognostic variables exceed a certain threshold. An avalanche day is predicted when the daily mean air temperature exceeds −3.9 °C, the daily sum of positive energy balance exceeds 2.5 mm w.e. or the maximum local LWC exceeds 6.3% in one or more of the four main virtual slope aspects. These thresholds were determined to provide the highest HKS for the 7 calibration years from WFJ, and were subsequently verified using the other 7 years from WFJ as well as the full dataset for LAG and COM. For the validation datasets, Figure C.4 shows five characterizing statistics (POD, PON, FAR, ACC and HKS) describing the quality of this prediction method. Using the maximum local LWC provides the highest HKS for all three sites WFJ (0.46 (±0.05)), LAG (0.38 (±0.07)) and COM (0.29 (±0.08)), as well as the highest ACC. For all sites, the daily sum of positive energy balance is showing larger skill (HKS of 0.38 (±0.05), 0.19 (±0.07) and 0.06 (±0.09) for WFJ, LAG and COM, respectively) than using the daily mean air temperature (0.37 (±0.05), 0.12 (±0.07) and 0.04 (±0.09) for WFJ, LAG and COM, respectively), although differences between both variables are smaller than the difference with maximum local LWC. The fact that both the calibration
C.3. Results and Discussion

Figure C.2: Box and whisker plot showing the distribution of daily mean air temperature (TA), highest daily sum of positive energy balance (EB) and highest daily maximum local LWC in one of the four simulated virtual slopes separated into avalanche days and non-avalanche days. Boxes represent inter-quartile ranges (25th to 75th percentiles), thick horizontal bars in each box denote the median (50th percentile) and whiskers (vertical lines and thin horizontal bars) represent the highest and lowest value within 1.5 times the inter-quartile range above the upper or below the lower quartile, respectively. Notches are drawn at ±1.58 times the inter-quartile range divided by the square root of the number of data points. Outliers are not shown.

and validation dataset were constructed from the WFJ data explains, at least partly, the higher HKS score for WFJ compared to LAG or COM. Also the high quality of the meteorological measurements for WFJ may contribute positively here.

When using the threshold of 6.3 % for maximum local LWC for the eight individual slope aspects in the WFJ dataset, the HKS ranges from 0.40 to 0.60. Although the prediction skill is acceptable in individual slope aspects, only 4 out of 8 aspects showed higher HKS scores for the maximum local LWC than for the daily sum of positive energy balance. The concept of virtual slopes regarding snow height and meteorological forcing is likely not necessarily representative for the slopes where the avalanches occurred. Moreover, higher skill scores could be achieved for the individual slopes if the threshold would be reduced to 5%.

The proportion of correctly predicted avalanche days (POD) is lower when
C. Assessing wet snow avalanche activity using detailed physics based snowpack simulations

Figure C.3: Box and whisker plot showing the distribution of the daily sum of positive energy balance (EB) and daily maximum local LWC per slope aspect and separated into avalanche days and non-avalanche days. The number in brackets below the x-axis labels denote the number of days in the respective distributions. Boxes represent inter-quartile ranges (25th to 75th percentiles), thick horizontal bars in each box denote the median (50th percentile) and whiskers (vertical lines and thin horizontal bars) represent the highest and lowest value within 1.5 times the inter-quartile range above the upper or below the lower quartile, respectively. Notches are drawn at ±1.58 times the inter-quartile range divided by the square root of the number of data points. Outliers are not shown. The dashed horizontal lines indicate the thresholds to distinguish between avalanche and non-avalanche days, determined by calibration, for daily sum of positive EB (red) and maximum local LWC (blue).

using the maximum local LWC, whereas this variable is generally better in predicting the abundant non-avalanche days (i.e., a higher PON). Therefore, the overall accuracy of all predictions (i.e., ACC) using maximum local LWC is higher than those using the daily sum of positive energy balance or the daily mean air temperature, even for individual slopes (not shown). However, the FAR is relatively high in all cases for all variables. Thus, although avalanche reports are probably not providing a complete record of all avalanche activity in the region, water accumulating on capillary barriers inside the snow cover is likely not a sufficient condition for a release. Long-term exposure of a snowpack to wet conditions and associated wet snow metamorphism may stabilize the snowpack, while capillary barriers or crusts may continue causing ponding. Furthermore, the number of avalanche paths in a region is limited and multiple avalanches in the same
C.3. Results and Discussion

Figure C.4: Probability of detection (POD), probability of null events (PON), false alarm ratio (FAR), accuracy (ACC) and Hanssen-Kuipers skill score (HKS) for predicting wet snow avalanche days based on the exceedance of a threshold for: daily mean air temperature, daily sum of positive energy balance and the daily maximum local LWC, for WFJ, Switzerland (blue), LAG, Chile (red) and COM, Spain (green). Error bars extent over ± one standard deviation for the HKS.

The size of an avalanche is, among many factors (e.g., release area, and the topology of the avalanche path), partly determined by release depth. As the capillary barrier at which liquid water is accumulating can be considered the potential failure layer for a wet snow avalanche, a relationship of this depth with avalanche size is expected. Figure C.5a shows the distribution of the depth below the snow surface where the maximum local LWC is found (ponding depth) on days and in slope aspects where avalanches were reported as a function of the largest observed avalanche size for the WFJ dataset. An increasing trend of the median in simulated ponding depth with observed avalanche size is present, ranging from 34 cm for very small
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Figure C.5: Box and whisker plot showing the distribution of the depth below the snow surface, perpendicular to the slope, where the maximum LWC is found (a) and the total snow thickness (i.e., perpendicular to the slope) (b), for the maximum avalanche size reported, based on the WFJ dataset. Boxes represent inter-quartile ranges (25th to 75th percentiles), thick horizontal bars in each box denote the median (50th percentile), its value shown directly above the bar. Whiskers (vertical lines and thin horizontal bars) represent the highest and lowest value within 1.5 times the inter-quartile range above the upper or below the lower quartile, respectively. Notches are drawn at ±1.58 times the inter-quartile range divided by the square root of the number of data points. Outliers are not shown.

Availanches to 70 cm for large avalanches. The Kendall Tau-b non-parametric rank correlation test showed that the correlation between ponding depth and avalanche size is statistically significant with $\tau_B = -0.17 \ (p < 0.05)$. An other important factor determining avalanche size is the total snow depth (e.g., Eckert et al. [2010]). Figure 5b shows that this relationship is also present in the WFJ dataset, with $\tau_B = 0.13 \ (p < 0.05)$. Thus, the correlation of avalanche size with ponding depth is stronger, but of similar order of magnitude as with total snow depth. Fracture depth and snow cover properties in the release zone may serve as valuable input for avalanche dynamics models (e.g., Vera Valero et al. [2015]).
C.4 Conclusions

Simulated water accumulations of more than approximately 5 – 6% LWC at capillary barriers formed by microstructural transitions inside the snowpack could be related to wet snow avalanche activity. A higher prediction skill in terms of HKS was achieved than using commonly used parameters like daily mean air temperature or the daily sum of positive energy balance. The prediction skill also holds for individual slope aspects and was verified for three climatological regimes. Additionally, a correlation was found between the depth inside the snowpack where liquid water is accumulating, which we consider the potential failure layer, with the observed avalanche size. This information is crucial to estimate runout distances and the potential harm to infrastructure and society. Although many more factors determine the eventual avalanche risks, we demonstrated that physics based snowpack models can nowadays provide useful information for assessing regional wet snow avalanche risks, specified for individual slope aspects and altitude bands. Furthermore, the information of the snow cover state from the simulations can be used to drive avalanche dynamics models.

As we only focused on one simple physical quantity to relate water flow to wet snow avalanche activity, we interpret our results as a first step that seems to indicate a large potential of physics based snowpack models for wet snow avalanche forecasting. If future research focuses on improving the representation of the wet snow avalanche formation process in snowpack models, particularly regarding mechanical properties of wet snow, as well as acquiring representative meteorological forcing conditions for avalanche slopes, we anticipate physics based snow cover models to further improve their skill for assessing wet snow avalanche risks.
Bibliography


Bibliography


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