# Looking beyond the powder/dense flow avalanche dichotomy

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## Abstract

Köhler et al. (2018) deploy a high spatial and temporal resolution GEODAR radar system to reveal the inside of snow avalanches over the entire slope. They detect a rich variety of longitudinal and slope normal flow structures across a data set of 77 avalanches recorded over 6 years. Distinctive features in the radar signatures permit the definition of seven flow regimes and three distinct stopping signatures, illustrating behaviours much richer than the conventional dichotomy between dense flow avalanches and powder snow avalanches. This presents modellers with the challenge of exploring the physics of these regimes, the transitions between them and their relationship with the surrounding conditions.

## Full text

Snow avalanches, alongside other gravity mass flows such as debris flows and landslides (e.g. Takahashi, 1981), rockslides and rock avalanches (Voight & Pariseau, 1978), volcanic pyroclastic flows (e.g. Woods & Wohletz, 1991), and submarine slides (e.g. Meiburg & Kneller, 2010), can cause considerable damage to inhabited areas or ecosystems and induce large economic losses. Deciphering, modelling and then predicting how snow avalanches evolve and the impact force they can exert on structures, such as buildings or protection dams, is crucial for the design of hazard maps delimiting endangered zones and for the development of appropriate construction codes. Effective mitigation must also involve planning, and this process of predictive modelling is essential to understand the life cycle of mitigation structures and for emergency response planning.

To date, our view of avalanches has been primarily restricted to measurements taken at a point (e.g. through sensors mounted on a pylon or dam which an avalanche interacts with), providing a signature of the avalanche as it evolves and moves past this point (e.g. McElwaine & Turnbull, 2005). The instantaneous view of the avalanche along its length, or the time varying view of particular structures in the avalanche is thus not accessible. Videogrammetry addresses this, providing data of the full avalanche surface evolution (Vallet et al., 2004); however, the technique is sensitive to subjective user choices and, crucially, much of the core dynamics of an avalanche is typically optically obscured by a powder cloud of fine airborne snow. Gubler and Salm (1985) introduced Continuous Wave Doppler RADAR to measure avalanche front velocity along the whole track. In a next step, Randeu et al. (1990) also measured velocities from within the flowing avalanche using a pulsed Doppler RADAR and Gauer et al. (2007) used data of pulsed Doppler RADARs to obtain information

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on retardation within avalanche flows. Looking into the interior of snow avalanches over the entire slope at high temporal (111 Hz) and spatial (0.75 m) resolution was recently made possible (Köhler et al., 2016) thanks to the use of pulsed Doppler radar for geophysical flow dynamics (GEODAR), pushing forward the initial technical developments and tests previously done on GEODAR (Vriend et al., 2013; Ash et al., 2014; Keylock et al., 2014). Continuing those *in situ* investigations and coupling non-intrusive GEODAR measurements with a series of more established experimental techniques, Köhler et al. (2018) take a step forward by producing and analysing a wide series of 77 avalanches, both artificially triggered and naturally occurring, at the avalanche test-site of Vallée de la Sionne (Switzerland) over the period 2010-2015. This constitutes a significant body of new, quantitative insight into the complicated internal physics of snow avalanches in terms of both their propagation and stopping phases.

Köhler et al. (2018) reclassify our understanding of avalanche flows according to seven flow regimes, systematically identified from patterns within an avalanche's radar signature: these are four fully developed dense flow regimes, two more dilute regimes, and one regime corresponding to snowballs rolling down the slope. Significantly, the existence of these regimes could be linked to environmental conditions. For example, two dense flow regimes (either cold or warm) exhibit shear throughout the entire flow height, resembling a non-cohesive granular flow. Two other dense flow regimes (in the form of either a slab or a plug) are characterised by significant sliding at the bottom and active cohesion inside the bulk, resembling a solid-like object sliding on a thin shear zone. One dilute regime flows as a suspension and the other has highly fluctuating density, characterised by surging. The last of these connects dense flow and suspension regimes. Most of those flow regimes were already recognized by, e.g., Coaz (1881) and Paulcke (1938), but not fully articulated with recognition of their possible coexistence until now.

This richness of flow regimes is indicative of complex underlying dynamics, and the significant longitudinal and temporal variations in avalanche behaviour should be acknowledged by modellers. Most practical models currently adopt a 'one-size fits all' approach, reflecting the conventional dichotomy between dense (sometimes referred to as flowing) and powder snow avalanches. The inconvenient transition between these is dealt with by *ad hoc* parametrisation (e.g. Bartelt et al., 2016; Sampl & Zwinger, 2004), which undermines the predictive nature of the models and maintains reliance on observational data for tuning. These models may be well suited to providing information of bulk behaviour but are limited in their capability to handle subtler questions, such as variations along the avalanche length. As avalanche mitigation becomes an increasingly global activity - where past events can be less rigorously relied on for calibration, and where an entirely different approach to engineering solutions may be more appropriate - this subtlety is essential. If a (defence) structure is to be properly specified, an engineer should be concerned with peak loadings, fatigue and resonance and not solely mean impact. The vertical and longitudinal variations in particular regimes reported by Köhler et al. (2018) remind us how poorly equipped we currently are to understand the true interaction between avalanche and structure.

The regimes identified each have their own distinct dynamics, each corresponding to different modelling assumptions. For example the dry granular regimes mirror observations from simple theoretical models and laboratory flows of dry granular materials (Edwards et al., 2017) and roll wave formation is a well-known phenomenon in both classical granular and also muddy flows (e.g. Ng & Mei, 1994). Thus, the differences in flow regimes revealed by the data show that modellers need to be particularly aware of the approximations they make. But the new classification also links more closely than has been possible before, flow behaviour with local environmental conditions, which themselves determine model boundary conditions. If we are aware of the underlying assumptions we adopt to model each flow regime, then we have an opportunity to move away from parametrisations of poorly understood processes towards variable, but measurable, boundary conditions feeding into first-principle models.

In addition, Köhler et al. (2018) find striking patterns in the stopping signatures of avalanches. They identified three types of deposition processes in the run-out zone that they call 'starving', 'backward propagating shock', and 'abrupt stopping'. A specific deposition process occurring at the avalanche tail is also described, confirming earlier findings based on laser scanning measurements (Sovilla et al., 2010). The stopping signatures are suggested to be primarily controlled by the snow temperature and liquid water content. Under dry cold snow conditions, avalanches tend to stop from the tail, the flowing region behind the head being shortened in length (starving). In contrast, warmer snow avalanches tend to stop first at the front followed by a progressive pile up (development of a backward propagating shock), and avalanches can even stop instantaneously throughout their entire length (abrupt stopping).

Finally, the high GEODAR resolution enables precise spatial and temporal localization of the different flow regimes and automation of the data acquisition permitted the measurement of a large number of naturally occurring and artificially triggered avalanches. This enables Köhler et al. (2018) to show that multiple flow regimes coexist simultaneously within a single avalanche event and that transitions between those regimes are common. Köhler et al. (2018) accentuate the role of transitions between different regimes, and how these transitions may link above all to ambient conditions. In some respects this simplifies things for us. As noted above, linking flow behaviour to the boundary conditions rather than to interactions between flow components, we can avoid opaque parametrisations that control the interactions and replace them with more directly verifiable links to environmental conditions. A good example of progress towards verifying transitions lies in the granulation experiments of Steinkogler et al. (2015), who experimentally linked the growth of particles in a snow avalanche through granulation to the ambient temperature. These types of simple experiment can start to uncover the physics behind the transitions and support the new detailed classification of flow regimes.

The existing GEODAR database available (see information about GEODAR data repository in McElwaine et al. (2018)), which will (has to) be expanded further in the future, opens many paths for experts in granular physics, fluid mechanics, advanced numerical modelling, to revisit current models and/or invent new and elegant theoretical approaches capable of capturing the richness of the avalanche flow dynamics. The expansion of the database would benefit from effort to systematically correlate the GEODAR measurements with other measurements, such as pressure measurements, upward pointing FMCW (Frequency-Modulated Continuous-Wave) measurements, and density measurements. The GEODAR database can be expanded in other ways, such as recording variations in dielectric constant, indicative of moisture content that has been shown to be dynamically significant through lubrication and granulation (Naaim et al., 2013; Turnbull, 2011; Steinkogler et al., 2015) but remains far from being modelled. This information may help in understanding the transition of a cold snow avalanche into a warm snow flow. Moreover, to draw truly general information from the data, it is important that similar measurements are obtained in other avalanche paths to uncover possible scaling behaviour, and to monitor also other types of geophysical flows like pyroclastic flows and debris flows. The level of automation now built into GEODAR makes it feasible to monitor such flows that can not be artificially triggered. In addition, the only regime that GEODAR has not mapped fully is the powder cloud. A shorter wavelength radar capable of resolving the finest snow particle sizes would complete this picture and should be a target for future work.

On a more general note, the multiple flow regimes and the transitions between them observed within one single avalanche presents an excellent opportunity for modellers to rethink their approaches and to be bold in adopting new positions concerning some of the current 'hot topics' in the field of snow avalanche dynamics and the ways they are traditionally addressed. The physical processes usually associated with -for instance- erosion and deposition (e.g. Gauer & Issler, 2004; Issler, 2014; Sovilla et al., 2006), "fluidisation" between dense and suspension flows (e.g. Gauer et al., 2008; Carroll et al., 2013), the avalanche-flows disturbed by dams (e.g. Faug et al., 2008; Faug, 2015), the impact force on structures (e.g. Ancey & Bain 2015; Sovilla et al., 2016), and the ways they are currently modelled, will need to be revisited. A challenging question then arises: how to shape the future models by accounting for the multiple flow regimes and transitions between them - which can occur during the propagation of a single avalanche - and still keep models applicable for practitioners in their daily consulting work? A significant open problem in modelling avalanches is the role of erosion, i.e. the mobilisation of the snow pack around and underneath the avalanche, which can increase the size of the avalanche many times (Sovilla et al. 2006). The dynamic behaviour of each of the regimes will lead to different erosion behaviours. Previous work by Köhler et al. (2016) showed that an avalanche can remotely trigger additional slides that become incorporated within the original flow; such a growth mechanism may not even relate to the specific dynamics of the avalanche, as one may expect. Another key problem is the interaction between avalanches and protection structures. The distinct stopping signatures highlighted by Köhler et al. (2018) may have important implications for the design of avalanche protection dams and their maintenance. In particular the abrupt stopping regime may lead to unwanted filling of the available storage space upstream of a dam, and then make the dam inefficient if another avalanche occurs.

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