

Plume Formation in Powder Snow Avalanches

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ABSTRACT: A long-standing problem in avalanche science is to model the formation and propagation of ice-dust clouds that accompany fast moving dry snow flowing avalanches. Since the winter of 2002/2003 photogrammetric measurements of snow avalanche clouds have been performed at the Vallée de la Sionne test site. Synchronized images acquired from two different viewing angles allow the construction of three-dimensional powder cloud surface models. Between 2003 and 2006 seven avalanches with initiation volumes over 50'000 m³ were recorded. Plume heights reached over 100 m and the avalanches entrained up to 10 million m³ of air. Using high resolution laser scans of the terrain it was possible to investigate the formation and development of the powder clouds as a function of terrain and avalanche speed, thereby gaining valuable information concerning the flow dynamics. The plumes form continuously at the avalanche front and then diffuse slowly. Using isolated plumes as markers, we calculate the travel distance between the point of initiation and the final suspension height. The upward velocity appears to be divided into a high-velocity, forced expulsion stage and a slower diffusion stage. Segregation effects are also visible as packets of extruded mass are thrown upwards and then descend, leaving an ice-dust suspension hanging in the air. Lateral spreading speeds are significantly slower than the front propagation. Furthermore, there is also definite terrain influence as plume formation appears to be concentrated at gullies and extreme changes in slope angle.

KEYWORDS: Avalanche dynamics, powder snow avalanches, plume formation, ice-dust cloud, blow-out height, suspension layer.

1 INTRODUCTION

Two, largely different models have been developed to describe the destructive movement of powder snow avalanches (Fig. 1).

This first class describes the powder cloud using simple semielliptical geometries; see for example (Fukushima and Parker, 1980; Eglit and Revol, 1998; Ancey, 2004 and references therein). These models are strongly related to so-called plume theories of suspension currents: the driving physical assumption is that the flow is driven by the density difference between the particle suspension and surrounding air (Simpson, 1997; Turnbull and McElwaine, 2007). The models have been primarily developed to parameterize the role of air and snow entrainment in the dynamics of powder snow motion (Ancey, 2004). Two important assumptions of these models are that (1) the flow of the powder cloud can be decoupled from the flowing core and (2) snowcover entrainment is necessary to sustain the density difference and the motion of the powder avalanche. Although simple, this class of models has found very little practical application as they poorly represent the avalanche geometry; that is, the predicted avalanche volume is often too large and therefore the cloud height and flow densities are typically over-estimated.

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Figure 1. Plume formation of VdIS avalanche no. 509, February 7th, 2003. Note the isolated plumes forming at the avalanche front. The plumes reach 40m in height.

One-to-one comparison with field data is therefore difficult and limited to front speeds: the models assume two-dimensional geometries that marginally account for three-dimensional effects, such as the longitudinal variation of velocity in the cloud, lateral spreading of the avalanche or density stratifications within the flow.

The second class of models relies on the numerical solution of the general two-phase mixture equations (Scheiwiller and others, 1997; Naaïm and Gurer, 1997; Sampl, 2004). Two-layer, depth-averaged approximations have been formulated by Russian researchers (Nazarov, A. N., 1991; Bozhinskiy, and Losev, 1998). These models postulate a closer relationship between the avalanche core and cloud; however, they suffer from poorly defined mass and momentum closures between the phases and/or layers, especially relations describing the all-important buoyancy flux of suspended particles. As mixture models are computationally demanding, their application is limited in practice. No one-to-one comparison exists between measured and calculated powder cloud heights and plume structure. Again comparison to field experiments is limited to avalanche leading edge velocity.

In this paper, we experimentally investigate the explosive, blow-out of mass at the avalanche front using photogrammetric analysis. We term these air-ice-dust blow-outs *plumes*, in analogy to the theory of turbulent jets. Our primary goal is to parameterize the formation of the suspension layer height with the purpose of improving both plume-type and numerical avalanche dynamics models.

2 PLUMES

What is commonly termed the *powder cloud* of a snow avalanche (Fig. 1) can be easily defined because it contains air mixed with particles of ice-dust (Rastello and others, 2011). The surface of the powder cloud is not smooth, but contains lobe shaped extrusions separated by valleys (clefs). The particles serve as tracers that help delineate the surface of the cloud and therefore can be used to track the movement – the location, speed and height – of the lobes and clefs; that is, the surface velocity of the powder cloud.

The source of the particles is the avalanche itself, the flowing snow, since the ice-dust is a product of abrasive granular interactions within the avalanche, or, is created during the rapid destruction and granularization of the incumbent snow cover.

The dust occupies the free pore space of the flowing mass, before it is carried upwards by severe interstitial air movements, particularly at the front of the avalanche. The tracers are elevated to substantial heights, sometimes higher than 100 m above the ground, providing the powder cloud with its alternative name, the *suspension layer*. Most importantly, the tracer particles allow us to visualize with photogrammetric methods the front dynamics of an avalanche and therefore to understand how air is entrained into the flowing mass and subsequently expelled to create the plume-cleft structure of the cloud. The plumes (Fig. 2), that are such a distinct feature of powder avalanche flow, are a direct result of the air entrainment/blow-out process.

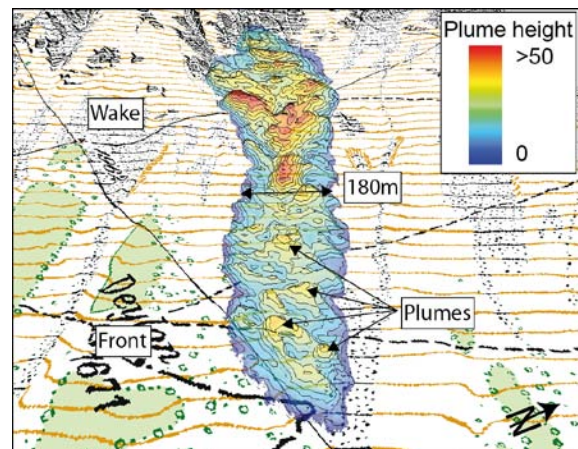


Figure 2: Reconstruction of the suspension layer surface with contour lines. Closed contours were used to define plume location and height.

3 PHOTOGRAMMETRIC POWDER CLOUD MEASUREMENTS

To visualize the ice-dust cloud and the plume formation, photogrammetric measurements were conducted (Vallet and others, 2004).

During the winters 2004/05 and 2005/06 two Canon EOS 20D digital SLR (single lens reflex) cameras with 8.2 million pixels were installed at the counter slope of the Vallée de la Sionne avalanches track. The baseline between the camera positions was 240m and the camera settings were identical. By setting the focal distance to 18mm (equivalent to 29mm with analogue frame cameras) the entire avalanche track can be captured in a single image, resulting in an image scale of 1:140'000 in the release zone and 1:30'000 in the deposition area of the avalanche (Pixel resolution of 0.93 to 0.21m). The distance between the cameras and the powder cloud vary between 2600m (release) and 600m

(deposition).

During the avalanche event, pictures were taken simultaneously every 5 seconds. All images of an event were orientated in one block. The calculated average RMS values were 1.6m in horizontal and 1.0m in vertical direction. Due to the weak block-geometry and the imperfect internal orientation of the cameras additional accuracy assessment measurements were taken manually resulting in RMS values of 5.4m in the release zone and 2.2m in the deposition zone (Wicki and Laranjeiro, 2007). The measurement accuracy decreases with longer distance between the object and the cameras.

The avalanche outline and a digital surface model DSM of the powder cloud surface were digitized by manual stereo-image measurements. By subtracting the digital terrain model DTM from the DSM, we generate a height map (Fig. 2) of the powder cloud, enabling the calculation of the powder cloud volume (Fig 3). Often at the tail of the avalanche (near the release zone) the volume could not be determined as the particles settled, diluting the cloud to point where it was no longer visible.

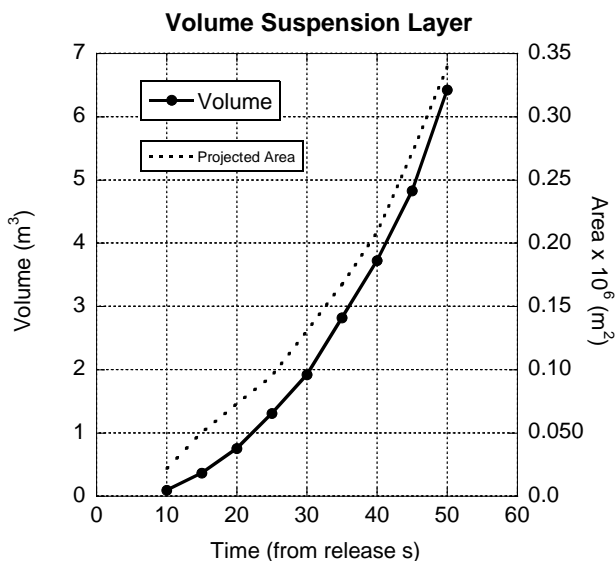


Figure 3: Powder cloud volume. The avalanche entrained over 6 million m^3 of air.

4 RESULTS

4.1 Plume velocity

After reconstructing the powder cloud surface, we identified isolated peaks (plumes) extruding from the cloud. The plumes were found by mapping elevation contours onto the surface (Fig. 2); a plume was defined as an extrusion at least 5m above the average surface height (approximately 20m). It was then possible to track the location of the plume from surface to surface, allowing us to determine the velocity of the cloud surface at 5s intervals. We identified 13 plume structures in avalanche no. 509 between $t=45s$ and $t=50s$ (Fig. 4).

Although the plumes move, their velocity is smaller than the speed of the avalanche leading edge (Table 1). The plume velocities range between 4 m/s and 16 m/s; the leading edge velocity of the avalanche is 47 m/s. When the plumes are created at the avalanche front they decelerate quickly. At the very tail of the avalanche, they become almost stationary. The braking process appears to start immediately after extrusion. The velocity of the powder cloud is therefore defined by the leading edge velocity of the avalanche near the ground and not the flow velocity of the cloud, which is small. Powder avalanches, at least in the transition zone, do not appear to flow, but are continually formed by the plume blow-out process. Moreover, the propagation speed of the powder cloud is given by persistent and repetitive creation of new plumes and not by the downward movement of existing plumes. This suggests that the cloud has no driving force other than the initial momentum imparted to it at its creation by the fast moving basal layer and a slight turbulent diffusion. The vertical velocity gradients from the basal layer to the upper surface of the cloud are large.

Plume no.	Distance (m)	Velocity (m/s)
1	55/24/40	11.0/4.8/8.0
2	53	10.6
3	20	4.0
4	79/82	15.8/16.1
5	35	7.0
6	37	7.4
7	32	6.4
8	25	5.0
9	74	14.8
10	25	5.0
11	81	16.2
12	38	7.6
13	65	13.0

Table 1: Distanced travelled between t=45s and t=50s by the 13 plume structures identified in Fig. 4. Plume 1 is located at the tail of the avalanche; plume 13 near the front. The velocities moved at speeds between 4.0 m/s and 16 m/s. The velocity distribution does not continually decrease from front to tail. In the same time period the leading edge of the avalanche travelled 237 m with a mean speed of 47 m/s.

4.2 Lateral spreading

The interior plume velocities are similar to the small lateral spreading speeds of the cloud (Table 2). Between t=45s and t=50s, the lateral spreading speeds vary from 2.0 m/s (250 m behind the avalanche front) to 9.0 m/s (50 m behind the avalanche front). The spreading speeds are slightly larger on the left side (with respect to the flow direction) of the avalanche. The right side is slightly channelized by the main Vallée de la Sionne gully. Approximately 380 m behind the avalanche front, the spreading stops.

Distance behind leading edge (m)	RIGHT SIDE Distance (m) Velocity (m/s)	LEFT SIDE Distance (m) Velocity (m/s)
50	30 6.0	46 9.2
120	35 7.0	36 7.2
190	21 4.2	33 6.6
250	14 2.8	22 4.3
380	0 0.0	0 0.0

Table 2: Lateral spreading speeds of the avalanche. The spreading speeds are similar to the interior plume velocities.

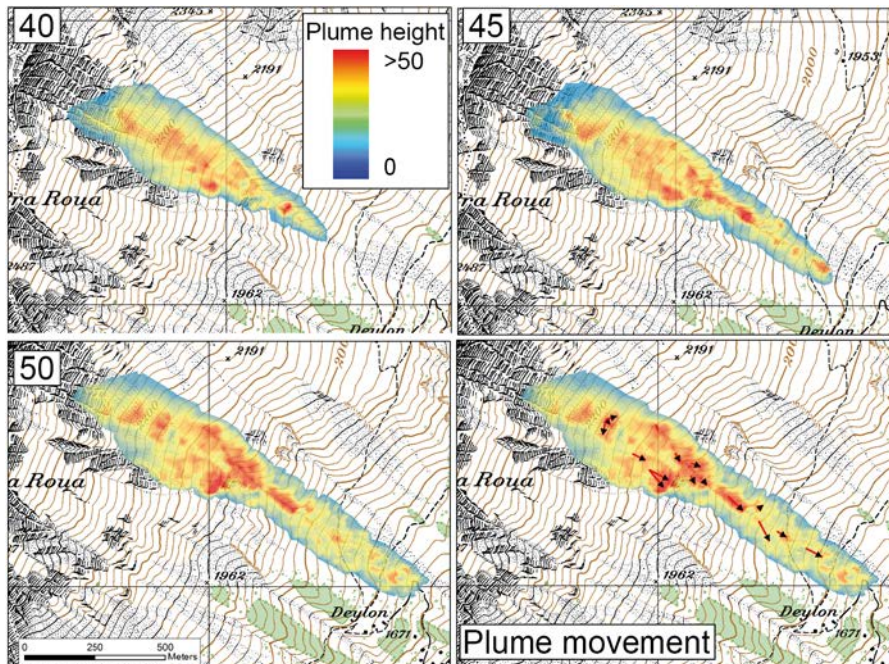


Figure 4: Plume heights at 40s, 45s and 50s. Isolated plumes reach heights of 40m. The average height of the suspension layer is approximately 20m. The downward velocity of the plumes can be determined by tracking plume location. The plumes are moving slower than the leading edge velocity of the avalanche.

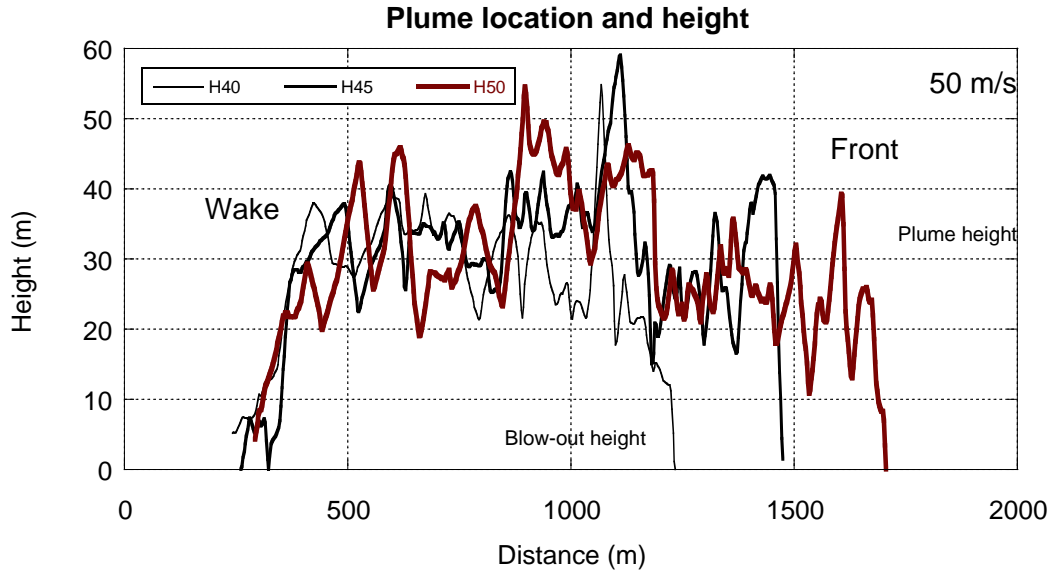


Figure 5: Cross-section of powder cloud at three different times: $t=40s$, $t=45s$ and $t=50s$. The avalanche is moving at 50 m/s. Plumes rise 40 m above the running surface in a two-step process: blow-out (note the joints at the avalanche front) and segregation-suspension of ice dust (plume heights).

4.3 Blow-out

4.3 Plume heights

To obtain a two-dimensional cross-section of the powder cloud, we placed a line profile along the middle of the avalanche. The profile points were selected at the tip of the leading edge at each time sequence. We then visualized the powder heights (Fig. 5). The powder-cloud cross section reinforces the idea of a stationary wake with the continual creation of plumes at the avalanche front: Between $t=45s$ and $t=50s$ two well-defined plumes were created (Fig. 5); a third plume (plume no. 13, located at the avalanche front at $t=45s$) moved 65 m forward (Table 1). At the tail of the avalanche, the plume heights remained more or less stationary, with turbulent eddies and diffusion raising and lowering the measured cloud surface.

The highest plume heights are located at the upper end of a gully where the Vallée de la Sionne path narrows (at a distance of 1000m from the initial profile point, Fig. 5) and the flow conflues. The avalanche was travelling at high velocity (55 m/s) when it entered the gully. The plumes at the front at $t=50s$ are, in comparison, smaller and located in open terrain. This suggests that plumes are primarily created by the internal dynamics of the avalanche, but also that terrain can influence the suspension height.

The plumes are created at a frequency of approximately 0.4 Hz (plumes/s); the distance between plumes (or the plume length) is 80 m. The creation phase does not appear to be a single upward motion but is divided into two distinct phases: in the first phase the plumes quickly reach a height of 10 m, which we term the initial blow-out phase or height. This is followed by a slight pause, seen as a discontinuity in the growth of the plume at the leading edge of the avalanche (these are depicted in Fig. 5 at $t=40s$ and $t=50s$). This first stage is followed by another rising phase. The second phase is no longer at the leading edge, but located between 20 m and 50 m behind the front. The first phase is clearly associated with the vertical, upward motion of mass – both larger particles as well as the ice-dust air suspension. As some of this mass remains in suspension it is often termed the vertical buoyancy flux (Turnbull and McElwaine, 2007).

The plume blow-out at the leading edge is associated with air-intake. The expanding volume of the surface requires air-mass. The intake rate is clearly related to avalanche speed. If the source of air needed to expand the plume volume was in any way limited, the upward movement of particles would be damped as the air intake speed (and therefore the air velocity) would be lower than the vertical particle motion, implying a strong vertical damping. In the blow-out phase, the entrained air, ice-dust and particles are all

seemingly moving with the same velocity. Otherwise, the ice-dust would not reach the observed heights, which are often quite large (up to 40 m in Fig. 5).

4.3 Segregation and Sedimentation

Note that some of the plumes can collapse as they move forward, indicating that the advected movements are not always associated with air intake (volume expansion and upward movements), but also sedimentation/segregation effects, leading to decreasing plume heights. These effects are difficult to isolate as the plumes diffuse.

When particles are vertically accelerated upward at the front of the avalanche, they reach a maximum height from which they will begin to descend (Fig. 6). During the blow-out, these heavy particles were moving upwards with the air. The relative velocity differences are small. However, once the heavy particles begin to descend, they will displace the volume occupied by the entrained air, pushing the plumes higher. This process segregates the ice dust suspension from the heavy particles and explains the two-stage plume growth observed in Fig. 5. Both the upward and downward movements of particles are associated with upward movements of ice-dust.

5 CONCLUSIONS

Understanding how powder avalanche plumes form is thus central to constructing avalanche dynamics models that accurately account for the destructive front dynamics of a powder avalanche

We found that the surface velocities of the cloud as well as the lateral spreading velocities behind the front are significantly smaller than the leading edge velocity of the avalanche. The surface velocities of the cloud were found by tracking isolated plumes from photogrammetric surface reconstructions. In the avalanche no. 509, the leading edge was travelling at a mean speed of 50 m/s, whereas the plume velocities displaced at speeds of sometimes only 4 m/s. The lateral spreading velocities are similar to the plume velocities. These velocity differences indicate large

horizontal and vertical velocity gradients within the avalanche. The leading edge velocity is driven by slope parallel mass and momentum fluxes that appear to be concentrated at a higher density basal flow layer.

Therefore, our analysis indicates that the powder cloud is more of a blow-out wake phenomena, than a gravity driven suspension current. The gravity driven current exists at the near-ground basal layer and produces the cloud in repetitive and frequent blow-outs at the avalanche front. These are the plumes. The velocities in the cloud – essentially the wake -- are small and should not be compared to the frontal propagation speeds of the fast moving basal layer. Apparently strong density gradients exist between the blow-out wake and the basal layer. Numerical models which resolve the vertical direction are necessary; a practical compromise would be to introduce depth-averaged layers – one representing the fast moving basal layer, the other representing the suspension cloud. However, the flow density of the near-ground layer is more than the suspended blow-out wake (say 5 kg/m³), but certainly less than a dense flowing avalanche (say 300 kg/m³). Therefore, the basal layer cannot be modelled with standard depth-averaged flowing avalanche models which do not account for density variations or vertical motions; however, it is also unlikely that this layer can be modelled by plume theories which ignore slope perpendicular motions produced by granular processes.

We do not recommend that snowcover entrainment be considered for the blow-out wake directly; however, they are absolutely necessary to understand how ice-dust becomes suspended through vertical motions within the basal flow layer.

We conducted this analysis in the transition zone where the powder cloud (blow-out wake) is formed and therefore strongly coupled to the basal layer. It is certainly possible that when the basal layer stops, the plume production will cease, but the cloud wake will continue to displace with velocities near those we have measured (say between 10 m/s and 20 m/s).

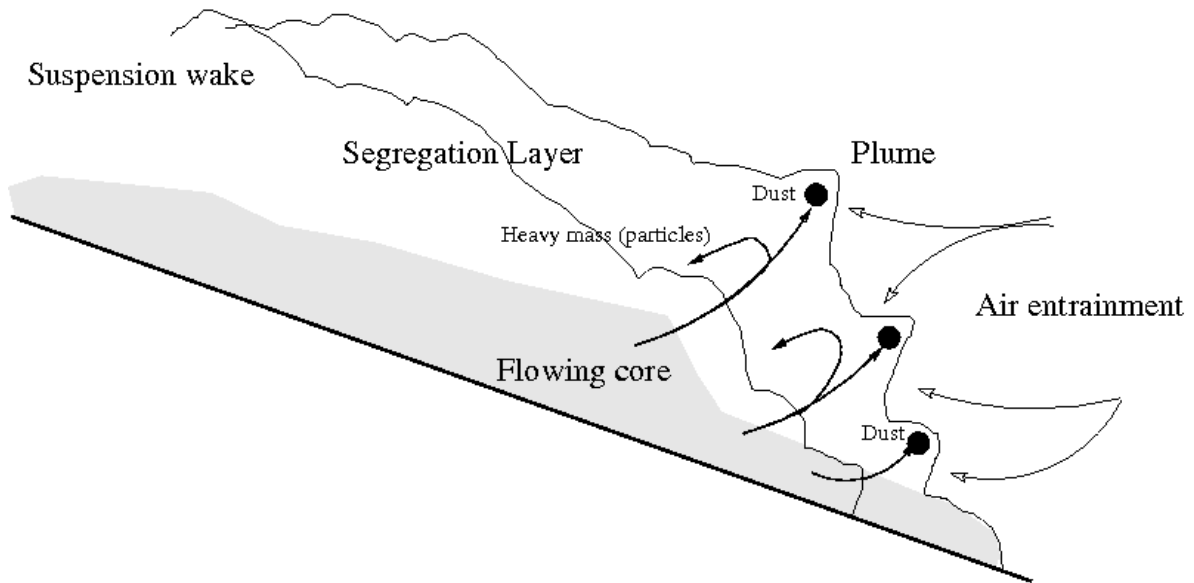


Figure 6: A mixture of air-dust and particulate mass is blown-out of the avalanche core with strong slope perpendicular accelerations. These accelerations are advected in the flow direction. The lighter ice-dust reaches the highest elevations; heavy particulate mass is also accelerated upwards, but segregates out of the dust plume, forming the suspension layer.

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