

Saltating Snow Mechanics: Three Species Classification from High Speed Videography

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ABSTRACT

The current understanding of blowing snow transport is derived from coupling time-averaged measurements of particle saltation and suspension with nearby wind measurements. Recently, two-phase aeolian flow studies have benefited from high frequency turbulence measurements and particle tracking, allowing a stronger comprehension of particle flow dynamics. However, these sand-based transport observations cannot be directly adopted for saltating snow because they assume an underlying bed of discrete particles and so neglect the bonds and structural metamorphism unique to snow crystal matrix structures. To examine the potential distinctive nature of snow saltation, this study employs laser illuminated high-speed videography and ultrasonic anemometry to examine snow transport over a natural snowpack in detail. A saltating snow measurement site was established at the Fortress Mountain Snow Laboratory, Alberta, Canada and instrumented with two Campbell CSAT3 ultrasonic anemometers sampling at 50 Hz and a two dimensional Particle Tracking Velocimetry (PTV) system. The experiment has demonstrated the applicability of PTV methods to outdoor environments for blowing snow studies. A three species sub-classification of saltation from blowing sand studies allows for description of overlooked snow transport and initiation processes. However, complex behaviour that is specific to blowing snow such as the tumbling and disintegration of aggregate snow crystals, which eject smaller grains and feed disintegrating grains into the atmosphere has also been documented, complicating direct sand subspecies application. This unique avenue of data informs a new conceptualization of saltating snow transport mechanisms.

Keywords: Particle Tracking Velocimetry, Blowing Snow, Saltation, Canadian Rockies, Mountain Snow.

INTRODUCTION

Wind transport of snow influences the variability of alpine summer runoff (Winstral et al., 2013), is a large contributor to the growth or ablation of small mountain glaciers (Dyunin and Kotlyakov, 1980), and affects snow stability for avalanche forecasting (Schweizer et al., 2003). Blowing snow field measurements often present an oversimplified view of the stochastic natural phenomenon. Trap mechanisms such as snow socks provide averaged mass flux measurements over a prolonged collection period and therefore little possibility to relate fluxes to turbulence, whereas snow particle counters provide little to no information about what type of particle is in transport or its trajectory and velocity (Kinar and Pomeroy, 2015). Neither device elicits information about individual particle transport mechanics. As such, currently only a basic understanding of blowing snow exists with a lack of detailed particle velocity observations.

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Kobayashi (1972) pioneered blowing snow recordings with outdoor, 1/8-second shutter speed images. This was the first visual evidence of particle mechanics in the snow saltation layer, but the photographs consisted of blurred snow particle streaks or were saturated with particles, leaving many unanswered questions (Figure 3). Gromke et al. (2014) and Lü et al. (2012) utilized faster frame rates in recent years but were limited to wind tunnels for their blowing snow studies and were not focused on the mechanics of transport.

Current theory represents blowing snow in two layers, saltation and suspension with a poorly understood creep mechanism recognised at the lower boundary of saltation (Pomeroy and Gray, 1990). Saltating particles are thought to exist below 20 cm and follow ballistic trajectories, rebounding off the ground. Suspended particles begin in saltation and disperse upwards. Closely following wind streamlines, suspended snow particles rarely encounter the ground (Pomeroy and Male, 1992).

Two proposed modes of saltation initiation are *aerodynamic lift*, the direct drag induced ejections of grains, and *splash*, the ejection of grains by rebounding saltating particles (Doorschot and Lehning, 2002). However there are substantial uncertainties about these mechanisms; Schmidt (1986) showed that direct aerodynamic lift was not possible under average flow conditions over a level snow surface due to strong snow particle bonding. Subsequently, Pomeroy (1988) showed that lower saltation threshold (initiation) wind speeds due to splash could not be observed in the field and was unable to relate threshold wind speeds to physical properties of the snowpack such as hardness and density. As a result, these two modes of initiation have not been parameterized in saltating snow models (Pomeroy and Gray, 1990) and empirical techniques have been required to account for crystal bond strength effects on threshold conditions for snow transport and saltation efficiency (Li and Pomeroy, 1997a; Pomeroy and Li, 2000). However, few blowing snow transport studies have focused on direct measurements within the first 10 cm above the snow surface, the region responsible for rebound and ejection dynamics.

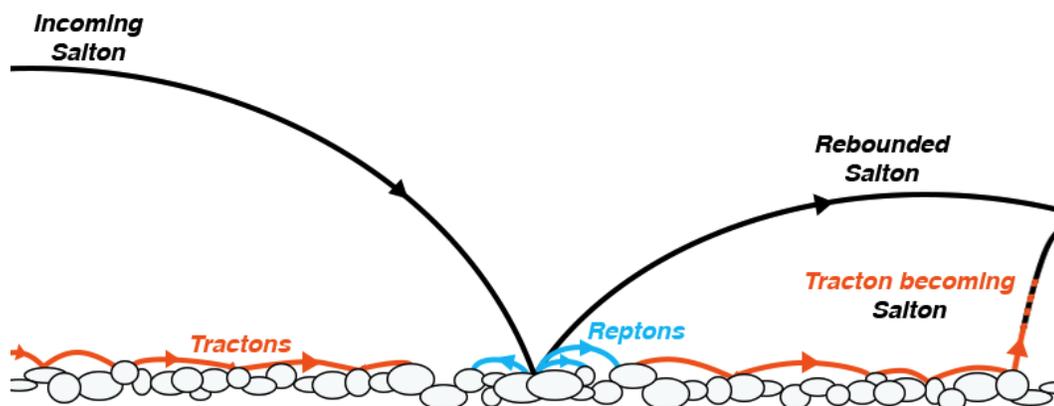


Figure 1. Schematic of three modes of motion: Reptons, Saltons, and Tractons

While Anderson and Haff (1988) utilized a computationally expensive continuous spectrum of particle motion in a two-phase saltating sand model, recent sand saltation research has highlighted a variety of distinct transport modes for saltating particles. Andreotti (2004) introduced a simple conceptual three species classification of saltating sand particles, which was implemented by Lämmel et al. (2012) into a more economical saltation model. In this model particles are distinguished by kinetic energy rather than physical properties such as grain size. These saltation particle species are saltons, reptons, and tractons (Figure 1).

High-energy saltans are particles that impact the surface with great momentum, rebounding and ejecting lower-energy reptons into motion. Reptons are particles gaining fewer than several grain diameters in height above the snow surface upon ejection, existing for only one hop. Tractons, also known as creeping particles, roll and tumble across the surface, bouncing along the way. Tractons that gain sufficient kinetic energy bounce higher into saltation, becoming further accelerated by the wind. Saltans often begin motion as reptons or tractons (Willets et al., 1991), and are reclassified upon acceleration.

At sufficiently high wind speeds, splash is known to be exponentially more effective at entraining sand particles than wind drag alone (Willets et al., 1991). The transition to a splash dominated snow initiation regime and the role of crystal cohesive forces is not yet well understood. Additionally, the role of tractons and reptons in initiation of snow transport has not yet been investigated in detail and may play a crucial role in setting transport threshold wind speeds.

To improve the physical theory governing snow erosion, transport and deposition in a turbulent boundary layer, this study focussed on the short timescale mechanisms of snow saltation initiation and transport in order to examine variability in snow surface impact mechanics for natural meteorological and snow surface conditions. To accomplish this a unique field research campaign was designed to measure 3D wind velocity and individual snow particle velocities at frequencies of 50 and 1000 Hz, respectively. In doing so, the approach introduces high-speed laser-light illuminated videography to an alpine setting and to the outdoor study of blowing snow particle motion.

STUDY SITE AND METHODS

Fieldwork was conducted from February to April, 2015 at the Fortress Mountain Snow Laboratory (FMSL), Kananaskis Valley, Alberta, Canada. FMSL is home to several well-instrumented high-altitude, wind-swept observation sites. Meteorological stations include precipitation and standard measurements, as well as specialized eddy correlation, and acoustic and dielectric snow water equivalent measurement systems. The area is topographically interesting in that there is access to relatively flat terrain, a modest ridgeline and very pronounced steep slopes.

The blowing snow site (2000m A.S.L.) is located in a clear-cut base area of the Fortress Mountain ski area. The area was lightly used, allowing for clear upwind fetch, with a moderate ridge flanking the west. The ground was snow covered and shrub vegetation buried for the duration of the experiment with snow depths fluctuating from 70 to 120 cm. The measurement location was equipped with two Campbell Scientific CSAT3 three-dimensional ultrasonic anemometers positioned at varying heights on a single mast. The anemometers were typically situated 40 and 200 cm above the snow surface, though heights varied during snow accumulation and wind erosion events. The anemometer heights were reset once during the field campaign due to snowfall burying the lower instrument.

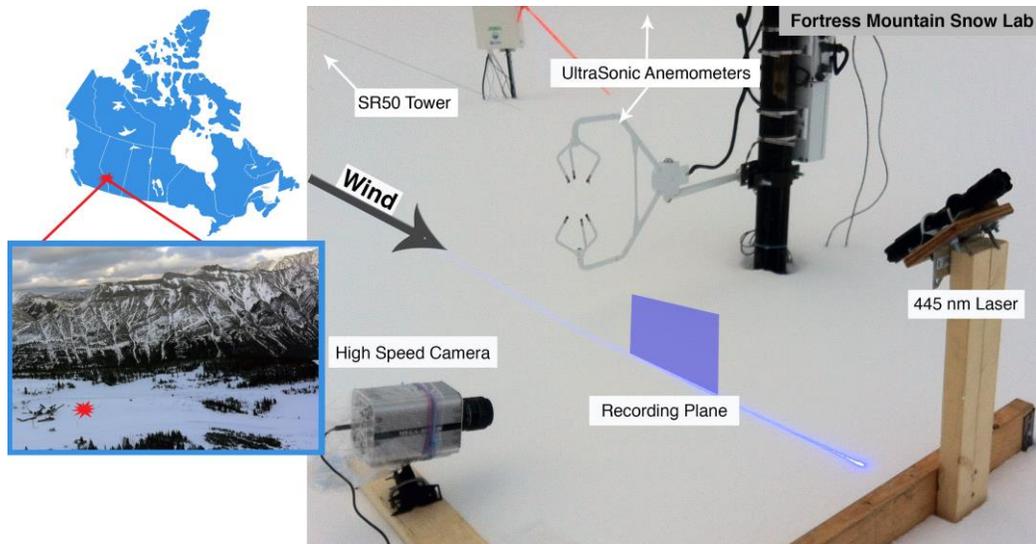


Figure 2. Field Site Location and High Speed Videography Setup

The most unique aspect of this experiment was the implementation of high-speed videography for nighttime particle tracking observations. A rigid frame equipped with a Megasppeed MS85K high-speed camera and a 445 nm wavelength 1.5-Watt continuous-wave laser was placed on the snow surface, typically 1 m downwind from the anemometer mast. The frame sat flush on the snow allowing the camera a nearly tangent view of the surface, perpendicular to the flow of saltating particles. Laser light was projected through a cylindrical lens to create a 2 mm wide plane orthogonal to both the snow surface and the view of the camera (Figure 2). The light plane was oriented in the direction of the prevailing winds, such that the plane illuminated saltating snow particles and allowed recordings in the lowest 10 cm of the atmosphere with minimal foreground shadowing and background reflection.

The camera was controlled by a laptop located downwind in a nearby portable office trailer. Nighttime campaigns typically lasted from four to eight hours over a variety of wind directions. A wide spectrum of snow crystal types was imaged, sometimes changing during the course of one night. At the beginning of each recording session, the camera and data logger timestamps were synchronized to minimize drift for future analysis.

The resolution of the images captured by the MS85K varied depending on snow conditions and particle behaviour. Typical resolutions allowed a recorded region of interest averaging 30 mm x 120 mm. Frame rates varied from 870 to 1300 FPS depending on the selected image resolution. The frames rates possible in this campaign have not previously been achieved in blowing snow field research and are critical for observing the natural mechanics of particle ejection and saltation. This non-intrusive method of observation also allows measurements in the lowest mm of the atmosphere, a region typically impossible to monitor with snow particle counters.

One major complication for 2D recordings is the inherently three-dimensional nature of turbulence. Though positioned with respect to the prevailing wind, particle motion did not always stay parallel to the laser light sheet. As well, wind direction would change throughout a night of recordings. This necessitated the rigid frame to be portable to allow reorientation of the laser into the wind.

Particle Tracking Velocimetry (PTV) provides measurements of snow particle velocities by way of tracking algorithms that match individual particles in subsequent frames imaged by a high-speed camera. Calculations must then be made to convert pixels to the mm displacement of each particle. In this study, the laser light plane creates a two-dimensional projection of saltation

preventing the need for additional cameras and three-dimensional displacement calculations. Knowing the time step between pairs of frames then allows sparse velocity vector field creation.

DaVis 8 software by LaVision calculated PTV vector fields to quantify the blowing snow subprocesses displayed in the high-speed recordings. PTV, and Velocimetry in general, is most often used for wind tunnel studies, with few applications, in any discipline, in an outdoor environment (e.g. Rosi et al., 2014; Zhu et al., 2007). This is the first known application of PTV for boundary-layer blowing snow studies in a natural environment.

OBSERVATIONS

The high-speed saltation recordings provide a degree of clarity of particle motion impossible to attain at lower frame rates or without the use of 2D laser illumination (i.e. Kobayashi, 1972). As the camera was focused close to the snow surface, hundreds of thousands of rebound and splash events were recorded over the season. Video was later reviewed with playback reduced 100 times, providing insight to the mechanics of saltating particle motion and bed interactions.

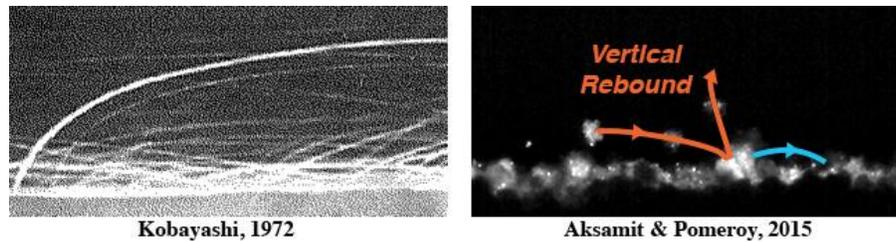


Figure 3. 1/8 Sec exposure Kobayashi image and vertical rebound diagram overlaid on 21:38 Mar 23, 2015 particle images

For example, it has been speculated as to the source of vertical ejections of snow particles from the surface as seen in Kobayashi's photographs (Figure 3). The vast majority of vertical trajectories in this measurement campaign are easily ascribed to particles rebounding off the complex and rough snow surface at odd angles while reptating, tractating or in saltation (Figure 3). Vertical aerodynamic lift of snow particles as suggested by Doorschot and Lehning (2002) was not evident.

Many classic sand saltation models rely heavily on grain diameter based statistics. Adapting these ideas to snow is problematic as identifying snow particle size is inherently subjective because the snowpack is not a bed of distinct grains. Snow is a matrix with an ice crystal lattice structure that must be shattered to produce measureable grains (Schmidt, 1982). In addition, snow particles are often non-spherical and are sintered during transport due to impact and ablated due to sublimation. Over the course of this field campaign, the applicability of diameter-based theories was challenged as particle size was found to be an extremely dynamic characteristic. Focussing exclusively in the first 30 mm above the surface, the present observations challenge the classic entrainment framework, showing that a new conceptual model including subcategories of saltation and additional initiation sub-processes should be considered.

The nights of February 5 and 11 provided fresh, warm ($\sim 0^{\circ}\text{C}$) concurrent snowfall with large (~ 5 mm diameter) aggregate crystals and moderate 6 ms^{-1} wind speeds at 0.4 m height. Both nights of recording spanned four hours, providing ample evidence of large snow particles tumbling as tractions, resembling tumbleweeds – something not observed in other aeolian materials. Their relatively large mass contributed to ejecting many smaller grains into reptation and saltation upon impact (Figure 4). After gaining sufficient momentum, the large particles fractured into smaller

crystals, themselves ejecting into saltation. This does not fit the Doorschot and Lehning (2002) “splash versus entrainment” theory of initiation and does not allow for permanent definitions of particle size.

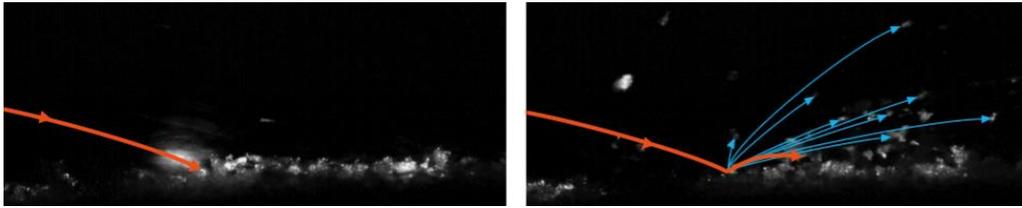


Figure 4. Splash and Inbound Salton Collapse. Timestep 11.4 ms, Feb 5, 2015 21:22

In agreement with Willetts et al. (1991), all recordings show many saltions beginning motion as reptons and tractons. While rolling on the uneven snow surface, tractons may bounce into saltation after impacting a well-lodged particle and quickly accelerate from wind drag as they rise above the surface (Figure 1 & 3). Extensive review of the field recordings suggests particles accelerating out of an active creep layer are needed as a third component of initiation in blowing snow theories. Reptons and tractons provide an efficiently entrained source of blowing snow particles as they have already broken their snow surface bonds and supply their own momentum prior to vertical ejection. This lowers the drag forces necessary for tracton and repton entrainment, all the while the stationary bed concurrently undergoes classic aerodynamic drag and splash initiation.

Particle flow observations of and over different snow crystal types provided insights into the variable nature of snow saltation mechanics, sometimes closely resembling blowing sand theory, but other times diverging in important ways. In contrast to sand, snow saltation initiation and rebound changed dramatically as snow particles shattered, sintered and sublimated and the snow surface hardened. The elasticity of blowing snow particles and ability of the snow surface to absorb momentum upon impact appeared to change substantially over a two-hour span of recordings on April 1 (Figure 5). Over this period, 0.4 m wind speeds varied from 0 to 8.6 ms^{-1} , with a mean of 1.4 ms^{-1} , resulting in a decrease in blowing snow particle size. Eventually a hard wind crust masking an old radiation crust was revealed by the next day.

Figure 5 exhibits wind conditioning of the saltating and surface snow crystals shortly after cessation of snowfall at precisely the same location over a 105-minute period beginning 20:15. Frame ‘a)’ displays initial conditions with large fresh stellar crystals and a rough snow surface with many exposed snow crystal structures. The subsequent frame ‘b)’ is five minutes later, after 2.44 ms^{-1} 0.4 m wind speed, showing a variety of sizes of sintering and shattering grains in motion and a relatively smoother snow surface. Frame ‘c)’ was captured after 100 more minutes elapsed, exhibiting mostly small, rounded snow grains in saltation and a much smoother surface. The wind-scoured snow surfaces upwind contained a low percentage of loose grains available to be dislodged, greatly reducing the effectiveness of splash actions. This left many saltions rebounding out of frame without ejecting any reptons or tractons, effectively reducing the particle number concentration. As well, there was an obvious change in surface roughness.

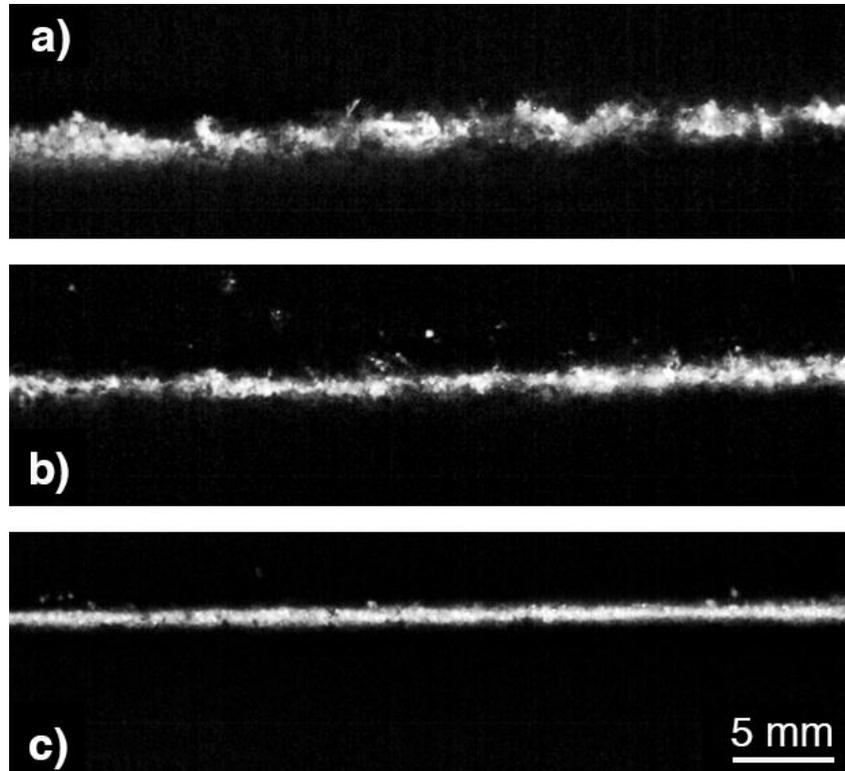


Figure 5. Reducing surface roughness and particle size on April 1, 2015

Li and Pomeroy (1997b) documented trends similar to the snow surface evolution on April 1 and developed a probability function of blowing snow transport that depends on wind hardening. In the present data set, the average threshold velocity did not appear to increase as particles are still in transport at relatively low wind speeds. A decrease in number concentration with increasing wind speed appears to be a more physically accurate description of the April 1 trend and is consistent with the Li and Pomeroy (1997) theory of reduced probability of transport with wind hardening.

This temporal evolution of entrainment and transport dynamics cannot be ascribed to particle diameter alone as evolving bed structures played a significant role. As well, the April 1 two-hour transition in grain size was relatively quick compared with other nights of recording exhibiting no apparent change in particle size. This reveals more variability in blowing snow dynamics that may be snow type or even storm specific. Further research into wind hardening and slab formation may elucidate the evolution of grain availability for blowing snow.

ANALYSIS

The recordings allow visual qualitative analysis of blowing snow processes previously invisible to researchers, and the ability to quantify individual 2D projected particle velocities over a variety of time scales through PTV. Certain particle behaviour trends reappear in all PTV conducted for the February-April field campaign. Example PTV data calculated from March 23 recording #6 is displayed in Figure 6. The saltating snow consisted of graupel-like spherical grains with a mean 0.4 m wind speed of 4.78 m s^{-1} . The recording comprises 16,000 frames spanning 13 seconds of continuous transport in non-constant winds beginning 21:38. For clarity, the vector field displayed was calculated from only 4 seconds of recorded video. The highlighted green area indicates an uneven region of surface topography providing unreliable statistics for particle motion.

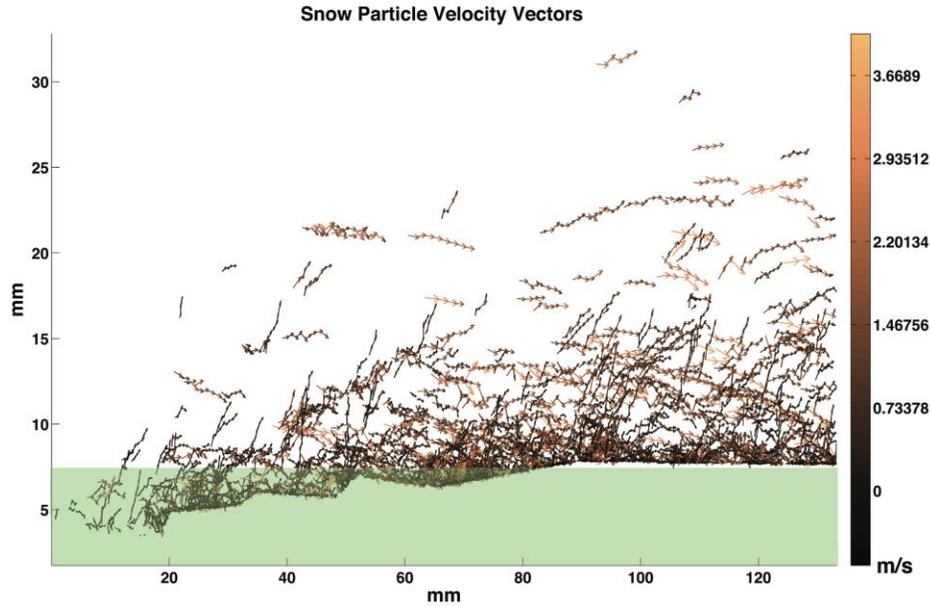


Figure 6. Sparse Snow Particle Velocity Vector Field from recording 3-23 #6

When comparing regions above and below 10 mm, the vector field visualization (Figure 6) shows the relatively high concentration of particles near the surface. Figure 7 further corroborates this observation. The left graph shows the percentage of total particles $P_z = \frac{n_z}{\sum_z n_z}$, where n_z is the number of particles identified in a horizontal 0.1 x 130 mm slice at height z . The right graph shows the influence of increasing particle velocity with height on particle flux. At a given height z , the percentage of particle flux F_z was calculated as

$$F_z = \frac{n_z * v_z}{\sum_z n_z * v_z}$$

where v_z is the average velocity at height z . The highlighted green region is consistent in Figures 6, 7 and 8. For the 3-23 #6 recording, the percentage of particles approaches zero above $z = 15\text{mm}$ whereas in the flux profile, concentrations are notable until $z = 20\text{mm}$. In both plots of Figure 7, the maximum exists immediately above the unmoving snow surface.

Figure 8 consists of mean velocity profiles for ascending particles (left) and both ascending and descending grains (right). Heights of $7 < z < 10\text{ mm}$ consists of saltons at either the beginning or end of a ballistic trajectory, as well as the reptons and tractons. This 3 mm thick layer contains 50% of total particles tracked, but constitutes only 10% of the layer of investigation. The number of low-energy particles with velocities $V_x < 0.75\text{ ms}^{-1}$ vastly outweighs the number of high-energy saltons in this region, contributing 70% of particle velocities calculated. For the layer $z > 15\text{mm}$ particles with velocities $V_x > 1.5\text{ ms}^{-1}$ constitute 70% of particles tracked. This shows a transition in both particle number density and particle motion mechanics within a 20 mm thick layer.

There is general agreement between the shape of velocity profiles for the ascending and total particle plots in Figure 8. Deviations from characteristic profiles are found in the layers influenced by microtopography, and in the lower density upper salton layer. There is a tight fit to the characteristic profile in the layer $7 < z < 15\text{ mm}$ though noticeably more linear for ascending particles. This is consistent with particles being ejected from the surface with an initially small

horizontal velocity that increases linearly with jump height and therefore transport-time. The linear fit could also be attributed to a layer of constant shear stress and momentum transfer by the wind immediately above the surface. The layer of tight fit below 15 mm coincides with high particle concentrations. The velocity of grains in this layer provide less variance from mean profile values and show the strong prevalence of tracted and repton motion over saltons, whereas upper regions appear to be more turbulently influenced.

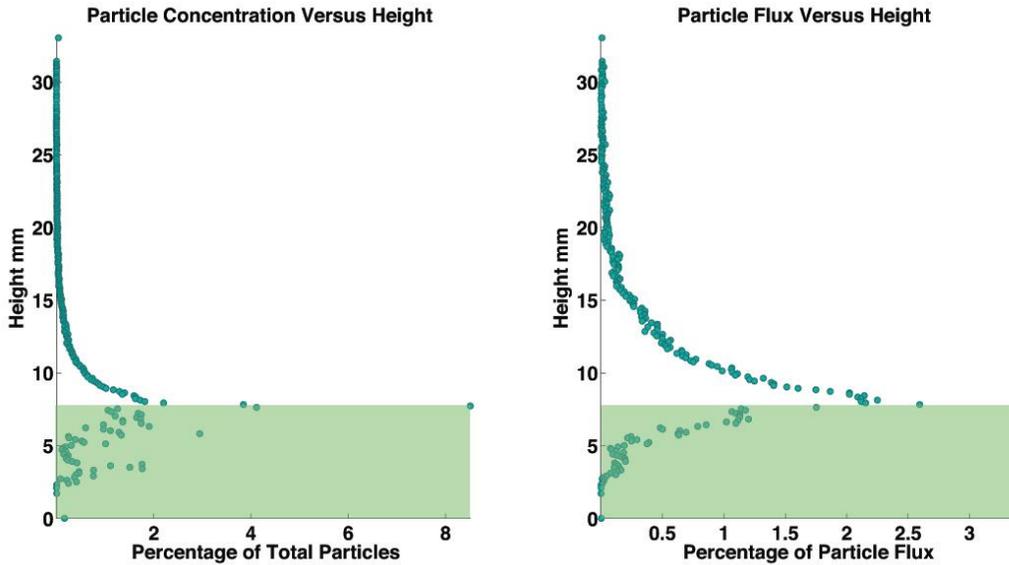


Figure 7. Snow Concentration Profiles for 0.1mm slices from 3-23 #6

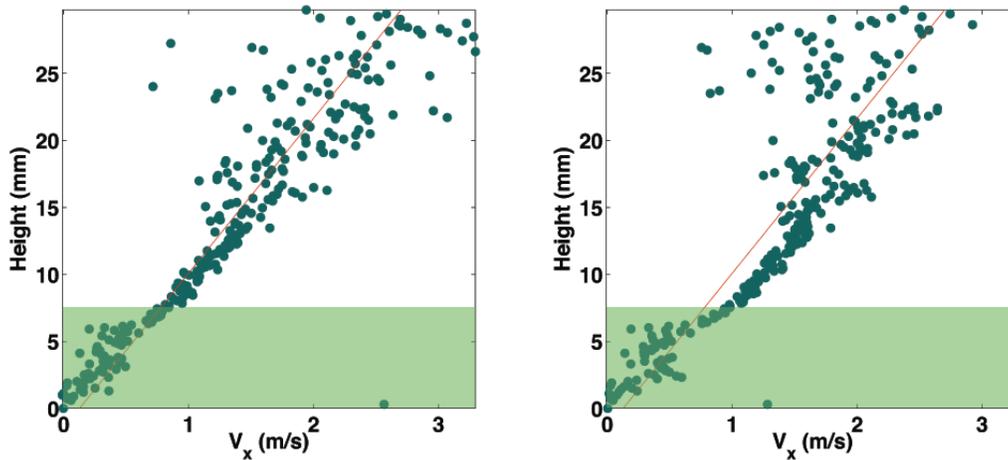


Figure 8. Velocity Profiles for 3-23 #6. Left: Ascending Particles. Right: Ascending and Descending

DISCUSSION

The existence of creeping snow particles has been previously recognized but neither their importance nor prevalence was understood (Gauer, 1998). Several common traits in snow particle motion, previously neglected in blowing snow literature, were found in this study. Three species of motion were distinguished in saltating snow. Salton, repton, and tracted behaviours were evident in the majority of recordings, regardless of snow crystal size and shape. The prevalence of low energy particles was further corroborated by initial PTV analysis. Thus far, creeping particles have been largely overlooked as a source of saltation initiation, mass transport and wind

momentum deficit. At the wind speeds observed, blowing snow particle density has been found to be highest in the lowest 15 mm of the saltation layer. The significant proportion of moving particles that reptons and tractons constitute in this layer suggests they may indeed play a critical role in snow saltation dynamics.

Including reptons could also present an improvement to wind components of two-phase snow saltation models. Classical single trajectory models of saltation assume a uniform trajectory in the saltation layer (e.g. Pomeroy and Gray, 1990) and force an unstable or non self-consistent momentum transfer from wind to particles (Andreotti, 2004). Utilizing reptons in a two-species model allowed Lämmel et al. (2012) to achieve a stable wind momentum deficit during saltation. As well, repton creation helps balance the reduced velocity of a rebounding salton. These momentum balances have not been investigated for blowing snow.

The large concentration of slow moving grains in the first 3 mm above the snow surface has not been previously measured and likely impacts the lower boundary condition for wind flow. For instance, the no-slip assumptions for momentum transfer calculations may need to be re-evaluated to better represent the snow surface as a porous wall under a dense moving bed of particles during saltation. Tractation and reptation motions are responsible for breaking most snow surface bonds, but how they break these bonds is not yet known. Neither of these issues have been investigated for snow saltation.

Over the course of the field campaign, some snow particle trajectories exhibited classic sand-like behaviour. However, when enormous aggregate crystals, decomposing grains, and mixed grain types were present, particle behaviour unique to snow was exhibited. Further observations will show to what degree saltating snow can be described using saltating sand-like motions. New blowing snow particle motion descriptions may also need to be considered.

CONCLUSIONS

For the first time, high-speed video employed outdoors has been used to investigate the motion of saltating snow in great detail. Over short timescales, snow particle behaviour appears to be influenced by complex initiation and rebound dynamics, including reptation and tractation, which have not previously been described for snow. The ability of the snow surface to absorb impact momentum into the bed, or through repton and tracton generation, and the elasticity of particles were all found to be temporally variable and heavily dependent on snow crystal type. Sintering, shattering, and sublimation of saltating snow particles appear to be factors influencing mass flux and turbulent momentum transfer that should be further investigated.

The first environmental PTV computations for snow have proven to be a viable avenue for exploring complex wind-snow interactions at millisecond timescales. Initial results have supported a new three species conceptual model of snow saltation, though exact initiation and rebound dynamics are dependent on snow crystal characteristics. PTV shows potential to solve many unanswered problems in blowing snow research allowing quantification of energy dispersal in very near surface particle motion. In addition, the high temporal resolution measurements may prove useful in future work for understanding the turbulent influences on blowing snow processes.

ACKNOWLEDGEMENTS

The authors wish to acknowledge field assistance from students and staff of the Centre for Hydrology, often in very inclement conditions. Financial assistance from NSERC through the Changing Cold Regions Network, Research Tools and Instruments and Discovery grants programme, the Canada Research Chair and Canada Excellence Research Chairs programme, the Canada Foundation for Innovation, and Alberta Environment and Sustainable Resource Management is gratefully acknowledged. Fortress Mountain Resort is thanked for their support of snow science and particularly this study.

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