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Key Points:

- We found evidence of weak and strong saltation regimes from wind tunnel experiments
- Weak saltation is characterized by short and narrow peaks, while strong saltation presents wider and larger peaks with a reduced growth rate
- The probability of occurrence of splash entrainment increases with the saltation strength

Correspondence to:

E. Paterna,
paterna@slf.ch

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Wind tunnel observations of weak and strong snow saltation dynamics

E. Paterna¹ , P. Crivelli¹ , and M. Lehning^{1,2}
¹WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland, ²School of Architecture, Civil and Environmental Engineering, Swiss Federal Institute of Technology, Lausanne, Switzerland

Abstract Theoretical considerations suggest that saltation dynamics is dominated by either aerodynamic entrainment or by a combination of ejection and rebound at a given time and location. Calling these two regimes “weak” and “strong” saltation, respectively, we have investigated high-resolution snow mass flux measurements by shadowgraphy in a cold wind tunnel to determine whether these two regimes can be experimentally reproduced. In this contribution, we first suggest that aerodynamic entrainment should lead to a negative correlation in the growth rates of horizontal versus vertical mass fluxes, while for the ejection regime, a positive correlation is plausible. Based on this criterion, we find evidence of weak and strong saltation in our data. Weak saltation is characterized by smaller peaks of horizontal mass flux; however, these peaks have a higher growth rate and therefore are typically narrow. The larger peaks are associated with strong saltation, are wider, and their frequency of occurrence increases with increasing overall saltation mass flux.

1. Introduction

Aeolian transport of snow significantly affects the mass and energy balances in polar and mountainous regions, and it also shapes the snow surface with ripples [Cornish, 1914; Kobayashi and Ishida, 1979; Kosugi et al., 1992], sastrugi [Mather and Goodspeed, 1959; Kobayashi and Ishida, 1979], snow waves [Cornish, 1914], snow dunes [Frezzotti et al., 2002a, 2002b; Dadic et al., 2013], and cornices [Mott et al., 2010].

Aeolian snow transport occurs in three modes: creep, saltation, and suspension [Kok et al., 2012]. Creep accounts for the rolling on the snow surface of the largest crystals, too heavy to get entrained by the flow [Dong et al., 2003; Wang and Zheng, 2004]. Saltation consists of the transport of smaller crystals in a shallow layer within a few centimeters from the snow surface; it is mainly driven by wind drag and gravity, and it results in ballistic trajectories [Bagnold, 1941; Pomeroy and Gray, 1990]. Suspension consists of the diffusion of the smallest particles in a much deeper layer, from several centimeters to a few hundred meters from the surface, under the influence of the turbulent flow at high wind speed [Pomeroy and Male, 1992; Bintanja, 2000a, 2000b]. Saltation is triggered as soon as the wind flow has sufficient momentum to entrain snow crystals from the surface (aerodynamic entrainment), and it is also maintained by the momentum of entrained particles rebounding or impacting and destabilizing the crystals at the surface and projecting them into the saltation layer (splash entrainment). The interaction between wind and saltation is often viewed as consisting of four subprocesses: aerodynamic entrainment, particle trajectory, splash entrainment, and air-flow modification. Snow particles are first entrained by the flow (aerodynamic entrainment) and then follow ballistic trajectories until they impact the snow cover again. Upon collision, they fracture and destabilize the snow crystals at the surface and might project further particles or fragments into the saltation layer (splash entrainment). In the fourth subprocess (flow modification), the saltating particles induce a feedback on the flow, by reducing the flow momentum and increasing the flow stratification. This ultimately reduces the sediment entrainment and consequently the sediment mass flux, which, in turn, promotes a new increase in the flow momentum and the entrainment of particles, thus completing the saltation cycle. Note that continuous saltation is observed if sufficient momentum is provided by the flow.

The study of snow saltation historically derives from the theory of aeolian sand transport formulated by Bagnold [1941]. A relevant difference between aeolian sand and snow transport processes lies in the cohesion between particles at the surface. Sand grains are nearly cohesionless, while snow crystals are bonded by cohesive forces that are often much larger than the gravitational forces [Schmidt, 1980]. These forces are dependent on crystal size, time elapsed after the snowfall, air temperature, and humidity and

determine the threshold wind velocity for transport [Oura *et al.*, 1967; Schmidt, 1980, 1986]. A comprehensive overview of the mechanism occurring during aeolian snow transport has been given by Mellor [1965], Radok [1978], Schmidt [1982a], and Pomeroy and Gray [1990].

Field campaigns have first quantified the mass flux in the saltation and suspension layers at different wind strengths [Budd *et al.*, 1966; Kobayashi, 1978; Takeuchi, 1979; Schmidt, 1982b; Takahasi, 1985; Mahesh *et al.*, 2003; Nishimura and Nemoto, 2005; Savelyev *et al.*, 2006; Gordon and Taylor, 2009; Gordon *et al.*, 2009], surface roughness [Schmidt, 1986; Bintanja, 2001a; Leonard and Maksym, 2011], meteorological conditions [Tabler and Schmidt, 1972; Li and Pomeroy, 1997; Vionnet *et al.*, 2013; Lenaerts *et al.*, 2014; Naaim-Bouvet *et al.*, 2014], and surface topography [Föhn, 1980; Schmidt *et al.*, 1984; Meister, 1987; Pomeroy, 1991; Doorschot *et al.*, 2001, 2004; Michaux *et al.*, 2002; Vionnet *et al.*, 2013]. The impact of aeolian snow transport on the mass and energy balances have also been addressed and particular attention was given to the sublimation and stratification induced by the snow transport [Schmidt, 1982b; Mann *et al.*, 2000; Bintanja, 2001b; King *et al.*, 2001; Savelyev *et al.*, 2006; Thiery *et al.*, 2012; Barral *et al.*, 2014].

Laboratory experiments have later followed the first field campaigns with the aim of controlling and more closely observing the process. The first wind tunnel experiments have investigated the contribution of the saltating particles to the aeolian snow transport by means of laser visualization and a photographic acquisition system [Oura *et al.*, 1967; Kobayashi, 1972] and later provided more quantitative information on the particle trajectories [Araoka and Maeno, 1981; Sugiura *et al.*, 1997]. Subsequently, photographic techniques were also employed to obtain mean profiles of velocity, particle concentration, mass flux, and particle dimension [Naaim and Martinez, 1995; Naaim-Bouvet and Naaim, 1998; Tominaga *et al.*, 2013; Gromke *et al.*, 2014], and later frequency analysis of the snow mass flux [Paterna *et al.*, 2016]. Mechanical traps and optical detectors were also largely employed to measure mean profiles and time series statistics [Sugiura *et al.*, 1998; Nishimura and Hunt, 2000; Nemoto and Nishimura, 2001; Kosugi *et al.*, 2004; Clifton *et al.*, 2006; Guala *et al.*, 2008; Okaze *et al.*, 2012], as well as to investigate the splash entrainment process [Sugiura and Maeno, 2000; McElwaine *et al.*, 2004].

The first descriptions of the aeolian snow transport considered steady state and equilibrium conditions. Nevertheless, spatial fluctuations of the saltation fluxes were early observed by Kobayashi [1972] who linked them to the erosion and deposition patterns of the snow cover. The steady state formulation was later questioned by Schmidt [1986] who brought the attention to the temporal and spatial features (streamers) of snow saltation, which are analogously observed in sand saltation [Stout and Zobeck, 1997; Baas and Sherman, 2005; Baas, 2008; Davidson-Arnott and Bauer, 2009; Sherman *et al.*, 2013]. Finally, the interaction between unsteady winds and snow saltation was later addressed by Doorschot *et al.* [2004] and Doorschot and Lehning [2002], Zwaafink *et al.* [2014], and Paterna *et al.* [2016]. Also, in the field of sand saltation several studies have challenged the paradigm steady state saltation. Among them Kok and Renno [2009] showed that turbulence affects the trajectories of particles smaller than 200 μm .

Despite the substantial literature on aeolian snow transport, the current understanding of the saltation dynamics and unsteadiness is incomplete. In our previous contribution we observed a significant unsteadiness of the mass flux signals of both the streamwise and vertical components of the mass flux [Paterna *et al.*, 2016]. We have noticed that often mass flux is concentrated in short time intervals yielding peaks in the mass flux time series and dense saltation clouds, and time intervals of weak or no saltation activity. We have also observed that when the saltation strength increases, the occurrence of large saltation peaks also increases and with that the associated saltation timescale. We have also noticed that the correlation between turbulent fluctuations and mass transport is always highest close to the turbulent production range. We have hypothesized that two different regimes of saltation might exist, a “weak” and a “strong” regime, and that they might derive from two different entrainment dynamics. At weak saltation, the aerodynamic entrainment of snow crystals, triggered by the turbulent flow, might dominate, while at strong saltation the splash entrainment resulting from particle bed collisions would produce a local sudden increase of the saltation mass flux resulting in the development of significant mass flux peaks. The predominance of either aerodynamic or splash entrainment constitutes the basis of the equilibrium saltation model of Doorschot and Lehning [2002] and date back to the earlier work of Shao and Li [1999]. Note, however, that weak and strong saltation have previously also been used with respect to growing and shrinking saltation lengths and that we now use these terms in connection with the two entrainment mechanisms. Furthermore, our observed increase of the saltation timescales with the saltations strength

Figure 1. Experimental setup and approach, adapted after Paterna *et al.* [2016]. (a) Diagram of the cold wind tunnel. (b) Diagram of the measurement setup. (c) Raw images obtained with digital shadowgraphy, after estimating the size and velocity of all the imaged particles and determining the spatially averaged mass flux for each time step.

is determined by the coupling between mass flux and wind fluctuations at scales larger than the length of the particle trajectories. A saltation regime classification was also proposed by Ho *et al.* [2011]. In their work they observed that over an erodible bed particle velocity and saltation length do not depend on the wind strength, while over a rigid bed they reveal a strong dependence. This resulted in a cubic dependence of the sediment transport rate on the friction velocity over a rigid bed and a quadratic dependence over an erodible bed, in contrast with Bagnold's prediction. In our study of snow saltation we only focus on saltation over an erodible bed, and we expect the mass flux dependence on wind strength to be close to what was observed for sand saltation over an erodible bed. Nevertheless, the snow cohesion produces a more complex dependence of the saltation mass flux on the wind strength, which is beyond the scope of the current work. No dependence of our observed snow saltation on the bed boundary conditions has been observed. Hence, our observed saltation regimes are expected to depend on different entrainment mechanisms rather than on different bed boundary conditions.

The current work has the aim of investigating the link between saltation strength, entrainment mechanisms, and saltation dynamics (e.g., mass flux peaks). A better definition of weak and strong saltation is necessary to demonstrate the existence of the two regimes in order to associate the two regimes with the two entrainment modes.

2. Experimental Setup

The experiments were conducted in the cold wind tunnel of the Institute for Snow and Avalanche Research (SLF/WSL) in Davos (Switzerland) in winter 2014/2015 [Paterna and Crivelli, 2016]. The wind tunnel is located at 1670 m above sea level in the Swiss Alps, and it is not heated, thus allowing testing the saltation of real snow crystals. In particular, the snow cover employed in our tests has naturally settled outside the laboratory [Paterna *et al.*, 2016]. The wind tunnel is an open loop type operating in suction mode. The wind tunnel measures 14 m, and the cross section measures 1×1 m (Figure 1a). The first 6 m from the inlet is occupied by a roughness fetch and Irwin vortex generators to allow a rapid growth of the turbulent boundary layer. The snow cover employed in the experiments is collected outside the laboratory on a shaded and wind sheltered area, on custom designed metal trays. After a snow fall deposits a snow layer 0.06–0.18 m deep, the trays are carefully transported by means of a cart and positioned

in the test section, flush with the upstream rough surface, forming a continuous 8 m snow cover. A motorized stage beneath the wind tunnel floor allows positioning the snow-filled trays at the same height of the fixed inlet roughness fetch. Prior to each experiment the wind tunnel was run at low speed to allow thermal equilibrium between the snow cover inside the wind tunnel and the air drawn from outside.

We conducted measurements of flow turbulence and mass flux of the saltating snow crystals. We employed a Kaijo ultrasonic anemometer DA-600 (USA) equipped with a miniature probe (TR-90AH) to measure the turbulent flow and a LaVision digital shadowgraphy system (SG) to measure the mass flux (Figure 1b).

Sonic anemometry has been chosen for its ability to measure the flow during snow drifting, as opposed to hot-wire anemometry where the impact of snow crystals on the heated wire would produce discontinuities in the time series which are difficult to handle [Sugiura *et al.*, 1997]. The vertical path length of the USA measures 50 mm and is centered at about 40 mm above the snow cover. The instrument acquires the three components of the flow velocity at 20 Hz. During each experiment the snow saltation intensity is kept low enough to minimize the erosion and to allow the USA to be always a few millimeters above the snow cover.

Shadowgraphy was chosen for its robustness, nonintrusiveness, and its ability to detect the dimension and displacement of the snow crystals which allows the estimation of the mass flux. Moreover, the SG is able to resolve the two components of the mass flux in the saltation layer which conventional one-dimensional laser sensors cannot afford [Schmidt, 1977; Sato *et al.*, 1993]. The technique consists in back illuminating the saltating snow crystals from one side of the wind tunnel and acquiring images of them from the opposite side [Gromke *et al.*, 2014; Paterna *et al.*, 2016]. The acquired images show dark saltating crystals on a bright background (Figure 1c). The postprocessing of the images is conducted by applying image analysis for the detection of the particles and the estimation of their size and by employing an algorithm designed for Particle Tracking Velocimetry (PTV) [LaVision, 2011; Gromke *et al.*, 2014; Crivelli *et al.*, 2016], as shown in Figure 1c. Preliminary experiments were conducted to calibrate the digital shadowgraphy [Crivelli *et al.*, 2016] using a calibrated Snow Particle Counter (SPC), which is considered the standard measurement technique for snow and sand mass fluxes [Sato *et al.*, 1993].

Shadowgraphy is operated by means of a high-speed CMOS camera with a spatial resolution of 1024×1024 pixels and a maximum acquisition frequency of 3.6 kHz at the latter spatial resolution. The camera is equipped with a telescopic objective (Nikon 70–180 mm $f/4.5$ – 5.6) that is chosen as a trade-off between camera resolution and extent of the field of view. The light source employed is a standard halogen lamp, equipped with a diffusers and a Fresnel lens to straighten the light rays directed towards the camera. The optical system was already checked for angular distortions [Gromke *et al.*, 2014]. The camera is mounted on a vertical translation which allows accurate vertical alignment with the snow cover.

The depth of field was centered in the wind tunnel midplane, and it includes most of the near-surface saltation layer. To detect the particle's displacement, the separation time between the two consecutive images was set between 2.5 and 5 kHz. To detect the time fluctuations of the saltation mass fluxes the acquisition frequency of the image pairs was set between 20 Hz and 25 Hz. A third relevant parameter controlling the image acquisition is the camera exposure time which was set to 12 μ s. An excessively large exposure time would produce blurred shadow particle images that would alter the dimension estimation, while an excessively small exposure time would reduce the background light intensity in the images thus increasing the uncertainty in the particle detection.

In the winter 2014/2015 we have conducted nine experiments and acquired 2728 image pairs for each experiment [Paterna *et al.*, 2016]. We have varied the wind tunnel free stream velocity in such a way that we could resolve a wide range of mean mass fluxes, which finally spanned about 2 orders of magnitude. To allow consistency among all the conducted experiments, we have restricted the field of view in the analysis such that all the images measure 18 mm along the vertical dimension and are centered 19 mm above the snow surface, while the mean depth of field measured 31 mm. The spatial resolution of the acquired images was 47 μ m. We have also estimated the error around the mean values of the acquired mass flux samples by bootstrapping. With bootstrapping a subset of the acquired mass flux data was randomly sampled with replacement several times to obtain the sampling distribution of the sample means and allow the

Table 1. Mean Streamwise Mass Flux ($q_{x,m}$), Mean Vertical Mass Flux ($q_{z,m}$), Free-Stream Velocity (U_∞), Friction Velocity (u_*), and Air Temperature ($T_{a,\infty}$)^a

Test	$q_{x,m}$ ($\text{kg m}^{-2} \text{s}^{-1}$)	$q_{z,m}$ ($\text{kg m}^{-2} \text{s}^{-1}$)	U_∞ (m s^{-1})	u_* (m s^{-1})	$T_{a,\infty}$ ($^\circ\text{C}$)
1	1.18×10^{-3}	0.067×10^{-4}	9.64	0.25	−6.2
2	8.63×10^{-3}	1.37×10^{-4}	9.69	0.26	−5.5
3	5.51×10^{-3}	0.39×10^{-4}	11.02	0.36	−5.5
4	29.08×10^{-3}	20.22×10^{-4}	9.50	0.38	−2.8
5	37.52×10^{-3}	10.11×10^{-4}	10.23	0.54	−2.8
6	1.90×10^{-3}	-0.34×10^{-4}	10.07	0.23	−2.6
7	3.89×10^{-3}	-0.94×10^{-4}	11.12	0.26	−2.4
8	2.39×10^{-3}	0.22×10^{-4}	12.03	0.22	−4.5
9	3.37×10^{-3}	0.53×10^{-4}	13.10	0.27	−4.6

^aMeasurements of U_∞ and $T_{a,\infty}$ are taken at $z = 0.5$ m from the snow surface.

estimation of the errors. The median of the standard errors of the mass flux is estimated to be around 12% with 95% confidence for both the components, while the 75th quartile is close to 13% for the streamwise component and 16% for the vertical component. Such estimated error is clearly determined by both the measurement acquisition and by the mass flux unsteadiness that slowly converges in time toward the mean. Table 1 shows, for each experiments, the mean streamwise mass flux $q_{x,m}$, the free-stream velocity U_∞ , and the air temperature $T_{a,\infty}$ measured at about 0.5 m from the snow surface.

3. Shadowgraphy Postprocessing

The most important operation preliminary to the experiments aims at estimating the depth of field of each particle size. Smaller particles tend to be out of focus more easily than the larger ones at the same distance from the measurement plane [Kim and Kim, 1994]. This results in an underrepresentation of the detected (in-focus) small particles. This is quantified by conducting a depth of field calibration, which consists in acquiring images of dots of multiple dimensions on a transparent target. During the calibration the target is translated along the viewing axis of the camera at steps of 1 mm between two opposite positions across the measurement plane. This calibration allows obtaining the linear relation between particle size and particle depth of field.

Once the image pairs are acquired, a series of postprocessing steps are conducted until the mass flux time series can be obtained. Image analysis operations, such as background subtraction and image segmentation, allow the determination of the position and diameter of each detected particle. Subsequently, an algorithm designed for Particle Tracking Velocimetry (PTV) determines the displacement of each detected particle by cross correlation of its image at the initial and final position. The information of particle diameter and velocity allows determining the mass flux components, along the streamwise and vertical direction, in the measurement domain at each time realization.

Once the particles dimension, position, and velocity are determined, an analytical postprocessing is applied. At first a velocity threshold is used to remove spurious velocity vectors. The threshold is chosen sufficiently below the expected minimum particle velocity. Afterward, the same position and extent of the shadowgraphy probing volume among all the tests was retained. Particles detected outside this common volume were discarded from the analysis. The images acquired during the depth of field calibration were employed at this stage to estimate the depth of field for each particle on the basis of its diameter. Finally, the mass flux for each particle is determined assuming that the saltating particles have the density of ice $\rho_{\text{ice}} = 917 \text{ kg m}^{-3}$. Spatially averaged values of mass flux over the probing volume are then obtained at each time step and are subsequently decomposed in their streamwise q_x and vertical q_z components to obtain the time series used in the following analysis.

4. Results

In the winter 2014/2015 we have conducted nine experiments [Paterna and Crivelli, 2016] at different values of the mean streamwise saltation mass flux $q_{x,m}$, which we consider an indicator of the saltation strength. For

each experiment we obtained time series of both the streamwise q_x and vertical q_z mass flux components (Table 1).

As the sonic anemometer is positioned in the saltation layer, the measured momentum flux corresponds to the airborne momentum flux only. The total momentum flux $\tau(z)$ is given as

$$\tau(z) = \rho u_*^2 = \tau_p(z) + \tau_a(z) \quad (1)$$

where $\tau_a(z)$ is the airborne momentum flux, $\tau_p(z)$ is the particle-borne momentum flux, and u_* the friction velocity. To correctly estimate the friction velocity, we estimated the particle-borne momentum flux τ_p at three positions above the snow cover ($z = 0.013, 0.019, 0.025$ m) as

$$\tau_p(z) = |q_z(z)| \Delta v_x(z) \quad (2)$$

where

$$\Delta v_x(z) = v_{x\downarrow} - v_{x\uparrow} \quad (3)$$

is the difference of the streamwise velocity v_x between descending ($\downarrow$) and ascending particles ($\uparrow$) [Kok *et al.*, 2012; Pähtz *et al.*, 2012]. The particle-borne momentum flux $\tau_p(z)$ grows exponentially toward the surface [Kok and Renno, 2009]. The particle-borne momentum flux $\tau_p(z)$ at the height of the sonic anemometer (0.04 m) is interpolated from the values of $\tau_p(z)$ computed at the latter three heights, such that $\tau_p(z)$ and $\tau_a(z)$ can be directly compared. The airborne momentum flux $\tau_a(z)$ is determined by the

$$\tau_a(z) = -\rho \overline{u'w'} \quad (4)$$

where $\overline{u'w'}$ is the product of turbulent velocity fluctuations, measured by the ultrasonic anemometer, obtained according the Reynolds decomposition:

$$u' = U - \overline{U} \quad (5)$$

$$w' = W - \overline{W} \quad (6)$$

and U and W are the instantaneous values with the overbar denoting the time average operator. The friction velocity is therefore obtained as

$$u_* = \sqrt{\frac{\tau(z)}{\rho}} \quad (7)$$

4.1. Saltation Regimes

In our previous contribution we have hypothesized that two different regimes of saltation might exist, a strong regime and weak regime, and that they might be linked to two different entrainment mechanisms [Paterna *et al.*, 2016]. To provide further arguments in support of our hypothesis, we have now advanced our analysis inspecting the dependence of the time increments of the mass flux components on the saltation strength. The acquired time series show strong unsteadiness, high peaks, and periods with little or no activity (Figure 2). Additionally, a mass flux signal is often observed associated with positive vertical mass flux (Figure 2, top). while both positive and negative mass-observed signals are for reduced mass flux strengths (Figure 2, bottom).

We assume a relation between particle entrainment mechanisms and distribution of mass flux time increments based on kinematic reasoning. In particular, we expect that the streamwise particle velocity is positive and increases from ejection toward impact with the bed during almost the entire trajectory. The positive vertical velocity should decrease from ejection toward impact on the bed during the ascending phase and become negative in its descending phase. Our time-resolved mass flux measurements are obtained from a spatial average of the mass flux from each detected particle within the imaged portion of the saltation layer. We now introduce the mass flux time increments as an approximation to the mass flux time derivative. The mass flux time increments are obtained by subtracting from each mass flux value at a given time t the mass flux measured at time $t-\tau$, where τ is the time between the acquisition of two consecutive image pairs and is equal to 0.05 s. In the limiting case where only a single particle per image is detected, a scenario compatible with a weak saltation regime, if the particle is

Figure 2. Time series of the streamwise q_x (blue) and vertical mass flux components q_z (red) for (top) test 5 and (bottom) test 2.

in its ascending phase at time $t-\tau$ and in its descending phase at t , the resulting mass flux time increment will be positive along the streamwise direction and negative along the vertical direction as described above. Also, in case the particle is captured in its descending phase at time $t-\tau$ and in its ascending phase at t , the resulting mass flux time increment will again be positive along the streamwise direction and negative along the vertical direction. In weak saltation we assume equal probability of detecting particles in their ascending and descending phases; therefore, the correlation of the mass flux time increments is expected to be negative. In strong saltation we postulate that due to splash entrainment, the number of entrained particles increases after each splash producing an exponential increase of both the streamwise and vertical mass flux with time until the mass flux peak is reached. Both in the increasing mass flux phase toward the peak and in the decreasing phase past the peak, when both the streamwise and the vertical mass flux will decrease, the time increments of the mass flux components will have the same sign which will result in a positive correlation. We can therefore test our main hypothesis that splash entrainment mainly dominates at strong saltation and aerodynamic entrainment at weak saltation [Paterna *et al.*,

2016] by determining the correlation between the time increments of q_x and q_z . The time increments of the two components of the saltation mass flux are defined as

$$\Delta q_x(t, \tau) = q_x(t + \tau) - q_x(t) \quad (8)$$

$$\Delta q_z(t, \tau) = q_z(t + \tau) - q_z(t) \quad (9)$$

with $\tau = 0.05$ s. The time increment $\tau = 0.05$ s was chosen as a trade-off between resolving the saltation system in time and ensuring enough uncorrelated samples in favor of statistical convergence of the mean quantities for each test. We developed a criterion to

Figure 3. Quadrants of the mass flux time increments Δq_x and Δq_z .

Figure 4. Scatterplots of the mass flux time increments Δq_x and Δq_z for (top) test 6, (middle) test 1, and (bottom) test 4 and the corresponding correlation coefficients $\rho_{\Delta q_x, \Delta q_z}$.

subdivide each time realization of the main (streamwise) mass flux component $q_x(t)$ into four groups, or quadrants, on the basis of the sign of Δq_x and Δq_z (Figure 3). The conditions for the assignment of each realization $q_x(t)$ to a specific quadrant are

$$\begin{aligned} q_x(t) \in Q_1 &\Leftrightarrow \Delta q_x(t, \tau) > 0, \Delta q_z(t, \tau) > 0 \\ q_x(t) \in Q_2 &\Leftrightarrow \Delta q_x(t, \tau) < 0, \Delta q_z(t, \tau) > 0 \\ q_x(t) \in Q_3 &\Leftrightarrow \Delta q_x(t, \tau) < 0, \Delta q_z(t, \tau) < 0 \\ q_x(t) \in Q_4 &\Leftrightarrow \Delta q_x(t, \tau) > 0, \Delta q_z(t, \tau) < 0 \end{aligned} \quad (10)$$

The mean absolute contribution $q_{(x,m)_i,a}$ from the mass flux time realizations $q_x(t)$ due to the quadrant condition Q_i is given as

$$q_{(x,m)_i,a} = \frac{1}{n_i} \sum_{j=0}^{n_i} q_{x,Q_i}(t) \quad (11)$$

where i indicates the quadrant number, n_i the number of realizations in quadrant Q_i , and n the total number of time realizations having $q_x(t) > 0$.

Figure 4 shows examples of the distribution of Δq_x and Δq_z across the four quadrants for three of the conducted experiments and their corresponding linear correlation coefficients $\rho_{\Delta q_x, \Delta q_z}$. The figure shows different distribution patterns where Q_2 and Q_4 dominate in one case (Figure 4, top) and Q_1 and Q_3 prevail in others (Figure 4, middle and bottom).

We have formulated the hypothesis that the mass flux time increments could be linked to the dominating entrainment mode. With the aim of gaining insight to support the hypothesis, we analyzed the dependence of the quadrant contributions $q_{(x,m)_i}$ on the two saltation mass flux components $q_{x,m}$, indicating the saltation strength, and $q_{z,m}$, indicating the net erosion/deposition. We obtained a clear trend of $q_{(x,m)_i,a}$ with the saltation strength $q_{x,m}$, showing the contributions from Q_1 and Q_3 increasing while those from Q_2 and Q_4 decreasing (Figure 5a). We can also see that the contributions due to the positive signed quadrants $q_{(x,m)_+}$, in absolute values, tend to increase more than the negative signed quadrants $q_{(x,m)_-}$. Thus far, we have

Figure 5. (a) The mean absolute contributions $q_{(x,m),i,a}$ as a function of the saltation strength $q_{x,m}$. (b) The ratio $q_{(x,m),r}$ as a function of the saltation strength $q_{x,m}$. (c) The vertical mass flux $q_{z,m}$ as a function of the saltation strength $q_{x,m}$. (d) The ratio $q_{(x,m),r}$ as a function of the normalized vertical mass fluxes $q_{z,m}/q_{x,m}$.

shown that the entrainment mode might be linked to either $q_{(x,m)+}$ or $q_{(x,m)-}$. To represent the hypothesized saltation, dynamics in one parameter only and evaluate its dependence on the saltation strength $q_{x,m}$ we computed the ratio:

$$q_{(x,m),r} = \frac{q_{(x,m)+}}{q_{(x,m)-}} \quad (12)$$

The obtained ratio $q_{(x,m),r}$ shows a logarithmic trend with the saltation strength $q_{x,m}$ (Figure 5b). The ratio is lower than 1 for low saltation strength, larger than 1 for high saltation strength, and equal to 1 at a value of saltation strength that we defined as critical and that corresponds to $q_c = 2.7 \times 10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$. We observed $q_{x,m}$ and $q_{(x,m),r}$ to be correlated with $R^2 = 0.45$, suggesting that the quadrants representation of the mass flux time increments might be a valuable indicator of the weak and strong saltation regimes. When considering also the mean vertical mass flux $q_{z,m}$, we could clarify the link between the mass flux time increments and the net erosion. The vertical mass flux $q_{z,m}$ oscillates around zero for most of the experiments suggesting the saltation is in equilibrium (Figure 5c). Nevertheless, in two experiments (tests 4 and 5), characterized by the highest saltation strength, positive $q_{z,m}$ indicates net erosion. This indicates that although for most of the cases the saltation reaches equilibrium upstream of our measurement location, in case of high mass flux (tests 4 and 5) the saltation may reach equilibrium farther downstream, therefore revealing net erosion. With the aim of understanding the dependence of the mass flux time increments with the erosion fluxes, we employed the normalized vertical mass flux $q_{z,m}/q_{x,m}$, so as to discard any dependency on the saltation strength $q_{x,m}$, as a measure of erosion. The ratio $q_{(x,m),r}$ was observed to strongly correlate with $q_{z,m}/q_{x,m}$ with $R^2 = 0.92$. These results imply that in weak saltation, where we assumed that aerodynamic entrainment prevails, the streamwise Δq_x and the vertical mass flux time increments and Δq_z are negatively correlated (dominating $q_{(x,m)-}$), while in strong saltation, where we assumed that splash entrainment prevails, they are positively correlated (dominating $q_{(x,m)+}$). Besides the saltation strength, it is clear that the observed high $q_{(x,m)+}$ at high saltation strength can be better explained by the erosion fluxes, as erosion fluxes better correlate with $q_{(x,m),r}$ than the mass flux strength $q_{x,m}$. We have also assessed the sensitivity of the four quadrant contributions to variations of τ from 0.05 s to 2 s. We did not observe any significant change for most of the tests, while a further increase in the ratio $q_{(x,m),r}$ was observed for the two tests characterized by the highest saltation strength (tests 4 and 5). The reason for such increment can be mainly attributed to the reduced weight of the narrowest peaks, which mainly contribute to the negative quadrants (Q_2 and Q_4), but it does not alter our conclusion regarding the link between mass flux time increments and entrainment mechanism. The obtained critical saltation strength q_c is employed to subdivide the acquired time series between weak and strong saltation for the analysis that follows.

4.2. Saltation Peaks

In our previous contribution we have also noticed that the occurrence of the large saltation peaks increases with the saltation strength [Paterna et al., 2016]. Large mass flux peaks were the clearest features in strong saltation experiments, while they were less clearly visible in the experiments at lower saltation strength. Hence, we also aimed at understanding the dependence of the dynamics of the mass flux peaks on the

Figure 6. Conditional average of q_x and q_z around the (left) weakest and the (right) largest saltation peaks. The shadow envelopes show the upper and lower standard deviation from the 20 considered samples. The black solid lines indicate the mean standard deviation of all the 20 samples.

saltation strength and on the entrainment mode. In weak saltation we expected the mass flux to consist of aerodynamically entrained particles, and the resulting peaks were expected to indicate local peaks in the local particle entrainment due to random turbulence bursts. In strong saltation, where the saltation is assumed to be mainly characterized by splash entrainment, the process that brings the splashed particles to increase the mass flux up to the peak and to decrease after it is expected to be longer than any peak solely induced by the random aerodynamic flow entrainment.

For this purpose we subdivided our experiments into two subsets on the basis of the previously determined critical saltation strength q_c . We obtained a subset with weak saltation experiments ($q_{x,m} < q_c$) and a subset with strong saltation experiments ($q_{x,m} > q_c$). We then employed conditional averaging to the mass flux time series around the main peaks of the q_x time series in weak and strong saltation tests separately. The method consisted in extracting a certain number of shorter subsets of the original mass flux time series around predetermined conditioning signals. We have employed as conditioning signals the streamwise mass flux peaks that have a magnitude larger than 3 times the standard deviation measured in each time series. We applied this method separately for the two groups of weak and strong saltation regimes in order to determine a conditional average for each of the two groups. We merged the obtained subsets in each group in order to obtain two sets for strong and weak saltation, respectively. We then set a threshold that limits the number of peaks for each of the two sets to 20. In particular, we set the threshold such that 20 peaks within the weak saltation experiments, and 20 peaks within the strong saltation experiments were included. We have chosen to include 20 peaks as a trade-off between accuracy and representativeness. A smaller number of peaks would have determined a higher scatter in the conditional average while a larger number would have prevented the eduction of the largest mass flux peaks that were observed to be limited in number. Subsequently, the conditional average of q_x and q_z in a 3 s wide window around each peak was computed for both the sets and normalized with each windowed mean mass flux. Figure 6 shows the conditional average of the mass flux components around the mass flux peaks in weak (left) and strong saltation (right).

We observed that the educed mass flux peaks at weak saltation are, as expected, more compact in time than those at strong saltation. We also estimated the time duration of the peaks.

For the purpose we determined the time span of the conditionally averaged mass flux above the time-averaged standard deviation from all the 20 samples. We obtained a width of 0.2 s for the weak saltation peaks and 1.15 s for the strong saltation peaks.

Furthermore, we observed in weak saltation a slightly negative q_z around the main q_x peak. This implies that the correlation between the time increments of the two mass flux components is mainly negative around the weak saltation peaks. In case of strong saltation the vertical mass flux q_z is always positive and increases

Figure 7. Conditional average of q_x and q_z around the (left) 20 largest positive peaks of $\Delta q_x \Delta q_z$ in weak saltation tests and (right) 20 largest negative peaks of $\Delta q_x \Delta q_z$ in weak saltation tests.

toward the q_x peak. This suggests that the correlation between the time increments of the two mass flux components is mainly positive around the strong q_x peaks.

These results provide a first confirmation of the link between mass flux peaks and saltation strengths showing the prevalence of wide mass flux peaks in strong saltation and narrow peaks in weak saltation.

A further analysis in support of our hypothesis was conducted employing conditional averaging. We already observed that the positively signed quadrants increase with the saltation strength, while the negatively signed quadrants are relevant only in weak saltation. With the help of this information, we conditionally averaged the mass flux time series around the peaks in the product $\Delta q_x(t, \tau) \Delta q_z(t, \tau)$, with $\tau = 0.05$ s. Similarly to the previous conditional averages around the q_x peaks, we determined for each time series the $\Delta q_x \Delta q_z$ peaks that have a magnitude larger than 3 times the standard deviation of the time series. We then merged the obtained subset in order to obtain two sets for strong and weak saltation, and each of them was further subdivided in positive and negative signed quadrants. We again applied arbitrary thresholds such that the 20 largest peaks in each of the four subsets were included. Similarly to the previous analysis, the conditional average was determined around a 3 s wide window. In weak saltation tests, when the mass flux was educed around negative peaks of $\Delta q_x \Delta q_z$, we observed short saltation peaks characterized by negative q_z (Figure 7, right). The duration of these events is observed to be similar to that of the conditionally averaged weak saltation peaks (Figure 6, left). A clear difference with respect to the former case is that in this case the negative q_z around the q_x peak is more clearly observed, as a result of having chosen the negative peak of $\Delta q_x \Delta q_z$ as triggering event for the conditional average. We also determined the conditionally averaged mass flux around positive peaks in $\Delta q_x \Delta q_z$ (Figure 7, left). The resulting educed mass flux structures are also similarly compact in time as in the case of those educed around negative peaks of $\Delta q_x \Delta q_z$; however, in this case both q_x and q_z , as expected, show a positive peak.

The conditional average applied to all the weak saltation peaks (Figure 6, left) suggests that negative correlation is the most relevant case and might translate into prevailing aerodynamic entrainment. Nevertheless, the existence of positive correlations cannot be ignored. This shows that ejection of a small number of particles still occurs even during weak saltation but the ejection dynamics does not show a significant growth.

In strong saltation tests, when the mass flux time series are conditionally averaged around positive peaks of $\Delta q_x \Delta q_z$, we observed significantly wider mass flux peaks having positive q_x and q_z , as expected (Figure 8, left). On the other hand, the educed mass flux time series around negative peaks of $\Delta q_x \Delta q_z$ also show a wide peak with closely matching normalized q_x and q_z except close to the peak, where the vertical mass flux reduces before and increases after the peak (Figure 8, right). This produces a negative correlation of the mass flux time increments only in the closest proximity of the peak and a positive correlation in the remaining larger part of

Figure 8. (left) Conditional average of q_x and q_z around the 20 largest positive peaks of $\Delta q_x \Delta q_z$ in strong saltation tests. (right) Conditional average of q_x and q_z around the 20 largest negative peaks of $\Delta q_x \Delta q_z$ in strong saltation tests.

the peak. The overall contribution of such inner negative peak must be minimal if we recall the overall conditional average determined around the large peaks in strong saltation which shows positive peaks in q_x and q_z (Figure 6, right).

These results suggest that the observed positively correlated mass flux time increments in strong saltation might be linked to dominating splash entrainment (Figure 8, left). Nevertheless, the observation of minor narrow negative peaks might reveal the occasional combination of aerodynamic entrainment (near the peak) and splash entrainment mechanisms (Figure 8, right).

The observations obtained by means of conditional averaging therefore give support to our initial hypothesis. These results confirm the link between mass flux peaks and saltation strength revealing dominating large mass flux peaks in strong saltation and smaller peaks in weak saltation. Furthermore, they significantly support the hypothesis that in strong saltation the large saltation peaks are mainly linked to splash entrainment and in weak saltation to aerodynamic entrainment. They also suggest that such large saltation events are due to net surface erosion. Nevertheless, we should not intend the two saltation regimes as absolute categories. Although in strong saltation splash entrainment is hypothesized to be the prevailing entrainment mechanism, aerodynamic entrainment might also still occur, and the opposite might result in weak saltation.

4.3. Saltation Growth Rates

A further clear difference between the educed mass flux peaks in strong and weak saltation lies in the growth rate of the mass flux around the peaks. The peaks conditionally averaged in weak saltation show a growth rate significantly larger than the peaks observed in strong saltation. This suggests the presence of different mechanisms sustaining saltation in the two saltation regimes. To understand the reasons for such difference, we qualitatively modeled the normalized conditionally averaged mass flux $q_{x,ca}(t)$ around the peaks on the basis of the ejection function e_f . The ejection function corresponds to the mean number of ejected particles at each particle bed collision, therefore characterizing the splash entrainment process. Our modeled conditional average is therefore defined as

$$q_{x,ca}(t + \tau) = q_{x,ca}(t) e_f^{\tau/T_q} \quad (13)$$

where τ is the time increments between two consecutive mass flux realizations with $\tau = 0.05$ s. The saltation timescale T_q is defined as follows:

$$T_q = \frac{L_q}{\bar{U}} = \frac{(3.45u_* - 0.36)}{\bar{U}} \quad (14)$$

where L_q is the saltation length scale, parameterized according to *Sato et al.* [2004], $\bar{U}$ is the mean streamwise flow velocity in the saltation layer where the mass flux is determined, and u_* is the friction velocity, obtained by applying equations (1)–(7).

Figure 9. Measured (black solid line) and modeled (blue solid line) conditional average of the mass flux peaks during (left) weak and (right) strong saltation.

We have considered the conditional average $q_{x,ca}$ around all the weakest and strongest saltation peaks (Figure 6) and compared it with the modeled conditional average $q_{x,ca}$ based on equation (13). Due to the observed short duration of weak saltation peaks, that brings the saltation time series to be discontinuous, we expected that in case of sharp transition between no particles at time $t - \tau$ and a few particles at t or vice versa the resulting mass flux time increments Δq_x would be high. In contrast, in strong saltation, for a significant fraction of time, the saltation will have lower Δq_x due to the splash entrainment process. The ejection function e_f , given by the number of particles ejected per impacting particles, is expected to be proportional to Δq_x , therefore lower in case of splash entrainment. This method, although it does not accurately determine the ejection function, helps us to recognize the splash entrainment time fraction in our tests and to test our main hypothesis of a link between entrainment dynamics and saltation strength. We observed that the best agreement between model and experiments requires $e_f = 3.33$ in weak saltation and $e_f = 1.37$ in strong saltation (Figure 9). Previous studies have presented experimentally determined values of $e_f = 0.25 \div 1.75$ for splash entrainment of fresh snow with $u_* = 0.17 \text{ m s}^{-1}$ [Sugiura and Maeno, 2000]. The value of ejection function we have determined in strong saltation peaks is therefore in the range of what already measured in splash saltation for snow saltation. This clearly further support our hypothesis that the large peaks in strong saltation are caused by splash entrainment. On the other hand, in weak saltation, the conditionally averaged peak is best fitted by a value of e_f larger than 3, which appears not to be compatible with the mass flux growth rate induced by the splash entrainment process. We therefore argue that in weak saltation the observed peaks mainly derive from pure aerodynamic entrainment of sparse particles or groups of them.

5. Conclusions

We have conducted wind tunnel measurements of the snow saltation mass flux with an optical measurement technique and conducted time series analysis to obtain a better understanding of the saltation dynamics. In particular, we aimed at further investigating whether the two main saltation regimes, weak and strong saltation, respectively, which are the basis of the equilibrium saltation model of Doorschot and Lehning [2002], can clearly be distinguished from the wind tunnel experimental data.

We have at first hypothesized, on the basis of particles kinematics, that we can distinguish the two main entrainment modes by employing joint probability distributions of the time increments of the two mass flux components. This led us to further develop our understanding of the dependence of the entrainment mode on saltation strength. We observed that positive (negative) signed quadrants increase (reduce) with the saltation strength and that at the critical saltation strength the two are equal. This provides a further argument to support our main hypothesis that the probability of occurrence of splash entrainment increases with the saltation strength. We therefore subdivided the tests based on the critical strength and defined strong saltation tests those with strength larger than the critical value and weak saltation tests those having strength smaller than the critical strength.

We also noticed that the mass flux time increments strongly correlate with the erosion fluxes, suggesting the dependence of the latter on both the saltation and the erosion strength. Although the link between mass flux time increments and the structure of saltation can still be explained by the saltation strength in our conducted experiments, they appear to be more universally explained by the erosion and deposition fluxes when extrapolating the results to any snow saltation process that is near equilibrium.

We also investigated the saltation dynamics by considering the saltation peaks and their possible link to the prevailing entrainment mode. We have shown that the saltation peaks in strong saltation are significantly wider than those in weak saltation and that they are mainly characterized by positively correlated mass flux time increments, a signature that was previously attributed to the splash entrainment mechanism. Conversely, the peaks in weak saltation show mainly negatively correlated mass flux time increments, a signature that was linked to prevailing aerodynamic entrainment.

Furthermore, we analyzed the mass flux growth rate during saltation peaks on the basis of the number of ejected particles from particle bed collision. As a further confirmation of our main hypothesis we observed that the large mass flux peaks in strong saltation are compatible with splash entrainment and that the time fraction of their occurrence grows with the saltation strength.

We have deduced from our tests that aerodynamic entrainment might not be negligible in snow saltation, in contrast to what is often observed in sand saltation. We argue that the main difference between snow and sand saltation relies on the cohesion of the erodible material, which is higher in snow than in sand and alters the erodibility of the material at the surface [Comola and Lehning, 2017]. The snow cohesion might be responsible for a higher resistance of the surface to be eroded by splash entrainment because momentum of impacting particles is lost. Additionally, the larger drag of the snow particles might enhance the aerodynamic entrainment therefore reducing the relative contribution of splash entrainment. Overall, we present a very detailed quantitative analysis of snow saltation together with the data [Paterna and Crivelli, 2016] that will be useful to test current and future models of saltation.

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