Shadowgraphy Measurements of Snow Particle Sizes in Saltation

Shadowgraphie Messungen von Schneepartikelgrößen in Saltation

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Key words: particle sizes, snow, saltation, snow transport, shadowgraphy
Schlagworte: Partikelgrößen, Schnee, Saltation, Schneetransport, Shadowgraphie

Abstract

Shadowgraphy was employed to study the size characteristics of wind transported snow particles during saltation. The experiments were performed with fresh and naturally deposited snow under controlled flow conditions in the boundary layer wind tunnel of the Institute for Snow and Avalanche Research SLF in Switzerland. The shadowgraphy method enabled for a temporarily and spatially highly resolved investigation of snow particle characteristics within a measurement area of up to 50 x 50 mm^2.
The following observations were made for the snow particle size characteristics and their variation with height in the saltation layer: (i) the particle number decreased exponentially with height, (ii) the particle mean diameter was fairly constant with a very slight tendency to decrease with height, (iii) the particle maximum diameter decreased linearly with height, and (iv) the snow particle size distribution could be adequately described by gamma probability density functions. The shape and scale parameter of the gamma distribution varied systematically with height over ground where the shape parameter increased and the scale parameter decreased with height.

Introduction

The saltation layer encompasses the lower 50 (100) mm directly above the snow surface and the particle movement within is adequately described by ballistic trajectories. The study of saltation is highly relevant for the process of snow redistribution itself and subsequent processes like e.g. avalanches or melt water runoff since it accounts for the majority of the total transported snow mass during low to moderate wind speeds and constitutes a lower boundary condition for the transport by turbulent suspension during high wind speeds. It is estimated that 50 to 75% of the total mass of transported snow is accomplished by saltation and Liston and Sturm (1998) state that for shear velocities below approximately 0.45 ms^{-1} the transport of snow by saltation is larger than that by turbulent suspension.

Since the saltation layer depth is comparatively large or small relative to the measurement area and detection resolution of the instruments usually employed in studies of drifting snow, e.g. Snow Particle Counter SPC (Sato and Kimura 1993), compartment traps (e.g. Schmidt 1986), or the FlowCapt sensor (Chritin et al. 1999), a detailed height-resolved analysis of the saltation layer structure is difficult or even impossible to achieve. This explains why the height variation of snow particle size characteristics or dynamics in saltation layers have been addressed only in a very limited number of studies. Sugiura et al. (1998) measured particle size distributions and snow mass fluxes at different levels between 16 and 61 mm above the snow surface for different shear stress velocities in a cryospheric wind tunnel. Their results show an increase in the frequency of smaller particles and an exponential decrease in the snow mass flux with height. Nishimura and Hunt (2000) and Gordon et al. (2009) report exponentially decreasing snow mass concentrations for the saltation layer.
In this work shadowgraphy was employed to study snow particle size characteristics and their variation with height in the saltation layer. The novelty of this study is a so far unprecedented detailed height-resolved analysis with the aim to contribute to a better understanding and improved modelling of snow transport.

Experimental Setup and Measurement Technique

The snow drift experiments were performed in the boundary layer wind tunnel of the WSL Institute for Snow and Avalanche Research SLF in Davos/Switzerland. It is accommodated in a non-heated building at 1650 m a.s.l. For the experiments, 8 m long and 1 m wide snow packs of approximately 0.10 m thickness were placed in the test section (see Fig. 1 in Gromke et al. 2011). The snow packs were assembled by trays of 2 m length and 1 m width. Prior to each experiment, the trays were placed outside the building in a wind sheltered and sun shaded area so that, during a snowfall, they are homogeneously filled with naturally deposited snow (see Fig. 2 in Gromke et al. 2011). The trays were then carefully positioned in the wind tunnel test section and flush mounted to the level of the upwind smooth floor fetch by means of lifting tables.
In total four erosion experiments organised in two measurement series with different snow packs were performed. In each measurement series two experiments with the same snow pack were performed for constant free-stream velocities U_δ. Each experiment was subdivided into three recording sequences between which the camera position was traversed along a vertical axis to capture the entire saltation layer with an estimated height of 100 mm by the given field of view with 50 mm vertical extent. The decrease of the snow surface height by erosion during an experiment was accounted for in the subsequent evaluation by linearly distributing the snow surface height difference between the first and the last image of a recoding sequence. A more detailed description of the experiments and the measurement procedure can be found in Gromke et al. 2014. Tab.1 provides an overview of the experiments boundary conditions and settings.

experiment label	U_δ [m/s]	T_{air} [°C]	grain size* [mm]	#frames [-]	rec. time [s]	FoV** [mm]
exp. 1a	10.0	-1.4 ± 0.1	0.5 – 2.0	1500	30	50 x 50
exp. 1b	9.5	-1.4 ± 0.1	0.5 – 2.0	3000	60	50 x 50
exp. 2a	9.0	-4.5 ± 0.2	0.5 – 2.0	6000	120	25 x 50
exp. 2b	10.0	-4.5 ± 0.2	0.5 – 2.0	6000	120	25 x 50

Tab. 1: Experiment boundary conditions and settings; *initial grain size of snow pack before erosion experiment; **FoV: Field of View (horizontal x vertical).

For the recording of snow particle size characteristics a shadowgraphy system consisting of a diffuse area light source and a CMOS-camera (LaVision 2010) was employed (Fig. 1a). The CMOS-camera recorded shadow images of the snow particles passing the illuminated volume with an aperture exposure of 10000^{-1} s and a frame rate of 50 Hz where the smallest resolvable particle dimension was approximately 0.05 mm. The image recording was controlled in the DaVis 8 hardware and software environment (LaVision 2011a).
The image processing and basic evaluation was performed in the software environment DaVis 8 (LaVision 2011b). The basic steps together with recommendations for the choice of parameter settings required in the image processing and evaluation are described in the supplier's shadowgraphy manual (LaVision 2011c). A sensitivity analysis was performed to assess the influence of the parameter settings used for image processing and evaluation on the outcomes. It was found that the parameter settings strongly affected the number of detected particles but did only marginally impact the statistics of the particle size characteristics and hence were without consequences for the scope of this study. A Depth of Field Correction DoF was applied to correct for the depth dependency of the focal plane on particle size. For more information about the image processing and evaluation, the sensitivity analysis and the Depth of Field Correction DoF, the reader is referred to Gromke et al. 2014.
Fig. 1b shows a processed and evaluated shadowgraphy image. The first 100 mm above the snow surface accommodating the saltation layer were subjected to the analysis. This area was subdivided into 20 height-level intervals of 5 mm where the lowest height-level (0 to 5 mm) was excluded since it was covered by the snow surface behind the focal plane on the images (Fig. 1b).

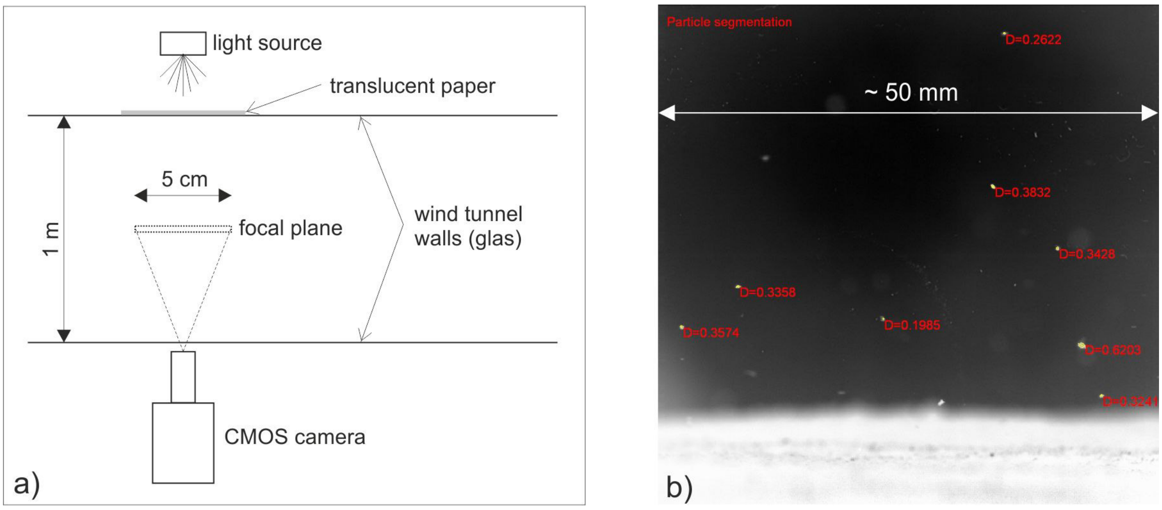

Fig. 1: Measurement setup and processed and evaluated shadowgraphy image.

Results and Discussion

The particle number per height-level normalized by the maximum particle number in the 5 to 10 mm height-level (lowest evaluated height-level) is presented in Fig. 2. As can be seen, the particle number decreases rapidly with height and suggests to follow an exponential relation. At a height of approximately 45 mm, the particle number is diminished to approximately 1 to 3% of that in the near surface 5 to 10 mm height-level. The larger scatter in the upper height-levels ($z > 75$ mm) is due to the small numbers of particles detected which do not provide a sufficiently large data basis to be statistically representative. The discontinuities in the particle number between the height-levels between 35 and 50 mm and between 70 and 85 mm are due to the different saltation activities during the recording sequences. To this end, only the data of the first recording sequence ($z < 45$ mm or smaller) from each experiment were employed to determine a functional relationship for the snow particle number variation with height according to

$$n^+(z) = \frac{n(z)}{n(z_{ref})} = \exp\left(-\lambda\left(\frac{z}{z_{ref}} - 1\right)\right) \tag{1}$$

where $n^+(z)$ is the normalized particle number at height z, n(z) the particle number at height z, z_{ref} the reference height (here z_{ref} = 7.5 mm). The exponential decay parameter λ was determined by regression analysis to λ = 0.86, 0.83, 0.84 and 0.70 for exp. 1a, exp. 1b, exp. 2a and exp. 2b, respectively, where the coefficient of determination R^2 was always large than 0.90. It is acknowledged that the obtained λ values are specific for the present experiment boundary conditions; they depend in particular on the chosen reference height z_{ref}. However, they indicate the range in which the decay parameter may be expected to lie in. Moreover, the similar values obtained for the first measurement series suggest that the decay parameter λ does not strongly depend on the saltation activity which was very different for exp. 1a and exp. 1b where a factor of 59 in the quantity of detected particles during the first recording sequences, i.e. at the lowest camera position, was found.
The exponential decrease in particle number with height in the saltation layer is corroborated by wind tunnel experiments of Nishimura and Hunt (2000). In contrast, Guala et al. (2008), suggest a power law to describe the particle number variation with height. A more elaborate analysis and discussion on the particle number variation with height in a general context as well as in the specific context of the present wind tunnel experiments is provided in Gromke et al. 2014.

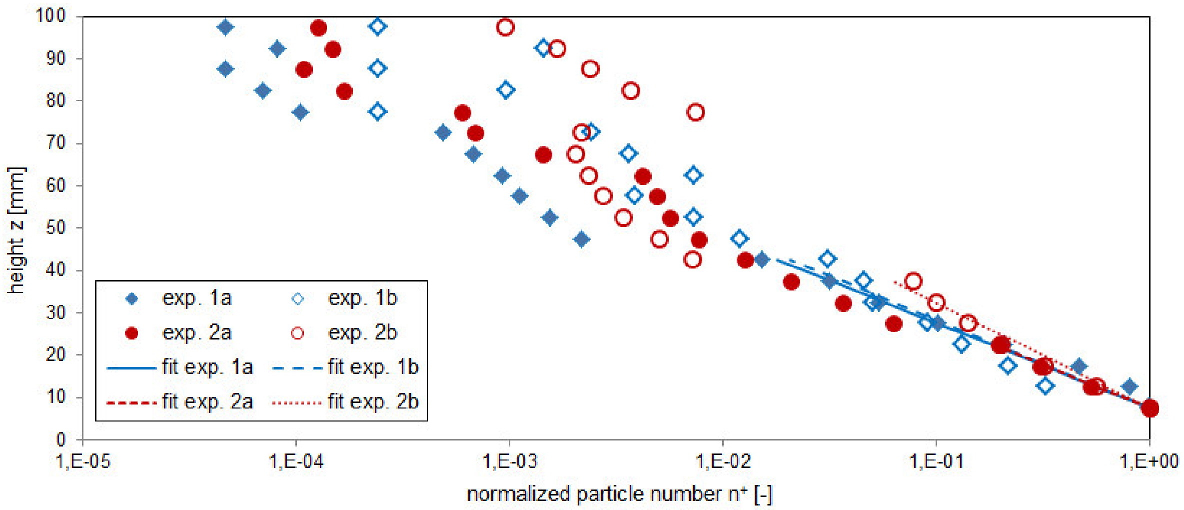

Fig. 2: Normalized particle number n^+ variation with height z above ground.

Fig. 3 shows snow particle size characteristics in the lowest 100 mm above ground for exp. 1a as an example. The diagram reveals an overall fairly height-independent snow particle mean diameter and standard deviation where the standard deviation is approximately 50% of the mean diameter. In contrast, the diagram shows the snow particle maximum diameter to decrease roughly linearly with height. At the lowest height-levels, the maximum diameters are multiple times (~ 5 to 7) larger than the mean diameter. The variation of the particle size characteristics of the remaining three experiments exhibit the same properties and are not shown here. They can be found in Gromke et al. 2014.

These findings are partly in contrast with observations made by Nishimura et al. (1998) and Sugiura et al. (1998) who, using Snow Particle Counters (SPC), report an increase in the share of small particles and a decrease of the snow particle mean diameter with height. The phenomenological difference may be attributed to the resolution of the CMOS-chip (0.05 mm) in combination with the image processing and evaluation employed in this study which did not allow to resolve the smallest particle sizes in such a detail as the SPC did, and / or due to the different snow particle characteristics in their and our experiments. Furthermore, since the data of Sugiura et al. (1998) show a less pronounced increase in the share of small particles at lower heights for larger free-stream and friction velocities, the question arises whether the observation of an increasing share of small particles with height is a feature of the saltation layer or of the suspension layer which blend into each other. The reader is referred to Gromke et al. 2014 for a more in-depth discussion of the above issue.

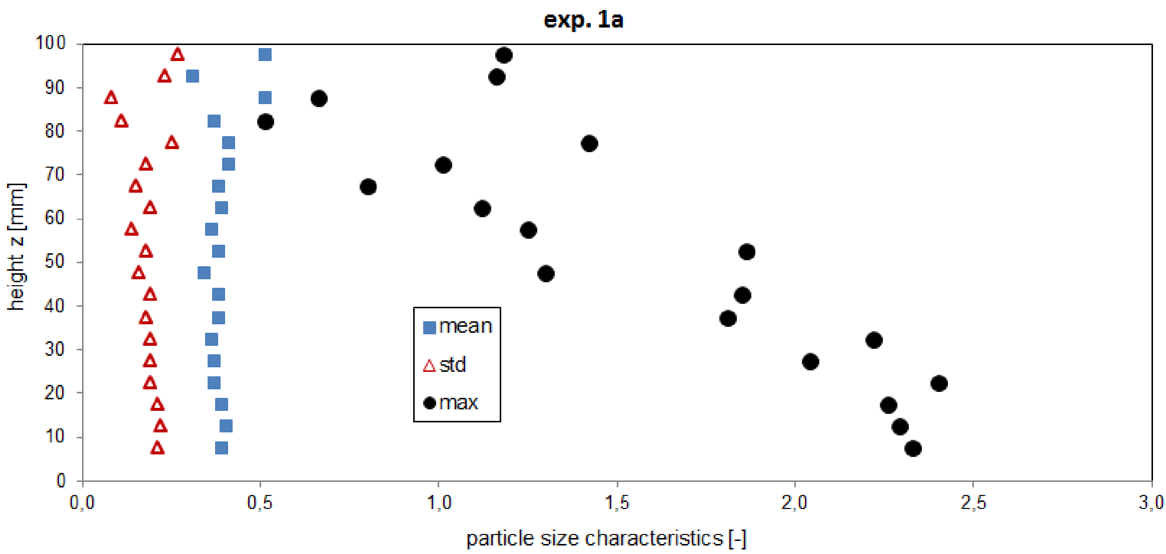

Fig. 3: Particle size characteristics with height z for experiment “exp. 1a”.

The values for the snow particle size characteristics obtained within this study are, of course, specific for the boundary conditions before and during the experiments. It is evident that different snow pack characteristics, atmospheric and topographic conditions (age of snow, crystal form and size, air temperature, wind speed and length of saltation fetch) result in different mean diameters, standard deviations and maximum diameters of saltating snow particles. In particular the length of the saltation fetch and therefore the average number of snow particle rebounds are hypothesized to have an influence on the snow particle size characteristics. However, the fundamental characteristic of a linearly with height decreasing snow particle maximum diameter appears to be independent of all influencing factors. This motivated to plot the particle maximum diameter $d_{max}(z)$ normalized by the saltation layer height-independent particle mean diameter d_{mean} versus the height z above ground normalized by a certain reference height h_{ref}. For the reference height h_{ref}, the height above ground where the saltation activity expressed by the number of particles has dropped to 1% of that in the lowest height level, i.e. 5 to 10 mm.
Fig. 4 presents the normalized particle maximum diameters $d^+_{max}(z)$ over height for all the experiments performed within this study. The collapse of the data points on a straight line in turn motivated to formulate a linear relationship according to

$$d^{+}_{max}(z) = \frac{d_{max}(z)}{d_{mean}} = a_1 - a_2 \frac{z}{h_{ref}} = a_1 - a_2 z^{+} \quad (2)$$

where a_1 and a_2 are coefficients which, using a least square fit, were determined to $a_1 = 6.53$ and $a_2 = 2.50$ with a coefficient of determination $R^2 = 0.74$. However, the decrease of the particle maximum diameter does not translate into a reduction of the particle mean diameter with height.

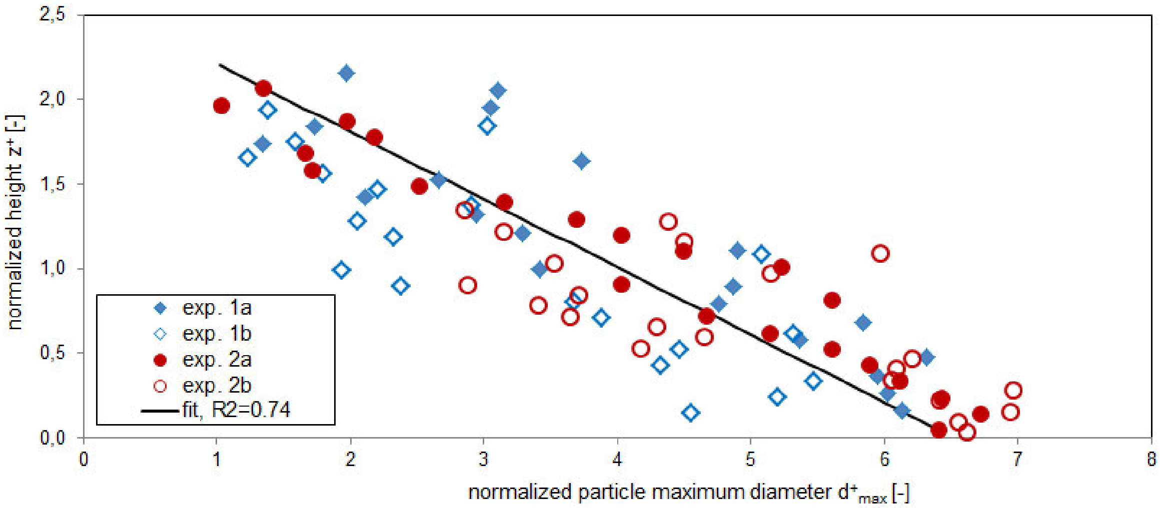

Fig. 4: Normalized particle maximum diameter variation with height z.

In the remainder of this contribution, the snow particle size distribution is analysed and discussed. For each height-level, the snow particle sizes were sorted into size classes of 0.1 mm bin size and various statistical distributions were fitted. It was concluded that the two parameter gamma probability density function according to

$$\mathrm{pdf}(d) = \frac{1}{\beta^{\alpha}\,\Gamma(\alpha)}\, d^{\alpha-1} \exp\left(-\frac{d}{\beta}\right) \quad (3)$$

pertinently fitted the measured snow particle size distribution of every height-level in the saltation layer where d is the particle diameter, α is the shape parameter, β is the scale parameter (with $d_{mean} = \alpha * \beta$) and Γ is the gamma function.

Fig. 5a and 5b show the height variation of the shape and scale parameter, α and β, respectively. As can be seen, the shape parameter shows a general tendency to increase with height and the scale parameter shows a general tendency to decrease with height. The stronger scatter of both parameters in the upper height-levels is due to the relatively small number of snow particles which strictly prevents a reliable estimation of both parameters.

Regarding the saltation layer, only few studies have reported shape parameters and the documentation of scale parameters is completely unknown to the authors. Nishimura and Nemoto (2005) report values for α of around 3 for friction velocities $u_* = 0.28 - 0.56\ ms^{-1}$ and of around 5 for $u_* = 0.21\ ms^{-1}$ from field measurements. Gordon and Taylor (2009) found values for α of 1.4 and 2.25 also in field measurements. The deviation to this study may be, next to different snow pack characteristics, attributed to the presence of a much longer fetch in the field and larger number of particle rebounds which resulted in different snow particle size characteristics. In particular the smaller shape parameters α found in the field studies are attributed to the larger number of rebounds whereby the fragile dendritic arms of the snow crystals break away and rather spherical or ellipsoidal ice cores remain with a more narrow size distribution, see Gromke et al. (2014) for further analysis.

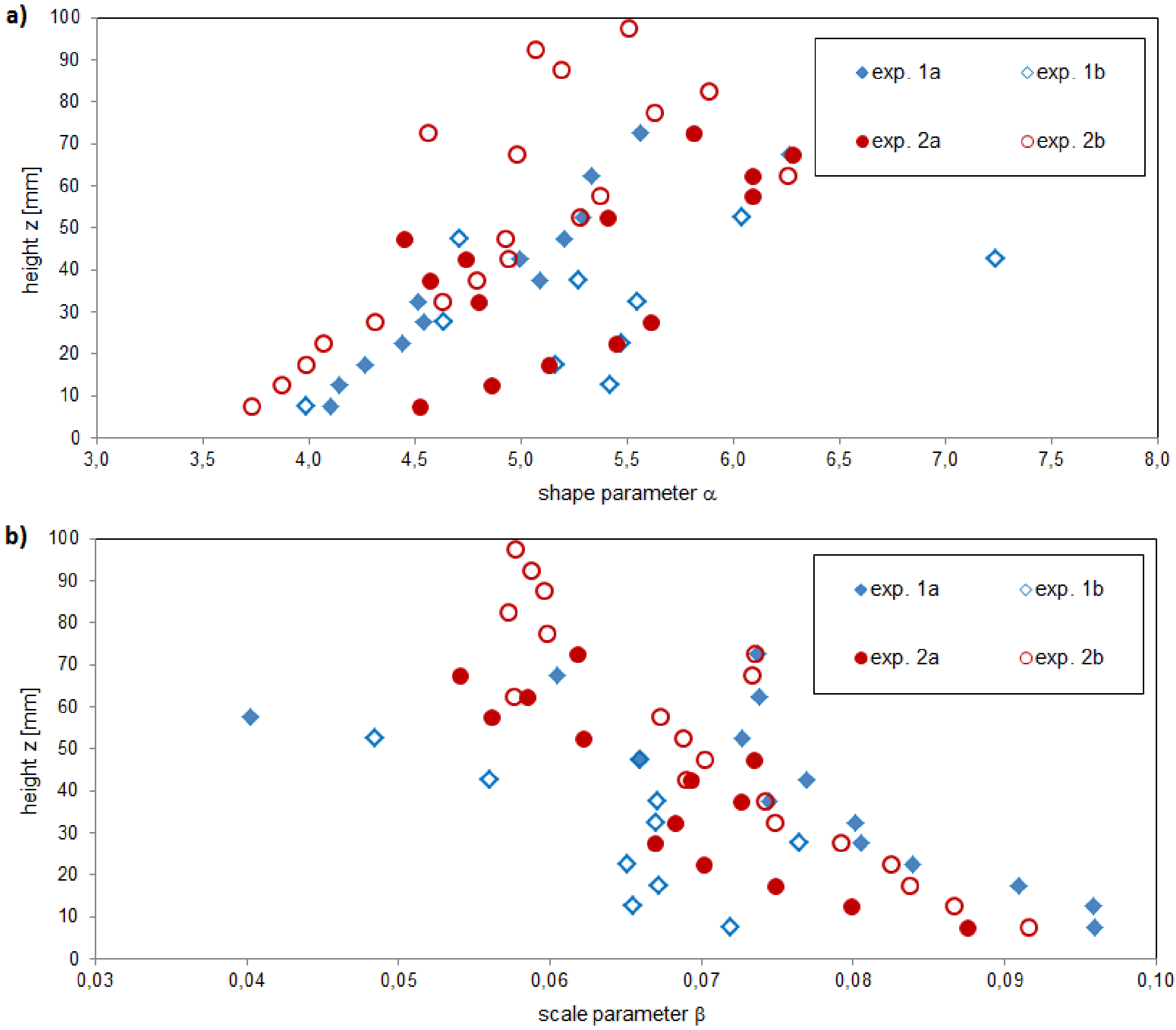

Fig. 5: Vertical variation of shape parameter α and scale parameter β of the gamma probability distribution function.

Conclusions and Outlook

Shadowgraphy was employed to study snow particle size characteristics in the saltation layer in wind tunnel experiments with fresh and naturally deposited snow. Vertical profiles of particle number, particle size characteristics, and particle diameter distribution were analysed. Functional relationships for the particle number variation with height (Eq. 1) and the variation of the snow particle maximum diameter with height (Eq. 2) were established. It is acknowledged that the universality of the parameter values in the functional relationships still requires clarification. The present data set is too limited to allow for general conclusions and hence it is not identified to what extend the herein found parameter values depend on the specific snow pack and boundary conditions of our experiments.
The analysis outcomes of the shadowgraphy recordings in terms of snow particle size characteristics was fairly independent of the image processing and evaluation settings used. This suggests shadowgraphy to be a robust method for the analysis of particle size characteristics of snow in saltation, or more general, of drifting and blowing snow. In comparison to Snow Particle Counters (SPC), shadowgraphy allows also to detect larger snow particles. Further-

more, compared to conventional snow particle count and size measurement techniques, it is a volume measurement technique with a high resolution in space and time. This enables the study of so far unexplored drifting and blowing snow characteristics, e.g. the exploration of coherent particle movements. Next to the study of snow particle size characteristics, shadowgraphy bears the potential to be extended to the investigation of aeolian sediment transport of other earth surface materials, e.g. soil and sand grains.

Acknowledgement

The authors are indebted to the Swiss National Science Foundation (SNF) for the measurement equipment grant (R'Equip grant No. 206021_133786). Thanks also to the SLF workshop for support in the installation of the measurement equipment.

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