Size distribution, Schmidt number and terminal velocity of blowing snow particles in the French Alps : comparison with previous studies

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ABSTRACT: Wind-transported snow is a common phenomenon in French Alps, creating snowdrifts and contributing significantly to the loading of avalanche release areas. The wind erodes snow from high wind speed areas and deposits it in low wind speed areas. The resulting snowdrifts often cause problems for infrastructure and road maintenance and contribute significantly to the loading of the avalanche release area. Numerical blowing snow model can be a useful tool to investigate this phenomena but they need input parameters such as size distribution of snow particles (Vionnet et al., 2013), Schmidt number and terminal snow particles velocity (Michaux et al., 2001) (Naaim-Bouvet et al., 2000) (Naaim-Bouvet et al., 2008). Some studies have already been conducted to address the size distribution of snow particles at a given height (Budd (1966), Schmidt (1982), Nishimura and Nemoto (2005), Gordon and Taylor (2009)). Such data could depend on topography and snow type and all of these studies have been conducted under different conditions than those encountered in the Alps.
Consequently, the present study was carried out at the Lac Blanc Pass (2700 m), an experimental site in the French Alps, using three snow particles counter set up at different heights. Such optical devices are able to detect particles between 20 and 500 µm in mean radius size particle, divides them into 32 classes. In the main cases and as usual, the size distribution of snow particles is represented by a gamma density function. The Schmidt number, the shape parameter and the mean particle diameter were studied as function of height, friction velocity and the results were compared with previous studies.

KEYWORDS: Snow, wind, drifting snow, blowing snow, model, sensor.

1 INTRODUCTION

Wind-transported snow is a common phenomenon in French Alps, creating snowdrifts and contributing significantly to the loading of avalanche release areas. The wind erodes snow from high wind speed areas and deposits it in low wind speed areas. The resulting snowdrifts often cause problems for infrastructure and road maintenance and contribute significantly to the loading of the avalanche release areas. Numerical blowing snow models can be useful tools to investigate this phenomena but they need input parameters such as size distribution of snow particles (Vionnet et al., 2013), Schmidt number and terminal snow particles velocity (Michaux et al., 2001) (Naaim-Bouvet et al., 2000) (Naaim-Bouvet et al., 2008). Some studies have already been conducted to address the size distribution of snow particles at a given height (Budd (1966), Schmidt (1982), Nishimura and Nemoto (2005), Gordon and Taylor (2009)). Such data could depend on topography and snow type and all of these studies have been conducted under different conditions than those encountered in the Alps. That's why we chose to conduct similar experiments in the French Alps, at Lac Blanc Pass (2700 m), an experimental site in the French Alps, during winter 2010-2011.

The paper is organized as follows. Section 2 describes the experimental site and related sensors necessary to measure size distribution and to estimate Schmidt number and terminal velocity. Section 3 focus on results obtained during heavy drifting snow events which occurred on February and March 2011.

2 DESCRIPTION OF THE SITE AND AVAILABLE INSTRUMENTATION

2.1 Observational site :Lac Blanc Pass

The experimental site (Figure 1) is located at the Alpe d' Huez ski resort near Grenoble, France. The large north–south-oriented pass (Col du Lac Blanc) has been dedicated to the study of blowing snow in high mountainous regions for approximately 25 years by IRSTEA –

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previously Cemagref (Snow Avalanche Engineering and Torrent Control Research Unit) and Meteo France (Snow Study Centre). The area consists in relatively flat terrain on a length of about 300 meters (Figure 1). Then the slope becomes steeper both in northern and southern parts of the place. In the eastern part of the site stands an high alpine range called “Grandes Rousses” (Figure 2) culminating at about 3500 meters (Pic Bayle), whereas a lower summit (Dome des Petites Rousses) lays on the West. The pass orientation and the specific configuration of the “Grandes Rousses” range make the pass very close to a wind-tunnel (Naaim-Bouvet et al., 2000). North-East or South stands for 80% of the wind directions.

Figure 1. Lac Blanc Pass (Dôme des Petites Rousses in the background)

Figure 2. Turbulent diffusion on the “Grandes Rousses” range. Photo is taken from Lac Blanc Pass.

2.2 Sensors and measurements

Three snow particle counters (SPC-S7, Niigata electric) (Sato et Kimura, 1991) are mounted on a 3 m vertical mast which aims at better investigate drifting snow flux profiles (Figure 3 – left side). SPC (Figure 3 – right side) is an optical device in which the diameter and the number of blowing snow particles are detected by their shadows on photosensitive semiconductors. It detects particles between 50 and 500 µm in size particle, divided into 32 classes and allows to calculate the horizontal snow mass flux assuming spherical snow particles (equation 1).

$$Flux = \sum Flux_D = \sum n_D \frac{4}{3}\pi\left(\frac{d}{2}\right)^3 \rho_p \qquad (1)$$

where $Flux_D$ is the horizontal snow mass flux (kg.m^{-2}.s^{-1}) for the diameter D, n_D is the number of drifting snow particles, S the sample area (m²), t the sample period (s), and ρ_p the density of the drifting snow particles (917 kg m^{-3}).

One SPC was set up at a fixed position (4.4 m above the ground). Two others were set up near the snow pack surface. A fixed distance of one meter separates them. They could be raised manually when the snow depth increases and buries the sensors. A Jenoptik SHM30 laser snow depth (Figure 3 – left side) measured the exact position of the SPC above the snow pack due to the low laser divergence (0.6 mrad). An heated ultrasonic anemometer (USA1 – Metek) supplemented these devices : short pulses of ultrasonic sound are exchanged on three different directions by couples of sound probes which are used alternately as transmitting and receiving units so that a 3-dimensional wind vector can be determined. Turbulence variables as variance, covariance, heat and momentum flux are calculated on-line. Friction velocity is calculated by the eddy correlation method (equation 2)

$$u_* = (\overline{u'v'}^2 + \overline{v'w'}^2)^{1/4} \qquad (2)$$

where u_* is the friction velocity (m.s^{-1})and u', v' and w' (m.s^{-1}) are fluctuating velocity components.

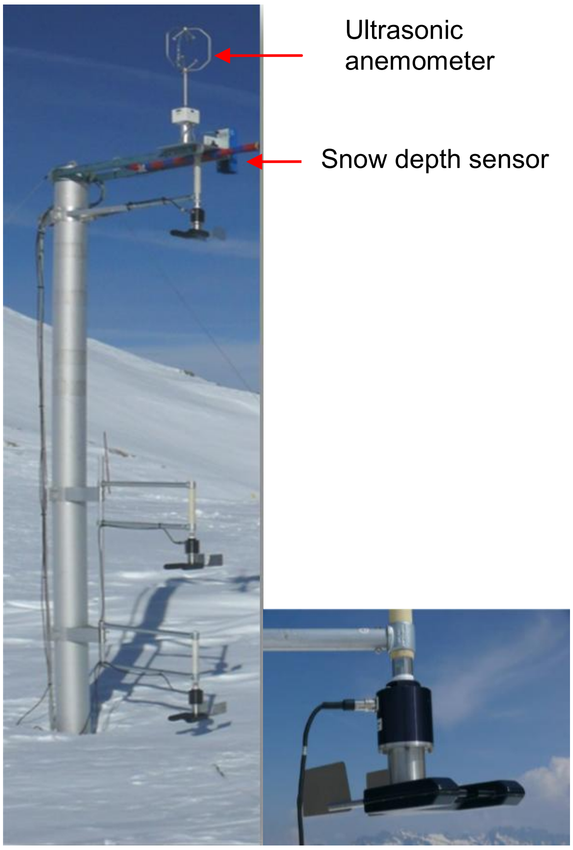

Figure 3. On the left side : the mast with 3 Snow Particles Counters, one snow depth sensor and an ultrasonic anemometer. On the right side a close up of Snow particle Counter

3 RESULTS OBTAINED DURING WINTER 2010-2011

3.1 Choice of events

We focused on events during which no snow-fall occurred. For that purpose we first develop a method using the concomitant analysis of wind speed, snow flux, mean diameter of particle measured by a SPC (Snow particle Counter) to detect blowing snow event with and without precipitation over a winter season (Naaim-Bouvet et al., 2013, submitted). Then samples with less than 120 particles $.cm^{-2}.min^{-1}$ are rejected to treat data statistically significant. If the highest SPC did not record more than 120 particles $.cm^{-2}.min^{-1}$, the 3 samples (corresponding to the three SPC) are not included in the present analysis. If the diameter of a snow particle is larger than the maximum diameter class, the snow particle is considered to belong to the maximum diameter class (500 µm). Consequently mass flux and mean diameter are underestimated. We chose to reject samples with more than 2,5% of particles in the upper bin to avoid biases in the analysis.

Between January and March 2011, only 2 major events satisfied these conditions :

-23-26 February 2011 (Event n°1) and 17-19 March 2011 (Event n°2).

There are similar events with intensive North wind and fresh snow. This is the most frequent type of events encountered at Lac Blanc pass. Only the first event will be introduced in this paper. The second one gave similar results.

3.2 Particle size distribution

The size distribution of snow particles at a given height is usually (Nishimura and Nemoto, 2005) represented by a gamma density function where *D* denotes the particle diameter, *α* is the shape parameter determining the skewness and *β* is the scale parameter determining the width/scale of the distribution. *α β* is equal to the mean and α β ² is equal to the variance.

$$f(D) = \frac{d^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)}\exp(-\frac{\beta}{D}) \qquad (3)$$

α and *D* allow to fully characterize the particle size distribution

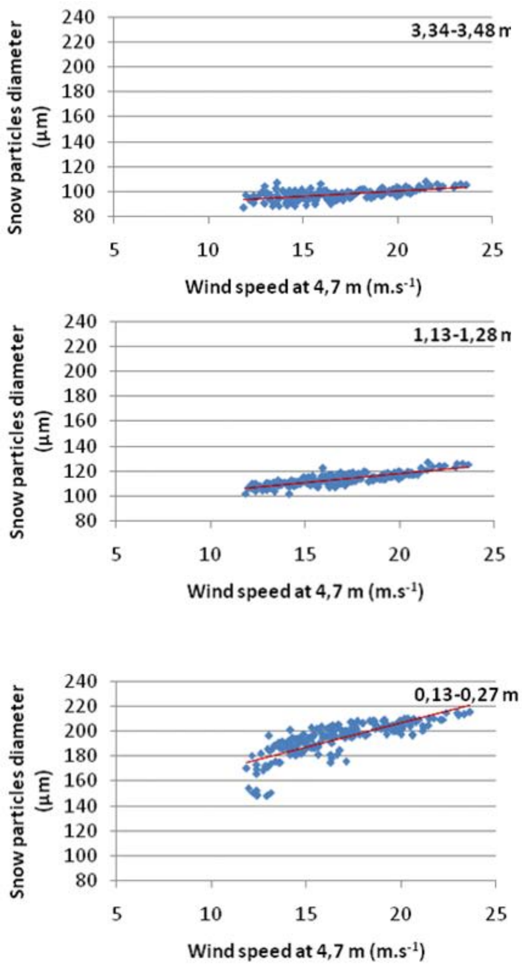

Figure 5. Snow particles diameter as function of wind speed for different heights

As expected larger particles are being carried aloft at higher wind speed (Figure 5) and the size distribution of snow particles can be represented by a gamma density function (red curve in Figure 6).

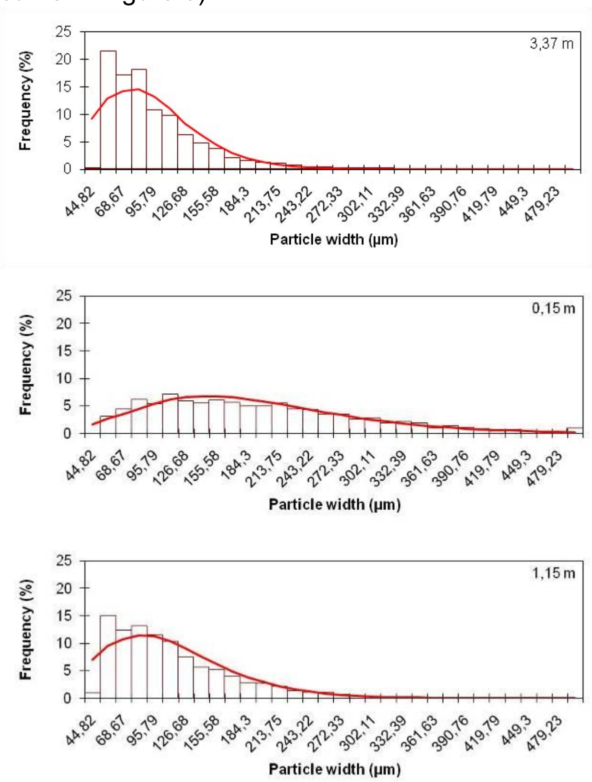

Figure 6. Snow particles size distribution at different heights

Nevertheless the formula (equation 4) proposed by Pomeroy (Pomeroy and Male, 1992), and which is widely used, allow to fit data from Antarctica in the highest layers (Nishimura and Nemoto, 2005) but leads to an underestimation of the snow particles diameter in the Alps for the given events : there is an offset of about 30 µm in the velocity range studied (Figure 7).

$$D(y) = 9{,}12.10^{-5}\, y^{-0{,}258} \qquad (4)$$

with *y* the height above the snow surface (m).

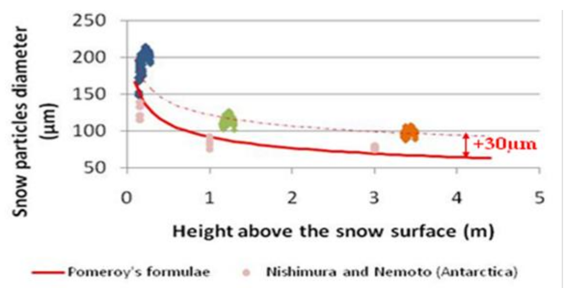

Figure 7. Snow particles diameter as function of height (Event n°1 – blue / green / orange). Data from Antarctica are drawn in pink. Solid line corresponds to equation 4. Dotted line corresponds to *D(y)* calculated by equation 4 plus 30 µm.

During experiments in Antarctica, friction velocity varied from 0.21 m.s^{-1} to 0.56 m.s^{-1}. At Lac Blanc Pass, during event n°1, friction velocity varied from 0.36 m.s^{-1} to 0.92 m.s^{-1}

There is some overlapping between the recorded wind speed. Nevertheless higher wind speed are recorded at Lac Blanc Pass.

So the obtained results can be due to the type of particle (fresh snow) and the relatively high velocity. Similar results are obtained for the second event.

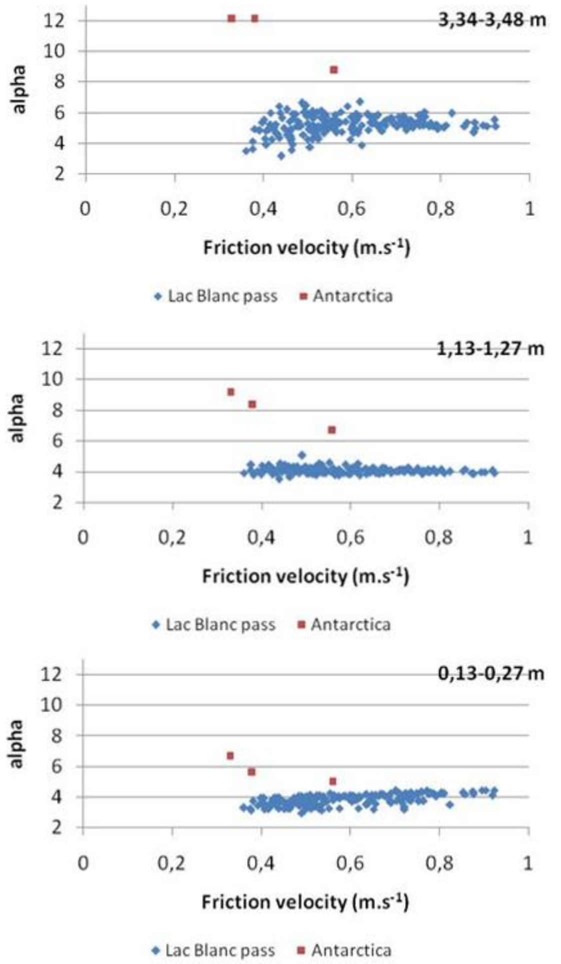

Figure 8. Shape parameter α plotted as function of velocity (Lac Blanc Pass)

There is a constant α layer near the surface (α=3,5-4,5 between 0,1-1 m) and then it seems to increase with height. In Antarctica the constant α layer near the surface is smallest and the value of α is larger particularly in the highest layers (Nishimura and Nemoto, 2005).

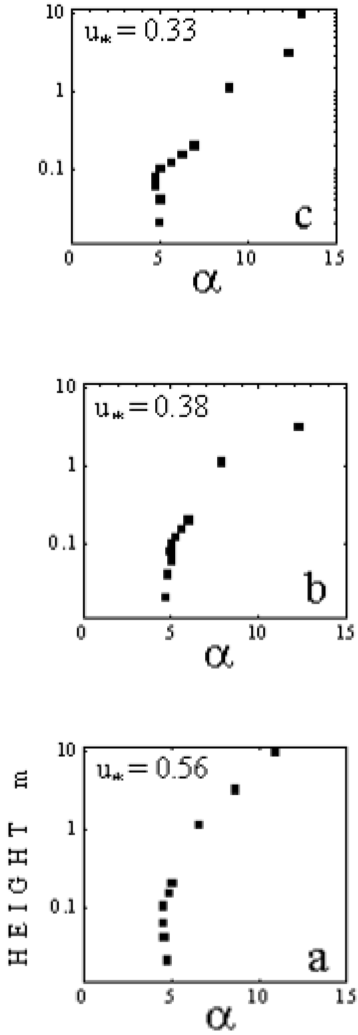

Figure 9. Shape parameter α plotted as function of velocity (Antarctica) (Nishimura and Nemoto, 2005)

3.3 Snow particle settling velocity and Schmidt number

In the suspension layer there is an equilibrium balance between upward transport by turbulent diffusion and downward settling of particles due to gravity.

Assuming there is no net influx of particle from the surface and ignoring sublimation, we obtain for a given particle radius :

$$C(z,r) = C(z_{ref},r)\left(\frac{z}{z_{ref}}\right)^{-\frac{\sigma_s U_{F,r}}{\kappa u_*}} \quad (5)$$

where $C(z_{ref},r)$ is a reference blowing snow density for a given particle radius r at height z_{ref}, $U_{F,r}$ is the average particle settling velocity for a given radius, K is the von Karman constant and σ_s is the Schmidt number.

The Schmidt number is the ratio between the eddy viscosity (K_{s0}) and eddy diffusivity (K_s) (Dery et al., 1998).

Equation 5 is sometimes modified to give :

$$C(z) = C(z_{ref})\left(\frac{z}{z_{ref}}\right)^{-\frac{\sigma_s U_{F,}}{\kappa u_*}} \quad (6)$$

Where $C(z)$ is a reference blowing snow density for all particles sizes at height z and U_F is a bulk settling velocity representing all particle sizes.

The joint use of ultrasonic anemometer ($U(z)$, u_*), snow depth sensor and Snow particle Counter profiles allow to determine $\sigma_s U_F$ which was drawn as function of friction velocity (Figure 10).

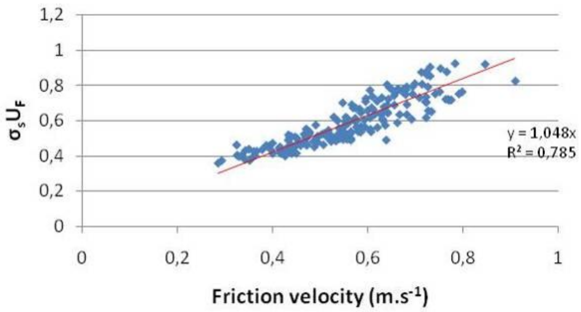

Figure 10. $\sigma_s U_F$ as function of friction velocity for event n°1.

As already observed, the increase in $\sigma_s U_F$ with friction velocity ($\sigma_s U_F = Au_*$) implies that larger particles are being carried aloft at higher wind speed (see Figure 8).

Value of A, that is 1.05 in this study, is higher than those observed by Naaim-Bouvet et al. (1996 – A=0,4) Mann et al (2000 – A=0,29) and Gordon et al. (2009 – A=0,39).

We determine the snow particle settling velocity (equations 7 and 8) representing all particle sizes assuming a mean diameter equal to the mean diameter of particles drifted at the intermediate height (i. e. the mean diameter of particles recorded by the second SPC set up at 1.2 m above the snow surface).

$$A_r = \frac{\rho_a(\rho_p - \rho_a)gD^3}{\mu^2} \quad (7)$$

$$U_F = \left[\frac{\rho_a^{\,2}}{\mu(\rho_p - \rho_a)g}\right]^{-1/3}\left[\frac{18}{A_r^{\,2/3}} + \frac{0{,}591}{A_r^{\,1/6}}\right]^{-1} \quad (8)$$

With ρ_a air density (kg.m^{-3}), ρ_p particles density (kg.m^{-3}), μ is the dynamic viscosity of the fluid (N·s.m^{-2}), g is gravitational acceleration (9.81 m.s^{-2}). Ar is named Archimedes number.

For the Schmidt number, as proposed by Mann et al. (2000), we follow Rouault et al. (1991).

$$\sigma_s = (1 + \frac{c_2 U_F{}^2}{1{,}56 u_*{}^2}) \quad (9)$$

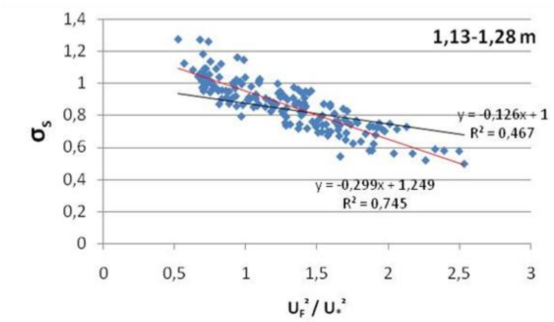

Figure 11. σ_S as function of $U_F{}^2/u_*{}^2$ for event n°1.

We draw (Figure 11) σ_S as function of $U_F{}^2/u_*{}^2$ in order to test the validity of equation (9). It was shown that the Schmidt number is mainly smaller than 1 and that there is a decrease in σ_S with an increasing value of $U_F{}^2/u_*{}^2$

We found a value of c_2, named "counter diffusion" parameter lower than 0 (-0.081), which means that the particle eddy diffusivities is larger than the eddy viscosity. The correlation coefficient is rather low.

There are several other explanations to understand why $\sigma_S U_F$ (calculated thanks to the 10 min mean profiles of snow particles density) is lower than U_F (calculated thanks to equations 7 and 8) as already mentioned by Mann et al. (2000) :

- Particles in the non linear drag regime may experience a significant extra upward drag force due to the fluctuating turbulent eddies causing the fall velocity to be on average less than the still air terminal velocity calculated by equations 7 and 8.
- Particles may not be sufficiently spherical (it is fresh snow) for equations 7 and 8 to apply.

4 CONCLUSIONS AND PERSPECTIVES

The experiments provide data which can be used to improve the accuracy of model.

For the given data, the size distribution of snow particle is well represented by a gamma distribution also in the Alps ; but the mean diameter seems to be higher than those obtained in Antarctica and α ranges between 4-6 in the first meters above the surface.The snow particle eddy diffusivity seems to be larger than the eddy viscosity.

These conclusions are based on limited data, fresh snow drifted at high wind speed.

But we have now to analyze the physical processes and/or hypothesis which lead to these differences and also to acquire data during drifting snow event involving different snow types. That's why during winter 2012-2013 we set up an additional Snow particles counter and six anemometers mounted on a 3-m vertical mast with logarithm vertical spacing nearby the Snow Particles Counters and the ultrasonic anemometer.

Figure 12. New configuration for winter 2012-2013 / Four Snow Particles Counters and Six anemometers

5 ACKNOWLEDGMENTS

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6 REFERENCES

Budd, W.F., Dingle, W.R.J., Radook, U. (1966) - The Byrd Snow drift project : outline and basic results, in Rubin. Studies in Antarctic Meteorology:Antarctic Research Series, 9: 71-134.

Nishimura, K., Nemoto, M. (2005). - Blowing snow at Mizuho station, Antarctica, Phil. Trans. R. Soc. A 363: 1647-1662.

Déry, S. J., Taylor, P. A. and J. Xiao (1998). The thermodynamic effects of sublimating, blowing snow in the atmospheric boundary layer. Boundary-layer Meteorology, 89 : 251-283.

Gordon, M. and P.A. Taylor (2009). - Measurements of blowing snow, part I: particle size distribution, velocity, number and mass flux at Churchill, Manitoba, Canada. Cold Regions Science and Technology. 55 : 63-74.

Mann, G. W., Anderson P.S., and S.D. Mobbs (2000) - Profile measurements of blowing snow at Halley, Antarctica. Journal of Geophysical Research, 105(19) : 24491-24 508.

Michaux, J.L, Naaim-Bouvet F., and M. Naaim (2001) - Drifting-snow studies over an instrumented mountainous site : II. Measurements and numerical model at small scale. Annals of Glaciology, 32: 175-181.

Naaim-Bouvet, F., Bellot, H., Cierco, F-X. and M. Naaim (2008). - Input for a blowing snow numerical model : in situ measurements are still needed. International Snow Science Workshop, Whistler, BC, Canada.

Naaim-Bouvet, F., Durand, Y., Michaux, J-L., Guyomarc'h, G., Naaim, M., and L. Merindol (2000). - Numerical experiments of wind transport over a mountainous instrumented site at small, medium and large scales. Proceedings of international snow science workshop, October 1st-6th, 2000, Big Sky, Montana: 302-308.

Naaim-Bouvet, F., Naaim, M., and H. Martinez (1996). – Profils de concentration de la neige soufflée : Théorie, résolution numérique et validation expérimentale in situ. La Houille Blanche, 5 : 53-57.

Naaim-Bouvet, F., Bellot, H., Nishimura, K., Genthon, C., Palerme, C., Guyomarc'h, G., and V. Vionnet – Detection of snow fall occurence during drifting snow event. Submitted to Cold Regions Science and Technology.

Pomeroy, J.W. and D.H. Male (1992) – Steady-state suspension of snow. Journal of Hydrology, 136 : 275-301.

Rouault, R.R., Mestayer P. G. and R. Schiestel (1991) – A model of evaporating spray droplet dispersion. Journal of Geophysical Research, 96(C4) : 7181-7200.

Sato, A., Kimura, T., (1991). - Measurement of snow mass flux with snow particle counter, Proceedings of the Japan US Workshop on Snow Avalanche and Landslide, Debris Flow Prediction and control, 67-74.

Vionnet, V., Martin, E., Masson, V., Guyomarc'h, G., Naaim-Bouvet, F., Prokop, A., Durand Y. and C. Lac, (2013b) - Simulation of wind-induced snow transport in alpine terrain using a fully coupled snowpack/atmosphere model", The Cryosphere Discuss., 7, 2191-2245.