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Effect of unsteady wind on drifting snow: first investigations

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Abstract. Wind is not always a steady flow. It can oscillate, producing blasts. However, most of the current numerical models of drifting snow are constrained by one major assumption: forcing winds are steady and uniform. Moreover, very few studies have been done to verify this hypothesis, because of the lack of available instrumentation and measurement difficulties. Therefore, too little is known about the possible role of wind gust in drifting snow. In order to better understand the effect of unsteady winds, we have performed both experiments at the climatic wind tunnel at the CSTB (Centre Scientifique et Technique des Bâtiments) in Nantes, France, and in situ experiments on our experimental high-altitude site, at the Lac Blanc Pass. These experiments were carried out collaboratively with Cemagref (France), Météo-France, and the IFENA (Switzerland). Through the wind tunnel experiments, we found that drifting snow is in a state of permanent disequilibrium in the presence of fluctuating airflows. In addition, the in situ experiments show that the largest drifting snow episodes appear during periods of roughly constant strong wind, whereas a short but strong blast does not produce significant drifting snow.

Key words. Drifting snow, blowing snow, gust, blast, acoustic sensor

1 Introduction and objectives of the studies

Contrary to most of current numerical models of drifting snow, wind is not always a steady flow, sometimes oscillating and producing blasts. These models of drifting snow depend on the important assumption that forcing winds are steady and uniform. There has been little research to verify this hypothesis given the difficulties in measurement and the lack of available instrumentation and as a result, too little is known about the possible role of wind gust in drifting snow. This leads to the question of whether it is possible to take into account only the average velocity of the wind in drifting snow modelling. To validate our numerical model of drifting snow, we need to answer this question in both temporal and spatial regimes.

To this purpose, we have performed two experiments at the climatic wind tunnel of the CSTB (Centre Scientifique et Technique des Bâtiments) in Nantes, France, and in situ experiments on our high-altitude experimental site at the Lac Blanc Pass. These experiments were done in a collaborative effort between Cemagref (France), Météo-France, and IFENA (Switzerland).

2 Previous studies

A review of the literature shows that, as Meunier points out (Meunier, 1999), there are very few experimental data concerning the effect of an unsteady wind on drifting flux. The exceptions are his PhD thesis and Butterfield's paper (Butterfield, 1991). Meunier (1999) describes this nonsteady flow as a function of three variables: mean velocity, amplitude and frequency of oscillations. Moreover, their results are partly contradictory. Indeed, Butterfield (1993) found that in unsteady airflow, the drifting saltating sand mass flux correlated well with wind speed, for low variations in wind speed. For sand, he found that the flux followed the increase in wind speed instantaneously, whereas during the decrease, the flux was roughly 1 to 2 s late relative to the wind speed. Meunier (1999), who works with PVC, polystyrene or glass spheres, distinguishes two types of wind blasts. The first type corresponds to wind gusts of weak amplitude (mean velocity: 7.8 m/s, amplitude: 0.6 m/s) and weak frequency (0.2 Hz), for which the flux was late relative to the increase in wind speed and was well correlated with wind speed during the decrease. Moreover, for such a wind blast, the flux measured with non-steady wind was weaker than the corresponding flux with constant wind. The second type of wind blast corresponds to oscillations with a weak frequency, but with a high amplitude. In this case, the flux measured with non-

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Fig. 1. Pole no. 1 (Wind gauge, acoustic drifting snow sensor and drifting snow mechanical traps).

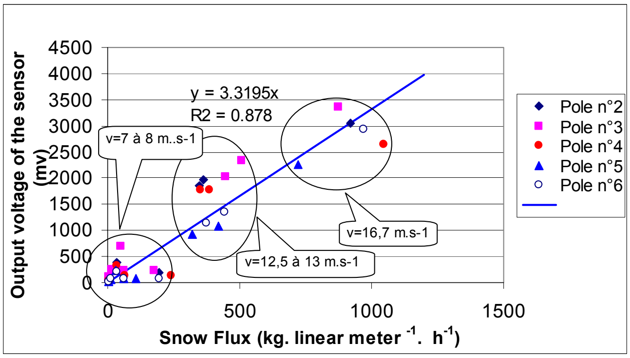

Fig. 2. Relation between output voltage of acoustic sensor (without offset) and blowing snow flux obtained in the CSTB cold wind tunnel (thanks to mechanical traps).

steady wind was stronger than the corresponding flux with constant wind.

3 Gust effects in cold wind tunnel

3.1 The CSTB cold wind tunnel and measurement techniques

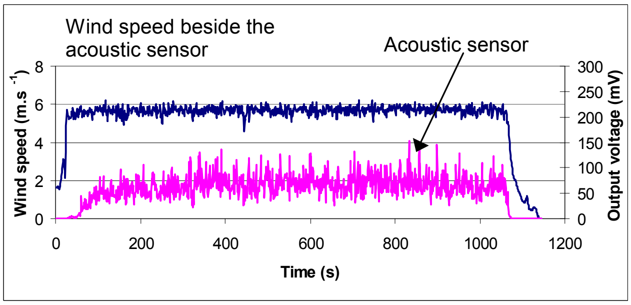

Fig. 3. Temporal development of mass flux for a wind speed near the threshold (experiment no. 1).

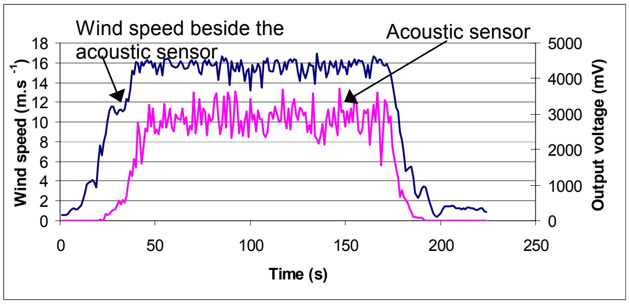

Fig. 4. Temporal development of mass flux for a higher wind speed (experiment no. 2).

The experiments reported here were performed at the climatic wind tunnel at the CSTB (Centre Scientifique et Technique des Bâtiments) in Nantes, France. The measurement section of the wind tunnel is 27 m long, 10 m wide and 8 m high and snow is artificially produced by three snow guns.

The first part of the experiments, devoted to the study of drifting snow inside the experimental chamber, was the object of a previous paper (Naaim-Bouvet, 2002). Certain practical problems were encountered, as outlined below:

- The artificial snow is not dendritic, but consists of small ice pellets with grain diameters between 0.1 and 0.5 mm. Despite the low temperatures used (between −10 and −20° C), the snow sinters very quickly on the ground due to the high humidity. Thus we observed a variation of threshold velocity as a function of time.

- The trajectory of droplets coming out of the snow cannons is a function of the diameter, varying from 0.1 mm to 0.5 mm, so that the distribution of particle size was not uniform along the experimental chamber: the diameter, and consequently the threshold velocity, decreased with distance from the snow guns.

- The cold wind tunnel is a return flow, closed-circuit type and the lack of filter led to the permanent presence of small particle clouds during all the trials: we observed a second maximum of snow particle concentration at a certain height above the ground in addition to the maximum particle concentration in the saltation layer close to the ground.

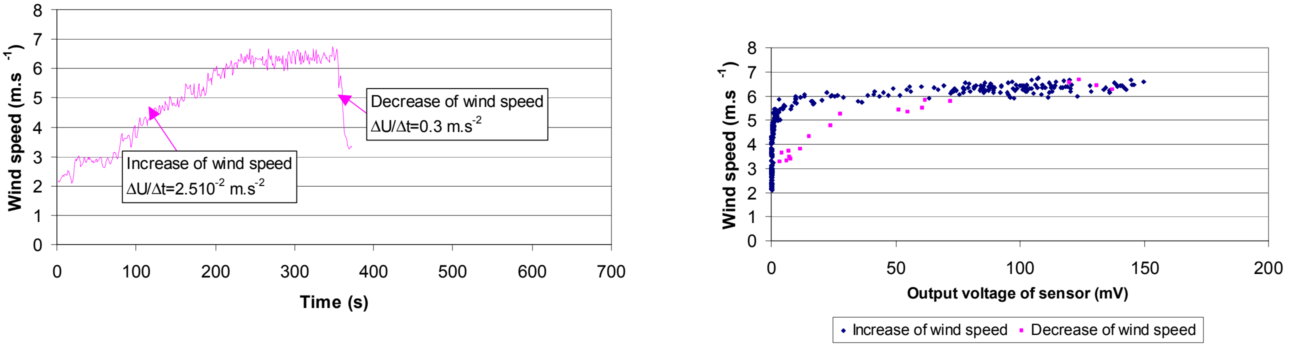

Fig. 5. Experiment no. 3: Output voltage as a function of wind speed for a progressive acceleration flow followed by a rapid deceleration flow.

The second part of the experiment was conducted to study the effect of unsteady wind on drifting snow events. After operating the three snow guns with a low wind speed (between 2 and 3 m/s) at −15° C for approximately 20 min in order to obtain a substantial and uniform snow depth, we started the wind tunnel.

The wind tunnel experiments reported here were conducted using unsteady free stream velocity regimes over a snow bed. There were two simulation variants:

- a more or less rapid increase or decrease in free-stream velocity,

- free-stream velocity increases and decreases in a pattern simulating a simplified gust sequence (sinusoidal shape). Synchronous measurements of mass flux and velocity were made at the end of the experimental chamber (17 m leeward of the snow guns) and were recorded every second at the measurement station. Mass flux was determined with an acoustic snowdrift sensor, a miniature microphone located at the base of a 2-m-long aluminium pole. During the snowdrift event, the pole was exposed to the snow-particle flux and part of the flux impacts on the pole. The sound produced by these impacts is recorded as an electrical signal on the data logger. Beforehand, this acoustic wind drift sensor was evaluated against different mechanical snow traps and one optical snow particle counter (Michaux, 2000; Lehning, 2002) (see Fig. 1). From this sensor, it was unfortunately not possible to distinguish saltation from turbulent diffusion. The wind speed was recorded at a height of 3 m, i.e., outside of the boundary layer. In fact, saltation and turbulent diffusion in the air introduced a two-phase flow that substantially modified the boundary layer. But due to the constraints imposed by available instrumentation, the flow inside the boundary layer was not investigated.

3.2 Drifting snow responses to flow accelerations and decelerations

First, we increased or decreased free-stream velocity, simulating conditions arising when an erosive gust initiates snow transport from a still air condition, as done by Butterfield (1993) for sand.

He observed two stages from his physical wind tunnel experiments: mass flux responded initially within 1 s or less to moderate changes in wind velocity and corresponded to the time for saltating particles to saturate the flow. Further system regulation occurred over periods of 100 s or so as the boundary layer and bed adjust to the new mass flux. The primary response time is found to increase with decreasing shear velocity. Response to wind decelerations occurred in a more complex two-stage process: mass flux lags 2 or more seconds behind decelerations. These experimental results are in agreement with numerical models developed for sand saltation by McEwan and Willets (1991). Moreover, Butterfield observed that sudden velocity excursions transgressing the entrainment threshold condition may induce initial transport spikes several times the magnitude of the mean mass flux.

In our own experiments (see Figs. 3 and 4), we encountered some of these characteristics. The primary response of the system can be roughly determined from the data presented on Figs. 3 and 4. For a wind speed near the threshold (experiment no. 1), mass flux may lag up to 70 s behind wind whereas mass flux lags up to 8 s for the higher wind speed (experiment no. 2). Thus, the trends were the same (response time increased with decreasing wind), contrary to the orders of magnitude. This longer time to approach partial equilibrium can be attributed to the splash function of snow particles. In fact, the primary response of the system results from grain-bed collision processes that greatly differ from sand to snow due to the bonds between snow particles, as pointed out by Naaim-Bouvet (1998). We repeat that the snow sinters very fast on the ground due to the high humidity. The time for particles to saturate the flow and the maximum length necessary to obtain saturation are closely linked (the saturation length is the length along a transect parallel to the

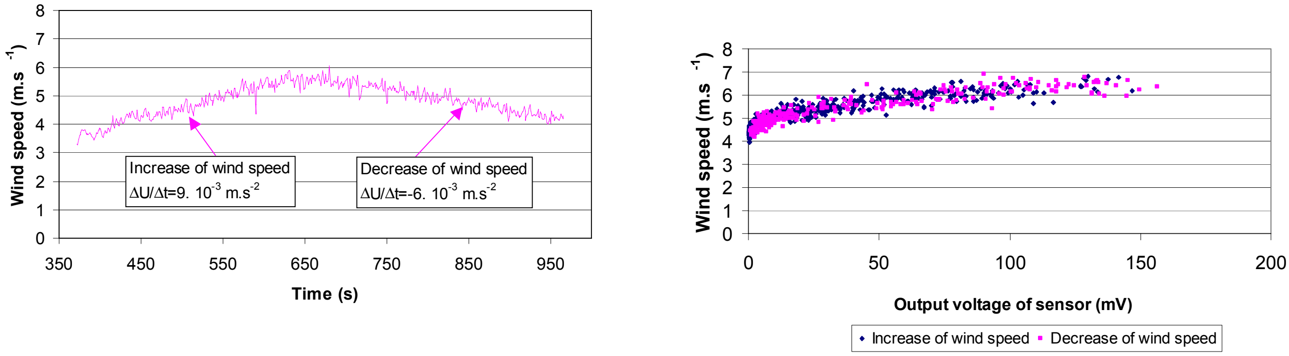

Fig. 6. Experiment no. 4: Output voltage as a function of wind speed for a progressive acceleration flow followed by a progressive deceleration flow.

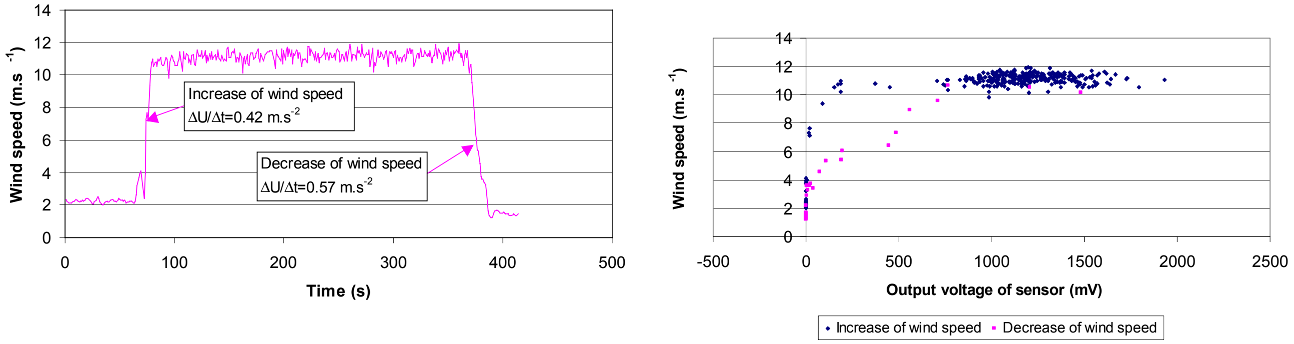

Fig. 7. Experiment no. 5: Output voltage as a function of wind speed for a rapid acceleration flow followed by a rapid deceleration flow.

wind, between a theoretical point serving as the starting point of drifting snow, and a plot where the drifting snow begins to saturate). As a first approximation, we can consider that:

$$L_{abl} = \frac{T_{sat} \cdot L_s}{T_s},$$

where L_{abl} is the length necessary to obtain saturation, L_s is saltation length i.e., the length of one jump by a snow particule in saltation, H_s is saltation height, i.e., the height of one jump by a snow particle in saltation, T_s is saltation time (s), u∗ is the friction velocity.

Knowing the time for particles to saturate the flow, it will be possible to determine the orders of magnitude of the length necessary to obtain saturation for the two cases presented in Figs. 3 and 4.

These lengths are in agreement with those from the literature: for loose granular snow particles, the fetch necessary to reach saturation seems to be several tens of centimetres, according to wind tunnel experiments carried out by Kosugi (1992). Kobayashi (1972) showed that this fetch ranged from 30 to 60 m whereas Takeuchi (1980) estimated that the snowdrift flux reached saturation about 350 m downwind from the starting point.

Contrary to Butterfield (1993), the initial transport spike and the second system regulation were not observed during our experiments. This could be due to a lack of sensitivity in the acoustic sensor.

In our case, snow mass flux lagged 1 or more seconds behind decelerations of the free-stream velocity. As explained by Butterfield, stress adjustment to the profile apparently propagates more rapidly during flow accelerations than during decelerations. Thus the response of drifting snow to sudden velocity decreases does not seem to be the exact reverse of the response to sudden increases. But experiments carried out in the cold wind tunnel merit closer examination.

The experiments presented in Figs. 5, 6 and 7 simulate sudden or more gradual free-stream velocity increments and decrements. Three typical configurations were simulated:

- progressive acceleration followed by rapid deceleration of flow (Fig. 5),
- progressive acceleration followed by progressive deceleration of flow (Fig. 6),
- rapid acceleration followed by rapid deceleration of flow (Fig. 7).

We note that for the same wind speed, the snow mass flux was greater during a rapid wind decrease than during the previous increase (rapid as well as progressive). This hysteresis in the phenomenon was translated into differences between threshold erosion velocity and threshold deposit velocity, as shown in Table 2. For a progressive increase followed by a progressive decrease, the hysteresis was much less pronounced.

Table 1. Rough estimation of length necessary to obtain saturation

	u∗ (m/s)	$H_s = \frac{1.6\,u_*^2}{2\,g}$ (Pomeroy, 1988)	L_s (from Kikuchi's data, 1981)	$T_s = \frac{2}{g} \cdot 1.5\,u_*$ (Mellor and Radok, 1968)	L_{abl}
Experiment no. 1	0.3	7.3 mm	47 mm	$9.17\ 10^{-2}$ s	36 m
Experiment no. 2	0.8	52 mm	210 mm	$2.45\ 10^{-1}$ s	6 m

Table 2. Threshold erosion and deposition velocity for different experiments

	Experiment no. 1	Experiment no. 2	Experiment no. 3
Threshold erosion velocity (wind speed at 3 m)	5.6 m/s	4.7 m/s	3.9 m/s
Threshold deposit velocity (wind speed at 3 m)	3.6 m/s	4.6 m/s	2.9 m/s

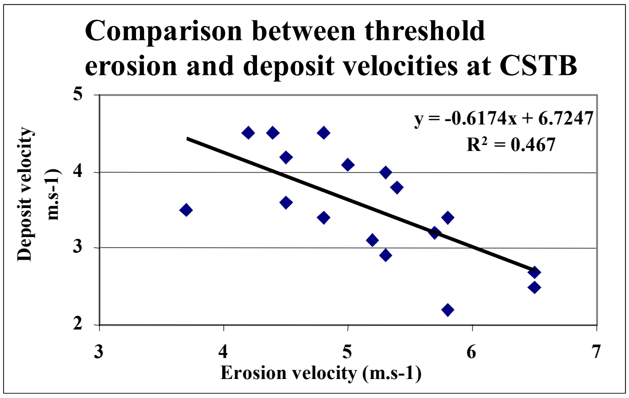

Fig. 8. Comparison between threshold velocities of erosion and deposit at CSTB.

These differences between threshold erosion and deposit velocities appeared for most experiments (see Fig. 8). On this graph, we plotted the threshold velocities for the different experiments with or without wind blast, and with oscillated winds. We obtained a decrease in the threshold deposit velocity when the threshold erosion velocity increased. This shows that for the same initial type of snow (ice spheres from snow guns), the threshold erosion and deposit velocities can be very different, depending on the wind flow (constant wind or gust), the time between the snow fall and the beginning of the wind velocity increase, and also on the humidity in the air (ice bond formation between snow grains).

In summary, in rapidly fluctuating airflows, the mass flux for blowing snow seems to be unable to follow the velocity variations exactly, leading to a permanent disequilibrium, which is consistent with results from Butterfield (1993) for drifting sand. Nevertheless, this effect seems to be more pronounced for snow resulting from grain-bed collision processes, which lead to a longer time for saltating particles to saturate the flow. This first hypothesis is confirmed by experiments presented in the next paragraph.

3.3 Drifting snow responses to fluctuating winds

In this case, we studied adjustments of mass flux under fluctuating winds over snow bed. We simulated wind gusts of relatively high amplitude (mean velocity: 7.85 m/s, amplitude: 2.9 m/s) and weak frequency (1/12 Hz).

Drifting snow responded to flow accelerations and decelerations so that the temporal development of mass flux roughly reproduced the sinusoidal shape of wind velocity (see Fig. 9). But we must point out that the amplitude of the signal measured by acoustic sensors increased progressively until it reached a steady value. There is evidence that antecedent velocity magnitude, velocity history and drifting snow activity influenced the mass flux response, as shown by Butterfield (1993) for sand saltation. Natural drifting snow transport was in a state of permanent disequilibrium with fluctuating airflows, as shown on Fig. 10, that is, contrary to gradual airflow increments and decrements, mass flux and velocity were poorly matched for fluctuating airflows.

4 Gust effects in field experiments: Lac Blanc Pass

Natural gust sequences could have a multitude of forms and may not be characterized by such sudden velocity increments and decrements.

4.1 The Lac Blanc Pass experimental site

In order to study the drifting snow problem, the Cemagref Etna Unit and the Snow Study Center of Météo France have developed a joint experimental site located at Lac Blanc Pass, with the logistic support of SATA (the Alpe d'Huez ski resort management company), and with the financial support of the Rhone-Alpes Region (Michaux et al., 2000).

This site, which is located 2700 m a.s.l. near the Alpe d'Huez ski resort, is a nearly flat area. It is a kind of natural cold wind tunnel with prevailing winds from north and south. On this site, the high wind speeds and the snow cover are favourable to drifting snow. This area is both an erosion

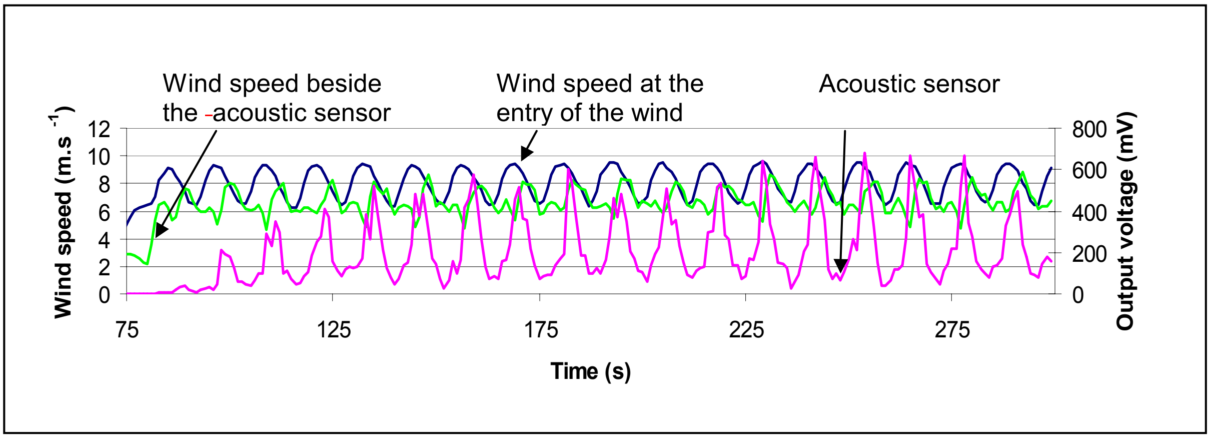

Fig. 9. Experiment no. 6: Temporal development of mass flux for fluctuating wind (mean velocity: 7.85 m/s, amplitude: 2.9 m/s and weak frequency: 1/12 Hz).

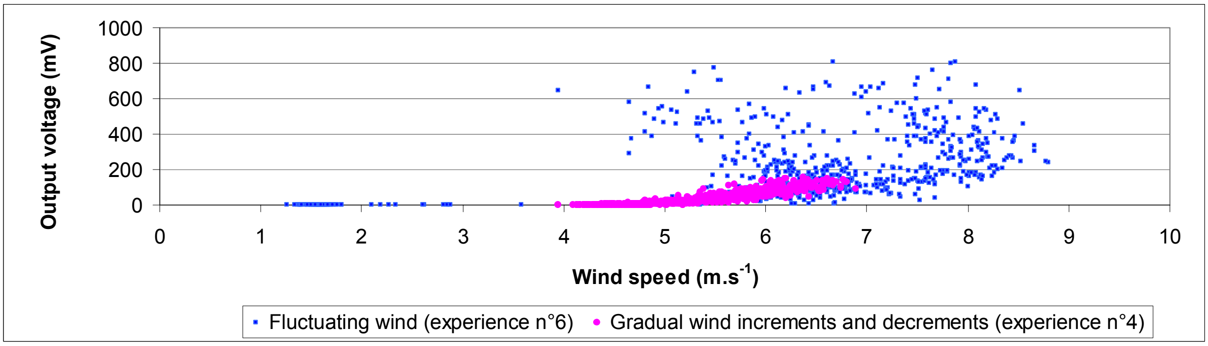

Fig. 10. Output voltage as a function of wind speed for fluctuating wind (mean velocity: 7.85 m/s, amplitude: 2.9 m/s and weak frequency: 1/12 Hz) and for gradual wind increments and decrements

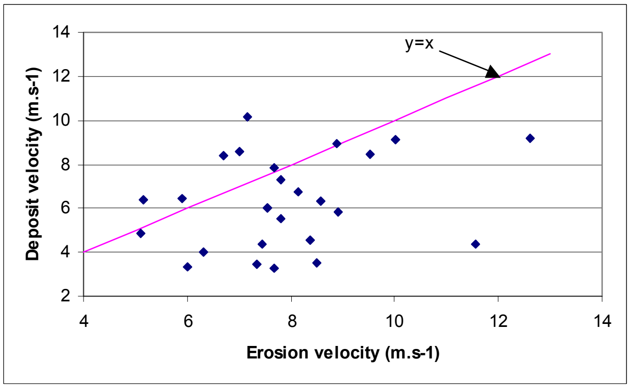

Fig. 11. Threshold erosion and deposit velocities at Lac Blanc Pass.

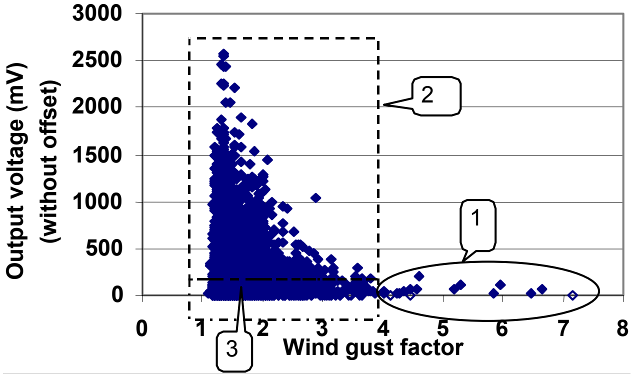

Fig. 12. The average snowdrift signal on the acoustic sensor.

zone (near the pass) as well as an accumulation zone. A data logger records the following parameters every 15 min (with a scan rate of 1 s): average, maximum and minimum wind speed (with a Young anemometer), direction, precipitation, and temperature. Also six acoustic sensors are installed on this site. These sensors are located in the erosion area, in the transport zone and in the deposition zone.

4.2 Threshold velocity of erosion and deposit

As for wind tunnel experiments, we observed in situ differences in threshold velocities between erosion and deposit (see Fig. 11). These differences can be explained by snow surface conditions, temperature, and snowfall history. Like Castelle (Castelle, 1994), we did not find a simple link be-

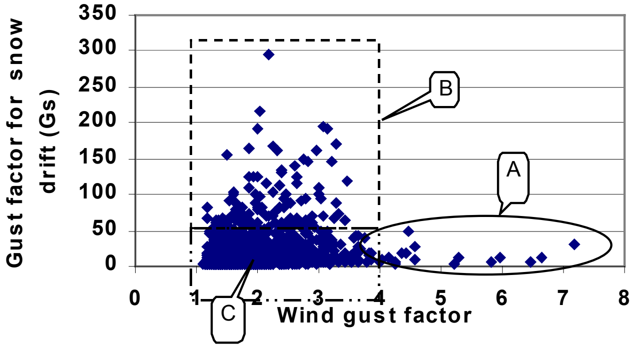

Fig. 13. The snowdrift gust factor recorded by the acoustic sensor.

tween threshold erosion and deposit velocities, with sometimes a threshold deposit velocity greater than the threshold erosion velocity. Castelle explained this by an increase in sintering during the drifting snow episode. An other explanation is that we can have different layers of snow type in the snow mantle. If two or more snow layers are eroded during an episode, the threshold velocity of erosion will correspond to the upper layer, and the threshold velocity of deposit will correspond to the lower layer. If these two layers are different, there is no direct link between these velocities.

4.3 Drifting snow response to natural wind fluctuations

We studied the gust factor (for wind and drifting snow), defined as the ratio of the maximum and average data for a given period (Michaux, 2000).

The wind gust factor, defined as the ratio:

$$\text{Gw} = \frac{\text{Maximum wind speed}}{\text{Average wind speed}}$$

can provide information on the non-stationary aspects of the wind. Similarly, the gust factor relating to the signal of the acoustic snowdrift sensor, defined as the ratio:

$$\text{Gs} = \frac{\text{Maximum signal of the acoustic sensor}}{\text{Average signal}}$$

can provide information on the snowdrift.

To this purpose, data from the acoustic sensor were used. We first removed the offset of the sensor (50 mV). Then, we filtered out the average signal lower than 5 mV, because lower values do not correspond to snowdrift. The gust factor was then calculated every 15 min for the entire winter (sampling frequency of 1 Hz).

We determined two types of drifting-snow events:

- a first type of periods of weak snowdrift,
- a second type of periods of heavy snowdrift.

The first scenario (weak snowdrift) corresponds to areas 1 and 3 in Fig. 12, and areas A and B in Fig. 13. In the first case (areas 1 in Fig. 12 and A in Fig. 13), high wind gust factors were found, indicating highly gusty winds, but very low average snowdrift signals and snowdrift gust factors were observed. Thus, this scenario does not show significant erosion, snowdrift, and deposit. This case fits in well with experiments done at CSTB with a rapid increase and decrease in the wind, since we also have a non-equilibrium between wind speed and drifting snow. The second case (areas 3 in Fig. 12 and B in Fig. 13) is characterised by gusty snowdrift episodes with sporadic wind gusts generating moderate snowdrift.

The second scenario (heavy snowdrift) corresponds to zone 2 of Fig. 11 and part C of Fig. 12. Due to the limited output voltage of 5000 mV for the acoustic sensor, the maximum snowdrift gust factor is 50 for average signals greater than 100 mV, causing the cut-off in Fig. 12. This type of snowdrift occurs during more regular wind episodes characterised by low wind gust factors.

This study of the snowdrift gust factor demonstrates that snowdrift is more substantial and voluminous when it is generated by a regular, sufficiently strong wind than when it appears with sporadic wind gusts. Moreover, in the case of sporadic wind gusts, the equilibrium between wind speed and flow is not reached.

5 Conclusions and further developments

This study gives the first results concerning the possible role of wind gust in drifting snow. Indeed, through the wind tunnel experiments, we found that in fluctuating airflows, drifting snow is in a state of permanent disequilibrium. Moreover, the in situ experiments show that the heavier drifting snow episodes appear during a period of roughly constant strong wind, whereas a short but strong blast does not produce significant drifting snow.

However, we need to keep in mind that this study is only a first investigation. Further experiments should be conducted in order to better understand this phenomenon. Indeed, the type of snow grain was not taken into account in this study of in situ experiments. This type of grain can influence the threshold velocity of erosion, therefore the flux of drifting snow for a given wind. Moreover, this grain type may have an influence on the signal recorded on our acoustic sensor. Until now, this influence has not been taken into account. Moreover, experiments at Lac Blanc Pass were performed with a data logger that records only the average wind speed over 15 minutes, and the maximum and minimum wind speed over 15 min. Consequently, we need to conduct new experiments, with a smaller time period.

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References

Butterfield, G. R.: Sand transport response to fluctuating wind velocity turbulence: Perspectives on flow and sediment transport, John Wiley and Sons, 305–333, 1993.

Kobayashi, D.: Studies of snow transport in low-level drifting snow, Contrib. Inst. Low Temp. Sci, Ser. A 24, 1–58, 1972.

Kosugi, K., Nishimura, K., and Maeno, N.: Snow ripples and their contribution to the mass transport in drifting snow, Boundary layer Meteorology, 59 (1–2), 59-66, 1992.

Lehning, M., Naaim-Bouvet, F., Naaim, M., Doorschot, J., Durand, Y., Guyomarc'h, G., Michaux, J. L., and Zimmerli, M.: Snow drift: acoustic sensors for avalanche warning and research, Natural Hazards and Earth System Science, this issue, 2002.

McEwan, I. K. and Willets, B. B.: Numerical model of saltation cloud, Acta Mechanica Supp, 1, 53–66, 1991.

Meunier, M.-A.: Envol et transport de particules en couche limite instationnaire, Thèse de l'université de Valenciennes et du Hainaut Cambresis, 1999.

Michaux, J.-L., Naaim-Bouvet, F., and Naaim, M.: Drifting snow studies over an instrumented mountainous site: II. Measurements and numerical model at small scale, Annals of Glaciology, 32, 175–181, 2000.

Michaux, J.-L., Naaim-Bouvet, F., and Naaim, M.: The acoustic snowdrift sensor: interests, calibration and results, Proceedings of International Snow Science Workshop, Big Sky, Montana, 390–395, 2001.

Naaim-Bouvet, F. and Naaim, M.: Snowdrift modelling in wind-tunnel: vertical and horizontal variation of the snowflux, Annals of Glaciology, 26, 212–216, 1998.

Naaim-Bouvet, F., Naaim, M., and Michaux, J.-L.: Snow fences on slope at high wind speed: physical modeling in the CSTB cold wind tunnel, Natural Hazards and Earth System Science, this issue, 2002.

Takeuchi, M.: Vertical profile and horizontal increase of drifting-snow transport, Journal of Glaciology, 26 (94), 481–492, 1980.