SNOW TRANSPORT RATE: FIELD MEASUREMENTS AT SHORT TIME SCALES

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ABSTRACT: So as to study snowdrift at short time scales on an experimental field located in l'Alpe d'Huez, France, at an elevation of 2700 meters, mass flux and wind speed were simultaneously recorded at short time rates. The devices able to process such measurements in so hard meteorological conditions are driftometer for transport rate and sonic anemometer for wind vector. Few models of acoustic driftometers are now available but performances of two sensors will be compared on the basis of a complete recording performed during winter 2003-2004. Influence of snow grains types seems to play a significant role in the data sets. Results of specific tests realised in a biphasic wind-tunnel are delivered in this paper with the aim to checking this parameter.

Keywords: snow drifting, snow engineering, acoustic sensors.

1. INTRODUCTION

Snowdrift events play a relevant role in modifying the snow cover. The effects of snow transport are often well known because of the damages or the disagreements caused to buildings or people. Indeed unexpected and sudden accumulations can block roads or other infrastructures whereas the possible increase of avalanche risks worries skiers and ski patrol men. There is then great interest in understanding and modelling such phenomena. Goals of such researches can deal either with hydrology resources in flat open terrains or public equipments management.

The difficulties met in leading this kind of investigations comes both from the field measurements that are still hard to perform and to interpret and from the characteristics of the wind velocity. Local scales and short time rate need actually deeper investigations because of the non-negligible role they play in the observable consequences of snowdrift. That's why, studies on blowing snow are one of the priorities of the research program in Cemagref.

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The present paper deals with a new instrumented mast devoted to snowdrift studies. First field measurements performed with both a sonic anemometer and an acoustic driftometer are delivered here. Results are compared to one's provided by the French National Agency for Weather Forecasting (Météo-France). Flux profiles comparisons are also available and sensor reliability tests are presented.

2. NOTATIONS

C : Particles mass concentration ($kg.m^{-3}$)
C_0 : Particles mass concentration at the reference altitude y_0 ($kg.m^{-3}$)
C' : Constant for z_0 calculation
F : Mass flux ($kg.m^{-2}.s^{-1}$)
L : Length of a tube from Flowcapt (m)
T : Virtual temperature (°C)
Tmf : Air temperature measured by CEN (°C)
U_F : Terminal particle fall velocity ($m.s^{-1}$).
U_h : Horizontal component of particle velocity ($m.s^{-1}$).
U : Wind velocity ($m.s^{-1}$).
U_x : Wind velocity component in the main flow direction ($m.s^{-1}$).
u_* : Friction velocity ($m.s^{-1}$).
y : Altitude above the ground (m)
y_0 : reference altitude (m).
z_0 : Aerodynamic roughness (m).
κ : Von Karman constant.
ρ_p : Particles density ($kg.m^{-3}$)
σ_S : Turbulent Schmidt number
Ψ : Adaptation coefficient

3. SHORT DESCRIPTION OF THE EXPERIMENTAL SITE

3.1 Site description

The "Col du Lac Blanc" station, is located in an alpine pass at an elevation of 2700 meters oriented from North to South. The area consists in relatively flat terrain on a length of about 300 meters. Then the slope becomes steeper both in the northern and southern parts of the place. Far away, the terrain is flat again and lakes occupy many depressions. In the eastern part of the site stands an high alpine range called "Grandes Rousses" culminating at about 3500 meters with Pic Bayle, whereas a lower summit (Dome des Petites Rousses) lies on the West. The photograph printed in fig. 1 depicts the general aspect of the site.

Figure 1 : The "Col du Lac Blanc" altitude station during a snowdrift event. On the left "Grandes Rousses" range rises above the snow-covered pass. The sky line is disturbed by the measurement mast and a graded stick devoted to snowpack thickness measurements. A typical erosion area can be observed in the foreground.

The pass orientation and the specific configuration of the "Grandes Rousses" range make the pass very close to a natural wind-tunnel. Besides, the statistics of wind direction are quite relevant indicating that North or South stand for 80% of the wind directions.

3.2 Instrumentation

So as to study snowdrift at different spatial and time scales, the whole site has been fitted with different kinds of instruments. First, some graded masts allow estimation of snow repartition along a transverse line across the pass. In addition, two standard meteorological stations work here with Young anemometers located 7.5 meters above the dry ground and TT100 platinum temperature probes. Second, a specific mast devoted to snowdrift measurements stands up in an erosion area of the site. It's located at roughly 50 meters from the meteorological stations.

The "snowdrift" mast (fig. 2) is fitted with an ultrasonic anemometer (Metek USA-1) and a transport rate acoustic sensor (IAV Engineering FlowCapt). It's located close to the graded sticks, one of which is fitted with an other acoustic sensor developed in Cemagref, Grenoble, France. This latter device consists in a single sensitive tube. Its measurement process (see Font et al. (1998)) is quite similar to this of Flowcapt even if the selected band of frequencies is not the same. Mechanical traps can be easily set between the two acoustic sensors on an additional structures. Further information about this instrumentation can be found in Chritin et al. (1999), Jaedicke (2001), Lehning et al. (2002), Michaux et al. (2000 and 2001).

The sonic anemometer can simultaneously record each component of the wind vector at time rates up to 10 Hz. Moreover, temperature estimation is computed from a measure of the sound celerity at the same time rate. FlowCapt is a six sensitive piece acoustic sensor that records the noise caused by snow grains impacts against the device frame. It's thus possible to obtain an estimation of the transport rate with respect to the height above the snow surface. This latter sensor is delivered with a standard program that allows solid transport rate measurements every 5 minutes. The available results consist in averaged data computed every 15 minutes. These time constants can be decreased down to 5 or 15 seconds for samples or averages respectively. This standard program has been modified in Cemagref so as to study shorter time scales. Unfortunately the measurement is realised through a successive scanning of

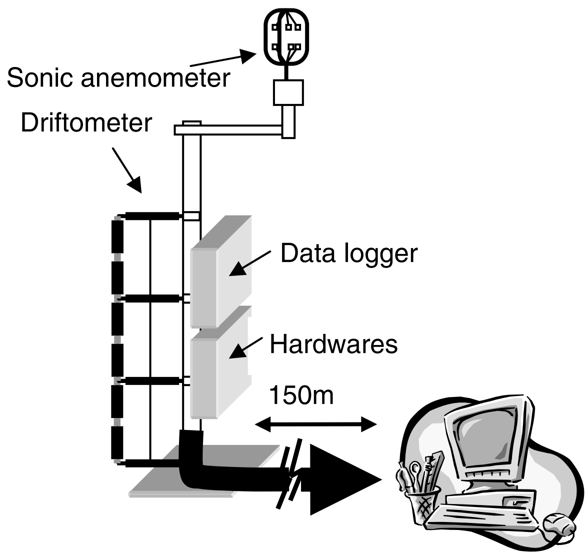

Figure 2 : Scheme of instrumentation system in “Col du lac Blanc” station.

each tube. Duration of a complete scanning lasts more than 2 seconds so that higher frequencies would be impossible to reach.

After we had done our modifications, the effective recording from FlowCapt consisted of a default setting giving mass flux samples every 5 minutes, data averages every 15 minutes. A threshold level of transport rate was fixed, above which FlowCapt commuted automatically to a fast process including one complete recording every 4 seconds.

4. FIELD DATA FROM WINTER 2003-2004

Because of our experimental setting was brand-new, one of our main goal was first to compare our recorded data with some taken on the same site by the French national agency for weather forecasting (Météo-France). First of all, data sets have been cut so that two data bases could have been constituted, the first one including the 5 minute samplings and the latter one devoted to the fast recordings. Averages have been computed every 15 minutes for purpose of comparison with the results from Météo-France as it will be specify in what follows. Data from Météo France comes from two Campbell data loggers that sample horizontal wind speed and direction, temperature and solid charge in the flow every second. Averages, minima and maxima are evaluated every 15 minutes.

4.1 Wind data

Figure 3 shows 15 minute averaged wind data recorded by USA1 sonic anemometer and Young Anemometer against time. It’s to be noticed that despite the sampling rates were different, agreement appears to be very good

4.2 Temperature data

Comparison of temperature recordings by Cemagref and Météo-France has been plotted on figure 4. Despite a noticeable underestimation of temperature by USA1, the general trend is very well reproduced by our new sensor. For additional information on USA-1 temperature measurement and influence of particles on this sensor, see Cierco and Naaim-Bouvet (2003).

4.3 Transport rate data

The information provided by Météo-France comes from the acoustic sensor developed in Cemagref and described in last section. Since the Flowcapt purchase, no recent calibrations or checking have been conducted on this device so that its data series would be purely indicative. The presented results have been obtained from a roughly calibration processed in CSTB cold wind tunnel (Michaux et al., 2000). A very low saturation threshold (about 1500 mV i.e. 330 $g.m^{-2}.s^{-1}$) is to be noticed on figure 5 for this latter device which leads to disputable agreement between the two data sets. Nevertheless, it’s very interesting to observe coincidence of spikes on figure 5. This graph

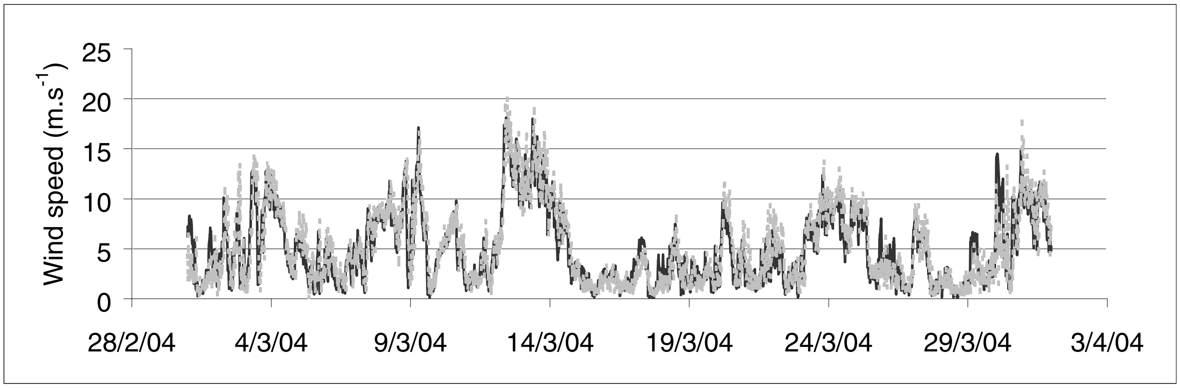

Figure 3 : Comparison of field data from Cemagref (USA1 – grey line) and Météo-France (Young anemometer – black line). The recording consists in 15 minute averaged wind speed during March 2004.

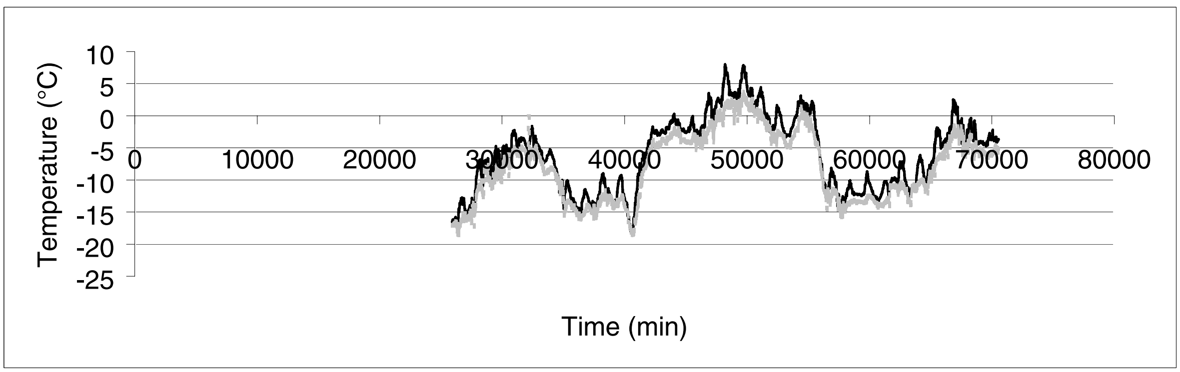

Figure 4 : 15 minute averaged temperature from Usa1 (grey line) and TT100 platinum probe (black line) during March 2004. Time is here given in minutes, 00 minutes corresponding to February 12th 14:45.

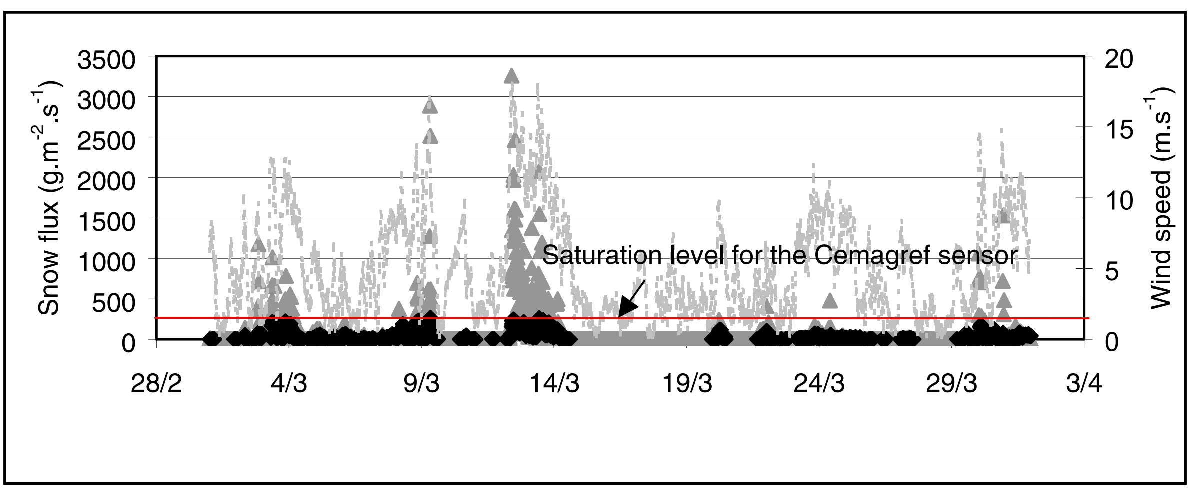

Figure 5 : Comparison of snowdrift direct measurements from two different acoustic sensors during March 2004. Grey triangles stand for data from Flowcapt, whereas dark symbols represent the measurements from the Cemagref sensor.

is then an evidence of good detection of snowdrift events by Flowcapt even if rare exceptions can be noticed.

4.4 High frequency measurements

Interest of the 4 seconds sampled recordings were substantially to find temporal correlations between snowdrift and wind speed so as to check if the results from Butterfield (1993) or Michaux (2003) could be reproduced with snow during field experiments.

Unfortunately, neither direct correlations nor cross correlations between horizontal wind speed and snow flux have been found. The method we used did not allow us to determine any characteristic delay or so on between the two signals. This is probably a consequence of the too large time scale selected for the measurement. But once again, we used the deeper capabilities of the device.

A measurement is nevertheless presented on figure 6. Indeed, it's to be observed that z-component play as quite negligible role in transport rate variations. Moreover, although quasi-steady wind blew on the fields (Averaged wind speed was 20.33 $m.s^{-1}$ with turbulent intensity of 1.8%), huge variations of transport rate are to be noticed (mean flux was 13.91 $g.m^{-2}.s^{-1}$ and ratio of its standard deviation to this mean value was 28.55%).

5. FLUX PROFILES COMPARISON

Some specific field measurements have been performed so as to get an estimation of snowdrift from mechanical snow traps that could be compared with data recorded by Flowcapt. The traps consisted in "butterfly nets" i.e. in a metallic frame fitted with a specific piece of cloth able to retain particles whereas clean air could flow through. Cross section of a frame is 0.02*0.15 square meters. The traps were fixed horizontally at heights corresponding to those of the middle of each FlowCapt tube.

These experiments took place on March 12th, the 23rd and the 24th, 2004. On March 12th the wind blown quite strongly so that 5 minutes were enough to fill the trap located close to the ground. During the following days, wind was not so strong so that each run required 20 or 30 minutes. Comparison between manually recorded profiles and FlowCapt measurements are available on figure 7

The flux profiles obtained manually with snow trap permitted to (re)compute some parameters that play a significant role in concentration equation given against the height above the ground :

$$C(y) = C_0\left(\frac{y}{y_0}\right)^{\frac{-|U_F|\sigma_S}{\kappa u_*}} \qquad (1)$$

So as to simplify this expression, let's call α the power exponent :

$$\alpha = \frac{|U_F|\sigma_S}{\kappa u *}$$

Then u_* has been estimated from the main horizontal wind speed U_h recorded with the sonic anemometer located et about 3 meters above the ground assuming that the wind profile follows a logarithmic law. (The snow cover thickness modified the anemometer nominal height of about 20 cm which does not influence the order of magnitude for u_* This latter parameter was found to be 1.2 $m.s^{-1}$ and 0.42 $m.s^{-1}$ respectively).

Moreover the power exponent $\alpha=U_F.\sigma_S/(\kappa.u_*)$ has been directly evaluated applying a power law regression. R^2 correlation coefficient were 0.9788 and 0.9235 for events presented on figures 10/a and b. α was respectively 0.485 and 0.539. The order of magnitude for U_F and σ was thus about 0.49 and 0.28 which is acceptable despite it's a bit lower than expected for the last data set.

Naaim-Bouvet et al. (1996) proposes the two next empirical laws for $U_F*\sigma$ whether snowfall happens or not (cf. equation (2) and (3) respectively) :

$$U_F\sigma = 0.383u_* + 0.121 \qquad (2)$$

$$U_F\sigma = 0.382u_* + 0.066 \qquad (3)$$

We then compared our α*κ experimental values to the 0.382 and 0.383 coefficients. It's to be interestingly noticed that our data do not

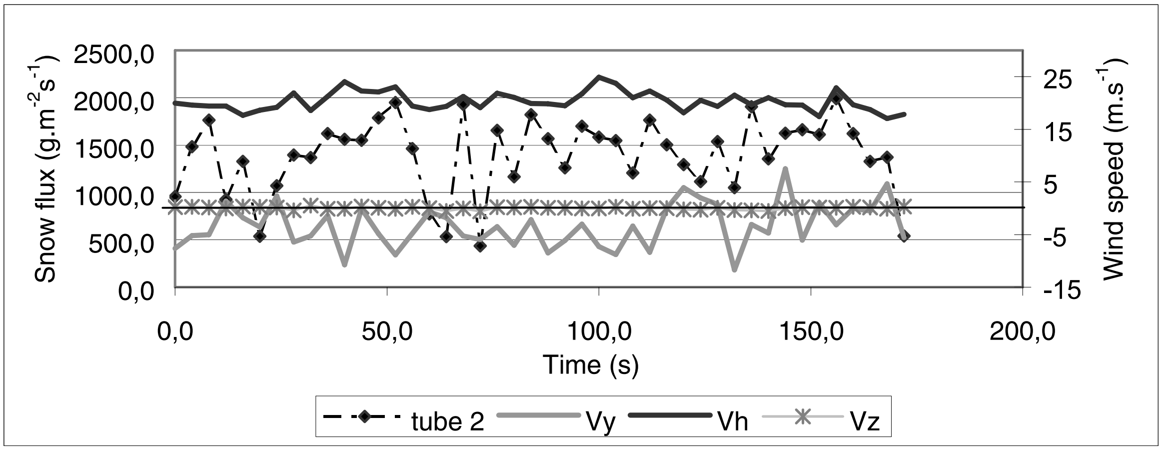

Figure 6 : Fast recording of transport rate and wind speed at “Col du Lac Blanc” station. The line with stars, which stands for the z-component of the wind velocity collapses with the abscissas-axis. The transport rate (dotted line) shows very important fluctuations whereas the horizontal wind speed (dark line) does not vary too much.

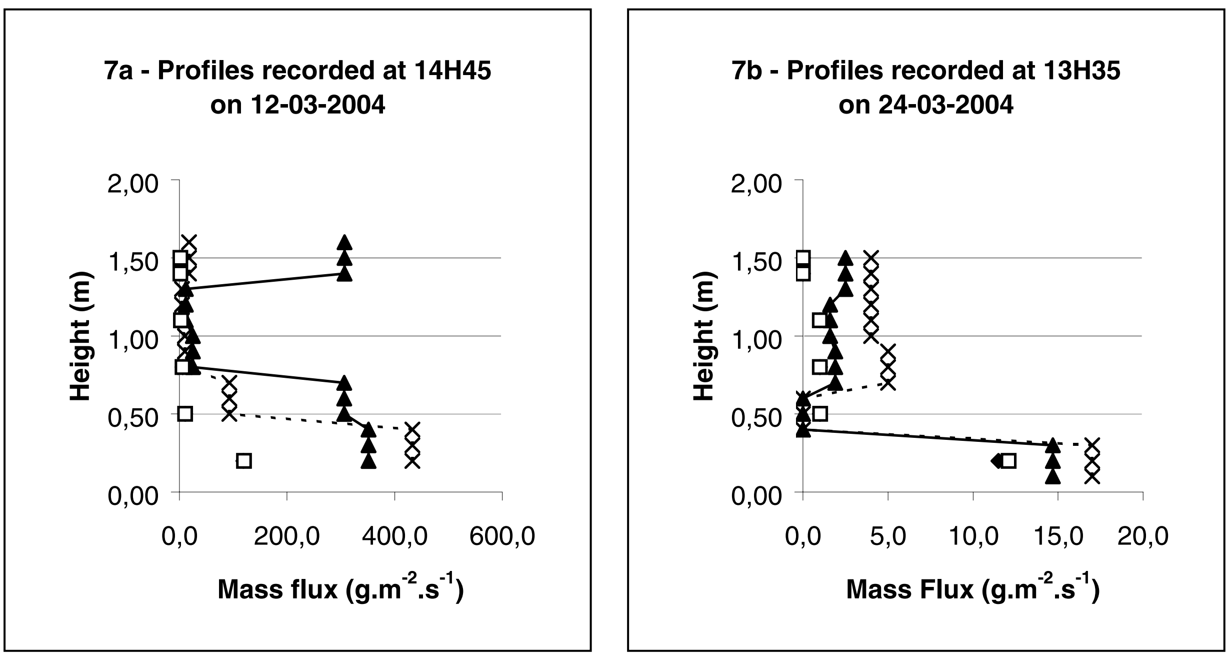

Figure 7 : Mass flux profiles recorded with snow traps and FlowCapt on March 12thand 24th. The dark lozenges stands for the measurement realised thanks to the traps. They are often hidden by the single white squares which corresponds to the same data adapted with the Ψ-coefficient computed thanks to field data. The dotted line is one of the automatic average processed by the modified FlowCapt software every 15 minutes. Except on March 12th, it has been checked that each of the three samples used for the average computation were included in the time interval of the experimental run. At last, the dark continuous line is a manually computed average of the instantaneous data issued from FlowCapt on the time interval that matched exactly the time of the run for the traps.

match exactly these equations with typical values of 0.199 and 0.221.

Figure 7/a shows that the upper tube (tube 6) measured an amazingly high transport rate. Similar results can be found in Jaedicke (2001). Deeper investigations about this unexplained particularity of the device showed that throughout the winter, tube 6 measures higher flux than tube 5 in 86% of cases. Because there is no admitted physical reason to explain this phenomenon, it has been considered like an measurement error. (This could be an additional valuable reason for drastic differences between the recordings of the two driftometers presented in fig. 5).

Measures issued from the different sensors are difficult to compare and direct readings of the two data sources are not necessarily consistent. Indeed, each tube from FlowCapt realises actually a spatial average of the snow mass flux. Since transport rate variation with respect to the height are non-linear a direct confrontation of the data sets could lead to erroneous conclusions. According to the model that rules the diffusion layer, these averaged data (from one tube of FlowCapt) can be compared to one punctual estimation of the mass flux taken between the bottom and the top of the tube. And yet, this particular point is not necessarily the middle of the tube.

A correcting factor has then been applied to the results from the mechanical traps so that they could be confronted to those from FlowCapt. This coefficient denoted by Ψ was computed according to the following equation :

$$\Psi = \frac{F(tube\_n)}{F(y_0)} \qquad (4)$$

where F(tube_n) denotes the flux theoretically measured by a determined tube from FlowCapt whereas $F(y_0)$ stands for the flux caught by mechanical traps located at the height y_0 over the snowy ground. In equation (1) α can't be negative or equal to zero so that, excluding the case when α equals to 1, equation (4) could be written as follows :

$$\frac{F(tube\_n)}{F(\frac{H1+H2}{2})} = \Phi * \left[\frac{y^{1-\alpha}}{1-\alpha} \ln \frac{y}{z_0} - \frac{y^{1-\alpha}}{(1-\alpha)^2} \right]_{H1}^{H2}$$

where :

$$\Phi = \frac{1}{(H2 - H1) * \left((H1+H2)/2\right)^{-\alpha} * \ln\left(\frac{H1+H2}{2z_0}\right)}$$

Here, H1 and H2 denote the respective heights of the top and bottom of tube_n. It's to be noticed that z_0 is the aerodynamic roughness, i.e. it does not correspond to the ground characteristics but it has been adapted due to the development of the saltation layer at the bottom of the validity domain for turbulent diffusion. z_0 can here be expressed by :

$$z_0 = C' \frac{u_*^{\;2}}{2g}$$

C' denotes an empirical constant and g stands for the gravity acceleration.

The C' constant has been chosen to be consistent with the literature. The empirical measure from Pomeroy and Gray (1990) has been retained assigning to C' the value of 0.1203. So that to check the influence of this parameter, values determined by Rasmussen, Sorensen and Willets (1985) (C'=0.16), and by Owen (1964)) with sand (C'=0.021) have been confronted to a limit case (i.e. : C'=0.5) but dependence on C' appears to be quite weak.

Influence of friction velocity, turbulent Schmidt number and terminal velocity appears to be quite important below 80 cm but totally negligible above 1 m.

Comparison of the results from the sensors after correction is available on figure 7. Insofar as to establish this curve, and due to the important variability of Ψ-coefficient, this latter one has been computed from experimental data. u_* and α have been estimated as explained in the precedent paragraph.

Correcting the values of each trap with field data (i.e. the six values of C_0 at the different heights for each tube) implies the followings :

Adapted measures are not supposed to fit a power law on the entire profile in the way that despite it's one of our assumption, the modifications have been applied for one tube each time (value for tube 1 has been corrected with the corresponding trap measurement and so on). That's why, the adapted data can't fit the power law regression with a R^2 coefficient better than this obtained with the measured data and given in this section. Nevertheless, this way to correct our data is better adapted to field conditions and is less sensitive to erroneous measurement than a classical correction that would have used a single measurement and a single reference altitude to built Ψ-coefficients

The comparison now concerns the dark continuous line (equivalent averaged data from Flowcapt) and the single squares (corrected data from the traps using field data). It can be noticed that the curves present bad agreement except for the event recorded on March 24th (see fig. 7/b). Generally FlowCapt gives an overestimation of the flux, (even if some rare underestimations during low snowdrift conditions have been recorded on March 23rd). Ψ-coefficients computed with field data do not bring any change to the initial measurements which means that flux measured punctually at the middle of each tube of Flowcapt is a good approximation of the sensor result.

Among the many reasons that could explain such observations, four main cases have to be more deeply investigated.

First, variability of the Ψ-coefficient could explain why no correlation can be found between corrected signals from the traps and Flowcapt but computations based on field data should avoid such bias.

Second, spatial variability of snow transport can be investigated. Indeed the two masts that support the different sensors can't be set at the same place exactly. Even the distance between them is still less important than the typical scale of topography changes, doubt can be emitted on the "spatial regularity" of snow transport.

Third, cylindrical tubes from FlowCapt confers to this latter a real advantage on mechanical traps for which incorrect lining up with main flow direction leads to underestimation of snow flux. For example an angle of 20 degrees lead to an error of 6% of the transport rate estimation. It can be observed that this error source is not sufficient to explain the gap between the sensors recordings that appears on figure 7.

Fourth, variability of the FlowCapt response to impacts caused by different kinds of particles could be incriminated. The sensor calibration could be made very intricate in the way that no standard calibration could exist due to the variability of snow types. Fresh snow may not be supposed to give rigid elastic shocks against the tubes contrary to some other snow grains. Besides the treatment applied to the recorded signal assumes that the nature of the shocks are rigid and elastic. Such hypothesis could be dismissed for "soft" particles. According to Meteo-France, the presented events took place no more than 24 hours after the last snowfall. That's why fresh snow could be expected for these recordings even if time scales for snow metamorphosis can be very short during windy weather.

6. INFLUENCE OF PARTICLES TYPE: WIND TUNNEL EXPERIMENTS

A more accurate study of the last point of last section was allowed by wind tunnel experiments. That's why sand and corn dust have been tested in a biphasic wind-tunnel. This wind tunnel includes a 4 meter-long experimental channel whose cross-section is 1.0*0.5 square meters. More details can be found in Michaux (2003). Measurements have been performed with one tube from FlowCapt and with a mechanical trap.

The mean diameter of sand grains varied from 40 to 315 µm. The bulk density for sand and corn dust was respectively 1456 and 516.5 $kg.m^{-3}$

Because of the too large influence of the wind-tunnel walls on the flow and then on the drifting flux, the different apparatus can't have been tested at the same time. Nevertheless successive runs leaded to good reproducibility of measured flux. Comparison of three successive runs with sand for the same lateral position of the sand trap showed an error rate of about 5%, regardless of the lateral position of the trap. That's why we made two runs for each setting of the wind-tunnel. First, one tube from the six-piece FlowCapt sensor was selected and fixed inside the experimental channel. Then a specific trap was set at the same place exactly.

This trap was quite similar to those used on the field but it was set vertically. Moreover its cross-section fitted exactly the dimensions of a sensitive tube from FlowCapt. The retained volume of loose sand or sawdust were then weighted at the end of each run.

The noise generated by the engine, the fan or any kind of vibration from the whole metallic structure don't disturb the acoustic sensor for wind-tunnel setting up to 60 (which roughly corresponds to wind speed of about 10 m/s). For an higher range of wind speed FlowCapt records non zero transport rates even for experiments without any particles. The curve plotted after a so-designed test is available on fig. 8. Nevertheless, at high wind speeds, filters are not totally efficient so that residual transport occurs. Moreover compared to values recorded by FlowCapt at such wind velocities, signal found without particles can be assumed to be negligible.

The timing of the experiment has been realised manually and confirmed by determination of the periods during which FlowCapt was really in operation, i.e. when its measurements differed from 0. Because of acceleration and deceleration of the wind-tunnel duration of transport event during the runs using sand trap are known with a possible error of ±10 seconds. Then, after weighing the trapped particles, mass flux expressed in $g.m^{-2}.s^{-1}$ could have been computed from the mechanical trap. Similar results were automatically delivered by FlowCapt. Fig 9 and 10 allow a rapid comparison between results from the different sensors for both sand and corn dust. In both case, the curves lead to the conclusion that FlowCapt gives an overestimation for high transport rate whereas it may underestimates weak fluxes (case of sand, fig. 9). This result disagrees with those of Lehning et al. (2002) but it's to be known that calibration process of FlowCapt radically changed from one experimental session to the other, i.e. experiments performed before and after year 2001.

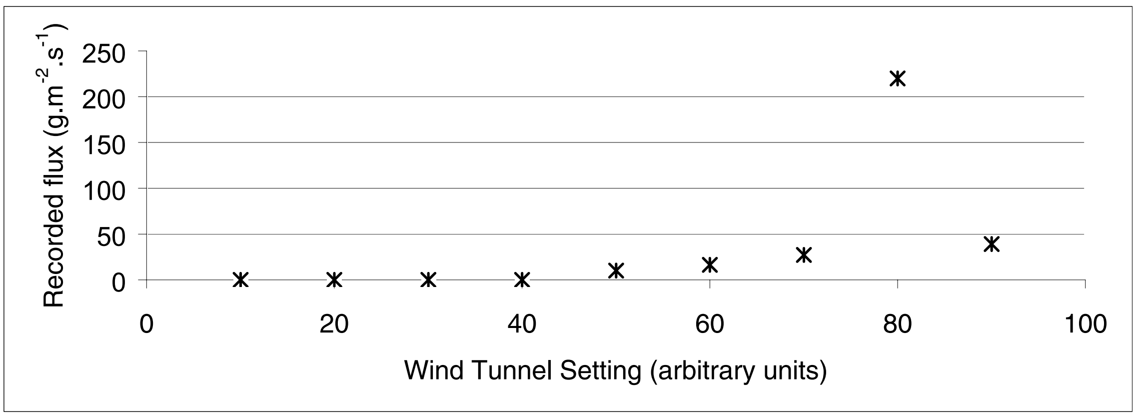

Figure 8 : Maximum recorded flux by Flowcapt during a wind-tunnel experiment without any particles. Samples were taken every five seconds in every tube. Each setting of the wind-tunnel lasted one minute. The maxima plotted here have been selected among all samples and all tubes. Except an isolated point recorded by tube 1 at more than 200 $g.m^{-2}.s^{-1}$, no sample overflowed 50 $g.m^{-2}.s^{-1}$ indicating negligible sensor perturbation.

Next comparison permits to check the reliability of snowdrift measurement when snow grains are modified. Once again, the test can't have been realised with snow but solid particles have been used within a large range of density or fall velocity. Indeed, the acute

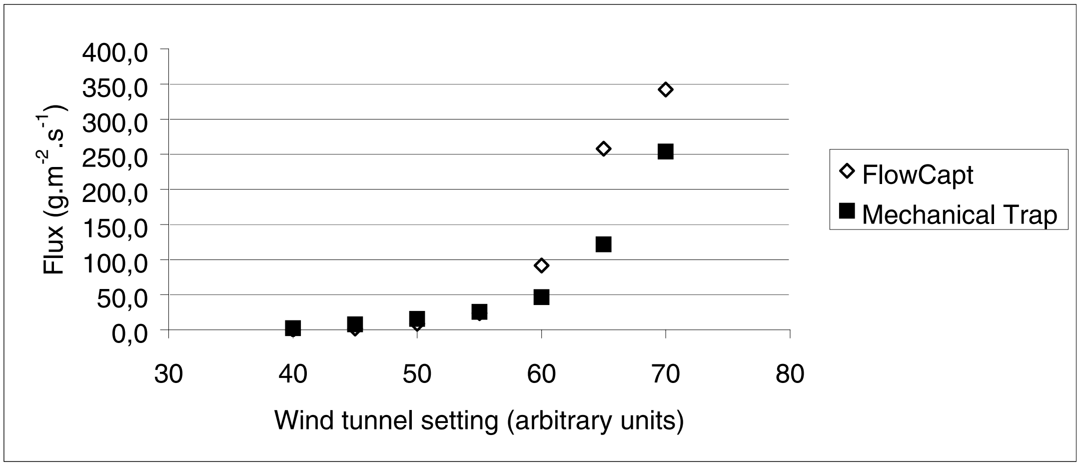

Figure 9 : Comparison of the measurements performed by FlowCapt and a sand trap in a wind-tunnel with sand. A slight overestimation from FlowCapt seems to characterize this graph.

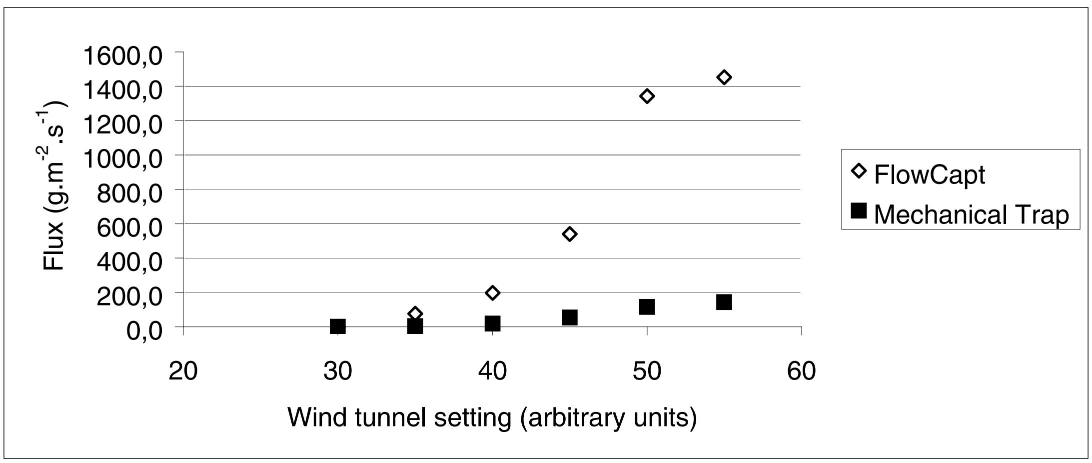

Figure 10 : Comparison of the measurements performed by FlowCapt and a sand trap in a wind-tunnel with corn dust. The overestimation performed by FlowCapt is evident for this type of particle.

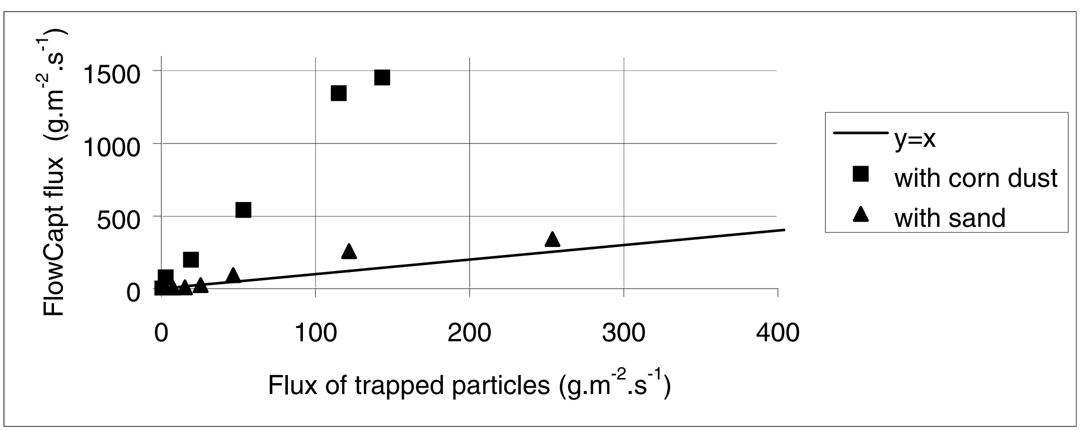

Figure 11 : Sand fluxes (squares) and corn dust fluxes (triangles) taken down by FlowCapt

difference of aerodynamic behaviour and consistence from fresh snow to sintered grains invite to think that a same mass flux can lead to a large variability of impacts and then of “noises”. Results for sand and corn dust are plotted on fig 11.

The general trend appears to be the same as this noticed about our field data i.e. FlowCapt gives slightly overestimation of fluxes for high particle drifting but it may underestimates weak transport rates. The overestimation becomes huge when shocks against the tubes are no more rigid elastic. Factors able to give any explanation for such a trend can be searched among error in experiment reproducibility or bad aerodynamic of our specific “butterfly nets” which allows less particles enter the trap. But because of the large number of measures we performed, the first factor cannot be seriously retained.

Figure 11 shows that estimation from FlowCapt appear to be a linear function of fluxes measured by traps whatever are the particles type. This conclusion should permit to develop a correcting factor in case of transport events implying flabby particles like fresh snow for example.

8. CONCLUSIONS

News devices have been tested on the fields to obtain snow concentration profiles at short time scales. Even the first results agree those of well known sensors, improvements are needed so that shorter time scales could be investigated.

Results from acoustic driftometers are to be taken carefully with snow because of the large variability of snow grains. Indeed, particles whose shocks against the sensitive tubes of such devices do not satisfy the assumption of rigid elastic shock lead to important overestimation of their flux.

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