MODELING AND VALIDATION OF SNOW REDISTRIBUTION BY WIND.

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ABSTRACT : As part of the effort of the Centre d'Etudes de la Neige - Météo-France (Snow Research Centre), for the improvement in modeling snow cover evolution and avalanche hazard forecasting, a numerical simulation of snow transport by the wind has been developed over the last years. This application is based on field measurements at a high altitude experimental site (2700 m) that leads:

- Firstly, to improve the knowledge concerning wind speed thresholds according to the types of snow surface particles and to verify the mechanisms of snow transport in alpine environment,
- To develop and to validate a first attempt of snow transport modeling based on the results of these previous studies and on a modeling of a refined wind field centered on the experimental site,
- To use a Digital Elevation Model with a resolution of 45 m integrating the experimental site, in order to develop a 2D/3D version of the modeling.

Then, the measurements carried out or recorded at the experimental site allow to validate the results of these last developments thanks to:

- A horizontal profile (transect) of snow stakes along a part of the experimental site,
- The determination of an "albedo map" of the snow cover around the site by analyzing digital geo-referenced images through a novel remote sensing technique adapted to our problem,
- Additional measurements performed on a set of several points around the site,
- The following through video records of the evolution of snow redistribution due to wind (erosion-accumulation areas) on the experimental site.

This presentation will also focus on the difficulty to verify the results of 2D modeling of snow redistribution. The final purpose is to incorporate validated results of wind effects modeling on snow distribution into the operational chain Safran-Crocus-Mepra for avalanche risk forecasting.

KEYWORDS : blowing snow, modeling, in-situ validation.

1 – INTRODUCTION

Because the effects of wind on the snow pack have a great influence on the increasing of avalanche risk, the CEN (snow research laboratory of Météo-France) has started experiments and studies on a high altitude site in the French Alps for 15 years. The moving of snow due to wind is observed and numbers of sensors dedicated to this study were carried out in order to follow precisely the evolution of the snow distribution on a site which undergoes snow transport by wind. Then, by using the results of measurements, observations and field experiments, the snow redistribution is modelled by using classical physical equations.

According to its own objectives: improving the operational forecasting of avalanche risk, the CEN has developed some modeling tools by using the results of these studies (Durand and others, 2005,). In parallel, different attempts were performed in order to improve and refine a wind field assessment at a fine scale in such an environment: high altitude mountain site with a statistical approach (Guyomarc'h and others, 1998b) and with a more physical approach (Mérindol and others, 2000).

After the first developments of the modeling (named Sytron for : System for Aeolian

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Transport of Snow), the results can be validated by using some observations of the snow distribution on the site, which are not included in the simulation.

These studies have then led to the two models: 1D simulation of the snow pack on both sides of an imaginary crest which undergoes drifting snow (**Sytron1**), 2D/3D evolution of a set of grid-point snow packs using a Digital Elevation Model centered on the experimental location (**Sytron2**). The last developments of this model, **Sytron3** are described in detail in Durand and others (2005).

The following stage is to be able to verify the modeling results at the experimental site. One of the main problems is the scale difference between the grid mesh of the model and the great number of small features of snow accumulation and erosion that can be observed on the terrain. Another difficulty is the lack of observation at the same scale as the model outputs. It is why several attempts have been made to verify the modeling results (Corripio and others, 2004) by comparing erosion and accumulation snow surface areas.

This paper presents the field measurements, the more recent results of this work, the last steps of the modeling attempts and the different ways to validate this modeling approach, keeping in mind the objective of an operational version that we can use for the avalanche risk forecasting in France.

2 – EXPERIMENTAL SITE

2.1 – Description of the study site

For about fifteen years, the CEN has been run an experimental site for investigation concerning drifting snow. This experimental site is situated in a large pass at an altitude of 2,700m in the "Grandes-Rousses" massif near "Alpe d'Huez" ski resort. The experiment area is a large flat terrain (around 300 m) with steeper slopes in the northern and southern directions (figure 1). The wind in this pass is controlled by the "Grandes Rousses" range at the East and the "Dôme des Petites Rousses" range at the West. Thus at this site, the major part of the observed winds are blowing from North or South facilitating the observations of snow deposition before or after blowing snow events.

This site is also used by others laboratories, particularly for the development of specific sensors very useful for the detection and intensity measurement of blowing snow (Cierco and others, 2004).

Figure 1: view from West of the experimental site situated near the "Grandes Rousses" range at 2,700 m of altitude.

2.2 – Equipment

Lots of sensors measuring specific parameters related to snowdrift events have been carried out at this site on three automatic stations: two of them are situated at each side (North and South) of the pass and the third is on a surrounding point (120 m above the pass) and give information on the synoptic wind (figure 2). In all sites, at least wind direction and velocity (using heating system in order to avoid icing) are being measured and recorded.

Figure 2: the southern automatic weather station.

In complement, in the pass, snow depth and water equivalent of precipitation are measured at each weather station. The available data consist in averaged, maximum and minimum values recorded every 15 min. steps. The climatologic description of these parameters has been made in Guyomarc'h and others (2000).

For five years, a horizontal snow profile of fifteen graded snow poles has been set-up along a northern-southern axis on both sides of the pass. Snow accumulation and erosion can be manually observed with a precision of +/-5cm (figure 3).

Figure 3: a part of the horizontal profile of snow poles.

2.3 – Measurements and observations

Lots of manual measurements and field campaigns have been conducted regularly over the winter seasons, especially around drifting snow periods. During these periods, we have collected snow samples for a later study in our cold laboratory. Many snow pits have been performed in order to evaluate the quality and cohesion of each kind of snow particles.

The recording data allow to determine precisely the beginning and the end of every snowdrift events (figure 4). The field measurements have permitted to describe the type of snow particles, the quantity of transported snow (by using vertical snow profile), the wind velocity profiles close to the snow surface and all relevant parameters useful for describing the phenomenon. In order to follow-up the weather situation, a web-cam was carried out at the experimental site.

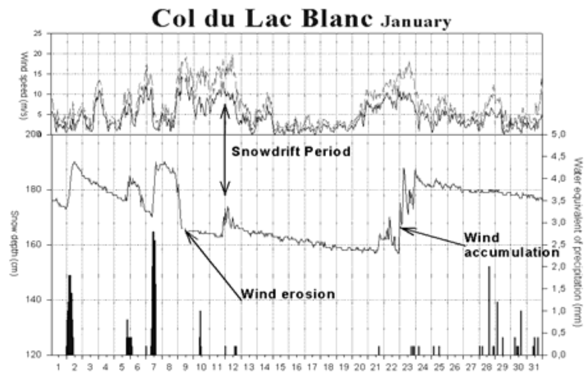

Figure 4: an example of some drifting snow events highlighted by the recordings of sensors.

These measurements, in addition to the automatic data, have led to develop the first specific modeling of drifting snow (Guyomarc'h and Mérindol, 1998a) (Durand and others, 2001).

This last 2 years, in order to verify the model results, we have added 10 points of measurements surrounding the experimental site (apart from around 200 m). At these points snow depth, morphology and types of snow particles are being observed in at least the first 60 cm of the snow pack (figure 5).

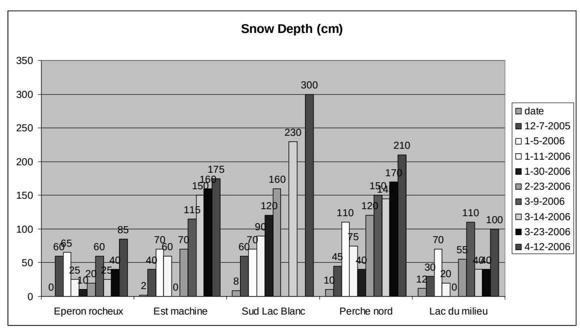

Figure 5: The data from 3 measurement points show the great scattering of snow distribution.

3 – RESULTS OF FIELD MEASUREMENTS

In a first time, lots of measurements have been made at the experimental site, in order to understand the mechanisms of blowing snow movement and the relationship between the type of snow particle and the wind velocity which determine the start of a drifting snow event.

The first way to use the results of measurements and field observations was to define a drifting snow index based on the "driftability" (depending on inter-granular cohesion and shear strength of different snow grains) of the snow particles associated to the wind velocity (figure 6).

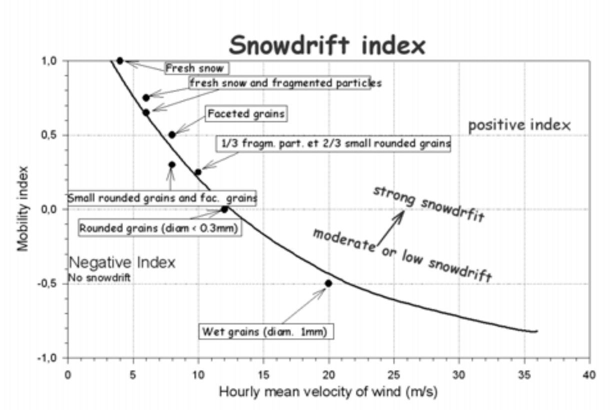

Figure 6: definition of a drifting snow index using field measurements. The Y-axis shows the mobility of snow grains using dendricity and sphericity (Brun and others, 1992) which are directly correlated with the inter-granular cohesion. The X-axis shows the mean wind velocity at 5 m above the snow pack.

This "drifting snow" index was the start of the snow drift modeling, it has to be completed by a wind forecasting model at the relevant scale.

4 – MODELING OF SNOW TRANSPORT BY WIND

A correct avalanche risk estimation requires accurate knowledge of the snow and temperature profile evolution as well as the type of snow grain, the density, strength and cohesion. However, a modeling tool for the estimation of these parameters should incorporate not only the snow from direct precipitation but also that being added by wind transport. In addition we have to take in consideration the morphological transformation of the snow particles due to the wind (Gauer, 2001).

After some winter seasons of intensive observations and measurements during snowdrift events, the CEN has developed some modeling tools by using the results of these studies.

4-1 – Wind field modeling

The need of a specific method for the forecasting of wind at a local scale appears clearly when the orographical effects prevail. It is why several attempts has been made in order to estimate a wind field that we need for calculating the snow repartition in mountainous environment.

The first attempt was a statistical approach using a relationship between the data of the experimental site and the outputs at a greater scale of meteorological models (Guyomarc'h and others, 1998b). The limits of this approach are well known : the applicability of this kind of model is limited to the site where the study has been made.

At present, we use a downscaling process from the meso-scale to the orographic scale using the existing models developed at the CEN/Météo-France. This wind model (Samver) is based on the conservation of the potential vorticity and divergence on isentropic surfaces close to our interest site (Durand and others, 2003). The near-surface wind field is calculated (or estimated) according to topographic patterns (slope and curvature). For simplicity, the wind velocity is kept constant every hourly time-step (figure 7).

A new version, using non-hydrostatic equations, is presently in test and shows improved results especially for the vertical velocity.

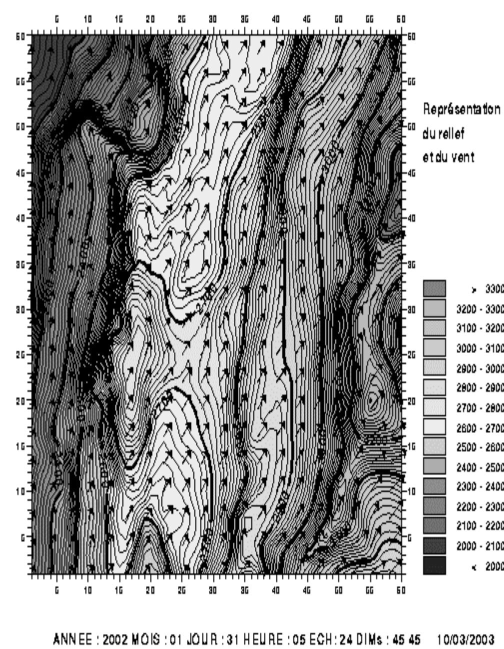

Figure 7: an example of the output of a **Samver** simulation on a limited area integrating the test site.

4.2 - 1D modeling

In order to improve the current operational avalanche risk model, the first development of snow drift modeling (**Sytron1**) has been made on two numerical snow profiles on both sides (South and North) of the experimental site. It determines the snow redistribution depending on wind velocity and direction. This model is now fully integrated into the operational automatic chain. **Sytron1** has been verified by using the field data and has proven to give reliable results at the massif scale (figure 8). Nevertheless, it has shown the need to develop a new two-dimensional application for refined scales.

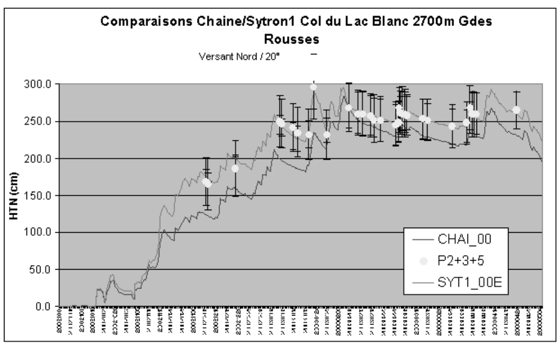

Figure 8: A comparison between the operational chain without effects of wind and **Sytron1**. The dots correspond to field measurements.

4.3 - 2D/3D modeling

The **Sytron2** and 3 versions of drifting snow modeling take advantage of the previous limited realization **Sytron1**. It runs presently on a rectangular grid, with a mesh size of about 45 m, covering an area of 3.0 X 5.0 km around the observation test site. **Sytron2** is initialized with a realistic snow pack representation (up to 50 layers, interpolated at each grid point before being subjected to the wind action) and coupled to a wind field computed by **Samver** (see § 4.1). The model can simulate the occurrence of blowing snow event and estimate the total snow mass transport. The losses due to sublimation, as well as the modifications of density and crystal morphology, are considered. The centre of the modeled domain corresponds to our experimental observation site (figure 9).

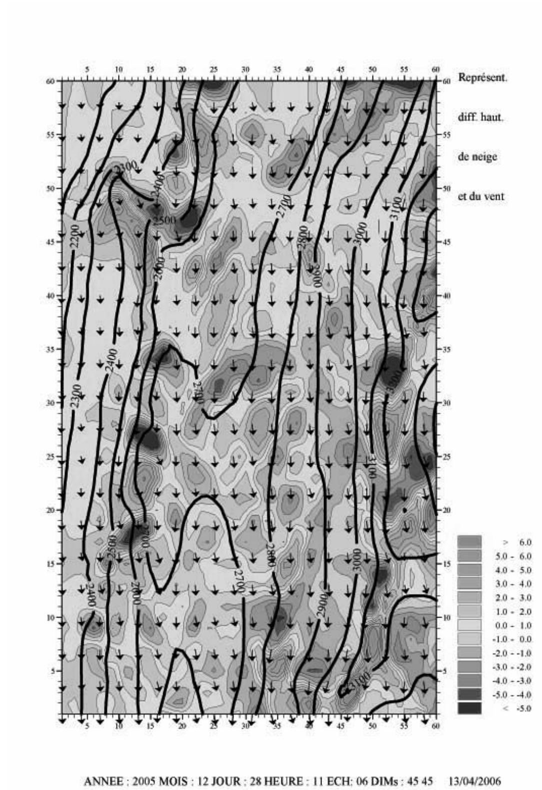

Figure 9: results of **Sytron2** model: estimated wind field, topography and erosion/accumulation areas for the first snow layers.

The last four years, a new formulation **Sytron3** has been developed , the principle is to have a version more physically based while preserving the functioning of the previous version. One of the aim of this new version is to have a less empirically based model, in order to be less directly linked to the field observations and thus to be able to generalize the process to others locations (Durand and others, 2005). The same grid (horizontal – 45 m) is used. However, the large size of the grid cell makes the comparison with observed blowing snow events difficult. It is impossible to take into account the smallest scale which is induced by micro-topography resulting in the formation of sastrugis, cornices and slabs directly involved in avalanche risk increasing.

5 – VALIDATION USING DATA FROM EXPERIMENTAL SITE

The result of drifting snow modeling is difficult to validate because we lack objective tools to observe all the quantities of snow involved. Tests are performed by using different snow-depth pole measurements and photographs of the test site in order to locate erosion and accumulation areas. In addition, a web-cam registers an image of the site each 5 minute time-step and, at a set of ten points, we made complementary measurements of snow depth, type and size of snow particles and snow pack temperature.

5.1 - Image monitoring

Three years ago, a new remote sensing technique was being applied in order to observe by using terrestrial photography the snow surface changes after a blowing snow event. Basically, the idea is to recognize accumulation and erosion areas by measuring their reflectivity and patterns. As the albedo of snow particle are different according to the type of snow grains, especially in near infra-red radiation, we took numerical photography (included photo with spectral filtering) of the observation site from a surrounding point. Then, after an appropriate post-processing, we estimate the albedo of snow surface taking into account the effects of:

- Direct and scattered radiation,
- Reflected radiation from the surrounding topography,
- Atmospheric transmittance

The result is a geo-referenced map of reflectance values that we can fit with in-situ albedo measurements in order to have a map of the relative estimated albedo of snow surface. This map can thus been compared with the albedo of snow surface modeled by Sytron2/3 (figure 10).

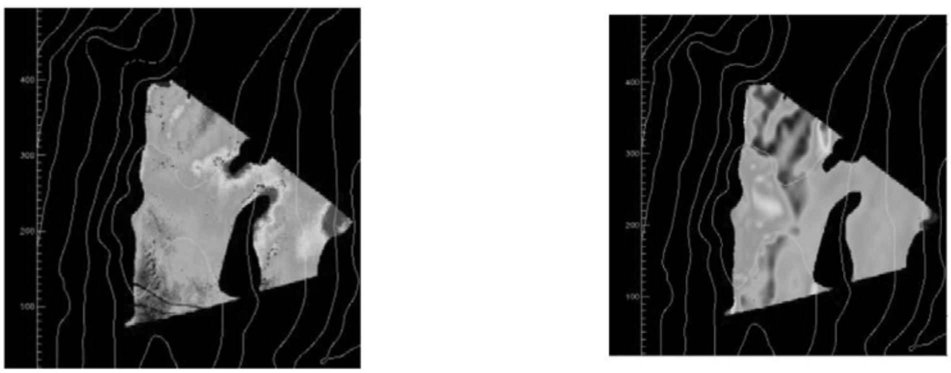

Figure 10: a comparison between the relative albedo map estimated from photography (on the left) and the albedo derived from the model Sytron2 (on the right) at the "Col du Lac Blanc".

This approach is a land-based remote sensing tool based on recognizing the optical variations on snow reflectivity. This novel technique shows satisfactory results in qualitative comparison of modeled and measured outputs at a scale of a few tens meters. The monitoring process has revealed to be a useful tool to detect points in the model that can be improved. The weakness of this validation method is the difference of scale between the model and the photography. The variations of snow depth are not directly measured, but the techniques allow to have a good approximation of the snow distribution due to wind on the limited area.

5.2 – Complementary field measurements

Last winter season, we have started a new set of complementary measurements around the observation site. A dozen points, separated from approximately 200 m, were selected to measure the depth of the snow cover and to determine the types of snow particles. Every weeks, observations, photos and measurements were performed. The figures 11 and 12 show an example of these measurements made during the 2005-2006 winter season, illustrating the difficulty of field observations in order to validate the numerical approach at fine scale on complex topography.

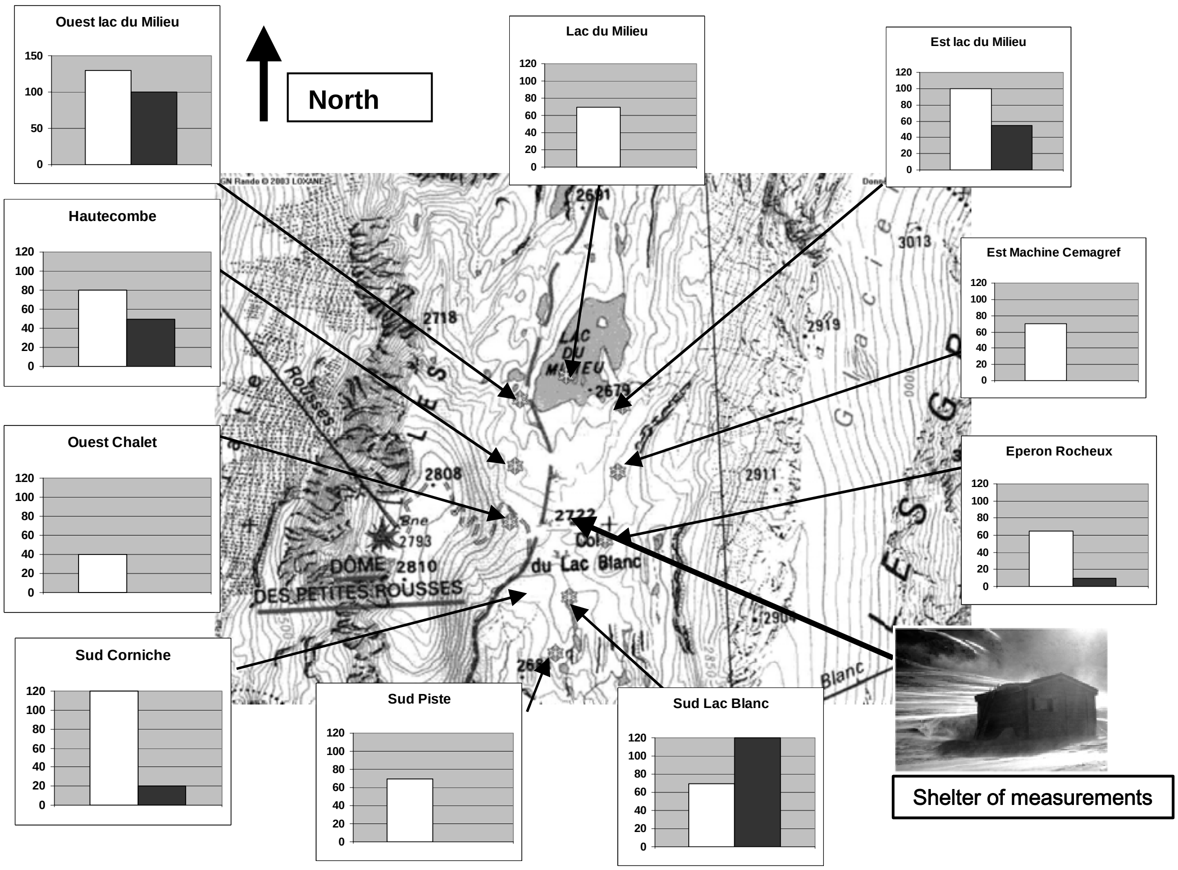

Figure 11: This figure shows the different points of measurements at the experimental site. Each graph shows the snow depth difference between 2 series of measurements (01-05-2006 and 01-30-2006). Around the 15th , there was a snow precipitation (70 cm in 48h) and strong wind from North (up to 22 m/s) just afterwards. We can observe a great difference of snow depth after this period of drifting snow: a great quantity of eroded snow at the site exposed to northern wind and the deposit of snow on some points which are sheltered from wind. These 10 point measurements show the great heterogeneity of the snow distribution after two drifting snow periods.

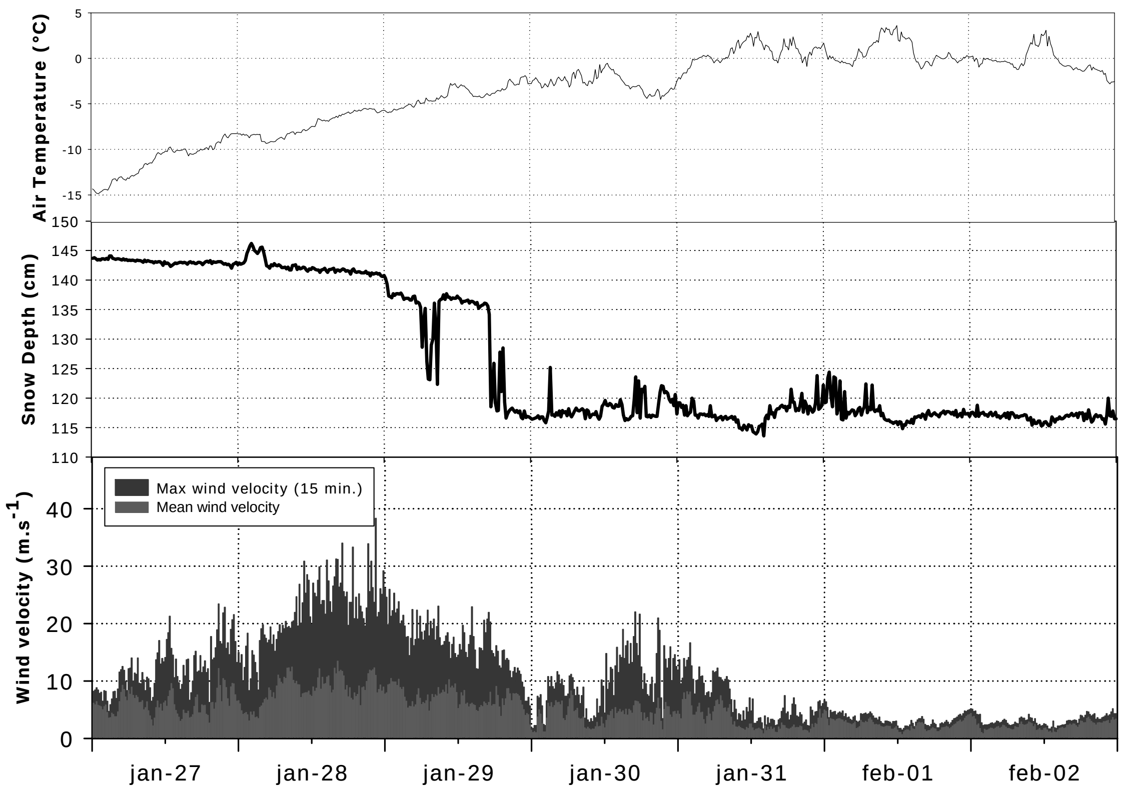

Figure 12: from top to bottom, air temperature, snow depth and wind velocity over the period described in the previous figure.

6 – ACKNOWLEDGEMENTS

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7 – CONCLUSION

The modeling of blowing snow and the redistribution of snow over a large area is a difficult task. Two complementary ways were chosen to go ahead in this direction:

- A rough modeling of drifting snow which can be directly used in the operational models for avalanche risk estimation has been developed. **Sytron1** simply simulates the changes in snow particle morphology and the distribution of snow depending on the wind exposure. This model is validated by using a comparison with the field observations of the test site.
- A 3D approach, using a digital elevation model, is at present under development. This model simulate the evolution of a set of vertical snow profiles taken into account the precipitation, the effects of wind on the snow distribution, as well as the changes in snow particles and the different modes of drifting snow over a limited area. The verification of this modeling is quite difficult because of the difficulty to observe in-situ

the distribution of snow. Because of the computer running time, which is very expensive, of this kind of model (as example, for a simulation of a drifting snow period of 6 hours, the model needs approximately 1 hour of computer time), we can not use this model in real-time. Nevertheless, it can be very useful to simulate afterwards some typical drifting snow events in order to better understand the re-distribution of snow according to the wind velocity field and the topography. We need this information to improve the knowledge of the impact of the wind effects on the snow cover stability, especially for the formation of wind-slab which are at the origin of lots of avalanche accident in the mountainous regions.

This work has continued for more than 12 years of experiments and recorded data from the instrumented site at "Col du Lac Blanc" which gives now a good climatology of the different events. We tried to model the observed wind-transport phenomena while keeping in mind the necessity to build a system able to run operationally or able to improve the operational chain for avalanche risk forecasting.

8 – REFERENCES

Brun, E., David, P., Sudul, M., and Brunot, G., 1992: A numerical model to simulate snow cover stratigraphy for operational avalanche forecasting. Journal of Glaciology 38 (128), 13-22.

Cierco, F.X., Naaim-Bouvet, F., and Bellot, H., 2004: Snow transport rate: field measurements at short time scales. ISSW 2004 proceedings, 205-216.

Corripio, J.G., Durand, Y., Guyomarc'h, G., Mérindol, L., Lecorps, D., Puglièse, P., 2004: Land-based remote sensing of snow for the validation of a snow transport model. Cold Region Science and Technology 39, 93-104.

Durand, Y., Guyomarc'h, G., Mérindol, L. and Corripio G., J., 2004: Two-dimensional numerical modeling of surface wind velocity and associated snowdrift effects over complex mountainous topography. Annals of Glaciology, 38, 59-70.

Durand, Y., Guyomarc'h, G., Mérindol, L. and Corripio G., J., 2005: Improvement of a numerical snow drift model and field validation. Cold Region Science and Technology 43, 93-103.

Gauer, P., 2001: Numerical modeling of blowing and drifting snow in Alpine terrain. Journal of Glaciology, 47, 97-110.

Guyomarc'h, G and Mérindol, L., 1998a: Validation of an application for forecasting blowing snow. Annals of Glaciology, 26, 138-143.

Guyomarc'h, G., Mérindol, L. and Olafsson, H., 1998b: A method for the forecasting of wind in mountainous regions. ISSW 1998 procedings, 171-177.

Guyomarc'h, G., Durand, Y., Lecorps, D., Mérindol, L. and Puglièse, P., 2004: 2D snowdrift modeling and validation. ISSW 2004 proceedings, 227-231.

Mérindol, L., Durand, Y. and Guyomarc'h, G., 2000: Simulation of snowdrift over complex terrain. Icam 2000, proceedings, Innsbruck (Austria), 9/11-15, 2000.