BLOWING SNOW AND AVALANCHES

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INTRODUCTION

Blowing snow is one of the most important factors for avalanche forecasting, but the effect of this phenomenon is difficult to quantify and most observations are based on experience. The importance of this phenomenon has been known for a long time, essentially through empirical and field observations. However, the transport of snow by wind is not actually taken into account in most of models for avalanche hazard forecasting. The objectives of our research is to fill this void, in a first time by field measurements and then by developing models to help avalanche forecasters.

Over the last five years, three laboratories, specialised on snow research, have conducted a research program called "Snow, Wind and Avalanches". In this paper we describe experiments conducted in a high altitude site equipped for this aim.

BLOWING SNOW EFFECTS

Framework

The effect of wind on snow grains begins during a precipitation. The weak structures of crystals are quickly fragmented and their size decreases. If the wind starts to blow soon after a snowfall, snow flakes begin to move as soon as wind velocity reaches a threshold characteristic for each type of snow. Threshold wind speed depends on air temperature, time since snowfall or deposition and on the quality of the cohesion between snow particles.

Redistribution of snow by wind is essential for snow-slab formation. Snow particles are picked up in windward zones where the wind near the snow cover surface is efficient and deposited in leeward zones. This deposit is often at the origin of overload that can conduct to slab avalanche release. The small fragmented particles will have several contact points and tend to bond in a time depending on snow grain size and air temperature, by sintering effects. So these snow grains produce accumulations with more or less high cohesion and hardness.

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Research directions

The adopted method aims to investigate and analyse the main phenomena, to study the relationships between transported snow and avalanche activity and to introduce the results of this research in forecasting avalanche models in order to improve them.

Our understanding of blowing snow mechanisms has begun with several observations and measurements on an high altitude site. In mountainous regions, the local topography is very important and the effect of snow transported by wind has been less studied. For this reason, we have quickly chosen to equip a site in order to record meteorological conditions and to take measurements during strong wind conditions and snow storms.

In a second time, we have used the collected measurements to develop a snowdrift forecasting model and to validate existing models. Another way is to make work together complementary avalanche forecasting models such as the chain **Safran-Crocus-Mepra** (respectively Durand-93, Brun-92, Giraud-94) developed by the CEN and **Elsa** (Buisson-93) developed by the CEMAGREF.

FIELD MEASUREMENTS

Experimental site

For this research program, we have chosen a large pass ("Col du Lac Blanc"-2700 m a.s.l.) north-south oriented, where the wind is similarly canalised, excepting cases of east bound catabatic wind. Above this site ("Dôme des Petites Rousses"-2800m), we can follow and observe avalanche activity on two east oriented slopes: one of it is artificially released according to the snow cover conditions, the other have a completely natural avalanche activity.

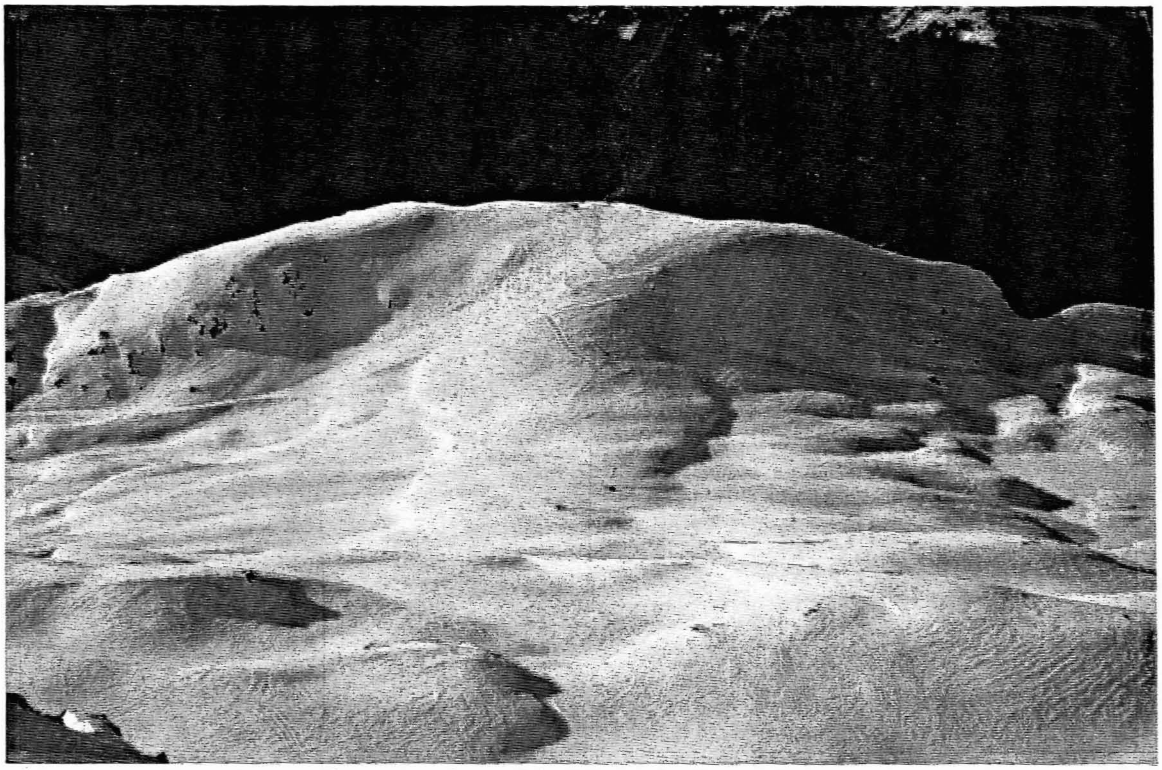

Fig 1 : View of the south-eastern slope of the "Dôme des Petites Rousses" experimental site.

Instrumentation

Several parameters (air temperature, wind direction and velocity, snow depth (two locations on each side of the pass), snow cover surface temperature and water equivalent of precipitation) are hourly recorded on a sheltered computer and transmitted to Grenoble on request (Guyomarc'h 93 - Castelle 94). For 2 years, we have completed these measurements with another meteorological automatic station at the top of the "Dôme des Petites Rousses".

In addition to this instrumentation, one sensor has been developed in order to detect beginning and end of snow transport periods. One of this "Snow Particle Counter" has been set up at the "Col du Lac Blanc" pass and three of them have been mounted on a mast, one above the other, at the "Dôme des Petites Rousses" to obtain a vertical profile.

Measurements

Our goal is to measure precisely the different wind velocity thresholds allowing snow transport in connection with the morphological and physical features of snow particles and to analyse the wind effects on the snow distribution. Thus as often as possible, we have completed these automatic measurements with manual observations in order to describe with a maximum of details each period of snow drift :

-before snowfalls or strong wind conditions, we made snow pack observations (type of snow, density, temperature profile, shear strength, surface conditions, ...) in the first meter near the snow cover surface. Stereo-photographs were taken at this moment.

-during snow storms or snowdrift periods, drift flux measurements were made at different levels above the snow surface and wind profiles were neared.

-after these periods, we made once again snow pits. If a slab avalanche has been released, we made snow profile observations on the failure and studied slab stratigraphy. Snow redistribution due to the snow drift and slab geometry (width and length) were measured by a photogrammetric technique.

Several samples of snow grains were collected at the different previous steps and then transported in a cold laboratory where they have been analysed under a microscope. We have recorded the pictures of grains on a video-tape and then determined the characteristics of wind drift snow particles. These observations have been very useful to associate snow morphological parameters and wind velocity.

Over the last season, we took regularly measurements on two horizontal snow profiles along a slope submitted to wind effects. These measurements gave us the possibility to follow the evolution of the snow depth during snow drift events.

RESULTS AND TOOLS DEVELOPED FOR AVALANCHE FORECASTING

One of our concrete objectives is to provide to the users (avalanche forecasters, snow safety services, practitioners, ...) some snow drift diagnostic tools for a better understanding of wind effects on snow in mountainous regions.

Snow particle mobility

For our objective it was then necessary to know precisely the state of snow cover surface day after day. For this we have used **Safran-Crocus** to simulate on the experimental site the evolution of the snow pack (see figure 3). The first model (**Safran**) provides to the second one (**Crocus**) an estimation of relevant meteorological parameters. Then **Crocus** gives for our site a detailed stratigraphy of the snow cover. One of the most important problem is to have a good description of snow grain characteristics, so a modification of the used formalism has been necessary to describe snow evolution as a function of continuous parameters. These variables are dendricity, sphericity and grain size. Dendricity varies from 1 to 0 according to the part of the original crystal shapes which is still remaining in a snow layer. Sphericity varies from 0 to 1 and describes the ratio of rounded versus angular shapes. Figure 4 shows the relation between these parameters and the international snow classification.

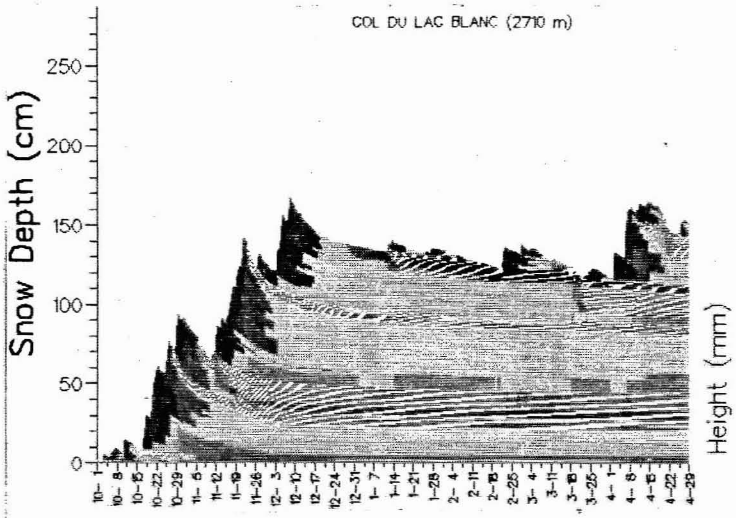

Fig 3 : Evolution of stratigraphy on the experimental site simulated by CROCUS throughout the whole winter 1992-1993 season.

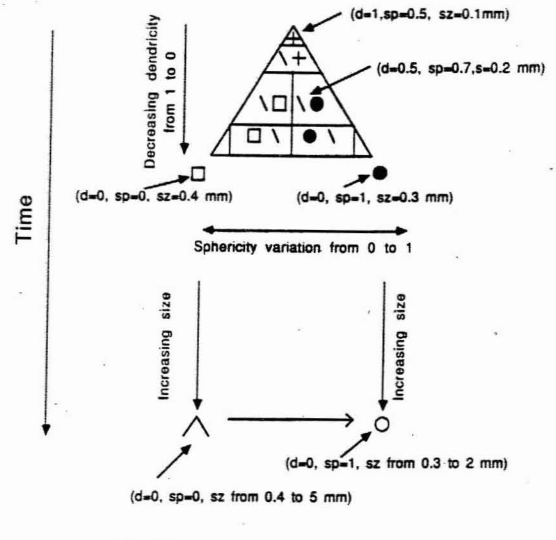

Fig 4 : Correlation between formalism used to describe snow types with continuous parameters and the International classification (from Brun-1992).

From an empirical approach, we combined grains morphology, cohesion between snow particles and grain size to define a function given a "mobility index". From the top, snow pack has been analysed and for layers simulated by **Crocus**, we calculate this index (m.i.). For each type of snow particle, it has been necessary to describe snow with the same parameters that in **Crocus** profiles. We have separated the analysis in two cases :

- For the first one, fresh snow is still present in a layer (its dendricity is then greater than zero). In this case the possibility of snow transport depends essentially on sintering cohesion between snow grains. The function is :

$$\text{m. i.} = 0.75d - 0.5s + 0.5$$

d : dendricity (1 to 0) s : sphericity (0 to 1)

-in the other case, the grain type is only the result of snow metamorphism and its possibility of being transported by wind depends on its size and sphericity. The used function is then :

$$\text{m. i.} = -0.583gs - 0.833s + 0.833$$

gs : grain size (0.4 to 1.5) s: sphericity (0 to 1)

It has been considered that a crust layer greater than 3 mm or a wet layer prevents the possibility of snow drift and consequently stops our analysis. This mobility index takes a value between 1 for fresh recent snow and -1 for spherical melted snow. It will be considered that each layer associated to a mobility index is potentially movable.

Snow drift Occurrence

The last step of our study consists in associating both previous information (m.i. and wind's velocity) to forecast the occurrence of snow drift for a day by 6 hours steps. By using our measurements and observations on site over the last 4 years, we have determined for several type of snow each wind velocity threshold which allows snow drift in connection with different types of snow. Thus, we have compared each 6 hours step the snow mobility index value with the forecasted wind velocity. Then it has been possible to define a function using snow mobility index and wind velocity which discriminates between no transport cases and the others, we calculate the snow drift index (s.i.) as below :

$$\text{s.i.} = -2.868*(\exp(-0.085*w)-1-mi$$

w : wind velocity mi : mobility index

If the value of this function is positive snowdrift will be forecasted on the site (figure 5) and we will provide the thickness of the wind eroded layer (figure 8).

A snow drift event forecasting model

Avalanche hazard forecasters have to evaluate, among number of other parameters, the wind's effect on the snow distribution and on the snow pack stability to determine the risk of slab avalanche release. One of their problems is to know if snowdrift appears at the current time on a site. It is why we have used our field measurements to develop a model called **Proteon** (**PR**évision de l'**O**ccurrence de **T**ransport **EO**lien de la **N**eige - Forecasting of Wind Snowdrift Occurrence). The method presented below consists of :

-an estimation of the wind velocity on the site by using a statistical method.

-a simulation of the snow particle mobility at snow cover surface.

-a calculation of a "snow drift index".

Wind parameters estimation

This first part of our application has been developed to estimate wind velocity and direction at the "Col du Lac Blanc". For our study, we use an extraction of a meteorological model analysis : the European Centre for Medium Range Weather Forecasting, and then we search for statistical relationships between their estimated results (on a 3X3 grid covering the French Alps) of every synoptic meteorological points and wind measurements on the site. We have used multi-linear regression methods to calculate equations for the daily calculation of wind direction and velocity. The comparison between measured wind parameters (over the last season not included in the learning file) and the forecasted one done with our method is shown in figure 2. In most cases wind velocity is well estimated. The highest difference of wind direction appears only with low velocity (under the threshold of snowdrift start), in the other cases analysed direction is quite correct.

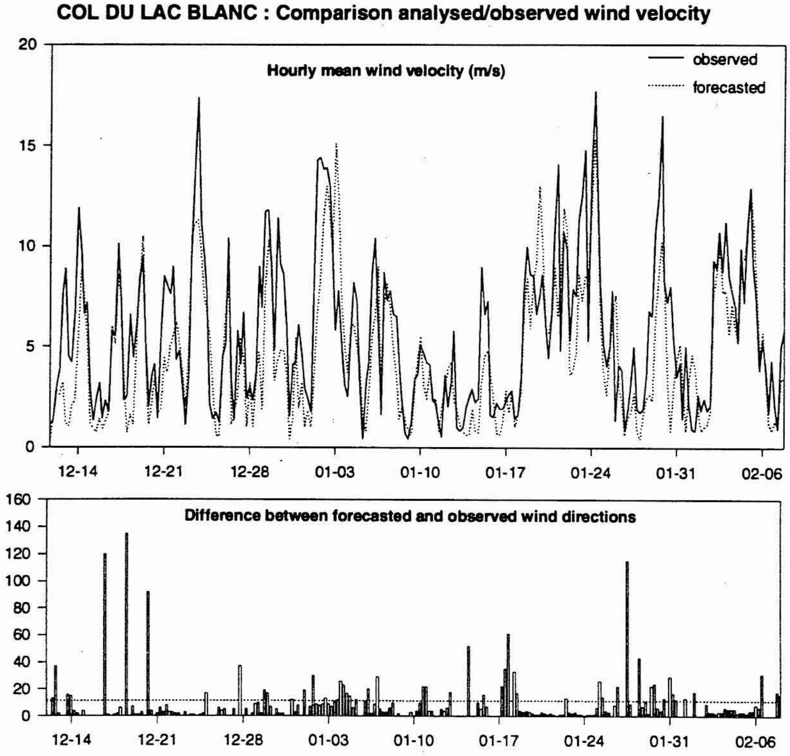

Fig 2 : Comparison between measured wind velocity (continuous line) and the analysed one (dotted line) on the "Col du Lac Blanc" site. The graph below shows absolute value of difference between forecasted and observed wind's direction (dotted line represents the mean).

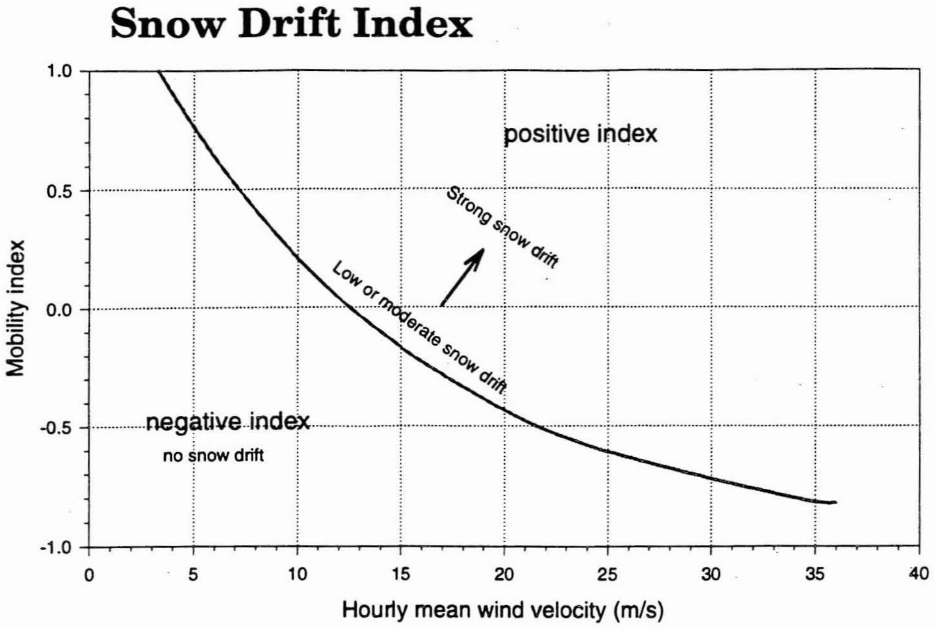

Fig 5 : This graph shows the 2 domains of index values.

We can display on a graph the evolution of this "snow drift index" for the last 7 days. These information are available for an avalanche forecaster on his computer screen (figure 6).

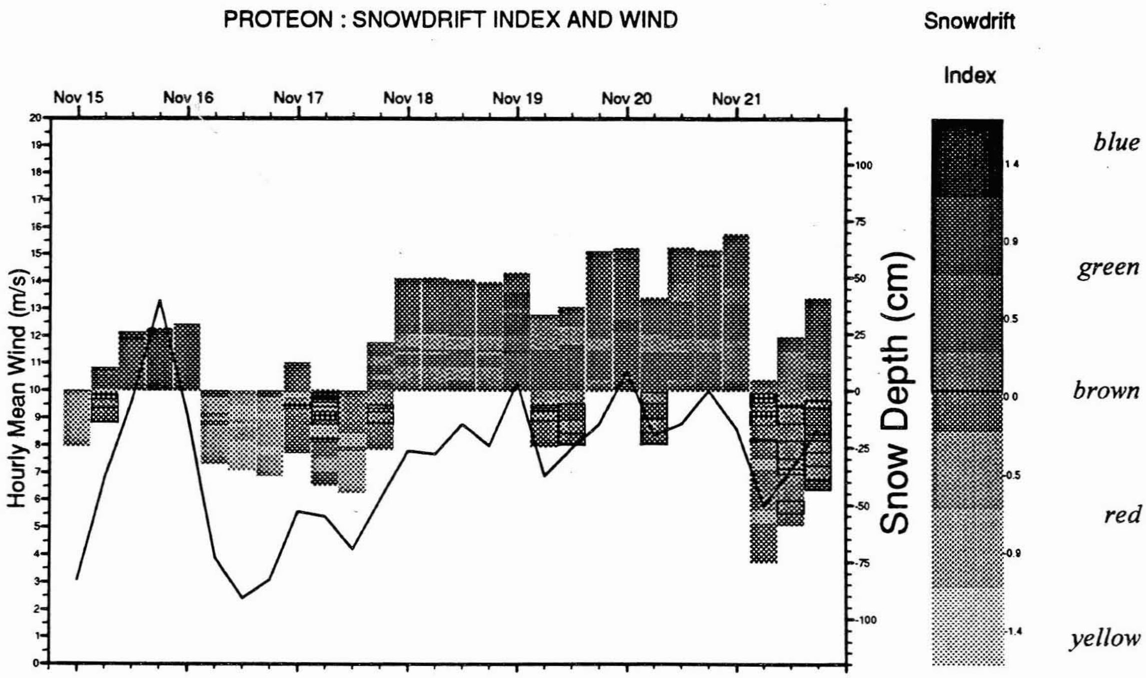

Fig 6 : Evolution of the "snowdrift index" on the site between the 16th and the 30th of November 1992. The Y axis figures the snow depth that could be eroded by wind. Green and blue colours (dark grey) describe a positive snowdrift index for the snow layer (snowdrift occurred). Yellow and red colours (light grey) describe a negative snow drift index for snow layers which cannot be eroded by the forecasted wind's velocity. These layers are drawn under the zero line.

Test and validation of the model

For the validation of this model, the snowdrift index has been calculated, for each 6 hours step on the 92-93 winter season, by using measured wind's velocity. Then it has been compared with the snow drift periods detected on the "Col du Lac Blanc" site by using different sensors. We have used the difference between the hourly maximum and minimum values of the depth sensor, when this difference increases more than 3 cm we have established that a snow drift event occurs on the site (or a snowfall, but we are able to detect it by using the heated precipitation gauge).

The results of this comparison (made each 6 hours for a total number of 776 cases) are reported on the figure 7.

Forecasted events / **Observed events**	Without snow drift	Snow drift
Without snow drift	75.7 %	14 %
Snow drift	2.3 %	8 %

Fig 7 : Comparison between observed snow events and simulated ones (Proteon) on 776 periods of 92-93 winter season

On this period we have been able to detect about 80% of the snow drift events which represents only 10,3% of the time during the winter season. But we will have wrongly forecasted snow drift in 14% of the time (false alarm). We can expect to ameliorate this result : actually, we don't know exactly the necessary time to remove a layer of snow. So when the same conditions (snow surface state and wind velocity) remain more than 12 or 24 hours, the same thickness of transported snow will be forecasted for each 6 hours step . For the next winter season we plan to explore this way by measurements along an horizontal profile. In conclusion : the more field observations and measurements we will get, the better the validation of the computer models will be, especially to perfect the snowdrift index function.

This application is integrated in the **Safran-Crocus-Mepra** computer chain for an experimental test in practical conditions and will be used by the avalanche risk forecaster from Grenoble next winter season (figure 8). These information can be transmitted, on request, to the Snow Safety Service of Alpe d'Huez. One must not forget that this tool is built to be used by forecasters, that means results must fit forecaster's hopes, and this is not always measurable in terms of correlation coefficients and contingency table.

Date	09-16-94			09-17-94				09-18-94	
Hour	6h	12h	18h	0h	6h	12h	18h	0h	12h
Proteon's wind	1 var	4 180	2 360	7 360	2 10	2 20	2 20	1 var	2 20
Snowdrift	no	no	no	yes	no				
Movable thickness				16					
pot. movable thickness	19	21	24	15	33				

Figure 8 : Table of Proteon's results as it will appear for the forecaster.

DISTRIBUTION OF SNOW

Determination of the snow distribution by photogrammetry

We use terrestrial photogrammetrical techniques to estimate :

- the spatial redistribution of snow by wind in the leeward slope of the "Dôme des Petites Rousses" after each snowstorm;

- the slab position and geometry.

During two winter seasons 1992-1993 and 1993-1994, about 20 pairs of photographs were taken from the "Col du Lac Blanc" to the "Dôme des Petites Rousses". The photograph dates correspond as closely as possible to the beginning or to the end of a snowstorm. It is therefore possible to assume that the snow cover state is directly influenced by the snowstorm.

This technique allows us to obtain a lot of information concerning the distribution of snow-cover on the slope.

FIRST TEST OF THE SYMBOLIC SIMULATION OF SNOWDRIFT

Elsa (Etudes et Limites de Sites d'Avalanches) is a knowledge base system intended for avalanche paths analysis for avalanche engineering (Buisson, 1993). In this model, snow redistribution is simulated with empirical knowledge. In order to test the result of the snowdrift analysis in **Elsa**, we used our measurements on the "Dôme des Petites Rousses".

In ELSA, the topography is described mathematically by a digital terrain model. This terrain model was provided by stereo-photogrammetry. In order to analyse the terrain, ELSA used a unit of terrain considered to be homogeneous according to the criteria of the avalanche path analysis as slope, exposure and distance to the main ridges.

In order to estimate distribution of the snow on each "panel", several parameters has been used : relative position of the panel to the ridge incidence, angle between the wind and the ridge, shape of the ridge. The results of the snowdrift analysis are an empirical distribution of a coefficient between 0 and 5. A coefficient of 1 means that the snowdrift has no effect. A coefficient less than 1 means that there is wind erosion, a coefficient greater than 1 means that there is deposition of snow due to wind (Buisson, 1993).

Validation of this analysis consists of : to select wind and snow transport measurements at the south-eastern slope of the "Dôme des Petites Rousses" and to compare the simulated distribution of the snow with distribution measured on the field. Only a simple and characteristic blowing snow event (single wind speed direction) was chosen.

The validation has been realised on a period (5th to 14th of April 1994) chosen for its regular wind direction (North). In a first analysis, it appears that :

- most of the points are snow erosion areas (points where the new-snow depth is lower than one meter, which is the quantity of the snowfall);

- the points of important snow erosion are on a steep slope.

All these results were compared with the simulation of this meteorological episode. **Elsa** takes into account the transportable snow depth, the wind direction and speed, to "point out" where the snow erosion and snow accumulation zones are. These first results of this comparison show us that it is possible to choose some realistic parameters in **Elsa** to obtain a qualitatively good simulated distribution of the snow on the slope.

CONCLUSIONS

Our next work will be :

- to take into account the results of the practical tests with **Proteon** and to quantify the necessary time to erode snow layer,

- to study the opportunity of running together the avalanche path analysis (**Elsa**) and the chain **Safran-Crocus-Mepra** which is used to simulate temporal evolution and stability of the snow pack. These systems are at current time totally independent, but their complementary suggested associating them to study the functioning of an avalanche site submitted to snow transport by wind.

We will validate these models running together by using the field measurements that we have already recorded and the expected variables of the next winter season.

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PROJECT ORGANISATIONS

Financial : Pôle Grenoblois - Rhône-Alpes Region - French Government

Technical : Snow Safety Service of Alpe d'Huez (SATA)
Association Nationale pour l'Etude de la Neige et des Avalanches

Scientific : Centre d'Etudes de la Neige - METEO-FRANCE
Division nivologie - CEMAGREF
GEOLEP - Swiss Federal Institute of Technology Lausanne