In-situ observations and snowdrift modeling on alpine topography.

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Abstract: Recently, the Snow Study Centre (Météo-France, CNRM) has begun to develop some new tools for the modeling of snowdrift in order to improve the avalanche hazard forecasting. These works use the results of in-situ studies carried out on an experimental site dedicated to multi-field researches on blowing snow and its consequences on the snow distribution and the increasing of avalanche risk.
The current works concern the following axes of development:

- **Protéon** is the first attempt to diagnose the occurrence of snowdrift event depending on the morphological features of the snow grains at the snow pack surface and the corresponding wind velocity threshold.
- **Sytron1** is an operational modeling of snow transported by the wind. This model simulates two aspects of a pass and manages the evolution of the snow pack that undergoes wind effect.
- **Sytron2** is an experimental modeling of snowdrift on a limited area (5X5 km).

At the same time, we have started to take numerical photographs from pre-determined points on our experimental site. By using an image post-processing, we aim to reproduce over the winter season the snow erosion and accumulation zones in order to verify our modeling approach.

Keywords: snow drifting, alpine experimental site, snowdrift modeling, snow cover distribution

1. Introduction.

Since the beginning of the nineteen's, the **Cen** (Snow Study Centre) laboratory (Météo-France) specialized on snow and avalanche researches, has started studies on snowdrift effects in an alpine experimental site. The first step of these works was to multiply and to vary in-situ measurements. To maintain the permanent observation of this phenomenon, many relevant expected sensors were developed and tested at this site.

After some winter seasons of intensive measurements, the **Cen**, according to its own objectives, has developed some modeling tools by using the results of these studies. These works have been focused on the consequences of drifting snow events on the increasing of avalanche risk. Some modeling tools of the phenomenon occurrence and their consequences on the snow distribution in mountainous regions have been developed. At the current time, these tools are tested and continuously improved. The actual goal is to understand how this phenomenon affects the avalanche risk and to introduce this new knowledge in the operational forecasting of avalanche hazard.

This paper reviews the works performed at the experimental site and the various tools developed by the **Cen** team. In a first step (Durand and others, 2001), we have not simulated the phenomena exactly, but we tried to capture their effects in a larger scale simulation; such an attempt has already been mentioned by Gauer (1998b) and led to the model **Sytron1** presently operational at Météo-France. Durand and others (2002) describe the next modeling actually in development, (**Sytron2**). Our points of study have thus been:

- Firstly, various ways have been investigated in order to compute a fine scale wind modeling in a mountainous context.
- Secondly, by using the results of the first approach, two kinds of modeling of snow distribution have been developed on a domain including the experimental site. The development of these new tools is based on a strong constraint: they have to be available for the operational avalanche hazard forecast.

All the various formulations and empirical laws have been verified and validated by using data from the experimental site.

2. The experimental site.

For about ten years, an experimental site has been chosen and set-up with lots of specific devices for the study of drifting snow. The "Col du Lac Blanc" site is situated in the French Alps at 2,700 m asl near the

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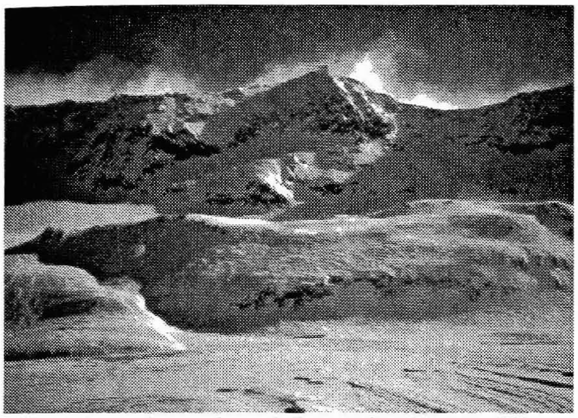
"Alpe d'Huez" ski resort. This site, as well as its climatology, has been described by Guyomarc'h and others (2000). It is representative of a large northern-southern pass where the wind is well channeled according to these orientations (figure 1). Several sensors have been set-up over this place and its surroundings in order to observe and quantify the amount of drifted snow both in the air and on the ground. All these data have been completed with in-situ detailed observations of the snow characteristics, by making snow pits and collecting snow samples during drifting snow events. Thanks to the elevation, the high wind velocity and the quality of snow cover allow lots of observation of the phenomenon (about 150 events over ten years).

This database is very useful for the validation of the models but the large variability of the local orography at very fine scale makes the comparisons with the models difficult.



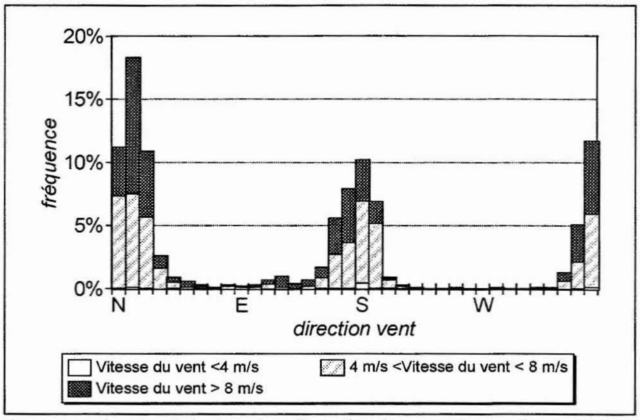


***Figure 1**: winds are channeled according to a northern-southern axis by the "chaîne des Grandes Rousses" on which we can observe eddy diffusion of snow.*

3. Measurements and experimental results.

Among the sensors developed and tested at this site, we have used the data from "acoustic detection of snowdrift" (Font and others, 1998), the results of vertical profiles of snow density, the automatic snow profile device (Guyomarc'h and others, 1996), snow samples, measurements at the snow cover surface, etc., in order to define a snowdrift index (Guyomarc'h and others, 1998a).

This first application (called **Protéon**) was based on three stages:

- Assessment of wind velocity at the experimental site (Guyomarc'h and others, 1998b),
- Estimate of the snow "driftability" at the snow pack surface,
- Calculation of a "snowdrift index".

The snow "driftability" is deduced from the morphological features of snow calculating by **Crocus** (Brun and others, 1989 and 1992) according to in-situ observations. Then by using the observed thresholds of wind velocity, a snowdrift index is calculated (figure 2). This application has been verified firstly by using the recording data of the experimental site and then has been tested in practical conditions by an operational avalanche forecasting service of Météo-France for several winter seasons.

Among the first concluding remarks, we have quoted that the results could be improved by taken into account in a dynamic way the erosion and accumulation of the snow layers in the **Crocus** simulation.

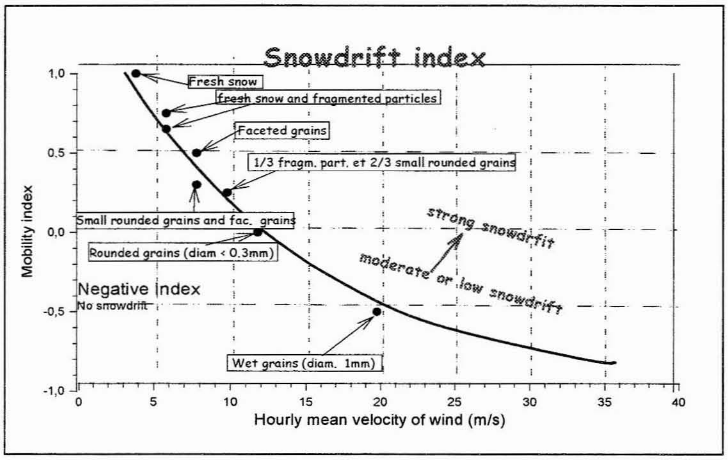


***Figure 2**: the snowdrift index defined from in-situ observations.*

At this stage, the main questions to be answered are summarized in the following points:

- How to manage the local erosion or accumulation of snow in operational tools for avalanche forecasters?
- How to take into account the topography for the re-deposition of the snow in motion?
- How to represent the changing in the particle morphology during a drifting snow episode?

The paragraphs above describe the way we have chosen to solve these problems.

4. The operational context

The currently operational system at Météo-France is based on the **Safran-Crocus-Mepra** chain (Durand and others, 1999) (SCM), which simulates the snow pack evolution at several mountainous points defined by several elevations, aspects and slope angles. Its working scale is of about 500 km^2 and it runs daily on 23 Alpine and 21 Pyrenean massifs over the whole year. SCM provides a set of both meteorological and snow conditions that includes a detailed stratigraphy of all layers. The results are calculated every hour for every "virtual" point by taking into account specific meteorological data. At the present time, the system does not integrate local features of the topography.

This operational suite is used by the professional forecasters in charge of the avalanche hazard estimate in parallel with other information as field observations and contacts with mountain professionals and users.

Except the **Protéon** diagnosis, there is no explicit parameterization of the snowdrift presently integrated in the operational chain.

5. The model Sytron1

5.1 Principle

The first step of this work is thus to routinely simulate the effects of snowdrift which occurs at smaller scales but has consequences at the SCM working scale. In a first approach, the phenomenon is not exactly simulated, but we used parameterizations deduced from the in-situ measurements at the experimental site.

Our points of study have thus been:

- Assessment of a shear wind velocity in order to initiate and to define the intensity of the drifting snow.
- Forecasting of the blowing snow occurrence as an interaction between morphological snow features and the local wind (by using **Protéon**'s method). Calculation of the corresponding rates for creep, saltation, suspension and sublimation have also been taken into consideration.
- Wind advection scheme of the suspended snow and re-deposition scheme have been considered too.

Sytron1 is close of the works made by Liston and Sturm (1998) or Gauer (1998a and b), but does not perform a full estimate over a real topography. For the development of **Sytron1**, we wanted to estimate the amount of snow that is removed from one slope and accumulated on the opposite one in treating only two fictitious points on the two opposite aspects. The evolution of the snow characteristics is determined by the snow model **Crocus** (Brun and others, 1989 and 1992) and was forced by the simulated wind. Special operators for the characteristics modifying of the blowing snow have been added. The computations are done hourly over the winter season, without any reinitialization, by using the transport velocity of the windward aspect.

5.2 Wind estimate

The initial wind velocity used in Protéon was estimated by using a statistical adaptation of meteorological models. It limits the use to a specific location. We have used the same approach as Li and Pomeroy (1997) that consists in linking the drifting wind velocity to the routinely observed wind.

As explained in Durand and others (2001), the wind velocity is calculated from a simple linear interpolation between two **Safran**'s wind velocities (the first one is used by **Crocus** for the heat flux exchanges at the snow surface and the second one is closer to the free atmosphere). This function has been verified at various mountainous locations as showed in figure 3.

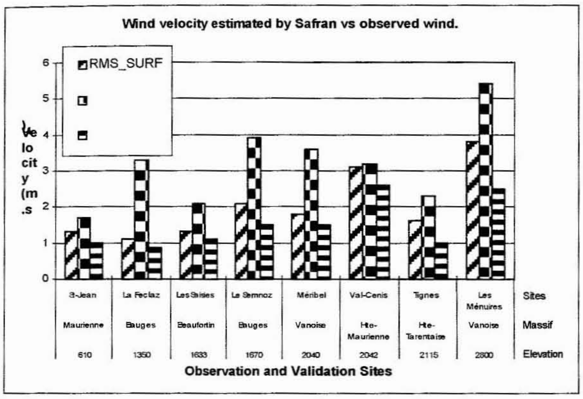


Figure 3: *RMS of the difference between measured values of wind velocity on 8 automatic sites and three SAFRAN wind valuations. The bars noted "SURF" correspond to the surface wind evaluation, while "FREE" represent the simulated "free-atmosphere" wind. The bars noted "MIX" correspond to the wind transport evaluation.*

5.3 Model definition

This approach is operationally developed for the diagnosis and then the estimate of drifted snow amount. In a first time, we have considered a "virtual crest" on the two aspects of the experimental site (Col du Lac Blanc). In order to simplify the parameterization, the snow depth and its variations due to snowdrift are directly used as variables (and not by using a formulation in fluxes as the mentioned authors). The different following parameterizations have principally been deduced from in-situ measurements and observations:

• Occurrence of snowdrift: calculated trough the snowdrift index of **Protéon**.

• Type and rate of snowdrift: the field observations have shown that the main part of the drifted snow is moved by saltation (measurements from vertical snow density). This has led us to simulate globally the two transport modes by using a critical threshold of wind velocity around 4 $m.s^{-1}$. For the suspension mode study, our experimental site is not well suited. It is why we chose to use a formulation from Pomeroy and others (1995). The snow mass that is transported by turbulent diffusion is separated from the amount of snow that will sublimate under the effects of air temperature and humidity.

5.4 Operational way of running

The purpose of the parameterization is to hourly transfer an amount of snow from the windward aspect to the opposite one. This snow mass is added to the **Crocus** profile and stems from a previous snowfall or snowdrift event. The blown snow is then aggregated with the surface layer. Several layers can be eroded at the windward aspect at the same hourly time step. The density of each eroded layer will increase during the snowdrift event. The new precipitation operationally calculated by **Safran** is fully applied to both aspects and the fresh snow is mixed with the drifted one. All these formulations have an implicit self-limitation: the drifted snow is less subject to erosion because of the morphological features of snow that changes during the phenomenon.

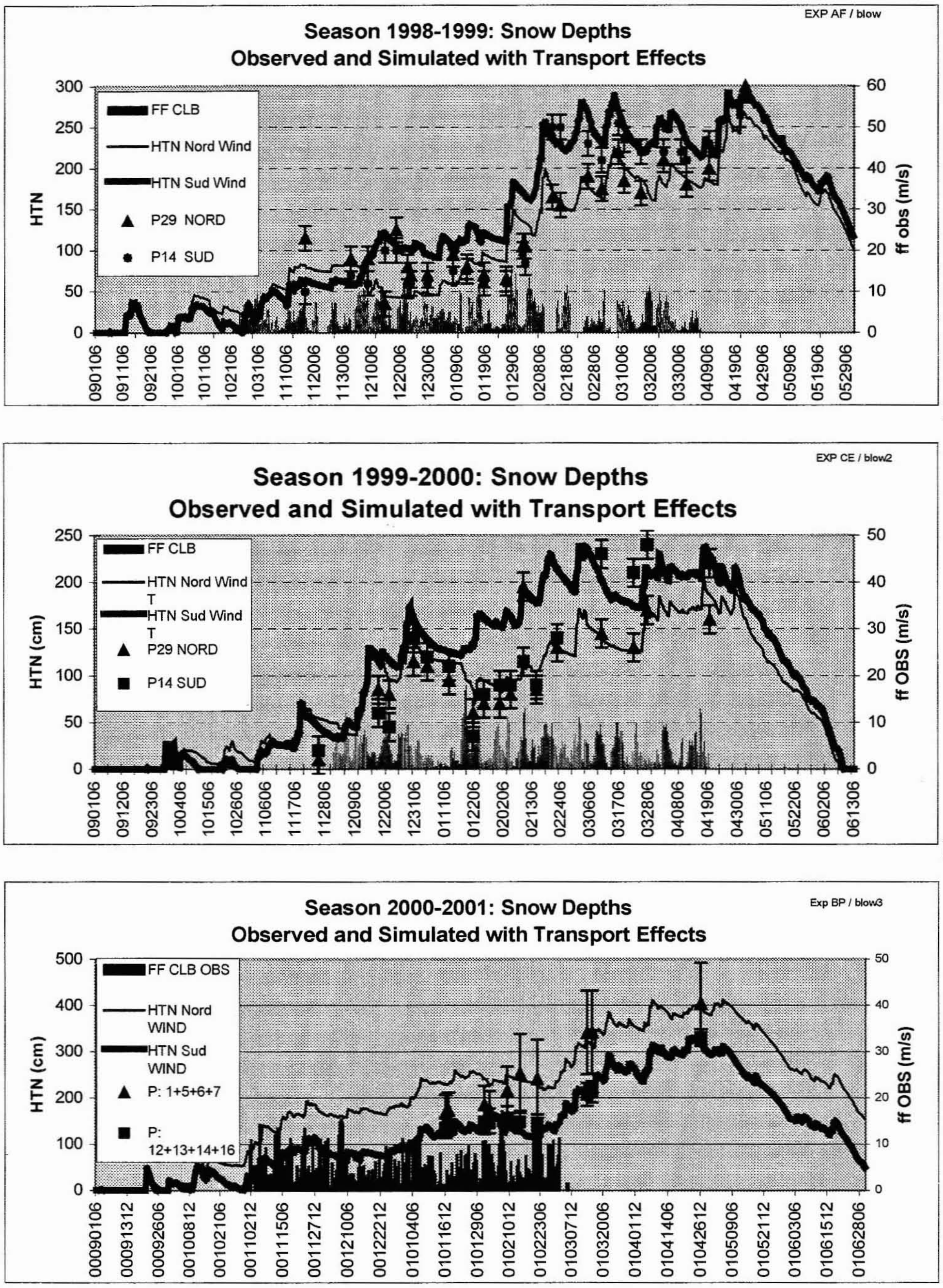
This system must only be evaluated in terms of parameterization inside a larger scale numerical modeling. The principal limitations are due to its functioning in 1D channel with only two fictive points of simulation. The wind field estimation in mountainous areas has to be improved in order to better take into account the local topography, this is one of our priorities (Mérindol and others, 2000) and (Durand and others, 2002).

6. Results and Validation.

All the results presented here referred to the "Col du Lac Blanc" experimental site and correspond to the preliminary tests. The data of this site are only used for validation. The experiment has been continued over the last 4 winter seasons. At this stage of development, the main monitoring is done on the snow depths on both aspects of the experimental site (North and South). The comparison refers to a set of snow poles that has been set up on both sides of the pass and is about 300 m long. But the small scale heterogeneities of this site make the comparison sometimes difficult (figure 4, panels a to c).

Others verifications are performed by comparison with the operational chain results, where no drift effect is integrated (figure 5 & 6). These pictures have been available for the avalanche forecasters since the last winter season.

Since the beginning of the 2001-2002 winter season, we have started to take regularly numerical pictures from determined points. We aim to perform a numerical post–processing on these images to identify the erosion and accumulation zones (figure 7). 12 points surrounding the site have been selected and we expect that this approach will be complementary of the horizontal profiles of snow poles for the validation of the modeling.



panel a

panel b

panel c

Figure 6: The different panels show different simulations of snow depths (HTN) representative of the experimental site (2700 m asl, Grandes Rousses massif, northern and southern aspects) compared to some pole observations during 3 winter seasons (see dates on bottom for each panel). The two lines correspond to the **Sytron1** runs. The thin line corresponds to the northern aspect and bold to the south. The plotted squares (South) and triangles (North) are representative of observed measurements on poles. The vertical bars represents observed wind (right vertical axis).

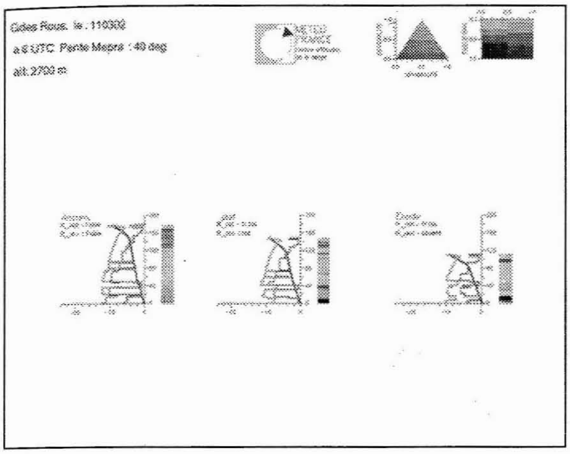


Figure 5: results of ***Sytron1*** *simulation: the left snow profile shows the accumulated snow from the beginning of the winter season and the right one the eroded snow.*

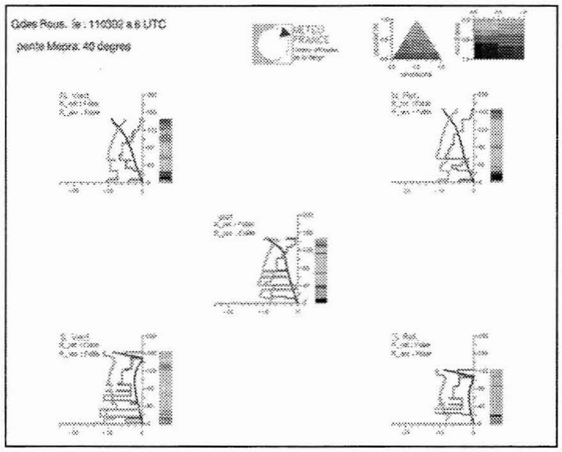


Figure 6: results of ***Sytron1*** *simulation and comparison with the operational model suite (on the right) for North (top) and South (bottom) aspects.*

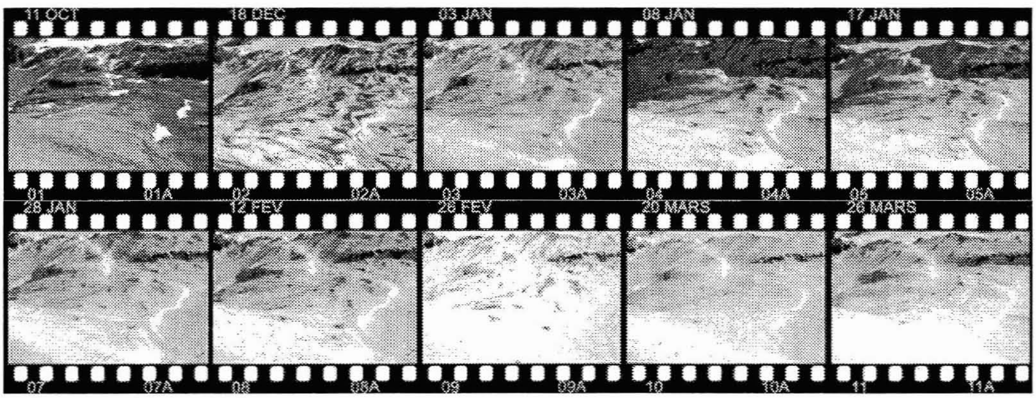


Figure 7: an example of a chronological series of images from the same shot point

7. Conclusion.

The 10 years of measurements and observations from the experimental site have been essential to these first developments and then for the validation of the modeling.

We have begun, by using firstly a simple approach, to insert the effects of the wind transport in an operational suite of numerical simulation of the snow pack, where this phenomenon was not taken into account before. All the different formulations and empirical laws used in the model both for the snow determination and for the wind determination come from the field and lead to a simple wind model.

The main difficulties come from:

- The differences in the length scales due to the involved phenomena,
- The strong influence of the topography,
- And the complexity to get a realistic wind field.

This 1D model (**Sytron1**) is coupled all the year long to the operational SCM suite and modify backward the simulated operational snow packs. The operational avalanche forecaster can visualize the results of these simulations. A 2D model is being elaborated in order to fill the gaps of **Sytron1. Sytron2** is an experimental modeling on a limited area (5X5 km) by using a forecasting of wind field at a small scale and a modeled snow state at a larger scale. The purpose of this new study is to diagnose and estimate the snow amount moved by the wind. Then, the goal is to simulate the distribution of snow on a two dimensional domain by taking into account the local topography. These simulations are made over well-documented periods for which we have in-situ observations (Durand and others, 2002).

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