NUMERICAL EXPERIMENTS OF WIND TRANSPORT OVER A MOUNTAINOUS INSTRUMENTED SITE AT SMALL, MEDIUM AND LARGE SCALES

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Abstract : For about ten winter seasons, the CEN and the CEMAGREF, two French laboratories involved in snow research, have performed intensive field measurement campaigns concerning various snow and weather parameters during blowing snow events. The observation sites are located near the Alpe d'Huez ski resort at elevations between 2700 and 2800 m (Col du Lac Blanc).
In order to determine the avalanche release hazard, it is necessary to take into account the spatial distribution of snow transported by wind in avalanche starting zone. So we have to determine the effect of the wind on the snow cover at the avalanche path scale.
Therefore the numerical simulation of such phenomena, in the framework of the operational avalanche hazard forecast, also began some years ago. All numerical experiments, presented here, benefit from all these archived data and aim at representing the local wind and their effects on the distribution of snow. The main difference is their working scale which can vary from the current operational massif scale (~ 20-30 km) to finer definitions varying between 1 m and 100 m.
The originality of this project consists in the coupling of this different numerical simulations, using outputs from models at large scale as inputs for models at small scale.
First results will be presented.
Keywords : drifting snow, wind, experimental site, measurement, numerical model

1. INTRODUCTION

In the seventies, after a dramatic avalanche accident killing more than thirty people, two research centers were created in France :

- the Snow Study Center (from Meteo-France) which has in charge the coordination of the operational avalanche hazard forecast.
- The Snow avalanche Engineering Unit (from department of Research and Agriculture) which has in charge snow avalanche mapping and related engineering.

Initially the research in these two laboratories were essentially dedicated to studies of snow pack and avalanches dynamics.

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These two teams progressively turned to blowing snow study because of the significance of this phenomenon producing cornices and creating dangerous avalanche starting zones. During ten years ago, they performed field measurement campaigns dealing with blowing snow on a common site in high mountain area. Therefore, they were able to test and validate their own models. Briefly we can say that Meteo France developed numerical models at a large scale (massif scale) to forecast drifting snow events and Cemagref developed physical and numerical models at small scale to prevent snowdrift formation.
Meteo-France developed SAFRAN (estimation of relevant meteorological parameters for snow models including wind speed), CROCUS (snow-pack evolution model) at the massif scale (the working scale is typically about 500 km^2). Meteo France subsequently developed PROTEON, an application for forecasting blowing snow, using the parameters (snow types and wind speed) calculated from SAFRAN and CROCUS.
The Cemagref team developed a numerical model of wind in complex topography called ARIEL,

which is dedicated to solve engineering problems and not to forecast weather. Moreover, they studied physical modeling of blowing snow in wind-tunnel to know the limits of this approach. Afterwards, they carried out a blowing snow numerical model in the framework of engineering, that means at a small scale (the working scale typically ranges between 1 and 100 m). The aim of research in the coming years is the forecasting snowdrift shape at the avalanche path scale by coupling these different numerical simulations, using outputs from models at large scale as inputs for models at small scale.
The global approach and the first steps, validated on a common experimental site, will be therefore presented in this paper.

2. DESCRIPTION OF THE METHODOLOGY

The following described approach is typically a downscaling problem.
The largest scales are treated by the operational suite composed of two main models SAFRAN and CROCUS. SAFRAN is an automatic meteorological analysis which combines and spatializes all the available information, such as observations or meteorological forecast fields, in order to provide hourly the relevant parameters affecting the snow pack evolution. CROCUS, fed by these analyzed data, simulates the different physical and mass processes into the snow cover and its complete stratigraphy.
PROTEON combines this information into a diagnostic application for snowdrift occurrence (Guyomarc'h,1998).
In the framework of those studies, these models are complemented by the model SYTRON which evaluates hourly the amount of wind-transported snow. Coupled with SAFRAN, for the wind computation, and with CROCUS, for the snow profile, it allows to insert into the automatic suite different effects due to the wind as erosion on the windward aspect and a corresponding accumulation on the leeward aspect.
As the previous models are running at the scale of the massif, it was necessary to get a finer scale (~100m) approximation of the surface wind field therefore to develop a small and flexible model coupled to SAFRAN outputs. The model SAMVER, integrating the Euler primitive equations on isentropic vertical surfaces, will be used to initialize different applications running at small scale.
SAFRAN and CROCUS have been presented in several publications (Durand, 1993, Brun,1992) and will not be explained in detail.

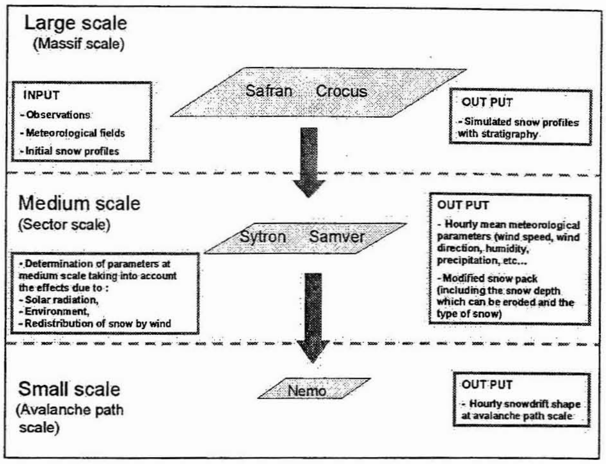

Figure 1 : Downscale of blowing snow numerical models

The NEMO model is dedicated to the determination of snowdrift shape. This numerical model is based on an eulerian approach in the framework of fluid-mechanics conservation laws where the snow is transported and diffused by the air flow. The saltation layer is considered as a boundary condition. The upstream boundary conditions are the wind speed and the wind direction (calculated by SAMVER), the amount of available snow (calculated by SYTRON). The input data depending on snow types (originating from the modified snowpack model) are the threshold velocity and the fall velocity. The threshold velocity could be calculated thanks to PROTEON but the fall velocity is still an unknown quantity and must be therefore estimated.
Moreover the real topography is needed.
This general approach corresponds to a short-term plan but is not yet completely achieved.
Until now, some key steps, which will be explained in this paper, have been performed and validated on a common experimental site.

3. EXPERIMENTAL SITE

The experimental site (Michaux (2000) and Guyomarc'h (2000)) is located on the ski resort of Alpe d' Huez near Grenoble, France,
The large north-south oriented pass (Col du Lac Blanc) has been dedicated to the study of blowing snow in high mountainous regions for about ten years. Indeed, on this site the high wind speeds and the snow cover are favorable to drifting snow. Several parameters (air temperature, wind direction and speed, snow depth, water equivalent of precipitation) are recorded every 15 minutes with a scan rate of one second. Moreover, the

speed and the direction of the wind are recorded in three other places located near the pass (see figure 2). This standard measurement device is supplemented by 6 acoustic snowdrift sensors (Michaux, 2000), consisting of a miniature microphone located at the base of a 2 -m long aluminium pole. The pole is exposed to the snow particle flux, and during blowing snow, part of the flux impacts on the pole (see figure 3). The sound produced by these impacts is recorded as an electrical signal. Until now, the sensor is not completely calibrated : the relation between signal and blowing snow mass flux is not yet given. Nevertheless, it makes it possible to determine in a reliable way the periods of beginning and end of blowing snow events as well as the threshold velocity. Moreover, in order to investigate the three-dimensional spatial distribution of snow during the winter and to determine where snow accumulates and settles for a given meteorological event, we set up a network of metallic snow poles on erosion zones as well as on accumulation zones (see figure 3). A square of 20 fixed poles and a 200 m long profile of fixed poles have been set up. Moreover, on both slopes of the pass (varying around 15°), two areas of about 300 m^2 have been chosen where complementary snow depth measurements (averaged on 20 points) are performed regularly. In fact, the teams climbed to this experimental site at least once a week, depending on snowdrift event forecasts in order to carry out measurements, which are not recorded by data logger (snow depth, stratigraphic profile, ram test, ...).

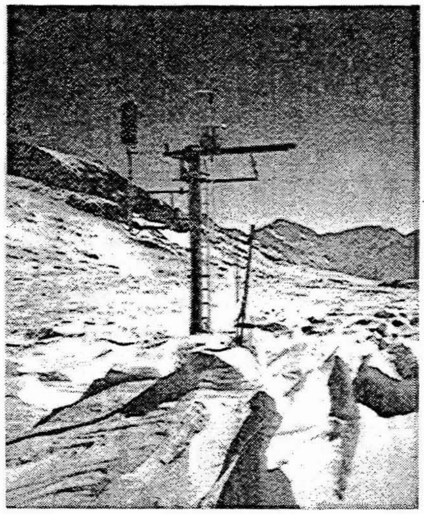

Figure 2 : One point of measurements (wind velocity, wind direction, air temperature, blowing snow) at Col du Lac Blanc near the snow poles network

Figure 3 : Network of fixed snow poles.

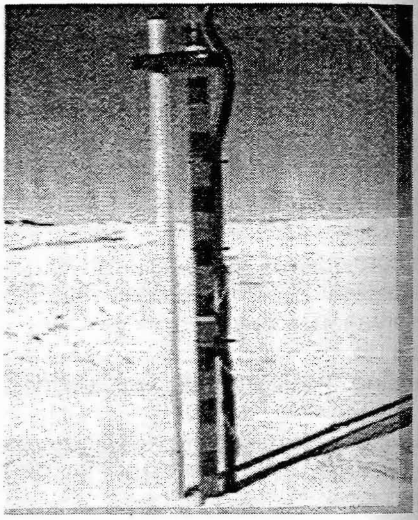

Figure 4 : Acoustic snowdrift sensor fixed to a snow pole.

4. WIND NUMERICAL MODEL AT MEDIUM SCALE : SAMVER

SAMVER is also a downscaling tool, aiming at inserting the effects of the orography into a large scale surface wind field. Initialized by SAFRAN (data provided according to the elevation and the orientation), it provides a surface wind field over a regular grid up to 100 m. The model is based on the conservation of the vorticity and the divergence over different vertical isentropic surfaces. The limitations of such a model are numerous, but it has the advantage to run quickly and is well suited to provide immediate information on all the studied areas.

5. DRIFTING SNOW NUMERICAL MODEL AT LARGE and MEDIUM SCALE : SYTRON.

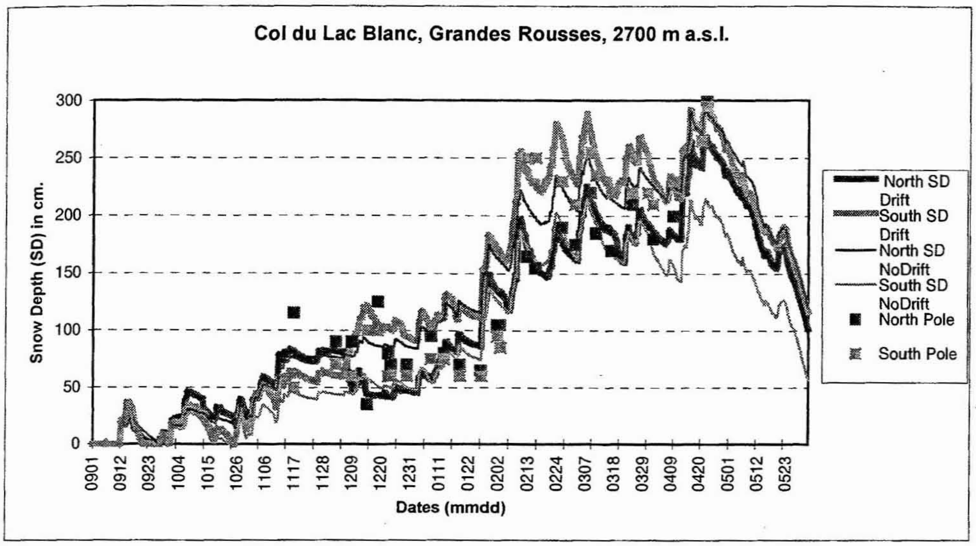

Figure 5 : SYTRON numerical simulations on the 1998-1999 winter season.

Unlike different previous models, we do not want to perform, at large scale, a full 3D estimation of the different transport fluxes over a real orography. As we have simulated hourly information on snow and meteorological conditions at different elevations of the massifs, we stay at this scale in simulating the effects of an "imaginary" crest between two opposite aspects at every elevations in steady-state conditions. We shall thus consider a 1D channel forced by the normal simulated wind where we want to estimate the amount of snow which is removed from one slope and accumulated on the opposite one in treating only two fictitious points. The computations are done hourly over long periods (figure 5), without any re-initialization, using as estimated transport velocity on the windward aspect from SAFRAN; the evolution of the snow characteristics is determined by CROCUS except for the aggregation of the blowing snow. The blown snow is easily aggregated to the new fallen snow if a snowfall occurs during the transport, in a coherent manner. As the computations are done hourly, the different snow-packs change simultaneously and allow the deposited snow (blown or fallen) to be eroded again in the next hour. The different following parameterizations have principally been deduced from in-situ measurements on the experimental site for ten years.

A new version of SYTRON, running at medium scale over realistic orography over some parts of the massif, is under development. Unlike the previous large scale 1D version, it is a full 2D model integrating all the different transport phenomena. Coupled to SAMVER it will provide the different input parameters needed by the small scale models.

6. DRIFTING SNOW NUMERICAL MODEL AT SMALL SCALE : NEMO

6.1 Brief description of the model

In the past years, the Cemagref team studied the physical modeling of blowing snow in wind-tunnel. But the difficulties lied in the disagreement between the scientists concerning the most appropriate sets of modeling requirements, specially for time similarity criteria (Naaim-Bouvet, 1993). Moreover, it was not possible to simulate the evolution of snow pack. Therefore, in the framework of operational snowdrift hazard forecast, Cemagref turns to numerical modelling.

This numerical model is based on a physical model for saltation and turbulent diffusion (Naaim, 1998). The saltation layer is described by its height, its concentration and two turbulent friction velocities, one for the solid phase and one for the gaseous phase. The suspension layer is described by mass and momentum conservation equations. These equations were formulated both for the solid phase and the gaseous phase. The interaction between these two phases was taken into account by an equation based on the drag force of a particle in a turbulent flow. Turbulence was modelled by the k-ε model, in which a reduction of the turbulence with the concentration was introduced (Chen and Wood, 1985). The exchange between the saltation layer and the snow cover was described by an erosion and deposition model (figure 6).

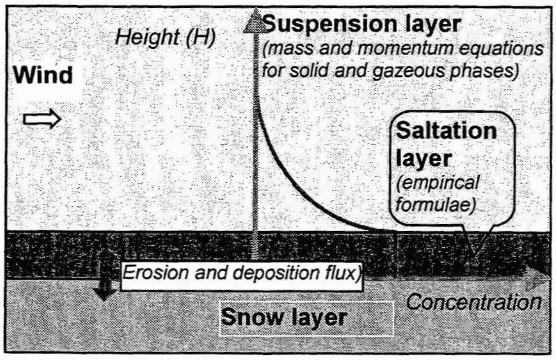

Figure 6 : Principles of NEMO numerical model

The sublimation of snow particles is not taken into account because we consider that its influence is insignificant at this scale. It must be repeated that this physical process is taken into consideration at medium scale.

6.2 Comparison between numerical model and experiments in laboratory

NEMO has been tested by comparing leeward and windward drift equilibrium obtained in a wind tunnel near a small-scale snow fence (Naaim, 1998). The numerical simulations were performed with all input parameters known (fall velocity, threshold shear velocity, shear velocity, mass concentration) which stayed constant throughout the experiment. The obtained results were quite satisfactory (figure 7).

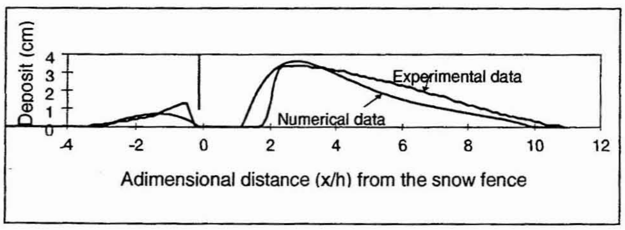

Figure 7 : Comparison between numerical model and experimental data obtained in wind-tunnel around a small-scale snow-fence ($u_*=0.23\ ms^{-1}$, $u_{*t}=0.21\ ms^{-1}$)

6.2 Case of a real blowing snow event

Modification of NEMO model :

The real case, however, is more complex. The input parameters not only change during all the blowing snow event, but the time of computation has to be short in the framework of operational forecasting models. That is why we can not use the fully coupled wind and snowdrift model, as in the case of the simulation presented on figure 6, and some additional assumptions are made.

We consider the flow as a fully developed turbulent flow. A logarithmic velocity profile represented by the friction velocity ($u_*(x=0, t=0)$) will be introduced at the upstream boundary. The outputs of this first calculation on the real topography at $t=t_0$ are the turbulent friction velocity ($u_*(x,t=t_0)$) near the snow surface, the concentration field $C(x,t=t_0)$ near the snow surface, and the mass flux exchange with the snow cover ($M(x,t=t_0)$). So, if we changed the upstream friction velocity at the upstream boundary condition from $u_*(x=0, t=0)$ to $u_*(x=0,t)$, the resulting friction velocity in each cell in contact with the snow cover, $u_*(x,t)$, may be determined by:

$$u_*(x,t)=u_*(x,t=0).(u_*(x=0,t)/u_*(x=0,t=0)) \quad (1)$$

The mass exchange flux with the snow cover is a function of the concentration and the friction velocity near the ground. According to (Pomeroy and Gray, 1990) the saltation mass flux is given by:

$$Q_s \propto \frac{u_{*t}}{u_*}(u_*^2 - u_{*t}^2) \quad (2)$$

where u_{*t} is the threshold friction velocity.

In each bottom cell, the reference saltation mass flux is:

$$C(x,t=t_0).u_*(x,t=t_0) \propto \frac{u_{*t}}{u_*(x,t=t_0)}\left(u_*^2(x,t=t_0) - u_{*t}^2\right) \quad (3)$$

During the episode, in each bottom cell, the saltation mass flux is :

$$C(x,t).u_*(x,t) \propto \frac{u_{*t}}{u_*(x,t)}\left(u_*^2(x,t) - u_{*t}^2\right) \quad (4)$$

From the ratio between these two formulae, we deduce the concentration in each bottom cell:

$$C(x,t) = C(x,t=t_0)\frac{u_*^2(x,t=t_0)}{u_*^2(x,t)}\frac{u_*^2(x,t)-u_{*t}^2}{u_*^2(x,t=t_0)-u_{*t}^2} \quad (5)$$

Comparison between numerical model and field experiments :

The needed inputs of NEMO are the friction velocity, the threshold friction velocity, the fall velocity, the amount of available snow.
We have to keep in mind that NEMO model has to use the output data from SYTRON. This two models (SYTRON and NEMO) have been developed in parallel. Until now, the output data from SYTRON are not completely available. In a first step, we have therefore to use measured data, which will be later forecast by SYTRON, that is hourly mean velocity, average precipitation rate, duration of blowing snow event, given by the acoustic sensors. The snow type, which will be available, allows us to determine the threshold velocity using PROTEON. At the present time we don't know the relation between fall velocity and snow types. Therefore the fall velocity is estimated.
So, by introducing the in situ measured wind velocity (figure 8) at the upstream boundary of the simulation area during the storm, we obtain the following snowdrift shape at the end of the drifting snow event (figures 9 and 10).

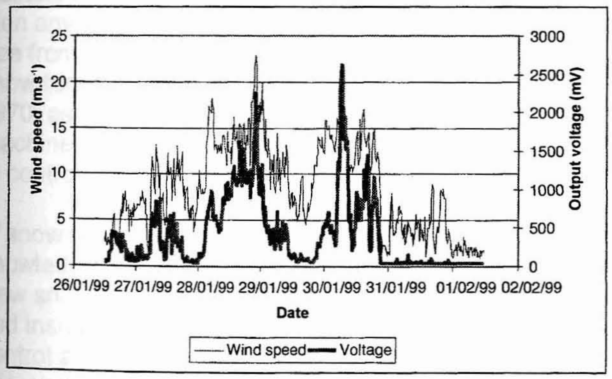

Figure 8 : Wind speed and output voltage from the acoustic sensor during the storm

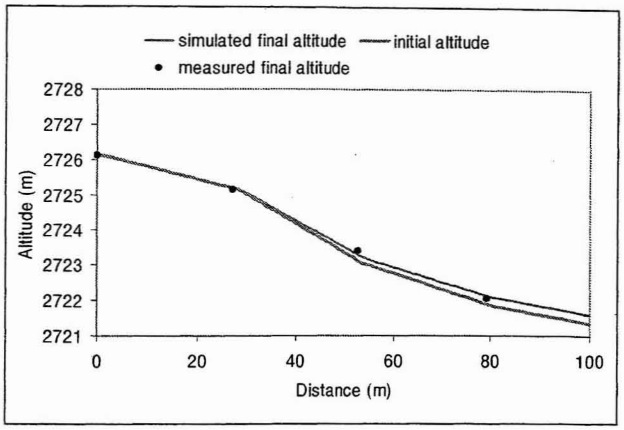

Figure 9 : Comparison between numerical model and experimental data obtained at "Col du Lac Blanc" pass

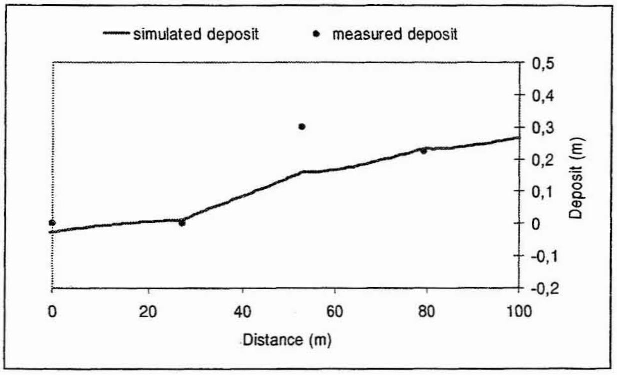

Figure 10 : Comparison between numerical model and experimental data obtained at "Col du Lac Blanc" pass

By comparing the numerical model results with the measured data, we can notice that the numerical model correctly localizes the snowdrift accumulation (figure 9) but an error in the accumulation height can reach 30 % (figure 10). This can be due to the strong hypothesis we adopted or to the empirical formulae we used to determine the flux. Therefore this work will be continued using the fully coupled model on the whole episode and using calibrated data from the acoustic sensor.

7. PERSPECTIVES

Two French laboratories specialized in snow and avalanches research have joined their means and their models to investigate snowdrift phenomena. First results have been presented and further common research is needed in a near future. But this approach only constitutes a first step. Such studies have been carried out with the aim of improving avalanche hazard forecast. We have now to develop and/or improve numerical models of avalanches (triggering and flow) and to include them in the chain of models presented in this paper. That will be our research issues in the coming years.

8. ACKNOWLEDGMENTS

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