# Research and Developments on wind transport at Méteo-France and its modelling.

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**Abstract:** Snow drift modelling is a difficult challenge due to different factors as the large range of the working scales and the permanent interaction between snow, meteorological conditions and local orography. Nevertheless, these phenomena cannot be omitted in the framework of an automatic suite of snow modelling and avalanche hazard forecasting. The present version of this suite runs at a scale of about 400 km$^2$ and provides the "large scale" conditions for wind and snow. The final purpose is to build a new local system, coupled with the larger system, at fine mesh where the drift effects can be modelled. An important task is the development of "downscaling operators" for the initialisation of the local model on a realistic grid of 50m length. This scale, which exceeds the current accuracy of the automatic evaluation of wind and snow in mountainous conditions must be considered carefully. Once initialised with realistic conditions, the 2D drifting model (SYTRON2) is able to simulate the occurrence of blowing snow and to estimate the different snow mass exchanges by creep, saltation, suspension. The losses by sublimation as well as the modifications of density and crystal morphology are also treated. The centre of the modelled domain corresponds to an experimental observation site, located in the French Alps at an elevation of about 2700 m a.s.l where drifting snow events have been investigated for 10 years. These observations allow an useful validation of the modelled results.

**Keywords:** snow drifting, snow cover ablation, snow cover accumulation, snow evaporation, snow modelling

## 1. Introduction.

The main effects of snow drifting are well known by all the mountain professionals at once in matter of safety (avalanche warning, protection of roads and buildings..) and also of management (ski resort, water content estimation..). The purpose of this work is thus to simulate at a fine spatial scale the effects of the wind transport which occurs at different smaller scales but affects larger scales (massif scale) where Meteo-France is in charge of the operational avalanche hazard forecasting.

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 and described also by (Guyomarc'h and others, 2002). The work presented here is its continuation and concerns a more complete 2D simulation based on the model SYTRON2 which run at a finer horizontal scale (~1 km of characteristic length based on a mesh size of 50 m) with a realistic orography at this mesh size.

The main originalities of this work are first its coupling with the operational larger scale meteorological and snow models which provide the initial snow conditions and the wind field every hour and secondly the constant modification of the transported snow during the drift phenomena. The problem of the validation of the result is difficult because we lack of objective tools of observation for the different involved quantities but some attempts will be presented.

## 2. Problem Definition.

Our points of study have thus been :

- Computing an appropriate wind parameter (as the shear velocity) to assess the initiation and the intensity of the snow transport and to force at each time step the wind advection scheme of the suspended snow.
- Defining the occurrence of blowing snow as an interaction between snow characteristics and the local wind. The corresponding snow transport rates for creep, saltation, suspension and sublimation have also to be considered.
- Integrating the modifications of the crystal characteristics of the drifted snow after deposition.
- The re-deposition scheme and the corresponding rates.
- The validation of the results with field data.

All these points will be resumed in the following paragraphs. Concerning the last point, all the numerical simulations (SYTRON1 and 2) are performed around an experimental observation site where observations have been done for more than 10

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years, that just shows how familiar is this location for our team. This site, as well as its climatology, has been described by Guyomarc'h and others (2000). It is located at 2700m a.s.l near the ski resort of Alpe d'Huez in the Grandes Rousses massif and is representative of a large northern-southern pass where the wind in well channelled according to these orientations. 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 but the large variability of the local orography at very fine scale makes the comparisons with the models difficult.

## 3. State of the art.

The well-known general effects of wind transport on the snow pack have been well described by many authors. We shall quote principally Pomeroy and Gray (1995), and Liston and Sturm (1998), because we work in the framework of a numerical operational system of avalanche hazard forecasting and we aim to better take into account the effects of snow accumulation and erosion along the wind-flow direction. Our use of computed snow crystal characteristics, variable in time, is also very close to the approaches of Lehning and Doorschot (1999) or Fierz and Gauer (1998) who combine a complete numerical modelling of the snow cover with additional effects due to the drifted snow.

## 4. Operational context at Météo-France.

### 4.1. The SCM chain.

All these works are based on the operational SAFRAN-CROCUS-MEPRA chain (Durand and others, 1999), thereafter called SCM. Its working scale is of about 500 km$^2$ and it runs daily on 23 Alpine and 21 Pyrenean massifs over the whole year. It is used by the professional forecasters in charge of the avalanche hazard estimation in parallel with other information as field observations and contacts with mountain professionals and users.

The SCM chain simulates the snow pack at different fixed elevations and aspects of the considered massifs. The results are only obtained hourly on three slopes (flat, 20° and 40°), which doesn't represent finely the real terrain. This is one of the main weaknesses of the system, which cannot thus take into account small features due to the local effects of wind, orography or vegetation. No explicit parameterisation of the snow drift are presently inserted, however, SCM provides an hourly set of both meteorological and snow conditions which includes a detailed stratigraphy of all layers; all these quantities are thus mean values representative of large slopes at different elevations and aspects.

### 4.2. SYTRON1.

Unlike Liston and Sturm (1998) or Gauer (1998, a, b) this model does not perform a full 3D estimation of the different transport fluxes over a real orography. SYTRON1 aims only at simulating the effects of an "imaginary" crest between two opposite aspects at all the computation elevations of SCM 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, without any re-initialisation using the transport velocity of the windward aspect. The evolution of the snow characteristics is determined at once by the snow model CROCUS (Brun and others, 1989 and 1992) and by special operators for the modification of the blowing snow. More details on SYTRON1 can be found in Guyomarc'h and others, (2002)

## 5. The model SYTRON2.

### 5.1. Presentation.

SYTRON2 exhibits a lot of differences when compared to SYTRON1 and has been described by Ramalingom (2001). Unlike SYTRON1 and its two "fictive" locations, it is a real 2D model which runs at fine scale on a "real", and so more realistic, orography (DEM: Digital Elevation Model) which grid mesh is about 50 m and a time step of about 2 s. Over its running area, one can so get different aspects, slopes and elevations, which will lead to a complex interaction of the different phenomena of snow transport, erosion and accumulation. The snow initial conditions at each grid point are deduced from the operational SCM snow profiles through appropriate downscaling operators. Presently, the wind field stays constant by step of one hour, the elaboration of this will be presented in further paragraph.

When compared to SYTRON1, two new operators have been added and concern the transport mechanism and the accumulation rates; they will be described later. The erosion occurrence and its rates as well as the morphological modification of the snow deposed crystals (density and grain shapes) are common with SYTRON1; this so allows a common upgrade and improvement of these operators through the distinct validations of these two models with the measurements of the instrumented site.

Presently, the main difference between the two models consists in the impossibility for SYTRON2 to modify backward the snow profiles of the SCM chain after its own run; it is so used now for the study of specific drift events in relationship with the observation of the instrumented site. SYTRON2 is an "open" model which is still in development and different new improvements are in study.

### 5.2. Downscaling operators.

As suggested previously, the main difficulties come from the fact that we have to consider different spatial working scales for different snow and meteorological entities. This has been presented by Bouvet-Naaim and others (2000). The operationally known quantities, as wind or snow state, are at the massif scale but we have to run our models at smaller scales. We thus have to develop different operators suited to derive small scale fields from the corresponding quantities available at the massif scale. This operation is often called "downscaling" and concerns mainly the meteorological fields if we assume that the snow pack is principally forced by the meteorological conditions (and also by the effects of a known fine orography) with weak relationships between different locations. The main affected fields are the wind, the precipitations and the snow pack state which are strongly dependent of the fine scale orography. Presently, no formal modelling can describe exactly these quantities at our working scales and so the used operators are issued from statistical-dynamical methods.

It is presently very difficult to get a realistic fine mesh estimation of the wind field in mountainous conditions because it exceeds over many points both the computer capacities and the state of the art especially in the turbulence formulation. It is also very difficult to validate the obtained modelled results at these scales. We are fully aware of all these difficulties but the modelling of the snow transport is entirely dependant of a prior wind estimation as realistic as possible.

One of the most accurate model for this purpose is Meso-NH (joint program between Météo-France and the Lab. of Aérologie of Toulouse) and described by Lafore and others (1998). This model has been presently validated for simulations in complex areas over a grid of 600m mesh and has participated in several inter-comparison experiments.

We have so chosen to simulate with Meso-NH about 20 specific situations (over the last past winters) where snow transport was observed at the Lac-Blanc site. The purpose was to get a good wind field estimation over a grid of 500m covering our working area. Such a result was obtained by the coupling of 3 embedded forecasts over different mesh sizes (12km, 1200m, 600m). The 20 final wind fields were considered as the best possible estimation at this scale and used then as reference fields. The methods and domains used in these experiments as well other experiments are described in Mérindol and others (2000).

As it is not possible to run Meso-NH routinely, we have developed a simple and crude 2D model covering the range 500m-50m. This model (named SAMVER) is initialised directly by the temperature and wind estimations at the massif scale produced routinely by the SCM chain. It performs then a temporal evolution of the potential vorticity and the divergence over an isentropic surface close of our interest site. The limitations of such a model are numerous and the final wind field evaluation has to be improved. However, the simplicity of this model makes it possible to run quickly on any wished past date or routinely and to provide at a hourly time step a continuous representation of the wind field based on values available at the massif scale. An illustration of the raw wind field issued from SAMVER will be presented on the different figures.

However, this first estimation has to be improved in order to be more representative of the orography at different scales. In order to achieve this purpose, SAMVER ran on the 20 reference situations chosen for Meso-NH and the two wind fields were compared on the same grid. The SAMVER wind estimation, at the scale of 500m, has then been modified in taken into account the topographic slope and curvature in the wind direction in order to be as closer as possible of the reference Meso-NH wind. These relationships, based only on orography features are then used routinely and are very close of those described in Liston and Sturm (1998). Another correction, at the scale of 50m, is also performed and is based on the orography at this scale. The obtained wind is then used as shear velocity as done by Li and Pomeroy (1997) in linking the wind-transport to the measured wind.

### 5.3. SYTRON2 operators.

The base of SYTRON2 is a mass balance equation which guarantees the conservation of the drifted snow mass in the transport operators and manages also the other variation operators as erosion, accumulation and sublimation. The transport operator is included in this basic equation which is treated through an Eulerian scheme; the final result is a change in the drifted snow mass at each grid point along the temporal integration. In parallel, the "variation operators" have also to be computed at each grid point, especially the erosion operator which gives the different amounts of snow mass which is pulled out from the snow bed.

As previously said, only the accumulation operator differs from SYTRON1. It has been assumed that, from an equilibrium conditions, 95% of the drifted snow was re-deposited after a transport along a fetch distance of about 1200m with a wind velocity of at least 15m/s; for lower wind values the fetch distance is reduced proportionally. These values are not completely fixed now and are in field validation. The fetch distance does not take into consideration the way of transport which can be composed of multiple jumps (saltation) or included in turbulence processes (suspension) or others (creep, ...); it gives only a mean composite instantaneous evaluation of the deposition rate for a given wind value and is so characteristic of the distance after which a crystal cannot be mobilised any more by the wind due to its undergone changes in shape and density.

At the difference of the Eulerian scheme used for the transport processes, a Lagrangian method is used to determine the initial characteristics (i.e before transport) of the accumulated snow through the use of the previous fetch distance. Once known, the features of the crystals are modified. The algorism tends to make a new drifted crystal which is closer to small rounded grains than the previous shape; but such transformations are not obtained in one time step and can take more time. The snow crystal characteristics are described by using the parameters of Crocus (Brun and others, 1992). A fresh snow crystal is thus defined in terms of dendricity (1-0) and sphericity (0-1). When drifted, its dendricity decreases and its sphericity increases according to the wind velocity. When the crystal has undergone some metamorphism, it is mainly described in terms of sphericity and size (>0.3 mm). Such drifted crystal will thus decrease in size and increase in sphericity, always in function of the wind velocity. This operator is based on the observation of the drifted crystals, done at the instrumented site for many years. At each grid point and time step, the deposited snow is then added to the snow bed by aggregation to the first layer or through a new layer if the amount is deep enough.

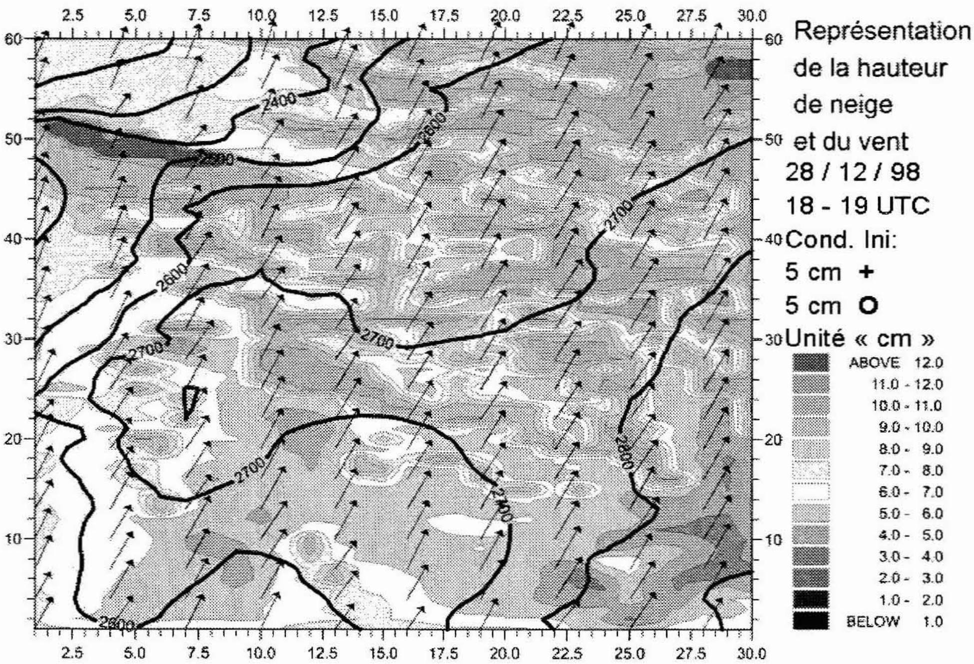


**Figure 1:** *Imaginary snow depth field (in grey code) subject to the effects of the real plotted wind field (darts). The initial and constant snow depth of 10cm has been modified according to the expositions through the action of the different snow transport operators. See details and discussion in the text.*

Fresh snow, in case of snow fall, is simply added to the snow mass in movement and treated as it was eroded snow. This allows a deposition of the fresh snow suited to the wind and orography conditions.

All these formulations have an implicit self limitation; the transported snow is less subject to a new drifting effect during the following hours because it underwent some crystal changes which decrease the corresponding snow-driftability index and thus the transportability.

### 5.4. Results and Validation.

*5.4.1: December 28th 1998 18 UTC simplified case (Figure 1).*

The first results, presented here in Figure 1, exhibit both the raw wind field (without topographic corrections) obtained by SAMVER and its impact over an imaginary snow cover initially composed of 5cm of fresh snow (+) on the top and 5cm of rounded crystal (o) at the bottom (10cm of snow depth everywhere without effects of altitude or exposition).

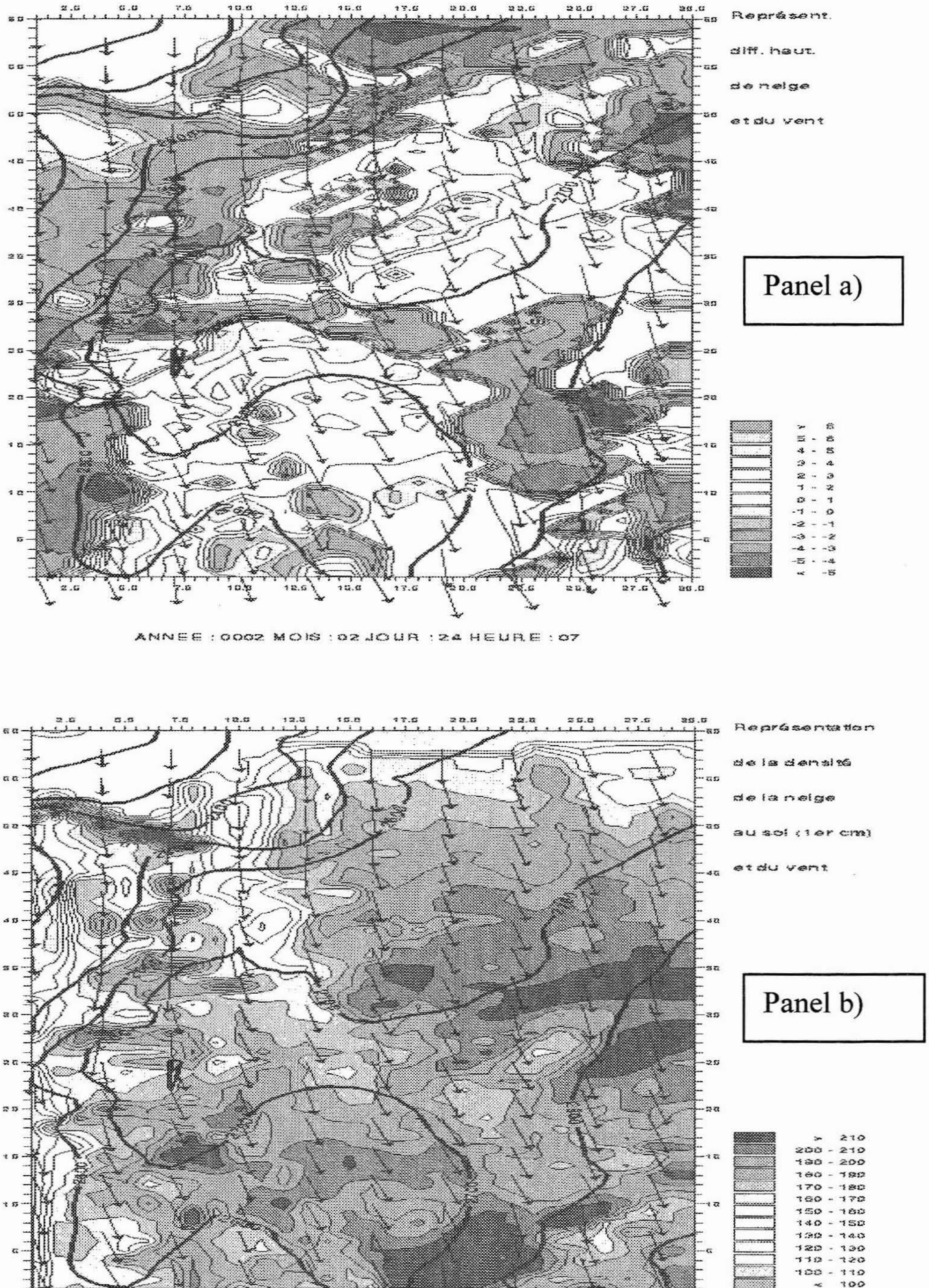


**Figure 2:** *Snow depth field (in grey code) deducted from the SCM snow profile on February 2nd 2002 06 UTC and subject to the effects of the SAMVER plotted wind field (darts) during one hour. The panel a) illustrates the variation of the snow depth during one hour of drift event and the panel b) shows the final density of the first layer of the snow pack after this event. One can thus see how the snow cover has been modified according to the expositions through the action of the different snow transport operators. See details and discussion in the text.*

Even if SYTRON2 can be initialised with operational SCM results, this figure illustrates well the modelled mechanisms of snow transport. The mesh size is of 50m and the results are representative of one hour of transport with a southward wind field valid for the 98/12/28 18UTC. The map is centred on the location of the instrumented site of "Col du Lac Blanc" (elevation 2700m a.s.l) and the North direction is on the top. The bold lines represent the elevations by step of 100m and show well how our instrumented site is located inside a natural channel with at the West the "Dome des Petites Rousses" (2800m a.s.l) and at the East the "Chaîne des Grandes Rousses" (> 3000m a.s.l). The snow depth is represented by several grey levels and varies between "0cm" and "above 12cm".

The South-Southwest wind will induce theoretically a transport from the Southern windward aspects to the Northern lee ones through the action of the different involved fluxes as described, for instance, by PG95. One can recognize such patterns on the figure where the Southern expositions (at the bottom of the map) exhibit less snow depth ("light grey values") than initially (10 cm represented by medium grey colour) and also than the Northern aspects in deeper grey colours. One can also notice a certain kind of variability into the snow depth field in all aspects due to several small orography features.

On the right bottom of the map, the snow pack is nearly completely eroded (dark grey), which is representative of an intense erosion process because the rounded crystals of the second layer are less erodable due to their initial density and shapes. At the left top, an important accumulation near the 2400 bold line indicates roughly the presence of a cornice at the top of a deep slope. The intense accumulation at the right top of the figure is representative of a lake (flat orography).

*5.4.2: February 24th 2002 6UTC complete case (Figure 2).*

At the difference of the previous situation, this case has been obtained by the full system, as described before and running on the same geographical location. The initial snow cover state (including the stratigraphy and internal variables) was deducted in real-time through appropriate operators from the outputs profiles of the operational SCM chain at different elevations, slopes and aspects. SCM has also initialised the SAMVER guess field in order to get a wind field better suited to the local orography; the result of this is plotted on the figure.

As presented on the figure, the strong Northern wind is slightly deflected by the high elevations at the East of the domain (right side of the figure) and induces various drift effects on the snow cover. The panel a) shows the differences of snow depth during this drift event (here one hour). The snow depth variation is represented by several grey levels and varies between "less than 6cm" and "above 6cm". An important feature is visible on this panel exactly at the top of the Col (middle of the figure) where a large erosion area is present on the Northern windward side and immediately followed by an accumulation area on the Southern lee side. Other intense erosion areas are also visible on the left top of the figure and are representative of a windward slope effect.

The panel b) represents the density of the surface layer after the event. The density value is represented by several grey levels and varies between "less than 100 kg.m$^{-3}$" and "above 210 kg.m$^{-3}$".We can state there that even on the areas where we had observed erosion on the previous panel, the density is high and representative of accumulation. This is mainly due to the fact that the two mechanisms (erosion and accumulation) are merged in the model and run together. When we have accumulation, a part of this deposited snow is taken again by the erosion and inversely we can have a light accumulation over greatly eroded areas. This merging leads to an over densification of the first layer (which can be very small) in our model but this point has to be investigated by field campaigns.

*5.4.3: Validation difficulties.*

The validation of such maps is difficult, even on a well instrumented site composed of many poles and devices due to the great fine scale variability of the real orography which can differ greatly at many locations from the smoothed 50m grid where the computations are performed. In order to identify correctly the accumulation and deposition areas which size can be described with our grid, we are presently testing (not presented here) the treatment of digital photographical pictures representing the evolution of the site during all the winter season.

## 6. Conclusion.

We have tried 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 heretofore. The differences in the length scales due to the involved phenomena, the strong forcing of the topography and the difficulty to get a realistic wind field, make this approach difficult but challenging. Two models have thus been elaborated which can simulate the different phenomena in 1D and 2D manner. Only the 1D model is coupled all the year long to the operational SCM suite and modify backward the simulated operational snow packs.

We tried to take the best benefit of 10 years of experiments and archives on the instrumented site of the Lac Blanc in the tuning and the validation of the different formulations and empirical laws used in the models both for the snow determination and for the wind determination which leads to a simple wind model.

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