INTEGRATION OF WIND AND DRIFTING SNOW NUMERICAL MODELS IN GIS
SNOWDRIFT RISK ON ROADS : A TOOL FOR ENGINEERING

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1. Abstract

Snowdrift problems concern many regions in France. They have significant economical consequences because this phenomenon may stop traffic. The paper deals with a first prototype of an almost automatic tool, which will help any user to locate risks of snowdrift on roads. It has been developed in a Geographic Information System *(G.I.S)* using wind and drifting snow numerical models realized in our team. Both numerical models integrated in this GIS can be used by road engineers to localize the different road cut sections where drifting snow will occur and to determine snowdrift shape. In order to reduce the duration of computation, the wind *(3D)* is calculated on a large area including the road and the drifting snow model *(2D)* is only used in some problematical road cut sections.

After a general description of the context, this article describe :

- the used numerical models,
- their integration in a GIS,
- an example of application on a new highway in the center of France.

2. Introduction

Blowing snow is responsible for many safety problems in mountainous areas. It produces snow cornices and slab accumulations and increases avalanche hazard. On roads and motorways, the development of snowdrifts and the lack of visibility during blowing snow hinder driving and increase the risk of accidents on the roads. Moreover, drifting snow on roads, occurring across many regions in France, have significant economic consequences. Road safety and snow removal professionals need a tool to analyze the risk and locate the areas of potential snowdrift formation. The first approach developed several years ago was based only on expert knowledge. In 1999, with the development of computers and numerical models, we elaborated a first nearly automatic tool for the assessment of this problem. By combining wind and drifting snow numerical models and a Geographic Information System (G.I.S) we can now localize the different road sections where snowdrift formation is probable.

3. Previous approach: determination of a risk index

Until recently, field surveys have been the main method of snowdrift mapping and have contributed greatly to risk management. Tabler *(1975)* proposed a statistical method to localize snowdrifts according to the terrain's slope angles. Several years ago, Brugnot *(1995)* developed an expert system to assess the snowdrift risk on roads subjected to snowfall and wind using the following input data elevation, aspect, orientation compared to the prevailing wind direction, road slope, roadside vegetation, type of road section *(cut or embankment).*

For each input parameter, the system empirically determines a partial risk index. Then all the risk indexes are combined in a global index ranging from 1 to 100 and taking into account all the road characteristics *(see Table 1).*

Road profile number	Distance from road beginning	Ground spot height	Road spot height	Depth embankment (m)	Slope	Aspect	Roadside vegetation	Prevailing wind direction	Orientation risk index	Elevation risk index	Road section risk index	Slope risk index	Exposur factor	Vegetation risk index	Aspect risk index	Global risk index
1	660,00	887,93	886,96	0,97	0,013	N	ao	135	11	1,00	1,00	0,00	1,00	1,00	0,62	93
2	690,00	887,68	886,59	1,09	0,015	N	ao	135	11	1,00	1,00	0,00	1,00	1,00	0,62	93
3	720,00	887,93	886,18	1,75	0,016	N	ao	135	11	1,00	0,80	0,00	1,00	1,00	0,62	78
4	750,00	887,95	885,70	2,25	0,017	N	ao	135	11	1,00	0,80	0,00	1,00	1,00	0,62	78
5	780,00	887,98	885,18	2,80	0,019	N	ao	135	11	1,00	0,80	0,00	1,00	1,00	0,62	78
6	810,00	887,75	884,60	3,15	0,021	S	ao	135	11	1,00	0,50	0,00	0,00	1,00	0,62	49
7	840,00	887,47	883,97	3,50	0,023	S	ao	135	11	1,00	0,50	0,00	0,00	1,00	0,62	49
8	870,00	887,06	883,29	3,77	0,024	S	ao	135	11	1,00	0,50	0,00	0,00	1,00	0,62	49
9	900,00	886,51	882,56	3,95	0,026	S	ao	135	11	1,00	0,50	0,00	0,00	1,00	0,62	49
10	930,00	885,85	881,77	4,08	0,028	S	fd1	135	11	1,00	0,50	0,00	0,00	0,00	0,62	12
11	960,00	885,07	880,93	4,14	0,030	S	fd1	135	11	1,00	0,50	0,10	0,00	0,00	0,62	13
12	990,00	884,21	880,03	4,18	0,031	S	fd1	135	11	1,00	0,50	0,10	0,00	0,00	0,62	13
13	1008,46	883,65	879,46	4,19	0,032	S		135	11	1,00	0,50	0,10	0,00	0,00	0,62	13

Table 1: Example of results from the Global Risk Index system developped by Brugnot *(ao=field, fd1=forest)*

The required data are obtained from the maps and topography provided by the project manager, meteorological measurements *(or data from a survey)* and an accurate description of roadside vegetation.

4. Recent approach: Numerical models and G.I.S

The previous methodology is not automated : a significant part of the engineering work consists in bringing all documents and available information together and in transferring these data to a single map. Therefore it seems very interesting to gather information in Geographic Information System and to add results stemming from numerical models.

On one hand, Geographic Information Systems *(G.I.S)* can manipulate spatially related phenomena. They can store, handle, retrieve and analyse spatial information in digital form and make hard-copy maps. They have proved to be good tools in environmental, transportation and hazard studies. The G.I.S should be able to play a very important part in the study of snowdrifts given that they are spatially related phenomena.

On the other hand, many numerical models have been suggested to simulate mesoscale wind and snowdrift and they fit the results of field surveys and experiments very well. They make it possible to predict the wind and the snowdrift formation using topography, snow cover and possibly other parameters.

There have been no attempts to combine them in snowdrift mapping until now. Realising the great potential of this combination, we conducted a study to investigate its effectiveness. We developed a tool *(called OLRIC)* within a geographic information system *(ARCVIEW with the extension Spatial Analyst)*. This tool allows to locate risks of snowdrift on roads using wind and drifting snow numerical models. In order to reduce the duration of computation, the wind *(3D)* is calculated on a large area including the road and the drifting snow model *(2 D)* is only used in some problematical road cut sections.

4.1 Short Description of numerical models used

4.1.1 Numerical modelling of wind in complex topography: ARIEL

The aim of the model is to evaluate the relief influence on a flow a priori known at the synoptic scale. Different hypotheses are adopted. Air is considered as a perfect polytropical gas which is dry and compressible, and is assimilated to a Newtonian fluid. We don't adopt the hypothesis of anelasticity *(as is usually done for many existing meteorological models)*, making it possible to consider air as incompressible and to take into account its compressibility only with the Boussinesq model. The model we developed is based on the conservation laws of continuum mechanics. The turbulence closure is obtained by using the k-ε model which is recommended for the simulation of the turbulent boundary layer. Consequently, turbulence properties are represented by the k and ε quantities. We also implemented Smagorinsky's turbulence model which is used in the Large Eddy Simulation.

In the mesoscale model of atmospheric flow simulations, it is important to represent the ground surface layer correctly. Indeed, it is where the exchange of momentum and heat take place, which strongly influences the low atmospheric layer behaviour. In our case, this layer is modelled by a logarithmic law, which is the solution of the established boundary layer. The turbulent velocity expresses the flow and the roughness height stands for the state of the ground surface. The main hypothesis on turbulent quantities states that the local turbulence balance in the surface layer is expressed by equality between turbulence production and turbulence dissipation.

Each site is introduced as a digital terrain model. For each cell of this mesh, an estimation of the roughness is made using the Panoffsky and Dutton table *(1984)* which estimates the roughness height from the ground cover. At the ground level, we decompose this digital terrain model grid. From this surface mesh, we obtain a vertical mesh by superposing layers covering the volume in which we calculate the wind field. This volume is generally equal to the volume situated between the ground and the altitude for which we consider that the wind is no longer disturbed by the topography. This corresponds to the synoptic height *(about 5000 m)*. The altitudes of the intermediate points are calculated by interpolation between the ground and the top of the domain in order to have an increasing variation of the vertical space step. This gives small cells near the ground where exchanges are strong, and larger cells at high altitudes. The equation system is written on its conservative form. The numerical scheme used is based on finite volume techniques and is accurate to the second order in space and to the first order in time.

Five types of boundary conditions are examined: 1) the surface layer (bottom) where the flow is assumed to be a boundary layer parallel to the slope; 2) vertical lateral sides which are considered as impermeable smoothed boundaries; 3) the high boundary condition in which there is a special treatment for the pressure term; 4) the upstream boundary which is considered as a boundary layer represented by a logarithmic profile; and 5) the downstream boundary in which a free output condition is imposed.

After its construction, the numerical model was successfully compared to different theoretical solutions. It was tested on analytical solutions as relief Lee waves in stable thermal situations. The next test consisted of comparing results from the numerical model with measurements from the Askervein hill published by Taylor et al. (1987). These tests showed that the model can predict the average velocity field very well, but the model gave poorer results for turbulence characteristics, with turbulence kinetic energy prediction downstream from the hill with an error of approximately 30% *(see figures 1 and 2).*

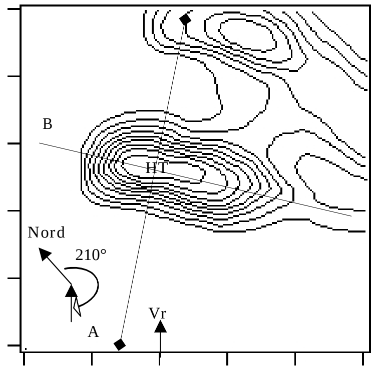


Figure 1 : Simplified topography of Askervein hill

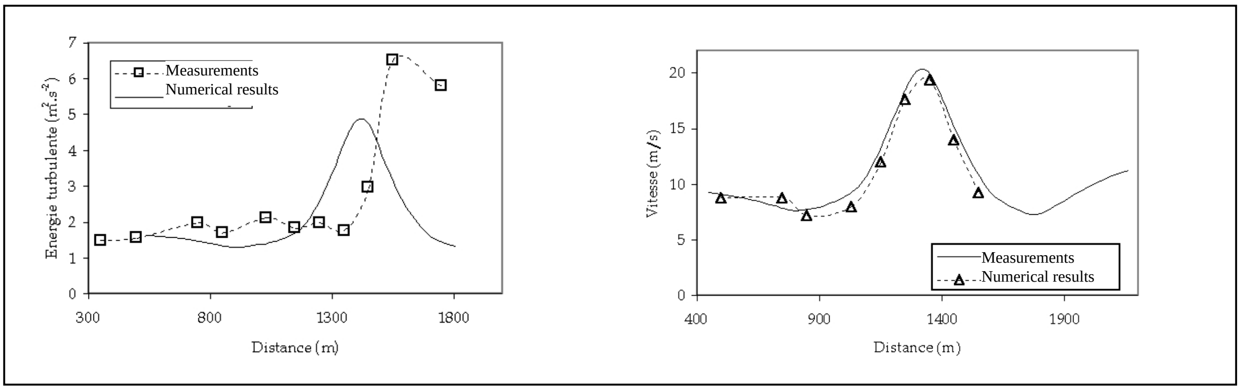


Figure 2 : Speed and turbulence kinetic energy prediction downstream from the hill (line A)

This model, initially developed for snow transport by wind, provides other applications such as predicting, from the synoptic data, the local wind in the mountain areas and mapping zones exposed to strong winds. It has been used, in this case, to reconstruct scenarios of past storms in the Combe de Savoie and in the Maurienne Valley, both in south-eastern France *(Naaim and Naaim-Bouvet, 1996).*

4.1.2 Numerical modelling of drifting snow : NEMO

After a detailed analysis of the snow erosion, transport and deposition mechanisms, and the existing numerical models, we built a numerical model for drifting snow. It is based on a pertinent physical model for each mechanism and an adequate mathematical formulation *(Naaim-Bouvet, Naaim, Martinez, 1998).* We decompose the transport layer into two zones: the suspension layer and the saltation layer. The suspension layer is described by mass and momentum conservation equations. These equations are built both for the solid phase and the gaseous phase. The interaction between these two phases is taken into account by an equation based on the drag force of a particle in a turbulent flow. Turbulence is modelled by the k-ε model, in which a reduction of the turbulence with the concentration is introduced *(Chen and Wood, 1985).* The turbulent diffusion of the solid phase is considered higher than the turbulent diffusion of the gaseous phase. This is taken into account through a Schmidt number less than 1. This is estimated to be 0.6 for snow particles *(Naaim, Martinez, Naaim-Bouvet, 1995).* The saltation layer corresponds to the layer immediately in contact with the snow mantle. In our model, it is described by its height, its concentration and two turbulent friction velocities, one for the solid phase and one for the gaseous phase. A progression model of these two velocities with the concentration was proposed. The saltation layer is considered as the lower limit of the suspension layer. The exchange between these two layers is determined from the balance between the sedimentation flux and the diffusion flux. The exchange between the saltation layer and the snow mantle is described by an erosion and deposit model which takes into account the effects of the aerodynamic force as well as the effects of particle impact forces and sedimentation. The equations of the global model thus constructed are solved by a finite volume method.

In order to validate each part of the model, specific experiments were carried out in a wind tunnel. For example, accumulation behind snow fences have been studied in wind-tunnel and have been simulated with the numerical model. The comparison between experimental measurements and numerical results has shown that the proposed model reproduces the experimental observations well *(see figure 3).*

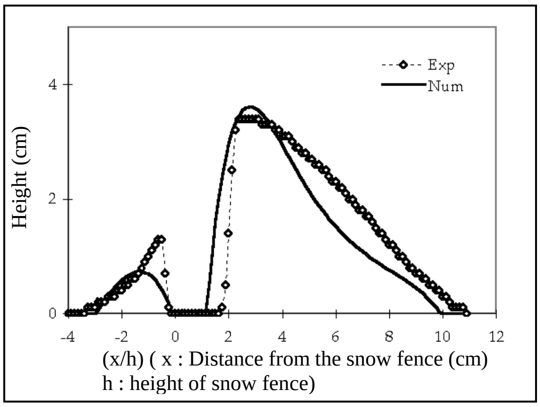


Figure 3 : Comparison between experimental observations and numerical results of a snowdrift generated in wind-tunnel

4.1.3 OLRIC : Principles

Numerical models are able to model the wind and snowdrift process in greater detail than analytical models. To take advantage of this improvement, it is necessary to feed the model with more detailed information and efficiently analyze the often very large amount of resulting data. We therefore elaborated routines for 1) the preparation of basic digital input (i.e. DEM); 2) the wind model input specification; 3) the visualization of the simulation of the wind model results; 4) the determination of risk according to wind and road profile; 5) the determination of the deposit on different cross sections. All these topics are governed by the same Graphical User Interface in the G.I.S.

4.1.3.1 Preparation of basic digital input

Numerical models can solve the equations of a very complex topography as long as these equations are based on the input of a detailed topographical survey, itself requiring special tools to generate a high-precision digital terrain model. It goes without saying that the better the topography is modeled, the more reliable the results of the models are. It is important to note that the officially available Digital Elevation Models (DEM) in European countries are generally accurate enough for mesoscale wind calculation purposes. They typically have a horizontal spatial resolution of 100 m, which is not accurate enough for snowdrift calculation. Therefore it is important to find a DEM that represents the topographic elements of the road profile and its cross sections more accurately. The common interface allows importing the road profile and the road cross sections from software designed to trace roadways. Roughness is determined thanks to vegetation maps.

4.1.3.2. On the Regional scale: localisation of the zones with snowdrift formation risks

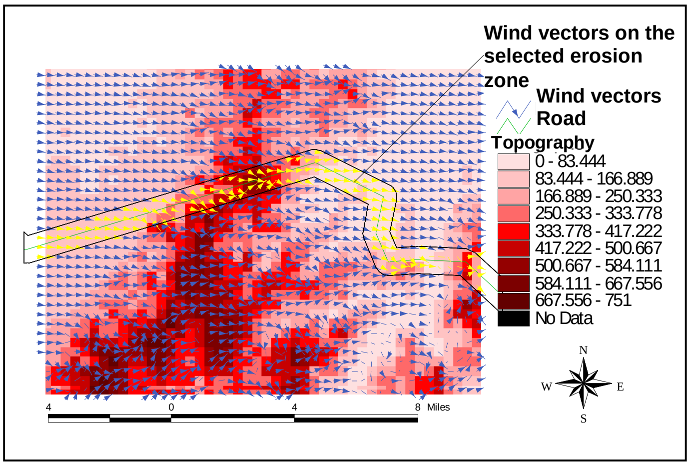
The localization of a snowdrift depends on the prevailing wind direction near the ground. The numerical wind model calculates these directions starting from the synoptic wind. Knowing the direction and the intensity of the wind as well as the road orientation will allow us to determine the zones undergoing snowdrift formation. The following table *(table 2)* summarises the functioning of OLRIC at the mesoscale level.

Georeferenced data	Boundary conditions	Numerical model used	Results
Digital Terrain Model Roughness Road layout	**Regional compass map (synoptic wind)**	**Mesosclae wind (for example ARIEL)**	**Map of the zones where snowdrift formation is possible**

Table 2 : Functionning of OLRIC on a large scale

The map of the zones subjected to snowdrift formation is elaborated automatically following several phases and using various criteria.

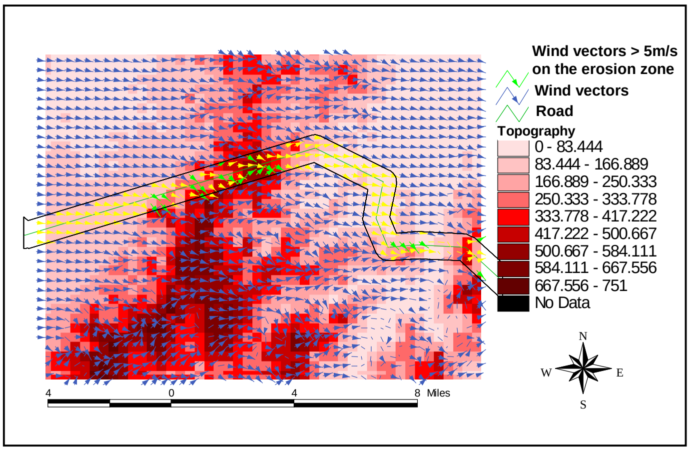
Geographical criterion : presence of erosion area around the road



Locally, across the road, we consider the neighbourhood area *(300 m)* on each side *(see Figure 4)*. The erosion in this area depends on the snow and the vegetation. For example, snow is not eroded in the dense forest.. The width of the erosion area could be modified by the user.

Figure 4: Automatic selection of wind vectors on the erosion zone

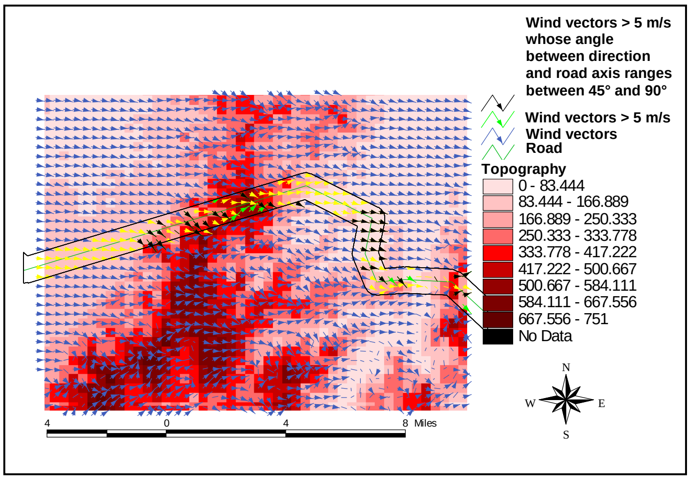
Wind speed criterion



Drifting snow occurs only if the wind speed observed in the erosion zone exceeds the threshold value according to snow quality *(see Figure 5).* Users can limit the studied area by choosing a threshold value.

Figure 5: Automatic selection of the strong wind vectors on the erosion zone

Wind direction criterion



The risk of snowdrift formation is maximum when the prevailing wind direction is perpendicular to the road axis. We consider that this risk remains high for an angle between the road axis and wind direction ranging from 45° to 90° *(see Figure 6).*

Figure 6: Automatic selection of road section subject to snowdrift formation

All these values *(width of the erosion area, wind speed threshold, angle between road axis and wind direction)* can be modified by the user.

4.1.3.3. At the local scale: determination of snowdrift shape

Following the previous steps, we can restrict the study zone to a few road sections. We can now accurately determine the shape of a snowdrift on road cross sections. The following table *(table 3)* summarises the functioning of OLRIC on a small scale.

Georeferenced data	Boundary conditions	Numerical model used	Result
Road cross section where snowdrift formation is probable	Wind vectors (stemming from previous steps)	Numerical model NEMO Library	Visualisation of snowdrift on road cross section

Table 3: Functioning of OLRIC on a small scale

The user directly selects the road cross sections on the screen. Then there are two possibilities:

- using a library for the most usual cases *(fill section, cut section or cut-fill section , two or four lanes, slope 3/2, fill or cut height of 1, 2, 4 or 8 meters).* The results available in the library come from previous calculations using the numerical model and storing the results.
- directly using the NEMO numerical model for unusual cases : the calculation time of such a numerical model on a personal computer remains quite high; therefore these possibilities are designed for complex topography. The standard case corresponds to road cross sections with smooth slopes generally recommended by a landscape engineer or on the contrary with steep slopes due to the local geology.

The figure 7 summarises the functioning of OLRIC.

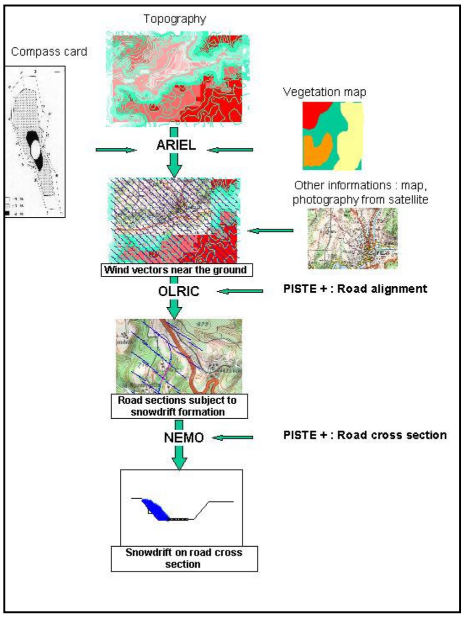


Figure 7 : Functioning of OLRIC

5. Example of application: the A75 Motorway

The A75 Motorway, which connects Beziers to Clermont-Ferrand is located in a plateau zone. Such areas are characterised by a low altitude *(< 1200 m)*, moderate snowfall, a fairly flat relief but a great erosion zone, such as the Massif Central in France. These great erosion zones lead to the formation of considerable snowdrifts even though the snow layer is not very deep.

We present here the study made for this motorway. The studied area, approximately 6 km long, is situated south of the Engayresque Pass *(888 m)*. The meteorological station, situated near the road line, allows us to initialise the mesoscale wind model *(ARIEL)*, with synoptic wind direction north-west and an intensity of 10 m s^{-1}. The three steps *(with a threshold speed of 5 m s^{-1} and an angle between the* *wind direction and the road axis ranging from 70° to 90°)* described in paragraph 4.1.3.2. gave the following result *(see figure 8):*

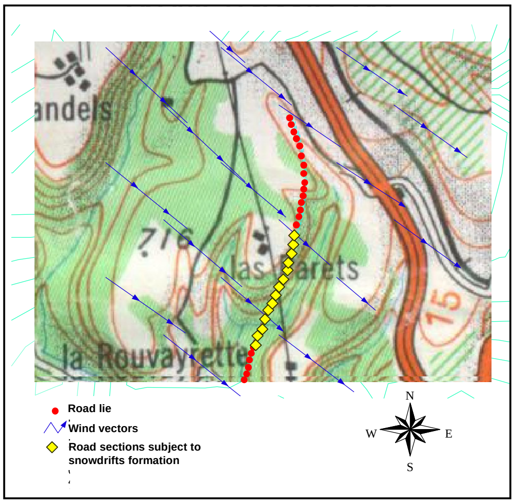


Figure 8 : Automatic selection of road section subject to snowdrift formation

An example of snowdrift in one cross section (n°55) subjected to snowdrift, obtained by the NEMO, is presented in figure 9 :

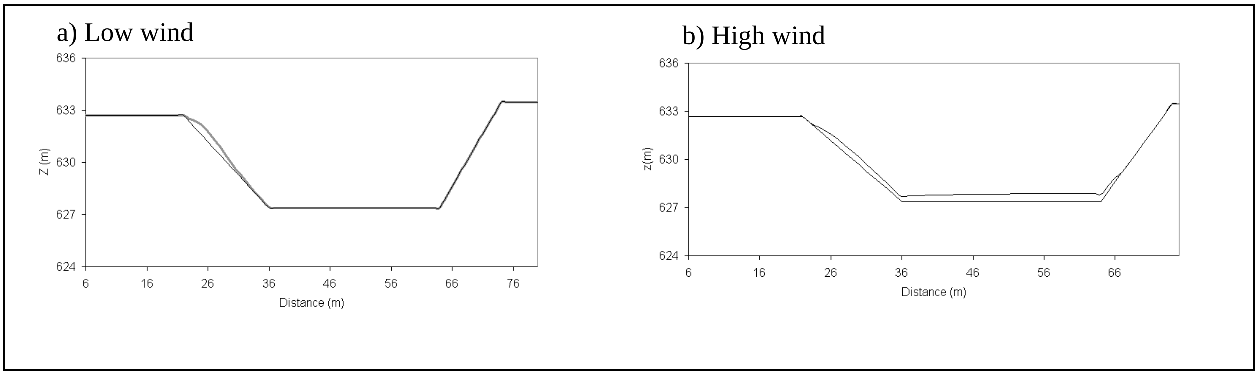


Figure 9: Snowdrift formed after a 600-second simulation first (a) with a low wind ((u_*-w_f)/u_*=0.1 (maximum height deposit = 65 cm)), secondly (b) with a high wind ((u_*-w_f)/u_*=0.4 (maximum height deposit = 50 cm)). u_* is the friction velocity (ms^{-1}) and w_f is the fall velocity (ms^{-1})

5. Conclusions and further developments

The most important achievement of this study was the creation of an environment in which to solve problems using the wind and the snowdrift models.

This first prototype has been presented to end-users from the Public Road Administration and private companies, in order to prepare further developments according to the end user's needs, which are conditioned by the type of roads they have to manage. A survey carried out in 1999 shows that:

- the Public Road Administration would like to use this software not only for new projects but also for old roads. In fact, their experience has taught them where snowdrifts will occur on old roads, but they would like to computer test the different solutions *(snow fence erection, afforestation, modification of road cross sections)* that could solve the problem.
- private companies, responsible for motorways in France, would like to have more information about forecasting drifting snow so as to improve snow removal.

According to these suggestions, further developments could take two directions:

- Snowdrift forecasting,
- testing of different kinds of protection against drifting snow.

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