A METHOD FOR THE FORECASTING OF WIND IN MOUNTAINOUS REGIONS.

Gilbert Guyomarc'h[1], Laurent Mérindol[1] and Haraldur Olafsson[2]

[1] Météo-France Centre d'Etudes de la Neige Grenoble - FRANCE
[2] Icelandic Meteorological Office and Institute for Meteorological Research Reykjavik - ICELAND

ABSTRACT: To forecast blowing snow in mountainous regions one needs precise information on the velocity and direction of the wind.

In order to reach this objective, we have developed a statistical application (VENTOSE) for the forecasting of wind parameters at ground level by using as long as possible series of data. These data are collected by automatic measurements in a high altitude location (Col du Lac Blanc in the French Alps, alt. 2800 m -) which is exposed to strong winds during the winter season. This experimental site has been well equipped for studies of snowdrift.

For this study, various atmospheric parameters from the ECMWF (European Centre for Medium range Weather Forecast) data archives have been extracted and statistical relationships between these parameters and wind measurements at the site have been established. A multi-linear method was used to calculate equations in order to estimate the wind velocity and the wind direction for the following day.

The comparison between observed and forecast wind done with this method was calculated in the same location during a winter period not included in the learning file. In most cases, wind velocity is well estimated (correlation coefficient equal to 0.77).

In the framework of a joint research project with the VI (Icelandic Meteorological Office) that started in 1997, we have tested this method in Icelandic locations. The project has been initiated in order to enhance the exchange of expertise between VI and Météo-France in research on snowdrift and avalanche hazard. The testing phase will take place in Iceland where simulated snowdrift will be compared to observations.

The method and the results of this study will be shown and discussed in the presentation.

KEYWORDS: avalanche forecasting, snow drifting, blowing snow, wind forecasting.

1. INTRODUCTION

The transport of snow by wind is an important process for the distribution of snow in mountainous regions and for the increase of avalanche hazard. Unstable wind-slab deposits are common occurrences especially on lee slopes (Meister, 1989). Avalanche forecasters require a knowledge of threshold wind velocities (Takeuchi, 1980) and the conditions under which snow is transported and deposited, notably the characteristics of snow-surface particles. Furthermore, they need to know how long this phenomenon will persist. Blowing snow is one of the most important factors for forecasting accidental release of avalanches and most methods are based only on empirical rules and experience.

For five years the CEN (French Centre for Snow Study) has investigated blowing snow through research projects. The aim of this research, among other things, is :

- to study the relationships between blowing snow and avalanche activity,

[1] Météo-France Centre d'Etudes de la Neige 1441 rue de la piscine 38406 St Martin d'Hères Cedex FRANCE
tel: 33 4 76 63 79 18; fax: 33 4 76 51 53 46 email: gilbert.guyomarch@meteo.fr
[2] Vedurstofa Islands(Icelandic Meteorological Office) and Institute for Meteorological Resaerch, Bustadavegur 9, IS-150 Reykjavik ICELAND. email: haraldur@vedur.is

- to introduce the results of the studies into snow pack evolution models

- to provide the avalanche forecasters (or the people in charge of safety in snow resorts) with diagnostic tools in order to better estimate wind effects on the snow pack.

In order to reach this last goal, we have developed an application called Protéon. The originality of Protéon is to take into account the wind speed thresholds according to the morphological features of snow grains (Guyomarc'h, Mérindol - 1998). In a first stage it is necessary to know as well as possible the velocity and direction of the wind in a site. The final objective of this project is to improve the 24 hour forecast of avalanche hazards.

1. METHOD

The need of a specific method for the forecasting of wind at a local scale appears clearly when the orographical effects prevail. One solution consists in using statistical methods in order to establish relationships between the results of large scale meteorological models and the local wind. This method needs as long as possible series of data.

2.1 Experimental sites in France

For several years, two experimental sites have been run by three laboratories for the investigation concerning drifting snow in high mountainous regions (Castelle - 1995). A large, North-South oriented pass (Col du Lac Blanc, 2700 m a.s.l.), where the wind is generally similarly channelled, was equipped for this research program. Close by, at Dôme des Petites Rousses (2800 m), avalanche activity on two slopes which are submitted to wind effects has been followed (figure 1). At both sites wind direction and velocity (hourly mean, maximum and minimum values) have been measured (by using heating system) and recorded since respectively 1989 and 1992.

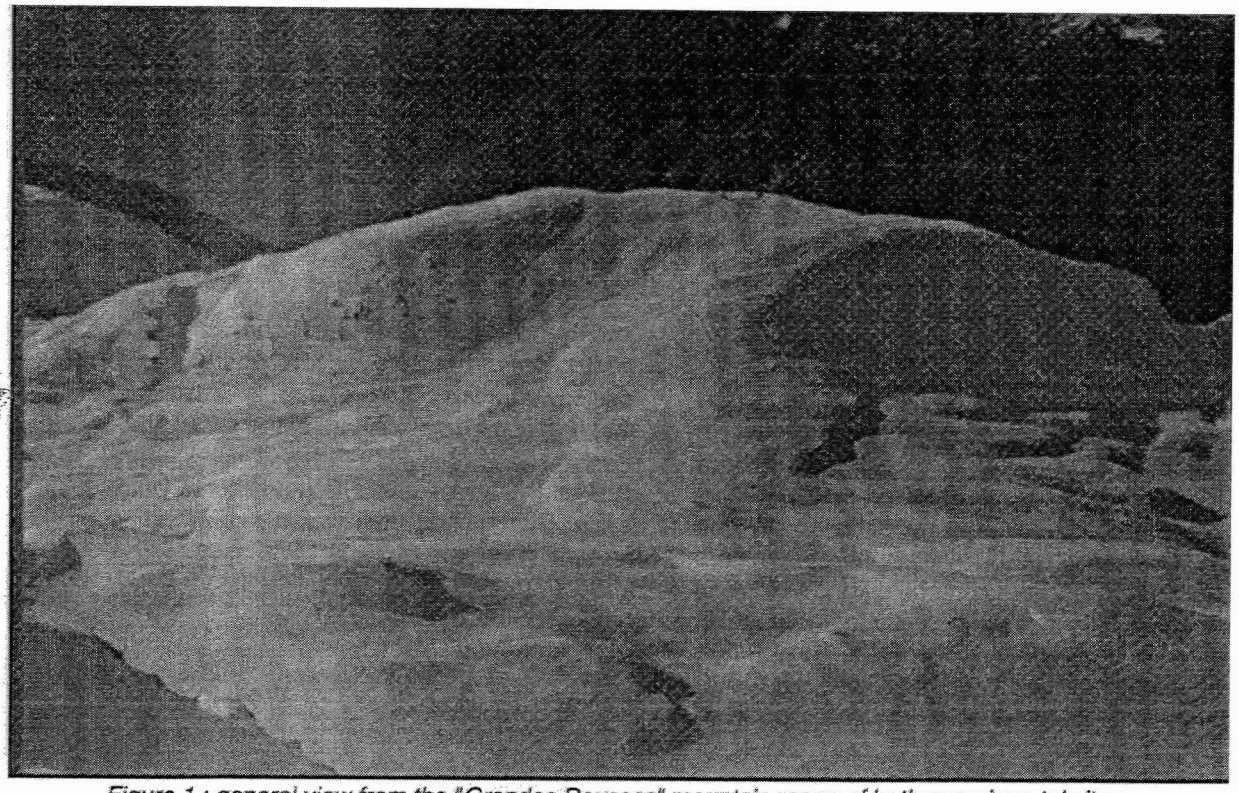


Figure 1 : general view from the "Grandes Rousses" mountain range of both experimental sites.

2.2 Data description

The wind parameter features of both experimental sites are shown in figures 2 and 3.

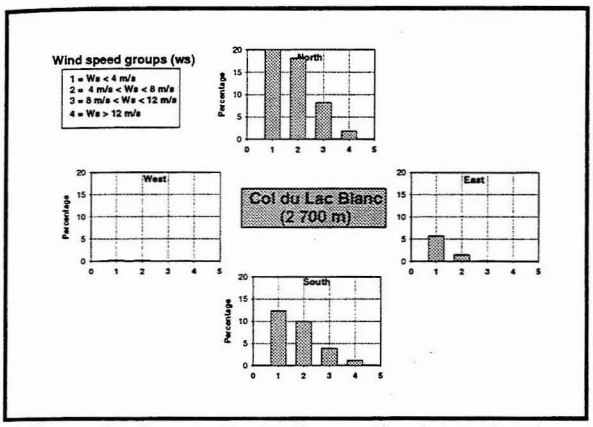


Figure 2 : Automatic weather station located at the "Lac Blanc" Pass

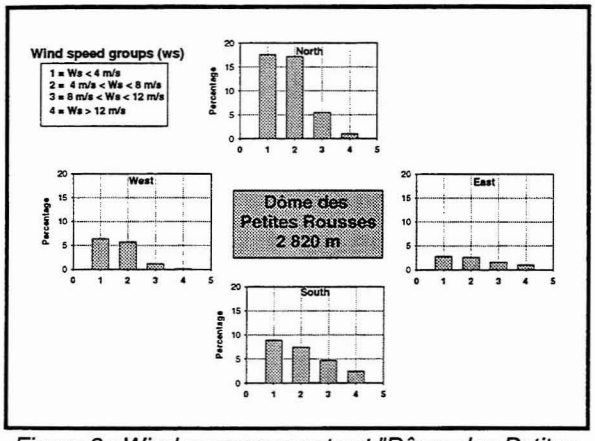


Figure 3 : Wind measurements at "Dôme des Petites Rousses".

The first site is strongly influenced by the local orography : a large pass between a long mountain ridge (Grandes Rousses 3 300 m) and a large dome (Petites Rousses 2 800 m). This characteristic is clearly shown by the frequency of winds from either North or South (92 % of the cases). There are only a few cases of easterly winds and almost no cases of westerly winds.

The second site is less affected by the relief, nevertheless the distribution of the wind directions shows that winds from the North are most frequents (48 %). Easterly winds are stronger than the average (mean wind speed around 6 m/s). The mean wind speed for the whole period is 4.8 m/s.

2.3 The statistical method

The principle of the statistical method is based on well-known methods which have been already published (Mérindol, 1987). The general function is :

$$ws = f\left(P_1, P_2, \ldots Pn\right) + \varepsilon \quad (1)$$

where ws (wind speed) is the local wind,
Pn are the parameters used for the estimation (chosen for their assumed links with ws),
ε is the error term,
f represents the statistical function.

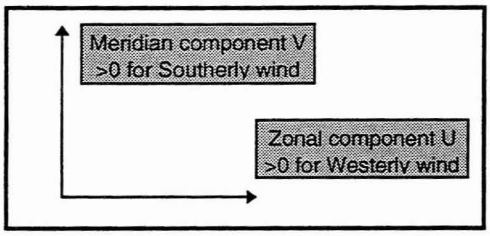
For this application - called Ventôse - we have chosen to use several meteorological parameters from the ECMWF data base (European Center for Medium-range Weather Forecast) analyses. Data (Geopotential Z, Air temperature T, Wind components U & V) are extracted on a 3 X 3 grid (covering the North of the French Alps). The grid mesh is 150 km in latitude and 100 km in longitude. These parameters are only available at the main synoptic hours (00h, 06h, 12h & 18h utc) for 3 pressure levels (850, 700 and 500 hpa). In addition to these basic fields, there are calculated parameters (such as temperature gradient, vorticity, geostrophic wind velocity, ...) in order to have the greatest number of variables which can be related to the local wind. Then the relationships between the model parameters and observed wind at the site are calculated.

Name and number of parameters	850 hPa	700 hPa	500 hPa
Geopotential	1	12	23
Air temperature	2	13	24
Zonal Wind component (U)	3	14	25
Meridian wind component (V)	4	15	26
Wind velocity	5	16	27
Geostrophic wind velocity	6	17	28
Meridian comp.of the geost. wind	7	18	29
Zonal comp. of the geost. wind	8	19	30
Vorticity	9	20	31
Meridian gradient of temperature	10	21	32
Zonal gradient of temperature	11	22	33
34 : Vertical difference of temp.	35 : Vertical difference of Temp.		

List of the 35 fields used for the statistical development

For this study a multi-linear regression method was used to calculate equations for the daily estimation of wind direction and velocity. After several tests calculating directly the wind velocity, it has been chosen, to split the wind pa-

rameters into two components according to the following scheme. This method, applied for the whole process permitted to improve the results and to calculate wind velocity and direction.



Each stage of this method is detailed below:

- For every (n) parameters (field) from the ECMWF, a regression is calculated to provide a linear combination of the 9 grid points of the domain for a first estimation of the local wind at the chosen location. The equation for each parameter takes the following shape :

$$U'^n = \alpha_0^n + \sum_{i=1}^{9} \alpha_i^n P_i^n \quad (2)$$

$$V'^n = \alpha_0^n + \sum_{i=1}^{9} \beta_i^n P_i^n \quad (3)$$

for n in {1 ... 35}
where : P_i^n is the value of the point "i" of the "n"th ECMWF field.
α_i^n and β_i^n are the linear coefficients of the first stage regression.
U' and V' being the "n" preliminary evaluation of the wind horizontal components.
By using these equations, a value for U and V is calculated for each field.

- The second step consists of a final regression using the value calculated at the previous stage. For the operational and definitive equation, we only retain the parameters which give the best information (test of the R^2 increasing). Generally, we only need 2 or 3 parameters (m in equations 4 and 5). At this stage the equations are :

$$U = \gamma_0 + \sum_{i=1}^{m} \delta_i U_i' \quad (4)$$

$$V = \gamma_0 + \sum_{i=1}^{m} \gamma_i V_i' \quad (5)$$

- The last stage consists of re-calculating the wind velocity and direction with the estimated components by the following equation :

$$ws = \sqrt{U^2 + V^2} \quad (6)$$

where ws is the wind velocity
U is the estimated zonal component
V is the estimated meridian component.

3. RESULTS WITH DATA FROM EXPERIMENTAL LOCATIONS

In order to evaluate the quality of the estimated wind, the initial files (wind measurements have been split in 2 files. The first one (learning file) is used for the calculation of the statistical relationships and the second one (test file) is used to test the method. For the choice of this sample file, several tests have been performed; we have finally chosen to use data at 12 hour intervals : it was the best way to reduce correlation between observations following each other in time (auto-correlation less than 0.25).

At the final stage, an example of selected parameters for the " Dôme des Petites Rousses" is shown below :

- for the U component : the geopotential (altitude of the pressure level) at 700 hpa and the zonal wind component at the same level.

- for the V component : the meridian wind component at 700 hpa, the wind velocity at 700 hpa and the temperature at 500 hpa.

The results presented below (figure 4 to 6) display a comparison between measured parameters from the "test file" and the estimated ones calculated for the same period by Ventôse. For the Col du Lac Blanc site, the zonal component is badly simulated because of the small number of cases of wind blowing from East or West. In the learning file the zonal component is very often equal to zero. The second site is quite different (the westerly winds represents around 12 % of the total amount), so the zonal component is better estimated. Nevertheless in both sites the correlation between the observed wind velocity and the estimated one (calculated with the equation 6) is equal to 0.77.

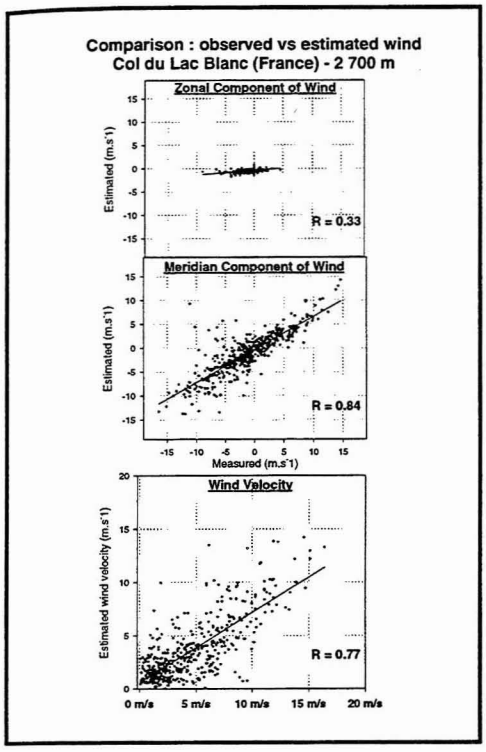


Figure 4 : comparison on "test period". R is the correlation coefficient between observed and estimated wind in the "Col du Lac Blanc" site.

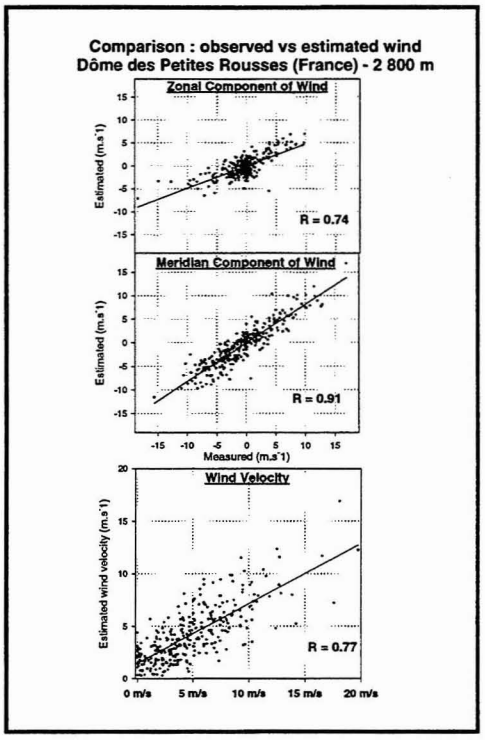


Figure 5 : comparison on "test period". R is the correlation coefficient between observed and estimated wind in the "Dôme des Petites Rousses" site.

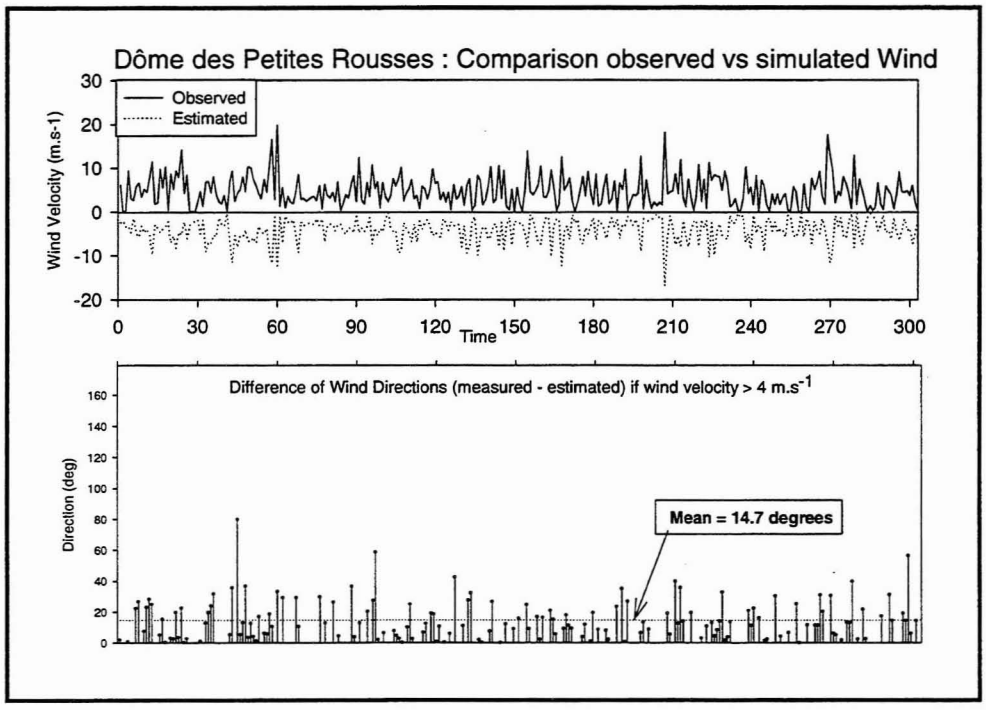


Figure 6 : the graph above displays a comparison between the measured wind velocity (continuous line) and the estimated one (dotted line). The graph below shows the absolute value of the difference between estimated and measured wind direction.

In figure 6, we have also compared the wind directions (also calculated from U and V). In most cases the absolute value of the difference between forecast and observed wind direction is less than 20 degrees. For the forecasting of snowdrift events, these results are corrects.

4. VALIDATION WITH DATA FROM ICELAND

The *Ventôse* system has also been tested on data from Iceland within the framework of a French-Icelandic research project (NEVOS) on wind, transport of snow and the development of the snow cover in mountainous terrain. The NEVOS project was initiated after a series of deadly avalanches where transport of snow in strong winds played a major role. Its objective is to test the tools that are used and being developed at Météo-France to predict local winds and the development of the snow cover. In the long run, the aim is to be able to numerically simulate the accumulation of snow in complex terrain and thereby predict the risk of avalanches.

Iceland is suitable for this kind of research for various reasons. Firstly, the wind conditions in Iceland differ significantly from the conditions in the Alps. The climate of Iceland is characterised by frequent, and often deep extra-tropical cyclones with strong winds from various directions. There is little vegetation, the mountains are not as steep as the Alps and the ground surface is relatively smooth. Consequently, strong winds are often observed. Such winds in an environment different from where *Ventôse* was developed provide an excellent test for the model. Secondly, there is heavy precipitation : more than 3000 mm/year on mountains in some coastal regions. Much of the precipitation falls as snow, and is being transported by the wind. Thirdly, Iceland offers a dense network of reliable weather observations and sites where blowing snow is a prevailing weather factor during a large part of the year. Many of these sites are at a walking distance from towns and villages and consequently close to a transport network that is working all year around.

For a pilot test of *Ventôse*, an inland synoptic observation site at Hveravellir (alt. 642 m) was chosen. Hveravellir is manned all year around and extended measurements of snow depth for the NEVOS project are planned in the winter 1998-1999.

The observed winds and the atmospheric fields as analysed by the ECMWF were compared during the period from August 1994 to July 1997. The resulting correlation (figure 7) was used to predict the wind for a test period defined with the same criteria (see paragraph 3) as at the French locations. The strength of the wind components is very well simulated and a good degree of correlation is reached on the wind speed (0.74). However, strong winds are often badly predicted, especially when they last only for a short period. This is particularly bothering, since the quantity of transported snow can be expected to increase non-linearly with the wind speed.

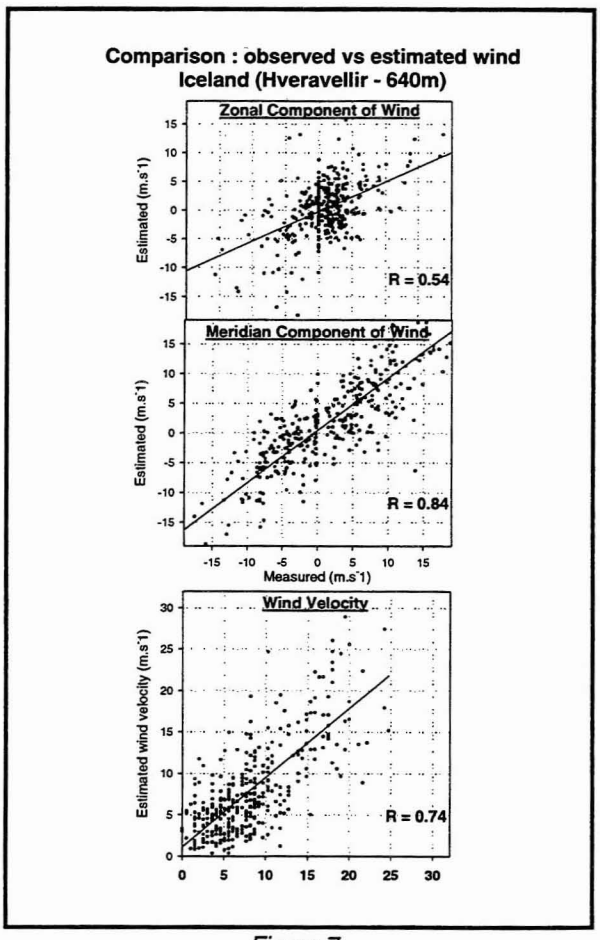


Figure 7

The reason for the model failing in predicting some of the peaks in the wind speed is presumably related to meso-scale wind structures that are indeed not always resolved in the ECMWF analysis. Better results can be expected with an analysis with better resolution.

Some other tests have been carried out at other locations in Iceland, and the results are similar as in Hveravellir. It is noteworthy that good correlation is reached with only a few atmospheric parameters from the analysed fields, sometimes just one. In the Alps, the correlation improved more steadily as the number of parameters was increased.

5. CONCLUSION

The *Ventôse* system has shown its feasibility for the estimation of wind velocity and direction. At the experimental sites the results are good enough for the expected use : the 24 hour forecasting of blowing snow events. The method can be used at other locations as shown by the results in Iceland. Moreover, *Ventôse* does not need great computational resources.

Nevertheless, this method reveals some disadvantages like the necessity to dispose of a long series of local data for the calculation of the preliminary equations and to have access to the analyses of a large scale meteorological model.

Others ways are possible :

- particularly the recent development of mesoscale meteorological models, but they still need considerable means
- or the improvement of other statistical adaptive models developed for snow pack modelling like Safran (Durand, 1993).

This kind of statistical adaptation has still good times ahead. The method is quite simple and better results could be associated with the improvement of the resolution of meteorological models.

6. REFERENCES

Castelle T., 1995. Transport de la neige par le vent en montagne: approche expérimantale du site du Col du Lac Blanc. Ph . D. EPF Lausanne (Switzerland) 297 P.

Durand Y, Brun E., Mérindol L., Guyomarc'h G., Lesaffre B. And Martin E. 1993. A meteorological estimation of relevant parameters for snow models. *Annals of Glaciology*, vol. 18, 65-71.

Guyomarc'h G. And Mérindol L. 1998. Validation of an application for forecasting blowing snow. *Annals of Glaciology*, vol. 26,138-143.

Meister R. 1989. Influence of strong winds on snow distribution and avalanche activity. *Annals of Glaciology*, vol. 13, 195-201.

Mérindol L. 1987. Faisabilité de la prévision de la vitesse du vent en montagne par adaptation statistique. Mémoire de DEA.

Takeuchi M. 1980. Vertical profile and horizontal increase of drift-snow transport. *Journal of Glaciology*, 26, 481-492.