
Avalanche forecast by the nearest neighbour method

OTHMAR BUSER, MONIKA BÜTLER* & WALTER GOOD

Federal Institute for Snow and Avalanche Research, CH-7260 Weissfluhjoch/Davos, Switzerland

ABSTRACT Searching practicable ways to supply the avalanche forecaster with useful information we found the K-Nearest Neighbour method to be a convenient tool. It is able to provide the forecaster with days of the past similar to the present enabling him to check on the avalanche activity of these days.

Based on a model that uses the weather and snow data of a single day we developed a new version by adding data of the previous weather conditions and the evolution of the whole snow cover. The resulting improvements were considerable although the reliability of the used data was limited. Compared with the conventional method the model is sharper in response to changes and riskier in the sense that it is, for instance, more detailed in the specification of the aspects of the avalanche slopes.

The nearest neighbours method can support a decision made in an extraordinary situation with unexpected consequences (esp. accidents).

Prévision des avalanches par la méthode des plus proches voisins

RESUME La méthode des plus proches voisins est très appropriée pour livrer aux prévisionistes des informations utiles. Elle fournit des jours passés similaires au jour actuel ce qui lui permet de comparer l'activité quant aux avalanches.

Basé sur un modèle utilisant les données météorologiques et nivologiques d'un seul jour, nous avons développé une nouvelle version en ajoutant les mesures des jours précédents. En comparant avec les méthodes traditionnelles nous avons trouvé que la réponse de la méthode présentée change plus vite et prend plus de risque dans le sense d'être plus précis, par exemple en ce qui concerne l'exposition des pentes d'avalanches.

La méthode des plus proches voisins peut justifier une décision prise dans des circonstances extraordinaires ayant des conséquences imprévues (accidents).

* Present address: SWISSAIR, 8058, ZUERICH-AIRPORT.
INTRODUCTION

The evaluation of avalanche danger (rather avalanche hazard or potential) is an art based on experience, intuition and process oriented, physical reasoning. It is difficult to learn and to teach this art and to transfer the experience from one area to another. These reasons were part of the motivation to find methods where more objective decision making is possible. The following is an incomplete list of landmarks in a 20 years search for valuable models:


The methods used range from linear regression analysis, multivariate discriminant analysis, time series analysis to the non-parametric and pattern recognition techniques. Together with these methods of numerical mathematics, the attempt to introduce more physical and process oriented reasoning was made at different levels.

We have applied many of these techniques to the same data set of nivo-meteorological observations from the standard test site at Weissfluhjoch and to the corresponding collection of avalanche records from the surroundings (test area of 100 km²), as described in Obled (1980). Included are avalanche/non-avalanche models and two stage models, where a weather type is evaluated first and the yes/no discrimination is then applied to the resulting subgroup. The accuracy of the forecast reached an upper level of .8 (a correct classification of 80% of avalanche and non-avalanche days) more or less independent of the level of sophistication of the models used. Therefore we tried to develop methods that are able to retrieve more of the original information from the data set. We wanted also to part with multi-normality assumptions that are only partially fulfilled.

FUNDAMENTALS

Data set

The data for our model are taken from daily observations of snow and weather on the observation site 'Weissfluhjoch' during 20 years (1960/61 - 1979/80). Proceeding on the assumption that one winter consists of 270 days, this amounts to a stock of about 5000 days.

The choice of the variables is based on previous avalanche forecast models (Obled, Good 1980). All the models use this data set, thus allowing comparison. As the stepwise linear discrimination analysis revealed the prevailing importance of raw variables, only these were used in the base model NXD and comparing data of only one single day. During the tests it seemed reasonable to consider only the data of the Parsenn area since, 1. they were easily available and 2. the model results could be verified on the spot. A list of the used variables can be found in the appendix.
Method

With the above data avalanche forecast days can be described by a number (p) of characteristic measurable parameters, thus forming a state-vector in a p-dimensional vectorspace. The problem is how to define a similarity, or in numerical terms, the distance between two days.

In our work we chose the euclidian distance between two days in the above vectorspace to determine the nearest neighbours:

\[
x_i = \text{vector of } m \text{ measurements for day } i (m=1,p)
\]

\[
d_{ij} = \sqrt{\sum_{k=1}^{p}(x_{ik} - x_{jk})^2}, \text{ distance between day } x_i \text{ and } x_j
\]

On each day the k nearest neighbours were calculated with snow and weather observations (of which some had to be predicted) of the actual day. In statistics the optimum for k depends on the size of the dataset, which for our set is about 20. We chose k to be 10 days because 1. 10 days can be easily viewed, 2. it allows a quick conversion to %-values for some evaluations or comparison with statistical methods and 3. model results that used 30 nearest neighbours hardly ever differed from model results using 10 days. The experience with previous statistical models showed that percentages of an event (interpreted as danger) often lead to misinterpretations since they are difficult to work with and to understand their significance. Therefore we were careful to establish a criterion for an avalanche danger in order not to withdraw the attention from the avalanche recordings of the found nearest neighbours which contain the essential information. However if for a given day 3 or more days with recorded avalanches appeared among the nearest neighbours, we found that avalanches are very likely to occur on that day. Therefore we used 3 days (or 30% avalanche danger) as a discrimination value.

Scaling and weighting

With the exceptions below the measuring units for the variables used were chosen so that their numerical values were in the same range. In the case of the binary variable snowdrift this was done by the corresponding weighting factor. In order to avoid or at least weaken the seasonal influence on the selection of the nearest neighbours, the values of some parameters were adapted: The snow depth of the actual day is compared with the average snow depth at the same day over the whole period of observation, sunshine and radiation are given in percent of the maximum value for the day in consideration. On the actual day of the forecast, a number of meteorological observables have to be predicted.

Problems of the base model NXD.

One must bear in mind that the NXD-version only takes account of a punctual event - a single day. The influence of previous weather conditions and the state of the whole snowcover were not considered
directly, although some variables such as the snow temperature at -10cm and the snow depth show a kind of memory, in the sense that they don't change drastically within a day and thus contain some information of previous days.

Nevertheless, using the mentioned discrimination value of 0.3, the results of the NXD-version were already satisfactory with 80% of the days correctly classified.

Experimental

The measurement of the variables is a daily routine. The same should apply to the observation and recording of avalanches. All the programs handling the dataset are written in FORTRAN F4P with overlays and are run on a PDP 16 bit machine. The programs and the forecast procedure are described in detail by Büttler (1985) (the report is available at our Institute). For editing convenience the components of the weighting vector are on a separate file. The program has several output options which can be chosen by dialogue. A hard disk as mass storage unit is essential.

EXTENSION OF THE NXD- MODEL

Concept

In previous models of the discriminant type, variables describing sequences of events showed to be very important. In various tests the essential variables of the previous days were determined and added to the base model as described by Buser, Good (1985). The size of the given dataset allows the consideration of 3 previous days. This number was also found in the discrimination analysis method.

A list of the used variables including their weighting factors for the latest extended version NXD3 can be found in the appendix.

Main Versions of the Model are:

(a) Base model: NXD-version, using data of one day only (Buser, Good 1985).

(d) NXD3: Latest version of the model mainly includes the following features: * The weighted sum of new snow of the preceding three days and the amount of new snow of the previous day. * Wind direction and velocity of the previous day (thus taking into account the influence of snow drift) * To a minor extent penetration depth, snow temperature at -10cm and air temperature at midday of the previous day (see appendix for more information).

Weighting

In a next step appropriate weighting factors had to be found for the parameters. The program was run and analysed with a number of suggested weighting factors with the data of a period containing accurate and reliable recordings of both the weather conditions and the avalanche activity (January and February 1984).
Avalanche forecast by the nearest neighbour method

Some relevant information could also be gathered in various realtime tests during winter 84/85 and many valuable contributions were made by the forecasters.

General Remarks, Problems

There are situations in the present when no or only few similar situations in the past can be found due to a low density of days in the vector space area. In that case a consideration of previous days cannot improve the results. Moreover the availability and reliability of certain variables cannot always be guaranteed. A measure for the similarity is given by the square of the distance between the day of the forecast and its nearest neighbours which is included in the model output. It enables the forecaster to estimate the reliability of the found days. Our study showed that in more than 90% of all cases the factor in the distance between the first and the tenth nearest neighbour was below 2 and could therefore be considered an indication of a sufficient resemblance of the found days. Otherwise the reliability of these days has to be doubted and the forecast must be based on a reduced number of similar days. A criterion as simple as the above factor may be helpful when dealing with a smaller data-set, for instance if the number of years taken into account is much smaller. The model results must then be analysed even more carefully. We found that the model can be used for a dataset of just three years.

By considering data of previous days as well as adapting the corresponding weighting vector the model could be refined considerably (see evaluation below). The results of the model asymptotically approach a state where additional changes showed little or no effect on the model-output.

Also it is interesting to know that not only similar days were found but similar periods of the past as well. Among the 10 nearest neighbours of some consecutive days an increasing number of days belonging to the same period can be observed. This is an additional indication for a fairly realistic behaviour of the model.

The above findings imply that any further refinements only can be achieved by better and more consistent data and especially by a more accurate recording of the avalanche activity with respect to space (aspects), time and type (natural or artificial).

INTERPRETATION AND RESULTS

The following aspects have to be taken into consideration:

(a) A sound verification of the results of any avalanche forecast depends on an accurate recording of the avalanche activity both realtime and in the past. This accuracy could NOT be guaranteed with the given data.

(b) The ten nearest days gain an equal weight in the evaluation thus disregarding their distance to the day of the forecast.

(c) The time-factor was omitted in most evaluations. Consequently some avalanche events stayed active although it could be shown that the very same avalanche had already occurred on an earlier date.
(d) Days appearing among the nearest neighbours were included in the evaluations uncritically. Their reliability was not checked and no corrections were made (i.e. to avoid the reproach of arbitrarily influencing the results). Therefore days with incorrect data may as well be included as days that are not considered similar enough to the day of the forecast. (This problem arises in low density areas of the vector space representing periods with extraordinary weather and snow conditions, e.g. January 1985 with extremely low temperatures and a shallow snow pack).

The verification and quantification of the obtained results turned out to be quite difficult. To give an idea of the model's overall performance, a couple of attempts to illustrate these points are included here.

Comparison of the Different Versions

The verification of the models is based on the assumption that a certain number of days with recorded avalanches among the 10 nearest neighbours can be found to establish a criterion for the occurrence of avalanches. As mentioned before this was found to be at least 3 days (Buser, Good, 1985).

To include the conventional method in this comparison, the avalanche potential (LaChapelle, 1977) was quantified accordingly. The forecasters use 6 levels of avalanche danger. Levels 1 and 2 here stand for "avalanche not probable" (N), levels 3 to 6 "avalanche probable" (L).

The following names apply to the evaluations:

(a) L/+ : Avalanches forecast and avalanches observed in the Parsenn area.
(b) L/- : Avalanches forecast but no avalanches observed.
(c) N/+ : No avalanches forecast but avalanches observed.
(d) N/- : No avalanches forecast and no avalanches observed.
(e) true: Number of correctly forecast situations (L/+ & N/-).
(f) false: Incorrectly forecast situations (L/- & N/+).

<table>
<thead>
<tr>
<th>TABLE 1 Comparison of the different versions of the model and the conventional forecast in January and February 1984</th>
</tr>
</thead>
<tbody>
<tr>
<td>JANUARY 1984:</td>
</tr>
<tr>
<td>base model</td>
</tr>
<tr>
<td>NXD3</td>
</tr>
<tr>
<td>conventional</td>
</tr>
<tr>
<td>L/+ . L/- . N/+ . N/- . true . false</td>
</tr>
<tr>
<td>10 . 7 . 7 . 4 . 14 . 14</td>
</tr>
<tr>
<td>16 . 8 . 1 . 3 . 19 . 9</td>
</tr>
<tr>
<td>15 . 11 . 1 . 1 . 16 . 12</td>
</tr>
</tbody>
</table>
FEBRUARY 84:

<table>
<thead>
<tr>
<th></th>
<th>base model</th>
<th>NXD3</th>
<th>conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>.5 . 6 . 4 . 14 . 19 . 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.8 . 7 . 1 . 13 . 21 . 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.8 . 12 . 1 . 8 . 16 . 13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 2 Summary of the results in table 1.

<table>
<thead>
<tr>
<th></th>
<th>L/+ . L/- . N/+ . N/- . true . false</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL 1984:</td>
<td></td>
</tr>
<tr>
<td>base model</td>
<td>.15 . 13 . 11 . 18 . 33 . 24</td>
</tr>
<tr>
<td>NXD3</td>
<td>.24 . 15 . 2 . 16 . 40 . 17</td>
</tr>
<tr>
<td>conventional</td>
<td>.23 . 23 . 2 . 9 . 32 . 25</td>
</tr>
</tbody>
</table>

Comments

January and February 1984 were chosen because of the already mentioned reliability on their avalanche recording as well as because they represent two considerably different weather situations:

(a) Frequently changing weather- and snow- conditions in January implying a difficult estimation of the avalanche situation.

(b) A clear situation in February with a period of heavy snow fall at the beginning followed by a long period of fine weather.

An improvement of the model can be noticed clearly especially in the dropping number of N/+ situations.

A comparison with the conventional method shows that the model NXD3 performs certainly not worse. The higher number of "true" forecasts for the model NXD3 is due to the situation where avalanches were neither forecast nor observed.

Observed Avalanche Activity versus Model and Conventional Forecast

Two diagrams (figures 1 and 2) give an impression of the behaviour of the new version of model NXD3 in January and February 1984.

The graph named "Observed avalanches" represents the density of observed avalanches according to Regli (1984), which is a linear representation ranging from 0% (= 0 avalanches) to 100% (= 7 avalanches or more). Small avalanches (length and width smaller than 50 m) gain half weight. The values of the model are determined according the number of days with avalanches recorded among the 10 nearest neighbours. As in the preceding evaluation the avalanche potential of the conventional forecast is quantified.

Among other features it can be seen that the model reacts more quickly and distinctively to changes in the actual avalanche situation, especially at the beginning and at the end of a period with a high avalanche activity.
FIG. 1 Comparison observed avalanches versus model and conventional forecast in January 1984.
— observed avalanches, —— model, —— conventional forecast.

FIG. 2 Comparison observed avalanches versus model and conventional forecast in February 1984.
— observed avalanches, —— model, —— conventional forecast.
The conventional forecast tends to a more conservative prediction in the sense that it forecasts an avalanche even if the actual avalanche density is low. The forecast may not be taken seriously anymore if it remains too long on the side of caution. In that way the model can indicate changes in the avalanche situation even if they may appear to be drastic and risky.

Analysis of the aspect records

For this analysis the 20 days with observed avalanches between January 14th and March 19th, 1985 were taken into account.

Evaluation method: The compass card of each day was subdivided into quarters according to the subdivision of the forecaster and the model respectively. To verify the forecast it was checked whether avalanches occurred in the given quarters or not.

The same annotation is used as in the above evaluation completed by the following:
L + Avalanches forecast (Total), N No avalanches forecast (Total).

Actual situation in the 20 days of the evaluation:
Number of quarters with observed avalanches: 43
Number of quarters with no observed avalanches: 34

TABLE 3 Comparison of the aspect forecast

<table>
<thead>
<tr>
<th>L+</th>
<th>L-</th>
<th>N+</th>
<th>N-</th>
<th>true</th>
<th>false</th>
<th>L</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>28</td>
<td>6</td>
<td>6</td>
<td>43</td>
<td>34</td>
<td>65</td>
<td>12</td>
</tr>
<tr>
<td>32</td>
<td>13</td>
<td>13</td>
<td>19</td>
<td>51</td>
<td>26</td>
<td>45</td>
<td>32</td>
</tr>
</tbody>
</table>

Interpretation

Apart from the already mentioned problems of an analysis, the test period proved to be part of an extraordinary winter in which an estimation of the actual danger was extremely difficult. Nevertheless a few observations can be made:

(a) The conventional forecast expects avalanches to occur at 5/6 of all aspects on an average in comparison to the model whose corresponding number amounts to 4/7 (which is about the observed ratio). Consequently the model is more restrictive.

(b) The model yields a higher percentage of correctly forecast aspects than the conventional method. However, since a low number of quarters has no avalanches forecast (N), the conventional forecast has fewer situations where avalanches occurred although no avalanches were forecast.

Summarizing these facts it can be said that, since the model is more restrictive, it can help the forecaster to come to a decision. It therefore shows once more its usefulness as a complementary method.
The method of the nearest neighbours does not relieve the forecaster or any user from taking his own decision. Being an interactive program however, it is a tool to provide responsible people with useful information comprising real situations of the past.

Using data of a restricted area, the model could be applied by local avalanche forecasters for control of ski resorts (Example 2).

If in the future equal information can be obtained from several small but well monitored areas, common features of the avalanche activity might be detected for an extended area (with the help of similar days), or regions of common features can be defined.

Bearing in mind the possible lack of similar days the model can be run with the data of just a single winter. Yet various tests showed that only 3 years of observation are needed on an average to get reliable information, provided the recording of the avalanche activity has been carefully done and the nearest neighbours given by the model are used with care.

Example 1

A number of cases have been reported where unexpected accidents killed people and caused property damage. In case of a trial it might be extremely difficult for the parties responsible to prove that the event was unforeseen, thus having to cope with heavy claims for the resulting damages.

This model can produce evidence that the event was totally unforeseen by providing the court with concrete situations of the past in which no avalanche had occurred under similar circumstances.

Example 2

Supplying detailed information about similar situations in the past, the model can support the local control in the decision to open ski runs or whether or not to shoot critical slopes.

The list of the nearest neighbours may show that bombing critical slopes on those days in the past released no avalanches. As there would be no use in shooting again, explosives and manpower can be saved and the ski runs can be opened earlier.

CONCLUSION

The method of the nearest neighbours has its advantages but also its limitations. It is a tool to provide the forecaster with detailed information. Although it does not relieve him from making his own decision it helps him to make a sounder one. He still has to take care of qualitative parameters, such as the structure of the snow cover or the avalanche activity of previous days, and it is still up to him to extrapolate the results for a much larger climatic region.

In addition we found that for a restricted area, only a few years of careful observation are needed. The method is felt to be most useful for ski resorts. The people responsible are given a basis for
Avalanche forecast by the nearest neighbour method

their decision which might prove invaluable in case of a trial. If the minutes are kept accordingly, they also will have a mean to decide whether it is necessary to use methods of artificial release for an avalanche slope or not.

In the future the model can be applied for an extended area if the information about the avalanche activity of the "similar" days from several small, but well monitored areas in a large region are available.

APPENDIX

TABLE 4 Parameters and their weighting factors for NXD3 (Büller 1985)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
<th>Weighting factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Day: n n-1 n-2 n-3</td>
</tr>
<tr>
<td>Precipitation</td>
<td>gram/dm*dm</td>
<td>0.5 0.5 0 0</td>
</tr>
<tr>
<td>New snow</td>
<td>mm</td>
<td>1.0 1.0 0.3 0.1 *1</td>
</tr>
<tr>
<td>Snow depth</td>
<td>cm</td>
<td>1.0 0 0 0</td>
</tr>
<tr>
<td>Penetration depth</td>
<td>cm</td>
<td>2.0 1.0 0 0</td>
</tr>
<tr>
<td>Snow temperature (-10cm)</td>
<td>1/10 degree</td>
<td>1.0 0.5 0 0</td>
</tr>
<tr>
<td>Snow drift</td>
<td>1/0 (yes/no)</td>
<td>50.0 25.0 0 0</td>
</tr>
<tr>
<td>Midday temperature</td>
<td>1/10 degree</td>
<td>1.0 0.5 0 0</td>
</tr>
<tr>
<td>Windspeed</td>
<td>dm/s</td>
<td>1.0 1.0 0 0</td>
</tr>
<tr>
<td>Winddirection</td>
<td>deka-degree</td>
<td>3.0 3.0 0 0</td>
</tr>
<tr>
<td>Cloudiness</td>
<td>% sky overcast</td>
<td>1.0 0 0 0</td>
</tr>
<tr>
<td>Duration of sunshine</td>
<td>1/10 hour</td>
<td>1.0 0 0 0</td>
</tr>
<tr>
<td>Radiation</td>
<td>J/cm*cm</td>
<td>1.0 0 0 0</td>
</tr>
</tbody>
</table>

Remarks

Dimensions and units were chosen for numerical convenience. The model uses the marked parameters as follows:

*1 The weighted sum of new snow of the days (n-1), (n-2), (n-3) as ONE parameter.
*2 In % of the average snow depth, calculated from the snow depth of the same day over all observed years.
*3 The weighting factor above applies only to windspeeds in excess of 5 m/s. For 0 m/s windspeed the weight is 0 and then increases in proportion to the windspeed until it reaches 3 when the windspeed is 5 m/s.
*4 In % of the maximum possible duration of sunshine respectively radiation of that specific day.

REFERENCES


Bois, Ph., Obled, Ch. & Good, W. (1975) Multivariate Data Analysis as
a Tool for a Day-by-Day Avalanche Forecast. Proceedings of the
Snow Mechanics Symposium, Grindelwald 1974. IAHS Publ. Nr. 114,
391-403.

Bovis, M.J. (1977) Statistical Forecasting of Snow Avalanches, San
Juan Mountains, Southern Colorado, U.S.A. Journal of Glaciology,
Vol. 18, Nrodo. 78. 87-99.

Buser, O. (1983) Avalanche Forecast with the Method of Nearest
Neighbours: An Interactive Approach. Cold Regions Science and

Buser, O., Föhn, P., Good, W., Gubler, H. & Salm, B. (1985)
Different Methods for the Assessment of Avalanche Danger. Cold

nearest neighbours. Proceedings, International Snow Science

Berücksichtigung der Vortage. Interner Bericht Nr.629 (including-
programs in Fortran 77). Swiss Federal Institute for Snow and
Avalanche Research, Davos Switzerland.

Thèse Présentée devant l'Université Claude-Bernard Lyon-1 pour
obtenir le diplôme de docteur de spécialité, Lyon.

Föhn, P., Good, W., Bois, Ph. & Obled, Ch. (1977) Evaluation and
Comparison of Statistical and Conventional Methods of Forecasting

Jaccard, C. (1965) Statistische Analyse der Lawinenereignisse und
Lawinenvorhersage. Interner Bericht Nr. 450, Swiss Federal
Institute for Snow- and Avalanche Research, Davos Switzerland.

Judson, A. & Erickson, B.J. (1973) Predicting Avalanche Intensity from
Weather Data: A Statistical Analysis. USDA Forest Service Research
Paper, AM 112, Fort Collins.

Kosarev M., V. (1969) Main results of a study of avalanche formation
conditions on the southern slopes of the western Tien Shan. Soviet
Hydrology, selected papers.


La Chapelle, E.R., Ferguson, S.A., Marriott, R.T., Moore M.B. &
of Scientific Investigations. Rep. 23.4 Dept. of Atmospheric

Obled, Ch. & Good, W. (1980) Recent Development of Avalanche
Forecasting by Discriminant Analysis Techniques: A Methodological
Review and some Applications to the Parsenn-Area (Davos,

Regli, B. (1984) Bewertung des Modells "Next days" für die Zwecke
der lokalen Lawinenwarnung. Interner Bericht Nr.620. Swiss Federal
Institute for Snow and Avalanche Research, Davos Switzerland.

Salway, A.A. (1976) Statistical Estimation and Prediction of
Avalanche Activity from Meteorological Data for the Rogers Pass
Columbia.

Shcherbakov, M., P. (1969) Method of predicting avalanche danger from
snowfall intensity in the Tien Shan. Alta Avalanche Study Center,
Wasatch National Forest, Alta.
DISCUSSION

S. Ferguson
During your test winter, where you compared the accuracy of the conventional forecast to the model forecast, were the conventional forecasters allowed to see the model output before they made their decision or was it after?

M. Butler
The forecasters were allowed to see the model forecast before they made their decisions. However in most cases they didn't have time or intention to look at the model output and therefore made their independent decisions.

C. Mätzler
Why was the temperature of the snow surface not used in your analysis? I thought that it is relevant for surface hoar formation.

W. Good
In a stepwise linear discrimination for variable selection, the surface temperature (as measured conventionally on the standard studyplot and not in the relevant slopes) does not appear as one of the most important ones. On the other hand, the temperature measured 10 cm below the snow surface introduces a time lag between air temperature and this variable has a welcome memory effect.