# ISOTHERMAL METAMORPHISM OF A NEW SNOW LAYER: SOME MEASUREMENTS AND SIMULATION

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ABSTRACT: Snow layer evolution is numerically modelled by physical parameters and its grain structure description. The simulation result depends directly of the quality of these input data. This article presents some analysis of the shape descriptors based on a 3D data set obtained from an isothermal metamorphism experiment by X-ray microtomography. The results are compared to simulations from existing physically-based snow layer models. The numerical evolution of the snow densification is performed using CROCUS and SNTHERM algorithms and compared to the experimental thickness of the layers and the density obtained from the 3D data. The grain shape evolution is evaluated by the CROCUS model based on grain shape descriptors (dendricity, sphericity and size) and 2D optical microscopy methodology. The main 3D radius evolution is compared to 2D image data and confirms the potentiality of X-ray based geometry descriptors to future improvements in the numerical model parameters.

Keywords: snow modelling, isothermal metamorphism, 3D shape descriptors.

## 1. INTRODUCTION

Snow cover evolution is a constant concern to avalanche forecasters. So, energy and mass models of snow cover have long been developed for avalanche forecasting. They are still improved and their domain of application have widen. At the same time research laboratories continue to conduct targeted experiments in order to improve the knowledge of physical processes that govern snow metamorphism.

The purpose of this paper is to use the detailed experimental data for checking the response of the classical snow models. In that case we use data from an isothermal metamorphism of a snow layer previously used for the development of a model of metamorphism at the grain scale. We compare the measures to the results of simulation with *CROCUS* and *SNTHERM* models.

We focus on the main aspects of the isothermal metamorphism that are the significant packing of the snow and the smoothing and rounding of the grain shapes.

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The experiment is described in section 2, followed by the settling and grain evolution laws used in the models presented in section 3. The simulations results are compared with measurements in section 4. Then main 3D geometry parameters (i.e.: REV, granulometry, etc.) are presented and discussed in section 5

## 2. MEASUREMENTS

Experimental data comes from an isothermal metamorphism experiment of a natural snow fall (Flin and others, 2003). A 0.5m x 1m slab, 12 cm thick, was collected in field then maintained at -2°C during 84 days. The initial snow consisted of 3 layers, from bottom to top: 4 cm at 110 kg/m$^3$, 5 cm at 100 kg/m$^3$ and 3 cm at 50 kg/m$^3$.

The following measurements and sampling were done at increasing time intervals during the experiment:

i) Total thickness and thickness of each layer;
ii) Sampling in the middle layer for microtomographic acquisition which provided 3D data of snow;
iii) Sampling of few grains for 2D analysis of their silhouette.

Figure 1 shows an outlook of the different stages of the snow metamorphism under isothermal conditions from new snow to rounded grains.

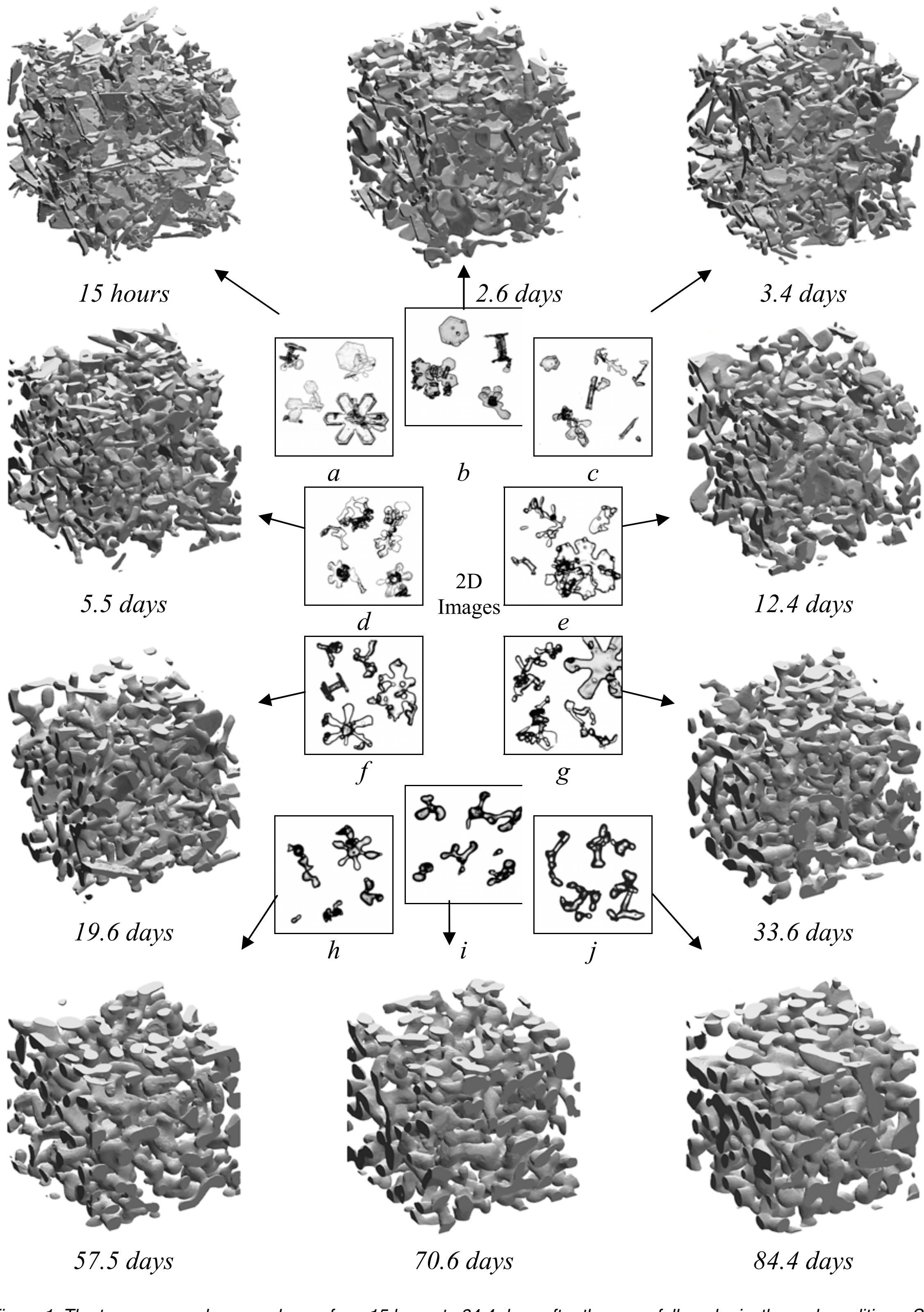


*Figure 1: The ten processed snow volumes from 15 hours to 84.4 days after the snow fall, under isothermal conditions. Size of each cube edge is 2.95 mm. (a) to (j) are outlines of grains collected at the same time that the snow sample for imaging, square size is 4 mm.*

3. MODELS

We use *CROCUS* and *SNTHERM* models to simulate the evolution of the initial snow slab under isothermal conditions at negative temperature. We focus on the settling law and the grain evolution.

3.1 <u>Settling law</u>.

Let CR be the compaction rate:

$$CR_{\mathrm{INDEX}}=\left[\frac{1}{\Delta Z}\times\frac{\partial \Delta Z}{\partial t}\right] \quad (1)$$

*CRO* index for *CROCUS* model, *ST* for *SNTHERM* model

Under isothermal conditions, at negative temperature, *CROCUS* only takes into account a mechanical settlement due to the weight of overlying snow. The compaction law actually used in *CROCUS* model is slightly different from that described in Brun et al., 1989.

Classically the deformation rate is assumed to be a linear function of the snow load pressure $P_s$

$$CR_{CRO}=\frac{-P_S}{\eta} \quad (2)$$

where $\eta$ is the mean viscosity (N.s.m$^{-2}$)

$$\eta=\eta_0\times e^{c1(273.15-T)}\times e^{c2\times\rho_S} \quad (3)$$

where $\rho_s$ is the density (kg/m$^3$), T the snow temperature (K), *c1*=0.1, *c2*=23, $\eta_0$ depends on the grain type. In the present case:

$$\eta_0=7.77\times10^4\times\frac{\rho_S}{250} \quad (4)$$

In the operational version of *CROCUS* model used for avalanche forecasting, in order to avoid some numerical problems that occurred in thin layers near the surface, the snow load applied is the minimum between 100 N.m$^2$ and the real load. So we consider two versions for *CROCUS* model:

*CRO_oper* with a load of 100 N.m$^2$ and *CRO_law* with the real load that is 42 N.m$^2$ in the middle layer of our experiment.

In *SNTHERM* model, the compaction process is considered in two terms.

$$CR_{ST}=CR_{metamo}+CR_{overburden} \quad (5)$$

$CR_{metamo}$ represents settling due to destructive metamorphism of the new snow and $CR_{overburden}$ the densification of snow due to the load of the overlying snow.

$$CR_{metamo}=-2.778\times10^{-6}\times c3\times c4\times e^{-0.04(273.15-T)} \quad (6)$$

For dry snow: *c4*=1

if $\rho_S\le\rho_C$ *c3* =1

if $\rho_S>\rho_C$ $\quad c_3=e^{-0.046(\rho_S-\rho_C)}$ (7)

$$CR_{overburden}=\frac{-P_S}{\eta} \quad (8)$$

where

$$\eta=\eta_0\times e^{c5(273.15-T)}\times e^{c6\times\rho_S} \quad (9)$$

*c5*= 0.08, *c6*=23 and $\eta_0$=3.6x10$^6$ N.s.m$^{-2}$

In different studies, the *SNTHERM* compaction routine was revised. These revisions mainly include decreasing the critical density to 100 kg/m$^3$ and modifying the snow viscosity from 1.0x10$^6$ N.s.m$^{-2}$ (Jordan et al., 1999) to 9x10$^7$ N.s.m$^{-2}$.

Consequently we consider two versions for the compaction law.

The first one is *SNTHERM* reference (*ST_init*) with $\rho_C$=150 kg/m$^3$ and $\eta_0$=3.6x10$^6$ N.s.m$^{-2}$.

The second one, called SHTHERM revised (*ST_rev*) with $\rho_C$=100 kg/m$^3$ and $\eta_0$=9x10$^7$ N.s.m$^{-2}$.

In that case the preponderant term is $CR_{metamo}$ in the range of the studied density.

Figure 2 shows the strong decrease of the compaction rates with increasing density and the important impact of the value of the critical density for *SNTHERM*.

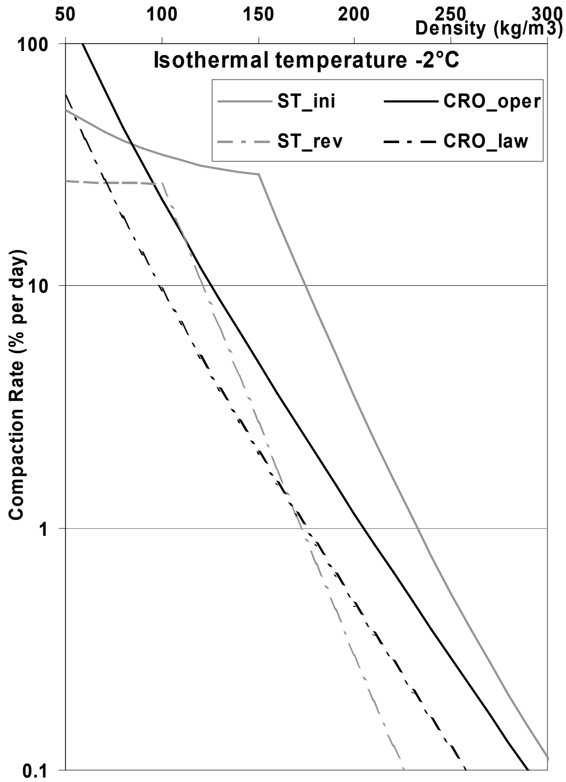


*Figure 2: Compaction rates versus density for each version of CROCUS and SNTHERM.*

3.1 <u>Grain evolution</u>

*SNTHERM* model does not allow the evolution of grain type. It only takes in account grain size which evolves as a function of temperature gradient or liquid water content. Therefore, grain size is assumed constant under isothermal conditions.

The *CROCUS* snow model introduces a formalism that describes snow as a function of continuous parameters : dendricity, sphericity and grain size (Brun et al., 1992). Dendricity decreases from 0 to 1 and describes the part of the original crystals shapes which are still remaining in a snow layer. Sphericity varies from 0 to 1 and describes the ratio of rounded versus angular shapes. When isothermal conditions, the first stage of their evolution is described by the following:

$$\frac{d(dendricity)}{dt} = -2\times10^{8}\times e^{\frac{-6\times10^{3}}{T}} \quad (10)$$

$$\frac{d(sphericity)}{dt} = 10^{9}\times e^{\frac{-6\times10^{3}}{T}} \quad (11)$$

where t: time in days.

When dendricity reaches 0, snow is then characterized by its sphericity and its grain size which is set at a diameter of 0.3 mm. As for *SNTHERM* model, grain size does not grow under isothermal conditions.

## 4. RESULTS

### 4.1 <u>Settling</u>

The observed packing of snow is dotted in Figure 3 showing the evolution of total snow depth. *CRO_law* and *ST_rev* are in rather good agreement with the measure. Settlement of *CRO_oper* and *ST_ini* are too important at the beginning, i.e. for low densities.

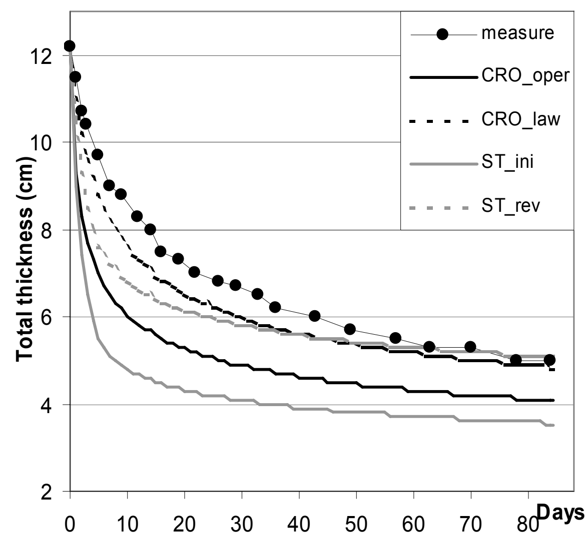


*Figure 3: Evolution of the snow total thickness.*

In figure 4, density of the middle layer is not a weighing measure. It is deduced from the thickness of this layer which decreases from 4 cm to 1.7 cm at the end of the experiment. Limits between layers were not always clear that leads to a large uncertainty of the values of density. The densities computed from 3D data are scattered, they does not evenly increase as it could be expected. This point will be discuss in section 5.2.

The curves of simulated densities fitted rather well the measures except for ST_ini which still overestimated the settling of new snow.

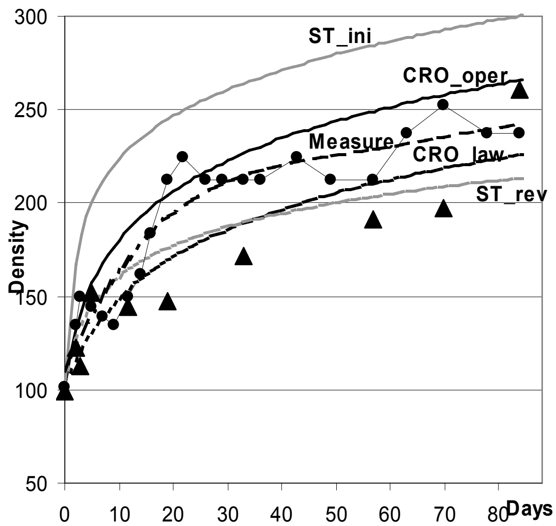

Figure 4: Evolution of the density of the middle snow layer. Measurements (circles) are deduced from the thickness of the middle layer. Triangles are densities computed from 3D data.

4.2 <u>Grain evolution</u>

We use an automatic system for the determination of snow-grain characteristics from 2D images (Lesaffre et al., 1998). This system provide parameters of snow-grain morphology. Some of them such as dendricity, sphericity, mean convex radius of curvature could be compared to the results of *CROCUS* model (Figure 5).

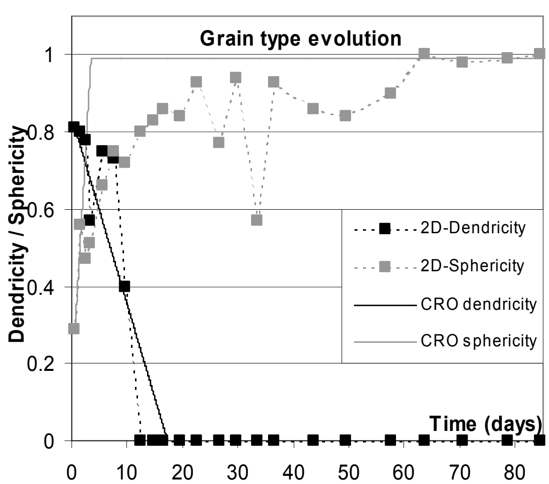

Figure 5: Evolution of the grain morphology parameters: Dendricity and Sphericity. 2D grain-analysis (dots) CROCUS simulation (solid line).

The initial profile for *CROCUS* simulation is set with the values of dendricity: 0.81 and sphericity: 0.29 analysed from the first sample, 15 hours after the beginning of the snow fall. There is good agreement for the decrease of dendricity. Partly branched particles have almost disappeared after 12 days. The rate of increasing sphericity is slightly overestimated by the model.

Definitions of snow grain size are many, so it is necessary to indicate what we used. For instance a stellar shaped new snow crystal has not characteristic length, for its maximum length can reach 1 cm but it is only 20 to 40 µm thick. When snow undergoes metamorphism, stellar branches become smoother, crystals become thicker then snow crystals change to granular shapes. 2D image analysis of grains allows to compute the mean convex radius of curvature (MCR) which is the inverse of the mean curvature along the periphery of the grain silouhette.

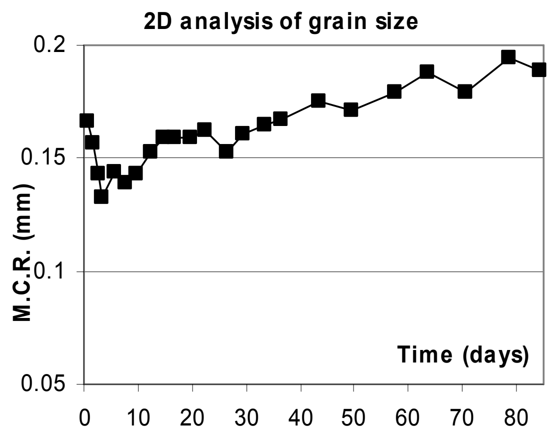

Figure 6: Evolution under isothermal conditions of the mean convex radius of curvature (MCR) computed by a 2D grain-analysis system.

The image analysis system overestimate MCR of new snow and partly decomposed particles which tend to lay flat on the plate. This parameter does not give a precise information for grain size at the beginning of the experiment. Under isothermal conditions, rounding and smoothing of the shapes bring snow microstructure closer to a set of spherical objects. MCR can then be consider as the radius of the grains.

Figure 6 shows a very slow increasing of MCR with time. The equivalent grain diameter is around 0.32 mm after 20 days, it is still less than 0.4 mm after 80 days at the end of experiment. So, it is quite reasonable assume constant grain size for isothermal metamorphism used in *CROCUS* and *SNTHERM* models.

## 5. THE 3D DATA

X-ray microtomographic technique can provide 3D data of snow where solid phase (ice) is distinguished from pore phase. It allows to visualize the snow microstructure without breaking the grain bonds. Unfortunately it is not easy to individualize grains and their bonds by this technique. Consequently it is difficult to directly compare results from 3D analysis to classical observations of grains. Nevertheless we can compute several parameters from 3D data that provide relevant information on grain morphology and its evolution, as:

### 5.1 *Curvature*

The curvature is a governing parameter for dry snow metamorphism at low temperature gradient. Curvature distributions also seem to be clearly different for each type of grain (Coléou et al., 2000). They have been presented for this experiment (Flin et al., 2004) and their evolution denotes the rounding and smoothing of the shapes along the metamorphism.

### 5.2 *Representative Elementary Volume* (REV)

The REV for solid phase (i.e. 1-porosity) is computed from embedded cubes. Each curve represents the percentage of solid (ice) computed for a cubic region of interest that increase from the centre of the 3D image. In a porous media this curve is supposed beginning at 0 or 1 (1 voxel cubic length), then tending to a constant property mean value independent of the cubic region of interest length. In such a case the REV is assumed to be reached.

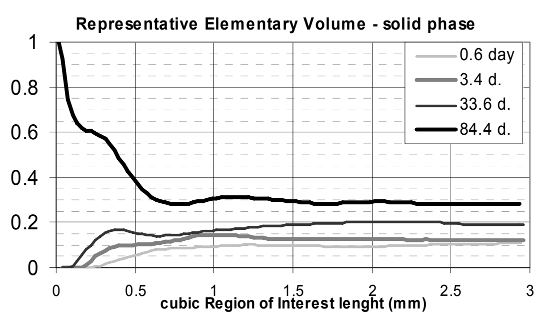


*Figure 7: Percentage of solid phase (ice) of embedded cubes. (only 4 samples are presented for readability).*

Observing the curves in figure 7 we can consider that the REV is reached for the last sample, but for previous samples it seems that the end of the oscillations is not clearly visible. Therefore, it could explain the discrepancy observed in figure 4 between densities deduced from thickness of the middle layer and the 3D samples.

### 5.3 *Granulometry*

The granulometry is computed using the method of 3D-opening granulometry with a spherical structural element (Serra, 1984). In figure 8, each curve represents the size distribution of an equivalent medium exclusively constituted of spheres. If the sample consists of non spherical elements, the relevance of this distribution is obviously questionable. In our study, the first sample consists of new snow, far from spherical shapes, so the granulometry does not represent the size distribution of the crystals. However for the last sample, grains have more rounded shapes, so the curve of granulometry tends probably to a grain size distribution. The general shape of the curves confirms it since the shape of the last one is more “Gaussian” than the first one.

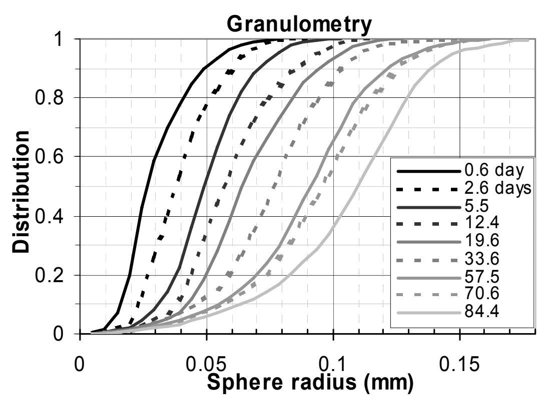


*Figure 8: Mathematical granulometry computed on the different 3D data.*

### 5.4 *Maximum sphere radius*

Granulometry distributions can provide an interesting parameter: the value of the maximum class of each sample. It corresponds to the maximum size of a sphere enclosed in the ice phase. Figure 9 shows the evolution of this parameter during the isothermal metamorphism. The increasing rate of the maximal radius is high in the first part of the metamorphism when the new snow crystals become thicker. Then it become slower and the value of the maximal radius of the sphere at the end of the experiment is close to the mean convex radius of curvature shown in figure 6.

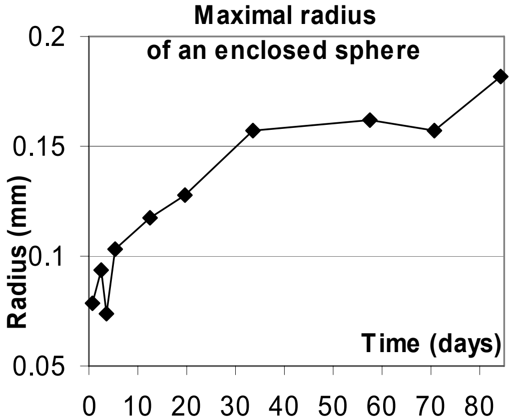


*Figure 9: Evolution of the radius of the maximal sphere that can be enclosed into the ice phase.*

5.5 *Specific Surface Area (SSA)*

The SSA is the total surface area of the air/ice interface per mass unity. It is computed using an algorithm described in Brzoska et al., 2001. Since it indicates the potential of the snow to undergo physical evolutions it is a useful parameter for the description of snow metamorphism. Figure 10 shows that the SSA evolution seems to follow a logarithmic law.

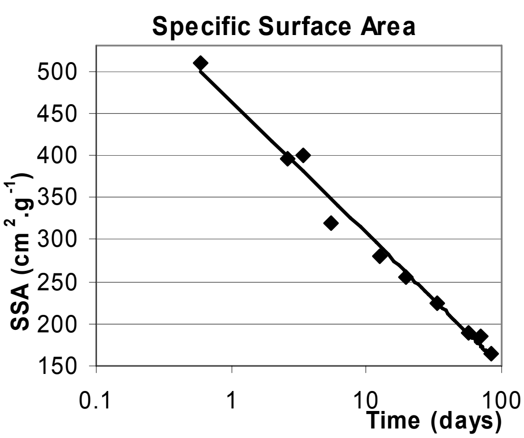


*Figure 10: Evolution of the specific surface area (SSA). Time is plotted on a logarithmic scale.*

The introduction in snow model as *CROCUS* of the specific surface area and its evolution can be consider. This parameter is closer to the physics but there are very few available measurements due to the difficulties obtaining the measure either by experimental measurement or from 3D data. A means for introducing parameters from 3D data in snow models might be the creation of a new index. For instance a geometry factor combining the maximal radius of the sphere and the specific surface area that might be related to existing descriptors as dendricity and sphericity.

6. CONCLUSION

Existing experimental data from an isothermal metamorphism of a new snow layer were used for a comparison to simulated results from *CROCUS* and *SNTHERM* models.

Settling laws give results in rather good agreement with the measurements, except for the critical density used in *SNTHERM* that needs to be lowered as it has already been done in various studies.

Grain evolution is well taken in account in *CROCUS* modelling of the isothermal metamorphism of a new snow layer.

Isothermal metamorphism is a simple situation, it will be interesting to conduct similar studies with different initial grains and for metamorphism with higher temperature gradient.

The study of 3D data from this experiment shows that they provide relevant information on grain morphology and its evolution. This kind of complementary shape descriptors can be used to improve the microstructure characterisation used in snow modelling.


7. ACKNOWLEDGMENTS

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