Isothermal Metamorphism of Snow:

Measurement of Interface Velocities and Phase-Field Modeling for a Better Understanding of the Involved Mechanisms

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1. Introduction

Once deposited on the ground, snow forms a complex porous material whose microstructure constantly transforms over time. These evolutions, which strongly impact the physical and mechanical properties of snow (e.g. Srivastava et al, 2010; Löwe et al, 2013; Calonne et al, 2014; Wautier et al, 2015) need to be considered in details for an accurate snowpack modeling. However, some of the physical mechanisms involved in metamorphism are still poorly understood.

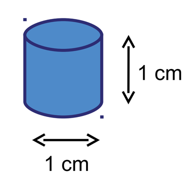
To address this problem, several investigations combining X-ray tomography and 3D micro-modeling have been carried out over the past decade (e.g. Flin et al, 2003; Kämpfer and Plapp, 2009; Pinzer et al, 2012) but precise comparisons between experimentation and modeling remain difficult. One of the difficulties comes from the lack of high resolution time-lapse series for experiments occurring with very well-defined boundary conditions, and from which precise measurements of the interfacial growth rates can be achieved.

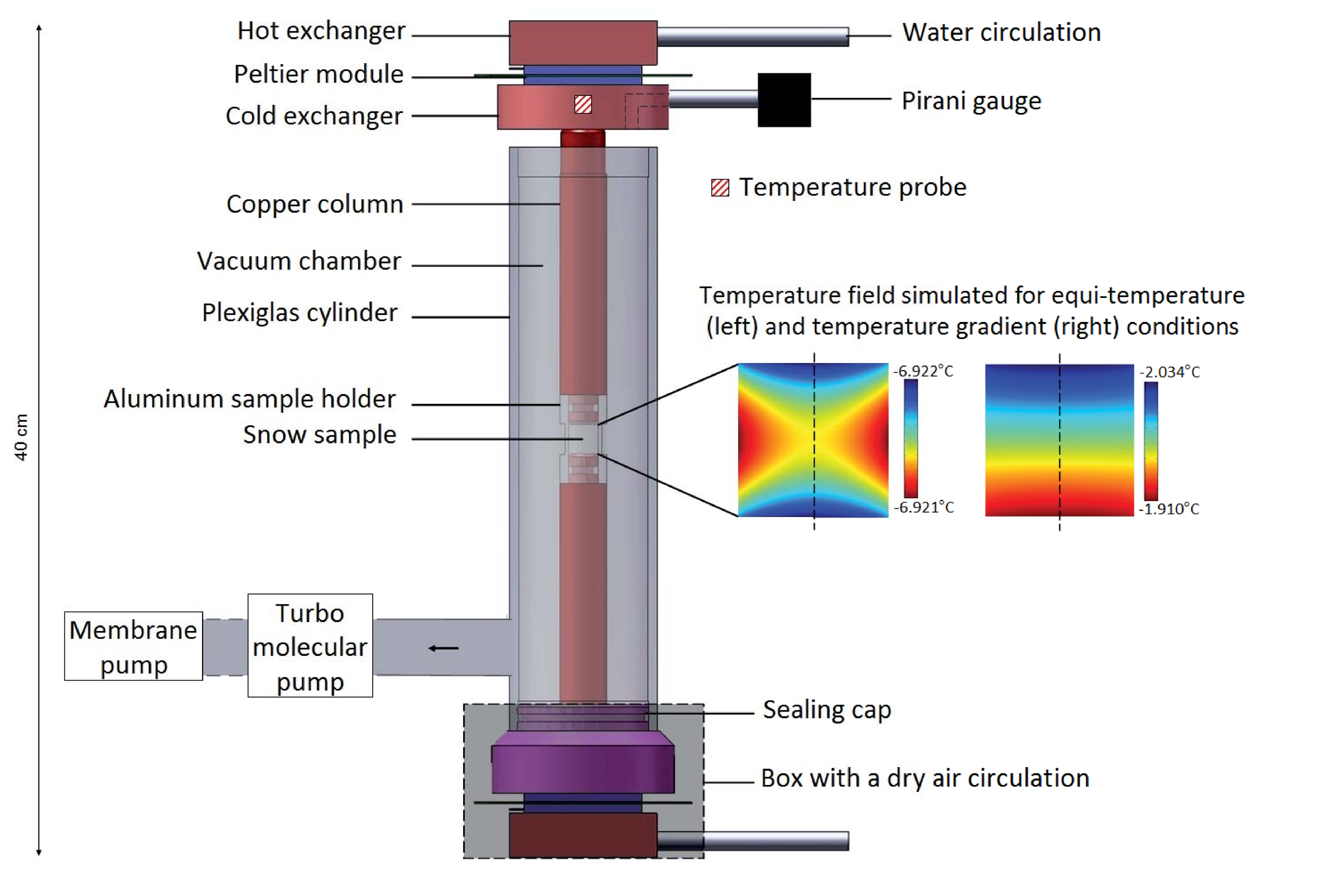
Using **CellDyM, a recently developed cryogenic cell** (Calonne et al, 2015), we conducted **in situ time-lapse tomographic experiments** on several snow and ice samples under various conditions. We focus here on a 28 h experiment of isothermal metamorphism at -7°C. The non-destructive nature of X-ray microtomography yielded a series of 8 micron resolution images that were acquired with time steps ranging from 2 to 12 hours. An image analysis method was then implemented to estimate the **normal growth rates on each point of the ice-air interface** and applied to the series obtained.

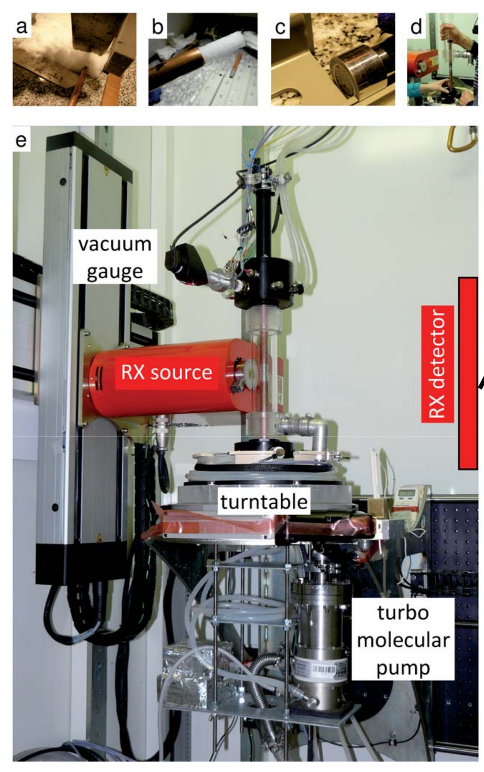
In addition, a curvature-based phase-field model (Bretin et al, 2015) was used on the first image of the experimental series to compute the snow evolution under a pure sublimation-condensation mechanism: the numerical morphologies were then compared to the experimental ones. The analysis of all the results gives interesting **outlooks for the understanding of the physical mechanisms involved** in snow isothermal metamorphism.

2. CellDyM: a Cryogenic Cell for Time-Lapse Tomography at Room-Temperature

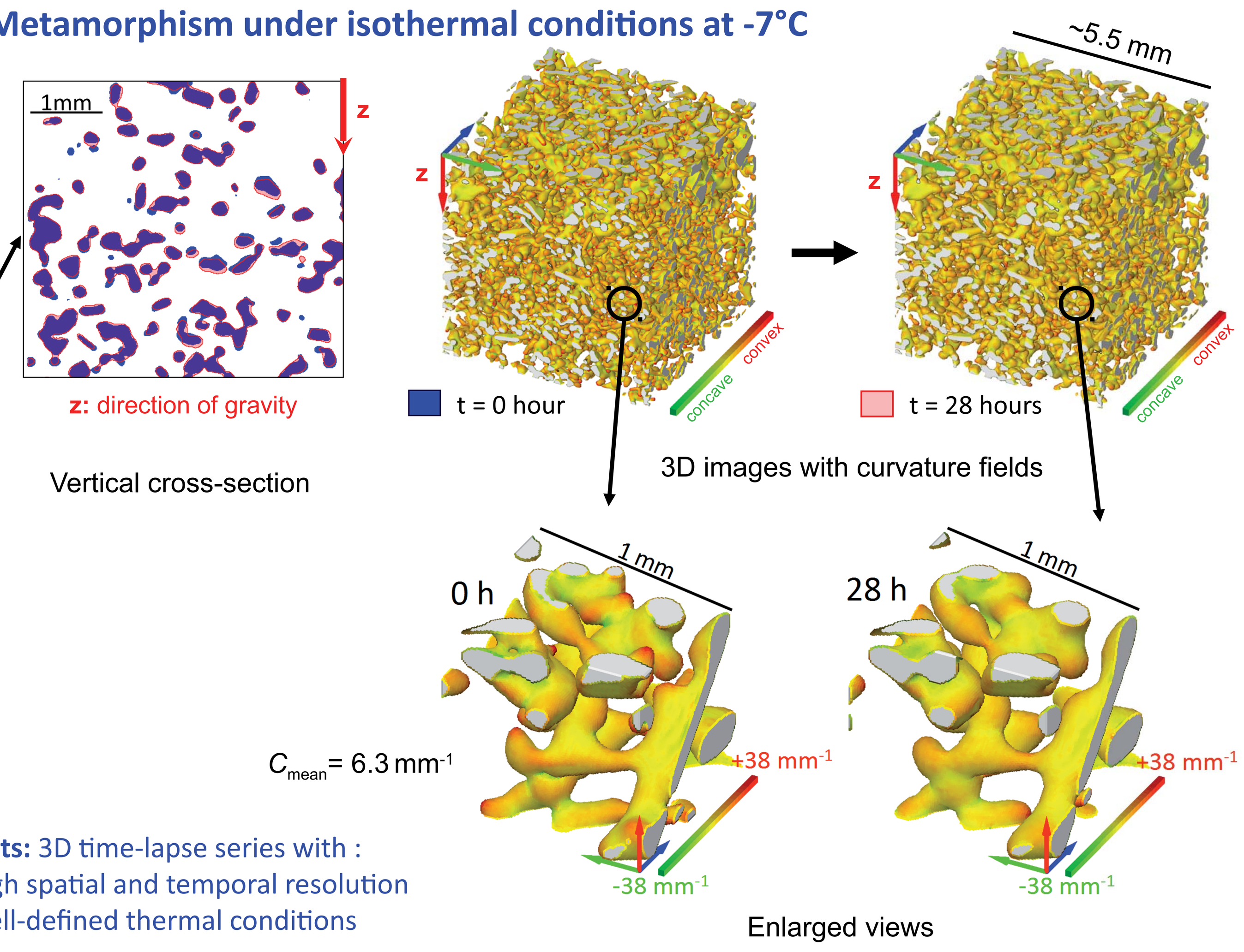
Based on the following principles:
- thermal regulation using 2 Peltier modules at top and base of the sample
- thermal insulation from room temperature using a vacuum chamber
- an amovible conductive sample holder that protects specimens during their installation into the cell







Metamorphism under isothermal conditions at -7°C

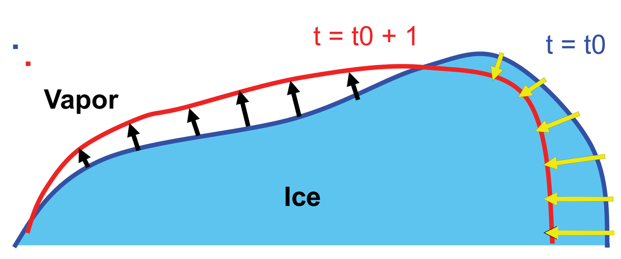


➔ **Results:** 3D time-lapse series with :
- high spatial and temporal resolution
- well-defined thermal conditions

3. A Simple Method to Measure Normal Growth Rates from 3D Time-Lapse Images

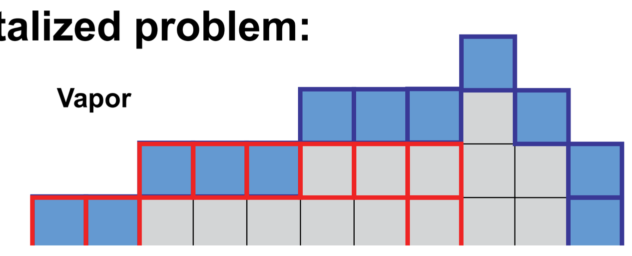
The (signed) distance of the red interface from the blue one is directly given by the distance map Φ as follows:

d = (5 - Φ) / 5 (pixels)



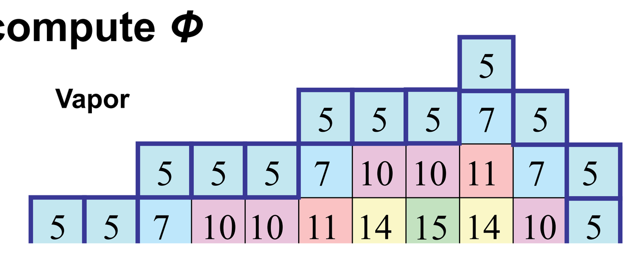
Continous problem

Digitalized problem:



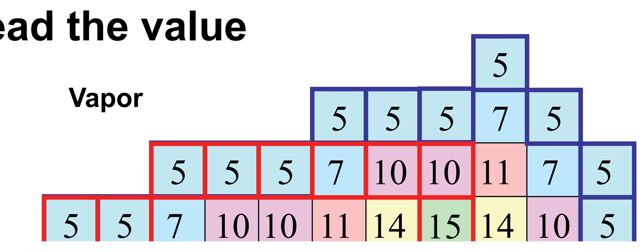
Binary image – interface in blue
In red: new position of the interface

Step 1: compute Φ



Binary image – interface in blue
Distance map Φ : proportional to the distance of the background (pores)

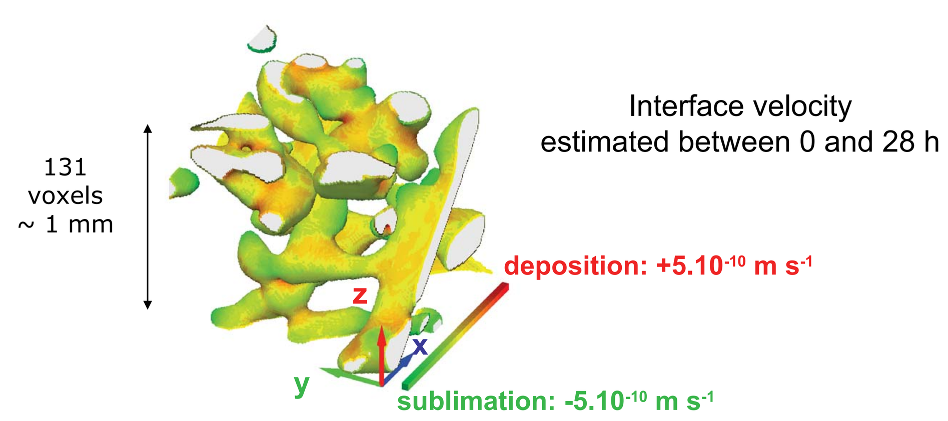
Step 2: read the value

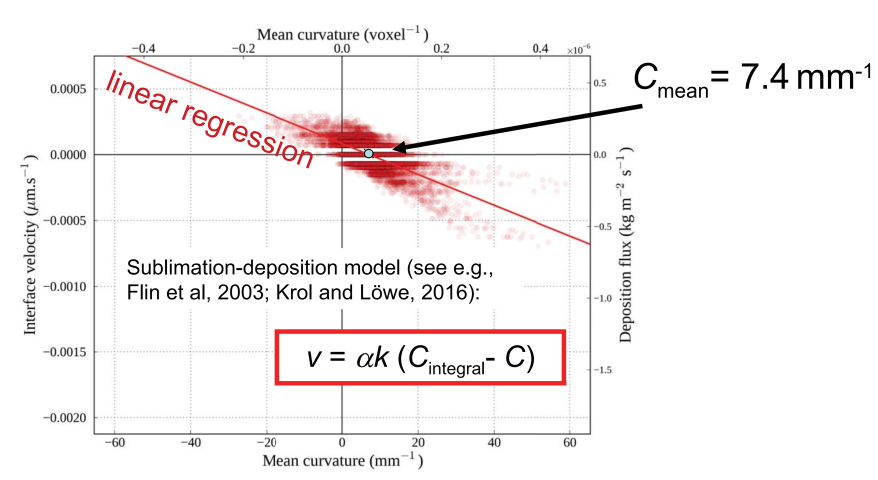


➔ local growth (and sublimation) velocities v
➔ local fluxes $j = v \cdot \rho_{ice}$ at the interface

4. Preliminary Results: Is Sublimation-Deposition a Limiting Mechanism at -7°C? Which Value for α_{eff}?

Approach 1: Growth rate measurements





Large scatter in the measurements + digitization effects

Determination of α based on the slope of the linear regression:

➔ $\alpha_{sublimation\text{-}deposition} = 1.18 \times 10^{-2}$

Approach 2: Phase-field model

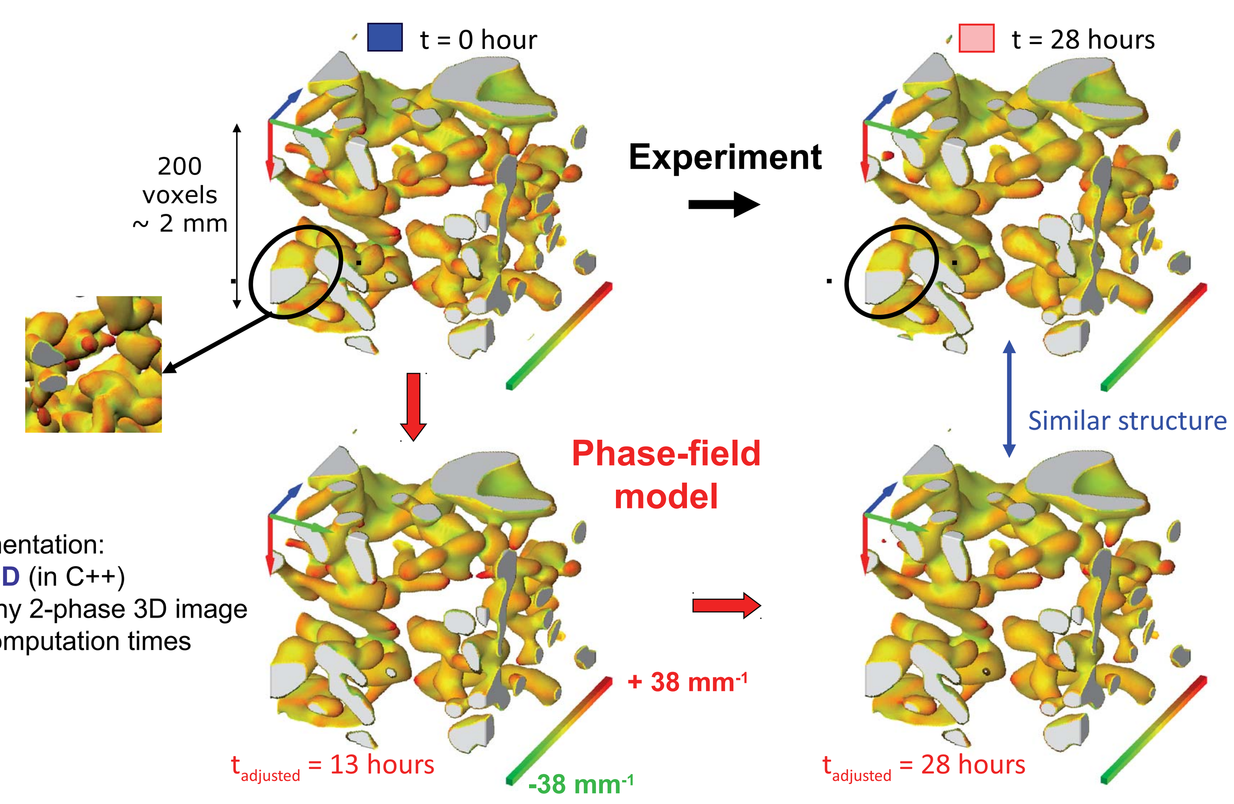
Hypotheses:
- sublimation-deposition mechanism
- ice volume conservation
- periodic boundary conditions

u: phase fonction between 0 (pore) en 1 (ice)
W and *Ɛ*: parameters of the phase field model

Allen-Cahn equation:

$$\frac{\partial u}{\partial t}(x,t) = \Delta u(x,t) - \frac{1}{\varepsilon^2} W'(u) \quad \text{on } \Omega$$

+ Lagrange multiplier (volume conservation)
See Bretin et al (2015) for details



Implementation:
Snow3D (in C++)
- with any 2-phase 3D image
- fast computation times

➔ $\alpha_{phase\text{-}field} = 1.26 \times 10^{-2}$

Diffusion case?

$v = B\,(C_{integral} - C) / \lambda$

with $\lambda = (2C^2 - K)^{-1/2}$

From approach 1, we have:
➔ $B = 1.79 \times 10^{-19}$ m³/s
➔ it is 3 times larger than the theoretical value at -7°C (5.92×10^{-20} m³/s)

➔ **sublimation-deposition seems more likely than diffusion to be the limiting mechanism**

Conclusions:
- We developed a room temperature operating cryogenic cell that provides images series of high spatial and temporal resolution and with well defined boundary conditions.
- We realized an isothermal experiment at -7°C with this cell and proposed a numerical method to efficiently measure growth rates in 3D.
- We performed growth rates measurements and concluded the sublimation-deposition seems predominant over the diffusion (at -7°C). It is in agreement with the results of Krol and Löwe (2016).
- We confirmed these results using a phase-field model and found an effective accomodation coefficient about 10^{-2}, which is consistent (1) with the estimation given by our growth rate measurements and (2) with the typical values given in the literature (usually between 10^{-3} and 10^{-1}).

Outlooks :
- Confirm these results (with different samples, sizes, time-steps…)
- Check other mechanisms (grain boundaries, surface diffusion, etc.)
- Use this approach with other experimental conditions (temperatures, etc.)

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