A snow isothermal metamorphism model applicable on microtomographic images

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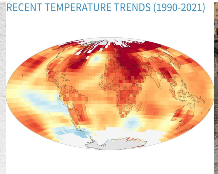
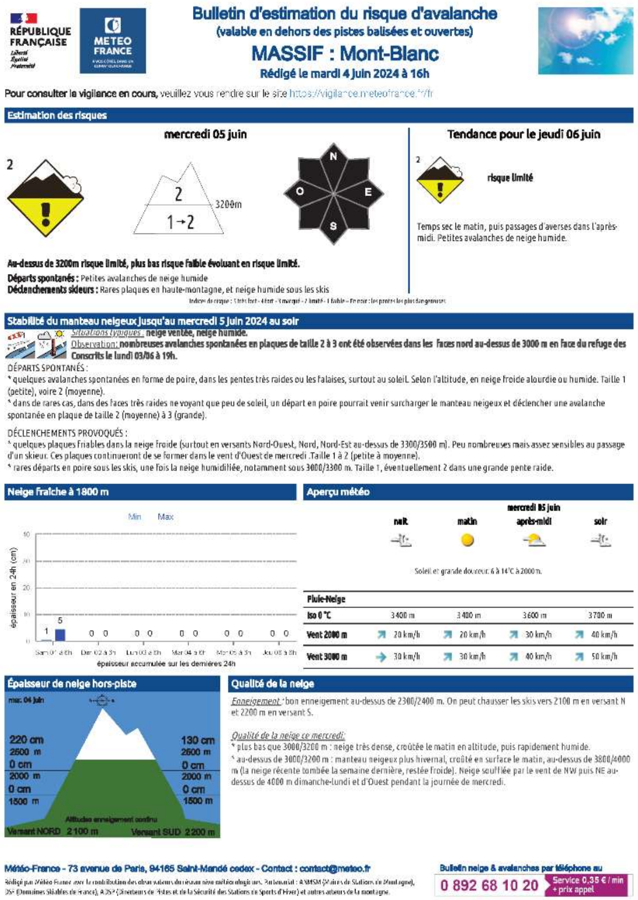
Context – importance of a good knowledge of the snowpack

Societal issues
- Avalanche risk forecasting
- Climate studies
- Water ressources management…





RÉPUBLIQUE FRANÇAISE
METEO FRANCE

Bulletin d'estimation du risque d'avalanche
(valable en dehors des pistes balisées et ouvertes)
MASSIF : Mont-Blanc
Rédigé le mardi 4 juin 2024 à 16h

Pour consulter la vigilance en cours, veuillez vous rendre sur le site https://vigilance.meteofrance.fr/fr

Estimation des risques

mercredi 05 juin

2

2 / 3200m / 1→2

N / O / E / S

Tendance pour le jeudi 06 juin

2 risque limité

Temps sec le matin, puis passages d'averses dans l'après-midi. Petites avalanches de neige humide.

Au-dessus de 3200m risque limité, plus bas risque faible évoluant en risque limité.
Départs spontanés : Petites avalanches de neige humide
Déclenchements skieurs : Rares plaques en haute-montagne, et neige humide sous les skis

Stabilité du manteau neigeux jusqu'au mercredi 5 juin 2024 au soir

Situations typiques : **neige ventée, neige humide.**
Observation: **nombreuses avalanches spontanées en plaques de taille 2 à 3 ont été observées dans les faces nord au-dessus de 3000 m en face du refuge des Conscrits le lundi 03/06 à 19h.**

DÉPARTS SPONTANÉS :
* quelques avalanches spontanées en forme de poire, dans les pentes très raides ou les falaises, surtout au soleil. Selon l'altitude, en neige froide alourdie ou humide. Taille 1 (petite), voire 2 (moyenne).
* dans de rares cas, dans des faces très raides ne voyant que peu de soleil, un départ en poire pourrait venir surcharger le manteau neigeux et déclencher une avalanche spontanée en plaque de taille 2 (moyenne) à 3 (grande).

DÉCLENCHEMENTS PROVOQUÉS :
* quelques plaques friables dans la neige froide (surtout en versants Nord-Ouest, Nord, Nord-Est au-dessus de 3300/3500 m). Peu nombreuses mais assez sensibles au passage d'un skieur. Ces plaques continueront de se former dans le vent d'Ouest de mercredi .Taille 1 à 2 (petite à moyenne).
* rares départs en poire sous les skis, une fois la neige humidifiée, notamment sous 3000/3300 m. Taille 1, éventuellement 2 dans une grande pente raide.

Neige fraîche à 1800 m

Min Max
épaisseur en 24h (cm)
1 5 0 0 0 0 0 0 0 0 0 0
épaisseur accumulée sur les dernières 24h

Aperçu météo

mercredi 05 juin

Soleil et grande douceur. 6 à 14°C à 2000 m.

	nuit	matin	après-midi	soir
Pluie-Neige				
Iso 0 °C	3400 m	3400 m	3600 m	3700 m
Vent 2000 m	20 km/h	20 km/h	30 km/h	40 km/h
Vent 3000 m	30 km/h	30 km/h	40 km/h	50 km/h

Épaisseur de neige hors-piste

mar. 04 juin
220 cm / 2600 m / 0 cm / 2000 m / 0 cm / 1500 m
130 cm / 2600 m / 0 cm / 2000 m / 0 cm / 1500 m
Altitudes enneigement continu
Versant NORD 2100 m — Versant SUD 2200 m

Qualité de la neige

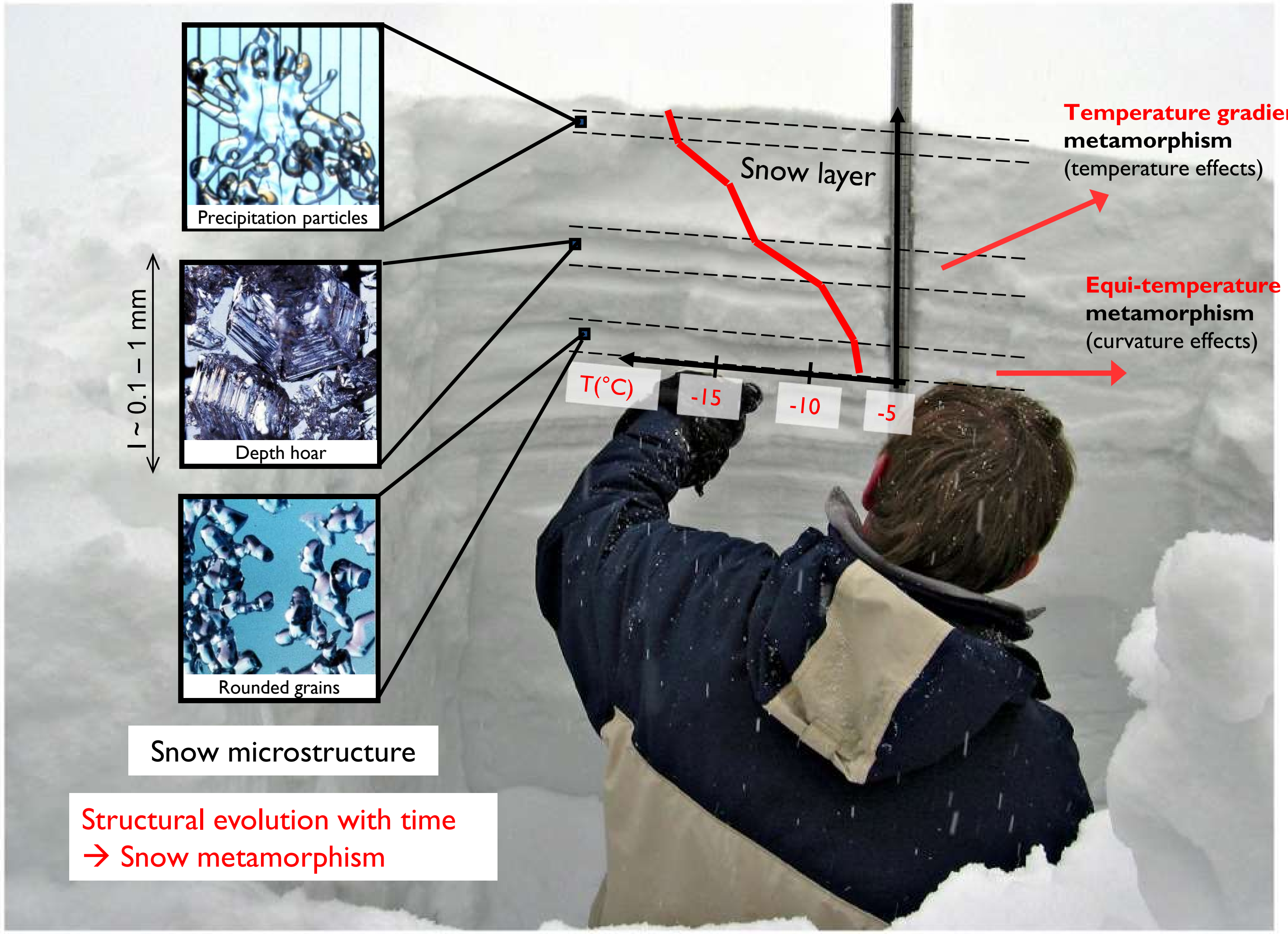
Enneigement : bon enneigement au-dessus de 2300/2400 m. On peut chausser les skis vers 2100 m en versant N et 2200 m en versant S.

Qualité de la neige ce mercredi:
* plus bas que 3000/3200 m : neige très dense, croûtée le matin en altitude, puis rapidement humide.
* au-dessus de 3000/3200 m : manteau neigeux plus hivernal, croûté en surface le matin, au-dessus de 3800/4000 m (la neige récente tombée la semaine dernière, restée froide). Neige soufflée par le vent de NW puis NE au-dessus de 4000 m dimanche-lundi et d'Ouest pendant la journée de mercredi.

Météo-France - 73 avenue de Paris, 94165 Saint-Mandé cedex - Contact : contact@meteo.fr

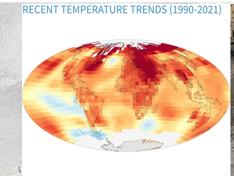
Bulletin neige & avalanches par téléphone au 0 892 68 10 20 Service 0,35 € / min + prix appel

Context – snowpack properties are changing with time

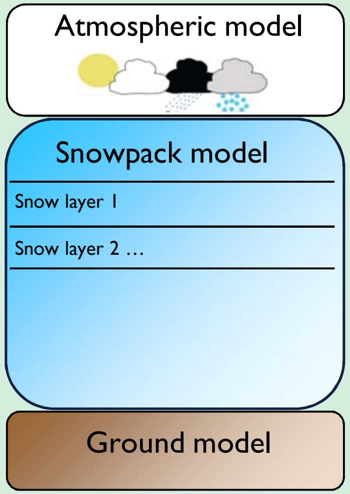


Context – need of microscale observations

Societal issues
- Avalanche risk forecasting
- Climate studies
- Water ressources…



Snowpack models for the prevision of the time evolution of the macroscopic properties (temperature, mechanical properties…)

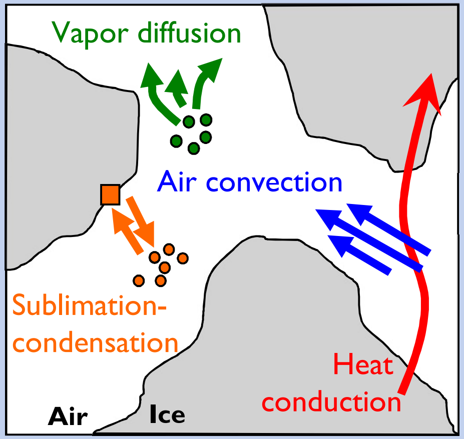


- Physical processes
  - Heat conduction
  - Vapor diffusion
  - Air convection
  - Phase change (source terms)
  - Compaction
  - …
- Effective properties = f (microstructure)

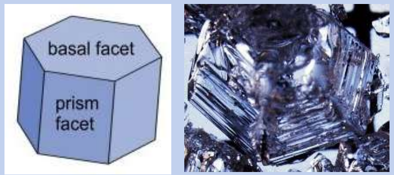
MACROSCALE (Snowpack)

Snow metamorphism

- Heat and mass transfer



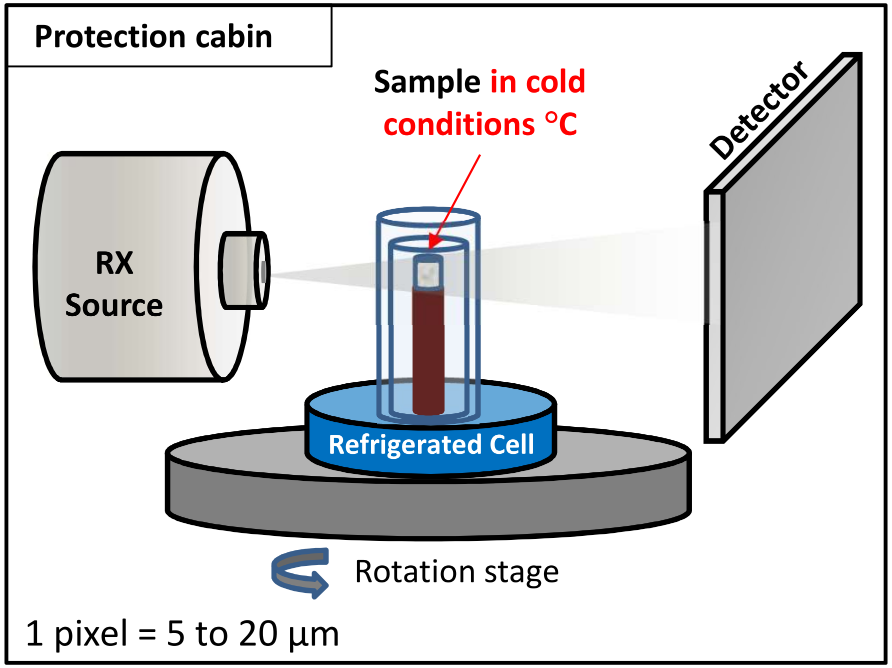
- Ice crystal growth

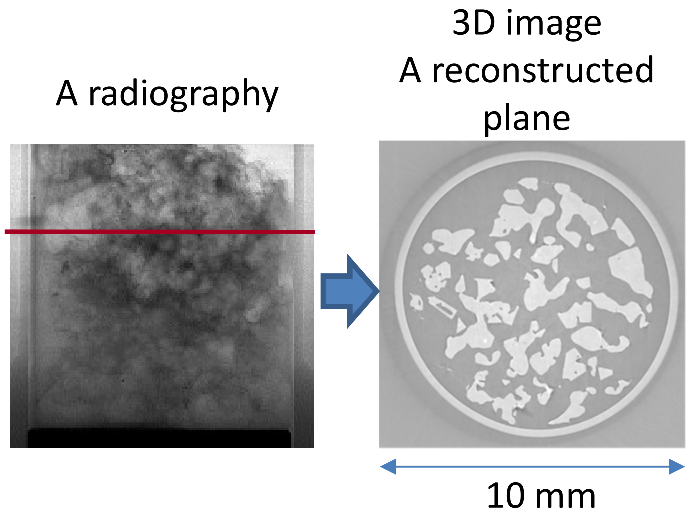


MICROSCALE (Grain assembly)

→ Needs fine observations

Context – X-ray microtomography to obtain 3D images





Segmentation

Access geometrical and physical properties

Brzoska et al, 1999; Flin et al 2003; Schneebeli and Sokratov 2004; Chen and Baker, 2010; Srivastava et al, 2010; Calonne et al, 2011; Loewe et al, 2011; Pinzer et al, 2012; Hammonds et al, 2015; Krol and Loewe, 2016; Ishimoto et al, 2018; Letcher et al, 2021; Robledano et al, 2023; Bouvet et al, 2023…

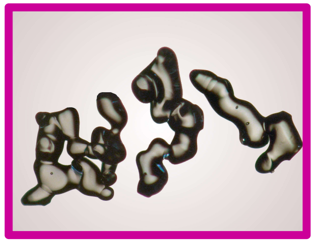
Context – Several types of grains and metamorphism regimes

Dry snow
small T gradient

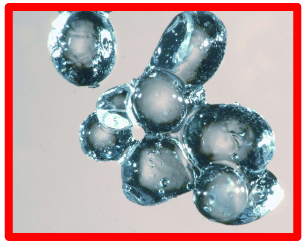
T<0° , TG<5° C/m,
Wcontent = 0

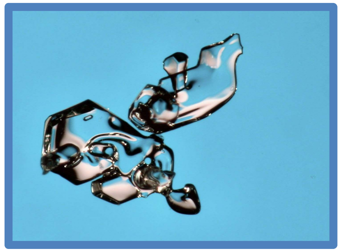
Dry snow
moderate to high T gradient

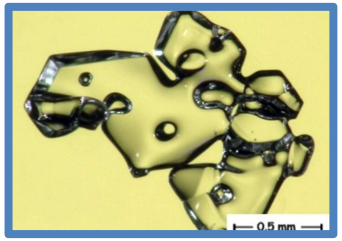
T<0° C, TG>5° C/m,
Wcontent = 0

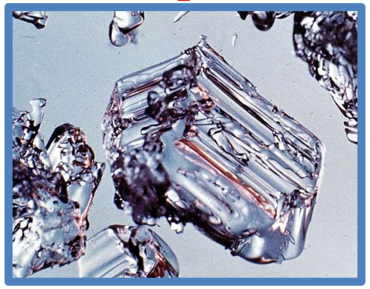


Wet snow
T=0° C, TG=0° C/m, Wcontent > 0





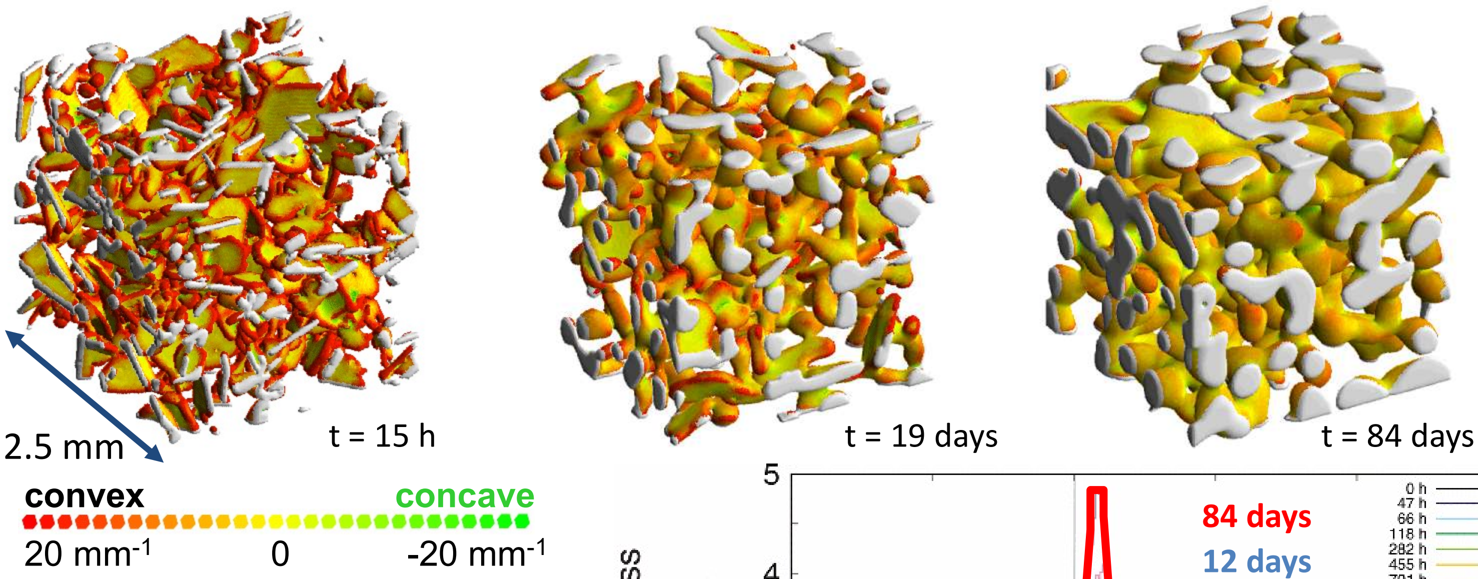




T<0° , TG>20° C/m,
Wcontent = 0

T: temperature
TG: temperature gradient accross the snow layer
Wcontent: liquid water content

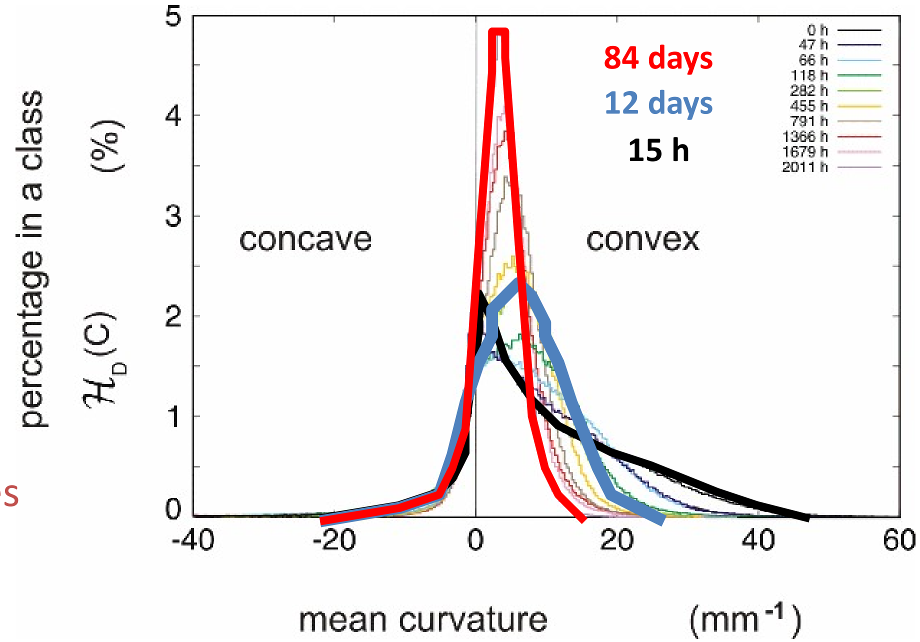
Context – Isothermal metamorphism



Curvature evolution with time

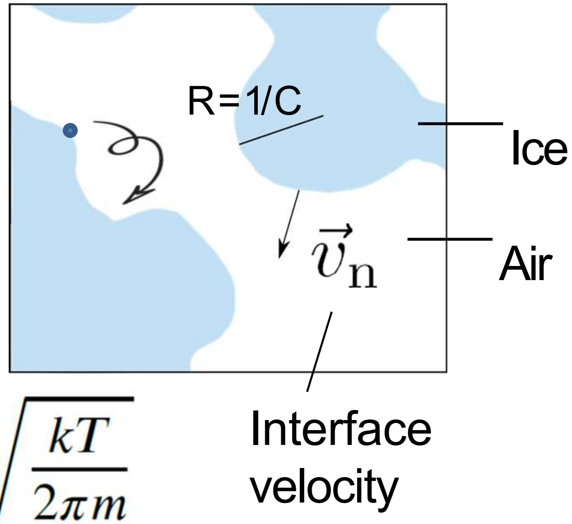
→ the mean curvature decreases

→ the standard deviation decreases



Flin *et al*, 2004

Equations – Physical modelling



Sublimation-deposition process:

without diffusion, convection and settling of grains

Mechanism: Hertz-Knudsen equation

$$\boxed{v_n = \alpha v_{\text{kin}} \frac{\rho_{vs}^{\text{amb}} - \rho_{vs}^{\Gamma}}{\rho_{vs}^{\Gamma}} \quad \text{on } \Gamma}$$

$$\text{with } v_{\text{kin}} = \frac{\rho_{vs}^{\text{ref}}}{\rho_i} \sqrt{\frac{kT}{2\pi m}}$$

ρ_{vs}^{Γ} : saturation vapor density on the ice-air interface

Deposition coefficient α : probability that a water vapor molecule is incorporated into the ice phase.
Today still poorly quantified!
Belongs to [0, 1] and depends at least on temperature T.

Driving force: Kelvin's (or Gibbs-Thomson) law

$$\boxed{\rho_{vs}^{\Gamma} = \rho_{vs}^{\text{ref}} \, e^{2d_0 C} \quad \text{on } \Gamma} \qquad \boxed{\rho_{vs}^{\text{amb}} = \rho_{vs}^{\text{ref}} \, e^{2d_0 C^{\text{amb}}}}$$

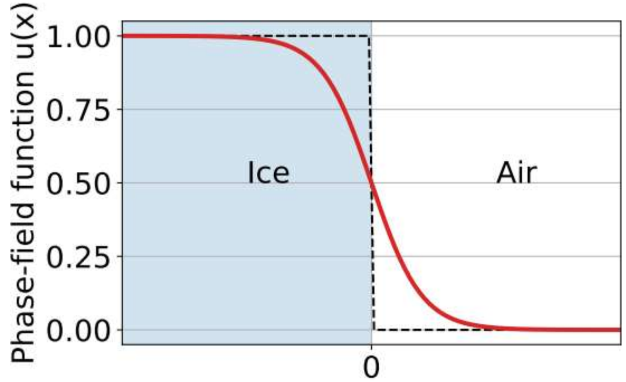
C: local curvature
C_{amb}: integrated curvature on whole interface
d_0: capillary length << 1

➔ $\boxed{v_n = 2d_0 \alpha v_{kin} (C_{amb} - C)}$ Typical case of volume preserving curvature flow

Equations – Phase-field modelling: Bretin et al (2019)

Application of classical phase-field equation to the case of isothermal metamorphism:

$$\frac{\partial u}{\partial t}(x,t) = d_0 \alpha v_{\text{kin}} \left(\Delta u(x,t) - \frac{1}{\varepsilon^2} W'(u) \right)$$



Following Bretin et al (2019), the canonical dimensionless equation can be written:

$$\frac{\partial \tilde{u}}{\partial \tilde{t}}\left(\tilde{x}, \tilde{t}\right) = \Delta \tilde{u}\left(\tilde{x}, \tilde{t}\right) - \frac{1}{\tilde{\varepsilon}^2} W' + \tilde{\mu} \frac{1}{\tilde{\varepsilon}} \sqrt{2W\left(\tilde{u}, \tilde{t}\right)}$$

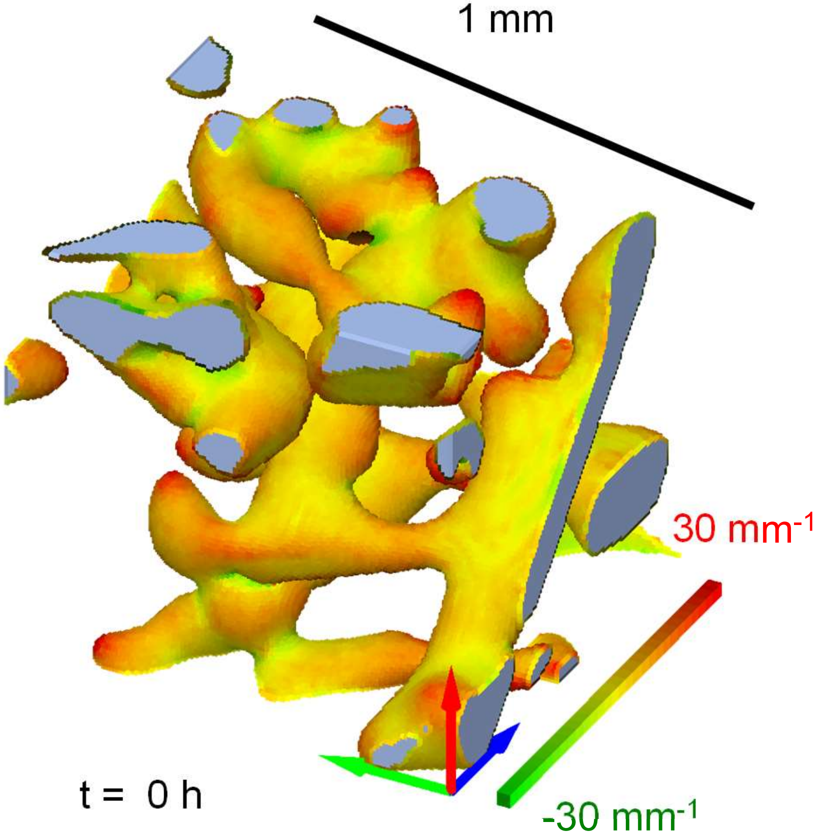
Where: $\tilde{t} = \frac{t \alpha v_{\text{kin}} d_0}{d_x^2}, \quad \tilde{x} = \frac{x}{d_x}, \quad \tilde{\varepsilon} = \frac{\varepsilon}{d_x}$

And $\tilde{\mu}$ is a Lagrange multiplier verifying: $\tilde{\mu} = \frac{1}{\tilde{\varepsilon}} \frac{\int_\Omega W'\left(\tilde{u}, \tilde{t}\right) \mathrm{d}\tilde{x}}{\int_\Omega \sqrt{2W\left(\tilde{u}, \tilde{t}\right)} \mathrm{d}\tilde{x}}$

Bretin et al, 2019: Phase-field modelling and computing for a large number of phases, Elie Bretin, Roland Denis, Jacques-Olivier Lachaud and Edouard Oudet, ESAIM: M2AN, 53 3 (2019) 805-832, DOI: https://doi.org/10.1051/m2an/2018075

Comparison between experiments and simulation

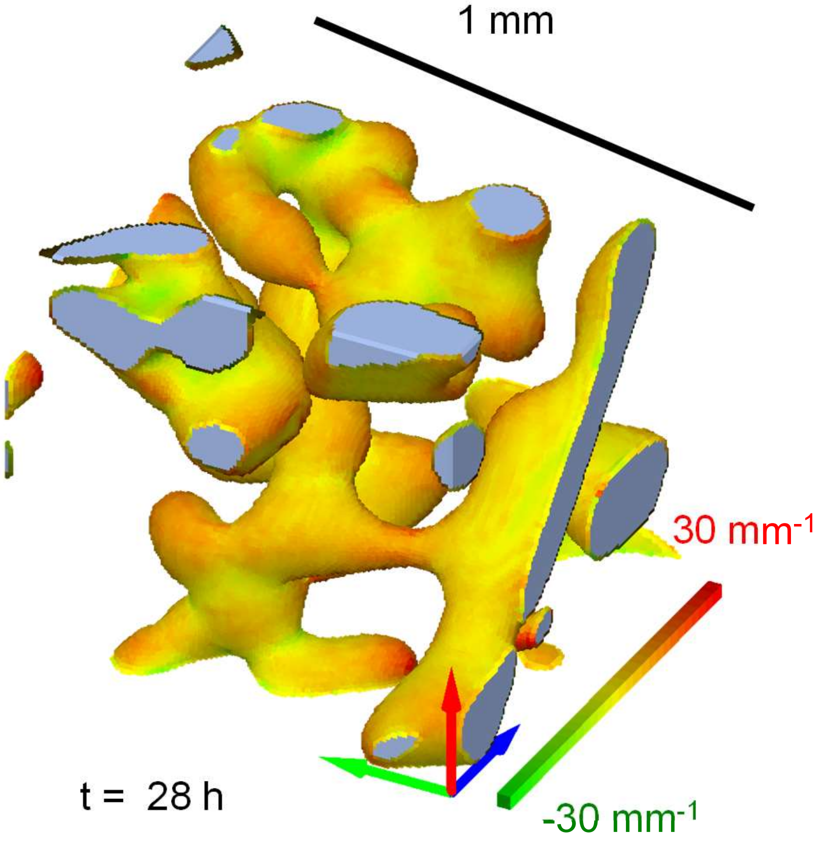
28 h of equi-temperature experiment at -7°C



Experimental result

Comparison between experiments and simulation

28 h of equi-temperature experiment at -7°C



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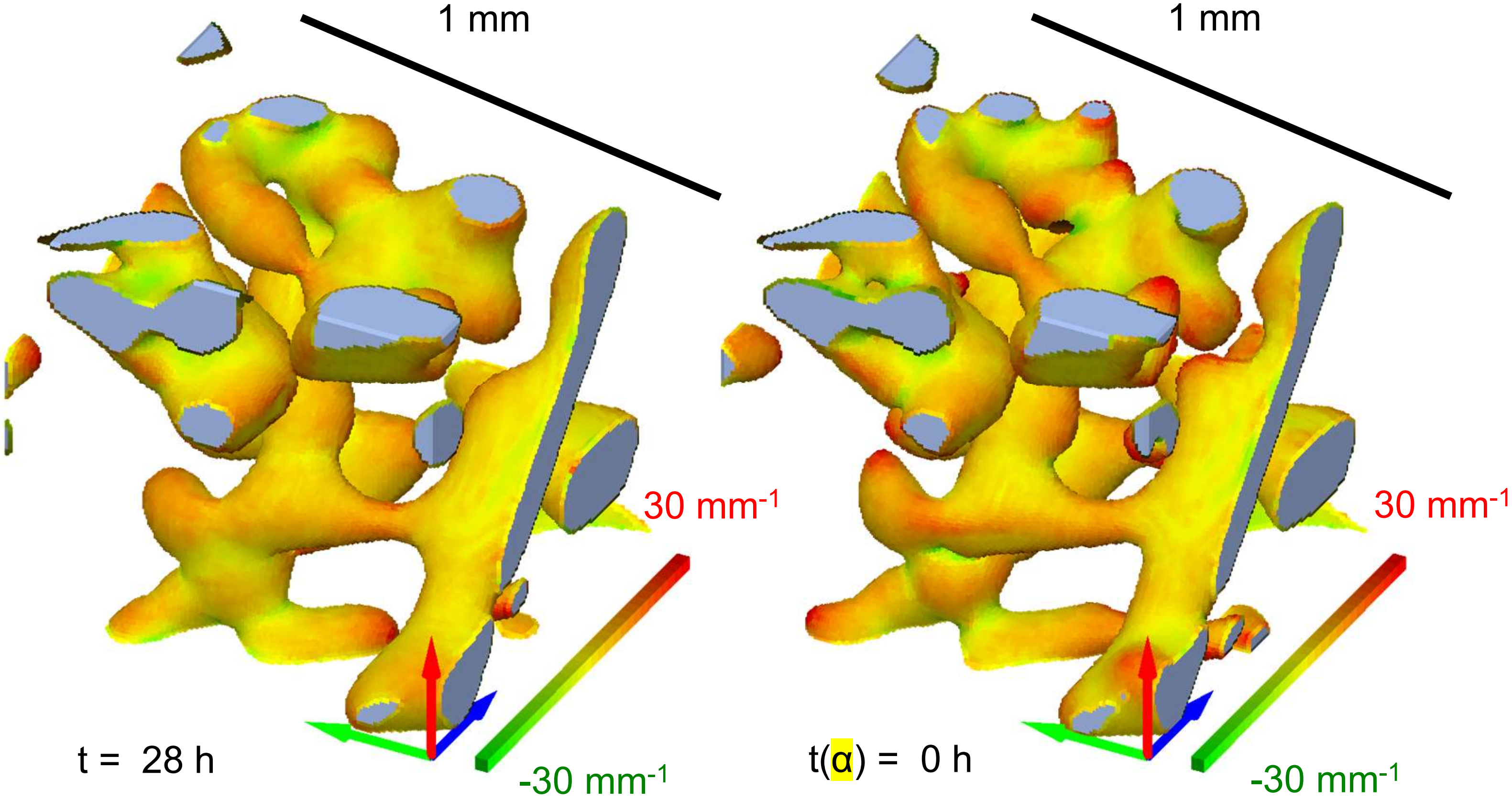

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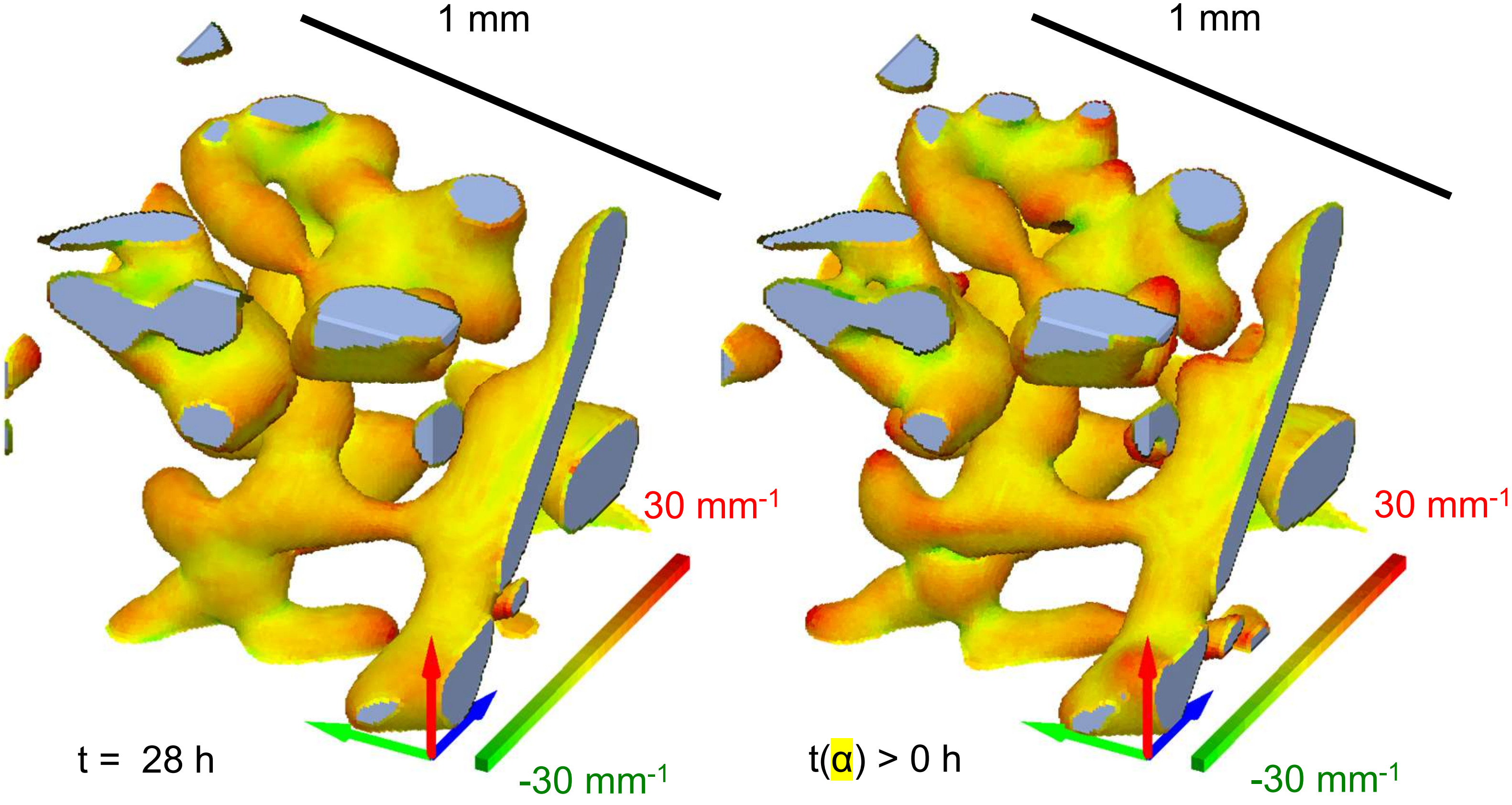

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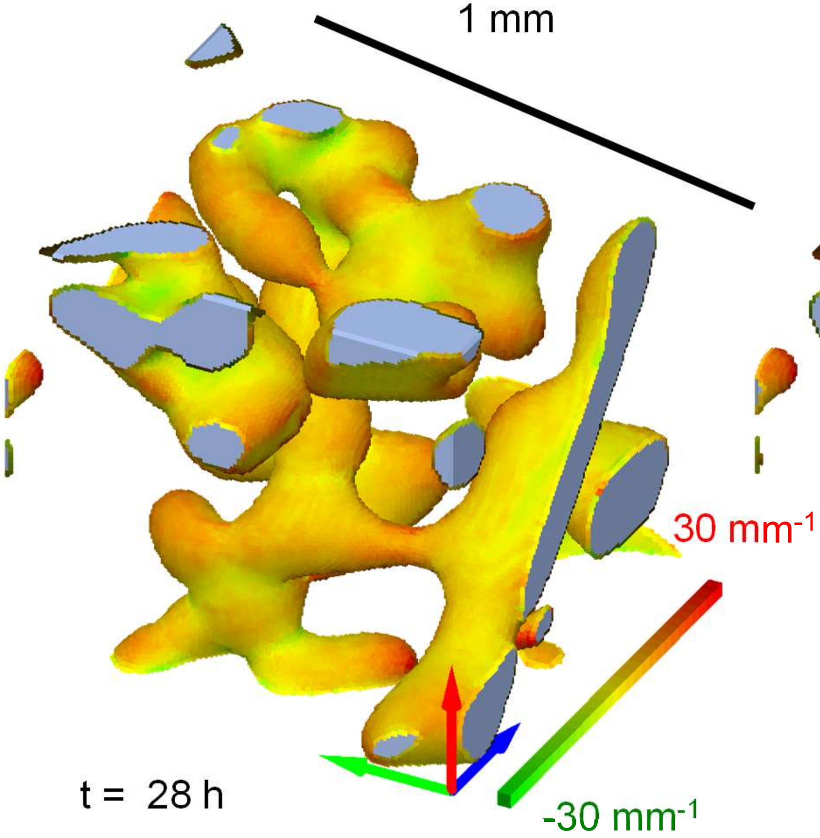

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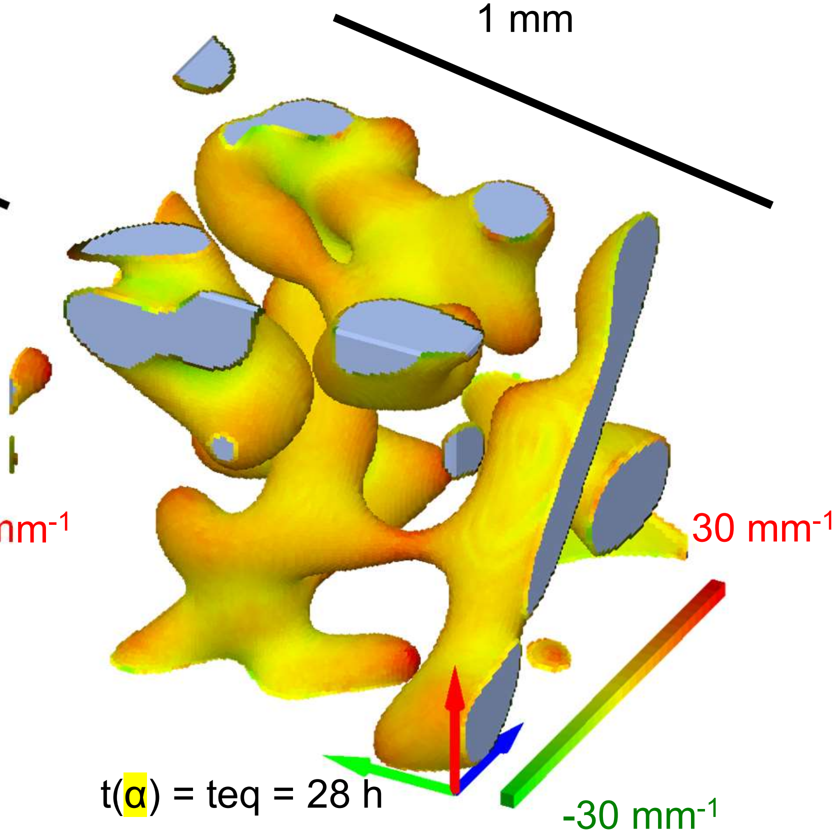

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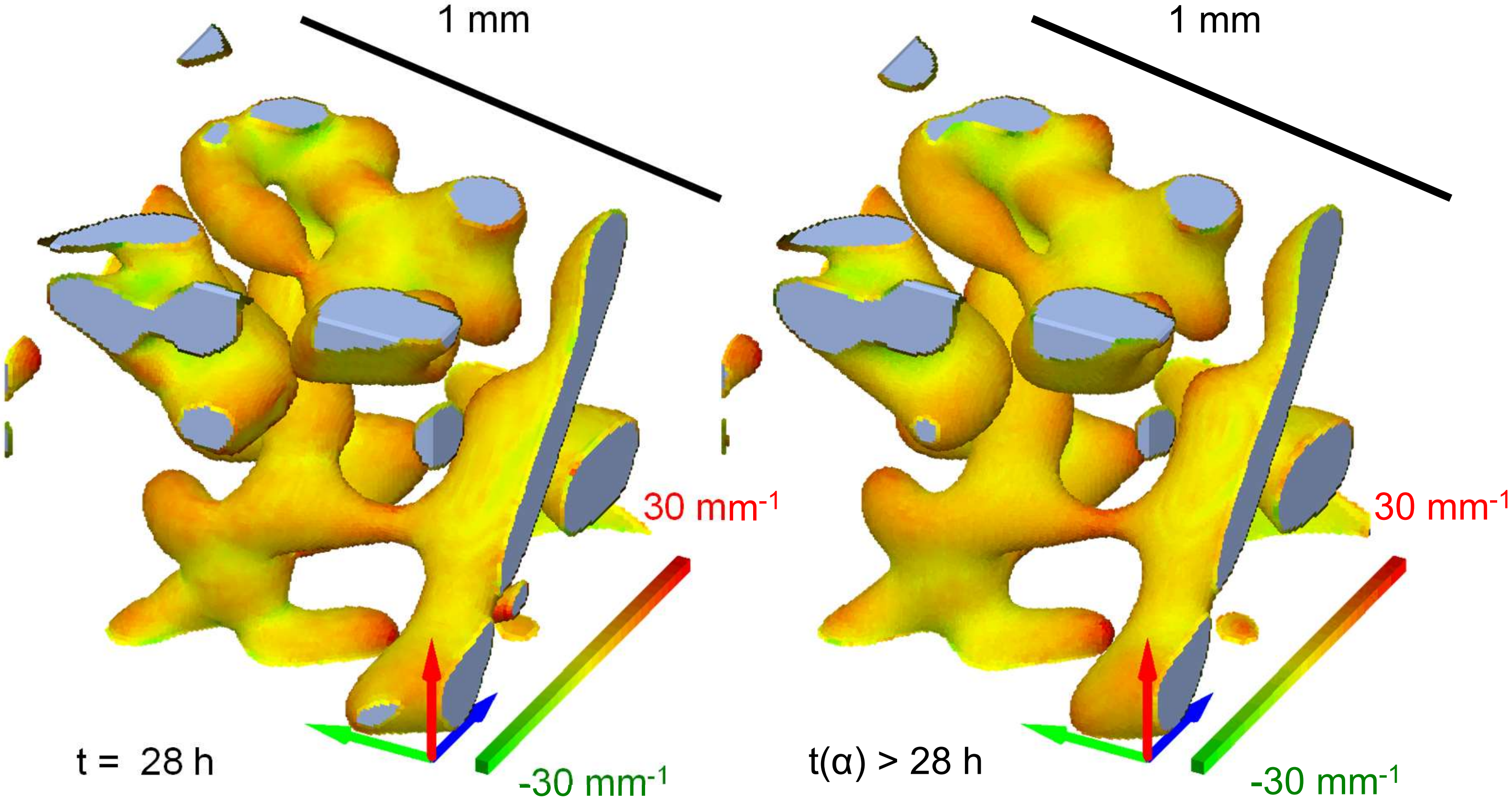


Experimental result

Simulation

Model calibration:

Link between the non-dimensional time $\tilde{t}$ and the physical time t :

$$t = \frac{\tilde{t}\ d_x^2}{\alpha v_{\mathrm{kin}} d_0}$$

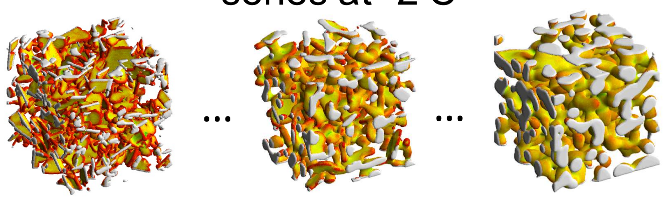
image resolution (cste)

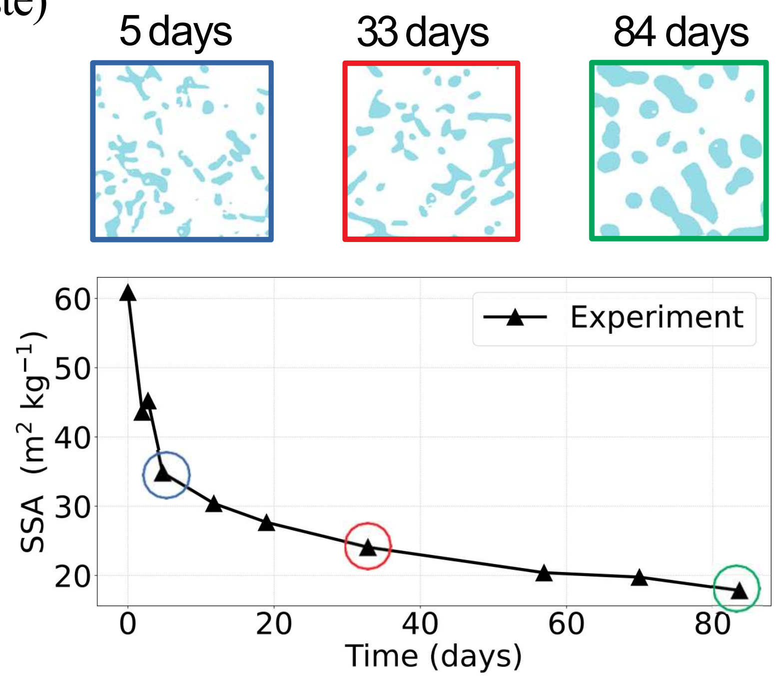
capillary length (cte) kinetic velocity (cste)

kinetic velocity (cste)

condensation coefficient

Experimental isothermal series at -2°C





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capillary length (cte) kinetic velocity (cte)

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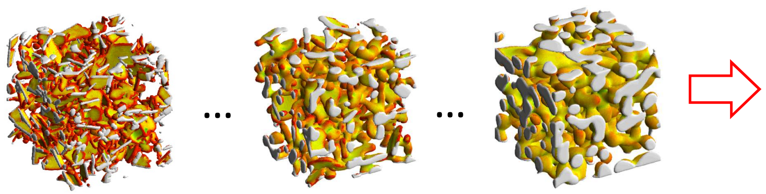
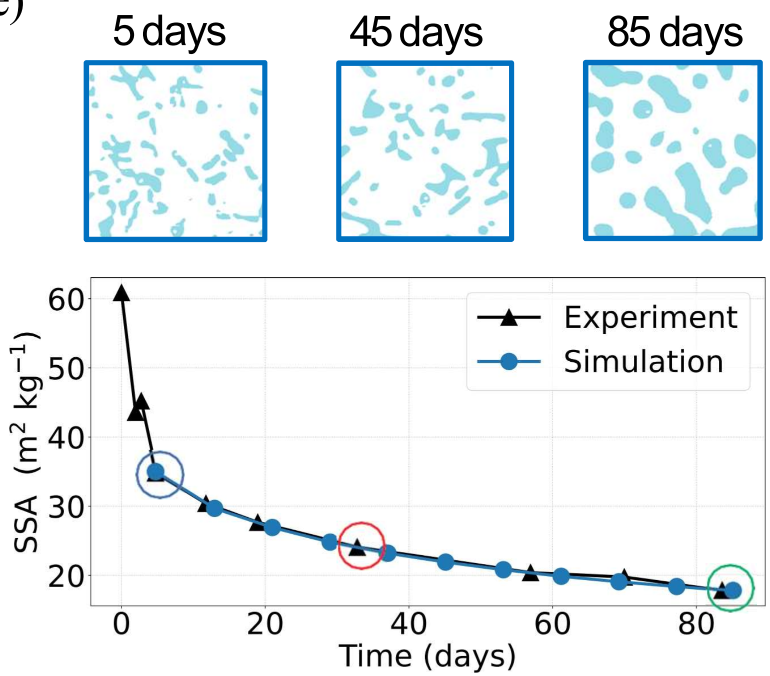
condensation coefficient

Simulated series

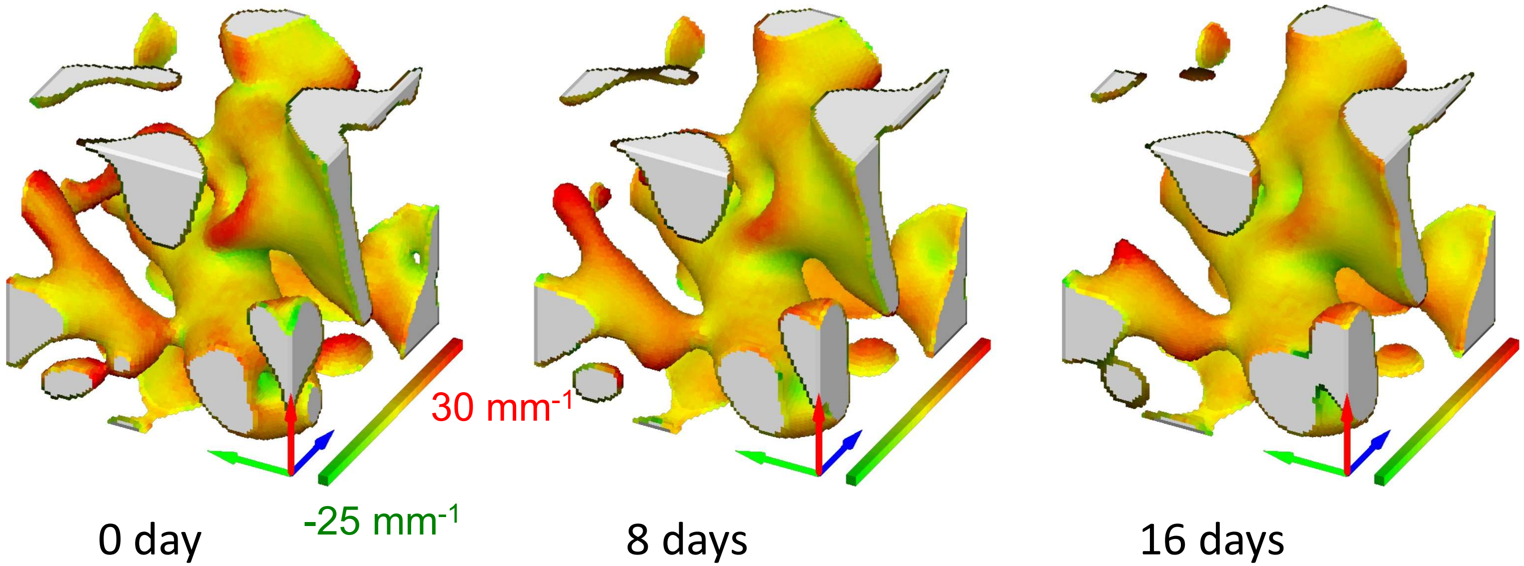


$\longrightarrow$ $\alpha = 9.8 \times 10^{4}$ at -2°C



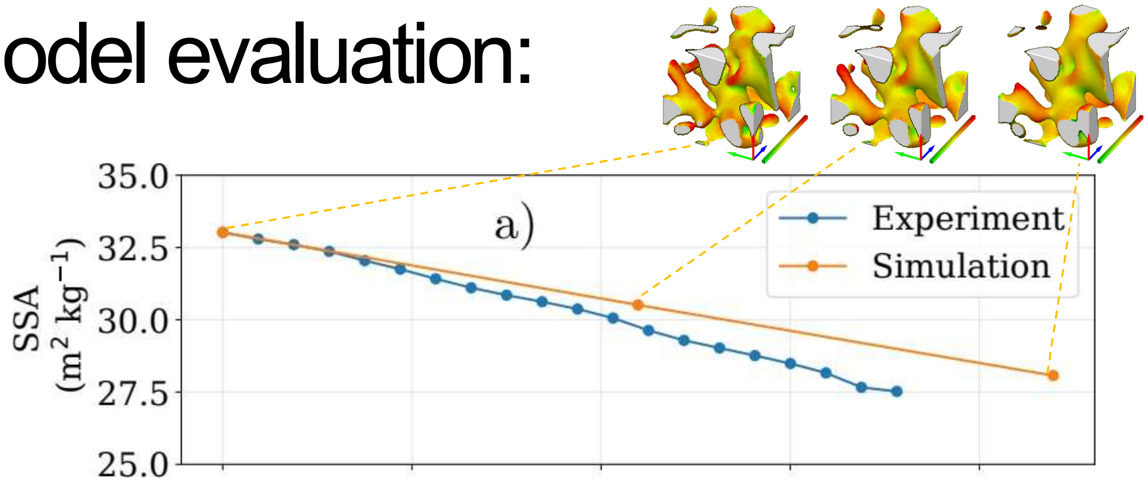
Model evaluation:

Evaluation of α using an independent experimental series of isothermal metamorphism at -2°C (Hagenmuller et al, 2019).

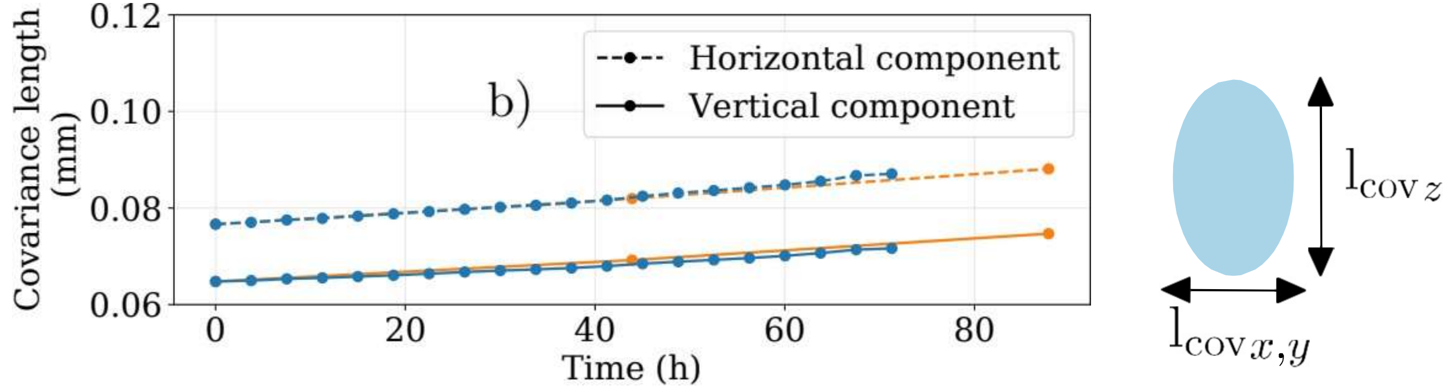


Simulation of isothermal metamorphism at -2°C .

Model evaluation:



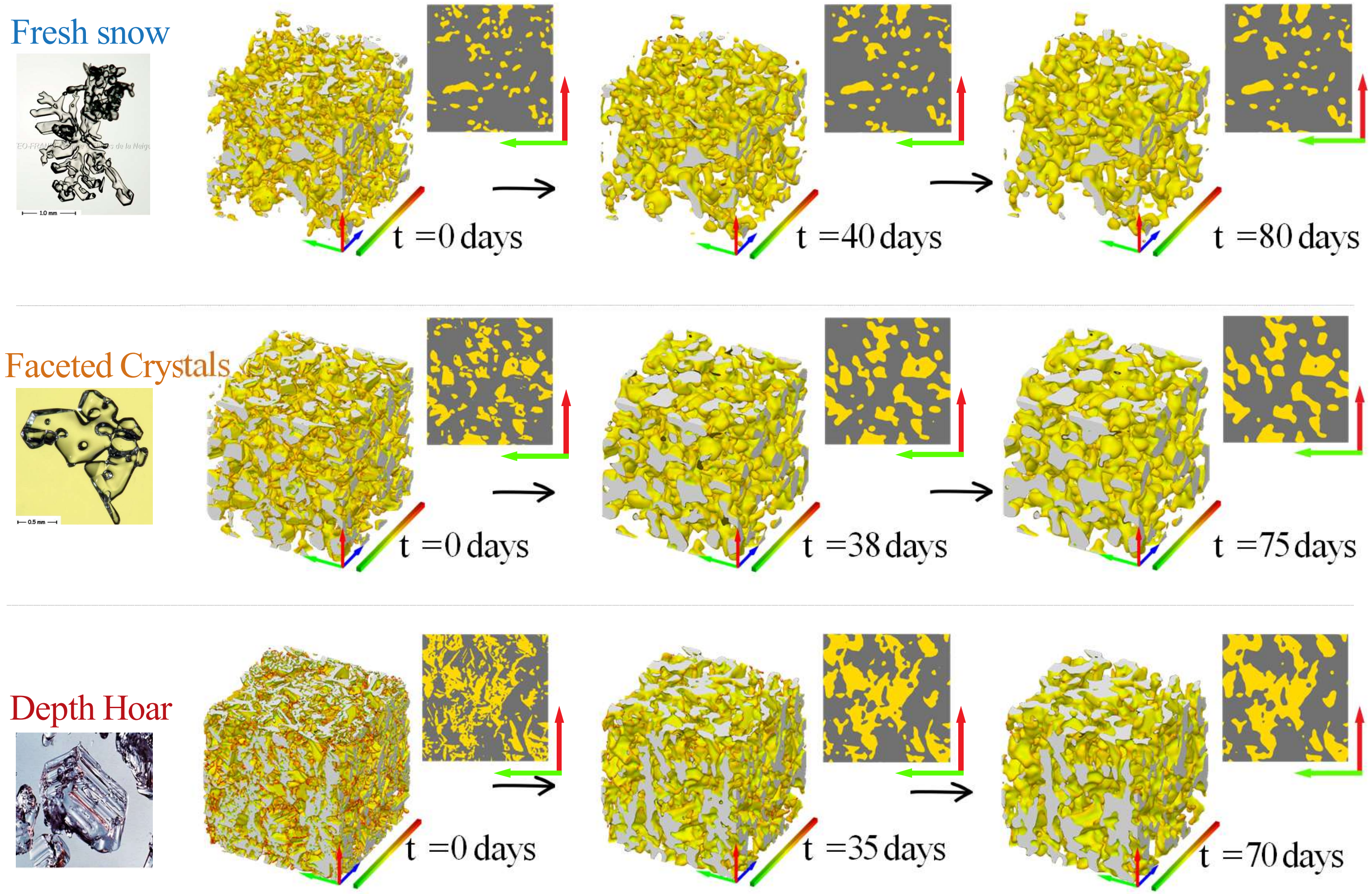
Specific surface area

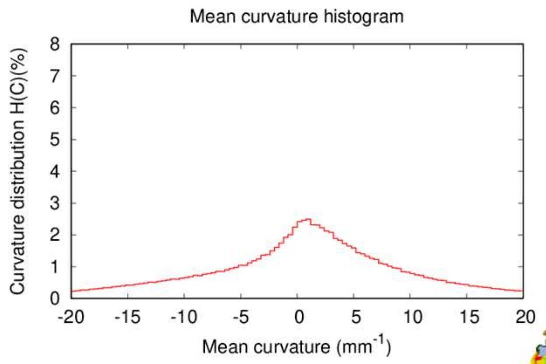


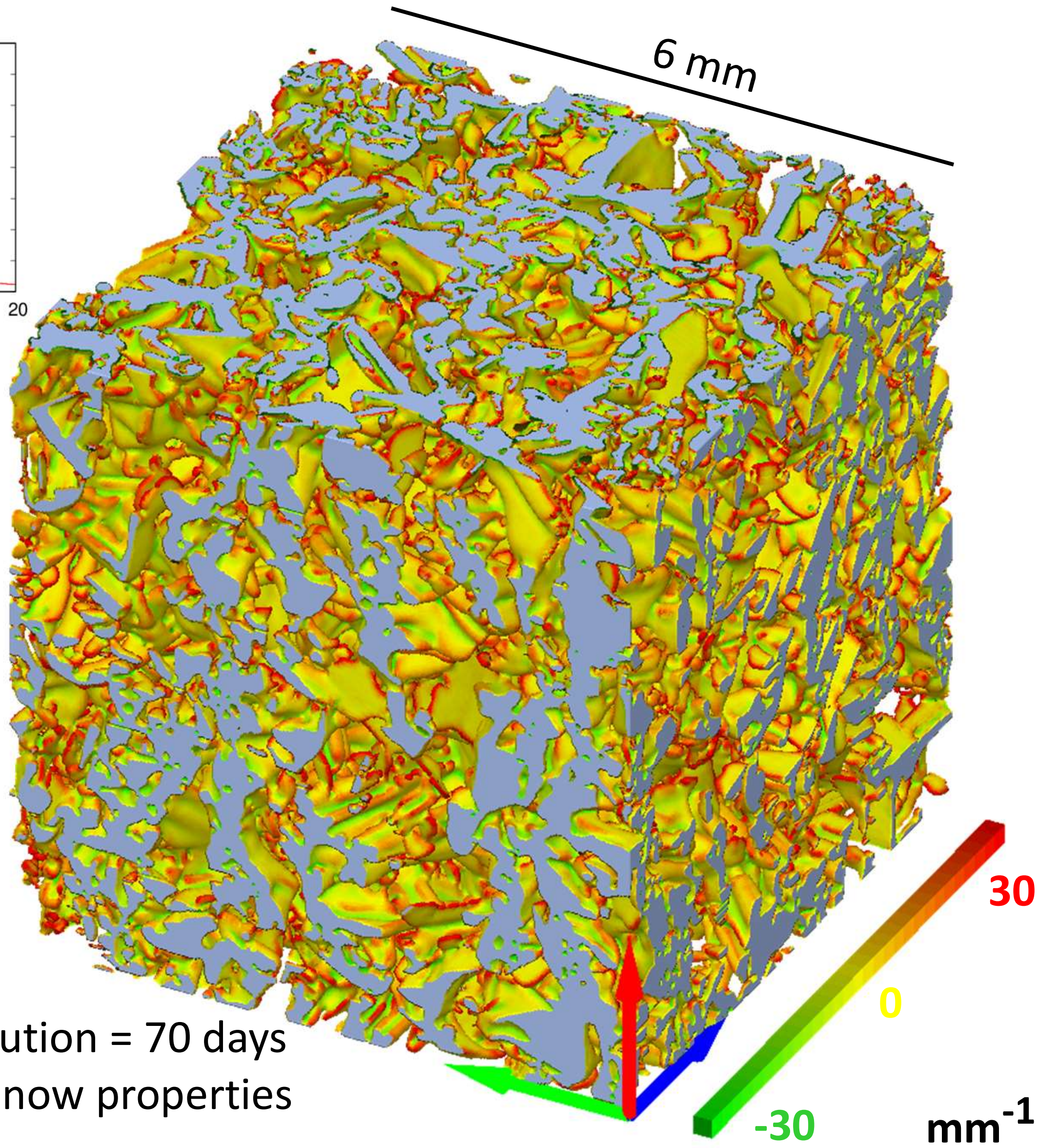
Size of the ice heterogeneities

➔ Good agreement between simulated and experimental microstructural parameters.

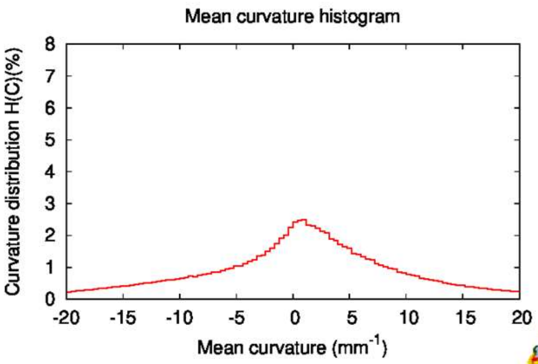
Model predictions: snow microstructures at -2°C

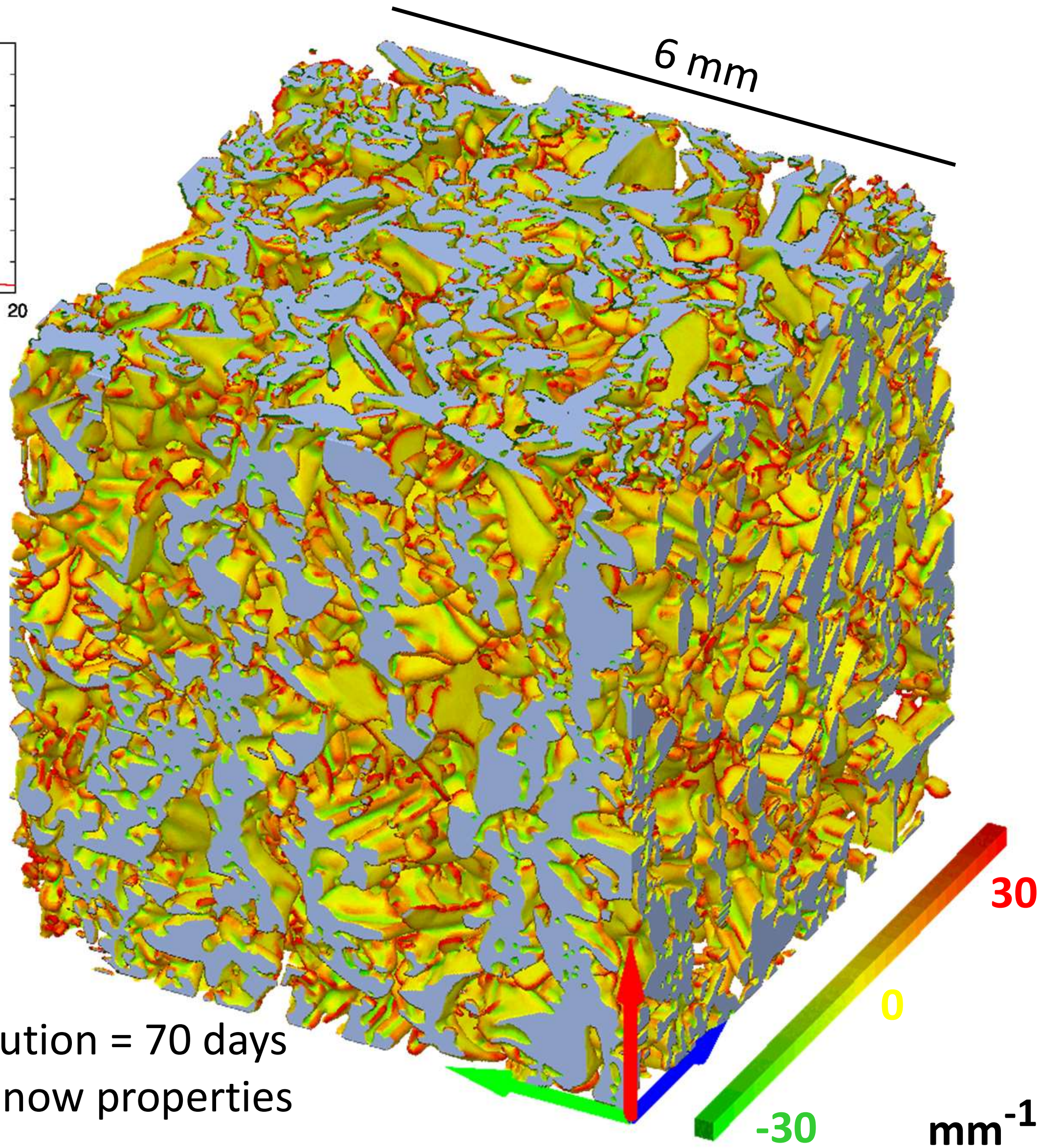






Simulation
of depth hoar
under isothermal
metamorphism at -2°C
Physical time of the evolution = 70 days
➔ Access modelling of snow properties





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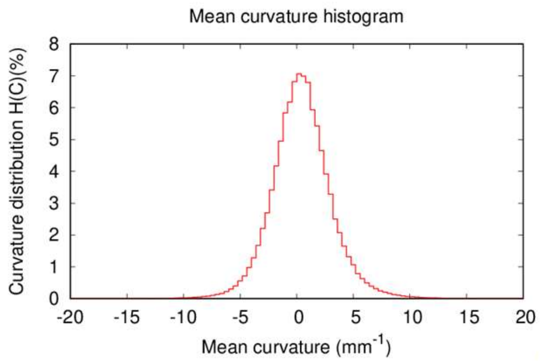

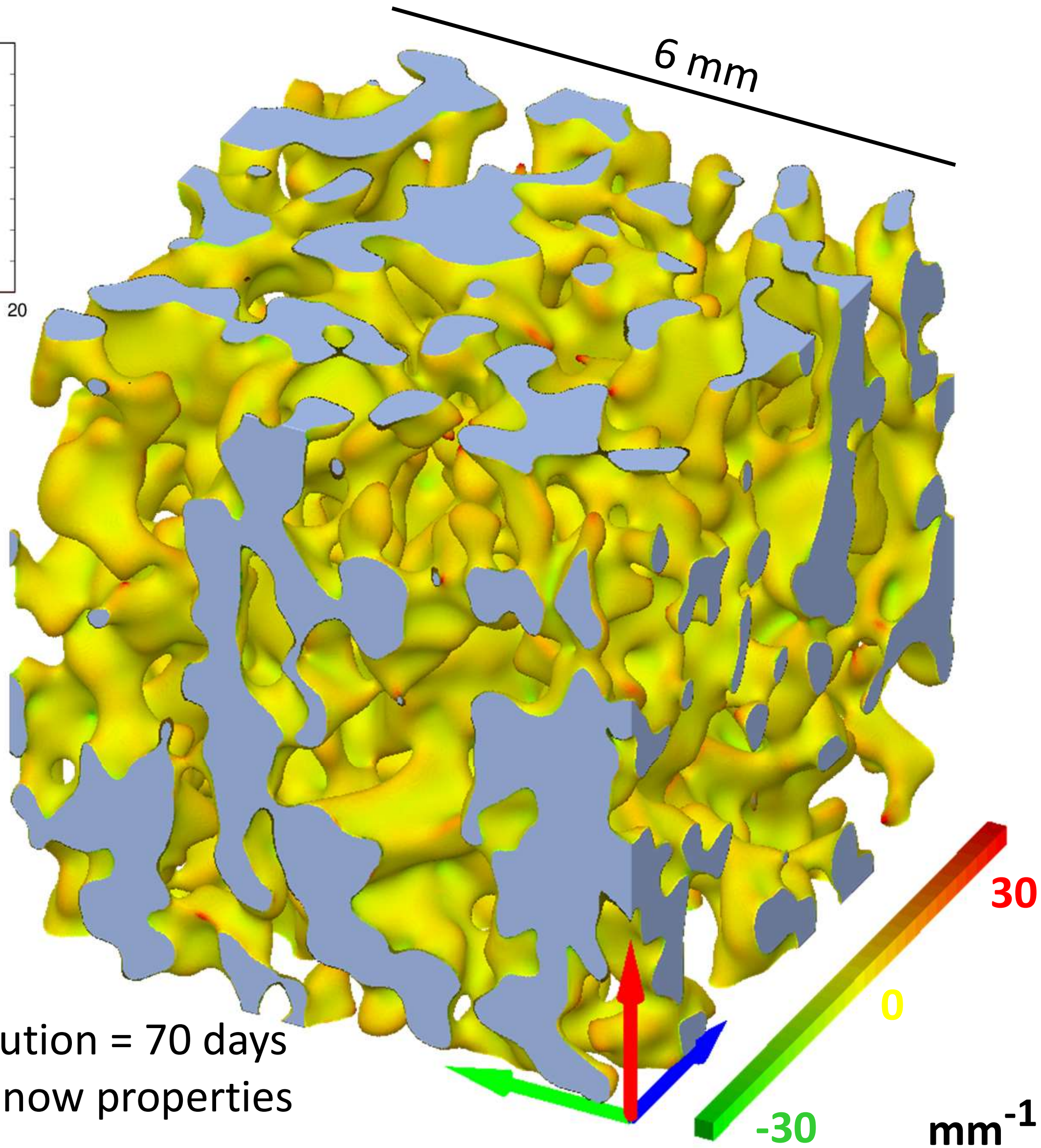

Simulation
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➔ Access modelling of snow properties

Conclusions:

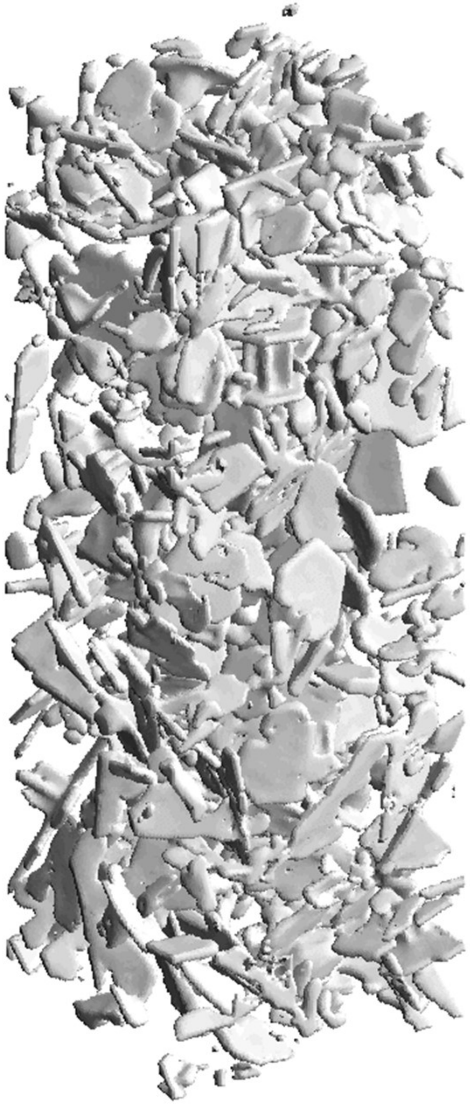
- Application of a 3D phase-field model developed for curvature flow with mass conservation
- The model is applicable on tomographic images, and gives consistent results for the isothermal metamorphism of snow
- It allowed calibrating the deposition coefficient α at -2°C, and this result has been confirmed by an independent time series

➔ Better understanding of the physical mechanisms involved

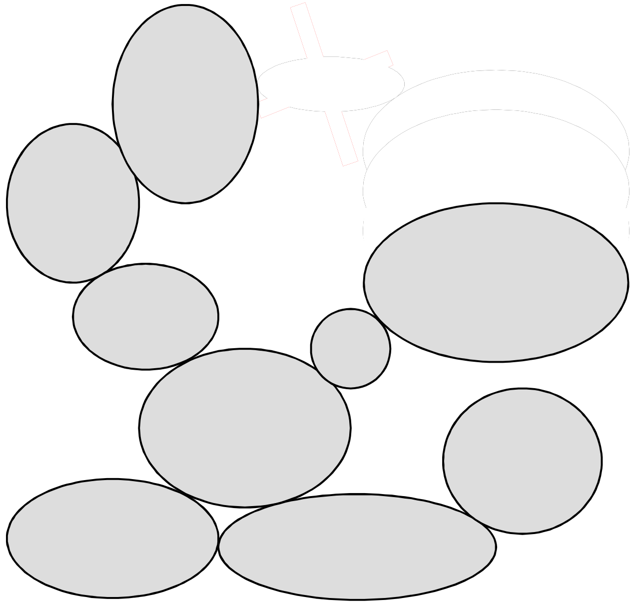
Perspectives:

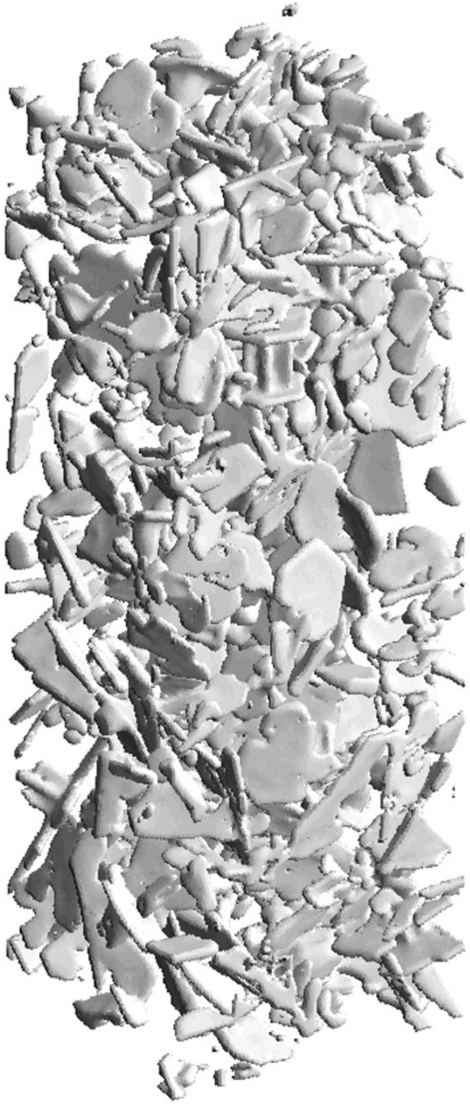
- At the beginning of the simulation: elongated grains are disconnected by curvature effects. How modeling their mechanical rearrangement?
- Extension to wet snow metamorphism (add another phase)
- Extension to Temperature Gradient metamorphism (add crystal growth effects, thermal field computation…)

➔ Suggestions are welcome!



An attempt to simulate the grain rearrangement





An attempt to simulate the grain rearrangement

Densification caused
by the breaking of the necks

Evaporation-condensation ➔ densification

Established principle in Material Sciences:
the evaporation-condensation mechanism
happens without any densification