Investigation of pore closure during polar firn densification

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Wednesday, November 29th - 9:30 am

Room Lliboutry (Molière building, IGE)

Abstract: Densification from firn to ice is an essential phenomenon for the interpretation of the climate record. A good knowledge of this mechanism is necessary for the precise dating of the air embedded in the ice. Pore closure (or close-off) is the stage at which air becomes entrapped in the ice. Typically, the close-off arises approximately 50-120m under the ice sheet surface. Because of gas flow in the firn column above close-off, the ice is older than the entrapped air. The difference between ice and gas is defined as Δage and may reach several millennia in certain sites. The precise determination of the Δage is mandatory to link temperature changes (recorded in the ice) and greenhouse gas concentrations (recorded in the gas phase). This issue may be addressed through the modeling of the firn densification processes that lead to pore-closure.

Firn densification consists of grain rearrangements, sintering and viscoplastic deformation. Although the viscoplastic behavior of the ice crystal is strongly anisotropic, densification models do not take into account this anisotropy. Firn also bears some granular characteristics that may affect its densification. The interactions between pore closure and microstructural mechanisms in the firn are still misunderstood. The aim of this PhD thesis is to incorporate both the granular aspect of firn and its anisotropy into an innovating approach of firn densification modeling. The mutual indentation of viscoplastic monocrystalline ice cylinders was experimentally carried out to propose a contact law that is based on indentation theory and that takes into account the preferential viscoplastic deformation on the basal plane. We have integrated this contact law into a DEM (Discrete Element Method) code for the prediction of firn densification. 3D X-ray micro-tomography was performed on polar firn at different stages of the densification (ρ = 0.55 – 0.88 $g.cm^{-3}$) and depths (≈ 23m – 130 m). A thorough investigation of pore closure and of different morphological and physical parameters was achieved for the Dome C and the newly drilled Lock In polar sites. In addition to these ex situ analyses, in situ X-ray micro-mechanical experiments were carried out on firn extracted from Dome C in order to model its densification. Ex situ and in situ microstructural observations indicate significant differences that can be explained by the relatively large strain rates imposed to the firn during in situ tests. These large strain rates allow for a decoupling of the effects of diffusion kinetics and of viscoplastic deformation. Their relative weights on the morphology of pores and on their closure are discussed. To measure pore closure, we propose a connectivity index, which is the ratio of the largest pore volume over the total pore volume. We show that this index is better suited for X-ray tomography analysis than the classical closed porosity ratio to predict the close-off density.

Key words: firn, densification, pore closure, anisotropy, X-ray tomography, discrete simulations