# Scientific Report: A short visit to Alfred Wegener Institute (AWI)

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## 1 Overview

I completed a short visit (15 days) to the Alfred Wegener Institute (AWI) firn-research group, where I met with Sepp Kipfstuhl (host), Johannes Freitag, Frank Wilhelms, Maria Horhold, Katharina Klein, Anna Wegner, Ilka Hamann, and many others. The AWI group has published observations of physical properties with high spatial resolution of firn cores [*Freitag et al.*, 2004; *Hörhold et al.*, 2011, 2012; *Bendel et al.*, In Prep, e.g.] that reveal physical and chemical properties that affect densification but are not currently included firn evolution models. A short visit to AWI provided an opportunity to learn more about observation-driven firn processes, which is helpful for understanding the ice physics used for modeling.

I am interested in modeling firn evolution to improve estimates of delta-age, the gas-age ice-age offset. It is critical to know the difference between the age of the ice and the younger trapped atmospheric gas to determine the best possible ice-core chronology. From these records we can reconstruct the climate history on the local, regional and global scale.

## 2 Purpose of the visit

I recently started a Post-doc position at the University of Washington with the International Collaboration and Education in Ice (ICEICS) project, funded through the NSF Partnerships For International Research And Education (PIRE) program. In this project, I will develop an open-source community firn-densification model. My Ph.D. dissertation included the development of a firn-evolution model that couples grain growth, heat transfer, and densification. Accounting for multiple physical processes provides an improved approach for estimating transient firn evolution, because the processes are dependent upon one another. From a Micro-DICE-sponsored short visit, I gained an improved understanding of the measurements of physical and chemical properties from firn cores and learn how to enhance the model physics to better reflect these observations.

This project is within the scope of the Micro-DICE mission, to improve numerical models of ice-sheet evolution by incorporating transient processes that affect physical properties.

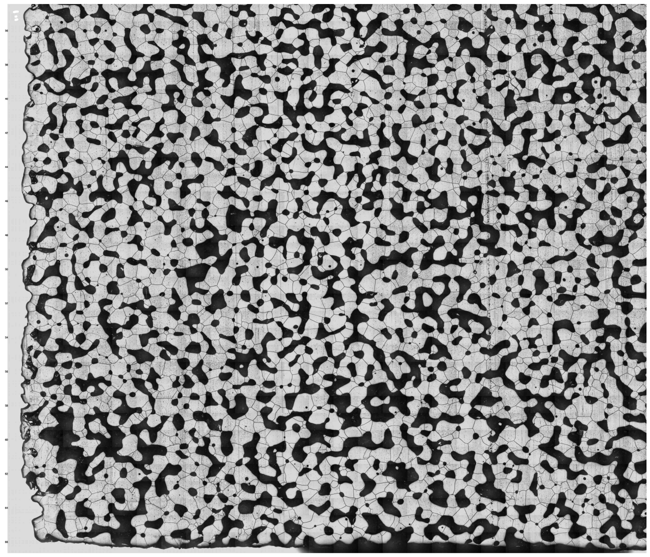

Figure 1: A $\mu$SM microscope image [*Kipfstuhl et al.*, 2006] of firn shows pore space (black) and grains (white) separated by thin lines. From $\mu$SM images along the depth of a firn core, it is possible to observe grain growth, grain splitting, and dynamic migration, none of which are currently in grain evolution models.

There is a exciting potential partnership and collaboration opportunity with the Micro-DICE network, based on a mutual interest in incorporating micro-scale processes to improve ice-flow models.

## 3 Description of the work carried out during the visit

Work carried out during the short-term visit including meeting the glaciology research group at AWI, giving an oral presentation at the weekly glaciology group meeting titled 'Ice-Core Physics and Paleoclimate', and individual and group meetings with AWI researchers.

Discussions about observations included the grain-scale processes not currently included in firn models. For example, grain growth models [*Gow et al.*, 2004, e.g.] describe the growth of the 50 largest grains, which is biased to the larger grains and therefore not representative of the distribution of sizes and growth rate of grains that differ in size. What is clear from observations (Figure 1) is that mulpile processes are occurring at the grain scale, including, growth, splitting, and dynamic migration (Prof. Kipfstuhl, pers. comm.).

Research during the stay included impacts of how to incorporate impurity concentrations in firn evolution models. Prof. Freitag has developed a way to include the impurity effect from calcium on densification through modifying the activation energy $E$ of the densification equation,

$$\frac{D\rho}{Dt} = A\exp(E/RT)(\rho_i - \rho)\sigma. \tag{1}$$

The densification rate $\frac{D\rho}{Dt}$ is affected by the coefficient $A$, density $\rho$, ice density $\rho_i$, stress $\sigma$ and Arrhenius function $exp(E/RT)$. The generic densification equation has the important components of firn densifcation models; however, there is tremendous variation in how these emperical models are parameterized [*Herron and Langway*, 1980; *Arnaud et al.*, 2000; *Goujon et al.*, 2003; *Arthern et al.*, 2010, e.g.]. Firn modeling is used to answer different research focuses within glaciology, including mass balance and delta-age modeling. High-resolution measurements from the last 5 years convincingly show that sub-annual scale physical and chemical properties are extremely important in firn density variability.

Through a short visit to the AWI firn-research group, I have gained a better understanding of firn profile observations, including high spatial-resolution density measurements from 16 shallow firn cores from Greenland and Antarctica. A thorough understanding of the observations will guide me as I add additional physical processes to the new community firn-evolution model so that it can more reliably reproduce observed firn profiles.

# 4 Description of the main results obtained

During the short visit I converted a heat-diffusion model from Matlab to C programming language, to be compatible with firn models being developed at AWI. Prof. Freitag has developed a 1-d, Langrangian firn densification model that incorporates calcium concentration in the densification rate. I was able to build this heat diffusion module during the short-visit, and I will continue to collaborate with Prof. Freitag to incorporate this piece in the densification model. As an example, Figure 2 shows the decay with depth of the surface temperature forcing, calculated from analytic equations [*Cuffey and Paterson*, 2010]. The amplitude of the seasonal signal is nearly extinguished at 10 m depth.

Future results led by Prof. Freitag include the thermo-mechanical densification model application to Antarctic ice cores. The model is able to predict the lock-in depth and age and it can be compared to $\delta^{15}$N values from ice cores. This is an important finding because previous models over predict the lock-in depth, relative to $\delta^{15}$N [*Schwander et al.*, 1997; *Goujon et al.*, 2003, e.g.].

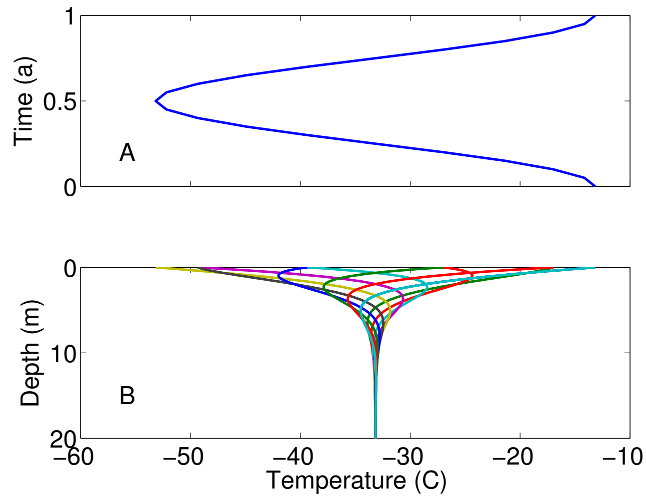


Figure 2: (A)The seasonal temperature surface forcing and (B) temperature evolution in the firn pack. The analytic model of seasonal temperature forcing decay with depth is from *Cuffey and Paterson* [2010].

# 5 Future collaboration with host institution

My Post-doc research with the ICEICS project is a good fit for the expertise of the AWI research group, for the shared interest in improving model estimates of ice-sheet evolution at the grain scale. I seek to include more grain-scale processes in a community firn-densification model because I recognize that small-scale processes can strongly influence and even control larger-scale firn deformation. The AWI firn group has stated there is mutual interest in this venture.

# 6 Projected publications / articles resulting or to result from the grant

I am leading a project on a firn-model inter-comparison, where the AWI firn group will be an active participant. We will compare the results of multiple models using the same climate conditions, in the form of temperature, density and accumulation rate (precipitation) boundary conditions. Firn models will differ in response to the same climate forcings. Analyzing the spread of model response will allow us to determine which models respond most similarly to firn strain observations. Similar inter-comparison work has been done with Global Climate Models (GCM)s and ice-sheet models [*Bindshadler and others*, submitted].

# 7 Other comments

Thank you to the Micro-DICE organizers, European Science Foundation and to Sepp Kipfstuhl for hosting my visit to AWI. Acknowledgements to the National Science Foundation for support of my Postdoc research through the Program for International Research and Education grant. It was a successful short term visit, with exciting collaborations and findings planned in the near future.

# References

Arnaud, L., J. Barnola, and P. Duval, *Physical modeling of the densification of snow/firn and ice in the upper part of polar ice sheets; in Physics of Ice Core Records*, Hokkaido University Press, 2000.

Arthern, R. J., D. G. Vaughan, A. M. Rankin, R. Mulvaney, and E. R. Thomas, In situ measurements of Antarctic snow compaction compared with predictions of models, *Journal of Geophysical Research*, *115*(F3), doi:10.1029/2009JF001306, 2010.

Bendel, V., K. Ueltzhoffer, J. Freitag, S. Kipfstuhl, W. Kuhs, C. Garbe, and S. Faria, High-resolution variations in size, number and arrangements of air bubbles in polar ice, In Prep.

Bindshadler, R., et al., Ice-sheet model sensitivities to environmental forcing and their use in projecting future sea-level (the searise project), *submitted to J. Glaciol.*, submitted.

Cuffey, K., and W. S. B. Paterson, *The physics of glaciers*, 4th ed., Butterworth-Heinemann/Elsevier, Burlington, MA, 2010.

Freitag, J., F. Wilhelms, and S. Kipfstuhl, Microstructure-dependent densification of polar firn derived from X-ray microtomography, *Journal of Glaciology*, *50*, 243–250, doi: 10.3189/172756504781830123, 2004.

Goujon, C., J. Barnola, and C. Ritz, Modeling the densification of polar firn including heat diffusion: Application to close-off characteristics and gas isotopic fractionation for Antarctica and Greenland sites, *Journal of Geophysical Research*, *108*(D24), doi: 10.1029/2002JD003319, 2003.

Gow, A., D. Meese, and R. Bialas, Accumulation variability, density profiles and crystal growth trends in ITASE firn and ice cores from West Antarctica, *Annals of Glaciology*, *39*, 101–109, doi:10.3189/172756404781814690, 7th International Symposium on Antarctic Glaciology (ISAG-7), Univ Milano Bicocca, Milan, ITALY, AUG 25-29, 2003, 2004.

Herron, M., and C. Langway, Firn densification: an empirical model, *Journal of Glaciology*, *25*(93), 373–385, 1980.

Hörhold, M., T. Laepple, J. Freitag, M. Bigler, H. Fischer, and S. Kipfstuhl, On the impact of impurities on the densification of polar firn, *Earth and Planetary Science Letters*, *325-326*, 93–99, doi:10.1016/j.epsl.2011.12.022, 2012.

Hörhold, M. W., S. Kipfstuhl, F. Wilhelms, J. Freitag, and A. Frenzel, The densification of layered polar firn, *Journal of Geophysical Research*, *116*(F1), doi:10.1029/2009JF001630, 2011.

Kipfstuhl, S., I. Hamann, A. Lambrecht, J. Freitag, S. H. Faria, D. Grigoriev, and N. Azuma, Microstructure mapping: a new method for imaging deformation-induced microstructural features of ice on the grain scale, *Journal Of Glaciology*, *52*(178), 398 – 406, 2006.

Schwander, J., T. Sowers, J. Barnola, T. Blunier, A. Fuchs, and B. Malaizé, Age scale of the air in the Summit ice: Implication for glacial-interglacial temperature change, *Journal of Geophysical Research*, *102*(D16), 19,483–19,493, doi:10.1029/97JD01309, 1997.