1) Summary (up to 1 page)

2) Description of the scientific content of and discussion at the event (up to 4 pages

3) Assessment of the results and impact of the event on the future direction of the field (up to 2 pages)

4) Final programme of the meeting

1. Travel expenses covered by micro-Dice :

Tobias Binder	**total**	**€ 1433.70**
Sergio Faria	**total**	**€ 1637.62**
Joseph Kennedy	**total**	**€ 1984.45**
Denis Samyn	**total**	**€** ***2073.22***
Travelling	***total***	***€ 7128.99***

Travelling

total

Further details below

2. Accomodation

Tobias Binder	5 days
Sergio Faria	5 days
Josef Kennedy	8 days
Denis Samyn	4 days

22 days à DKK 300	DKK 6600.00	
4 x cleaning room à DKK 300	DKK 1200.00	
Total:	DKK 7800.00	**€ 1046.85**

(covered by micro-Dice or University of Copenhagen)

Workshop fee	DKK 4000.00	**€ 536.85**
Grand total		**€ 8712.69**

Exchange rates from http://www.ecb.int/stats/exchange/eurofxref/html/index.en.html

Remark:
The expenses exceeding the micro-Dice contribution of € 8000 will be covered by the Centre for Ice and Climate, Niels Bohr Institute at the University of Copenhagen.

1. Tobias Binder

Aug 20 2011	**Frankfurt - Copenhagen & ret**			**€ 108.58**
Aug 21 2011	**Copenhagen - Nuuk**	**DKK 3 445.00**		**€ 461.88**
Aug 26 2011	**Nuuk - Copenhagen**			**€ 762.98**
Aug 20 2011	**Train Heidelberg - Frankfurt**			**€ 24.50**
	Hotel Copenhagen			**€ 48.24**
	Metro Copenhagen		**DKK 144**	**€ 19.33**
	Taxi Nuuk		**DKK 61**	**€ 8.19**
	Total		**✔**	**€ 1433.70**

Bank information:

Name: **Tobias Binder**
IBAN: **DE45200100200474103204**
BIC: **PBNKDEFF**
Bank: **Postbank Hamburg**
Account-Nr: **474103204**
Routing/BLZ: **20010020**

2. Sergio Faria:

Transportation Costs

date(s)	*description*	*Route*[§]	*costs (DKK)*	*costs (EUR)*	*I.T.F.* (EUR)*
20./27.08.11	bus	Göttingen ⇔ Göttingen Train Stn.	--	2 X 2,00	--
20./27.08.11	train (rail & fly ticket)	Göttingen Train Stn. ⇔ FRA	--	58,00	--
20./27.08.11	airplane (SAS)	FRA ⇔ CPH	--	157,62	--
20./21./26./27.08.11	train	CPH ⇔ Copenhagen (Hotel)	4 X 24,00	4 X 3,28	4X 0,05
21./26.08.11	airplane (Air Greenland)	CPH ⇔ GOH	9.199,00	1.259,30	20,78
			Total Transportation Costs (EUR)	**1.513,02**	

[§] The double arrow "⇔" means round journey (to and from).
* I.T.F.: International Transaction Fee.

Accommodation Costs

period	*place*	*costs (DKK)*	*costs (EUR)*	*I.T.F.* (EUR)*
20.-21.08.11	Go Hotel Copenhagen	499,00	62,10	--
26.-27.08.11	Go Hotel Copenhagen	499,00	61,49	1,01
		Total Accommodation Costs (EUR)	**124,60**	

Total Transportation and Accommodation Costs
1.637,62 EUR + daily allowances

The appropriate daily allowances must still be added to this figure.
(I do not know which rules and rates ESF uses to calculate it).

Bank Information
name: **Sergio Henrique Faria Santos**
bank: **Targobank**
IBAN: **DE20 3002 0900 1511 7406 41**
BIC code: **CMCIDEDD**
BLZ: **300 209 00**
account no.: **1511740641**

3. Joseph Kennedy

Aug 30 2011	**Anchorage - Fairbanks**		**$**	**111.50**
Aug 18 2011	**Anchorage - Kopenhagen & ret**		**$**	**1 038.00**
Aug 20 2011	**Copenhagen - Nuuk**	**DKK 8 905.00**	**€**	**1195.30**

Joseph Kennedy	**total 1149.50 $ / 1.4402 $/€ = ~821 €**	**€**	**789.15**
		€	**1195.30**
Total		**€**	**1984.45**

Bank information

Name: **Joseph Kennedy**
Bank**:** **AlaskaUSA Federal Credit Union**
Account: **1700014091908**
Routing: **325272021**

4. Denis Samyn

Train to Brussels Airport	**08/20/2011**	**€**	**5.20**
Flight Brussels-CPH-BRU	**08/08/2011**	**€**	**278.52**
Train from CPH airport	**08/20/2011**	**DKK**	**36.00**
Hotel in CPH	**08/21/2011**	**DKK**	**825.00**
Train to CPH airport	**08/21/2011**	**DKK**	**36.00**
Flight CPH-NUUK-CPH	**08/09/2011**	**DKK**	**10424.00**
Taxi Nuuk to Airport	**08/25/2011**	**DKK**	**160.00**
Train from CPH airport	**08/25/2011**	**DKK**	**36.00**
Hotel in CPH	**08/25/2011**	**DKK**	**1740.00**
Train to CPH airport	**08/27/2011**	**DKK**	**36.00**
Train from Brussels Airport	**08/27/2011**	**€**	**5.20**

Total Euros 288.92
Total DKK 13293 = 1784.30€
Total € 2073.22

Bank Dexia Belgium, Brussels
IBAN BE32 0639 7965 7902
BIC GKCCBEBB

1) Summary (up to 1 page)

Towards a microstructure-based flow law of ice

Workshop held at the Greenland Climate Research Center (GCRC) at the Greenland Institute of Natural Resources in Nuuk, Greenland from 21 - 26 Aug 2011

For the first time a small group of experts involved in microstructural analysis of ice cores and ice flow modelling met in Nuuk, Greenland. The main objective of the workshop was to summarize the most recent results obtained from ice core analysis and laboratory experiments in order to formulate a "microstructure-based" law for the flow of the large ice sheets. The presentations showed that on the microstructure side a large amount of new data became available during the last decade, however it became also clear that fundamental processes are still not yet fully understood. The deformation and recrystallization mechanisms under the low stress conditions encountered in ice sheets are not known well enough. Largely unclear is the role of dynamic recrystallization for the c-axis evolution assumed to control the viscosity of the ice. Despite the gaps in various aspects of the ice flow there was also significant progress reported. First results of deformation experiments with low stresses close to that in ice sheets were presented.

The little group felt that despite the many questions left open for the future the workshop was a first successful meeting. It expressed its strong will to meet again and to organize in the near future a large workshop or a conference on the same topic. The idea of a microstructurally- or physically-motivated deep ice core was postponed for later. There is some hope that modelling will provide good ideas where to go to. Furthermore, the idea of a community ice sheet model and a European centre for ice sheet modelling were discussed. The workshop participants supported this idea because the several groups developing ice flow models seem insufficient to include all necessary flow components in modern models.

The Climate Research Center in Nuuk with its highly motivating environment proved to be an excellent place for a workshop dealing with ice flow.

2) Description of the scientific content of and discussion at the event (up to 4 pages

Scientific content of and discussion at the event (up to 4 pages)

Ice is an important component in the global climate system. Understanding the behaviour of the large ice sheets, which cover a few percent of the Earth's surface and represent ~65 m of sea level, is crucial for reconstructing past climate and predicting future sea level in the expected warmer world. The currently accepted flow law of ice, developed in analogy to other geological materials as a power law, has been conceived under laboratory conditions hardly met in nature before the first ice cores were drilled through ice sheets. By the end of last century, when the first numerical ice flow models were developed, the contemporary concepts about ice deformation and recrystallization through ice sheets available from a few ice cores were implicitly implemented in those models. Since 1990, however, only within European drilling projects six ice cores have been drilled through the ice sheets in Greenland and Antarctica. The most recent results obtained from the analysis of the microstructure of these cores question the early concepts about deformation and recrystallization in ice sheets in many respects. In Nuuk a small group of experts in the microstructural analysis and modelling ice flow met for the first time to discuss and to develop strategies how the new results and ideas can flow into modelling. For example we realize that the impurities in the ice varying on the annual but also on the ice age cycle-scale (100 ka) make the ice extremely inhomogeneous. We also find evidence of dynamic recrystallization through the entire ice sheet with serious consequences for the formulation of the viscosity if it is a predominant process. The group is aware of the difficulty to combine micro- and macro-scale processes in a multiscale model. There is no quick solution to this challenge.

Nobuhiko Azuma: What are the issues of ice rheology for ice sheet models

In his introductory talk NA summarized the issues most relevant for the workshop.
- Do we really know the deformation mechanisms in ice sheets?
- Do ice fabrics tell us something about deformation histories?
- Can we incorporate ice fabrics into ice sheet modelling?
- Does anisotropic rheology of ice not affect ice sheet modelling if compared to bottom sliding etc?

His answers were that we know the deformation mechanisms in high stress regime (dislocation creep) but we do not yet know them well enough in the low stress regime (stresses smaller than 0.1 MPa). First results of his low stress experiments point to Harper-Dorn creep with a stress exponent of 1.2 and a significant contribution of diffusion along grain boundaries as accommodation process. Crystal rotation due to basal glide is well understood while dynamic recrystallization is not. Fabrics can be incorporated into ice sheet models but dynamic recrystallization (strain induced boundary migration with and without nucleation of new grains) has to be taken into account. In models all components affecting the rheology have to be included ice streams as well as the anisotropy of ice.

Sepp Kipfstuhl: Micro-scale observations - a summary

In his overview SK pointed out that particularly during the last 10-15 years the new methods of digital image acquisition and processing revolutionized microstructure analysis. Observations on the grain scale are possible. Slip bands, micro-inclusions, grain and subgrain boundaries can be routinely recorded along ice cores. c-axis fabric analysis is automated. Results obtained from the recently drilled cores question classic concepts, in particular the three-regime conceptual model of normal grain growth in the upper and grain boundary migration recrystallization in the bottom part of an ice sheet and polygonization/rotation recrystallization in between. Evidence of dynamic recrystallization occurs throughout the ice sheet independent on depth. To understand the evolution of the microstructure and the deformation/flow of ice means to understand the role of the impurities in firn and ice. Impurities clearly affect the densification of firn, air bubble formation and the shape of air bubbles down to the depth they convert to air hydrates. Impurities affect ice rheology on any scale. If the aspect ratio of air bubbles is interpreted as strain induced then glacial period and cloudy band ice is softer than interglacial and clear band ice and deform faster. New concepts are needed to understand and explain the many observed phenomena.

Sergio H. Faria: Multiscale modelling - what, when, why?

Physics happens on many different scales. SHF gave a general introduction about 'structure and emergence', 'emergence in physical systems' and the idea of 'mixtures with continuous diversity' he uses to formulate models for multiscale structures occurring in polycrystalline ice sheets, i.e. multiscale ice sheet models. Structures in ice sheets cover some 12 orders of magnitude, which is a great challenge for the modelling community. In general, models have to focus on a certain length scale. He summarised the stratigraphy and microstructure of the EDML deep ice core. Micro-folds are present in the ice (~1800 m depth) long before the climatic record is corrupted in a depth where simple shear becomes dominant (~2400 m depth). An interesting feature of the EDML core is the change in the geometry of the borehole possibly caused by grain boundary sliding. Relevant for the micro-macro perspective discussed in the workshop ice sheet modelling can generally only handle the larger scales. SHF also gives a short introduction into 'Elle', a modelling platform to simulate the evolution of the microstructure on the microscale. He discussed briefly modelling strategies within the historical context the models were developed. At the end of his talk he asked some thought-provoking questions concerning modelling; e.g. how we evaluate and verify models, or whether empirical, non-quantitative, or non-predictive models are useful.

Dorthe Dahl-Jenssen: Ice Rheology: results from flow modelling

DDJ showed that crystallographic information processed in the form of a cone half angle containing 90% of c-axes can be used to interpret results from ice compression tests in the laboratory. By tuning Azuma (1994) ice flow model and by doing Monte Carlo simulations of the ice fabrics at NorthGRIP, it is possible to derive a local flow law as well as some parameters which apparently fit to what has been measured in-situ.

Joseph H Kennedy: Exploring the link between climate history and fabric evolution in ice sheets

JK is interested in the following questions:

• Under what conditions (stress, temperature, time, etc) do subtle changes in fabric, induced by climate changes, get preserved and enhanced in the ice throughout time?
• How do crystal processes like polygonization and migration recrystallization affect the climate signal?
• How much of the strong change in fabric at the glacial-interglacial transition in the Siple Dome, West Antarctica, record can be explained by climate signal enhancement?
• What does the sonic velocity bore-hole data from Dome C, East Antarctica, tell us about the ice-sheet's climate history?

JK showed some preliminary results from a combined model being developed in his PhD and aiming at incorporating the notions of bulk strain rate, velocity gradients, crystal growth, polygonization, GBM recrystallization into a finite-element model.

Nobby Azuma: Role of grain boundaries on ice rheology

Grain boundary concepts derived for metals may fail if applied to ice. If a grain boundary is in its character a liquid-like layer a grain boundary may be a high diffusion path for any molecule. If it is a closely packed layer then the mobility in a grain boundary is low. Unfortunately, the nature of a grain boundary in ice is not well understood. Therefore grain growth and low stress deformation experiments are needed. NA presents first results of grain growth using degassed, bubble free ice. All grain growth experiments published so far may be biased by dragging of small air bubbles (<40 μm) which significantly affect grain boundary migration. Published grain growth rates and activation energies for grain boundary migration and diffusion have to be reconsidered. The activation energy for normal grain growth in bubbly ice is Q=40-60kJ/mol, while Q=120kJ/mol for bubble-free ice. NA presented also first results of normal grain growth experiments with sub-micrometer inclusions (~300 nm). Only small particles (radius <1μm) significantly affect the migration of grain boundaries in ice. Experiment and theory indicate that the presence of sub-micrometer inclusions may cause the small grain sizes observed in impurity-rich ice of glacial periods. He points out that the flow law for ice in the range between 0.001 and 0.1 MPa is not yet established. Ultra-low stress (ULS) experiments conducted to study the effect of grain boundaries on ice rheology indicate that the power law exponent in these experiments is close to n=1 and the activation energy is Q=128kJ/mol, very similar to the activation energy for grain boundary diffusion. He concluded that the low power-law exponent and the similarity of activation energies suggest the occurrence of Harper-Dorn creep.

Denis Samyn: Crystallographic heterogeneities in glaciers and ice sheets: implications for ice micro-deformation and its interpretation

DS main interest is to understand flow heterogeneities in deep and basal ice particularly relevant for dating ice core records. He reviews briefly the present-day concept of the recrystallization regimes in ice sheets, our understanding the relevant deformation and recrystallization mechanisms and concludes that the different dislocation motion systems, diffusion, recrystallization and accommodation processes lead to different 'flow laws' under different stress patterns and regimes. Several interaction lengths (multiscale interactions) are active in the deformation of ice. In particular, stratigraphy is affected by longer-range (larger-scale) interactions. DS shows that in the NEEM ice core dipping and folding are initiated below 1800 m depth the early folding phase starting with the formation of 'fabric stripes'. By applying the usual theory to the observed fold, he concluded that the viscosity contrast (ratio) between the higher viscous (competent) fold and the less viscous ice matrix may be up to ~40. This viscosity contrast can be explained by a significantly different c-axis orientation between the folded layer and its matrix. Kinking might be a source mechanism for the formation of folding at the micro-scale.

Tobias Binder: Recrystallization dynamics derived from grain boundary networks

TB presented an overview of digital image processing based methods to extract information about deformation and recrystallization from images of the grain boundary network as they emerge on the surface of polished ice sections. Image processing is made with the help of three methods: machine learning, watershed segmentation, and graphical models. He derives as many parameters as possible from a grain boundary network to describe the evolution of the microstructure. This can in principle be the length of a single grain boundary but also its local curvature or the length of subgrain boundaries - both might be used in the future to estimate the differences of the stored strain energy across the grain boundary. The hope is that the right combination of parameters characterizes the recrystallization regimes in an ice sheet. TB presented first results derived from the NEEM core. The high resolution of the images asks for a new definition of the 'mean grain size' as even the smallest grains identified are counted whether meaningful or an artifact of pressure relaxation. This work is new and accordingly the interpretation of the various parameters not straightforward.

Anders Svensson: Ice crystals and stratigraphy - what can we learn from ice cores?

AS gives an overview of microstructural results obtained from ice cores drilled recently in Greenland. He discusses questions like is there a normal grain growth regime or are fabric and microstructure coupled. He showed that polygonization is active in the normal grain growth zone in the upper 1000 m of the ice sheet, that the c-axis distribution in shallow depths just beneath the firn-ice transition is not isotropic and that the grains are increasingly flattened with depth in Holocene ice. In the Greenland deep ice there is no evidence of impurities being harvested by migrating grain boundaries even in the warmest and deepest ice. While ionic impurities diffuse dust particles appear non-diffusive. He does not find a relationship between grain area and c-axis orientation, nor does the climatic transition from the Holocene to the last glacial period (impurity concentration increases 10-100 fold; grain sizes drops) cause a distinguished signal in the c-axis distribution (profile of eigen values). Remarkable, however, is in glacial ice of the NRIP core an astonishing variability in the c-axis distribution on the cm-scale. Cloudy bands with high concentrations of impurities and small grain sizes show a weak girdle-type fabric pattern while in the clear bands with large grain sizes and the same climatic and thermal history the c-axis pattern tends towards an uniaxial distribution. On the longer term the cold periods with high concentrations in impurities and small grain sizes are imprinted in the fabric pattern most clearly seen in the Dome Fuji ice core.

Dorthe Dahl-Jenssen: RES information from Greenland and a little from Antarctica

DDJ showed radio echo sounding profiles from the NEEM region. The RES images give first ideas what causes the disturbances observed in the NEEM or any other deep core. Some feature looking like frozen-in turbulence may result from melting-freezing cycles along their flow path. Matlab simulation support this first idea.A central question is how the flow induced disturbances can be generated over a flat bedrock. Similar features were observed earlier in east Antarctica. Newest radar and signal processing techniques allowing tomography at the bedrock will help to avoid drilling climate cores in disturbed ice.

General discussion

All ice cores drilled until today are motived by climate and most cores were drilled on domes or ice divide positions. The idea of a physically motivated non-climate ice core was postponed until modelling suggests ice-dynamically interesting positions where most is learned in terms of ice dynamics. It was decided to have a second look on the DYE3 ice core first.

A widely discussed topic was the effect of the layering in ice (cloudy/clear band and glacial-interglacial ice). Is cloudy band-ice generally 'soft' and what are the consequences? Does it deform and thin faster than the clear band- and interglacial ice as the air bubble shape indicates? No clear answer was found. Although grain size is significantly reduced in cloudy band- and glacial ice grain size sensitive flow war never a hot topic.

3) Assessment of the results and impact of the event on the future direction of the field (up to 2 pages)

The main objectives of the workshop were to discuss the limitations of current flow laws for ice sheets and the possibilities to overcome these limitations through more realistic models. To this aim N. Azuma reviewed the known issues on ice sheet rheology and reported on recent experiments that bring new insights into the deformation and recrystallization mechanisms of ice. T. Binder, S.H. Faria and S. Kipfstuhl summarized the most recent understanding of ice microstructure (fabrics, grain and subgrain boundaries, etc.) and the potential of new methods of ice microstructure analysis through image processing. Recent results on the evolution and modelling of ice fabrics were presented by D. Dahl-Jensen, J. Kennedy and D. Samyn, while D. Dahl-Jensen, S.H. Faria, D. Samyn and A. Svensson examined the multiscale interrelations between stratigraphy, microstructure and flow. The participants came to the conclusion that the flow of ice sheets is in fact a complex, multiscale problem that cannot be satisfactory described by a simple, homogeneous, isotropic model. The recent results of microstructure analyses and deformation experiments indicate that different deformation mechanisms may control the flow of ice in different parts of the ice sheet. Furthermore, the stratigraphy seems to play a decisive role in the coupling between microscopic processes and the large scale flow. As a consequence, there is no single flow law that may describe the ice rheology throughout the ice sheet. Rather, the ice sheet must be regarded as a composite of strata with distinct rheological and microstructural properties. The challenge for the near future is thus to devise systematic methods to relate specific flow laws to layers with particular microstructural and rheological properties, as well as efficient methods to deal with these different flow laws in a multiscale ice sheet model.

4) Final programme of the meeting

Sunday 21 August 2011

Arrival of participants in Nuuk

16:00 Planning of program

17:00 Ice breaker in the Annex building

Monday 22 August

09:00 Workshop

Welcome to the Institute (Director Klaus Nygaard)

ROV for glacier research? (Nicolas Nowald)

NEEM (Dorthe Dahl-Jensen)

MICRODICE (Denis Samyn)

Nuuk Glacier and fjord system (Dorthe Dahl-Jensen)

What are the issues of ice rheology for ice sheet models (Nobuhiko Azuma)

12:00 Lunch at the Natur Institut

Tour through the institute by Søren Rysgaard

Microscale observations - a summary (Sepp Kipfstuhl)

Multiscale modelling - what, when, why? (Sergio H. Faria)

18:00 End of day

Tuesday 23 August

08:00 Departure for a day excursion on STEINA M/S to a glacier front in the Nuuk fjords

18:00 End of excursion

Wednesday 24 August

09:00 Workshop

Role of grain boundaries on ice rheology (Nobuhiko Azuma)

Ice Rheology: results from flow modelling (Dorthe Dahl-Jensen)

Crystallographic heterogeneities in glaciers and ice sheets: implications for ice micro-deformation and its interpretation (Denis Samyn)

12:00 Lunch at the Naturinstitut

Ice crystals and stratigraphy - what can we learn from ice cores? (Anders Svensson)

Image analysis - new results and parameters from the NEEM ice core (Tobias Binder)

Exploring the link between climate history and fabric evolution in ice sheets (Joe Kennedy)

18:00 End of day

Thursday 25 August

09:00 Workshop

RES information from Greenland and a little from Antarctica (Dorthe Dahl-Jensen)

Subjects that have been identified during the workshop

Logging requirements

A physical motivated ice core - IPICS

12:00 Lunch at the Naturinstitut

13:00 Workshop findings, conclusions and recommendations

15:00 Visit the Museum

18:00 Banquet dinner at Restaurant Nipisa

List of participants:

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