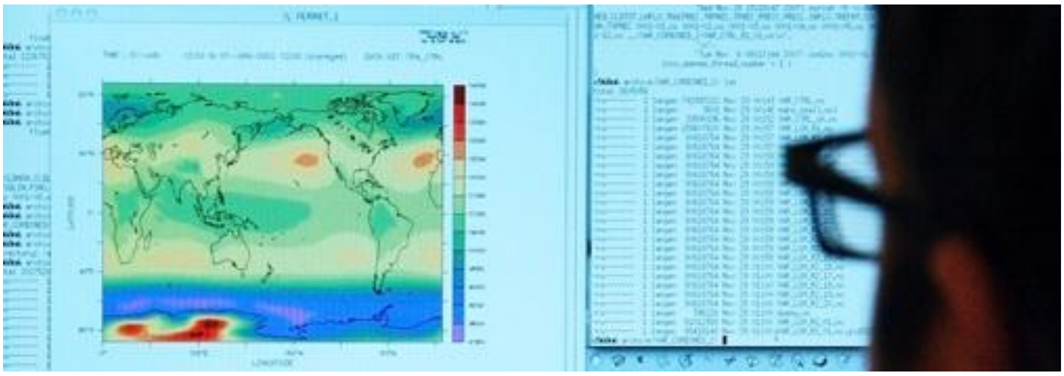
RESEARCH PLAN 2012-2017

DANISH NATIONAL RESEARCH FOUNDATION'S CENTRE OF EXCELLENCE FOR ICE AND CLIMATE

SEPTEMBER 13, 2010



CENTRE FOR ICE AND CLIMATE

Summary

The build-up of greenhouse gases is changing Earth's climate. The predicted global warming raises an urgent need to understand the processes relevant in a warmer climate. A major concern is sea level rise caused by the changing volume of the ice sheets. The ice cores from the large ice sheets contain palaeoclimate records from previous warm periods that can be studied to gain insight on the climate and ice sheet evolution during these periods. Our vision is to contribute to an improved understanding of the present and past warm interglacial periods by studying ice cores and developing models to explain observations and predict the ice sheet's response to climate change. Our strength is the collaboration between modellers and ice core experimentalists. We will build on this strength by using our extensive data collection from especially the Greenland ice cores in models to improve our understanding of the warm climate and the risk for abrupt changes in the future. We have a unique opportunity to study basal material from the NEEM ice core and this inspires us to include the role of the biology of the past.

The Evolution of the Greenland Ice Sheet

The Greenland ice sheet has waxed and waned in response to past climate change ever since its formation. Measurements of gasses and water isotopes from the well-dated ice cores will be used in connection with borehole temperatures and ice flow models to constrain past ice thickness, mass balance and temperature. The observations will constrain and validate ice sheet models in order to reveal the evolution of the Greenland ice sheet and its contribution to past sea level changes. Study of basal material might determine the age of the fauna from before ice covered Greenland.

The Eemian – the climate of a warm World

The Eemian period and the Holocene climatic optimum were warmer in Greenland than the climate of the recent 1000 years. The objective of the program is to identify processes that can be used as an analogue for our present warming climate and also to identify external forcings that caused these variations. What are the roles of the bipolar seesaw, the solar insolation and the greenhouse gases? Studies of methane and CO_2 and their isotopes can be used to understand their changing source strengths in the past and improve our predictions for the future.

Abrupt changes

The terminations of the last glacial and the previous glacial as well as the onset of the 25 interstadials in the glacial period in Greenland were very abrupt. The high resolution and well-dated records from the ice cores allow very detailed studies of these transitions. Earth system models will be used to understand the climate processes involved and in particular the role of the bipolar seesaw and low latitude processes in the termination of glacial periods.

What can the past tell us on the future climate?

Based on the experience gathered we will proceed and look into the future. How much mass will the Greenland ice sheet loose and when will it loose contact with the ocean? Can we improve estimates of the rate of sea level change and the total sea level changes? How will solar insolation and greenhouse gasses influence the climate the next 100 years? Our target is to provide results for the coming IPCC reports.

Impact

The international team and the centre's network of collaborators will be an international focal point for ice core driven climate and ice sheet research. The results will improve our understanding of the processes that drive the evolution of the ice sheets and climate as well as the role of the high concentrations of greenhouse gasses in the climate system. The high risk of the interdisciplinary research on the evolution of the biodiversity at abrupt climate changes is counterbalanced by the potential high impact of our understanding of future extinctions. The centre will educate a new generation of researchers, make a database on ice core related climate proxies available and provide climate input to the political decision makers.

Vision

Climate is warming and atmospheric concentrations of greenhouse gasses are at their highest recorded levels in the last 800,000 years (Wolff, 2010; Lüthi, 2008; Loulergue, 2008; Schilt, 2010). As a consequence, we are faced with the urge to reduce our emissions of greenhouse gasses and to adapt to the changing climate. During the last 100 years there has been a global warming of 0.8°C (Brohan, 2006; Hansen, 2006). This is still rather modest compared to the predicted global warming of 1.4-4.0°C and European warming of 1.0-5.5°C by the year 2100 (Joint EEA-JRC-WHO report, 2008). Understanding of the changes to come and the likely risks and costs of the climate-induced changes is a necessity for maintaining our quality-of-life and international competitiveness.

Palaeoclimatic records contain a wealth of information on the natural variability of climate and its ability to undergo abrupt changes. The overarching motivation for us to work with the palaeoclimate archive is the drive to understand the climate system, and the importance of predicting future climate changes. Our philosophy is that models used for predictions must demonstrate solid capacity to model the climate of the past, and in particular that of recent warm periods. The past offers an opportunity both to improve models, and constrain the range of predictions in the future.

The Eemian interglacial is the most recent epoch with a climate significantly warmer and with sea levels significantly higher than present (Kopp, 2009; Shackleton, 2003; Walbroeck, 2002; CAPE Members, 2006). The evolution and variability of this period is not fully understood (Couchoud, 2009; Shackleton, 2003). For example, the timing of the termination of the previous glacial into the Eemian is not yet well constrained by palaeoclimate data (Drysdale, 2009). Processes related to the terminations can be determined by using proxy data recorded in detail in the Greenland ice cores (Suwa, 2006). With the new records becoming available from the NEEM ice core, in conjunction with existing data from incomplete or disturbed Eemian sections from previous ice cores, we will produce the most detailed picture of the Eemian period in Greenland. This will provide a unique vantage point for investigating the Eemian climate and the Greenland ice sheet in response to the Eemian warming.

Through the first centre period the new NEEM ice core has been drilled and we expect the final years of the first centre period to result in a state-of-the-art ensemble of climate records from the ice core produced through the Danish program and by the partners from the 14 nations participating in the NEEM program.

Our vision is to use ice core data and models to gain insight into the behaviour of the climate in warm interglacial climate periods. We will focus further on using the obtained ice core records for understanding climate by applying a variety of components of earth system models to investigate the natural behaviour of the warm climate, the cause of natural climate changes, the role of the greenhouse gases in the warm climate and the risk of abrupt changes. The challenge for the Centre for Ice and Climate is to stay on the path of excellence by using the ice core data in the modelling by directly modelling the ice core climate proxies and use the earth system models in collaboration with the leading international centres.

In the second centre period we will use a wide range of measurements from the deep ice cores to constrain the evolution of the Greenland ice sheet throughout the past glacial-interglacial cycle. The ice sheet models that are used to project the Greenland ice sheet contribution to future sea-level rise will then be tested and validated by modelling the past evolution of the Greenland ice sheet. This is a much needed effort given that a number of the most advanced ice sheet models recently was found to be seriously lacking in their ability to model the Greenland ice sheet history during the Holocene (Vinther, 2009) and that the last IPCC report (IPCC, 2007), citing the major uncertainties in ice sheet modelling, provided no estimate of the future sea-level rise caused by a melting Greenland ice sheet. The past offers a unique opportunity to improve the ice sheet models, and thereby to constrain and ascertain the range of predictions in the future.

As a new initiative, we plan to enhance the ocean modelling performed in Copenhagen in order to better understand the connection between the climate records of the North and South, as ocean currents play a major role in the climate system and for the greenhouse gas cycle (the biogeochemical system). In connection to this, we will in particular look into the abrupt changes from glacial to interglacial climate and – where relevant – also into the abrupt stadial-interstadial changes in the glacial period.

The basal ice from the NEEM ice core very likely contains well-preserved biological material. We therefore plan a high-risk program for developing methods to detect biological material in ice cores to study the change of biodiversity during the abrupt climate changes that led into the warm interglacial period. This program will be carried out together with the DNRF Centre for Macroecology, Evolution and Climate and Centre for GeoGenetics. In addition, we plan to develop methods to identify the fauna and flora from before ice covered the NEEM site and date the time when the site was ice free. Another very promising line of research is the use of laser spectroscopy instruments to measure water isotopes and gas concentrations and isotopes (Gkinis, 2010; Stowasser, 2010). Our prime focus will be on the isotopes of major greenhouse gases (CO_2 and CH_4) and stable water isotopes (H_2O). Through our collaboration with the company Picarro we plan to develop new cutting-edge technology allowing us to obtain ice core data in unprecedented quality and resolution.

The program for the next centre period will build strongly on the data obtained through the first centre period by focusing more on the use of the data through models to increase our understanding of the climate system and the Greenland ice sheet. The program ties in with the strengths of the EU programs and networks we are already involved in, and contains several high-risk novel ideas. As a final initiative we propose to open an 'EEM challenge': Model the Greenland contribution to sea level change during the Eemian based on ice core data. The results from this challenge should contribute to the IPCC assessments.

Background

Results from ice cores, both Northern Hemisphere and Southern Hemisphere, are very important in understanding the dynamics of the climate system and improving our ability to predict future climate (Stocker, 2003; NGRIP Members, 2004; EPICA Members, 2006; Alley 2010). The Greenland ice cores have provided high-resolution data (of up to annual resolution) extending back about 123,000 years (Dansgaard, 1982; NGRIP Members, 2004; Capron, 2010a) while the Antarctic ice cores have provided lower-resolution data dating back 800,000 years (EPICA Members, 2006; Wolff, 2010; Jouzel, 2007). Within the field of climate research, the most cited climate researchers are those obtaining and analyzing ice core data.

The Centre for Ice and Climate started 1 April 2007 and has been active for 3.5 years of the first 5 year period. The centre has successfully achieved the goals and milestones laid out for the first 3.5 years and has a team of 11 senior researchers, 9 postdocs and 20 PhD students. Through the centre it has been possible to strongly expand the ice core and climate research in Denmark. Danish ice core research has been significantly strengthened via the international NEEM project with its 14 participating nations. It has been possible to measure greenhouse gasses on the Greenland ice cores and also to take a global lead in applying novel laser-based technology to ice core research. In collaboration with our partners we have pioneered pilot studies in interdisciplinary fields such as DNA, biology and tephra chronology (Willerslev, 2007; Davies, 2008; Davies, 2010). The International Union of Geological Sciences adopted the ice-core-derived definition of the onset of the Holocene as an official Global Stratotype Section Global Standard Section and Point, a so-called *Golden Spike* (Walker, 2009) and we have published high impact reports on the abruptness of climate changes (Steffensen, 2008) and sea level rise (Grindsted, 2009; Vinther, 2009; Dahl-Jensen, 2009). Through the centre period 124 peer reviewed publications and 7 book chapters have been produced with 12 in the highly recognized Nature and Science magazines. The senior personnel associated with this proposal are affiliated with the most cited climate groups in the world. The strong international collaboration is reflected by the amount of co-authors from other nations. The results from the last ice cores (NGRIP and EPICA) have been producing cutting-edge results, authored by the proposed centre investigators, in Nature and Science in recent years (21 publications in the last 10 years).

With the old Eemian ice recovered during the summer 2010 from NEEM, the gas lab now operational, and the high number of PhD students expected to finish their research in 2010 and 2011, we expect the number of publications to increase further during the coming years. The research of the centre has been recognized through the EU Descartes prize, several medals and high ratings in Danish Research.

A benchmarking of the impact of major ice core and climate groups has been performed and confirms that the Centre for Ice and Climate stands among the very strongest groups in the world (included in the self-evaluation report). We believe our strong international standing is based on our highly cited publications and the excellence and innovative spirit of our team, and a unique combination of ice drilling capacity, innovative ice core measurements and modelling capacity. When focusing on new goals, we believe it is important to recognize our niche of specialization and build on this.

The centre has played a significant role in recent University of Copenhagen high-priority activities, such as the International Alliance of Research Universities' conference *Climate Change: Global Risks, Challenges & Decisions* held in Copenhagen in March 2009, and the university's input to the UN Climate Change Conference 2009 (COP15) held in Copenhagen in December 2009. The centre is also often featured when the university receives guests and press teams.

As a further asset to the centre, we have been able to expand our research through additional grants. These include the EU FP7 large integrative project Past4Future coordinated from the centre with the objective to integrate palaeoclimate data from ice cores, marine sediment cores, terrestrial records, corals, etc. to improve our understanding of the interglacial climate. The project has connected us with strong earth system modelling groups in Europe. Also the ERC Advanced Investigators Grant WATERundertheICE aiming at using ice sheet models, ice cores, and radio echo sounding data to investigate the influence of water under the ice on ice flow and ice streams has expanded our ice sheet modelling capacity.

We are ready to take the next leap into novel and high-risk research. The programme will be described in the following sections.

Concepts

Before the science plan is presented, some concepts will be presented. We will use these concepts in the planning of our research program.

Follow the path that leads to excellence and state-of-the-art research. Our research group is characterized by a unique combination of ice drilling capacity, innovative ice core measurements (of which many are carried out in the field) and modelling capacity. Moving on to new and high-risk goals we believe it is important to build on this.

Our excellence is the interaction between ice core experimentalists and modellers. We plan to focus more on modelling. The research program is built on thematic research to ensure a strong interaction between experimentalists and modellers throughout our program.

Ice core measurements based on science-driven hypotheses. There will be a program for new measuring techniques, but the programs will be driven by scientific hypotheses and they will focus on proxies that can be used to constrain and validate climate and ice sheet model results.

Use the networks. We have a very extensive and strong network of additional projects. The research program presented here is formed to take advantage of this embedment and the resources applied for from DNRF are designated to advance novel and high-risk research with no overlap with the existing funding.

To involve young researchers and ensure a career path. A significant part of the budget will be allocated to young PhDs and postdocs. We will strive to support careers paths for young researchers as postdocs abroad, via career grants from ERC and the Danish Council for Independent Research, or in permanent positions.

Ensure the research is used for future climate political planning. Publications will be planned so they will be available for the United Nations Intergovernmental Panel for Climate Changes (IPCC) with deadline for AR5 for submitted papers July 31st 2012 (in press or published by March 15th 2013) and for the following AR6 expected five years later.

Key objectives

The key objectives of the program can be succinctly summarized by the following questions / mission statements:

- ***What internal and/or external processes govern the warm Eemian and Holocene climates?***
- ***Can we model the past evolution of the Greenland ice sheet and can the reconstruction of the Eemian size of the Greenland ice sheet teach us about the expected sea level rise in the future?***
- ***Can we understand the dynamics of abrupt climate change including the north-south coupling through the bipolar seesaw and is the bipolar seesaw also active in the warm climate periods?***
- ***What can the past tell us about the risk for abrupt climate changes/threats in the future?***

The team

The team consists of highly recognized researchers that, except for a few, will work full time in the centre. They represent an international group brought together because of their track record and expertise for accomplishing the goals of the centre.

Leader of the team

Dorthe Dahl-Jensen (DDJ, 52 yrs) has been a professor at the Ice and Climate group at NBI since 2002. She has a strong track record in research on the deep ice cores. Her major successes include development of models of past climate from ice core and bore hole data and relating them to the history of the Greenland Ice Sheet and its mass balance and evolution. She is internationally recognized for her work and has been a leader of national and international programs. She has received several prizes, including the Villum-Kann Rasmussen's Annual Grant for Scientific and Technical Research, the VEGA medal, the Amalienborg Prize and Ridderkorset. She is lead author of the Arctic Council's report on the state of the Arctic cryosphere presented at the COP15 meeting in Copenhagen, December 2009, with the final version to be presented in October 2010. She leads the international NEEM project and received an ERC Advanced Investigators Grant in 2009.

The team

J.P. Steffensen (JPS, associate professor at NBI, 53 yrs) was principal investigator on the Carlsberg Foundation-funded "Copenhagen Ice Core Dating Initiative" that closed at the end of 2006. He has received several prizes for excellent outreach, is ice curator and logistical responsible for NEEM. **Thomas Blunier** (TB, professor at NBI, 45 yrs) is an expert on measurements of concentration and isotopes of gases trapped in ice cores. He has built the gas lab at the Centre for Ice and Climate and has been strongly involved in the EPICA and NEEM programs. **Peter Ditlevsen** (PD, associate professor at NBI, 49 years) has developed new statistical tools to analyze and understand palaeoclimate time series and the mechanisms for tipping points and non-linear climate dynamics. **Christine Hvidberg** (CH, associate professor at NBI, 45 years) leads the activities in ice sheet and mass balance modelling. She is our member in the NBI teaching committee and strengthens the climate curriculum development. **Sune Olander Rasmussen** (SOR, 36 years) is 67% centre coordinator and 33% postdoc in the current centre and has strongly contributed with stratigraphic research and development of time scales. **Trevor Popp** (TP, 36 years) has a mixed position as coordinator of the lab activities, deep drilling and postdoc, and has focused his research on online laser stable water isotope measurements and abrupt climate changes. We have a group of younger researchers that have shown excellence during the first centre period that we would benefit by keeping in the centre team: **Anders M. Svensson** (AMS, 41 yrs**)** has an excellent track record in analysis and interpretation of dust and chemical impurities of the ice. He has concentrated on the stratigraphic dating of the last glacial cycle by means of visual stratigraphy and chemical impurity profiles from the NGRIP ice core. **Bo Vinther** (BV, 32 years) has together with Sigfus Johnsen (emeritus, 70 years) built the new stable water isotope lab and has been very innovative in combining data records from the Greenland ice cores together with Henrik Clausen (emeritus, 74 years) to understand the evolution of the Greenland Ice Sheet during the Holocene period**. Aslak Grindsted** (AG, 36 years) was headhunted from Finland and joined the ice sheet modelling group. He has published a series of papers on the expected sea level rise in the future. **Theo Jenk** (TJ, 33 years) has been instrumental in building the gas experiments to measure CO_2 in the Greenland ice cores. His expertise is needed to continue this line of experiments. **Peter Langen** (PL, 32 years) has developed and used GCM models and has a flair for creating collaborations in the field between observations and models. **Paul Vallelonga** (PV, 33 years) has been headhunted from Australia and leads the development of the high resolution CFA equipment. Before the next centre period starts we will have two positions as associate professors within the research areas of the Centre for Ice and Climate. We expect the six above-mentioned young researchers to be candidates for these positions, and budget in the centre for an additional three senior research positions for 3 years each for these younger researchers, who will also apply for the Young Investigators Starting Grant at Lundbeck, Villum Kann and ERC. To further strengthen our modelling efforts, we have two senior researchers working part-time at the centre: **Eigil Kaas** (professor at NBI, 20% at the centre), who is an expert in atmospheric modelling. To strengthen the earth system modelling in collaboration with NBI, we will have a strong collaboration with a future physical oceanography team consisting of a professor, an associate professor and a postdoc. We have budgeted for 2 years of salary for the professor from the centre and expect a starting date close to when the second centre period starts. The position is under evaluation and we expect the position to be manned before the second center period starts.

The gold of the team (the postdoc and PhD group)

A very central part of the centre will be the growth layer: The next generation of researchers. The centre expects to host 8-10 postdoctoral and 20 PhD positions. These positions will be internationally announced to recruit the best qualified candidates. The international reputation of the team and the importance of the planned activities will provide the basis to attract the world's best candidates. A significant part of the proposed budget is for young researchers, and we also expect to attract additional funds to support their work. We will use co-funding of the PhD positions through collaboration with national institutions like DMI (Danish Meteorological Institute), GEUS (The Geological Survey of Greenland and Denmark), DNSC (Danish National Space Center), several of the DNRF Centres of Excellence, with our international partners, and through European Marie Curie programs like NICE (Network for Ice Sheet and Climate Evolution) and INTRAMIF. Finally, we hope to co-fund PhD and postdocs within the framework of our collaboration with the company Picarro (California, US), the US National Science Foundation as well as any other international opportunities that arise.

Teaching the next generation

It is a goal for the Centre for Ice and Climate to become a focal point for climate teaching and education at the University of Copenhagen. We find it crucial to engage and motivate students to join the ice and climate studies. The entire scientific staff at the centre will participate in the educational program by teaching undergraduate, graduate, and PhD courses, supervising Masters and PhD students, and in the teaching boards at the institute. We will further be arranging journal clubs, seminars and workshops with participation of students, and provide field work and laboratory experience also using the Creative Playground for new developments.

At the Centre for Ice and Climate, new experimental techniques have already paved the way for many bachelor projects. An early-stage involvement is an active way of selecting the best students and we strive to enhance this by offering relevant student jobs to our students. In the larger measurement campaigns and field projects like NEEM, we involve students directly in the work. Because many aspects of climate have a direct impact on the society, climate studies have a very broad appeal. It is our experience that the field work attracts equally many male and female students.

We actively teach, organize and sponsor international PhD schools such as the Karthaus and INTRAMIF summer schools and we develop the skills of young researchers through participation in the scientific work at the NEEM ice drilling camp. We are involved in developing the coming climate education at the University of Copenhagen and we have been involved in the first e-learning climate courses offered by the University of Copenhagen. We plan to make it more visible that the Niels Bohr Institute offers Denmark's Climate Physics School and we plan to involve more graduate students from abroad as master students at the centre. Our graduate courses attract students from geology, physics and geophysics as well as foreign Erasmus students.

National and International networks to enhance the program

During the first centre period strong networks have been built through the NEEM project and several other national, European and American programs (appendix 3). We plan to maintain and develop these networks and the program suggested for the second centre period has carefully embedded the programs still active in 2012-2017 around the centre activities to avoid overlap and to enhance the outcome. For the novel initiatives we have formed new partnerships.

Biology. To investigate the evolution of the biodiversity over abrupt climate changes we have formed collaboration with the DNRF Centre for Macroecology, Evolution and Climate and DG Centre for GeoGenetics where a lead expertise is found. We will share PhDs between the centres to develop the interdisciplinary field. The basal material found at the NEEM drill site will lead to a strong NEEM collaboration with biology groups from the 14 nations involved in NEEM to study the biological components of this material.

Laser based optical detection instruments. To maintain the lead on new ice core detection methods with ultra high spatial resolution, we collaborate with the leading US company Picarro. Future collaboration will include expansion of the laser cavity ring down method to new trace gas isotopes and refinement of the resolution and reducing sample size. We propose to have joint PhDs and a strong guest program.

INFRASTRUCTURE for Ice Sheet Modelling. There is a need to advance the complexity of ice sheet models and their interaction with the atmosphere and ocean. An application has been placed in relation to the call for Infrastructures in Denmark and the first meeting between European modellers was held in Kuala Lumpur at the IPCC sea level meeting to prepare an ESFRI application.

Earth system modelling. A strong collaboration with Hans Renssen (Vrije Universiteit Amsterdam) and Bette Otto-Bliesner (NCAR) has been initiated to link to big atmosphere and earth system modelling groups to allow us to follow our ice core proxy focus modelling path (appendix 6).

Evolution of drill equipment and new ice cores. The NEEM deep drilling has been a major undertaking for our research group. While it is vital to keep the lead on development of deep drills and ice core drilling, we will need a few 'peaceful' years with less logistics and more science. Currently we partner two ice core drilling projects in Antarctica: the Roosevelt Island drilling in collaboration with University of Wellington, University of Washington and Oregon University, and the Aurora Basin drilling in collaboration with the University of Hobart. The logistics of these projects will be undertaken by our New Zealand and Australian partners.

Stronger guest program. The new (and coming) collaborations will be followed with a guest program especially focused on inviting partners for longer stays in Copenhagen.

Progress beyond the state-of-the-art

The Centre for Ice and Climate program integrates researchers working on palaeoclimate data gathering, analysis and modelling and is designed to move science beyond the state-of-the-art in areas of research of high policy relevance (Grindsted, 2009; Dahl-Jensen, 2009).

Understanding the interglacial climate. The United Nations Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) from 2007 delivered the most authoritative assessment of climate change yet undertaken and thus summarizes the present state-of-the-art. The chapter on palaeoclimate data and modelling compiles the present knowledge on past climate variability, past responses to climate forcing factors, and knowledge about the sensitivity of the climate system under boundary conditions different from the modern. The IPCC AR4 chapter "Palaeoclimate" also identified serious gaps in knowledge, which have been an inspiration for the foci of this program:

> *Page 463 (6.5.1.6 Are there long-term modes of climate variability identified during the Holocene that could be involved in the observed current warming?): "The current lack of consistency between various data sets makes it difficult, based on current knowledge, to attribute the millennial time scale large-scale climate variations to external forcings (solar activity, episodes of intense volcanism) or to variability internal to the climate system."*

The research program presented here is based on data from dated and very highly resolved ice cores. A broad range of data provides a comprehensive history of climate and documents the full dynamics of the coupled atmosphere-ocean-ice system. We will attempt to fill the gaps in lacking climatic understanding not just in the present interglacial, the Holocene, but also the previous interglacial, the Eemian. The program related to expanding the Greenland ice core time scale further back in time and to bring the Antarctic ice cores like EDC (EPICA Members, 2006) and the Dome Fuji ice cores (Watanabe, 2003) onto the same timescale will provide a unique dataset. The program will provide innovative data-model intercomparisons to test both state-of-the-art intermediate complexity earth system models (EMICs) and comprehensive climate models (IPCC AR5 class earth system models - ESMs) against the observational evidence.

Beyond the known. We will attempt to measure new parameters from the ice cores with the objective to be able to drive and develop models that will further our understanding of the climate and climate changes. The novel techniques we will attempt include the atmospheric component H_2, noble gases, the stable water isotope ^{17}O, black carbon, and biological material in the ice and at the base, to name a few. Measurement technology is moving fast toward optical methods. We are on top of this development and we attempt to expand the range of isotopes to be measured and to bring down the sample size. New methods involve a high-risk component, but addition of these data to the current range of proxies will in particular enhance the proxies' potential for understanding the biogeochemical processes.

Use of models to trace proxies directly. In our selection of ice sheet models, climate models and earth system models we will aim for model developments that allow us to trace the ice core proxies directly. It is our hope that in particular the expansion of research into ocean modelling will improve our knowledge on abrupt climate changes through a deeper understanding of the proxies.

Work packages

1. The evolution of the Greenland ice sheet

Improved understanding of the evolution of the large ice sheets in a warming climate is vital for our ability to predict the future sea level rise and also to predict the rate of change. The Greenland ice sheet (GIS) has waxed and waned in size during the previous glacial and interglacial period (Tarasov, 2003; Lhomme, 2005) and is believed to have covered Greenland for more than 1.5 million years (Maslin, 1998). We will focus on the evolution of the Greenland ice sheet during the last 150,000 years, thereby including the glacial termination before and the inception of the Eemian. We will use ice flow models and inverse methods to constrain key parameters controlling ice sheet flow and evolution, and to determine the present state of the Greenland ice sheet to be used as a starting point for predicting its future evolution. We will supplement the modelling with investigations of basal biological material especially at the NEEM drill site in Greenland to determine the fauna that covered the area before the site was ice free and the age of the ice and the biological material.

Key Questions:

- ***What was the contribution of the Greenland ice sheet to past sea-level change?***
- ***What were the relative roles of the generally warmer climate and the strongly increased local summer insolation for the size and geometry of the GIS during the Eemian?***
- ***How fast does the Greenland ice sheet respond to rapid climate change, both during the interstadials in the glacial and at the onset of the Holocene and the Eemian?***
- ***Where are the oldest stratigraphically undisturbed sections located? How old is the oldest isolated biological material?***
- ***How did basal meltwater, ice-stream flow, and interaction with the ocean water influence the evolution of the Greenland ice sheet?***

Program

1.1 Tracing stable water isotopes in ice sheet models. Greenland ice sheet models need to be developed to a degree where they faithfully reproduce the evolution of the Greenland ice sheet that can be established from the Greenland ice core records (Vinther, 2009) and geological evidence in coastal Greenland (Weidick, 1993; Funder, 1996). A set of different plausible configurations of the Greenland ice sheet will be used in isotope-enabled AGCM experiments[i] of selected time slices of past warm climate periods and the Last Glacial Maximum. The resulting spatial patterns of isotopic composition (and their temporal variability) across the ice sheet will be used to determine how isotopes were linked to ice sheet geometry in the past. We will also combine ice sheet models with a tracking tool to model directly the isotopic record at drill sites for different ice sheet geometries and scenarios of ice sheet evolution. The goal is to obtain records of ice sheet elevation changes that are consistent with the inferred climate records from ice cores, continuing the research of L'Homme (2005).

1.2 Climate forcing of ice sheets. It is not yet known which processes are most important in determining the ice sheet response to climate change in a warming climate and the contribution to future sea level changes. We will run several different ice sheet models from Last Glacial Maximum (LGM) to present day in order to investigate how they respond to climate forcing (summer insolation, mass balance, atmospheric and ocean temperature). We will use different ice sheet dynamics (shallow ice, shallow shelf, with or without basal sliding etc.) that are all accommodated in PISM and possibly alternative ice sheet models (SICOPOLIS, Elmer) to construct an ensemble of present day ice sheets. We will then use this ensemble to investigate the range of responses to future climate scenarios in order to see which processes and key parameters of the ice sheet are important for predicting the future ice sheet contribution to sea level rise.

1.3 Response time to climate changes. We will also study the ice sheet evolution from LGM to present day to determine the timing and pattern of retreat. The ice sheet retreat is not steady but occurs on shorter and longer time scales due to different processes. How would this affect its contribution to sea level over time? This is important for understanding the asymmetry between the response time of sea level contribution from ice sheets to a cooling climate and a warming climate, respectively, and to understand the response of the Greenland ice sheet to rapid climate change (Hansen, 2007; Siddall, 2009). We will use the PISM model forced

[i] All models mentioned in the work package are described in Appendix 2

with climate models and compare the present modelled response with the observed pattern of elevation change from satellites.

1.4 Parameters controlling the ice flow and evolution. The basal boundary conditions of the ice sheet have an important control on the dynamical evolution of the ice sheet, and basal meltwater is related to fast flowing ice streams and outlet glaciers. Observables such as surface topography, the surface velocity field and the internal radar layer structure contain information on the basal conditions. The internal layer structure shows the effect over time of accumulation patterns, flow and basal melting on the evolution of the ice sheet. We will link the layers to ice core records, and develop Monte-Carlo inverse methods and simple ice flow models to infer past accumulation rates, ice thickness history and basal heat flux and melt rates from the internal layers in the interior regions of the Greenland ice sheet. This work is done in collaboration with researchers working on the WATERundertheICE project. The present observed surface topography and velocities of the ice sheet contains further information on the basal driving stress and viscosity of the ice (Bueler, submitted), and we will use complex flow models to characterize the present state of the ice sheet and determine the key parameters controlling the present conditions. This is critical to predicting future changes. We will use PISM-type ice sheet models to reproduce present ice sheet configurations for sets of model parameters and compare with present topography, internal layers, and surface velocities.. The deep ice cores are located near the main ice divide, and higher-order models may be needed to infer the basal information at these sites and link the large scale flow pattern to the ice core records. We will investigate this by specially developed models (collaboration with E.D.Waddington) or by applying higher order models, as Elmer..

1.5 Constraining the ice sheet volume and extent during the Eemian. Model simulations have suggested that South-Greenland was ice-free during the Eemian (Otto-Bliesner, 2006), but ice cores from all deep Greenland ice cores contain Eemian ice (Johnsen, 1992; Alley, 2010) thus supporting Eemian ice cover at these sites. We will use present observations, palaeoclimate data and ice and climate models to constrain key parameters and advance current estimates of the Greenland ice sheet evolution during the Eemian (Robinson, 2010). We will run an ice sheet model forced with input from climate models to constrain the ice sheet volume and extent during the Eemian, so it is consistent with the ice core data. We will create ice sheet configurations during the Eemian for perturbations of surface mass balance, basal parameters and calving discharge parameters using the PISM model forced with climate from an AGCM. We will specifically test the effect of ice in South Greenland by investigating the effect of a southern dome in a climate model, and check whether the resulting pattern of precipitation and isotopic composition of the snow is consistent with ice core records and the ice sheet model scenario. We will compare with all available data to constrain key parameters controlling the Eemian ice sheet: climate records from ice cores, measurements of total gas content in ice cores, and geological and biological data to constrain ice sheet margins. We will investigate how important the summer insolation is in controlling the ice sheet size as compared to the topographically forced precipitation pattern and other key parameters.

1.6 Constraining the elevations by total gas content. Measurement of the gas content gives information about elevation changes of the Greenland ice sheet. The signal is modulated by changes in the firn structure potentially linked to insolation changes. We intend to re-measure samples from our archive to obtain an overview of mass balance changes of the Greenland ice sheet (Raynaud, 2007; Raynaud, 1997; Vinther, 2009).

1.7 Detecting the age of the Greenland Ice Sheet. The ice close to bedrock contains basal material in the form of silt, stones and biological material. This ice cannot be dated by normal stratigraphic ice core dating methods as the stratigraphy has been disturbed by ice flow. In Dye-3 basal ice two physical (^{10}Be/^{36}Cl ratios and optical stimulated luminescence) and two biological (amino acid racemisation and branch length of the invertebrate COI sequences) dating methods were successfully applied to constrain the age of both ice and DNA to be older than 450,000 years (Willerslev, 2007). We will work on dating basal material in the NEEM ice core in combination with studies of ancient DNA with the same four methods, and we will include a new Uranium-based method (Aciego, 2009). To improve the dating by optically stimulated luminescence, we will extract basal material at NEEM in 2011 in total darkness. We expect the five dating methods to give age brackets that constrain the possible age of the basal ice. The different dating methods are not likely to give the same age, as $^{10}Be/^{36}Cl$ ratios date the ice itself, amino acid racemisation and COI sequences date the biological material from the base, stimulated luminescence dates last exposure of minerals to sunlight, and the Uranium method dates the time when basal material was incorporated in ice. However, the time when ice permanently covered the site will be constrained by being older than the dates of the ice itself and material incorporation and younger than the biological material. Ancient DNA will also provide a picture of the biotope that existed in Greenland before it was ice covered, which will be used to reconstruct past temperatures and humidity.

1.8 Modelling the build-up of the Greenland ice sheet. We will investigate scenarios for the original formation and build-up of the Greenland ice sheet during Pliocene. We will simulate the ice sheet evolution for different scenarios of climate and geological history (Solgaard, submitted) using the PISM ice flow model and transient surface mass balance models. We will identify regions of very old ice and potential zones with isolated biological material for the different scenarios. We will use particle tracking to map large-scale folding (primarily due to ice divide migration) (Jacobson, 2005), and identify the regions with an undisturbed stratigraphy.

1.9 Modelling the flow of ice found in the ice core. We intend to study ice flow in the deep interior of the Greenland ice sheet from detailed fabric measurements across climatic and disturbed abrupt transitions in several of the deep Greenland ice cores. In combination with gas studies this may develop a fast method to determine which transitions are climatic and which are flow induced. Using radar profiles, we may be able to map folded/disturbed zones in the deep ice over large areas in Greenland (Drews, 2009).

Milestones

1.1.1	Use ice sheet configurations as boundary conditions in isotope-enabled AGCM experiments	Year 4
1.1.2	Model the isotopic signal of the Greenland drill sites for different scenarios of the ice sheet evolution.	Year 5
1.1.3	Determine spatial patterns of precipitation isotopic composition associated with distinct ice sheet geometries	Year 4
1.2.1	Drive dynamic ice sheet models with a wide range of boundary conditions and through a range of spin-ups to investigate the role of mass balance parameters on the evolution of the Greenland ice sheet and to yield a suite of possible Greenland ice sheet configuration.	Year 3
1.3.1	Determine response time and contribution to sea level change from the Greenland ice sheet during the last deglaciation.	Year 4
1.4.1	Use ice flow models, and different inverse methods to determine the flow pattern and map basal boundary conditions (heat flux, basal drag, basal sliding) of the Greenland ice sheet by interpreting internal radar data, surface topography data, and ice core data	Year 3
1.5.1	Using ice sheet models and proxies to determine the volume and extent of the Greenland ice sheet during the Eemian	Year 5
1.6.1	Obtain total gas content measurements on all suitable Eemian sections in Greenland ice cores (identical to 3.3.2)	Year 3
1.7.1	Reconstruct humidity and temperature from biological remains	Year 5
1.7.2	Date the basal biological material and the basal ice with DNA and cosmogenic isotopes	Year 3
1.7.3	Use ice flow models to map regions with isolated ancient biological material under the ice	Year 5
1.8.1	Investigate the formation of the Greenland ice sheet and identify possible regions of very old ice.	Year 5
1.9.1	Model the flow leading to the Greenland drill sites	Year 1

2. Abrupt changes

We observe very abrupt changes from the cold glacial climate to the warm interglacial climate in the Greenland ice cores (Dansgaard, 1993; Steffensen, 2008). In addition we find 25 interstadials (Dansgaard-Oeschger events) during the last glacial period (Johnsen, 1992; NGRIP Members, 2004). All the transitions are characterized by very abrupt warmings and the order of the events happening at the abrupt changes seems to be identical at the onset of the interglacials and at the DO events (Steffensen, 2008; Wolff, 2009). The Greenland ice cores are annually resolved and include a broad span of parameters that allow a very detailed study of what causes these very abrupt changes to occur (Steffensen, 2008). To interpret the events, earth system models including ice sheet, atmosphere and ocean models must be used. The main objective is to determine the set of leading-role processes responsible for the onset of the Eemian and the Holocene.

A refined, physically consistent model explaining abrupt climate change first requires the identification of the details emerging among unique rapid transitions (Steffensen, 2008). As more Greenland ice proxies and other data become available, the emerging picture shows that one common mechanism or sequence of events may not explain all of the details and processes of rapid climate transitions. Higher resolution time series of proxy data from multiple ice cores are a necessary first step to define the anatomy of abrupt transitions and to provide insight into physical processes responsible for them. It is these detailed time series that guide the construction of testable hypotheses for conceptual and numerical models increasing the understanding of the detailed processes responsible for initiating abrupt climate changes and the understanding of their geographical propagation and gradients (Flückiger, 2008; Denton, 2010).

Key Questions

- ***How important is the timing and phase of the background variability of the ocean meridional overturning circulation (bi-polar seesaw)?***
- ***What is the potential for low- and mid-latitude atmospheric dynamics to trigger or amplify the onsets?***
- ***When and how do biological and carbon-cycle processes change and what does this timing mean for their role as triggers vs. amplifiers?***
- ***Are the timing and processes of the abrupt changes identical?***

Program

2.1 The Terminations. The termination of the glacial and the onset of the present interglacial happened after a period of large climate variations, namely the Bølling, Allerød and Younger Dryas periods (Cheng, 2009; Rasmussen, 2006). These climate changes were different in the Southern Hemisphere which is characterized with the so-called “cold reversal” (Blunier, 2001; EPICA Members, 2006; Barker, 2009). Likewise, the abrupt transitions associated with DO-events in the Northern Hemisphere were preceded by a gradual warming in the Southern Hemisphere (Blunier, 1998; EPICA Members, 2006). This observation can be described by the simple phenomenological bi-polar seesaw model (Stocker, 2003). We want to substantiate this model by extending it to include the ocean currents and not just the southern ocean as a heat reservoir (Barker, 2009; Fischer, 2010). With the new isotope and gas measurements reaching further back in time becoming available, we aim for a deeper understanding of this climatic mechanism for abrupt climate changes (Ditlevsen, in press). At present no global climate model is capable of simulating the range of climate variations we observe in the palaeoclimate record (Cane, 2006). We thus rely on constructing simpler models capturing the essential dynamics and bridging the gap from the purely data-driven empirical models to the full earth system models (Flückiger, 2008). We believe that our team is capable of contributing substantially in bridging that gap.

2.2 The role of the low latitudes. What is the role of tropical atmospheric re-organizations in explaining the abruptness of D-O events and glacial terminations? We are inspired by the first interpretations of the termination into our present glacial period. (Steffensen, 2008; Denton, 2010). A number of specifically targeted climate model simulations will be performed to investigate whether the tropical atmosphere can enhance – and feed back onto – a high northern latitude initial development in the ocean (Rodgers, 2003; Chiang, 2005; Kang, 2008). Comparison of changed precipitation patterns during idealized simulations will be compared with tropical precipitation records.

2.3 Lead and lag of CO_2, temperature and methane. The approach to gain understanding is to postulate hypotheses for what drive abrupt changes and test with models with outputs that can be compared to data. The termination of the last glacial period was very abrupt and changes were much faster than the change in the insolation (Steffensen, 2008; Masson-Delmotte, 2005). Thus the climate response to the orbital forcing is strongly non-linear (Huybers, 2008; Ganopolski, 2009). The retrieval of a high resolution record of the termination of the previous glacial period and the onset of the Eemian climate gives us a unique opportunity to examine this non-linearity in the climate system (Steffensen, 2008). The orbital forcing in the Eemian was different from the present Holocene climate (Kukla, 1981): The Northern high latitude summer insolation was about 13% higher 130 kyr ago than today (Laskar, 2004), and the Eemian climate about 3 degrees warmer (CAPE Members, 2005; Leduc, 2010). Despite of the Eemian warmth, an extensive Greenland ice sheet was present in the Eemian (Johnsen, 2007). We want to test the hypothesis that the climate “locks into” a more or less unique warm interglacial state, where the Eemian would then be a close analogue to the present and a future warming climate.

2.4 The role of atmospheric dynamics in warm and cold climates: Do atmospheric dynamics and transports equilibrate high latitude temperature anomalies more efficiently in warm (small overall temperature gradient) than in cold climates (large overall temperature gradient)? Or put differently, does the atmospheric ability to dampen a high northern latitude temperature anomaly (driven by the ocean and/or the cryosphere) depend on the overall mean climate and the related meridional background temperature gradients? It is hypothesized that the atmospheric stabilizing effect is considerably stronger in warm than in cold climates (Li, 2008) and that this effect tends to limit the amplitude and duration of warm-climate temperature excursions (NGRIP Members, 2004). Models of different complexities will be applied for different climates with very different background meridional temperature gradients: Eemian (weak gradient), Holocene (less weak gradient), LGM gradients (strongest gradient and cold globally). Simulations with climate models of different complexity will be compared with the proxy records. The modeling will partly be done in collaboration with the our collaborators.

2.5 High resolution isotopes with laser instruments. To address the hypotheses mentioned above, we propose to continue the development of laser based optical detection of greenhouse gasses (CH_4, N_2O) and water isotopes (H_2O) in ultra-high resolution. Currently developed cavity ring down technology will be refined in our laboratories and in collaboration with the leading company Picarro. This will enable us to decide about leads and lags in the climate system i.e. feedback mechanisms between climate and trace gas concentrations (Ganopolski, 2009). As the measurement system becomes simpler with the application of optical methods, we expect to get data of higher quality which allows for more extended interpretation than what is possible today.

2.6 Looking for new proxies: H_2 is a central component of atmospheric chemistry linked to the methane cycle and biomass burning (Hammer, 2009). A palaeorecord of H_2 may give us fundamental insight into changes in the atmosphere in the past under climatic conditions very different from today's. Those results, on the other hand, can be used to predict changes in the future. At this time we do not know if H_2 is a component which is preserved in the bubbles of polar ice sheets. A firn air study we did in 2008 hints that H_2 is not altered in the first 70 m of the firn column. As long as no chemical processes are involved, the atmospheric record is preserved.

2.7 Combining ice core measurements of DNA with biodiversity models. As a new initiative we propose to include detection of biology and biological processes in our online high resolution CFA system. We would like to explore new methods based on fast DNA sequencing (Eid, 2009; Willerslev 2007), flow cytometry of stained samples (Meimaridou, 2010), determination of black carbon (McConnell, 2007) and other combustion products (Simoneit, 2002; Gabrieli, 2010) and total inorganic and organic carbon measurements (Federer, 2008). In collaboration with Centre for Macroecology, Evolution and Climate, we will collaborate on combining the climate models with the best models on marcoecology to reconstruct natural null models of biodiversity change over time. In addition we will combine models developed to study co-evolutionary processes of species interactions with macroecological statistical approaches, allowing us to evaluate the robustness of the large scale models when natural adaptations that track environmental change are included.

2.8 Using isotopes to constrain the temperature changes. To determine the temperature changes associated with the abrupt changes, we propose to use the dual isotope ratio (δD and $\delta^{18}O$) measurements to estimate relative diffusion and thereby reconstruct past temperature changes (Johnsen, 2000; Johnsen, 2006). For older times, this signal is lost. However, a precise temperature signal for rapid temperature changes is imprinted in the gas composition occluded in the ice (Capron, 2010a). We will exploit the effect of thermal fractionation between $\delta^{15}N$ and $\delta^{40}Ar$ (Severinghaus, 1998). We will start collaboration with Amaelle Landais from CEA on this topic as part of the NEEM collaboration. Additional constraints will be gained from noble gas measurements to be made at the centre.

2.9 Stratigraphy and dating. The carbon cycle change at the end of the last ice age and the atmospheric CO_2 increase are not yet completely understood. Especially the atmospheric ^{14}C changes can hardly be modelled quantitatively. There is a good chance that an improved ^{10}Be-based cosmic ray record with improved dating and a more regional coverage of ^{10}Be measurements (not only in one ice core) will become available through other programs like the EU FP7 Past4Future. Such records are indispensable for a quantitative discussion of ^{14}C-relevant changes in the carbon cycle. We will work with our partners on improving the geographical and temporal coverage of ^{10}Be measurements from ice cores with the objective of strengthening ^{10}Be-based dating, synchronization and cosmic ray reconstructions.

Milestones

2.1.1	Construction of a simple data-driven model connecting the climate records from the two hemispheres	Year 2
2.2.1	Using different reconstructions and model fields as the background glacial climate, high-latitude northern hemisphere temperature anomalies will be introduced in atmosphere GCM experiments where the low-latitude surface temperatures are fixed and interactive, respectively	Year 2
2.2.2	The role of low-latitude temperature and circulation changes in modifying and feeding back on the high-latitude energy budget will be assessed from the difference between the two sets of experiments	Year 4
2.3.1	Measure the methane response to rapid climate change in high resolution	Year 2
2.3.2	Determine potential methane source changes over fast climate changes	Year 5
2.3.3	Find the isotope response in the CO_2 signal of fast climate change	Year 5
2.5.1	High resolution N_2O measurements over the latest, and possibly also the penultimate, glacial termination	Year 2
2.6.1	Perform a pilot study measuring H_2 in a shallow firn core and later, if feasible, in deeper ice	Year 3
2.7.1	Develop new techniques for biological studies and implement them into high resolution CFA system	Year 2
2.7.2	Collection of biological data and integration with biodiversity models. Evaluation of species variations during the Eemian and assessment of existing carbon budget models	Year 5
2.8.1	Measure dual stable isotope samples from the NEEM core covering the past 30,000 years	Year 2
2.8.2	Establish past Greenland temperature conditions using the dual stable isotope samples	Year 3
2.8.3	Implement noble gas measurements at the centre.	Year 3

3. The Eemian – the climate of a warm world

The last interglacial, the Eemian, 130,000 years to 115,000 years before present, was warmer than our present interglacial (CAPE Members, 2006; Leduc, 2010). The objective of the program is to identify processes that can be used as an analogue for our present warming climate (Annan, 2009) and also to identify external forcings that cause the variations. In addition the Holocene Climatic Optimum 8.5 kyr before present was 2°C warmer than the pre-industrial climate in Greenland (Dahl-Jensen, 1998; Vinther, 2009). The newly drilled NEEM ice core contains ice from both climate periods and we thus have a very special opportunity to venture into studies that have not been possible before. The studies will focus on identifying the ice core observations and the models that can be combined to advance our knowledge on the climate of the Eemian including natural variability and risk of abrupt climate changes (Blanchon, 2009). The goal is to provide a clearer understanding of the climate and biogeochemical states (ice, vegetation, biology, dust, carbon cycle) of the Earth during the Eemian and the Climatic Optimum.

Key questions

- ***What is the phasing between the two hemispheres' natural variability (bipolar seesaw) and what determines the low-to-high latitude temperature gradient?***
- ***What influence do the changes in seasonality accompanying the changed orbital parameters have on the global energy budget in comparison to the present interglacial?***
- ***What is the isotopic imprint and quantitative contribution of terrestrial and oceanic processes that control the dynamics of the carbon cycle over interglacials?***
- ***Why was the CH_4 trend different during the last and the present interglacial: Can we successfully explain the Holocene trend without invoking an anthropogenic factor? How important were high latitude sources from thawing permafrost at the end of glacial-interglacial transitions and how important are there sources in the future?***

Program

3.1 Stability of the Eemian climate period. While the Holocene has displayed a remarkably stable climate (Vinther, 2009), the Greenland records suggest that the Eemian may have been significantly less stable (Dansgaard, 1993). It is thus of prime importance to assess the natural variability of Eemian climate and the processes that stabilize or destabilize it relative to the Holocene. Existing and new coupled atmosphere-ocean GCM experiments under Eemian boundary conditions (with specified, non-interactive ice sheets) during select slices of orbital settings will be analyzed (Otto-Bliesner, 2006). Apart from giving us an Eemian climate and variability to compare with ice core proxies (and other proxies), these runs will provide the backdrop for our further process studies in terms of surface temperatures and sea ice cover and their modes of variability.

3.2 Testing hypotheses to gain understanding of interglacial climate. How can the mid-Holocene seem (from the proxies) to have been about 1K warmer in global average than the recent pre-industrial when the global average insolation was relatively unchanged (Laskar, 2004) and the CO_2 levels were lower (260 ppm compared to 280 ppm for pre-industrial)(Braconnot, 2007a; 2007b; Monnin, 2004)? And how does this influence our understanding of the Eemian warmth? With the LOVECLIM (an intermediate complexity model) we can test a set of different hypotheses (Renssen, 2009; Polyak, 2010): 1) The low-latitude (or high-latitude) vegetation was such as to provide a lower planetary albedo. 2) The Arctic Ocean was partially ice free, leading to a lower planetary albedo. 3) The low-latitude decrease in insolation was not communicated poleward to yield globally averaged offsets of the increased high-latitude temperatures.

3.3 Reconstruction of Eemian temperatures. On the experimental side, we need measurements of total gas content in the ice cores to disentangle the Eemian climatic signal from the effects of elevation change (Raynaud, 1997; Vinther, 2009). Eemian temperatures can then be established from $\delta^{18}O$ measurements if the source areas for precipitation are similar to what is seen during the Holocene; this should be investigated by measuring deuterium excess (Johnsen, 1989; Masson-Delmotte, 2005).

3.4 Using CO_2 – including isotopes – to understand the carbon cycle dynamics. Effort will be focused on reconstruction of carbon and $\delta^{13}C$ dynamics during the present and last interglacials, as well as $\Delta^{14}C$ during the early Holocene and last termination. Reconstructions of carbon isotope abundance in atmospheric CO_2 trapped in ice cores, as well as in carbonate shells stored on the ocean floor, allow the reconstruction of changes in carbon storage on land and in the ocean. These data will be used for quantification of biogeochemical processes on the global and large-regional scales. Measuring CO_2 in northern hemisphere ice cores is at an early stage. In case of successful measurements, the CO_2 and $\delta^{13}CO_2$ records from high-accumulation Greenland ice cores will be used to better constrain timing of carbon cycle dynamics.

3.5 Including earth system models. Earth Models of Intermediate Complexity (EMICs) that include carbon isotopes to simulate the carbon cycle dynamics will be implemented through collaboration with our partners. The model output will then be compared with the data, and evaluated against new estimates of the $\delta^{13}C$ distribution in the pre-Suess-effect ocean. The Southern Ocean is a key region in the palaeo-carbon-cycle dynamics and little constrained by data. We are interested in model output of marine productivity data from earth system models (ESMs) and EMICs. Further, we would like to test analyses of the ESM outputs on changes in terrestrial carbon storage during the interglacials against the atmospheric $\delta^{13}CO_2$ in our ice core records. In connection with the reconstruction of biomass before the build-up of the Greenland ice sheet, we are interested in getting vegetation cover simulations from EMICs to be compared to available pollen archives and with analyses from ESM models.[ii]

3.6 Dating and matching ice cores using cosmogenic isotopes. In order to perform the above-mentioned ice-core-data-driven modelling, the ice cores from both North and South need to be dated and matched. We expect to use annually resolved records from part of, or all of, the MIS5e/the Eemian period from Greenland and Antarctic ice mainly based on high resolution CFA and impurity measurements. The North - South link can be improved through cosmogenic isotopes (^{10}Be) by identification of the 95 ka Blake geomagnetic excursion in Greenland and Antarctica. The Blake event is similar to the 41 ka Laschamp event, but it may be less well defined (Guyodo, 1999). A North-South gas synchronization has already been made in this period (Capron, 2010b), but ^{10}Be is independent and precision is potentially better than uncertainties of delta-gas ages (Raisbeck, 2007). The Blake event will also help linking ice cores to other palaeoclimate archives, such as marine records (Christl, 2003). We will work with our partners on improving the geographical and temporal coverage of ^{10}Be measurements from ice cores with the objective of strengthening ^{10}Be-based dating, synchronization and cosmic ray reconstructions.

3.7 Extending the annually matched time scales. The Greenland Ice Core Chronology 2005, GICC05, (Rasmussen, 2006; Vinther, 2006; Andersen, 2006; Svensson, 2006, 2008) will be extended to include all the deep Greenland ice cores based on the existing annual layer counting back to 60,000 years BP (Svensson, 2008) and on modelled time scales beyond this. Furthermore, GICC05 will be extended to include the Antarctic ice cores with annual resolution such as the EPICA Dronning Maud Land, EDML (EPICA Members, 2006), the coming WAIS ice core, and the Japanese Dome Fuji ice core.

Milestones[iii]

3.1.1	Set up and continue existing time slice experiments in collaboration with Bette Otto-Bliesner and the Palaeoclimate Group in the Climate and Global Dynamics Division at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado	Year 2
3.1.2	Analyze the results in terms of variability, phasing, meridional temperature gradients, seasonality, and energy budgets	Year 5

[ii] The University of Copenhagen is currently building up a significant group in oceanography with a strong focus on earth system modelling. The Centre for Ice and Climate has supported this activity strongly and the outcome will be 2

[iii] Milestones for the coming oceanographic team will follow because the future team needs to be involved in the formulation of these milestones. permanent oceanography positions at NBI. The precise program and explicit model will depend on the team. We have headhunted potential candidates to apply for the professorship that is under evaluation (appendix 5).

3.2.1	Make detailed design of the experiments in terms of preparation of boundary condition and initial files in collaboration with Hans Renssen of the Dept. of Earth Sciences, Vrije Universiteit Amsterdam	Year 1
3.2.2	Perform and post-process the experiments. Analyse the results	Year 3
3.3.1	Establish capability to measure total gas content established (link to 1.5.1)	Year 1
3.3.2	Obtain total gas content measurements on all suitable Eemian sections in Greenland ice cores	Year 3
3.4.1	Establish CO_2 and $\delta^{13}C$ measurements from ice cores	Year 1
3.4.2	If possible, improve understanding of carbon cycle dynamics based on CO_2 and $\delta^{13}C$ of CO_2 measurements from Greenland ice cores	Year 5
3.7.1	Measure the Eemian section of the NEEM ice core in highest resolution for CH_4	Year 1
3.7.2	Measure ice core parameters in the Eemian ice from Greenland and Antarctica in annual resolution and date the ice cores where it is possible.	Year 5
3.7.3	Complete measurements of δD and $\delta^{18}O$ on Eemian records from all Greenland ice cores	Year 2

4. What can the past tell on the future climate?

The understanding of processes achieved through the studies of the past in the previous three work packages will be used to improve the quality of our predictions of the future: how do we expect the sea level rise from the Greenland ice sheet to evolve, what will the risk for abrupt changes in our future be, will we expect ocean currents or atmospheric circulation to change? How will the different cause of the warming, mainly increased greenhouse gasses, influence the climate? The results from these studies will be prepared for inclusion in the IPCC reports.

Key Questions

- ***To which degree is the Eemian an analogy for the future?***
- ***How is the insolation-driven Eemian warming different from the CO_2-driven present warming?***
- ***How much and how fast will the Greenland ice sheet contribute to sea-level rise in the future?***
- ***Which areas of the Greenland ice sheet will retreat first in a warming climate?***

Program

4.1 Eemian as an analogue to the future. The Holocene and the Eemian have markedly different boundary conditions in terms of the seasonal insolation signal (Loutre, 2004) and in this sense it is risky to use the Eemian as a direct analogy for the future. It may be, however, that the different forcing projects onto a preferred mode of response in such a manner that its expression in terms of spatial patterns resembles that resulting from a greenhouse warming (Langen, 2007). If this is the case, it is more straightforward to talk of "a warm climate state" for both periods and the use of the Eemian as an analogue is better justified. By examining the responses of the full GCM (CCSM3) and the intermediate-complexity model LOVECLIM to Eemian insolation and to greenhouse forcing, we will quantify whether the responses are as would be expected by simple local energy balances or rather like excitations of a particular mode.

4.2 Future IPCC climates of the Arctic. To model the ice sheet response to warming and gain understanding of the role of the warming ocean, IPCC reconstructions for IPCC AR4 and IPCC AR5 will need to be accessed. We will continue collaboration with DMI on running models of the Greenland ice sheet into the future for different climate scenarios (PISM and ECEarth). The biggest task here is to downscale output from the climate model so it can be used to force an ice sheet model. This involves methods of interpolating and downscaling that also take into account the underestimation of precipitation in the climate models.

4.3 Including satellite observations of the Greenland Ice Sheet. CryoSat-2 provides observations of ice sheet elevation change. We will estimate the changes in ice equivalent thickness and thereby the present contribution to sea level change by modelling changes in the firn densification. We will investigate the present ice elevation response to different past ice sheet evolution scenarios in order to determine whether there is any information on the past evolution in the present ice sheet elevation change, and to estimate the dynamic response of the interior regions to the current marginal retreat. We will collaborate with DTU-Space on the use of CryoSat data.

4.4 Observations of surface mass balance and ice discharge. The future evolution of the Greenland Ice Sheet is very important for our ability to predict the future sea level rise. It has become clear that the role of the fast flowing outlet glaciers and the melt along the margin need to be better understood before we have any possibility to improve our predictions. We will collaborate with GEUS on the use of models to translate the observations into processes needed in the 3D models to model the evolution of the ice sheet in a warmer world.

4.5 Evolution of the ice sheet in the future. As a result of achievements in the present centre period, we are able to couple AGCMs and dynamical ice sheet models offline in configurations that allow the ice sheet models to be integrated forward for many tens of thousands of years while still having the atmospheric boundary conditions change with the evolution of the ice sheet (Abe-Ouchi, 2007). The ongoing project investigates the influence on Greenland ice sheet stability of the atmospheric temperature and precipitation changes that ensue from the changing orographic and thermal forcing that accompany ice sheet changes. Going from the current choice of an AGCM with a slab ocean to a fully coupled atmosphere-ocean GCM is the ambitious next step.

4.6 Semi-empirical models to predict future sea level rise. We will develop semi-empirical models of all the important contributions to sea level rise (Grindsted, 2009; Jevrejeva, 2009, 2010; Moore, in press): thermal expansion of the ocean, ice sheet retreat, and retreat of small glaciers. We will develop semi-empirical models for the contribution from each component based on considerations of physical processes and for example empirical relations between a glacier length and response time. We will test whether they can reproduce the response from more sophisticated models and tune model parameters to observed sea level records.

4.7 Dissemination of results. Centre for Ice and Climate plans to communicate with the policy-makers on the results regarding loss of mass from the Greenland Ice Sheet and related sea level rise.

Milestones

4.1.1	Use LOVECLIM to determine the responses to insolation and CO_2 changes, respectively	Year 1
4.2.1	Insert mass-balance parameterizations in ice sheet model	Year 4
4.3.1	Interpret CryoSat-2 data and develop methods to correct surface elevation changes for changes in the densification process in order to estimate the volume changes of the Greenland ice sheet (collaboration with DMI and DTU-Space) Use the present day spin-up of the Greenland ice sheet as a starting point for modelling the future evolution of the ice sheet (collaboration with DMI)	Year 2
4.4.1	Use observations of ice discharge and surface melt to gain understanding of the processes (collaboration with GEUS)	Year 5
4.5.1	Determine a suitable succession of ice sheet decline geometries for use as boundary conditions in the GCM and run the off-line coupled GCM using the different ice sheets.	Year 3
4.5.2	Use the Greenland ice sheet models to predict future sea level rise from the Greenland ice sheet in a warming climate	Year 5
4.6.1	Refine the semi-empirical models and publish in time for IPCC AR5	Year 1

Creative Playground and Database.

We plan to continue the “playground” which was opened during the first centre period. It has facilities for experimental work and tests of new methods related to ice cores studies. It comprises both an area in the cold room and a laboratory at room temperature. Through the first centre period the playground has been equipped with general tools and equipment, and several new measurement techniques have successfully been developed. We will add computing resources for running simple models and testing model ideas to playground activities. The playground is very successful and ensures synergistic activities between all members of the centre: students, researchers, guests, partners and technical staff. It draws on the expertise from the mechanics and the electronic engineer in the centre, as well as the expertise from the experimental physicists within the group. For students with an interest in doing experimental physics, the playground will be an excellent opportunity to do bachelor- and master projects and to take full advantage of the expertise in the group. We regard this facility as an essential first step in training top scientists, and in developing strong and focused research projects. The playground will be led by Trevor Popp and a budget will be assigned to the activities.

Playground activities not only include development of instruments for the ice core measurements described in the work package s but also a continuation of the development of our ice drill and borehole logging equipment and expertise. We will be involved in ice core drilling activities (logistically supported by other research groups) and will strongly benefit by keeping the world lead in drill equipment design and drilling know-how. The new designs will be defined in coming programs, but our ideas include epoch drilling (for fast access of near-basal ice), electrical conductivity measurements in the walls of the borehole and borehole camera to observe the base of the boreholes. To ensure capacity for all Creative Playground activities and in preparation of a generation change for our mechanical engineer, Steffen Bo Hansen, a budget is allocated for 50% co-funding from the centre for a ‘senior apprentice’ and our host institution has agreed to support the other half and to continue the position as a part of the permanent staff when Steffen Bo Hansen retires.

The Centre for Ice and Climate has the world's most extensive archive of ice cores and a database of measurements from Greenland ice cores maintained by our curator Jørgen Peder Steffensen. More than 50,000 ice core sections from 30 sites are stored in the freezer. Apart of keeping track of the archive, the database also contains data from more than 45 cores and includes records of about 25 parameters in 1mm to 55 cm resolution. Time scales, including the Copenhagen-based standard GICC05, can be applied to the depth records when available. All data that are used in publications are placed on our homepage (www.iceandclimate.dk) for open access, and we wish to continue to make our data as accessible as possible for our network and for the climate community. There is a goldmine of data available and an increasing amount of our publications use combinations of data from many of the ice cores.

With the vast amount of data produced from the continuous measurements from the CFA and laser instruments, the data base needs to be expanded and restructured in order to allow efficient viewing and handling of large data sets. It is also important to be able to store raw data and comprehensive meta-data, e.g. on data processing that has been applied to produce the final data sets. The recent “climate gate” issues in connection with the records used for the IPCC AR4 report has clearly demonstrated the need for good documentation. An increasing amount of the published work within our field is based on synthesis of data from many ice cores. We would greatly benefit from new tools for easy comparison of records from different cores and time periods and integrated resampling and synchronization tools to support the development and testing of new scientific ideas. To meet these new demands and increase the usability of our outstanding data resource, we plan to develop an updated ice core database that includes these tools.

We include resources in the budget for one full time person to construct and maintain the database and also to supplement the IT support the centre receives from our host institution.

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Appendix 2: Models, we refer to in the Work packages

At the Centre for Ice and Climate we plan to employ a range of modelling tools depending on the scientific questions investigated. The applications are run on a variety of computing platforms from in-house servers to supercomputing centres.

Earth Models of Intermediate Complexity (EMICs)

The LOVECLIM is an EMIC consisting of a series of climate component models developed by different European institutions (e.g., Université Catholique de Louvain in Belgium and KNMI in the Netherlands). It is running at the centre on our in-house servers and experiments have been performed in cooperation with Hans Renssen of the Dept. of Earth Sciences, Vrije Universiteit Amsterdam.

This type of model is intermediate in complexity relative to the more complete general circulation models in the sense that the representation of physics or dynamics is simplified or more coarsely resolved. This makes them computationally inexpensive and they are typically used for questions whose answers require multi-millennium long integrations. The LOVECLIM is due to its rather complex ocean component particularly well suited for ocean-variability studies.

Atmosphere general circulation models (AGCMs)

The CAM3 (Community Atmosphere Model ver. 3) is an AGCM developed at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. It is employed by centre researchers and is running on local Copenhagen supercomputing resources at the Danish Centre for Scientific Computing and on the resources available to us through our collaborators at the Arctic Region Supercomputing Center in Fairbanks, Alaska, and the Center for High Performance Computing at Sweden's Royal Institute of Technology (KTH) in Stockholm.

This type of model is used in studies where the details of the atmospheric circulation and energetics are of the essence. They may be run either in specified-SST mode or in interaction with a simple slab ocean model.

Isotope-enabled AGCMs

The CAM3 (and other AGCMs) has been fitted with the capability to model the transports and phase change effects that determine the isotopic composition of atmospheric water vapour and precipitation. The implementation used at the centre has been developed by David Noone of the University of Colorado, Boulder. The model is running on the same platforms as the CAM3 and experiments are performed in cooperation with David Noone.

This type of model is used to study the influences that modelled atmospheric effects have on the stable water isotopes in precipitation. At the centre we are, of course, mainly interested in the composition of precipitation on the Greenland ice sheet since this can be directly compared to the corresponding quantity measured in ice cores. The representation of isotope processes requires considerable extra computational resources and this model is thus only used when the scientific question specifically depends on it.

Atmosphere-ocean GCMs (AO-GCMs)

The CCSM3 (of which the CAM3 is the atmospheric component) is a coupled atmosphere-ocean-sea ice-land surface model also developed at NCAR. It gives the most complete representation of the different climate system components and is thus also the most computationally expensive of the models. It is running on the above mentioned supercomputing platforms.

The computational cost of this type of model implies that runs are typically only a couple of hundred years long. In this application, we refer to this type of model as an earth system model, a term which may also include models with e.g. integrated vegetation, carbon cycle, and ice sheet models. The choice of such higher-complexity models employed will depend on the topics studied as well as the experience represented in the future centre team.

Large-scale thermo-mechanical ice sheet flow models

The Parallel Ice Sheet Model (PISM) is an open source thermo-mechanical ice sheet flow model developed by Ed Bueler, University of Alaska, Fairbanks. It has been selected as our main large-scale model and implemented at the centre's computers, and we have performed experiments in collaboration with Gudfinna Adalgeirsdottir from the Danish Meteorological Institute (DMI) on DMI's supercomputer. The PISM solves the stress-balance for the shallow ice approximation and the shallow shelf approximation and combines the two flow fields. The model is fast, and represents the most complex large-scale model available for modelling the ice sheet evolution over a glacial cycle. Although ice streams are not completely described, the model includes large-scale effects due to ice stream physics and basal water. We are currently modifying boundary conditions modules in collaboration with the PISM developing group.

We run PISM over a glacial cycle with climatic input provided by climate models. We collaborate with DMI on using output from EC-Earth, an earth system model based on ECMWF modelling systems. The EC-Earth model is a GCM, and model runs are performed by Shuting Yang, DMI. We also run PISM with climate forcing from the climate models run by centre researchers as described above.

Simulation Code for Polythermal Ice Sheets (SICOPOLIS) is a thermo-mechanical ice sheet flow model using the shallow ice approximation, developed by Ralf Greve, Sapporo. The model is available to us through a collaboration with Ralf Greve, and we have the model running at centre computers. The model has some features, such as poly-thermal basal conditions and isostatic movement, but is generally a less complex alternative to PISM. It is particularly useful when mass balance is in focus, because modifications to the code are easily implemented into the model.

Finite Element Models

The ELMER-ICE model is a widely used open source finite element package with ice physics primarily developed by the Finnish Center for Super Computing (CSC). The Elmer-Ice model solves the full Stokes problem, i.e. the full coupled system of stresses and temperature fields. This model is time consuming for runs over the full glacial cycle, and we will mainly use it to model snapshots or specific areas that need a more complete description of the flow. We collaborate with Thomas Zwinger, CSC, and GEUS on implementing the Elmer model.

The Ice Sheet System Model (ISSM) is an open source parallelized multi-purpose finite element framework dedicated to ice sheet modelling model developed by JPL/UCI. This type of model will be used to investigate very specific problems where common approximations to ice physics are inadequate, i.e. at ice divides or in ice streams. The ISSM model system also includes a control method to infer the basal drag and ice viscosity from the observed surface topography and surface velocity field by fitting the calculated flow solution to the observations.

Surface mass balance models

We use a the Sub-annual firn compaction model (SAFCoM) designed by Sebastian Simonsen at the centre to correct observations of surface elevation change of the Greenland ice sheet for changes in firn densification due to climate changes. The model uses climate output from climate models. The dynamic structure of the firn is important when estimating the mass balance of the Greenland Ice Sheet. We use degree-day models to calculate the surface mass balance forcing the ice sheet in long model runs over the glacial cycle.