PROJECT PLAN

CENTRE FOR ICE AND CLIMATE

DANISH NATIONAL RESEARCH FOUNDATION

CENTRE OF EXCELLENCE

APRIL 2007

Summary

Vision and Ideas

The buildup of greenhouse gases is dramatically changing Earth's climate. It is intensively debated whether projected increases in global temperatures will melt the Greenland ice sheet and increase sea level by tens of meters. There is an urgent need to better understand past climate and improve future climate projections. 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 response to climate change. Ice cores provide a comprehensive history of climate with high resolution and they document the full dynamics of the coupled atmosphere-ocean-ice system. The centre will lead an international effort in cutting-edge climate research using deep Greenland ice cores and make a significant contribution to Danish International Polar Year activities on the evolution of the Greenland ice sheet.

Centre team

The centre goal is to combine Danish and international research expertise. World renowned ice and climate researchers will form the nucleus of the centre at the Niels Bohr Institute. The centre will include most frequently cited senior researchers in the world, post-doctoral researchers and young Ph.D. students. It will focus on ice-core related investigations with strong linkages to international institutions involved in climate and ice sheet research.

Cutting edge new ideas and goals for the centre

Finding the baseline: We will reconstruct Northern hemisphere climate during the last 11,000 years by using multi-disciplinary data and global-climate models. These studies will lead to a detailed reconstruction of the small 1-2 °C warming and its causes.

Studying a previous warm period: This work will involve reconstruction of the 5°C warmer climate during the Eemian period 120,000 years ago and its causes. It will supply input data to models of the evolution of the Greenland Ice Sheet and sea level increases in a warm world, without anthropogenic greenhouse gases.

The first CO_2 record from Greenland: CO_2 records from Greenland ice cores are corrupted by the high level of chemical impurities in the ice. Modern techniques that simultaneously measure chemical components, CO_2 gas and CO_2 gas isotopes will provide a high resolution record for Greenland. This will be the first time information on the cycle, sources and sinks of CO_2 are obtained in the Northern Hemisphere.

Understanding the climate: Climate changes are often out of phase in the Northern and Southern hemisphere. Ocean circulation moves energy and carbon between the poles. Better models based on ice core data will advance our knowledge of the relationship between the two hemispheres.

International Centre: The Centre will be a focal point of the International activity for a new deep drilling project, NEEM, and for the International Polar Year activities on the stability of the Greenland ice sheet. This will provide an innovative environment for education and exchange of young researchers.

Legacy

The centre goals include an improved scientific understanding of climate and enhanced ability to predict its future behavior. A fully integrated centre at NBI will attract a new generation of Danish and international researchers.

Vision

Climate change is a major threat to human survival and it is an issue that humanity must deal with immediately. Atmospheric concentrations of greenhouse gases are at their highest recorded levels in the last 800,000 years. It is almost certain that greenhouse gases will continue to increase and might reach double the preindustrial level (CO_2: from 280 ppm to 550 ppm) in the next 100 years or less. How much this will increase the global and regional temperatures, change precipitation, and increase sea level, are topics of intense debate. The recent Intergovernmental Panel on Climate Change (IPCC) assessment, documents expected global warming and its serious consequences.

Our vision is to contribute to the global climate research and ongoing debate by producing new and innovative ice core records, and to use them for climate studies. The previous interglacial period, the Eemian, 115-130k years before present, was about 5^oC warmer than the present in Greenland. The ultimate goal of the Centre is to use Greenland ice cores to assess whether the Eemian can be utilized as an analog of a future global climate warmed by anthropogenic produced greenhouse gases. Knowledge from the past combined with a strong observational network to register the present changes is a very strong tool in climate change research.

The science questions that motivate the centre are:

How did the Greenland ice sheet react to past climate change, and which changes can we anticipate? How do the changes influence global sea level?

To what extent can the previous Eemian period be used as an analog for a future warmer world?

What are the natural dynamics and variability of the climate in warm interglacial periods?

Can we get a deeper understanding of the relationship between greenhouse gases and climate change in interglacial periods?

Our ability to predict and respond to climate changes in the near future depends on answers to the above questions. These predicted changes include increases in sea level by melting from the large ice sheets. Recent satellite observations of the Greenland Ice Sheet show dramatic elevation changes and acceleration of several fast flowing outlet glaciers. The velocity of several outlet glaciers has doubled in recent years, and this has increased the amount of ice that is removed from the ice sheet. None of the existing ice sheet models can explain the rapid changes being observed. Models must be improved or new ones developed to incorporate the mechanisms responsible for observed changes. We will develop ice sheet models to simulate the evolution of the Greenland Ice Sheet during the Eemain period and use these models to simulate the ice sheet's response to a warmer climate.

Highly complex models to predict climate change and to simulate the biogeochemical cycles, such as the carbon cycle, have been developed. We need high resolution palaeo-data from the Greenland ice cores to validate these models. However, such data do not exist today. A major objective of the centre is to measure high resolution CO_2 records from Greenland ice cores for the first time. This has not been done yet because it needs parallel records of highly resolved chemical concentrations. A highly resolved Northern Hemisphere record of CO_2 to supplement the Southern Hemisphere record will allow a more detailed record to understand CO_2

concentrations, especially in the early Holocene and the Eemian interglacial periods. Insight in the small differences between the CO_2 concentrations in the Hemispheres and the more detailed record will allow an improved understanding of the global carbon cycle. The current knowledge of the past carbon cycle is poor and it must be improved to predict our future climate. The centre will produce very high resolution multi-parameter records during the warm interglacial periods from Greenland ice cores. The centre will generate state-of-the-art proxy data from ice cores together with advanced ice sheet, atmosphere and biochemical models. The centre will strengthen Denmark's contribution to climate change research and the concomitant, global climate policy debate. The knowledge produced will be critical for making informed decisions. The predicted climate changes are large, especially in high arctic regions like Greenland, and the impact on society and the changes that are needed to adapt to the warming require intense planning.

We need concerted international research collaborations to answer important questions on climate change and global warming. The Centre will make important contributions by finding answers to these questions enabled by the strong expertise in ice core research. We will bring together Danish and international researchers to accomplish the Centre goals.

The centre will attract and stimulate young students to pursue education in natural science. Polar research involving ice cores and climate is very exciting, and has a great appeal for primary and high school students. We expect that all scientists at the centre will participate in the education of students at the bachelor, master and PhD levels. The centre will also attract international students because of its unique expertise. The senior researchers involved with the Centre have participated in collaborative research with colleagues at institutions in several countries, including the USA, Germany, Australia, Japan, Sweden, Switzerland, Belgium, the Netherlands, Iceland, France, and Italy.

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. The Greenland ice cores have provided high-resolution (annual) data extending back about 123,000 years while the Antarctic ice cores have provided lower resolution data dating back 800,000 years. The ice core records are of immense importance to our current understanding of climate. When Prof. Richard Alley from Pennsylvania State University received the European Geosciences Union Medal for his research, he said in his award acceptance speech that *"Of the 19 most cited climate researchers in the world 10 are from the ice core-related groups and the rest use ice core data in the research."* A full list of important ice core related climate impact studies is too long to give here, but we mention a few relevant to this application.

- The stable oxygen isotopes are a proxy for past temperature changes and the detailed records of climate events like the Dansgaard/Oeschger have revolutionized our understanding of the earth system.
- Air bubbles entrapped in ice cores contain information of the long-term changes in greenhouse gas concentrations beyond direct atmospheric monitoring over the last 2-5 decades.

- Ice core data contain the full dynamics of the coupled atmosphere-ocean-ice climate system that are manifested through multi-parameter records.
- The sub-annual resolution allows precise dating of the observed climate events. Phasing of the various climate components and cross reference to other palaeo-climate records broaden our insight into the regional and global climate system.

So if all this has been already done – what is the reason for dedicating a centre to further research? Our climate is changing and our understanding of the climate system and thus our ability to predict our future is still too limited. The new methods presented here will provide new high resolution records that are needed to understand past climate, and these data will be assimilated into the most recent complex atmosphere, ocean, ice and biogenic models. The centre will combine data documenting climate changes with models to contribute to answering the most fundamental question of our time: 'How does the climate system work?' The timing of the centre is in good harmony with the upcoming International Polar Years, 2007-2009.

The centre will combine Danish and international research expertise. The Ice and Climate group at the Niels Bohr Institute is world renowned for its research on ice cores and climate [22,26,57,64,68,69]. The group has developed excellence in drilling technology, experimental methods to reveal climatic parameters from ice cores, modeling of glacier flow, and dating of ice cores by models and counting annual layers. In the centre we will expand our activities for determining CO_2 records from Greenland ice cores by collaborating with leading scientists from other international groups. The senior personnel associated with this proposal are affiliated with the most cited climate groups in the world. The results from the last ice cores (NGRIP and EPICA) have been producing cutting-edge results, authored by the centre team, in *Nature* and *Science* in recent years (21 publications in the last 10 years). At the Faculty of Natural Science at the University of Copenhagen, with more than 400 researchers, 71 papers have been published in *Science* and *Nature* in the period 2001-2006. Of these papers, the Danish applicants of this proposal, representing 3 permanent positions at the Niels Bohr Institute, have published 10% (7). Dr. Sigfus Johnsen was honored as the highest cited Danish researcher in the field of geosciences last year. The quality of the group is reflected clearly in the ability to attract world-class foreign researchers to the centre.

The Carlsberg Centre 'Copenhagen Ice Core Dating Initiative' expires with the end of 2006. We will strive to continue to produce scientific work with a high impact by forming a new group focused on both the original and ambitious new goals. The strong experience of the existing group is an asset that will support the reach towards new goals.

The CIC team

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

Leader of the team

Dorthe Dahl-Jensen (DDJ, 47 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[26,28]. 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 Rasmussens Årslegat for teknisk forskning. In 2005, she presented invited talks on 'Ice cores tell about climate' at venues including the White House, the Greenland Dialogue with 22 foreign environmental ministers, and OECD's Science Forum.

The team

Sigfus J. Johnsen (SJJ, Associate professor at NBI, 65 yrs) has been recognized as the most highly cited Danish author in Geoscience for the period 1990 to 2004. His strongest research tracks are in advanced modeling of stable isotope ratios in precipitation and in interpretation of climate evolution from a wide span of palaeo-records[15,26,41]. He has received several prizes for his research. **J.P. Steffensen** (JPS, Associate professor at NBI, 48 yrs) has built the Ice and Climate group's experimental laboratories for dust and impurity analysis[1,22,26]. He is principal investigator on the Carlsberg Centre 'Copenhagen Ice Core Dating Initiative' that expires at the end of 2006. He has received several prizes for excellent outreach. **Thomas Blunier** (TB, 41 yrs) will be the researcher with a high expertise in experimental gas measurements. He is an expert on measurements of concentration and isotopes of gases trapped in ice cores. He has run the experimental facilities at the University of Bern and published highly cited papers on the phasing between the north and the south. His recent work on isotopes from chemical components will facilitate the correction of the aimed Greenland CO_2 record. **David Etheridge** (DE, Senior researcher, 46 yrs) leads the Melbourne CSIRO ICELAB and GASLAB investigations of changes in atmospheric composition through measurements and interpretation of air in firn, ice cores and atmospheric samples[12,47,53]. His world-recognized expertise makes the ambitious plans for measuring CO_2 and other trace gases on Greenland ice cores possible. He expects to work 10% of his time with the centre, and we will use the facilities at the CSIRO ICELAB for additional measurements and position a Post Doc at CSIRO. **Anders M. Svensson** (AS, Associate research professor at NBI, 37 yrs**)** has an excellent track record in analysis and interpretation of dust and chemical impurities of the ice[3,20,36]. 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. **Katrine Krogh Andersen's** (KKA, Associate research professor at NBI, 37 yrs) strength is interpretation of climate data from ice cores and modeling of the climate system[9,14,33]. Her research using simple models of the global climate system and statistical analysis of ice core data is outstanding. **Matthias Bigler** (MB, Assistant research professor, 36 yrs), from the University of Bern, has developed efficient and accurate measuring techniques to obtain continuous and highly depth-resolved chemical ice core records by means of Continuous Flow Analysis (CFA)[1,8,31,35]. Combined with his research in interpretation of the records, his expertise complements the team.

The gold of the team (Post Doc and PhD group)

A very central part of the centre will be the growth layer: The next generation of researchers. The centre will include 8 Post Doctoral and 12 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 budget is for young researchers. We will use co-funding of the PhD positions through collaboration with sector research centres (DMU (National Environmental Research Institute), DMI (Danish Meteorological Institute), GEUS (The Geological Survey of Greenland and Denmark), DNSC (Danish National Space Center)) using the COGCI (Copenhagen Global Change Initiative) PhD research school, through collaboration and co-funding with the partners and through European Marie Curie programs like NICE (Network for Ice Sheet and Climate Evolution). We will co-fund international students through the Niels Bohr International School of Excellence, where Dorthe Dahl-Jensen is involved. The newly formed Niels Bohr Academy of Excellence has proposed Global Change as one of its first subjects, which could also be a venue for Post Doc and PhD positions. The global alliance IARU (International Alliance of Research Universities) has selected global change, including climate and greenhouse gas research, as one of five subjects of collaboration. This will give the centre exceptional opportunities for exchange of Post Docs and PhD students from 10 of the top universities in the world.

Research plan

The research plan is divided into four sub sections:
1) The first ice record of CO_2 from Greenland
2) Finding the baseline
3) Studying a previous warm period
4) Understanding the climate.

After the research plan the following sections are included:
5) Creative playground (Experimental Lab for new developments and students)
6) Methods to reach the goals described in sections 1-4
7) International and National Network
8) CIC Education
9) Outreach activities in the Centre
10) Time-line
11) Organization Structure
12) Management Plan

1. The first ice record of CO_2 from Greenland

1.1 Major objectives

Reconstruction of past Greenland CO_2 records is an essential prerequisite to better constrain the carbon cycle of the past, one not perturbed by human impacts, as well as to quantify the interplay between the climate system and the global carbon cycle during warm climate periods. The main questions to be addressed in the CIC are:

- What is the role of CO_2 as the main greenhouse forcing agent for long-term interglacial climate changes and in particular for ice sheet variations in Greenland?
- What is the true dynamics of the global carbon cycle on time scales of decades to centuries as archived in high-resolution ice cores?
- What are the causes of changes in pre-industrial CO_2 emissions?

1.2 Scientific rationale

Air bubbles entrapped in ice cores represent the only direct palaeo-atmospheric archive. Most of our knowledge of long-term changes in greenhouse gas concentrations beyond direct atmospheric monitoring of carbon dioxide (CO_2) and methane CH_4 (i.e., beyond the last 2-5 decades) stems from ice core research. At present the outstanding CO_2 and CH_4 records from the Antarctic EPICA Dome C and Vostok ice cores reach back in time over the last 650,000 years ([11,12,32,33]) and demonstrate how the levels of greenhouse gases have varied though the glacial and interglacial periods.

The large potential of Greenland ice cores for the reconstruction of high-resolution CO_2 records has not yet been fully exploited. This is mainly due to the occurrence of in situ formation of CO_2 in Greenland ice caused by its relatively high impurity content, especially in ice from the last glacial period[38,39]. For records of the early Holocene and before, scientists have so far relied mainly on ice cores from low snow accumulation sites in Antarctica, where in situ production of CO_2 has not been observed. The air bubble enclosure characteristics of polar firn mainly depend on the snow accumulation rate, and thus the central Antarctica ice cores provide only low temporal resolution greenhouse gas records. For example the highest resolution to be possibly achieved at Dome C or Vostok is about 150 years. The age of the gas at a certain depth is younger than the age of the surrounding ice because the air bubbles are not sealed off from the atmosphere until the transition zone, where snow is compressed to ice. At the Dome C site the gas age is offset about 2000 years [16] for recent conditions. The uncertainty of the Holocene age offset is about 10% [16]and constrains how well CO_2 variations can be assigned to climate variations as archived in stable water and aerosol records. Only a few Antarctic coastal cores with higher accumulation provide higher resolution, but those cores do not reach very far back in time. In the next five years the coming WAIS (West Antarctic Ice Sheet) deep ice core will be able to provide a high resolution record through the Holocene period. **Accordingly, we propose to obtain the first high resolution CO_2 record from Greenland ice cores where 1000-1500 m of Holocene ice is available in each core**. The high accumulation rate at central Greenland sites provides a gas record with a temporal resolution of around 20 years, and the age offset can be constrained within 30 years, providing extraordinary resolution and age control[37]. This will enable the study of the carbon cycle dynamics over the Holocene in unprecedented detail and will also allow detailed studies to resolve the carbon cycle response on fast climate variations such as the 8.2kyr event or the Little Ice Age. Furthermore, the access to already available and future Greenland ice from the Eemian will allow us to obtain a CO_2 record of similar resolution for the previous interglacial, the Eemian, where different orbital boundary conditions are expected to have a strong influence on the marine and terrestrial biosphere and thus, on the global carbon cycle. In addition to these major advances in the understanding of the link between climate and the carbon cycle, the new CO_2 record will also provide another means to synchronize Greenland and Antarctic records, especially with the anticipated WAIS record, and establish the North-South gradient to study the phase relationships between greenhouse gas and other climatic records. Improved synchronization between Greenland and Antarctic ice core climate records is a prerequisite to unambiguously interpreting the coupling of both Polar Regions via the bipolar seesaw.

To obtain the Greenland CO_2 record, we will establish state-of-the-art gas extraction and gas chromatography facilities at the CIC to enable high precision trace gas measurements on discrete ice core samples (i.e., CO_2 but potentially also including CH_4, N_2O, CO, and H_2 though collaboration with partners). We expect the system to simplify the sample preparation and handling and thus improve the measuring speed and the earlier availability of results. In addition, we will start a pilot study on continuous CO_2 analyses using laser spectroscopy on the air stream provided by the continuous chemical flow analysis (CFA) to advance the time resolution even further.

How will we tackle the problem of in situ formation? Comparison of Greenland and Antarctic CO_2 records shows that this contamination amounts only to a few ppmv during warm periods where impurity concentrations are relatively low[20]. Based on pilot studies made by the Bern group and the CSIRO group in Melbourne on the in situ formation process[20] and on recent improvements in analysis of the CO_2 isotopic signature ($\delta^{13}C$) on small ice core samples[2] , we will use the $\delta^{13}C$ to correct the data. In addition to the $\delta^{13}C$ measurements on the enclosed air, we will perform concentration measurements and high precision $\delta^{13}CO_2$ analyses of the potential contaminants (organic acids and carbonate) in the ice as well. To this end, we will install new detection lines for the CFA system to quantify the total organic (TOC) and inorganic (TIC) carbon content. Using this information, we can establish an isotopic budget which will allow for quantitative corrections for the small CO_2 contamination in interglacial ice. In addition, high resolution CFA profiles of the contaminants allow specific sampling of the ice core where the concentrations are at their minimum.

Besides being a tool to correct the CO_2 record, $\delta^{13}CO_2$ is an important constraint used in carbon cycle models to identify the processes and exchange fluxes in the global carbon cycle leading to changes in atmospheric CO_2 over the last 10,000 years and beyond. In collaboration with the Alfred-Wegener-Institute (AWI), Bremerhaven, we will install a specific sublimation extraction line[2] to provide $\delta^{13}CO_2$ samples for gas chromatography - mass spectrometry analysis at AWI and to derive the $\delta^{13}C$ signature of TOC and TIC in selected intervals.

At selected climatic events like the last centuries, the 8.2 kyr event and the deglaciation, detailed sampling programs using dry and wet extraction systems at our partners will be used for studies of CO_2, CO_2 isotopes, CH_4, CH_4 isotopes, CO and hydrogen.

The measuring program will be coordinated with the nations participating in the gas analysis either on the NGRIP or/and the coming NEEM ice core through the gas consortia, a working group under the project steering committees.

Following the analyses, our new CO_2 and $\delta^{13}C$ records will be interpreted in terms of changes in the global carbon cycle using coupled climate/carbon cycle models of different complexities (see modelling). While complex climate models allow studying the influence of decadal climate variability on the carbon cycle, models of intermediate complexity are well suited to quantify the effect of long-term climate changes on the carbon cycle over the entire Holocene. In addition, simple box models will be used to constrain the influence of single climate change processes on the global carbon cycle.

Milestones

1A Establish lab. facilities for trace gas measurements and continuous flow analysis for potential CO_2 contaminants (year 1)
1B Build an extraction line for $\delta^{13}C$ analyses on CO_2, TOC and TIC (year 1-2)
1C Attempt an isotopic budget for the in situ CO_2 formation (year 2-3)
1D If 1C is successful, derive a high resolution Greenland CO_2 record over the Holocene (year 3) and potentially for previous warm intervals (year 4)
1E Use the play ground (described in section 6) to explore the potential of continuous CO_2 laser spectroscopic analysis on the CFA melt water stream (year 1-3)
1F Quantify the high frequency carbon cycle dynamics using CO_2 records and coupled climate/carbon cycle models (year 5)
1G Study the influence of changing orbital conditions on the carbon cycle (year 4)
1H Decipher the role of CO_2 vs. solar insolation on ice sheet growth/decline (year 5)

2. Finding the Baseline

2.1 Major objectives:

Any approach to understanding present and future climate has to be based on thorough knowledge of the ‘baseline’ - the pre-industrial Holocene climate conditions. As of today there is no multi-component Greenland ice core record available covering the whole Holocene in sub-annual resolution.

The main questions to address in the CIC are:

- What are the natural dynamics and variability of the Holocene climate?
- To which degree can the small Holocene changes in past Greenland temperature and precipitation be reconstructed?

- How are changes in the Holocene climate system dynamics, like the North Atlantic Oscillation, reflected in the ice core records and how can we reconstruct these changes?

2.2 Scientific rationale:

The climate of our present interglacial period is characterized by temperature changes on the order of 1-2 degrees on time scales of 10-1000 years. The Holocene period covers the most recent 11,700 years and is the period with the most palaeo-climate information. To produce global and hemispheric records such as those used in the IPCC reports there is a need for records with annual resolution. **We propose to provide continuous ice core records of Holocene climate and atmospheric circulation changes in unprecedented sub-annual resolution for all the ice core parameters using novel ice core analytical techniques.**

2.2.1 Novel methods using five stable water isotopes (^{16}O, ^{17}O, ^{18}O, H, D)

Since Willi Dansgaard[51] proposed in 1954 that the relation between cloud condensation temperature and $\delta^{18}O$ in precipitation from frontal weather systems could be used to gain information of past climatic conditions from Greenland ice, the field of isotope glaciology[50] has evolved. For large glacial/interglacial climate changes, the relation between $\delta^{18}O$ and temperature can be found through calibration of the $\delta^{18}O$ thermometer to inverted borehole temperature profiles [34,40,49]. For the small Holocene variations, the isotope records have noise of the same order as the climatic signal, and it is necessary to average several records before a reliable signal is produced[42,47]. It is also recognized that atmospheric patterns change with climate and this can alternate the distribution of accumulation through a year and make the small Holocene climate changes difficult to detect[23]. We propose to use additional oxygen isotopes to improve the knowledge of the Holocene climate.

2.2.2 Improved climatic record from the traditional $\delta^{18}O$

The isotopic signal is smoothed by diffusion processes in the porous firn[48]. The degree of smoothing depends on the past temperatures and accumulation rates, and there is a difference of smoothing of the two isotopes, $H_2{}^{18}O$ and $HD^{16}O$. Our goal is to use high sub-annual resolution records of $\delta^{18}O$ to reconstruct the original annual signal and to use observed smoothing to estimate the past temperatures and accumulation rates by use of inverse methods. From the reconstructed original $\delta^{18}O$ signal, the seasonal $\delta^{18}O$ records will be used to understand features of the climate system. Analysis of the composite seasonal $\delta^{18}O$ signal from multiple Greenland ice cores over the past centuries has shown that the winter $\delta^{18}O$ content is closely coupled to the Greenland winter temperatures from coastal observation sites and the dominant mode of the North Atlantic Oscillation (teleconnection pattern)[23], whereas the summer signal shows closer correspondence to North Atlantic sea surface temperatures. We wish to extend this analysis back in time if high resolution records can be produced.

2.2.3 Including deuterium excess and ^{17}O

The climatic information from the $\delta^{18}O$ records can be improved by also measuring deuterium isotope which provides the deuterium excess. The excess constrains the temperatures and humidity in the source area for the vapor [8,9,28,41,44]. The new approach of also measuring $\delta^{17}O$ presents new possibilities for obtaining more detailed information about the temperature and humidity in the source region along with much better estimates of the site temperatures[1]. The goal is to include knowledge of all the isotopes in atmospheric transport models, as well as including past elevation changes of the Greenland ice sheet to produce the detailed past temperature and accumulation records from the Holocene and gain an understanding of the dynamics of the climate in this period.

2.3 High resolution multi-component chemical records.

At the moment no high resolution dataset of the chemical components of the whole Holocene ice has been produced. It is recognized internationally as a very important data set to obtain. A very high resolution dataset through the Holocene ice will contain seasonal information on the dynamics of the climate system. Chemical ice core measurements of important aerosol constituents (such as sea salt, mineral dust, volcanic emissions and biogenic species) in the Holocene will be performed with a continuous flow analysis system that allows for sub-annual resolution. The high resolution measurements will be done either on the NGRIP ice core in collaboration with all the nations involved in the project, or on the coming NEEM ice core, again in collaboration with all partners in this coming program. These measurements will lead to a completely new insight into atmospheric transport and aerosol emission on a seasonal basis, which will greatly improve our general understanding of climate and its variability on different timescales.

To reach the goals of CIC, a next-generation model of the continuous flow analyzer with an improved resolution will be developed. It is our aim to include the components in the flow system needed to correct and interpret the greenhouse gas records. We find that this is where we really will take advantage of having a fully integrated program. The chemical, isotope and gas records can be made on the same ice sections in the same ice core.

2.4 Combining records

Besides the new data records to be obtained at the Centre, the Ice and Climate group has a unique collection of isotope and chemical concentration records from 73 shallow and deep ice cores collected on the Greenland ice sheet during the last 50 years. Having a number of records from Greenland ice cores certainly calls for adding the spatial resolution to the picture of the climate dynamics and variability. We will combine records using state-of-the-art statistical methods and derive a spatial picture from the Greenland ice cores. The picture can further be broadened by including other palaeo records such as marine cores and lake sediment cores into the analyzing models. We have included Nanna Noe-Nygaard, Svante Björk and Keith Briffa as partners in the Centre to be able to cross-date and compare palaeo records from the Northern Hemisphere. The major part of the team are also involved in the European EPICA programs, focusing on deep Antarctic ice cores, and we thereby have a outstanding opportunity to compare Northern and Southern records too.

Milestones

2A	Set up preparation and mass spectrometer systems to measure five stable water isotopes: O16, O18, H, D (year 1) and O17 (year 2-4)
2B	Use the creative play ground (section 6) to implement online continuous laser technique methods of measuring the oxygen isotopes (year 1-3)
2C	Develop the high-resolution CFA system, including the components needed for gas interpretation (year 1-2)
2D	Measure the NGRIP or NEEM high resolution Holocene CFA records in an international team (year 3)
2E	Develop statistical and inverse model tools to facilitate climatic interpretation of the records (year 1-4)
2F	Use the records in models to achieve our objectives in regard to understanding the climate (years 2-5)

3. Studying a previous warm period

3.1 Major objectives

The realization that the most likely future climatic scenario will be a warmer climate places high priority on being able to predict future conditions. The Greenland ice cores have records of the 5°C warmer previous interglacial period, the Eemian, in an unprecedented resolution of 1 cm of ice per year. The goal of the Centre is to explore how the information from this period can be used to gain information on the coming warmer climate by attempting to answer these questions:

- What were the natural dynamics and variability of the Eemian climate?
- To what extent can the Eemian scenario be used as an analogue for a coming warmer period?
- How did the Greenland Ice Sheet react to the warmer Eemian climate?

3.2 Scientific Rationale

The Greenland ice cores contain information about the climate in the Northern Hemisphere. From stable oxygen isotope values during the Eemian period, it is derived that the annual mean temperature over Greenland was 5°C warmer than the present[17]. Due to the high precipitation rate on the Greenland ice sheet, the temporal resolution of the ice from the Eemian period is about 1 cm/yr. This allows a very detailed insight into the climatic dynamics of this previous warm period.

We will reconstruct climate in Greenland during the Eemian from ice core records obtained with similar methods as described in the above section on 'Finding the Baseline'. The challenge here is to gain as high a resolution as possible. For some parameters like insoluble dust, even an annual resolution is obtainable. These records are crucial for understanding the temporal and physical dynamics that control the climate evolution in interglacial periods and eventually lead to their terminations and the beginnings of glacial periods. With detailed records of stable isotopes, multi-parameter impurity concentrations and greenhouse gas concentrations, the climatic dynamics and variability of the Eemian period can be obtained and compared with the present interglacial period, the Holocene. The differences between the behaviour of the Eemian and Holocene climate will give unique information on a warmer climate and on the natural interaction and phasing between greenhouse gas concentration and climate changes. The temporal resolution we can obtain here is unmatched in all other palaeo records.

At present the oldest Greenland ice in an unbroken chronology is 123,000 years old and comes from the NGRIP ice core[17]. Included in this chronology is the 8,000 years of the youngest part of the 15,000-year-long Eemian period. As the Eemian period started 130,000 years before present, this part of the CIC program would certainly benefit by collecting the NEEM ice core that is believed to reach back into the glacial period before the Eemian period. It is our goal to improve the resolution of the CFA system so the annual variation of the impurity concentrations can be observed for those impurities such as insoluble dust where ion diffusion has not smoothed the annual signal from the ice. Physical properties of basal ice will also be carefully inspected with a recently developed automatic analyzer already acquired by the group to ensure the chronology is undisturbed and to correct for anisotropic effect on the ice flow.

We will reconstruct the evolution of the Greenland ice sheet during the Eemian in order to estimate volume changes and its contribution to the global sea level rise observed during the Eemian[6]. From the above analysis on the Greenland ice cores, we have climatic records (past temperature and past precipitation rates) to drive ice sheet models. Temporal changes in the $\delta^{18}O$ difference between the Greenland $\delta^{18}O$ records can be used to estimate past relative changes in altitude between different drill sites. In addition, observations of internal layers in the ice by radio echo sounding[19] (collaboration with Prof. P. Gogineni, CReSIS, University of Kansas) provide substantial information on the evolution of the Greenland Ice Sheet that will be included in the modelling. We will investigate the conditions at the base of the Greenland ice sheet, also by analysis of the internal layer structure, in order to identify areas with basal melting and map the geothermal heat flux beneath the ice sheet[19]. These basal conditions are crucial for the flow, and may determine the dynamic evolution of the ice sheet. The results will be compared and evaluated in the frame of the newly emerging knowledge on the fast response mechanism of the big ice sheets by acceleration of fast flowing outlet glaciers. For this purpose we will form collaboration with Rene Forsberg, DNSC, on interpretation of the observed current volume changes of the Greenland ice sheet from airborne laser observations, satellite observations from GRACE, ERS1 and ERS2 and the coming European CRYOSAT2.

A new and quite independent way of gaining information on the evolution of the Greenland Ice Sheet is just opening up through collaboration between the scientists at CIC and Eske Willerslev. Studies of DNA in the basal ice from ice cores tell about the flora and fauna and thereby the climate conditions from before the time when ice covered the sites. New methods combining the temperature dependent breakdown of DNA with a modelled basal temperature history of the ice can be used to date the biological material and thereby the time ice first covered the sites where we have deep ice cores reaching bedrock in Greenland. A first pilot study on this is just on the way to be submitted to *Science*.

Milestones

3A If 1C is successful, measure CO_2 and other greenhouse gases with a temporal resolution of 50 years through the Eemian period including the onset of the Eemian (if NEEM ice becomes available) and the onset of the glacial period following the Eemain period. (year 4)

3B Obtain detailed multi-component stable oxygen isotope records and annually resolved multi-component impurity concentration records through the Eemian period. (year 1-3)

3C Develop ice sheet models to reconstruct the evolution of the Greenland Ice Sheet based on all available ice core information. (year 1-4)

4. Understanding the climate

4.1 Major objectives

The challenge of understanding present-day and future climates is a rather unique one in science - it is not one where the system can be studied through a series of “in situ” experiments that eventually lead to the answer. Instead, we must turn to the vast palaeo-archive of climate proxies and ask the following questions:

- How can the ice core data be used to improve our knowledge of the interglacial climate system?
- What are the major interglacial climate interactions and feedbacks and how do they work?
- What is the relation between greenhouse gases and climate changes, especially in interglacial periods?

4.2 Scientific Rationale

The goal of the CIC is to deepen our knowledge of both the Eemian and the Holocene climates and thereby more firmly ascertain the applicability of the Eemian as the most recent analogue to present day global warming. We describe how to obtain data from ice cores, including innovative approaches both on the experimental and on the theoretical sides. **The final goal is to combine and use the new knowledge achieved in models to gain knowledge of the climate system**. We will develop models and form collaborations with partners so climate system models of various complexities can be used to investigate the mechanisms that characterize the interglacial periods of the climate system.

4.3 Natural dynamics and variability of the Interglacial Climate system.

High resolution measurements of isotopic composition and chemical constituents in the ice will be interpreted in terms of atmospheric transport and deposition, source strength, and large scale climate variability. To do this, it is of utmost importance to understand the climatic implications of the measured records. The Holocene period is characterised by climatic variations that are much smaller than what is encountered during the glacial period, and the noise contribution in the high resolution datasets is significant[3,4,47]. The chemical impurities in pre-industrial Greenland ice cores mainly derive from marine aerosols, continental aerosols and dust particles. The deposition occurs episodically and over short periods of time during very specific seasons of the year[43,46]. Studies of the chemical signal in Greenland ice cores over the past decades and centuries indicate that the concentration of these species is influenced by a combination of source strength, long-range transportation, and deposition[7]. Part of the signal is common to impurities from the two major sources which indicate some degree of common transport and deposition.

Analysis of several records from multiple closely spaced shallow cores will be produced and analysed in order to understand the noise in the signal due to surface processes such as blowing snow, sastrugi and precipitation events. This will improve our ability to extract the underlying climate signal, minimize the noise and carry out data analysis using meteorological re-analysis products in order to obtain a connection between the chemical impurities and meteorological features. The assembly of Greenland ice cores may then be used to obtain a spatial pattern of variability and ultimately to attempt reconstructions of meteorological fields.

Atmospheric modelling of simplified tracers will be used to investigate the influence of the meteorology on tracer transport and deposition over the ice cap. We will here prescribe tracer flux from specific source areas for tracer transport to Greenland and concentrate on aspects concerning the short-range as well as well as long range transport together with dry and wet deposition. The model may be forced with different insolation scenarios to simulate the effects of large scale solar forced variations in the atmospheric general circulation. On the regional scale the influence of teleconnections on tracer concentrations in the Greenland snow will be investigated.

With the high resolution isotopic composition and chemical concentration records from the Eemian period, it is our hope that some of the insight obtained for the Holocene period may be used on the records from the Eemian period. This will give a unique insight in the dynamics of a warmer climate than the present.

4.4 The interglacial seesaw

The small out-of-phase temperature variations between climate records from the Northern and Southern Hemisphere from the present interglacial period[31,34] resemble the pattern of the bi-polar seesaw[22] during the last glacial period. In the last glacial period the out-of-phase temperature variations were governed by abrupt changes in ocean circulation, shifting energy between the hemispheres. Identifying and understanding feedback mechanisms that govern an "interglacial seesaw" may lead to an altered understanding of both the present and glacial climate behaviour. We will investigate this "interglacial seesaw" using a variety of proxy data together with state-of-the-art climate system models. Idealized experiments with both general circulation models (GCMs) and Earth System Models of Intermediate Complexity (EMICs) will be performed in which we study the mechanisms interconnecting the two Polar Regions. The ocean is obviously a key player in bi-hemispheric interactions and we will consequently collaborate closely with our partner Trond Dokken from Bjernes Centre in Bergen with expertise on oceanic modeling. Our intent is to combine the oceanic output of Earth Models of Intermediate Complexity (EMICs) presently running in Bergen with the atmospheric general circulation models (AGCM) that we are running in Copenhagen.

4.5 Interglacial cooling events

The Holocene cooling events at 8.2 and 4.5 kyr BP provide an interesting testing ground for bi-polar interactions. The 8.2 ka BP event is believed to be caused by a major freshwater discharge to the North Atlantic associated with the final decay of the Laurentide Ice Sheet[13]. The 4.5 kyr BP event is less well identified in widely distributed proxies but is believed to follow a "cool poles, dry tropics" pattern[15]. With the use of EMICs we wish to extract the typical patterns of forcing that the ocean exerts on the atmosphere during these types of cooling events. This forcing may then be used to drive AGCM experiments in which the resulting changes in circulation and hydrologic cycle in both hemispheres can be studied and compared to the baseline records.

4.6 Carbon cycle modeling

In combination with our goal to construct a high-resolution record of Greenland CO_2, we will work with carbon cycle models that can aid its interpretation and provide insights to the reorganizations of carbon sources and sinks. The global CO_2 signal obtained from the Antarctic ice cores show that the general behaviour of the CO_2 concentration is in good correlation with the southern ocean temperature. In the warm interglacial period, the terrestrial source from the biosphere, mainly from the northern regions, becomes an important source. As a very ambitious goal of CIC, we hope the new high resolution record of CO_2 from Greenland can be used especially over the climate events found in the interglacial period to improve the quite poorly known behaviour of the carbon cycle. We will reach this goal by hosting Jørgen Bendtsen (DMU) as a guest at the Centre 20% of the time and through collaboration with the groups running simple and high complexity carbon cycle models (AWI, Max Planck Institute, Hamburg)

4.7 Orbital forcing

Insolation changes play a role for many of the processes that we wish to study and can thus influence ocean temperatures and circulation, atmospheric circulation patterns and variability and the mass balance of ice sheets[14]. Consequently, several different experiments will focus on changes in Earth's orbital parameters. By studying changes in magnitude and structure of atmospheric freshwater transports, we can determine which of these parameters has the greatest impact and how this impact comes about. Since a change in source region temperature or transport structure will be evidenced in the ice core deuterium excess records[8,9,29] our experiments may contribute an explanation of orbital control of ice-sheets. The effect of changed orbital parameters on ocean and atmospheric circulation and transport during the Eemian period and the glacial inception will be investigated with the use of complex models.

4.8 Broadening the picture

Our list of collaborators includes specialists on other palaeo-archives such as speleothems, tree-rings, corals, lake and deep ocean sediments. The very accurate dating of Greenland ice cores may be transferred to other sedimentary records and allow for investigations of the temporal and spatial development of climate changes in Europe and in Denmark. In this way we will be able to place our results within a larger context and draw conclusions on a wider geographical scale. With the described climate models and re-analyses described above, the palaeo records will also broaden our knowledge so we can better address direct impacts and predictions of the climate changes that will directly effect Denmark.

Milestones

4A	Setting up AGCM models for tracer and moisture transport studies. Initiate collaboration on EMIC runs with Bjerknes Centre. (year 1-2)
4B	Analysis of data from multiple shallow ice cores and other palaeo climatic records for meteorological and climatic conditions (year 1-3)
4C	Use simple carbon cycle models to prepare sampling program and predict expected variations in CO_2 (year 2-4)
4D	Collaborate with expert group on complex carbon cycle modelling (year 3-5)
4E	Couple atmosphere, ocean and carbon models for a climate system-wide approach (year 3-5)
4F	Evaluate to what degree the warm Eemian period can be used as analogue for a coming warmer period. (year 3-5)

5. Creative Playground

At the Centre we will build up a Creative Playground with facilities for experimental work and tests of new methods related to ice cores studies. It comprises both a space in the cold room and a lab at room temperature. It will be equipped with appropriate tools and equipment. The goal is that everybody at the Centre has easy access to experimental facilities.

The Creative Playground will provide physical conditions for synergistic activities between all members of the Centre: students, researchers, guests, partners and technical staff. It will draw 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 Creative Playground will be an excellent opportunity to play around and to interact with the expertise in the group. This facility will be an essential first step in training top scientists, and developing strong and focused research projects.

In the research plan we distinguish between experimental equipment, where methods have been developed around the world which we can reproduce or develop into a next-generation set-up, and new visionary experimental approaches.

Examples of equipment that can be reproduced/produced next-generation (even though not easily) are preparation/extraction system for gases, discrete measurement of CO_2, and some of the chemical components on the CFA system.

In order to extract new and high-resolution palaeoclimatic information from the ice cores, it is vital that old methods are improved and new methods are developed, especially focusing on continuous methods and non-destructive methods. As an example in the research plan above, we mentioned continuous stable oxygen systems using laser technique, online systems to measure CO_2, pilot studies of measuring hydrogen gas from air bubbles from the gas and several new chemical species and isotopes of chemical components that we would like to investigate if they could be coupled to the CFA system.

The team has many additional ideas; the quality of the CFA data can be improved by enhancing the resolution of the measurements and also by improving the filtering for ash, particles (volcanic tephra) and micrometeorites. Other methods that can be improved are treatment of ash grains, borehole logging and methods for examination of physical properties of the ice. New methods could be developed for scanning the core for radioactive horizons and for elemental composition along the core. A vacuum system also used for gas extraction could also be used for experiments concerning the porosity of firn and gases enclosed in ice cores.

We find that a creative playground is a very strong and innovative idea to be able to stay on the forefront in producing outstanding climate related ice core records.

6. Methods

6.1 Experimental methods to obtain high-resolution chemical records

To obtain multi-component high-resolution chemical ice core records we will set up a state-of-the-art Continuous Flow Analysis system (CFA) for key species in connection with a comprehensive sampling system for complementary parameters. We aim at merging all sampling activities, which requires farsighted planning and close collaboration with our star partners.

6.1.1 High-resolution CFA

Our main target is to make the world's best CFA instrument when it comes to resolution and phase control of the measured key species. Sub-annual resolution within the Holocene and the Eemian ice is an essential prerequisite to understand and interpret the proxy-information about past atmospheric circulation and source strength. A precise phase control is crucial to get detailed information of the seasonal variability of each species. Furthermore, only an unbroken coverage of the Holocene and the Eemian will allow us to get a complete picture and to track down any short-term climate variability of these interglacial periods.

Key species measured by CFA will reveal information concerning all the important aerosol constituents originating from sea salt, mineral dust, and biogenic sources: namely, sodium (Na^+), calcium (Ca^{2+}), ammonium (NH_4^+), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), and insoluble particles (dust). In addition, the electrolytical melt water conductivity contains an overall signal of the ionic content of the ice, and both hydrogen peroxide (H_2O_2) and formaldehyde (HCHO) measurements will be needed to correct CO_2 measurements. In addition, new detection lines for total organic carbon (TOC) and total inorganic carbon (TIC) will be developed for accurate correction of in situ formation of CO_2. To achieve the goal regarding phase control, we will regularly use multi-species standards in addition to the more accurate single-species standards used for concentration calibration series. To get the highest possible data resolution, we will follow two strategies: Firstly, we will improve the experimental setup to optimize chemical reaction times and to prevent signal diffusion as much as possible. Secondly, we will integrate mathematical resolution enhancement into the data processing, preferably almost in real time, which will also allow discovering measurement problems immediately. To determine the decisive parameters of the mathematical resolution enhancement, we will try to produce realistic artificial ice samples with well-known properties.

6.1.2 Additional sampling and measurements

In connection with the CFA system, we will run a comprehensive sampling system for melt water and filter samples with lower resolution. These samples will be used for complementary species or species showing diffusion behaviour in the ice, which prevents the preservation of the original high-resolution atmospheric signal. Liquid samples will be used for ionchromatography measurements, especially for ionic species not covered by CFA, such as methane sulphonic acid (MSA), lithium (Li^+), magnesium (Mg^{2+}), and fluoride (F^-). Also samples to determine the radionuclides ^{10}Be and ^{36}Cl could be taken. Filter samples will allow searching for volcanic glass shards (Tephra) or micrometeorites. Electrolytical melt water conductivity contains an overall signal of the ionic content of the ice, and both hydrogen perioxide (H_2O_2) and formaldehyde (HCHO) measurements needed to correct CO_2. We plan to try to adapt continuous methods to determine the total organic carbon (TOC) and the total inorganic carbon (TIC) too.

6.1.3 Melting device and sample preparation

The base for the CFA and the sampling system is a melting device, which is able to provide a sufficiently large melt water stream from a continuously lengthwise melted subsection of the ice core. A very good depth control of the melting process will be essential when the CFA data and the discrete samples are going to be compared with other high-resolution records such as visual stratigraphy data, electrical conductivity measurements of the solid ice (ECM) or for the correction of CO_2 measurements. However, to reduce complexity of the whole system, it might be suitable to set up two parallel melting devices, one for the CFA measurements and one for sampling purposes.

6.2 Mass spectrometry

6.2.1 Stable oxygen measurements

Our present system for making isotope measurements on water is based on the CO_2 equilibration method. The system that was built in the early seventies can still do 256 $\delta^{18}O$ measurements per day with a precision of 0.1 ‰.

We are planning on expanding our measuring capabilities by acquiring a new multipurpose mass-spectrometer together with appropriate peripheral systems. With this new system we will be able to do more than 100 δD measurements per day using the chromium reduction method and with a precision better than 0.5‰. The instrument can also do 120 $\delta^{18}O$ measurements per day with 0.05‰ precision using the equilibration method. Furthermore, by shifting from Cr to CoF_3 as reacting agent, the instrument can do both $\delta^{18}O$ and $\delta^{17}O$ measurements with an expected precision of 0.02 ‰. (This instrument has been granted by FNU and will arrive at the time of the Centre start. The use of it will be integrated in the Centre.)

6.2.2 The tuned laser isotope ratio method

Tuned laser isotope ratio method instruments are on the market now. The precision is not sufficient in table-top equipment, but we believe that the laser cavities can be reduced and accuracy improved. A portable version of the instrument for doing $\delta^{18}O$, $\delta^{17}O$ and δD measurement in water vapor has been purchased (Carlsberg, Copenhagen Dating Initiative 2001-2006) and we will develop it for ice core use as a CIC goal. This new portable technology opens up the possibility to do isotope measurements on ice cores in the field. Our intention is to develop methods to connect this instrument to the CFA high resolution system, currently under development, in order to obtain a continuous isotope profile.

6.3 Greenhouse gases

In order to allow for high precision CO_2 and other trace gas measurements, we will establish gas lab facilities comprising mechanical dry extraction of gases[18,35,45] and quantitative collection of the gas using a He cold head. From those samples, aliquots can be analyzed on gas chromatographs (GCs) equipped with specific detectors for the various trace gas analyses (flame ionization, reduction gas analysers, and electron capure detectors), mass spectrometers (MS) and highly sensitive GC-MS combinations. We believe the preparation system can be developed so the required sample size is 35g of ice.

In addition, we will develop a device for total air content estimates and a constant flow gas extraction from the melt water stream attached to a commercially available diode laser spectroscopy monitor for continuous CO_2 concentration measurements. Using the continuous information on the concentration of TOC and TIC in equivalent depth resolution, we should be able to correct for any potentially occurring additional CO_2 formation during melting.

Samples for $\delta^{13}CO_2$ analyses will be extracted and sampled in micro ampoules using a specifically developed sublimation extraction line developed by AWI. This line will be revised for automatic sample extraction to minimize the work effort in the lab and to guarantee reproducible extraction efficiencies. The micro ampoules will be measured at AWI, Bremerhaven, using a specifically designed gas chromatography mass spectrometer. The accuracy of individual $\delta^{13}C$ measurements using this technique is 0.05 ‰ on very small (35g) samples.

Large (100-500g) samples will be extracted with the CSIRO ICELAB system and gas extracted, allowing measurements of CO_2, CO, CH_4, NO_2 and some isotopes of the gases. Most of these measurements will be performed at the gas laboratories of our collaborators and partners.

Specific samples will be taken to determine the isotopic composition of TOC and TIC. To this end the TOC and TIC will be completely digested separately and the CO_2 produced collected for subsequent $\delta^{13}CO_2$ analysis.

6.4 Mathematical Modelling

The Centre for Ice and Climate will be an opportunity to extend ongoing mathematical data analysis and modelling through the integration of complex three-dimensional models. The approaches described here include statistical modelling, carbon cycle models, three-dimensional ice sheet modelling, atmospheric general circulation modelling, and an Earth System Model of Intermediate Complexity (EMIC). It is not intended to develop new complex three-dimensional models from scratch within the Centre in all directions, but rather to apply existing models, and to incorporate modifications relevant for the specific problems addressed here. Mathematical modelling is the required tool to understand the climate system using the observed multi-parameter palaeoclimatic records. It also allows us to use the information from the Greenland ice cores to predict changes of climate over other regions such as Europe and Denmark.

6.4.1 Statistical Modelling

Statistical modelling will also be used to advance the understanding of time series analysis methods suitable for ice core data analysis. Special focus will be put on modelling deposition-based glaciological noise, using Monte Carlo techniques to improve the resolution of the isotope and impurity records, and to develop tools to detect and extract unusual features from the immense data sets.

6.4.2 Atmospheric Modeling

General circulation modelling with a focus on the atmosphere will be used for investigations of the influence of insolation on the hydrological cycle, and the transport and deposition of oxygen and hydrogen isotopes. Meteorological re-analysis products (NCEP, ERA40) will be used together with implicit modelling of tracer transport and deposition from the atmosphere to the ice in order to improve the interpretation of the long-term chemical records obtained within the Centre. Time slice experiments will be carried out, simulating specific climatic scenarios during the Interglacial periods in order to investigate the influence on chemical impurity deposition in Greenland. The specific time slices will be modelled through fixed boundary conditions for the insolation, surface topography (ice sheets), estimated (or interactively model) vegetation, and sea surface temperatures. At present, the National Centre for Atmospheric Research’s CCM3 atmospheric general circulation model (AGCM) is available for the Centre. Our partners Prof. Eigil Kaas (NBI) and Jens Hesselbjerg Christensen (DMI) have experience with the ECHAM5 GCM. The goal is to initiate a collaboration with DMI, through which we will benefit from both expertise and computer power.

6.4.3 The Earth System Model of Intermediate Complexity

The Earth System Model of Intermediate Complexity (EMICS) used by our partner Trond Dokken, Bjerknes Centre, couples a 3D oceanic CGM with thermodynamic sea ice and a 2D (latitude/height) atmospheric model. The model includes a carbon cycle model and a land ice model is being implemented. EMIC runs will be performed in Bergen and the oceanic responses from these experiments will provide input for the AGCM run in Copenhagen.

6.4.4 Carbon cycle modeling

Global models of the oceanic and terrestrial carbon cycle will be used for explaining past changes in the atmospheric CO_2 concentration. The marine carbon cycle will be analysed with a physical and biogeochemical general circulation model (MPI-OM1) of the global ocean. The physical model is formulated on a curvilinear grid with a high spatial resolution in the polar and subpolar North Atlantic Ocean, and a dynamical sea ice model is also included[21]. For analysing the relative importance of physical and biological processes for the CO_2 levels during the Holocene, a simple biogeochemical model will be implemented in the circulation model[24,25]. A simple model of the atmospheric and terrestrial carbon reservoir will be coupled to the ocean model.

6.4.5 Ice sheet models, Evolution and stability, Bottom melting, Internal layering

We will use a combination of existing flow models and inverse methods to interpret the internal stratigraphy, derive basal melting rates and map the geothermal heat flux in northern Greenland from the Radio Echo Sounding data[10]. This will be done in collaboration with our partner Prasad Gogineni, and the Centre, CReSIS, he directs at the University of Kansas. We will develop a three-dimensional, thermo-mechanically coupled ice sheet flow model of the Greenland ice sheet in order to model the overall evolution of the ice sheet over time. We wish to enhance existing models by introducing new estimates of basal melting and ice stream dynamics. The effects of anisotropic deformation of the ice, including fabric deformation, will be included in this model. This is an ambitious effort that requires collaboration with our national and international partners (Ralf Greve, Hokkaido University; Andreas Ahlstrøm[27], GEUS; Jens Hesselbjerg Christensen, DMI; Christine Hvidberg[26,27], NBI). We will use a general ice sheet flow model, SICOPOLIS, developed by Ralf Greve[5,30,36], combined with models of accumulation and ablation. The model is based on the shallow ice approximation (no ice stream dynamics). We will couple the model with a regional three-dimensional model to investigate the effect of basal melting and ice stream flow.

7. International and National network

7.1 Star partners

The centre will become a “star” by research collaborations with strong national and international groups that allow the resulting unified research effort to grow beyond the contribution of the single parts. We believe that the described network of partners strengthens the centre and enhances the value of the results/goals. We envision that the collaboration with the partners will allow co-funded post doc and PhD programs, and where it has been possible at this stage, we have asked the partners for a statement of commitment.

7.1.1 Carbon Cycle Modelling

The great vision to measure greenhouse gases in the Greenland ice cores is driven by the goal to improve our knowledge of the carbon cycle and improve our ability to predict future climate changes. Jørgen Bendtsen (DMU) has focused on carbon cycle modelling and has collaborated with the Hamburg group of researchers to develop state-of-the-art carbon cycle models.

7.1.2 Atmospheric and intermediate complexity earth models

In the Centre we need to run atmospheric models to interpret the observed chemical, isotopic profiles, both to provide snapshots to reconstruct the past climate conditions and to address the transport of isotopes and chemical components to the ice sites.

Eigil Kaas (NBI) and Jens Hesselbjerg Christensen (DMI) are national partners with a clear expertise in the ECHAM5 model. As an international partner, we have just got word back from the EU that the Marie Curie program NICE has been approved, and here we expect to form a PhD position with Georg Hoffmann (Saclay) to model the transport of stable isotopes.

7.1.3 Stability of the Greenland Ice Sheet

An overall goal is to compile the knowledge produced by the Centre's experimental and theoretical initiatives to address the very timely question of how the Greenland Ice Sheet will respond to global warming. The Centre will produce and interpret data especially from the warm interglacial periods, and contribute to our understanding of the ice sheet stability. Nationally this work benefits from collaboration with Christine Hvidberg (NBI) working on the waxing and waning of ice sheets and their mass balance. Collaboration with Ralf Greve (Hokkaido University, Japan) will allow us use the SICOPOLIS ice sheet model to reach the goals. GEUS ice group (Andreas Ahlstrøm) are experts on observing and interpreting the mass balance in the melt zone, and we plan to develop dynamic ice sheet models in collaboration with GEUS and DMI (Jens Hesselbjerg Christensen) through joined post doc and PhD programs. We are international partners with the newly formed Science and Technology Centre, CReSIS, at the University of Kansas. CReSIS will develop a variety of sensors to perform 3-D characterization of the Greenland and Antarctic ice sheets, conduct field programs in Greenland and Antarctica and develop models in collaboration with the our Centre as described on ice flow, especially in the regions with fast flowing glaciers.

7.1.4 Understanding the Greenland Ice Sheet evolution by DNA studies

A very new and exciting contribution to the understanding of the evolution of the Greenland Ice Sheet is studies of the DNA found in basal parts of the deep ice cores.
The collaboration with Eske Willerslev (professor, DNA in ancient ice, Niels Bohr Insitute and Biological Institute) will continue, and we plan to expand this collaboration with a co-financed PhD or post doc position.

7.1.5 Integration with other palaeoclimate archives

The mechanisms of our climate system will be investigated by using all available ice core data together with climate system models of various complexities[14]. We will collaborate with researchers studying past climates in other palaeo-archives such as lake sediments, speleothems, tree-rings, corals, lake and deep ocean sediments through collaboration with Nanna Noe Nygaard (Professor, lake and peabog records; Geological Institute, University of Copenhagen), Svante Björk (multi-stratigraphic palaeoclimate research from ocean cores; Professor, Quaternary Sciences at the GeoBiosphere Science Centre in Lund) and Keith Briffa (Professor, dendroclimatology, Climatic Research Unit, University of East Anglia, Norwich, UK).

7.2 Ice core programs: NEEM, NGRIP and EPICA

Ice core drilling projects are done in large international collaborations. The NGRIP project, lead by the Danish group reached bedrock in 2004, the 2 European ice cores from Anarctica reached bedrock in 2004/2005 and 2005/2006. The applicants come from both the NGRIP and the EPICA groups. For the Centre we need mainly Greenland ice cores to reach our goals. The suggested programs can all be done on existing core material with the draw back that the NGRIP ice core only reaches back 123.000 years to the middle of the Eemian period. For this reason we would prefer to be able to perform most of the program on the NEEM ice core, which is an international IPY (International Polar Year 2007-2009) project. This would allow the CIC Centre to investigate the full Eemian period and perform the Holocene measurements on fresh and whole ice cores. The NEEM project has been identified as one out of four key projects of the ice core community as summarized in the white paper of the International Partnership in Ice Core Research (IPICS).

Regardless of which ice cores become available for the program it is clear that the ice cores are owned by joint international groups headed by Steering Committees. The measuring programs will be done in collaboration with all the partners interested in joining. The international consortia's will benefit by the next generation equipment available from CIC and the CIC Centre will benefit from the united effort needed to obtain the very time consuming CFA measurements. An agreement has been made between the ice core groups that it is a high priority goal to obtain high resolution CFA measurements from the Interglacial parts of the Greenland ice cores with first priority on the NEEM ice core, second priority on the NGRIP ice core. The Danish group is the international Centre of NGRIP project and it is our hope to become the international Centre for the upcoming NEEM project. For CIC this will ensure strong international collaborations and exchange of young researchers.

7.3 International Polar Year

The International Polar Year 2007-2008 (IPY) is a grand event in polar research. The international office expects 50, 000 people from 60 nations to be involved in the international coordinated projects. The Danish group has been selected to lead all activities related to 'The stability of the Greenland Ice Sheet' which will add a very strong international relation to CIC. It is also our goal to strengthen the research on the evolution of the Greenland ice sheet and thereby sea level change in Denmark through the Centre activities and through the partners we have mentioned from other Danish Universities and Sector Research Institutes.

7.4 Guest program

It is very important for the Centre to interact strongly with leading international groups through a strong guest program. We have the following program:

- We will have a guest program inviting guests for stays between 1-6 months (David Etheridge will spend 1-2 months and Jørgen Bendtsen 2 months at the Centre each year). We have identified other potential guests like David Braaten, Deputy Director of CReSIS at the University of Kansas, to spend longer periods of time at the Centre.
- We will budget for workshops and conferences during the Centre period. 1-2 workshops will be held each year on specialized subjects for a group of 10-20 scientists. A conference is planned in year 4 of the Centre on 'Interglacial Climate – where are we going'.
- We will open a system so international researchers from graduate students to full professors can apply to visit the Centre for a shorter period (1 week – 1 month). This will open the possibilities for new collaborations to form.

8. CIC Education

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 is 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.

The courses will be concerned with various aspects of climate. To strengthen the course program, we will invite guest professors from related fields to give lectures and participate in the education through the guest program. The staff at the Centre will also participate in the basic courses in physics and mathematics at University of Copenhagen in order to enhance the general education and attract students early in their career.

As CIC will set up new experimental techniques, there will be the possibility at the Centre to provide advanced courses both on the measurement techniques and on the interpretation of the results. Such courses will aim at the PhD level.

We wish to engage students in our work by offering them student jobs also at an early stage of their study. They can participate in carrying out measurements and field work. The students will get responsibility and become directly involved with the ongoing research. This is a very motivating factor.

In the Centre, we will strengthen and expand this unique and stimulating environment. For the graduate students at M.Sc. and Ph.D. level, CIC will offer a strong combination of theoretical courses and experimental work, where the students are directly involved in the research by doing laboratory measurements and/or field work. This will create a strong educational environment that should prove to be very attractive to students. In the larger measurement campaigns and field related projects that are planned in connection to CIC, we wish to involve students directly in the work, and we have included a small budget for student jobs.

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 attracts equally many male and female students.

9. Outreach activities in the Centre

The deep ice core drilling projects have a long and strong tradition for outreach activities aiming both at the general public and school children. They interest the public and we feel obliged to participate strongly in outreach. We are sure outreach on ice and climate research motivates young students to study natural science and the public to be more aware of climate change and environmental issues.

The Centre of Ice and Climate will continue this tradition of receiving visiting high school classes, giving popular talks to the general public, writing popular articles and participating actively in all media. The Centre homepage will supply background information on ice core and climate research together with information on ongoing research projects aimed at high school children and the general public. Published data produced within the Centre will be made available to fellow researchers through the Centre homepage.

Moreover it is an intention within the Centre to develop teaching material on climate research directly applicable in high schools and the oldest classes of elementary school. Climate studies, is a subject that fits well into the curriculum of both elementary school and high schools, combining aspects of all the natural sciences. Making current and factually accurate teaching material available will support the current effort to strengthen the natural science teaching in Denmark, provide the students with insights essential to the understanding of the ongoing climate debate, and hopefully support the recruitment to natural science studies.

The group will undertake development of teaching material usable in secondary school and high school. The approach is based on the formation of a user group of interested teachers and didactic professionals, in cooperation with which the Centre staff will identify subjects that are central to the study of climate and fits into the school and high school curricula. Staff at the Centre will produce text and illustrations and the material will be edited and compiled by a dedicated member of the group using the input and support of the user group.

The aim is to produce material that can be used in the school's 7th – 10th grade, in the new high school courses "Naturvidenskabeligt Grundforløb" and "Almen Studieforberedelse” that focus on interdisciplinary and current topics and play a large role in the reformed high school and material for high school physics and/or geography. The timing is fortunate, as the recent reform of the high school includes significant time allocated for projects of the proposed style and content. The material will be made available free of charge and will comprise text, exercises, web-based material (animations, interactive exercises and mini-models) and teacher's instructions. Some of the activities will be planned so that it can be used in connection with a visit to "Ungdomslaboratoriet" at the Niels Bohr Institute, or in connection with a visit to the research group. After the initial development phase, the material will be tested in practice in cooperation with the user group and improved according.

10. Time-line

Activity	Year 1	Year 2	Year 3	Year 4	Year 5	Responsible
Build Gas Lab		1B				TB, DE
Run Gas Lab			1C	1D 3A		TB, DE
Build CFA Lab	1A	2C	3B			AS, MB
Run CFA Lab			2D			AS, MB
Build Isotope Lab	2A					SJJ
Run Isotope Lab			3E 3B			SJJ
Play Ground			2B			MB,AS
Broadening the palaeoclimatic picture			4B			JPS
Statistic and Inverse Models				2E		PD
Atmosphere Models		4A				KKA
Carbon Cycle Models				1G 4C	4D	JB
Ice Sheet Models				3C		CH,DDJ
Coupled Models					1F 1H 4EF 2F	KKA, EK, all
Establish Center						DDJ
Education, Outreach						AS, KKA, all
Guest Program						DDJ
Workshops, Symposium						DDJ

The sections 1 to 4, where the research plan is described, include milestones (in colours). On the time line above the activities of the Centre are listed. The thickness of the grey time lines indicates the intensity of the activities as function of time and the delivery time of the milestones are included.

11. Organization structure

11.1 Institutional location

The Centre will be housed at the Niels Bohr Institute, University of Copenhagen, to encourage collaboration and make the Centre attractive for educators and visitors. The Centre will be located in a contiguous space to foster collaboration and interaction instead of housed in smaller units within the institute. All foreign participants except David Etheridge (referring to enclosure 3) will move to Copenhagen to participate in the Centre research, education and outreach programs. The Centre will provide office space and other resources needed for their stay at the Centre. Locating the Centre at the Niels Bohr Institute will provide a strong connection with the education programs at the institute and University of Copenhagen. The Centre will from the start be strongly connected with the University of Copenhagen. The Niels Bohr Institute will supply the infra structure including laboratory facilities and technical and administrative support as outlined in the Budget.

12. Management Plan

12.1 Approach

The Centre will accomplish its scientific, technical and educational objectives by drawing on the entire team, placed at the Centre in cooperation with the star-partners (see section 7.1) who will be mainly placed at their institutions. We will generate a detailed operational plan, based on the milestones described in the application during the first three months of the Centre operation. We will hold monthly team meetings to review progress and discuss any problems. Summaries from these meetings will be made available on the Centre's homepage.

12.2 Organization

Professor Dorthe Dahl-Jensen will serve as the Centre Director. She will be responsible for planning, organizing, directing and controlling the Centre's operation. She will maintain necessary relationships. The Director will be advised by an Advisory board consisting of the Centre team (see enclosure 3) and star-partners (see section 7.1). The Centre will hold two workshops each year and these workshops will also create opportunities for Advisory board meetings. The Advisory board will provide input and advice on the long-term Centre goals and strategies as well as short-term milestones (milestones described in enclosure 1). The Centre will coordinate the international programs and host/support meetings, workshops and visiting programs also for the international projects, NEEM and IPY Stability of the Greenland Ice Sheet.

Reference List

1. Landais, A., N. Combourieu Nebout, Masson-Delmotte, V., Jouzel, J., Blunier, T., Leuenberger, M., Dahl-Jensen, D., Johnsen, S., Barkan, E. & Luz, B. Millenial scale of the isotopic composition of atmospheric oxygen over MIS 4. *Earth and Planetary Science Letters* (in preparation).
2. Schmitt, M. & Fischer, H. A sublimation technique for high-precision $\delta^{13}C$ on CO_2 and CO_2 mixing ratio from air trapped in deep ice cores. *Rapid Communications in Mass Spectrometry* (2006, submitted).
3. Andersen, K. K., Svensson, A., Rasmussen, S. O., Steffensen, J. P., Johnsen, S. J., Bigler, M., Röthlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Dahl-Jensen, D., Vinther, B. M. & Clausen, H. B. The Greenland Ice Core Chronology 2005, 15-42 kyr. Part 1: Constructing the time scale. *Quaternary Science Reviews, Shackleton Special Issue* (2006, submitted).
4. Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., Johnsen, S. J., Muscheler, R., Rasmussen, S. O., Röthlisberger, R., Steffensen, J. P. & Vinther, B. M. The Greenland Ice Core Chronology 2005, 15-42 kyr. Part 2: Comparison to other records. *Quaternary Science Reviews, Shackleton Special Issue* (2006, submitted).
5. Greve, R. Relation of measured basal temperatures and the spatial distribution of the geothermal heat flux for the Greenland ice sheet. *Annals of Glaciology* **42** (2005, in press).
6. Alley, R. B., Clark, P. U., Huybrechts, P. & Joughin, I. Ice-sheet and sea-level changes. *Science* **310**, 456-460 (2005).
7. Fischer, H. & Mieding, B. A 1,000-year ice core record of interannual to multidecadal variations in atmospheric circulation over the North Atlantic. *Climate Dynamics* **25**, 65-74 (2005).
8. Masson-Delmotte, V., Jouzel, J., Landais, A., Stievenard, M., Johnsen, S. J., White, J. W. C., Werner, M., Sveinbjornsdottir, A. & Fuhrer, K. GRIP deuterium excess reveals rapid and orbital-scale changes in Greenland moisture origin. *Science* **309**, 118-121 (2005).
9. Masson-Delmotte, V., Landais, A., Stievenard, M., Cattani, O., Falourd, S., Jouzel, J., Johnsen, S. J., Dahl-Jensen, D., Sveinbjornsdottir, A., White, J. W. C., Popp, T. & Fisher, H. Holocene climatic changes in Greenland: Different deuterium excess signals at Greenland Ice Core Project (GRIP) and NorthGRIP. *Journal of Geophysical Research* **110**, D14102, doi:10.1029/2004JD005575 (2005).
10. Paden, J. D., Allen, C. T., Gogineni, S., Jezek, K. C., Dahl-Jensen, D. & Larsen, L. B. Wideband measurements of ice sheet attenuation and basal scattering. *Geoscience and Remote Sensing Letters, IEEE* **2**, doi:10.1109/LGRS.2004.842474 (2005).
11. Siegenthaler, U., Stocker, T. F., Monnin, E., Lüthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J.-M., Fischer, H., Masson-Delmotte, V. & Jouzel, J. Stable carbon cycle–climate relationship during the Late Pleistocene. *Science* **310**, 1313-1317 (2005).
12. Spahni, R., Chappellaz, J., Stocker, T. F., Loulergue, L., Hausammann, G., Kawamura, K., Flückiger, J., Schwander, J., Raynaud, D., Masson-Delmotte, V. & Jouzel, J. Atmospheric methane and nitrous oxide of the Late Pleistocene from Antarctic ice cores. *Science* **310**, 1317-1321 (2005).

13. Bauer, E., Ganopolski, A. & Montoya, M. Simulation of the cold climate event 8200 years ago by meltwater outburst from Lake Agassiz. *Paleoceanography* **19**, PA3014, doi:10.1029/2004PA001030 (2004).
14. Loutre, M.-F., Paillard, D., Vimeux, F. & Cortijo, E. Does mean annual insolation have the potential to change the climate? *Earth and Planetary Science Letters* **221**, 1-14 (2004).
15. Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlén, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., Kreveld, S. v., Holmgren, K., Lee-Thorph, J., Rosqvistd, G., Racki, F., Staubwasserj, M., Schneiderk, R. R. & Steigl, E. J. Holocene climate variability. *Quaternary Research* **62**, 243-255 (2004).
16. Monnin, E., Steig, E. J., Siegenthaler, U., Kawamura, K., Schwander, J., Stauffer, B., Stocker, T. F., Morse, D. L., Barnola, J.-M., Bellier, B., Raynaud, D. & Fischer, H. Evidence for substantial accumulation rate variability in Antarctica during the Holocene through synchronisation of CO_2 in the Taylor Dome, Dome C and DML ice cores. *Earth and Planetary Science Letters* **224**, 45-54 (2004).
17. North Greenland Ice-Core Project (NorthGRIP) Members. High resolution Climate Record of the Northern Hemisphere reaching into the last Glacial Interglacial Period. *Nature* **431**, 147-151 (2004).
18. Trudinger, C. M., Etheridge, D. M., Sturrock, G. A., Fraser, P. J., Krummel, P. B. & McCulloch, A. Atmospheric histories of halocarbons from analysis of Antarctic firn air: Methyl bromide, methyl chloride, chloroform, and dichloromethane. *Journal of Geophysical Research* **109**, D22310, doi:10.1029/2004JD004932 (2004).
19. Dahl-Jensen, D., Gundestrup, N., Gorgineni, S. P. & Miller, H. Basal melt at NorthGRIP modeled from borehole, ice-core and radio-echo sounder observations. *Annals of Glaciology* **37**, 207-212 (2003).
20. Francey, R. J., Steele, L. P., Spencer, D. A., Langenfelds, R. L., Law, R. M., Krummel, P. B., Fraser, P. J., Etheridge, D. M., Derek, N., Coram, S. A., Cooper, L. N., Allison, C. E., Porter, L. & Baly, S. The CSIRO (Australia) measurement of greenhouse gases in the global atmosphere. In: Report of the eleventh WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracer Measurement Techniques, Tokyo, Japan, S. Toru, and S. Kazuto (editors) (Global Atmosphere Watch, no. 148 ; WMO/TD ; no. 1138) . [Geneva]: World Meteorological Organization. p. 97-106. (2003).
21. Marsland, S. J., Haak, H., Jungclaus, J. H., Latif, M. & Röske, F. The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates. *Ocean Modelling* **5**, 91-127 (2003).
22. Stocker, T. F. & Johnsen, S. J. A minimum thermodynamic model for the bipolar seesaw. *Paleoceanography* **18**, 1087, doi:10.1029/2003PA000920 (2003).
23. Vinther, B. M., Johnsen, S. J., Andersen, K. K., Clausen, H. B. & Hansen, A. W. NAO signal recorded in the stable isotopes of Greenland ice cores. *Geophysical Research Letters* **30**, 1387, doi: 10.1029/2002GL016193 (2003).
24. Bendtsen, J., Lundsgaard, C., Middelboe, M. & Archer, D. Influence of bacterial uptake on deep-ocean dissolved organic carbon. *Global Biogeochemical Cycles* **16**, 1127, doi:10.1029/2002GB001947 (2002).
25. Brovkin, V., Bendtsen, J., Claussen, M., Ganopolski, A., Kubatzki, C., Petoukhov, V. & Andreev, A. Carbon cycle, vegetation, and climate dynamics in the Holocene: Experiments with the CLIMBER-2 model. *Global Biogeochemical Cycles* **16**, 1139, doi:10.1029/2001GB001662 (2002).

26. Hvidberg, C. S., Keller, K. & Gundestrup, N. S. Mass balance and ice flow along the north-northwest ridge of the Greenland ice sheet at NorthGRIP. *Annals of Glaciology* **35**, 521-526 (2002).
27. Mayer, C., Bøggild, C. E., Podlech, S., Olesen, O. B., Ahlstrøm, A. P. & Krabill, W. Glaciological investigations on ice-sheet response in South Greenland. *Geology of Greenland Surrey Bulletin, GEUS* **191**, 150-156 (2002).
28. Cuffey, K. M. & Vimeux, F. Covariation of carbon dioxide and temperature from the Vostok ice core after deuterium-excess correction. *Nature* **412**, 523-527 (2001).
29. Vimeux, F., Masson, V., Jouzel, J., Petit, J. R., Steig, E. J., Stievenard, M., Vaikmae, R. & White, J. W. C. Holocene hydrological cycle changes in the Southern Hemisphere documented in East Antarctic deuterium excess records. *Climate Dynamics* **17**, 503-513 (2001).
30. Greve, R. On the response of the Greenland ice sheet to greenhouse climate change. *Climatic Change* **46**, 289-303 (2000).
31. Dahl-Jensen, D., Morgan, V. I. & Elcheikh, A. Monte Carlo inverse modelling of the Law Dome (Antarctica) temperature profile. *Annals of Glaciology* **29**, 145-150 (1999).
32. Fischer, H., Wahlen, M., Smith, J., Mastroianni, D. & Deck, B. Ice core records of atmospheric CO_2 around the last three glacial terminations. *Science* **283**, 1712-1714 (1999).
33. Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Katlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E. & Stievenard, M. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**, 429-436 (1999).
34. Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G. D., Johnsen, S. J., Hansen, A. W. & Balling, N. Past temperatures directly from the Greenland ice sheet. *Science* **282**, 268-271 (1998).
35. Etheridge, D. M., Steele, L. P., Francey, R. J. & Langenfelds, R. L. Atmospheric methane between 1000 A.D. and present: evidence of anthropogenic emissions and climatic variability. *Journal of Geophysical Research* **103**, 15979-15993 (1998).
36. Greve, R. Large-scale ice-sheet modelling as a means of dating deep ice cores in Greenland. **43**, 307–310 (1997).
37. Schwander, J., Sowers, T., Barnola, J.-M., Blunier, T., Fuchs, A. & Malaizé, B. Age scale of the air in the Summit ice: Implication for glacial-interglacial temperature change. *Journal of Geophysical Research* **102**, 19483-19493 (1997).
38. Smith, H. J., Wahlen, M., Mastroianni, D., Taylor, K. & Mayewski, P. The CO_2 concentration of air trapped in Greenland Ice Sheet Project 2 ice formed during periods of rapid climate change. *Journal of Geophysical Research* **102**, 26577-26582 (1997).
39. Anklin, M., Barnola, J.-M., Schwander, J., Stauffer, B. & Raynaud, D. Processes affecting the CO_2 concentration measured in Greenland ice. *Tellus B* **47**, 461-470 (1995).
40. Johnsen, S., Dahl-Jensen, D., Dansgaard, W. & Gundestrup, N. Greenland palaeotemperatures derived from GRIP bore hole temperature and ice core isotope profiles. *Tellus B* **47**, 624-629 (1995).
41. White, J. W. C., Barlow, L. K. & Gorodetzky, D. (Wolfeboro, N.Y., 1995).
42. Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S. J. & Jouzel, J. Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. *Nature* **366**, 552-554 (1993).

43. Beer, J., Finkel, R. C., Bonani, G., Gäggeler, H., Görlach, U., Jacob, P., Klockow, D., Langway, J. C. C., Neftel, A., Oeschger, H., Schotterer, U., Schwander, J., Siegenthaler, U., Suter, M., Wagenbach, D. & Wölfli, W. Seasonal variations in the concentration of 10Be, Cl-, NO3-, SO4 2-, H2O2, 210Pb, 3H, mineral dust, and d18O in Greenland snow. *Atmospheric Environment* **25A**, 899-904 (1991).
44. Johnsen, S. J., Dansgaard, W. & White, J. W. C. The origin of Arctic precipitation under present and glacial conditions. *Tellus B* **41**, 452-468 (1989).
45. Etheridge, D. M., Pearman, G. I. & de Silva, F. Atmospheric trace-gas variations as revealed by air trapped in an ice core from Law Dome, Antarctica. *Annals of Glaciology* **10**, 28-33 (1988).
46. Steffensen, J. P. Analysis of the seasonal variation in dust, Cl^-, NO_3^-, and SO_4^{2-} in two Central Greenland firn cores. *Annals of Glaciology* **10**, 171-177 (1988).
47. Fisher, D. A., Reeh, N. & Clausen, H. B. Stratigraphic noise in time series derived from ice cores. *Annals of Glaciology* **7**, 76-83 (1985).
48. Johnsen, S. J. in *Proc. of Symp. on Isotopes and Impurities in Snow and Ice, I.U.G.G. XVI, General Assembly, Grenoble Aug. Sept., 1975* 210-219 (Washington D.C., 1977).
49. Johnsen, S. J. in *Proc. of Symp. on Isotopes and Impurities in Snow and Ice, I.U.G.G. XVI, General Assembly, Grenoble Aug. Sept., 1975* 388-392 (Washington D.C., 1977).
50. Dansgaard, W., Johnsen, S. J., Clausen, H. B. & Gundestrup, N. Stable isotope glaciology. *Meddelelser om Grønland* **197**, 1-53 (1973).
51. Dansgaard, W. Oxygen-18 abundance in fresh water. *Nature* **174**, 234-235 (1954).

Reference List:

1. Wolff, E. W. et al. Southern Ocean sea ice, DMS production and iron flux over the last eight glacial cycles. *Nature* (in press).
2. Landais, A. et al. Millenial scale of the isotopic composition of atmospheric oxygen over MIS 4. *Earth and Planetary Science Letters* (in preparation).
3. Svensson, A. et al. The Greenland Ice Core Chronology 2005,15-41 ka. Part 2: Comparison to other records. *Quaternary Science Reviews, Shackleton special edition* (In preparation).
4. Schmitt, M. et al. A sublimation technique for high-precision $\delta^{13}C$ on CO_2 and CO_2 mixing ratio from air trapped in deep ice cores. *Rapid Communications in Mass Spectrometry* (2066, submitted).
5. Andersen, K. K. et al. The Greenland Ice Core Chronology 2005, 15-42 kyr. Part 1: Constructing the time scale. *Quaternary Science Reviews, Shackleton Special Issue* (2006, submitted).
6. Svensson, A. et al. The Greenland Ice Core Chronology 2005, 15-42 kyr. Part 2: Comparison to other records. *Quaternary Science Reviews, Shackleton Special Issue* (2006, submitted).
7. Fischer, H. et al. Glacial/interglacial changes in mineral dust and sea salt records in polar ice cores: Sources, transport, and deposition. *Reviews of Geophysics* (2006, in press).
8. Bigler, M. et al. Aerosol deposited in East Antarctica over the last glacial cycle: Detailed apportionment of continental and sea-salt contributions. *Journal of Geophysical Research* **111**, D08205, doi:10.1029/2005JD006469 (2006).

9. Andersen, K. K. et al. Retrieving a common accumulation record from Greenland ice cores for the past 1800 years. *Journal of Geophysical Research* (2005, submitted).
10. Greve, R. Relation of measured basal temperatures and the spatial distribution of the geothermal heat flux for the Greenland ice sheet. *Annals of Glaciology* **42** (2005, in press).
11. Alley, R. B. et al. Ice-sheet and sea-level changes. *Science* **310**, 456-460 (2005).
12. Ferretti, D. F. et al. Unexpected changes to the global methane budget over the past 2000 years. *Science* **309**, 1714-1717 (2005).
13. Fischer, H. et al. A 1,000-year ice core record of interannual to multidecadal variations in atmospheric circulation over the North Atlantic. *Climate Dynamics* **25**, 65-74 (2005).
14. Jickells, T. D. et al. Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science* **308**, 67-71 (2005).
15. Masson-Delmotte, V. et al. GRIP deuterium excess reveals rapid and orbital-scale changes in Greenland moisture origin. *Science* **309**, 118-121 (2005).
16. Masson-Delmotte, V. et al. Holocene climatic changes in Greenland: Different deuterium excess signals at Greenland Ice Core Project (GRIP) and NorthGRIP. *Journal of Geophysical Research* **110**, D14102, doi:10.1029/2004JD005575 (2005).
17. Paden, J. D. et al. Wideband measurements of ice sheet attenuation and basal scattering. *Geoscience and Remote Sensing Letters, IEEE* **2**, doi:10.1109/LGRS.2004.842474 (2005).
18. Siegenthaler, U. et al. Stable carbon cycle–climate relationship during the Late Pleistocene. *Science* **310**, 1313-1317 (2005).
19. Spahni, R. et al. Atmospheric methane and nitrous oxide of the Late Pleistocene from Antarctic ice cores. *Science* **310**, 1317-1321 (2005).
20. Svensson, A. et al. Visual stratigraphy of the North Greenland Ice Core Project (NorthGRIP) ice core during the last glacial period. *Journal of Geophysical Research* **110**, D02108, doi:10.1029/2004JD005134 (2005).
21. Bauer, E. et al. Simulation of the cold climate event 8200 years ago by meltwater outburst from Lake Agassiz. *Paleoceanography* **19**, PA3014, doi:10.1029/2004PA001030 (2004).
22. EPICA community members. Eight glacial cycles from an Antarctic ice core. *Nature* **429**, 623-628 (2004).
23. Loutre, M.-F. et al. Does mean annual insolation have the potential to change the climate? *Earth and Planetary Science Letters* **221**, 1-14 (2004).
24. Mayewski, P. A. et al. Holocene climate variability. *Quaternary Research* **62**, 243-255 (2004).
25. Monnin, E. et al. Evidence for substantial accumulation rate variability in Antarctica during the Holocene through synchronisation of CO_2 in the Taylor Dome, Dome C and DML ice cores. *Earth Planetary Science Letters* **224**, 45-54 (2004).
26. North Greenland Ice-Core Project (NorthGRIP) Members. High resolution Climate Record of the Northern Hemisphere reaching into the last Glacial Interglacial Period. *Nature* **431**, 147-151 (2004).
27. Trudinger, C. M. et al. Atmospheric histories of halocarbons from analysis of Antarctic firn air: Methyl bromide, methyl chloride, chloroform, and dichloromethane. *Journal of Geophysical Research* **109**, D22310, doi:10.1029/2004JD004932 (2004).
28. Dahl-Jensen, D. et al. Basal melt at NorthGRIP modeled from borehole, ice-core and radio-echo sounder observations. *Annals of Glaciology* **37**, 207-212 (2003).
29. Francey, R. J. et al. The CSIRO (Australia) measurement of greenhouse gases in the global atmosphere. In: Report of the eleventh WMO/IAEA Meeting of Experts on

Carbon Dioxide Concentration and Related Tracer Measurement Techniques, Tokyo, Japan, S. Toru, and S. Kazuto (editors) (Global Atmosphere Watch, no. 148 ; WMO/TD ; no. 1138) . [Geneva]: World Meteorological Organization. p. 97-106. (2003).

30. Marsland, S. J. et al. The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates. *Ocean Modelling* **5**, 91-127 (2003).
31. Ruth, U. et al. Continuous record of microparticle concentration and size distribution in the central Greenland NGRIP ice core during the last glacial period. *Journal of Geophysical Research* **108**, 4098, doi:10.1029/2002JD002376 (2003).
32. Stocker, T. F. et al. A minimum thermodynamic model for the bipolar seesaw. *Paleoceanography* **18**, 1087, doi:10.1029/2003PA000920 (2003).
33. Vinther, B. M. et al. NAO signal recorded in the stable isotopes of Greenland ice cores. *Geophysical Research Letters* **30**, 1387, doi: 10.1029/2002GL016193 (2003).
34. Bendtsen, J. et al. Influence of bacterial uptake on deep-ocean dissolved organic carbon. *Global Biogeochemical Cycles* **16**, 1127, doi:10.1029/2002GB001947 (2002).
35. Bigler, M. et al. Sulphate record from a northeast Greenland ice core over the last 1200 years based on continuous flow analysis. *Annals of Glaciology* **35**, 250-256 (2002).
36. Bory, A. J.-M. et al. Seasonal variability in the origin of recent atmospheric mineral dust at NorthGRIP, Greenland. *Earth and Planetary Science Letters* **196**, 123-134 (2002).
37. Brovkin, V. et al. Carbon cycle, vegetation, and climate dynamics in the Holocene: Experiments with the CLIMBER-2 model. *Global Biogeochemical Cycles* **16**, 1139, doi:10.1029/2001GB001662 (2002).
38. Hvidberg, C. S. et al. Mass balance and ice flow along the north-northwest ridge of the Greenland ice sheet at NorthGRIP. *Annals of Glaciology* **35**, 521-526 (2002).
39. Mayer, C. et al. Glaciological investigations on ice-sheet response in South Greenland. *Geology of Greenland Surrey Bulletin*, *GEUS* **191**, 150-156 (2002).
40. Cuffey, K. M. et al. Covariation of carbon dioxide and temperature from the Vostok ice core after deuterium-excess correction. *Nature* **412**, 523-527 (2001).
41. Johnsen, S. J. et al. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. *Journal of Quaternary Science* **16**, 299-307 (2001).
42. Vimeux, F. et al. Holocene hydrological cycle changes in the Southern Hemisphere documented in East Antarctic deuterium excess records. *Climate Dynamics* **17**, 503-513 (2001).
43. Greve, R. On the response of the Greenland ice sheet to greenhouse climate change. *Climatic Change* **46**, 289-303 (2000).
44. Dahl-Jensen, D. et al. Monte Carlo inverse modelling of the Law Dome (Antarctica) temperature profile. *Annals of Glaciology* **29**, 145-150 (1999).
45. Fischer, H. et al. Ice core records of atmospheric CO_2 around the last three glacial terminations. *Science* **283**, 1712-1714 (1999).
46. Petit, J. R. et al. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**, 429-436 (1999).
47. Trudinger, C. M. et al. Long-term variability in the global carbon cycle inferred from a high-precision CO_2 and $\delta^{13}C$ ice-core record. *Tellus B* **51**, 233-248 (1999).
48. Dahl-Jensen, D. et al. Past temperatures directly from the Greenland ice sheet. *Science* **282**, 268-271 (1998).

49. Etheridge, D. M. et al. Atmospheric methane between 1000 A.D. and present: evidence of anthropogenic emissions and climatic variability. *Journal of Geophysical Research* **103**, 15979-15993 (1998).
50. Greve, R. Large-scale ice-sheet modelling as a means of dating deep ice cores in Greenland. **43**, 307–310 (1997).
51. Schwander, J. et al. Age scale of the air in the Summit ice: Implication for glacial-interglacial temperature change. *Journal of Geophysical Research* **102**, 19483-19493 (1997).
52. Smith, H. J. et al. The CO_2 concentration of air trapped in Greenland Ice Sheet Project 2 ice formed during periods of rapid climate change. *Journal of Geophysical Research* **102**, 26577-26582 (1997).
53. Etheridge, D. M. et al. Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice firn. *Journal of Geophysical Research* **101**, 4115-4128 (1996).
54. Anklin, M. et al. Processes affecting the CO_2 concentration measured in Greenland ice. *Tellus B* **47**, 461-470 (1995).
55. Johnsen, S. et al. Greenland palaeotemperatures derived from GRIP bore hole temperature and ice core isotope profiles. *Tellus B* **47**, 624-629 (1995).
56. White, J. W. C. et al. (Wolfeboro, N.Y., 1995).
57. Dansgaard, W. et al. Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* **364**, 218-220 (1993).
58. Grootes, P. M. et al. Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. *Nature* **366**, 552-554 (1993).
59. Beer, J. et al. Seasonal variations in the concentration of 10Be, Cl-, NO3-, SO4 2-, H2O2, 210Pb, 3H, mineral dust, and d18O in Greenland snow. *Atmospheric Environment* **25A**, 899-904 (1991).
60. Johnsen, S. J. et al. The origin of Arctic precipitation under present and glacial conditions. *Tellus B* **41**, 452-468 (1989).
61. Etheridge, D. M. et al. Atmospheric trace-gas variations as revealed by air trapped in an ice core from Law Dome, Antarctica. *Annals of Glaciology* **10**, 28-33 (1988).
62. Steffensen, J. P. Analysis of the seasonal variation in dust, Cl^-, NO_3^-, and SO_4^{2-} in two Central Greenland firn cores. *Annals of Glaciology* **10**, 171-177 (1988).
63. Fisher, D. A. et al. Stratigraphic noise in time series derived from ice cores. *Annals of Glaciology* **7**, 76-83 (1985).
64. Dansgaard, W. et al. A new Greenland deep ice core. *Science* **218**, 1273-1277 (1982).
65. Johnsen, S. J. in *Proc. of Symp. on Isotopes and Impurities in Snow and Ice, I.U.G.G. XVI, General Assembly, Grenoble Aug. Sept., 1975* 210-219 (Washington D.C., 1977).
66. Johnsen, S. J. in *Proc. of Symp. on Isotopes and Impurities in Snow and Ice, I.U.G.G. XVI, General Assembly, Grenoble Aug. Sept., 1975* 388-392 (Washington D.C., 1977).
67. Dansgaard, W. et al. Stable isotope glaciology. *Meddelelser om Grønland* **197**, 1-53 (1973).
68. Dansgaard, W. et al. A flow model and a time scale for the ice core from Camp Century, Greenland. *Journal of Glaciology* **8**, 215-223 (1969).
69. Dansgaard, W. Oxygen-18 abundance in fresh water. *Nature* **174**, 234-235 (1954).