Bjerknes Centre for Climate Research – combining past, present and future climate change

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Climate change is one of the most pressing issues facing the world today. With increasing levels of greenhouse gases in the atmosphere, climate changes will play an increasing role for society in the future. The Bjerknes Centre for Climate Research (BCCR) is a joint climate research venture between the University of Bergen (UoB), the Institute of Marine Research (IMR) and the Nansen Environmental and Remote Sensing Center (NERSC). The BCCR integrates observationalists and modellers in a concerted interdisciplinary research effort with the ambition to be a world-class centre on studies of high-latitude climate change. The BCCR is the largest climate research group in Norway and the ambition is to become a leading international centre for climate research and to be the principal provider of high quality knowledge on climate change for the Norwegian public and decision makers.

Introduction

Climate change is one of the most pressing issues facing the world today. With the increasing levels of greenhouse gases in the atmosphere, climate changes will play an increasing role for society in the future. Predicting future climates is a daunting and complex task where both basic knowledge of the way the climate system operates and prognoses of future socio-economic trends are required. Presently there are large uncertainties associated with future climate scenarios, particularly at the regional scale. To underpin policymaking and public awareness, there is a pressing need for updated and accurate understanding of the magnitude and expression of climate changes. We need to reduce the uncertainties in climate change predictions, in order to provide a sound basis for policymakers, and to provide a scientific basis for adaptation and mitigation strategies. This should be based on the best available fundamental knowledge of the climate system and how it operates. The ambition of the Bjerknes Centre for Climate Research (BCCR) is to become a leading international centre for climate research and to be the principal provider of high quality knowledge on climate change for the Norwegian public and decision makers. The centre has acquired unique expertise regarding high-latitude climate change.

The BCCR specifically aims to deliver important research results in order to understand and quantify regional climate changes in the context of the global climate system. It has a special focus on the role of the ocean in the climate system and the climate processes and climate variability in high-latitude regions. To reach its objectives the BCCR is organised in 8 multi-disciplinary research teams each consisting of 10-20 scientists and graduate students. These teams are formed to address three main research themes:

1. *To understand the causes and likelihood of high amplitude rapid climate change and assess the possibilities for major climate surprises affecting our region (Northern Europe and adjacent oceans including the Arctic).*
2. *To understand the causes of climate variability, both natural and manmade, to assess climate trends and the predictability of climate changes, in order to deliver high quality scenarios of future climate change*
3. *To study and understand key processes and feedbacks governing the response and sensitivity to climate forcing.*

Compared with other international climate research centres, the BCCR combines a unique combination of expertise. It combines strong research groups studying past climate change and natural climate variability (Palaeoclimatology), with groups studying and observing climate changes and climate processes as they unfold today, and a growing group of climate modellers who use numerical modelling of the climate system as a research tool. The BCCR has developed and operates a global Atmosphere/Ocean General Circulation Climate Model (GCM) tailored for studies of high-latitude regions and processes. This is the main modelling tool and is used for climate predictions. BCCR also takes part (in collaboration with scientists at MIT) in the development of a less complex model for climate simulations extending over thousands of years and for sensitivity experiments. Three institutions in Bergen collaborate in the BCCR. These include University of Bergen (host institution), Nansen Environmental and Remote Sensing Center and the Institute for Marine Research. This collaboration amounts to about 70 person years and involves about 100 persons. Funding for the activities comes from the Norwegian Research Council, the participating institutions and from EU Research Programmes. The research activities are performed in collaboration with the main international climate research centres. Since its start, BCCR scientists have published about 200 peer-reviewed research papers, several in influential journals, such as *Nature* and *Science*.

In the following pages we emphasise research activities that are most relevant for a geological audience, i.e. some of the palaeoclimatology activities. These are carried out by research groups working both in the marine realm and on land, as well as climate modellers focussing on palaeoclimate.

Abrupt climate change

The possibility of abrupt changes in the climate of Northern Europe is a question of great concern. Although most climate models indicate the likelihood that these will occur in the next 100 years or so, is not high, we know too little about the fundamental mechanisms behind them to be certain about such assessments. Abrupt changes constitute therefore a problem with low likelihood, but with a huge impact, should they occur. We know from palaeoclimatic evidence that such changes have occurred numerous times during the ice ages, with severe global impact (Fig. 1). The research community agrees that these took place due to major changes in ocean circulation (e.g. Dokken & Jansen 1999), during which the northward heat transport in the Atlantic ocean changed dramatically over time spans of a few decades. Another aspect of this pattern is the so-called 'bipolar seesaw', which is based on the observation that when the North Atlantic cools, the Southern Ocean warms (Crowley 1992; Broecker 1998).

It is therefore becoming increasingly clear that the current mode of circulation of the oceans is not unique

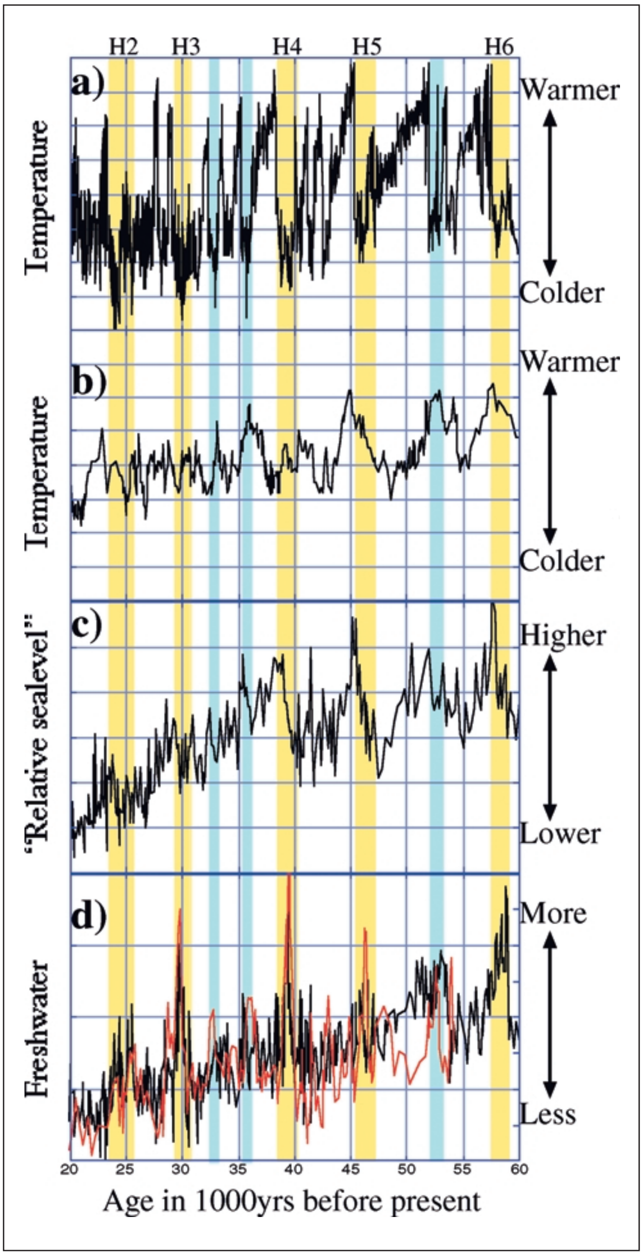

Fig. 1. Observations illustrating the "bipolar seesaw" and abrupt climate changes during the last glacial period. a) GRIP ice core isotope (temperature) data, b) Byrd ice core isotope (temperature) data (presented on same time scale as GRIP), c) benthic (deep water) isotope data (here a measure for relative global sea level), and d) planktonic (surface) isotope data (a measure of temperature and surface water salinity) from the North Atlantic (Dokken & Jansen 1999). All these data are synchronised with the Greenland GISP ice core record. Strong Northern Hemisphere cooling episodes during the last glacial commonly coincide with increased freshwater release to the North Atlantic region. The strongest freshwater perturbations are observed during so-called Heinrich events (yellow bars) and a few other cold episodes from Greenland temperature data (light blue bars), which occured at the same time as the most pronounced warm events in the southern hemisphere. Evidence for reduced deepwater formation is most significant during Heinrich events, which agrees with the predicted reduction in MOC and northward heat transport in response to a freshening of the North Atlantic. Sea level data c) indicate an in-phase relationship with southern temperatures and North Atlantic fresh water events, as is also reproduced in models.

and that, given the right boundary conditions, it may switch rapidly between dramatically different states with severe and far-reaching climatic repercussions. Yet, the various processes considereed to have driven these past oceanic reorganizations remain largely unconstrained, preventing reliable assessments of the ocean's vulnerability to future changes to be made. Most models attempting to simulate these oceanic switches activate them by disturbing the pole-to-pole density gradients in the oceans which support meridional overturning circulation (MOC).

Perhaps the most commonly invoked theories to explain MOC changes focus on the importance of Northern Hemisphere ice sheet-ocean interactions due to the ability of ice sheets to act as buoyancy capativators—slowly building up large stores of freshwater which are then discharged catastrophically. Numerous model simulations introducing freshwater (low density) anomalies near sites of deep-water formation in the North Atlantic are able to inhibit deep-water production and cause climate changes across much of the globe (e.g. Ganopolski & Rahmstorf 2001). An interesting test would be to see how well observed fresh-water anomalies in the North Atlantic region fit with ice core temperature data. The expected outcome from the models is that every cooling episode in the Northern Hemisphere that corresponds to a strong warming in the Southern Hemisphere should have an amplified melt water imprint in the North Atlantic. Such testing requires ocean sediment core data that can be synchronized with ice core data.

However, simulations introducing similar anomalies in the regions of Southern Ocean water mass formation indicate that this type of influence is not unique to the Northern Hemisphere (Weaver et al. 2003). In fact, a variety of Southern Ocean processes, from the strength of the westerly winds and the circumpolar current to gradual warming, have been postulated to modulate MOC (e.g. Ninnemann & Charles 2002; Lamy et al. 2004). Even ocean-atmosphere reorganizations far from sites of water mass formation, such as those involving the tropical hydrological cycle and Atlantic-Pacific moisture transport, have been implicated in MOC changes. Therefore, a better understanding why shifts in MOC occur requires an appreciation of both Northern and Southern Hemisphere processes. At present we lack the necessary material to provide palaeoceanographic constraints on the antecedents of MOC mode switches from this bipolar perspective. Within the BCCR this problem is tackled by involving reconstructions of the spatial and temporal development of the ocean circulation from records of past temperature and density structure of the oceans developed from sediment cores at key localities in the North Atlantic and other nordic seas as well as in the Southern Ocean. The reconstructions cover key phases when the abrupt changes unfold, such as the Younger Dryas cooling and the Dansgaard-Oeschger events of the last glaciation. Assisted by numerical model simulations, the objective is to determine both the structure and the dynamics of such changes. We believe this will also aid in our assessments of possible future changes and in strategies to monitor and detect abrupt changes if they should become triggered. Since instrumental measurements of the deep ocean only extend 50 years back in time, the only means we have to evaluate the full range of ocean circulation changes is via these palaeoclimatic methods.

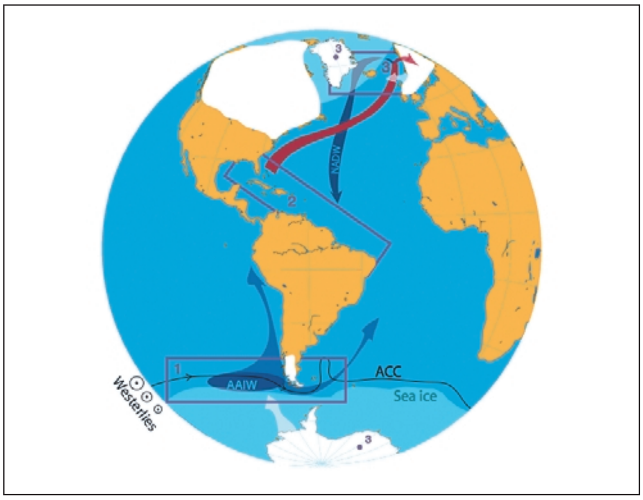

Fig. 2. Schematic diagram illustrating some of the key processes potentially driving abrupt climate changes, and the key regions in 1. The Southern Ocean, 2 The tropical Atlantic and 3. The Northern North Atlantic and Nordic Seas. NADW= North Atlantic Deep Water, AAIW= Antarctic Intermediate Water, ACC= Antarctic Circumpolar Current.

Another key aspect of this problem is the possible link between high-latitude and low-latitude processes. Palaeoceanographic evidence seems to confirm that the tropical and extratropical Atlantic are indeed tightly linked on longer timescales. Sediment records from the Cariaco Basin show that the tropical Atlantic Ocean and atmospheric changes are correlative with variations in the North Atlantic region since the last glacial period (Hughen et al. 1996; Lea et al. 2003). Specifically, southward shifts of the Intertropical Convergence Zone (ITCZ) and changes in the north-easterly trades regularly accompany cooling episodes recorded in Greenlandic ice cores. Model results suggest that these regions may be connected by an *atmospheric bridge*, whereby changes in the extent of high-latitude sea ice may affect meridional displacements of the ITCZ (Chiang et al. 2003). Figure 2 describes, schematically, some of these linkages.

The records of past oceanic-atmospheric changes contained in sediment archives provide a natural testing ground for the various hypotheses. Unfortunately,

Fig. 3. BCCR scientists take part in global sediment coring efforts onboard the French RV Marion Dufresne via the Images Program. Lower picture shows the Calypso giant coring system in operation, capable of taking 60m long cores. A modified version of the system is installed on the new research vessel G.O.Sars operated by the University of Bergen and the Institute of Marine Research.

palaeoceanographic constraints are not available from key regions for carrying out these tests, and the aim of the BCCR is to provide these critical data sets and models of associated dynamics to resolve the first order scientific issues raised by past abrupt climate changes. In doing so the BCCR participates in a number of international projects and programmes, e.g. the IMAGES Program (Marine Aspects of Past Global Changes) (Fig. 3) and IODP (the Integrated Ocean Drilling Program) and multilateral collaborative projects funded by the EU and national funding agencies.

Holocene climate variability in the North Atlantic region

BCCR is very active in reconstructing and understanding natural climate variability on different time scales. It is of great importance to know the natural variability: it interacts with human-induced changes, it can explain many of the modes of climate system behaviour, and it is highly useful to enable us to estimate climate system sensitivity to forcing factors, including the greenhouse gases, and to validate climate models

Fig. 4. Glaciers form a key climate archive for BCCR palaeoclimatologists. Here we see many of the worlds principal palaeoclimatologists visting the Nigardsbreen glacier in conjunction with a BCCR workshop on Holocene climate change.

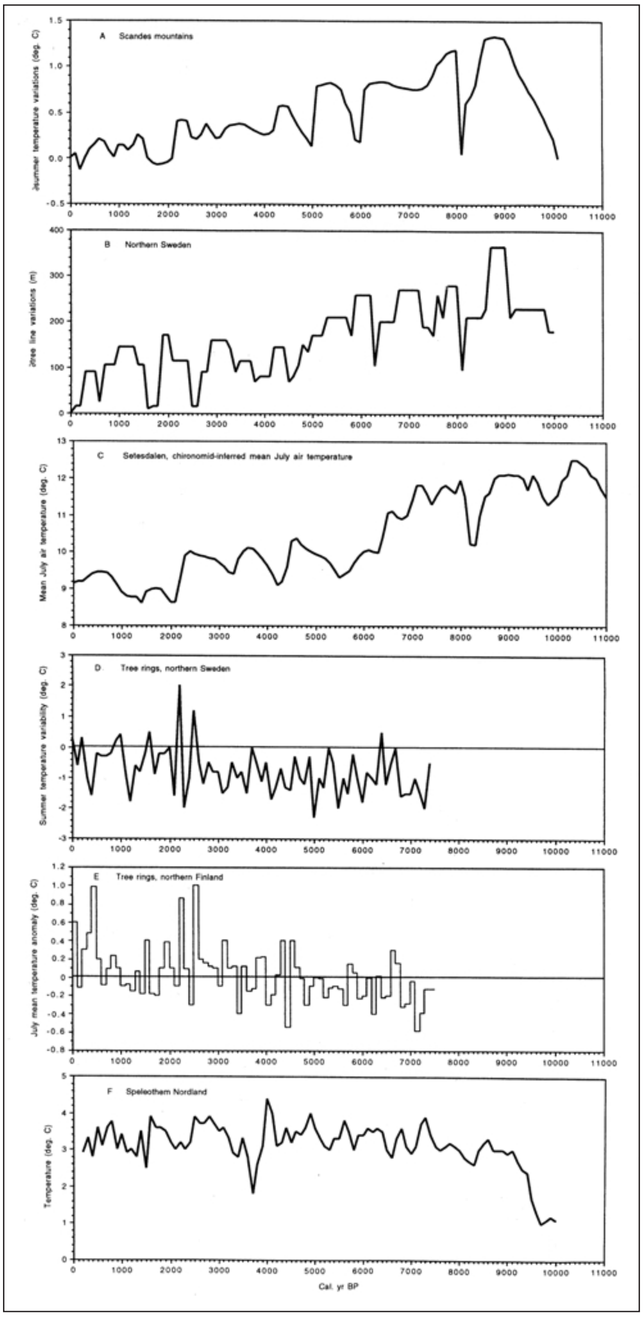

Fig. 5. (A) Holocene summer temperature in the southern Scandes mountains (Dahl & Nesje 1996) mainly based on pine tree-line variations reconstructed by Kullman (1981). (B) Pine tree-limit variations in northern Sweden relative to the modern pine tree-line (Karlén & Kuylenstierna 1996). (C) Chironomid-inferred mean July air temperature variations from the Holebudalen in Setesdalen, southern Norway. The error lines of ± 1.1°C with respect to the central line given in the original paper are not indicated (adapted from Brooks 2003). (D) Low-frequency (decadal to century) summer-temperature variability for the last 7400 years in northern Sweden expressed as anomalies from the period 1869-1997 (adapted from Grudd et al. 2002). (E) Reconstructed July mean temperature anomalies (°C) in Finnish Lapland (adapted from Helama et al. 2002) presented as non-overlapping 100-yr means of century-wise mid-summer temperatures. (F) Mean annual temperature record (smoothed) reconstructed from a speleothem (SG93) in Nordland, northern Norway (adapted from Lauritzen & Lundberg 1999).

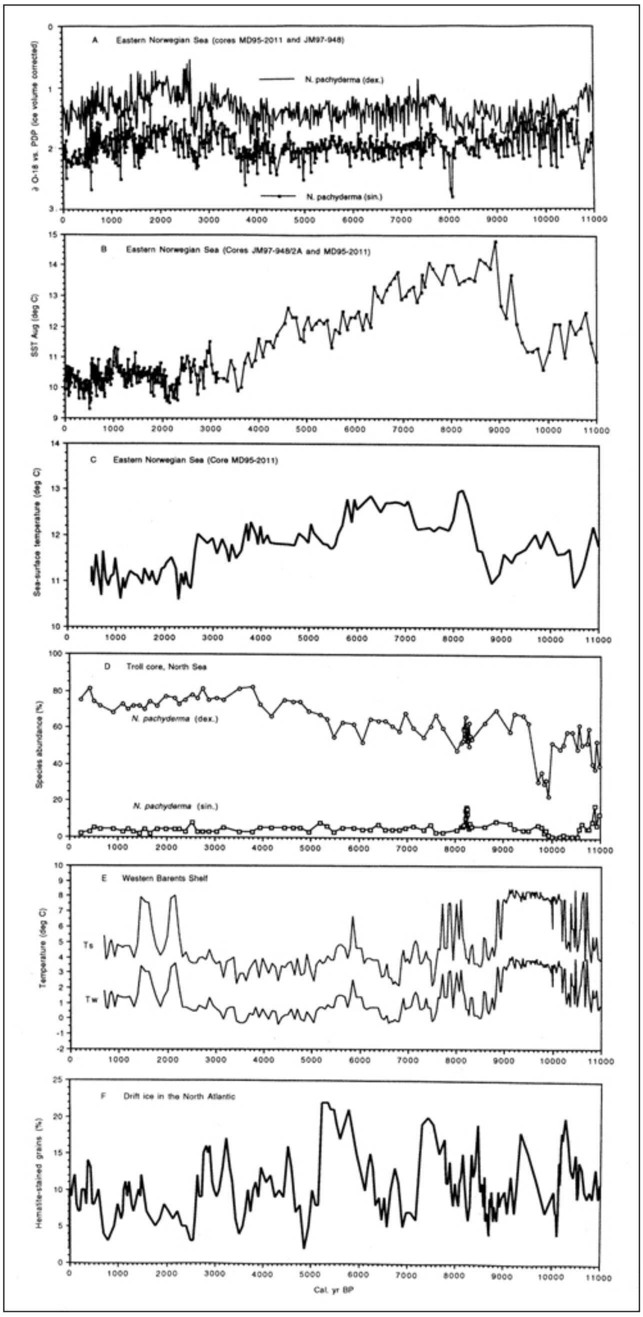

Fig. 6. Holocene climate indicators from the Norwegian sea and Scandinavia. (A) Stabile oxygen isotopes (ice-volume corrected) in N. pachyderma (dex.) and N. pachyderma (sin.) from cores MD95-2011 and JM97-948 obtained from the eastern Norwegian Sea (Vøring Plateau) (Risebrobakken et al. 2003). (B) Diatom-inferred SST (August) variations in the eastern Norwegian Sea reconstructed from cores MD95-2011 and JM97-948 in the eastern Norwegian Sea (Vøring Plateau) (Jansen & Koc 2000; Birks & Koc 2002; Koc & Jansen 2002). (C) Sea-surface temperature variations in the eastern Norwegian Sea reconstructed from alkenone index (UK37) from core MD95-2011 from the Norwegian Sea (Calvo et al. 2002). (D) Relative frequency of the planktonic foraminiferal species N. pachyderma (sin.) to the right coiled warm-water species of N. pachyderma (dex.) in the Troll core, North Sea. (Adapted from Klitgaard-Kristensen et al. 2001). (E) SIM-MAX-based sea-surface temperature records for summer (Ts) and winter (Tw) for core GIK23258-2 in the northeastern North Atlantic at the western Barents Sea shelf at 75°N. (Adapted from Sarnthein et al. 2003). (F) Variations in the occurrence of hematite-stained grains as an indicator of drift sea ice in the northern Atlantic (Bond et al. 2001).

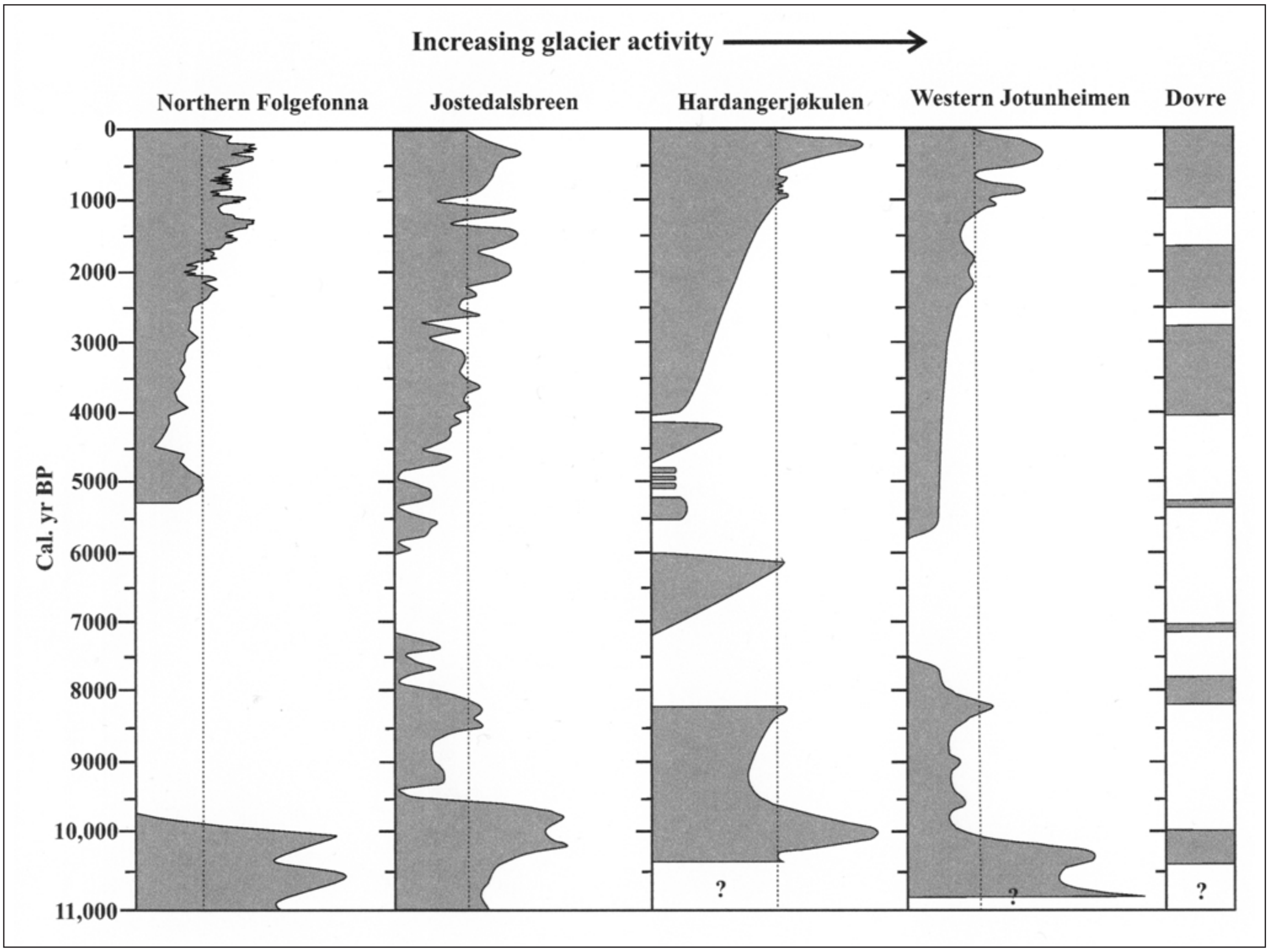

Fig. 7. Holocene variations of five glaciers located in maritime (left) and continental (right) regions in southern Norway. Northern Folgefonna (Bakke et al. in press), Jostedalsbreen (Nesje et al. 2001), Hardangerjøkulen (Dahl & Nesje 1994, 1996), western Jotunheimen (Matthews et al. 2000), and Dovre (periods with glaciers present and melted indicated; Dahl et al. unpublished data). Vertical dot-and-dash lines indicate present position of glacier front.

against the observed record (Fig. 4). The BCCR activities involve fieldwork capturing the climatic information in a number of natural climate archives as well as climate modelling. Holocene marine and terrestrial records from the North Atlantic region show, in general, a high degree of consistency, indicating strong links between the atmospheric and marine mean climate state in this region throughout the Holocene. Compared with the Weichselian climate, the Holocene climate in the North Atlantic region has been a period of low-amplitude climate variability.

The Holocene climate records, reconstructed from marine and terrestrial proxies, indicate that the Holocene climate, at least in our region, has not been as stable as suggested from the Greenland ice-core records. In particular, the early-Holocene (>~8000 cal. yr BP) was punctuated by several significant and abrupt climatic deteriorations (Figs. 5-7). Three cooling events were superimposed upon the general warming trend that took place between the termination of the Younger Dryas and approximately 8000 cal. yrs BP; the Preboreal Oscillation at 11,300-11,150 the Erdalen event 10,300-9700 cal. yr BP and the '8.2 kyr' event (Alley et al. 1997), termed Finse event in southern Norway (Dahl & Nesje 1994; Nesje & Dahl, 2000; Nesje et al. 2000). The cold event centred around 8200 cal. yr BP was the most prominent after the Younger Dryas and has been detected in a number of terrestrial and marine palaeoclimatic records. The cause that best explains its nature and spatial pattern is a major pulse of freshwater from the glacial lakes Agassiz and Ojibway in North America to the North Atlantic. This caused a weakening of the North Atlantic thermohaline circulation (Barber et al. 1999; Clark et al. 2002; Renssen et al. 2001, 2002; Clarke et al. 2003, 2004; Nesje et al. 2004).

Subsequent to the early-mid Holocene summer thermal maximum, most studies indicate several mid to Late Holocene coolings and glacier readvances in Scandinavia (Figs. 5-7; e.g. Seppä & Birks 2001, 2002; Barnett et al. 2001; Nesje et al. 2001; Davis et al. 2003; Lie et al. 2004), on Svalbard (Svendsen & Mangerud 1997; Snyder et al. 2000) and in the Norwegian Sea (Birks & Koc 2002; Calvo et al. 2002). The most

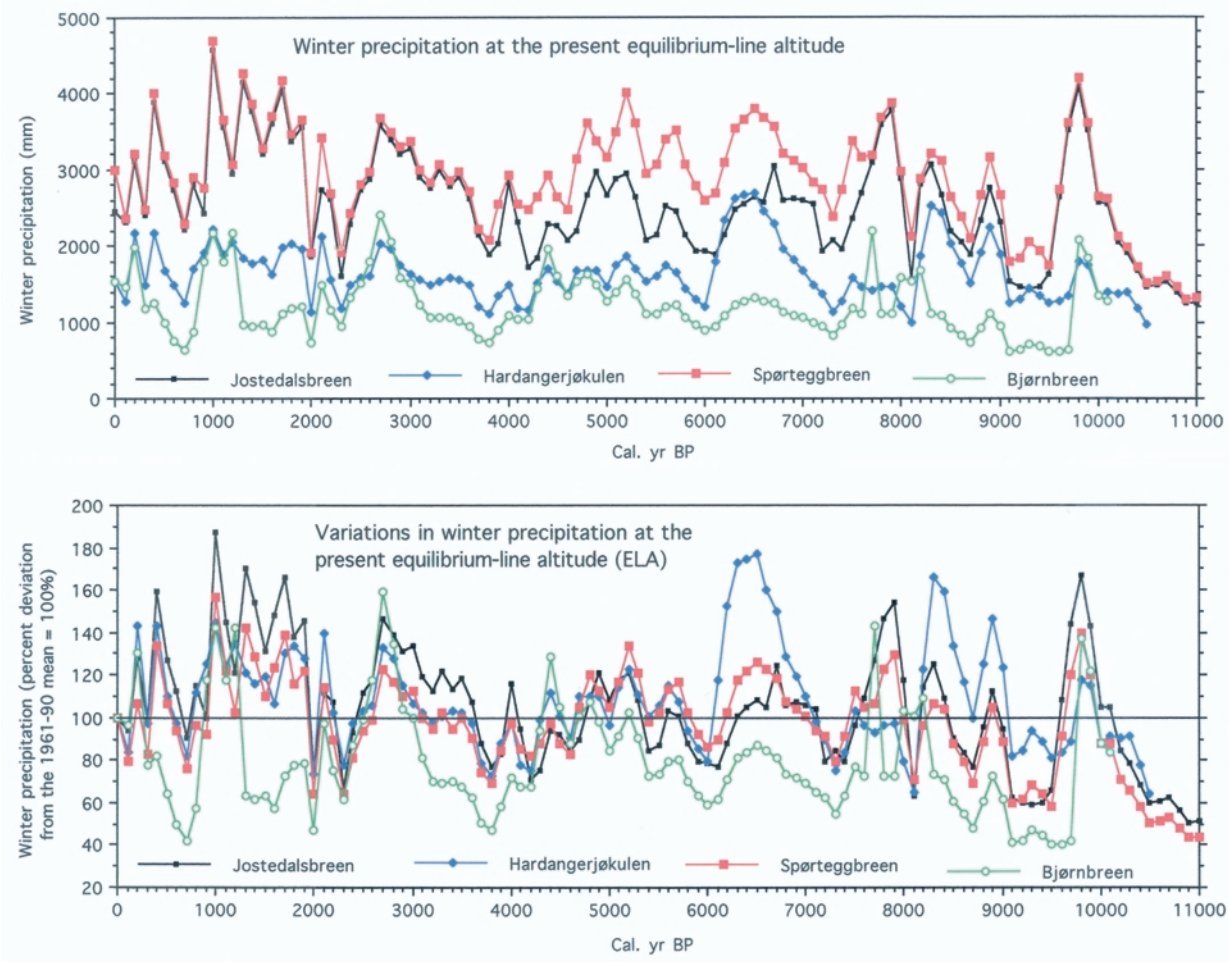

Fig. 8. Holocene variations in winter precipitation at the present equilibrium-line altitude (ELA) of four glaciers in southern Norway, in millimetre (upper panel) and in percent of the 1961-90 normal period (lower panel) (adapted from Bjune et al. in press and Matthews et al. in press).

prominent of these occurred around 6000, 5000, 4000-3800, 2700, 1500 cal. yr BP, and at the beginning of the 'Little Ice Age'. The Late Holocene decreasing temperature trend seen in many climate records from the North Atlantic region most probably reflects a regional summer season response to lower summer insolation due to the orbital parameters. Several short-term climate oscillations, however, have occurred during the last 4000-5000 years. The dominant anti-cyclonic atmospheric circulation pattern that prevailed during the Early-/mid-Holocene summers was probably replaced by a more variable and moister climate. During the Medieval Warm Period (MWP) (approximately AD 700-1300), temperatures were in the order of 0.5-0.8°C higher than at present over southern Scandinavia. The subsequent 'Little Ice Age' (LIA), was not only characterised by several cold winters and summers, but also periods of high winter precipitation (positive North Atlantic Oscillation index weather mode that caused glacier advance) and extreme weather-driven events (floods and avalanches) (e.g. Grove 1988; Nesje & Dahl 2003).

In contrast to the dominant role of Northern Hemisphere summer insolation on early-Holocene climate development, the cause of the relatively unstable climatic conditions and generally advancing mountain glaciers in the North Atlantic region during the Late Holocene may have been a combination of decrease in orbitally-induced summer temperature and increased precipitation (as snow) at high northern latitudes during generally milder winters (Moros et al. 2004). Superimposed on these trends were decadal to centennial scale variability driven by other external forcing factors such as solar variability and volcanism, as well as internal processes in the climate system.

By combining pollen-based reconstructions of mean July temperatures in southern Norway and equilibrium-line altitude (ELA) variations of glaciers in southern Norway, Holocene variations of winter precipitation at the ELA of four glaciers in southern Norway have been reconstructed (Bjune et al. in press) (Fig. 8). These reconstructions show that the Early Holocene (>~6000 cal. yr BP) and Late Holocene

(<~3000 cal. yr BP) were characterised by highly variable, but persistently wet winters. The winter precipitation variations are interpreted to mainly reflect large-scale variations in the prevailing 'NAO weather mode'.

A comparison between high-resolution, Late Holocene glacier records from western Norway and the Alps suggests that an anti-phase relationship has been in operation over at least the last millennium. This may suggest that the winter precipitation as snow (as a result of the NAO weather mode) has played a larger role for the annual net glacier mass balance and, with a few years delayed response, the glacier length variations, than hitherto recognized. The different timing of the 'Little Ice Age' glacier maxima in Scandinavia (~mid 18th century) and the Alps (~mid 19th century) may therefore be explained by the N-S European anti-phase, dipole NAO winter weather mode (Nesje & Dahl 2003).

In the future, a larger number of well-dated, high-resolution terrestrial and marine quantitative climate reconstructions are needed in order to be able to reconstruct better Holocene variations in atmospheric and oceanic climate and circulation changes along east-west and north-south gradients in the North Atlantic region. The BCCR is particularly well suited to tackle these challenges, with its combination of quantitative palaeoclimatologists working both in the marine and terrestrial realms, as well as the emphasis on paleoclimate modelling.

Due to its relevance for understanding ongoing climate changes, it has become particularly important to define climatic anomalies and the scales and patterns of decadal to millennial-scale climate variability. Correlations with records of similar time resolution in lower latitudes are required to understand possible teleconnections and causal mechanisms (solar activity, volcanic eruptions, melt-water spikes, variations in the ocean circulation). For this, much improved chronology and better age-depth models are also required. The combined Holocene climate reconstructions based on terrestrial and marine proxies provide data for climate modelling experiments. This in order to determine accurately the natural cause of climate change upon which the human influence on our climate system develops and interacts.

Weichselian glaciation history based on terrestrial archives

The margins of the Late Weichselian ice-sheet maximum in Scandinavia and northern Eurasia are now quite well constrained and major revisions of previous reconstructions have been made by geologists from the University of Bergen and the BCCR in recent years (e.g. Mangerud et al. 1999; Svendsen et al. 1999; Krinner et al. 2004; Svendsen et al. 2004). The vertical extent of the ice sheet is more difficult to estimate, however, but may be reflected in the lithospheric adjustment to iceload as observed in numerous relative sea-level curves in coastal regions and modern land-uplift patterns. More exact knowledge concerning the vertical extent of the Late Weichselian ice sheet is sparse, and only in some coastal regions of western Scandinavia are the glacial weathering limits ('trimlines') mapped in detail (Nesje et al. 1987) and dated to the Late Glacial Maximum (LGM) by exposure dates (Brook et al. 1996).

Even if the vertical extent is based on observations from marginal areas, the LGM has been tentatively reconstructed and/or tested in model runs to estimate the vertical ice-sheet configuration. The output of most of these reconstructions, however, appears to reflect a 'maximum model' with an almost entirely ice-covered land mass dominated by a central ice dome in the vicinity of the Gulf of Bothnia (e.g. Andersen 1981). In contrast, the 'minimum model' suggests a multidomed ice sheet with large ice-free areas (e.g. Nesje & Dahl 1990).

BCCR scientists are involved in several projects with main objective being to resolve this discrepancy and reconstruct the vertical extent of the Weichselian ice sheet along longitudinal, north-south transects on the Atlantic coast of Norway. The approach is based on mapping the trimline ('weathering limit') on mountains along former flow lines represented by major ice-drainage channels. By use of ^{10}Be exposure dating on mountains above and below the trimline, the vertical extent of the Weichselian ice sheets can be mapped and dated.

East-central southern Norway has some of the most continental climate regimes in central Scandinavia. Within this region the valleys north of Rondane are in the rain shadow for the south-southeasterly winds that occasionally bring heavy rainfall to this area. As a consequence, very little glacier ice has been produced here, and all major ice advances into the 'dry valleys' are produced elsewhere (Dahl et al. 2004). Because of very little winter precipitation, the ice-sheet inception which has taken place in the 'dry valleys' has most likely been cold based. An objective for the BCCR activity in this region is, therefore, to identify areas with cold based, low-erosive ice, its timing and duration. This is done by comparing the discrepancy between dates obtained by optically stimulated luminescence (OSL) and ^{10}Be exposure ages from contemporaneous settings (see Fig. 9).

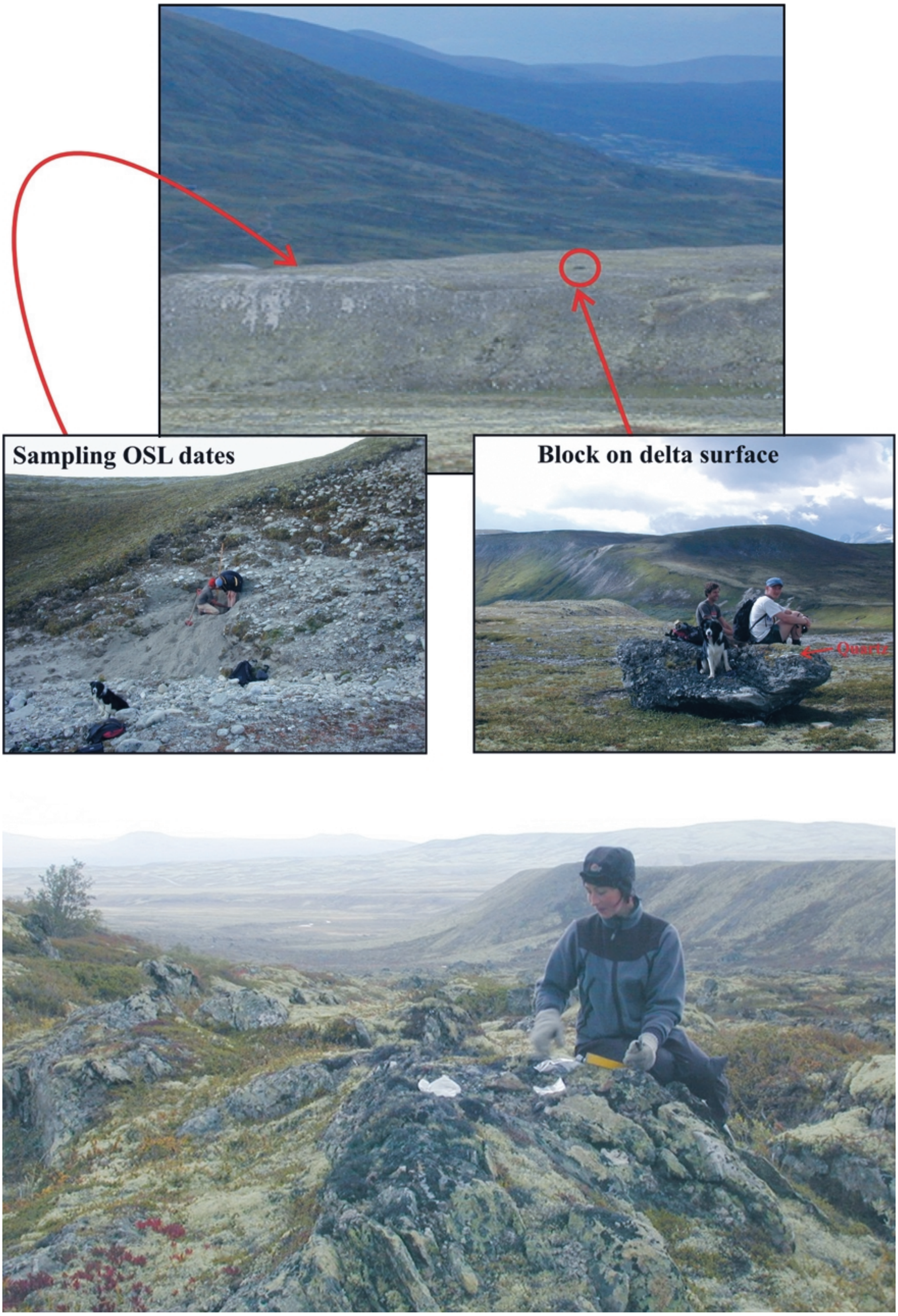

Fig. 9. Delta (upper photo) with a perched boulder on the surface. Middle right photo is a close-up of the boulder. Middle left photo shows OSL-sampling of fine sand from the delta. Lower photo: Henriette Linge is sampling quartz for ^{10}Be exposure dating in Fykfældalen north of Folldal (Photos: S. O. Dahl).

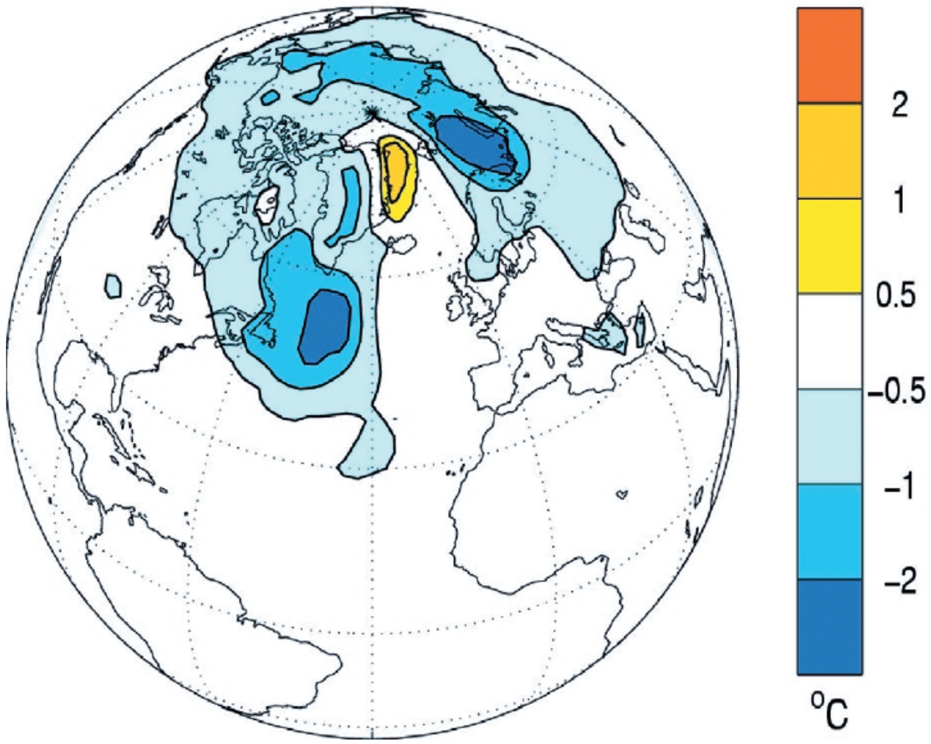

Fig. 10. Changes in the surface air temperature in the BCM in response to a weakening of the Atlantic thermohaline circulation of about 30%. The reduction was induced by a freshwater perturbation to the high northern seas. Continued experiments of this type are planned within the paleo-modelling activity at the BCCR.

Ice-marginal meltwater drainage with gradients of about 10 m/km is suggested reflect cold-based ice. By using OSL and ^{10}Be exposure-dated overflow gaps linked to ice-marginal meltwater drainage with such gradients, it is possible to reconstruct the contemporaneous ice-sheet surface and produce 3-D reconstructions of ice-sheet geometry during the Late Weichselian maximum and other well-defined events.

Palaeoclimate modelling

To improve our knowledge of climate variability on decadal to centennial time scales, it is crucial to use climate models in addition to palaeoclimatic reconstructions based on proxy data. Models are our most important tool for improving our knowledge of the mechanisms for natural climate variability, and can also help put the palaeoclimatic proxy data into a more spatial and dynamic framework. Depending on the nature of the questions asked, and the time-scales involved, there is a range of climate models available. On the one hand are conceptual, more intuitive models, and on the other are 3-dimensional, fully coupled, comprehensive models, such as the Bergen Climate Model (BCM) (Furevik et al. 2003), operating on the highest spatial and temporal resolutions. In between, are models of intermediate complexity. These describe most processes implicitly, although with a lower degree of freedom than fully coupled GCMs because more parameters need to be specified. At the BCCR all these different model types are used.

State-of-the-art climate models are able to reproduce the climate for the present-day reasonably well and are currently being used to simulate possible future responses of the climate system to human-induced changes. However, in order to have any confidence in such predictions, it is also important that the models are tested against data from different times in the past. This will be a key activity at the BCCR in years to come.

Some of the research topics that will be addressed in connection with the palaeoclimatic modelling at the BCCR in the forthcoming years are:

- *The climate of the last millennium*
  The simulation of the natural climate variability over the last centuries up to the last millennium using a coupled atmosphere-ocean general circulation model, and examine the relative role of external and internal forcing factors. There will be a strong

emphasis on model-data comparison.

- *The simulation of significantly different equilibrium climate states*
  This is an important way of evaluating climate models under different climates, such as the mid-Holocene (6000 years BP) and the last glacial maximum (21,000 years BP). In the coming years this approach, which is restricted to a few key periods (time-slices), will be extended to coupled atmosphere-ocean models and will complement the evaluation of such models.
- *Abrupt events in glacial and Holocene times*
  Abrupt events during the Holocene and glacial climates, such as the 8200 year BP, the Younger Dryas/glacial oscillations and Heinrich events, are important for understanding the transient response of the coupled system on the decadal to centennial time scale and, more especially the role of the meridional overturning circulation (see example in Fig. 10).

Due to computational restraints, the BCM experiments will be restricted to so-called time-slice experiments (typically 500-1000 years), where the climate variability on annual to centennial time scales can be studied. Climate variability on longer time scales (typically 10,000 years), including glacial-interglacial transitions, will be studied using a model of intermediate complexity. Such a model, together with more conceptual box-models, will also be useful for systematic sensitivity studies of the ocean circulation. All in all, model simulations combined with palaeoclimatic proxy data will be crucial in facing the challenges inherent in future climate changes. Therefore, collaboration between the different disciplines involved in the palaeoclimate research community is necessary.

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