Ocean circulation and climate at the Eemian and last glacial inception

Andreas Born
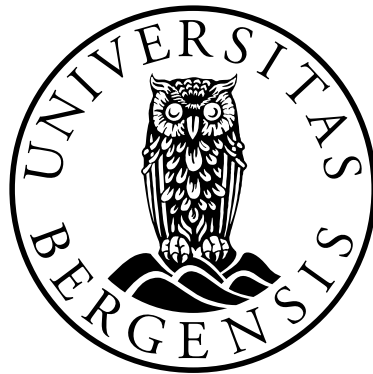
Look again at that dot. That's here.
That's home. That's us. On it everyone
you love, everyone you know, everyone you
ever heard of, every human being who ever
was, lived out their lives. The aggregate
of our joy and suffering, thousands of confident religions, ideologies, and economic
doctrines, every hunter and forager, every hero and coward, every creator and
destroyer of civilization, every king and
peasant, every young couple in love, every
mother and father, hopeful child, inventor
and explorer, every teacher of morals, every corrupt politician, every "superstar",
every "supreme leader", every saint and
sinner in the history of our species lived
there - on a mote of dust suspended in a
sunbeam.

Carl Sagan: Pale Blue Dot

Acknowledgments

This thesis would not have been possible without the help of countless people. First, to my advisers at the Bjerknes Centre for Climate Research. Thank you, Kerim, for your consistent support during the last three years. Your commitment was a key to the success of this work. The value of your guidance concerning all aspects of this work is impossible to overestimate. But most importantly your positive attitude despite temporal set-backs and your availability for discussions at all times made working with you a very enjoyable experience. I am grateful also for your support, Tore, which found its way into many aspects of this thesis. And the details of proxy data analysis would still be a mystery to me if it had not been for your advice, Bjørg. Many more people at the Bjerknes Centre shared their knowledge with me: Jan Mangerud, John-Inge Svendsen, Trond Dokken, Ulysses Ninneman, Tor Eldevik and Kikki Kleiven. I am grateful to my colleagues and fellow students at the Geophysical Institute and Department of Geology for the friendly atmosphere, in particular Jürgen Bader for generous help on many occasions. Francesco, sharing an office with you made working here truly memorable.

A large part of this thesis is the result of collaborations outside the Bjerknes Centre. Masa Kageyama and Pascale Braconnot are gratefully acknowledged for hosting me at Laboratoire des Sciences du Climat et de l'Environnement and for active collaborations. I learned a lot about ice sheet modeling in discussions with Christophe Dumas, Didier Roche and Sylvie Charbit. My work also benefited from fruitful collaborations with Anders Levermann of the Potsdam Institute for Climate Impact Research, Marisa Montoya of Universidad Complutense de Madrid and Juliette Mignot of Laboratoire d'Océanographie et du Climat.

I have been lucky to be part of the Marie Curie network NICE. The three 'all-but-summer' schools and meetings are among the best memories of my dissertation. Thank you Gilles Ramstein and Céline Moncourtois for organizing what has been so much more than a network of professionals.

Last but not least, I would like to thank my family and friends, close and afar, for reminding me of the world beyond my computer screen. I would not be writing this text today without your tireless encouragement. Thank you Cristina for giving your unconditional support, for believing in me and for sharing my life. And thank you, Álvaro, for wise questions about the North Pole and why I have to spend such long hours at work to study the ice there. Johann, you joined us barely four months ago. You do not speak yet but your smiles somehow make studying ice on the North Pole seem utterly pointless. You are perfectly right. Good thing you will not be able to tell anybody until well after the defense...

Andreas Born
Bergen, July 2010

Abstract

Combining a hierarchy of climate models of varying complexity with marine proxy data, we show that the North Atlantic surface circulation played an important role for the climate of the Eemian and the last glacial inception. As insolation decreases, increasing Arctic sea ice export causes a freshwater transport into the subpolar North Atlantic. Amplified by a nonlinear response of the subpolar gyre this leads to a reorganization of the surface currents and a stronger heat transport into the Nordic Seas. The resulting warming of this region delayed Scandinavian inception. This work introduces a relatively new concept into the field of paleoceanography: the subpolar gyre as an active component of the climate system. This is based on recent advances in physical oceanography and allows for a new and physically consistent interpretation of proxy data. Moreover, the sensitivity of the subpolar gyre to different boundary conditions is discussed, improving the understanding of the underlying mechanism.

Contents

1 Introduction

Over the last 65 million years Earth has gradually cooled resulting in a climate characterized by large ice masses periodically covering high latitude continents (Zachos et al., 2001). These glaciations increased in amplitude and duration about 700,000 years ago (700 ka) with three large ice sheets over North America, Greenland and western Eurasia. Since then, glaciated periods last approximately 100,000 years, only interrupted by relatively short interglacials, when only the Greenland ice sheet is present, lasting from 10,000 to 30,000 years.

The Eemian interglacial between 130 ka and 115 ka is the last interglacial before the present. Climate is assumed to have been relatively similar to today, albeit probably 3 to 5°C warmer in high northern latitudes at its peak (126 ka) due to exceptionally high summer insolation (Fig. 1a) (Berger, 1978). As a result, the Greenland ice sheet was approximately one third smaller than today (Otto-Bliesner et al., 2006) and sea level 4 to 6 meters higher (Rostami et al., 2000; Muhs et al., 2002), with an uncertain contribution from the western Antarctic ice sheet (Scherer et al., 1998; Overpeck et al., 2006). Greenhouse gas concentrations were similar to pre-industrial levels (Fig. 1b).

Following Milankovitch's orbital theory, the transition from interglacial to glacial climate occurs in periods of low northern high latitude summer insolation, enabling snow to persist through the warm season and accumulate even more during the following winter (Milankovitch, 1941). Following the Eemian, insolation approaches a local minimum at about 115 ka, marking the beginning of the last glacial inception. However, since insolation changes are small, internal amplification by the climate system is necessary to build continental scale ice sheets.

Several lines of evidence point to the ocean as a potential amplifier of the insolation forcing (Ruddiman and McIntyre, 1975; Otterå and Drange, 2004; Risebrobakken et al., 2007). All known ice sheet nucleation sites are close to the ocean, especially the Atlantic and Arctic Oceans. Ocean currents transport large amounts of heat to high latitudes with important consequences both for
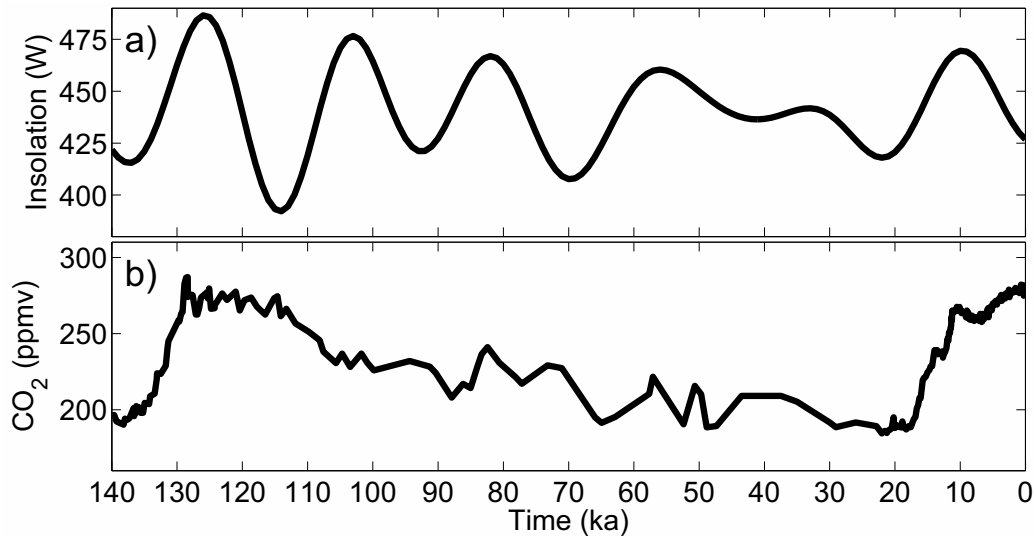
Figure 1: Summer insolation at 65°N **(a)** and atmospheric CO_2 concentration **(b)**. Insolation data by Berger and Loutre (1991), CO_2 by Petit et al. (1999); Monnin et al. (2001); Siegenthaler et al. (2005); Lüthi et al. (2008).

temperatures over coastal land and the extent of sea ice in the Arctic Ocean. The area covered by sea ice influences the amount of evaporation and thus the moisture source for ice growth. It has also been shown to impact large scale atmospheric circulation patterns (Li et al., 2005).

Hydrography and climate of the Nordic Seas and Arctic Ocean are strongly influenced by the exchanges with the Atlantic Ocean across the submarine ridge between Greenland and Scotland (Dickson and Brown, 1994; Hansen and Østerhus, 2000; Rahmstorf, 2002; Hansen et al., 2004). This ridge forms a barrier to the dense deep outflow from the Nordic Seas. Similarly, the inflow into the Nordic Seas is restricted mostly to the eastern side of the passage. Water masses flowing northward in this current are found to represent a mixture of subtropical and subpolar Atlantic waters (Hátún et al., 2005). While the contribution of subtropical water is relatively stable, the subpolar component shows pronounced variability in recent decades and probably also on millennial time scales throughout the Holocene (Thornalley et al., 2009), as a result of circulation changes of the subpolar gyre. Thus, the investigation of climatic

changes of the high latitude oceans requires a thorough understanding of the gyre circulation system.

This thesis investigates how the North Atlantic Ocean surface circulation and Arctic sea ice contribute to climate evolution of the last glacial inception. The underlying mechanisms are tested for other periods in time as well and in sensitivity experiments. The text is organized as follows: Section 2 provides an overview on orbital climate forcing, feedback mechanisms that potentially amplify the relatively weak forcing signal, and recent advances concerning the role of the subpolar gyre for climate variability. Based on this background information, the motivation for this thesis is outlined in section 3, followed by a summary of the main scientific results in section 4, and conclusions in section 5. A total of six research papers are included in this thesis and appended as manuscripts.

2 Background

2.1 Celestial mechanics and Climate, Milankovitch Theory

In theory, Earth's climate is a deterministic system that is effectually described by its boundary conditions: energy flux from the sun, dissipation of the moon's kinetic energy by tidal waves and radiochemical processes in the interior of the planet. The second is negligible, as well as the latter on all but the very longest time scales, thus making variations in solar power the most important driver of climate changes. However, besides the 11-year sun spot cycle, the sun's luminosity increases only slowly and gradually, about 10% every 1 billion years. A greater impact is caused by variations in the distribution of this energy between the equator and the poles which arise from cyclic changes in the Earth's orbit. Milankovitch first hypothesized that periodic reductions in northern high latitude summer solar irradiation (insolation) were instrumental for the growth of major ice sheets and thus the glacial-interglacial cycles

(Milankovitch, 1941). Strong support was found in the analysis of deep ocean
sediment cores (Hays et al., 1976).

The complex changes in the Earth's orbit can be summarized in three
fundamental cyclic movements (Fig. 2): The tilt (obliquity) of the Earth's
rotational axis relative to the plane of rotation around the sun varies between
22.1°and 24.5°on a 41,000 year cycle. With greater tilt, insolation at the poles
increases while it decreases at the equator, in phase in both northern and
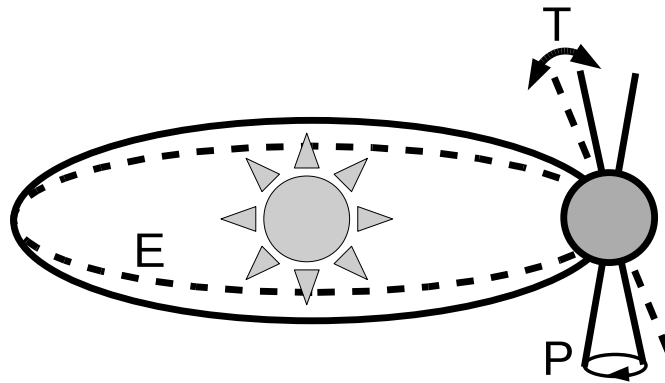southern hemispheres.

Figure 2: Variations of the Earth's orbital parameters: E denotes changes in
eccentricity of the orbit, P the precession of the equinoxes and T changes in
the tilt of the rotational axis.

The rotational axis is also subject to precession which does not change it's
angle but the position of the equinoxes on the orbit around the sun. Since the
orbit is elliptical, and distance from the sun and transition times are different
for summer and winter seasons, precession modulates the length of the seasons
as well as the seasonal insolation contrast. Summers are either relative cold and
long, or warm and short. However, because the seasons in the two hemispheres
are in exact antiphase, precession changes also have opposite sign. The period
of precession of the Earth's axis is approximately 26,000 years. Precession
also occurs in the orbital ellipse around the sun. This movement has the same
effect on insolation and the superposition of the two effects shortens the overall
cycle of precession to 21,000 years.

Table 1: Orbital parameters for the last interglacial and last glacial inception.

Time	Axial tilt (°)	Longitude of perihelion (°)	Eccentricity
126 ka	23.92	112.03	0.040
115 ka	22.40	291.72	0.041

Finally, the shape of the elliptic orbit around the sun changes with time. Increased eccentricity enhances the contrast between seasons, in antiphase for the two hemispheres, on periods of 100,000 and 400,000 years. Because the 'location' of the seasons around the orbit depends on precession, eccentricity changes can be thought of as modulating the precession cycle. With zero eccentricity, changes in precession become meaningless.

During the peak of the last interglacial at 126 ka, summer insolation at the top of the atmosphere at 65°N was at a local maximum, followed by a minimum at 115 ka (Fig. 1) (Berger, 1978). Low summer insolation at high northern latitudes is considered critical to the nucleation of large ice sheets. The decrease in summer insolation from 126 ka to 115 ka is due both to a change in precession and axial tilt (Table 1). The vernal equinox is rotated by 180°on the orbital ellipse, giving a relatively long but less intense summer season at 115 ka compensated for by a short and warm winter (Fig. 3). At the same time, the axial tilt is smaller at 115 ka, dampening the seasons mostly close to the poles and thus further cooling the northern hemisphere summer. The change in eccentricity is negligible.

2.2   Amplification of orbital forcing by feedback mechanisms

Previous model studies identified several potential feedback mechanisms amplifying the insolation signal. Retreating boreal forest over northern high latitude continents was found to increase albedo sufficiently to change local climate and favor ice growth (de Noblet et al., 1996; Meissner et al., 2003; Calov et al.,
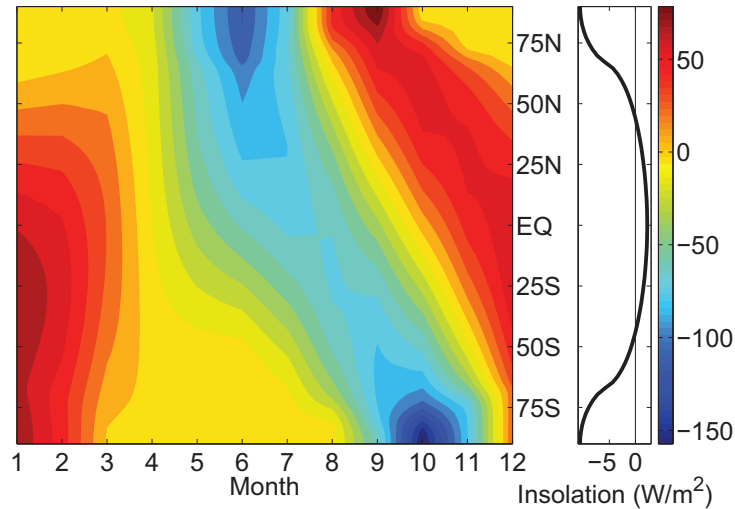
Figure 3: Incoming short wave radiation difference at the top of the atmosphere, 115 ka - 126 ka, in W/m^2. Left: Seasonal variations, right: annual average. The seasonal cycle was reduced in high northern latitudes and the Earth received less annual mean radiation poleward of 45° at 115 ka than at 126 ka.

2005; Kubatzki et al., 2006). Perennial snow cover is furthermore enhanced by an increased moisture convergence in the Arctic circle, as a result of less evaporation in a colder climate (Vettoretti and Peltier, 2003).

In addition to these mechanisms, several studies identified potential feedback mechanisms including changes in the strength of deep water formation and the Atlantic meridional overturning circulation. Realistic snow accumulation over the Canadian Arctic is only obtained in an atmospheric model with 116 ka sea surface conditions, and not with present day conditions (Yoshimori et al., 2002). Gröger et al. (2007) report that in their model experiments lower sea surface temperatures result in a higher density in the North Atlantic deep water formation regions at 115 ka and thus a more intense Atlantic meridional overturning circulation than at 126 ka. Calov et al. (2005) report a southward shift of Scandinavian land ice nucleation with a weaker Atlantic meridional overturning circulation.

Besides the direct effect of low annual average insolation at high latitudes,

the response of ocean circulation to changes in freshwater forcing has been investigated. One such study concludes that decreased sea ice melt at 115 ka yields higher salinities in the Nordic Seas sinking regions and intensifies the Atlantic meridional overturning circulation compared to 126 ka (Otterå and Drange, 2004). Similarly, less precipitation over the Arctic Ocean at 115 ka could have the same result (Khodri et al., 2003). An increasing Arctic sea ice cover as a result of a weaker Atlantic meridional overturning circulation has also been found to cool high northern latitudes and to favor accumulation of snow (Khodri et al., 2001). Proxy data studies, however, suggest that a persistent circulation might be crucial for building ice over Eurasia (Ruddiman and McIntyre, 1975; McManus et al., 2002; Risebrobakken et al., 2006).

2.3   The subpolar gyre as an active component of the climate system

While the importance of the Atlantic meridional overturning circulation in the climate system is beyond doubt, this two-dimensional simplification alone does not describe the complex system of ocean currents sufficiently. In particular, the northernmost limb of the overturning circulation, the inflow into the Nordic Seas connecting the Atlantic Ocean to the Arctic Ocean, was found to be modulated by the large scale surface circulation of the subpolar North Atlantic–the subpolar gyre (Fig. 4) (Hátún et al., 2005). This mechanism operated also on millennial time scales throughout the Holocene (Thornalley et al., 2009). Deep convection south of the Greenland Scotland ridge is directly related to the subpolar gyre (Eden and Willebrand, 2001; Levermann and Born, 2007; Lohmann et al., 2009), which has the potential to monitor AMOC changes (Häkkinen and Rhines, 2004; Böning et al., 2006; Zhang, 2008). Thus, a comprehensive understanding of climate variations clearly calls for a three-dimensional description, involving both the deep and surface circulation.

Observational estimates for subpolar gyre volume transport range from 25 Sv (Bacon, 1997) to 33.5 Sv (Clarke, 1984) (1 Sv = $10^6 m^3\ s^{-1}$), but these
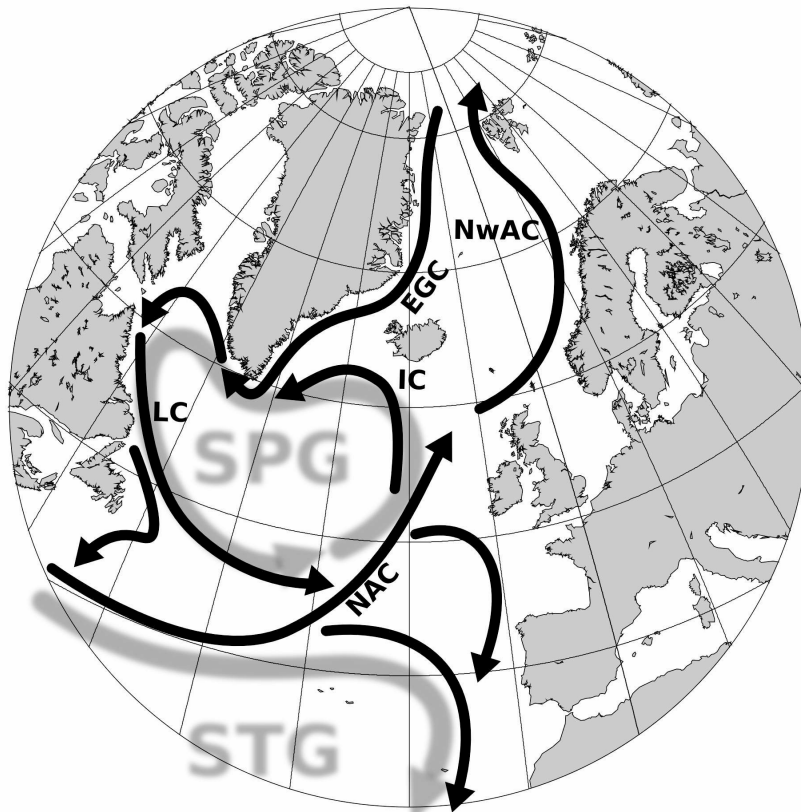
Figure 4: Map of the North Atlantic and Nordic Seas showing major ocean surface currents forming the subpolar gyre (SPG). Abbreviations: NAC, North Atlantic Current; NwAC, Norwegian Atlantic Current; EGC, East Greenland Current; LC, Labrador Current; IC, Irminger Current; STG, subtropical gyre.

likely underestimate the contribution of narrow coastal currents. High resolution models simulate a cyclonic circulation of approximately 40 Sv and more (Treguier et al., 2005). This can be compared to the overturning circulation volume transport of about 13 to 18 Sv (Ganachaud and Wunsch, 2000; Lumpkin and Speer, 2003; Talley et al., 2003; Wunsch and Heimbach, 2006; Cunningham et al., 2007).

While surface wind-stress has a large influence on its strength and variability (Curry et al., 1998; Böning et al., 2006), the subpolar gyre circulation is also controlled by baroclinic adjustments and therefore by the density structure in the subpolar North Atlantic (Mellor et al., 1982; Greatbatch et al., 1991; Myers et al., 1996; Penduff et al., 2000; Eden and Willebrand, 2001; Born et al., 2009). This has shown to have important consequences for the dynamics of the subpolar gyre, possibly leading to the existence of at least two stable circulation modes (Levermann and Born, 2007).

The underlying dynamics have been formulated conceptually in three positive feedback mechanisms (Fig. 5). First, a stronger gyre transports more tropical saline water into the subpolar region, as opposed to the Nordic Seas. This result is consistent with high-resolution model simulations (Hátún et al., 2005; Lohmann et al., 2009). Compared to a weaker gyre, less tropical waters are transported to the Nordic Seas, more recirculate in the subpolar gyre, making the center saltier. This increases the density gradient between the gyre and the relatively light exterior, sea surface elevation drops and the corresponding geostrophic response strengthens the circulation. Secondly, a stronger subpolar gyre results in stronger outcropping of isopycnals in the center of the gyre and more active deep convection. Therefore heat is removed more efficiently from the gyre's center which results in a cooling. This again increases the core density and therewith its strength.

In addition to these self-sustaining internal feedbacks, there exists an interaction with the deep outflow across the Greenland Scotland ridge. A stronger subpolar gyre reduces the salinity of the Atlantic inflow into the Nordic Seas. Thus, deep water formation north of the Greenland Scotland ridge weakens

and reduces the deep outflows. A less dense undercurrent results in stronger downwelling south of the ridge (Straneo, 2006; Spall, 2004; Deshayes et al., 2009). As a consequence, waters at the northern rim of the gyre get lighter, because they are fed by relatively light water that is formed south of the ridge as opposed to the dense overflow waters. This increases the density gradient across the gyre and enhances its strength.
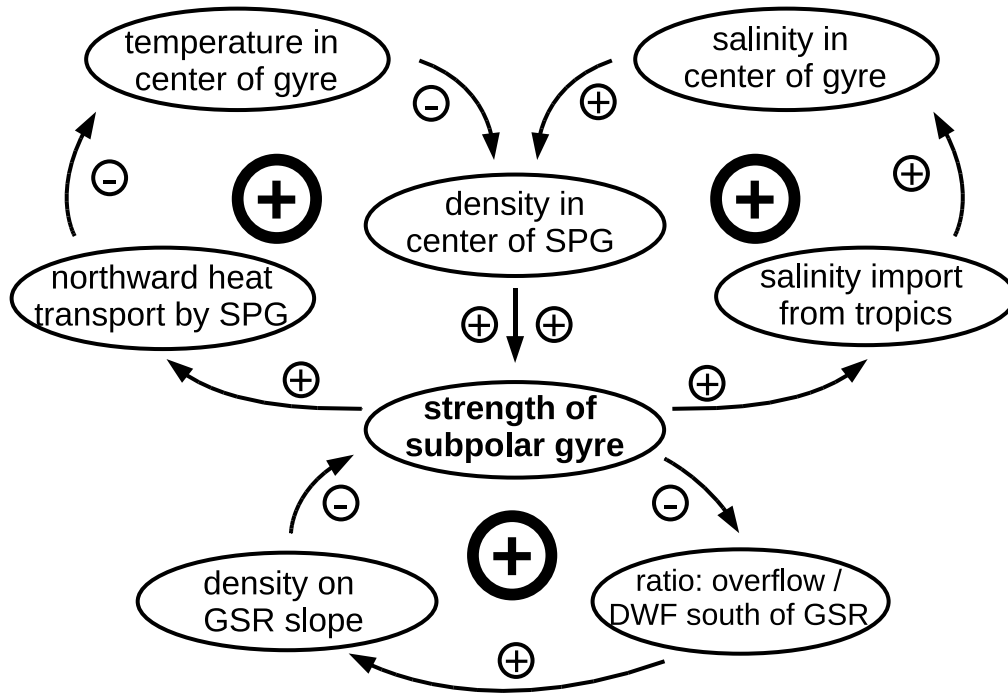

Figure 5: Three positive feedback mechanisms destabilize the subpolar gyre (Levermann and Born, 2007).

3   Motivation

This thesis addresses the role of the North Atlantic ocean circulation during the last glacial inception at 115 ka, using numerical models of varying complexity. The overall aim, however, goes beyond the simulation of specific periods of climate history into testing and advancing the relatively new hypothesis of the Atlantic subpolar gyre being an active component of the climate system. Paleoceanography has not kept up with physical oceanography in acknowledging this new understanding of the large scale surface circulation, despite the great explanatory power that this concept holds for proxy data. But benefit is mutual, as the study of past events has always brought forward the understanding of dynamic climate systems. This thesis represents an effort to narrow the gap between the two disciplines.

4   Summary of Results

The thesis is presented in six scientific papers that can be divided into two parts (see list on page 23). The first one (PAPERS I, II and III) addresses the climate evolution of the last glacial inception and the role of the ocean, combining coarse and high resolution climate modeling, ice sheet modeling, and discussion of marine and terrestrial proxy data. In accordance with the objectives outlined in the previous section, the analysis presented here is not restricted to the end of the last interglacial. The better coverage of marine proxy data for the Holocene than for the last interglacial allows for a more detailed study of the three-dimensional signature of subpolar gyre changes. In PAPER IV, a comprehensive discussion of data from the eastern and western North Atlantic, and the deep ocean is presented for the 8.2 ka event, the largest freshwater flood of the present interglacial. PAPERS V and VI investigate the driving mechanisms of the subpolar gyre under preindustrial and glacial boundary conditions, and the role of the subpolar gyre in decadal climate variability, complementing the description of its dynamics on shorter time

scales.

Based on two time slice simulations in a comprehensive coupled climate model, PAPER I establishes a causality between decreasing summer insolation at the last glacial inception and an abrupt reorganization of the subpolar surface circulation. As a direct result of weaker summer insolation, Arctic sea ice grows thicker and ice export in the East Greenland Current intensifies. The implicit freshwater transport into the subpolar North Atlantic reduces deep convection in the northwest Atlantic and thereby effectively changes the density structure of the region. This causes a nonlinear response of the subpolar gyre that amplifies freshening by sea ice.

This causal chain is reproduced in a coarse resolution coupled climate model in PAPER II. High computational efficiency of this model allows to test the physical mechanism proposed in the first paper in ensemble simulations and to expand previous work with a transient simulation of the period between 126 ka and 110 ka. The simulated temporal evolution shows that the weakening of the subpolar gyre results in a higher fraction of subtropical waters in the Atlantic inflow into the Nordic Seas and thus warming along the path of the Norwegian Atlantic Current. This mechanism is reversed when summer insolation increases again after 115 ka. Results compare favorably with marine sediment cores showing a clear late Eemian warming.

While a transient warm pulse in the Nordic Seas at the time of minimum insolation is consistent with two coupled climate models and marine proxy data, the consequence for land ice growth is still unclear. To address this question, PAPER III employs a three-dimensional ice sheet model forced by the simulated climate of the last glacial inception. The main result is that the strong heat transport into the Nordic Seas delayed glacial inception over Scandinavia. Ice started growing soon after this anomalous warm episode, in good agreement with available proxy data.

The concept of the subpolar gyre as an active component of the climate system allows for an improved understanding of proxy records beyond the last interglacial. In the example of the 8.2 ka event, addressed in PAPER IV, ac-

counting for a rapid change in the surface circulation resolves the apparent contradiction of increased freshwater inflow and enhanced deep water formation in the North Atlantic. This newly established causal relationship puts the 8.2 ka event into a new light, commonly regarded as a touchstone for the vulnerability of the Atlantic meridional overturning circulation to freshwater. While a temporary weakening of the overturning is beyond doubt, it might not have been as severe as previously thought.

The first four papers assume that the subpolar gyre is partly controlled by baroclinic adjustments and apply the resulting understanding to paleo events. Changes in wind stress are acknowledged throughout but consistently found to be negligible. In an effort to explicitly address the importance of stronger winds for the subpolar gyre, PAPER V investigates ensemble simulations with fixed observational wind stress multiplied globally by different factors between 0.5 and 2. The gyre transport is decomposed into Ekman, thermohaline, and bottom-transports. Two distinct regimes of the subpolar gyre are identified, depending on the existence of significant Greenland Scotland ridge overflows. These regimes largely correspond to the glacial and preindustrial ocean circulation pattern in this study but active overflows are also found with high wind stress amplification factors.

Finally, PAPER VI aims to identify the subpolar gyre feedbacks, originally described in a coarse resolution model, in a comprehensive coupled atmosphere ocean general circulation model. Important modifications are made to the original formulation, most notably on the characteristic time scales associated with the individual mechanisms. These delays form the basis for irregular decadal oscillations of the subpolar gyre and deep convection in its center. More intense air-sea coupling during convective events allows large scale atmospheric patterns to force the dynamical system stochastically. The analysis also suggests that the surface freshwater balance is critical for the pronounced variations of the subpolar gyre and that preindustrial climate is at a threshold defined by the feedback mechanisms. In the simulations of the Eemian and the last glacial inception with the same climate model, presented in PAPER I, the freshwater

budget of the subpolar North Atlantic is different with less and more sea ice transport compared to preindustrial climate. As a result, the strong and the weak subpolar gyre mode is stable without oscillations.

4.1   List of Papers

PAPER I

Sea ice induced changes in ocean circulation during the Eemian[1]

Born, A., K. H. Nisancioglu and P. Braconnot (2010)

Climate Dynamics, doi:10.1007/s00382-009-0709-2

PAPER II

Late Eemian warming in the Nordic Seas as seen in proxy data and climate models

Born, A., K. H. Nisancioglu, B. Risebrobakken and A. Levermann (2010)

Paleoceanography, (in revision)

PAPER III

Warm Nordic Seas delayed glacial inception in Scandinavia

Born, A., M. Kageyama and K. H. Nisancioglu (2010)

Climate of the Past, (submitted)

PAPER IV

The 8.2 ka event: abrupt transition of the subpolar gyre toward a modern North Atlantic circulation[2]

Born, A. and A. Levermann (2010)

Geochemistry Geophysics Geosystems **11**, Q06011

PAPER V

Reversed North Atlantic gyre dynamics in present and glacial climate[1]

Montoya, M., A. Born and A. Levermann (2010)

Climate Dynamics, doi:10.1007/s00382-009-0729-y

PAPER VI

The Atlantic subpolar gyre as a stochastically forced oscillator

Born, A. and J. Mignot (2010)

(manuscript in preparation)

---

[1]Reproduced with permission of the publisher
[2]Reproduced by permission of American Geophysical Union.

5   Conclusions and Perspective

The main conclusions of this study can be summarized in three points:

1) An improved understanding of the processes controlling the Atlantic inflow into the Nordic Seas allows for a physically consistent constraint on the advance of Scandinavian glaciers following the last interglacial. The role of the ocean for the last glacial inception over Scandinavia is investigated using coarse and high resolution climate models, an ice sheet model, and in combination with marine and terrestrial proxy data.

2) Recent advances in physical oceanography are successfully introduced into the paleoceanographic context. Rapid transitions of the large scale surface circulation, not only the deep overturning circulation, are used to improve our understanding of proxy data

3) The study of paleoclimate events and evidence for abrupt transitions of the subpolar gyre in response to known perturbations in the past improve the understanding of the underlying physical mechanisms and thresholds.

A comprehensive summary of the conclusions is found in the respective sections of the papers.

The understanding of the subpolar gyre presented is far from complete. Work presented here outlines the sensitivity of the subpolar gyre to changes in boundary conditions, as a consequence of self-amplifying feedbacks. At least two different modes of operation were identified that also differ in the strength of deep convection in the gyre's center. This indicates that thermal atmosphere-ocean coupling does not depend linearly on the background climate, but that qualitative shifts can occur, potentially decoupling a region of high atmospheric variability, the Labrador Sea, completely from the deep ocean in the case of a shut-down of deep convection. However, the question of how variability of the subpolar gyre is transferred to the deep ocean and consequences for the large scale meridional overturning circulation are not addressed here and require clarification.

Conclusions presented here are largely based on numerical models and the interpretation of proxy data with their inherent uncertainties. Comparison with instrumental observations could improve this approach significantly, but can not be used because the mechanisms highlighted work on relatively long time scales while observations cover only a few recent decades. PAPER VI represents an effort to overcome this gap and provide a hypothesis that can be tested with observations. Future work will need to address explicitly how variable atmospheric forcing, equivalent to stochastic noise from an ocean perspective, is communicated to the ocean. It is unclear how it modifies the stability of the two subpolar gyre regimes discussed here.

It was shown how the subpolar gyre evolves in response to orbital forcing at the end of the last interglacial (PAPER I and II) and that a major transition of the gyre occurred early during the present interglacial (PAPER IV). It is conceivable that variations in orbital parameters during the Holocene, albeit much smaller than at the last glacial inception, or changes in solar output influenced the gyre circulation in recent millennia. Recent analyses of marine sediments revealed that variations in subpolar gyre circulation occurred throughout the last 12,000 years, indeed, as observed in Greenland fjords (Ren et al., 2009; Kuijpers et al., 2009) and the eastern North Atlantic (Thornalley et al., 2009). A relation to the Medieval Climate Anomaly as well as with the demise of Norse colonies on Greenland was hypothesized. Our new understanding of the subpolar gyre might provide the basis for future investigations of these questions.

References

Bacon, S. (1997). Circulation and Fluxes in the North Atlantic between Greenland and Ireland. *Journal of Physical Oceanography*, 27:1420–1435.

Berger, A. (1978). Long-Term Variations of Caloric Solar Radiation Resulting from the Earth's Orbital Elements. *Quaternary Research*, 9:139–167.

Berger, A. and Loutre, M. F. (1991). Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews*, 10:297–317.

Böning, C., Scheinert, M., Dengg, J., Biastoch, A., and Funk., A. (2006). Decadal variability of subpolar gyre transport and its reverberation in the North Atlantic overturning. *Geophysical Research Letters*, 33:L21S01.

Born, A., Levermann, A., and Mignot, J. (2009). Sensitivity of the Atlantic ocean circulation to a hydraulic overflow parameterisation in a coarse resolution model: Response of the subpolar gyre. *Ocean Modelling*, 27 (3-4):130–142.

Calov, R., Ganopolski, A., Petoukhov, V., Claussen, M., Brovkin, V., and Kubatzki, C. (2005). Transient simulation of the last glacial inception. Part II: sensitivity and feedback analysis. *Climate Dynamics*, 24:563–576.

Clarke, R. A. (1984). Transport through the Cape Farewell-Flemish Cap section. *Rapp. P. V. Reun. Cons. Int. Explor. Mer.*, 185:120–130.

Cunningham, S. A., Kanzow, T., Rayner, D., Baringer, M. O., Johns, W. E., Marotzke, J., Longworth, H. R., Grand, E. M., Hirschi, J. J.-M., Beal, L. M., Meinen, C. S., and Bryden, H. L. (2007). Temporal variability for the atlantic meridional overturning circulation at 26.5°n. *Science*, 317:935–937.

Curry, R., McCartney, M., and Joyce, T. (1998). Oceanic transport of subpolar climate signals to mid-depth subtropical waters. *Nature*, 391:575–577.

de Noblet, N., Prentice, I., Joussaume, S., Texier, D., Botta, A., and Haxeltine, A. (1996). Possible Role of Atmosphere-Biosphere Interactions in Triggering the Last Glaciation. *Geophysical Research Letters*, 23:3191–3194.

Deshayes, J., Straneo, F., and Spall, M. A. (2009). Mechanisms of variability in a convective basin. *Journal of Marine Research*, 67(3):273–303.

Dickson, R. R. and Brown, J. (1994). The production of North Atlantic Deep Water: Sources, rates, and pathways. *Journal of Geophysical Research*, 99:12,319–12,341.

Eden, C. and Willebrand, J. (2001). Mechanism of Interannual to Decadal Variability of the North Atlantic Circulation. *Journal of Climate*, 14:2266–2280.

Ganachaud, A. and Wunsch, C. (2000). Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature*, 408:453–456.

Greatbatch, R. J., Fanning, A. F., Goulding, A. D., and Levitus, S. (1991). A Diagnosis of Interpentadal Circulation Changes in the North Atlantic. *Journal of Geophysical Research*, 96:22,009–22,023.

Gröger, M., Maier-Reimer, E., Mikolajewicz, U., Schurgers, G., Vizcaíno, M., and Winguth, A. (2007). Changes in the hydrological cycle, ocean circulation, and carbon/nutrient cycling during the last interglacial and glacial transition. *Paleoceanography*, 22:PA4205.

Häkkinen, S. and Rhines, P. B. (2004). Decline of subpolar North Atlantic circulation during the 1990s. *Science*, 304:555–559.

Hansen, B. and Østerhus, S. (2000). North Atlantic - Nordic Seas exchanges. *Progress in Oceanography*, 45:109–208.

Hansen, B., Østerhus, S., Quadfasel, D., and Turrell, W. (2004). Already the Day After Tomorrow? *Science*, 305:953–954.

Hátún, H., Sandø, A. B., Drange, H., Hansen, B., and Valdimarsson, H. (2005). Influence of the Atlantic Subpolar Gyre on the Thermohaline Circulation. *Science*, 309:1841–1844.

Hays, J. D., Imbrie, J., and Shackleton, N. J. (1976). Variations in the Earth's Orbit: Pacemaker of the Ice Ages. *Science*, 194 (4270):1121–1132.

Khodri, M., Leclainche, Y., Ramstein, G., Braconnot, P., Marti, O., and Cortijo, E. (2001). Simulating the amplification of orbital forcing by ocean feedbacks in the last glaciation. *Nature*, 410:570–574.

Khodri, M., Ramstein, G., Paillard, D., Duplessy, C., Kageyama, M., and Ganopolski, A. (2003). Modelling the climate evolution from the last interglacial to the start of the last glaciation: The role of Arctic Ocean freshwater budget. *Geophysical Research Letters*, 30(12):1606.

Kubatzki, C., Claussen, M., Calov, R., and Ganopolski, A. (2006). Sensitivity of the last glacial inception to initial and surface conditions. *Climate Dynamics*, 27:333–344.

Kuijpers, A., Malmgren, B. A., and Seidenkrantz, M.-S. (2009). Termination of the Medieval Warm Period: linking subpolar and tropical North Atlantic circulation changes to ENSO. *PAGES news*, 17(2):76–77.

Levermann, A. and Born, A. (2007). Bistability of the Atlantic subpolar gyre in a coarse-resolution model. *Geophysical Research Letters*, 34:L24605.

Li, C., Battisti, D. S., Schrag, D. P., and Tziperman, E. (2005). Abrupt climate shifts in Greenland due to displacements of the sea ice edge. *Geophysical Research Letters*, 32.

Lohmann, K., Drange, H., and Bentsen, M. (2009). Response of the North Atlantic subpolar gyre to persistent North Atlantic oscillation like forcing. *Climate Dynamics*, 32:273–285.

Lumpkin, R. and Speer, K. (2003). Large-scale vertical and horizontal circulation in the North Atlantic Ocean. *Journal of Physical Oceanography*, 33:1902–1920.

Lüthi, D., Floch, M. L., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., and Stocker, T. (2008). High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature*, 453:379–382.

McManus, J. F., Oppo, D. W., Keigwin, L. D., Cullen, J. L., and Bond, G. C. (2002). Thermohaline Circulation and Prolonged Interglacial Warmth in the North Atlantic. *Quaternary Research*, 58:17–21.

Meissner, K. J., Weaver, A. J., Matthews, H. D., and Cox, P. M. (2003). The role of land surface dynamics in glacial inception: a study with the UVic Earth System Model. *Climate Dynamics*, 21:515–537.

Mellor, G., Mechoso, C., and Keto, E. (1982). A diagnostic calculation of the general circulation of the Atlantic Ocean. *Deep-Sea Research*, 29:1171–1192.

Milankovitch, M. (1941). *Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitproblem.* (Royal Serbian Academy, Belgrade.

Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T. F., Raynaud, D., and Barnola, J.-M. (2001). Atmospheric CO2 concentrations over the last glacial termination. *Science*, 291:112–114.

Muhs, D. R., Simmons, K. R., and Steinke, B. (2002). Timing and warmth of the last interglacial period: New U-series evidence from Hawaii and Bermuda and a new fossil compilation for North America. *Quaternary Science Reviews*, 21:1355–1383.

Myers, P. G., Fanning, A. F., and Weaver, A. J. (1996). JEBAR, Bottom Pressure Torque, and Gulf Stream Separation. *Journal of Physical Oceanography*, 26:671–683.

Otterå O. H. and Drange, H. (2004). Effects of solar irradiance forcing on the ocean circulation and sea-ice in the North Atlantic in an isopycnic coordinate ocean general circulation model. *Tellus*, 56A:154–166.

Otto-Bliesner, B. L., Marshall, S. J., Overpeck, J. T., Miller, G. H., Hu, A., and CAPE Last Interglacial Project members (2006). Simulating Arctic Climate Warmth and Icefield Retreat in the Last Interglaciation. *Science*, 311:1751–1753.

Overpeck, J. T., Otto-Bliesner, B. L., Miller, G. H., Muhs, D. R., Alley, R. B., and Kiehl, J. T. (2006). Paleoclimatic Evidence for Future Ice-Sheet Instability and Rapid Sea-Level Rise. *Science*, 311:1747–1750.

Penduff, T., Barnier, B., and de Verdière, A. C. (2000). Self-adapting open boundaries for a sigma coordinate model of the eastern North Atlantic. *Journal of Geophysical Research*, 105:11,279–11,298.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davisk, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., pin, L. P., Ritz, C., Saltzmank, E., and Stievenard, M. (1999). Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, 399:429–436.

Rahmstorf, S. (2002). Ocean circulation and climate during the past 120,000 years. *Nature*, 419:207–214.

Ren, J., Jiang, H., Seidenkrantz, M.-S., and Kuijpers, A. (2009). A diatom-based reconstruction of Early Holocene hydrographic and climatic change in a southwest Greenland fjord. *Marine Micropaleontology*, 70:166–176.

Risebrobakken, B., Balbon, E., Dokken, T., Jansen, E., Labeyrie, C. K. L., Richter, T., and Senneset, L. (2006). The penultimate deglaciation: High-resolution paleoceanographic evidence from a north-south transect along the eastern Nordic Seas. *Earth and Planetary Science Letters*, 241:505–516.

Risebrobakken, B., Dokken, T., Otterå, O. H., Jansen, E., Gao, Y., and Drange, H. (2007). Inception of the Northern European ice sheet due to contrasting ocean and insolation forcing. *Quaternary Research*, 67:128–135.

Rostami, K., Peltier, W. R., and Mangini, A. (2000). Quaternary marine terraces, sea-level changes and uplift history of Patagonia, Argentina. Comparisons with predictions of ICE-4G (VM2) model of the global process of glacial isostatic adjustment. *Quaternary Science Reviews*, 19:1495–1525.

Ruddiman, W. F. and McIntyre, A. (1975). Warmth of the Subpolar North Atlantic Ocean During Northern Hemisphere Ice-Sheet Growth. *Science*, 204:173–175.

Scherer, R. P., Aldahan, A., Tulaczyk, S., Possnert, G., Engelhardt, H., and Kamb, B. (1998). Pleistocene collapse of the West Antarctic ice sheet. *Science*, 281:82–85.

Siegenthaler, U., Stocker, T. F., Monnin, E., Lüthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J.-M., Fischer, H., Masson-Delmotte, V., and Jouzel, J. (2005). Stable Carbon Cycle-Climate Relationship During the Late Pleistocene. *Science*, 310:1313–1317.

Spall, M. A. (2004). Boundary Currents and Watermass Transformation in Marginal Seas. *Journal of Physical Oceanography*, 34:1197–1213.

Straneo, F. (2006). On the Connection between Dense Water Formation, Overturning, and Poleward Heat Transport in a Convective Basin. *Journal of Physical Oceanography*, 36:1822–1840.

Talley, L. D., Reid, J. L., and Robbins, P. E. (2003). Data-based meridional overturning streamfunctions for the global ocean. *Journal of Climate*, 16:3213–3226.

Thornalley, D. J. R., Elderfield, H., and McCave, I. N. (2009). Holocene oscillations in temperature and salinity of the surface North Atlantic. *Nature*, 457:711–714.

Treguier, A. M., Theetten, S., Chassignet, E. P., Penduff, T., Smith, R., Talley, L., Beismann, J. O., and Böning, C. (2005). The North Atlantic Subpolar Gyre in Four High-Resolution Models. *Journal of Physical Oceanography*, 35:757–774.

Vettoretti, G. and Peltier, W. R. (2003). Post-Eemian Glacial Inception. Part II: Elements of a Cryospheric Moisture Pump. *Journal of Climate*, 16:912–927.

Wunsch, C. and Heimbach, P. (2006). Estimated Decadal Changes in the North Atlantic Meridional Overturning Circulation and Heat Flux 1993-2004. *Journal of Physical Oceanography*, 36:2012–2024.

Yoshimori, M., Reader, M. C., Weaver, A. J., and McFarlane, N. A. (2002). On the causes of glacial inception 115 kaBP. *Climate Dynamics*, 18:383–402.

Zachos, J., Pagani, M., Sloan, L., and andKatharina Billups, E. T. (2001). Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present. *Science*, 292 (5517):686–693.

Zhang, R. (2008). Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation. *Geophysical Research Letters*, 35:L20705.