The role of ocean circulation and sea ice in abrupt climate change

Jonathan Winfield Rheinlænder

Thesis for the degree of Philosophiae Doctor (PhD)
University of Bergen, Norway
2020

UNIVERSITY OF BERGEN

The role of ocean circulation and sea ice in abrupt climate change

Jonathan Winfield Rheinlænder

Thesis for the degree of Philosophiae Doctor (PhD)
at the University of Bergen

Date of defense: 17.01.2020

Year: 2020
Title: The role of ocean circulation and sea ice in abrupt climate change

Name: Jonathan Winfield Rheinlænder
Print: Skipnes Kommunikasjon / University of Bergen

Acknowledgements

First, I would like to thank my main supervisor Kerim Nisancioglu and my two co-supervisors Lars Henrik Smedsrud and David Ferreira. To *Kerim*, thank you for your guidance and for giving me the opportunity to visit some of the most remote places in the world, experiencing the climate system first hand. You have an unusual ability to inspire people, and you surround yourself with motivating and skilled scientists, which comes in handy as your PhD student. Although its been challenging at times, I look back on this period with great memories. To *Lars Henrik*, thank you for sharing your vast knowledge about sea ice and the polar regions, but also for helping me handling Kerim. To *David Ferreira*, it has been a pleasure working with you, and I want to thank you for giving me input on my ideas, helping out with the MITgcm and writing the papers.

Next, I would like to thank all the ice2ice project members for exciting meetings and workshops. In particular, thanks to all the ice2ice PhD's for the fun and educational bootcamps in Denmark and Norway. I would also like to express my gratitude towards the Bjerknes Centre, providing an inclusive and inspiring place to work. On that note, thanks to the Centre for Ice and Climate as well as Scripps Institution of Oceanography for your hospitality during my brief stays in Copenhagen and San Diego.

On a more personal note, I am very thankful to *Marianne* and *Geir* for letting me borrow their cabins - going to the mountains near Reime and Hamlagrø on weekends has been a true sanctuary and a well-needed rest from the PhD. Also thanks to my running, skiing, snowboarding, and climbing friends from Bergen (you know who you are), who made the weekends more adventurous.

To *Silje*, thank you for listening to my (what might seem endless) complaining and bickering about the PhD and for keeping me sane throughout these years. I am most grateful for all the wonderful experiences we had together during the PhD; field work in Greenland, living abroad in California and in the Copenhagen houseboat, not to mention all the conferences and meetings. PhD-life was more fun because of you, and I am looking forward to the next chapter!

Lastly, my family for reminding me about the important things in life. To my *mother*, who I wish could be here today, and my *father*: you inspire me to improve myself and become a better human being. You support me in everything that I do, and for that I am forever grateful. To my sister, *Kira*: thank you for pretending to listen, when I talk about equations and graphs, but most importantly for being there when life was difficult. You are amazing!

Abstract

Abrupt changes in Earth's climate have occurred repeatedly throughout the geological record. Evidence from paleoclimate data has revealed that climate changed most dramatically during the last glacial period, associated with the Dansgaard-Oeschger (D-O) events. These are characterized by large and rapid fluctuations in North Atlantic climate, with regional warming of up to 15°C over Greenland, within a few decades. The main hypotheses for these abrupt climate changes in the past, centers around changes in the Atlantic Meridional Overturning Circulation (AMOC) and its influence on poleward ocean heat transport. Recently, the role of sea ice has also been recognized as a critical player for the D-O events; linking the abrupt changes in Greenland temperature to a retreat of Northern Hemisphere sea ice, driven by internal variability of the coupled ice-ocean and atmosphere system. However, the mechanism for triggering rapid changes in sea ice, and how it is linked to ocean circulation changes, remains elusive.

This thesis focuses on the interaction between ocean circulation, sea ice and high-latitude climate in the context of abrupt climate changes in the past. The main goal is to improve our understanding of how internal dynamics of the coupled climate system can lead to rapid and unforced changes in climate. The first part of this thesis explores the mechanism behind abrupt changes in sea ice by studying the formation of open-ocean polynyas in the Southern Ocean. The second and third part, focuses on the dynamics of large-scale ocean circulation and its sensitivity to ocean bathymetry and the distribution of diapycnal mixing in the ocean interior.

We find that open-ocean polynyas in the Southern Ocean provide a mechanism to trigger abrupt sea ice retreat, similar to that seen during the last glacial period. These events drive increased bottom water formation, thereby impacting the large-scale ocean circulation. The formation of the polynya is preconditioned by a gradual build-up of subsurface heat and salt beneath the ice cover. This destabilizes the water column, triggering enhanced vertical mixing and causing the polynya to open. Our findings suggest that open-ocean polynyas, driven by internal ocean-sea ice dynamics, may play a fundamental role in abrupt climate changes such as D-O events.

It is demonstrated that ocean basin geometry has a major impact on ocean circulation. In particular, the presence of the Greenland-Scotland Ridge affects the location of deep water formation and plays a fundamental role in shaping the AMOC and high-latitude climate. Interestingly, the strength of the AMOC at 26°N is largely decoupled from deep water formation north of the ridge, and the AMOC plays a relatively small role in transporting heat northward across the Greenland-Scotland Ridge. This calls into question the role of the AMOC as the main driver of past abrupt changes in high latitude climate.

Finally, the distribution and magnitude of vertical mixing in the ocean is found to play a central role in the stability of the coupled climate system and for the existence of the D-O events. Unforced and self-sustained «DO-like» oscillations can occur when thermocline mixing is low and the AMOC is reduced, allowing heat to accumulate below the sea ice, thereby preconditioning the system for an abrupt change. In addition, we find that changes in the abyssal mixing do not have a large impact on AMOC strength and surface climate.

In summary, the results presented in this thesis confirm that ocean circulation has played a persistent and central role in abrupt climate change in the past, but emphasizes that variations in AMOC strength might not be the main trigger. In addition, the thesis highlights changes in sea ice as a necessary condition to drive large and rapid changes in high latitude climate. Such changes may occur in response to unforced and self-sustained oscillations of the coupled atmosphere-ocean-sea ice system, demonstrating that abrupt climate change can occur without being subject to large external forcing. This has important implications for predicting future abrupt changes in climate as a response to anthropogenic forcing, noting that the dynamics of abrupt changes as seen in the past can also operate in a warming climate.

List of papers

1. Jonathan W. Rheinlænder, Lars H. Smedsrud and Kerim H. Nisancioglu, *Internal ocean dynamics as a driver for open-ocean polynyas in the Weddell Sea*, **In revision, Tellus A: Dynamic Meteorology and Oceanography**.
2. Jonathan W. Rheinlænder, David Ferreira, and Kerim H. Nisancioglu *Topological constraints by the Greenland-Scotland Ridge on AMOC and climate*, **Submitted to Journal of Climate**.
3. Jonathan W. Rheinlænder, David Ferreira, and Kerim H. Nisancioglu *The impact of vertical mixing on glacial ocean circulation and sea ice*, **Manuscript in preparation for Paleoceanography and Paleoclimatology**.

Contents

Chapter 1

Introduction

Large and abrupt changes in earth's climate have occurred repeatedly throughout the geological record, with regional temperature changes up to 16°C in a matter of only 10 years or less. Evidence from the paleo record suggests that such climate changes involve the entire coupled climate system, including atmosphere and ocean circulation, the cryosphere and biological systems. A central question of present climate research is whether such abrupt changes in climate might occur in the future and if their likelihood increases as the climate continues to warm. Meanwhile, the mechanisms that lead to such rapid changes in the past is not yet fully understood, and makes predicting the impact of potential abrupt change in the future difficult. The current generation of state-of-the-art climate models, similar to those used for making projections of future climate, typically underestimate the magnitude and abruptness of these past changes (Seager and Battisti, 2007). Hence, an increased understanding of the possible drivers of past abrupt climate change and their impacts, is crucial to improve climate predictions and asses the likelihood of rapid and potentially catastrophic changes occurring in the future.

Recent scientific evidence emerging from research over the past decade, have shown that non-linear abrupt climate change can occur even due to slow, gradual forcing such as continental drift or orbital forcing, pushing the earth system across a critical threshold or "tipping point" (e.g., Rose et al., 2013; Stärz et al., 2017). The mechanisms that causes the climate system to transition into a new state may have natural causes (e.g. changes in solar insolation, or even stochastic processes internal to the climate system) or could be triggered by human-induced alterations of the earth system (e.g. greenhouse-gas emissions). Hence, the rapid increase in greenhouse gases and the ongoing global warming may increase the probability of crossing such a threshold and trigger large and abrupt climate shifts in the future (Broecker, 1997; National Research Council, 2002). If such changes occur too rapidly and unexpectedly, societal and ecological systems will have trouble adapting and could have catastrophic consequences for e.g., agriculture and food availability.

Observations from the historical record reveals that abrupt shifts in regional climate already occurs as a consequence of human-induced forcing of the climate system and share many of the same features as those observed in the past (Voelker, 2002). In the Arctic regions, in particular, the impacts of anthropogenic climate change is more evident than anywhere else on the globe due to the decline of Arctic sea ice (Holland and Bitz, 2003). In recent decades, the Arctic has experienced unprecedented sea ice loss and surface warming (e.g., Serreze et al., 2007; Stroeve et al., 2012). The abruptness and magnitude of the ongoing Arctic warming is not unlike those observed during the last glacial period (Jansen et al., 2019). Climate model projections into the near-future forecasts summer Arctic ice-free conditions by the year 2050 (Holland et al., 2006; Smedsrud et al., 2008), with the possibility of a critical threshold causing a rapid and complete disappearance of the Arctic sea ice cover (Eisenman and Wettlaufer, 2009). Understanding how the ongoing changes in Arctic sea ice can trigger non-linear and abrupt changes in future climate is of major concern, and requires an increased understanding of the ocean-atmosphere interactions underlying these changes as well as their impacts outside the polar regions.

To put these recent changes in perspective, it is instructive to look into the paleoclimate record, where the earth system is unperturbed by human activity, thereby offering critical information about the role of natural climate variability in abrupt climate change. This chapter gives a brief overview of what is known about abrupt climate change in the past inferred from the paleoclimate record, focusing in particular on the abrupt climate fluctuations in the North Atlantic region during the last glacial period (section 1.1) and introduces some of the main hypotheses that have been invoked to explain them. Section 1.2 focuses on the link between large-scale ocean circulation and glacial climate variability, while section 1.3 introduces the role of sea ice as a potential trigger for abrupt climate change.

1.1 Abrupt climate change in the past

During the last glacial period (60-27 ka; also known as Marine Isotope Stage 3, MIS 3) climate was much more variable compared with the warm and stable climate of the Holocene. This is evident in the δ^{18}O record from Greenland ice cores, which shows that North Atlantic climate fluctuated between cold (stadial) and relatively warm (interstadial) conditions (Fig. 1.1). These fluctuations are known as Dansgaard-Oeschger (D-O) events and can be identified as abrupt transitions between stadial and interstadial conditions occurring 25 times throughout the last glacial period (Rasmussen et al., 2014; Wolff et al., 2010). The D-O cycle is characterized by an abrupt warming from stadial to interstadial conditions with an amplitude varying from 5°C and 16°C completed in a few decades. This is followed by a slow cooling on a centennial timescale back to stadial conditions (Landais et al., 2004; Lang et al., 1999). This characteristic "saw-tooth" shape of the D-O cycle, with abrupt warming followed by gradual cooling, is a prominent feature of glacial climate variability and presents an essential clue to understand the dynamics underlying them (Seager and Battisti, 2007).

Evidence from different paleoclimate archives around the globe suggest that the dramatic and abrupt changes documented in the Greenland ice cores was not only confined to the North Atlantic region, but had a global footprint seen as large-scale changes in precipitation patterns, surface air temperature, wind-stress and atmospheric greenhouse gas concentrations (see e.g., Clement and Peterson, 2008; Voelker, 2002, for a

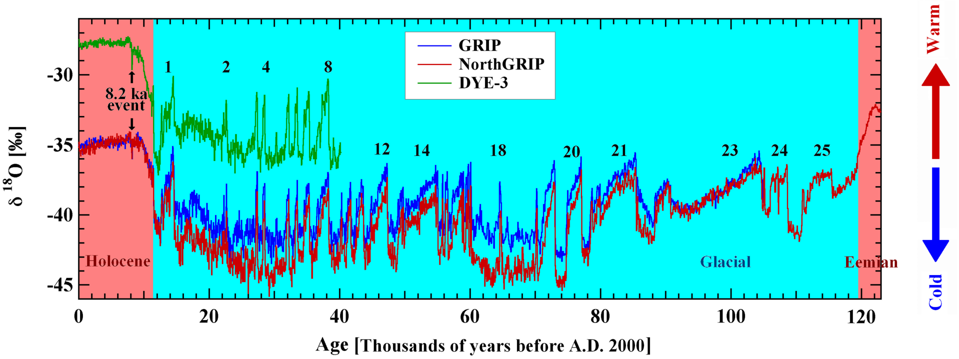

Figure 1.1: Profiles of $\delta^{18}O$ recorded in Greenland ice cores for the last 123,000 years. The $\delta^{18}O$ record is a proxy for surface temperature and offers a unique insight into Greenland climate during the last glacial period, which is characterized by rapid fluctuations between warm and cold conditions known as Dansgaard-Oeschger events. Source: Centre for Ice and Climate (2008)

review). For example, ice core records from Antarctica show a similar, but out-of-phase temperature response compared to Greenland (Barbante et al., 2006), indicating an antiphase coupling between the northern and southern hemisphere on centennial timescales known as the bipolar see-saw (see Pedro et al. (2018) for a review).

Over the past decades, considerable progress has been made in understanding the origin of the D-O events. In the following, some of the proposed mechanisms for explaining the rapid fluctuations in glacial climate will be discussed in more detail.

1.2 The Atlantic Meridional Overturning Circulation and abrupt climate change

The Atlantic Meridional Overturning Circulation (AMOC) consists of two overturning cells: an upper cell associated with a northward flow of relative warm surface waters, which sinks at high latitudes forming North Atlantic Deep Water (NADW), returning as a southward flow at depth and; a lower cell representing the northward flow of cold, dense Antarctic Bottom Water (AABW) formed in the Southern Ocean (Kuhlbrodt et al., 2007). This is shown in Fig. 1.2a, illustrating the global overturning circulation. Because the upper overturning cell spans a large temperature gradient between the surface and the deep ocean, it transports a large amount of heat from the tropics to the northern high latitudes, thus playing a key role for the global energy budget and especially North Atlantic climate (Buckley and Marshall, 2015).

The northern branch of the AMOC regulates the poleward transport of heat and salt to the Nordic Seas and Arctic Ocean via the Atlantic inflow. In the present climate about 2/3 of the Atlantic inflow can be attributed to an overturning circulation, associated with deep water formation in the Nordic Seas (Eldevik et al., 2013). These cold,

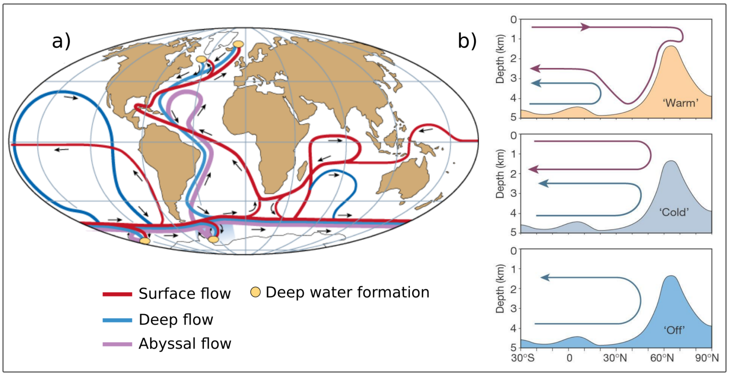

Figure 1.2: (a) Simplified schematic of the global overturning circulation, showing the main flow patterns associated with the large-scale ocean circulation and deep water formation sites. (b) Conceptual model of the three hypothesized states of the Atlantic meridional overturning circulation (AMOC) in last glacial period. Shown is a section along the Atlantic; the rise in bottom topography symbolizes the shallow sill between Greenland and Scotland (i.e. the Greenland-Scotland Ridge). North Atlantic overturning is shown by the red line, Antarctic bottom water by the blue line. Modified from (Rahmstorf, 2002).

dense waters subsequently spill over the Greenland-Scotland Ridge (GSR) and into the North Atlantic, where it mixes and entrains relatively warm ambient waters, contributing to the southward volume transport of NADW (see Hansen and Østerhus (2000) and Furevik et al. (2007) for a comprehensive review). Here, the GSR represents a topographic barrier that constricts the exchange between the North Atlantic and high latitudes thereby modulating the Nordic Seas overflow and potentially AMOC strength. As a consequence, variations in the depth of the GSR, is thought to have played a central role in the long-term evolution of North Atlantic and global climate (e.g., Stärz et al., 2017; Uenzelmann-Neben and Gruetzner, 2018). Meanwhile, roughly 1/3 of the Atlantic inflow occurs via a freshwater-sustained eustarine circulation, which leaves with the East Greenland Current and is independent of deep water formation at high latitudes (Eldevik et al., 2013).

Due to its control on the meridional heat transport, variations in the strength of the AMOC has long been the prevailing explanation for the abrupt changes in North Atlantic climate of the last glacial period (see e.g., Clark et al., 2002; Rahmstorf, 2002, for a review). In this traditional view, the AMOC exhibits a bi-stability with three different modes of operation over the last glacial cycle (Fig. 1.2b): a warm mode typical of the interstadials, characterized by a strong and deep AMOC with dense water formation in the Nordic Seas; a cold mode with a shallower and weaker circulation which prevailed during the stadials, where deep water formation occurred through open-ocean convection in the subpolar North Atlantic; and finally an off (or *Heinrich*) mode which followed after large freshwater input typically during Heinrich stadials (Heinrich, 1988). The existence of these different AMOC modes of the last glacial is largely based on ocean sediment records (e.g., Henry et al., 2016; Lynch-Stieglitz, 2016).

Transitions between stadial and interstadial conditions is thought to arise from abruptly switching between cold and warm circulation states, associated with latitude shifts in the location of deep water formation (Dokken and Jansen, 1999). Traditionally, freshwater perturbations are invoked to trigger transitions between the two AMOC states by weakening or shutting down NADW formation. This has long been motivated by the occurrence of ice-rafted debris (IRD) in marine sediment cores, indicating periodic iceberg discharge into the North Atlantic from the surrounding ice sheets during the cold phase of the D-O cycle (Bond et al., 1995; Broecker, 1994; Heinrich, 1988). Such ice rafting events may arise due to internal ice-sheet oscillations (MacAyeal, 1993) or ice-shelf instabilities driven by ocean subsurface warming (Marcott et al., 2011; Shaffer et al., 2004). The concept described by Broecker (1994), suggests that introducing large amounts of freshwater from melting icebergs into the North Atlantic results in a disruption of deep-water formation and leads to a weakening or even complete collapse of the thermohaline circulation. As a consequence, the northward ocean heat transport is reduced and causes a strong cooling of the Northern Hemisphere.

The idea that the AMOC is bi-stable and may switch in response to anomalous freshwater forcing, is supported by early conceptual and simple models first described by Stommel (1961). Over the past couple of decades, this inspired several "water-hosing" experiments with ocean and fully-coupled climate models (e.g., Ganopolski and Rahmstorf, 2001; Manabe et al., 1995; Stouffer et al., 2006), which confirm that a large freshwater input to the North Atlantic can trigger AMOC shut-down and drive widespread cooling of the high-latitude surface ocean in agreement with proxy data. However, the spatial imprint of the AMOC response varies substantially between models and is mostly confined to the North Atlantic region (e.g., Kageyama et al., 2013). Other models have demonstrated that AMOC weakening can also be attained by adding freshwater in the Southern Ocean, through the bipolar see-saw mechanism (e.g., Swingedouw et al., 2009).

Meanwhile, proxy-data indicate that large reductions in AMOC strength only occurred during Heinrich stadials (Lynch-Stieglitz, 2016), and the evidence for large AMOC changes during the D-O events is less clear. Several recent studies have thus questioned the role of the AMOC as the main trigger for D-O events (e.g., Barker et al., 2015; Clement and Peterson, 2008; Seager and Battisti, 2007; Wunsch, 2006). Seager and Battisti (2007) pointed out that the amount of freshwater used in most state-of-the-art climate models (e.g., Cheng et al., 2007) to obtain D-O warming or cooling events is unrealistic. Models using a more realistic amount (e.g., Stouffer et al., 2006), show a more modest AMOC weakening and produce a surface climate response that is much weaker than suggested by the proxy data. In addition, the hosing experiments does not seem to capture the abrupt warming at the stadial-interstadial transition, which is characteristic of the D-O cycle (Seager and Battisti, 2007). The second issue, is connected to the timing of the surface climate transition relative to the changes in AMOC and ice-rafting events. A recent proxy-based study by Barker et al. (2015) revealed that the input of freshwater, derived from melting icebergs, systematically lags the onset of North Atlantic cooling, and concluded that icebergs do not trigger cold events in the North Atlantic. Similarly, Marcott et al. (2011) found that the arrival of icebergs (i.e. the Heinrich event) is preceded by an AMOC slowdown by about 1,000 years. This questions the causality between past AMOC changes and meltwater discharge from Northern Hemisphere ice sheets as the primary trigger for D-O events, and suggests that other mechanisms must be involved to explain the abrupt changes in North Atlantic climate. Nevertheless, the freshwater input probably plays a big role in setting the timescale of the D-O cycles by prolonging and amplifying stadial conditions.

Alternatively, some models have suggested that self-sustained oscillations between warm and cold AMOC states can occur without invoking external freshwater perturbations, but are instead caused by internal variations in the North Atlantic heat and freshwater transports (de Verdière and Raa, 2010; Loving and Vallis, 2005; Wang and Mysak, 2006). Such oscillations strongly depend on the background climate state (e.g. Li and Born, 2019; Schmittner et al., 2003; Tziperman, 1997), and may be sensitive to ice-sheet and CO_2 configurations (Klockmann et al., 2018), which could explain why D-O events only occur under very specific glacial boundary conditions (Van Meerbeeck et al., 2009). To understand how such oscillations may arise, it is instructive to review the mechanisms that drive the overturning circulation.

1.2.1 Drivers of the AMOC

Although changes in deep water formation in the North Atlantic has received most attention in connection to abrupt climate change (Rahmstorf, 2002), other factors may be important for modulating AMOC strength in the past. Currently, the global meridional overturning circulation (MOC) is considered to be driven by two main processes: diapycnal mixing of heat and salt in the ocean interior; and wind-driven upwelling in the Southern Ocean. Meanwhile, the formation of dense waters at high latitudes largely determines the properties of the circulation (Kuhlbrodt et al., 2007; Wunsch and Ferrari, 2004).

Diapycnal mixing

Diapycnal mixing provides the energy to mix dense water masses, formed through high-latitude convection, across the deep stratification thereby controlling the rate of which bottom water is raised through upwelling into the low latitude thermocline (Munk, 1966). Warm surface waters are subsequently advected polewards into high latitudes, where it is transformed into deep waters by surface buoyancy forcing, thus closing the overturning loop (Stommel and Arons, 1959). This concept has been confirmed by model simulations (e.g. Bryan, 1987; Jayne, 2009; Scott and Marotzke, 2002), highlighting the role of diapycnal mixing in determining the strength of the MOC and its implications for past climate variability (Nilsson et al., 2003; Schmittner et al., 2015).

Based on tracer observations from the Pacific Ocean, Munk (1966) estimated a constant value of $1.3 \times 10^{-4}\,\mathrm{m^2\,s^{-1}}$ for the vertical diffusivity (κ_v) in the modern ocean. More recent observations have shown that vertical mixing is non-uniform, but varies both temporally and spatially (Munk and Wunsch, 1998; Polzin et al., 1997). Mixing is generally weak in the main thermocline and increases towards the bottom, where internal waves generated by the tides interact with the bottom topography and values as high as $10^{-3}\,\mathrm{m^2\,s^{-1}}$ has been observed (Polzin et al., 1997). During the last glacial period, on the other hand, the distribution of diapycnal mixing may have been significantly different due to a lower sea level relative to present, with potentially large consequences for the MOC and glacial surface climate (e.g., Green et al., 2009). However, there is still no clear consensus on the relationship between vertical mixing and glacial ocean circulation (Schmittner et al., 2015).

Southern Ocean winds

The second mechanism is wind-induced upwelling in the Southern Ocean proposed by Toggweiler and Samuels (1995). Based on observations, they argued that the amount of interior mixing is insufficient to maintain the observed overturning circulation of 15-20 Sv in the Atlantic ocean. Thus, an additional source of energy is required to close the overturning loop, which is provided by the strong Southern Hemisphere westerly winds, driving upwelling of deep waters formed in the North Atlantic. Due to a northward Ekman transport in the Southern Ocean, cold surface waters are forced equatorwards and is balanced by a poleward flow of deep water. In this view, the strength of the overturning is largely determined by the magnitude of the Southern Ocean winds, while the distribution of surface buoyancy fluxes and sea ice in the upwelling region has a big impact on its structure (Ferrari et al., 2014; Jansen and Nadeau, 2016).

While the relative contributions from Southern Ocean winds and diapycnal mixing remains poorly constrained, the current understanding is that both processes are important for maintaining the global overturning circulation (Kuhlbrodt et al., 2007; Marshall and Speer, 2012). Hence, both of these processes, in addition to changes in high-latitude deep water formation, are likely to have contributed to abrupt AMOC changes in the past (e.g., Nilsson et al., 2003; Wunsch, 2006).

1.3 The sea ice hypothesis for stadial-interstadial transitions

An alternative hypothesis relates the Dansgaard-Oeschger events to spontaneous and self-sustained oscillations in glacial climate, building on the concept of multiple equilibria of the climate system (e.g., Ferreira et al., 2018, 2011). As opposed to being externally forced, i.e. by freshwater or some other external forcing, models have shown that abrupt changes may arise from internal variability of the coupled ocean-atmosphere-sea ice system (Broecker et al., 1990; de Verdière and Raa, 2010; Peltier and Vettoretti, 2014), and may even occur under pre-industrial boundary conditions (e.g., Kleppin et al., 2015; Martin et al., 2015). The existence of these internal oscillations is strongly linked to changes in the Northern Hemisphere sea ice cover.

1.3.1 Evidence from proxies and models

Recent proxy-based and numerical studies have shown that periodic retreat and advance of sea ice in Nordic Seas and North Atlantic play a critical role in driving the abrupt warming in Greenland temperature associated with the D-O events (Broecker, 2000; Dokken et al., 2013; Gildor and Tziperman, 2003; Hoff et al., 2016; Li et al., 2010, 2005). Based on a high-resolution sediment core from the Norwegian margin,

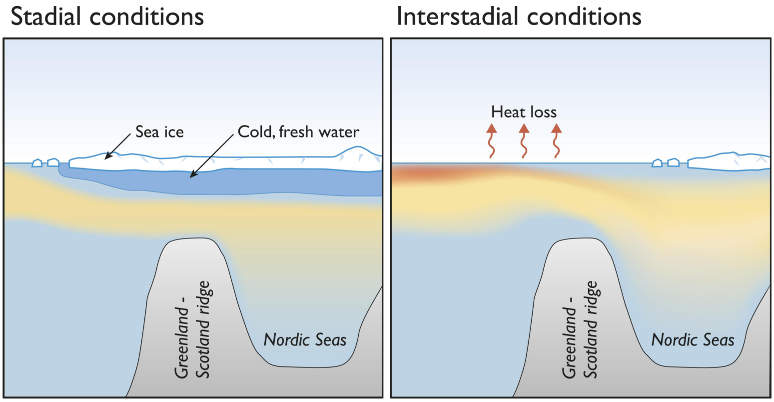

Figure 1.3: Schematic adapted from Dokken et al. (2013), illustrating the connection between stadial-interstadial transitions and intrinsic changes in Nordic Seas sea ice cover. *Stadial*: During stadial conditions the Nordic Seas are ice-covered and oceanic heat accumulates beneath the sea ice. Deep convection is absent. *Interstadial*: The build up of subsurface heat triggers convective overturning and leads to abrupt sea ice retreat, surface warming and active deep convection in the Nordic Seas.

Dokken et al. (2013) suggest that interstadial and stadial phases of the D-O cycle are associated with fluctuations between relatively ice-free and fully ice-covered conditions in the Nordic Seas, illustrated in Fig. 1.3. During cold stadial conditions the Nordic Seas are covered by an extensive sea ice cover, maintained by the presence of a strong halocline. As the stadial phase progresses warm Atlantic waters gradually accumulates beneath the ice cover (Fig. 1.3; left hand side). Eventually, the subsurface warming destabilizes the water column, oceanic heat is rapidly mixed up into the surface layer, causing sea ice to retreat and marks the transition to interstadial conditions (Fig. 1.3; right hand side). The hypothesis proposed by Dokken et al. (2013) suggest that the subsurface warming plays a critical role for triggering stadial-interstadial transitions, and relies on ocean-sea ice interactions intrinsic to the Nordic Seas and are thus independent of large-scale ocean circulation changes. This concept is confirmed by model simulations from Li et al. (2005), who showed that removing sea ice in the Nordic Seas can drive warming up to 10°C on Greenland on a timescale consistent with the ice core data. Li et al. (2010) further showed that removing sea ice in the Nordic Seas produced a significantly greater warming on Greenland, compared to when sea ice is removed in the western North Atlantic.

Displacements in the Northern Hemisphere sea ice cover between stadials and interstadials also affected deep water formation (Dokken and Jansen, 1999; Ezat et al., 2014; Rasmussen and Thomsen, 2004), providing a possible link between changes in sea ice and the different AMOC states illustrated in Fig. 1.2. During warm interstadials, conditions were similar to today with deep-water formation through open-ocean convection in the Nordic Seas, which contributes with a relatively large heat transport to the northern high latitudes. The subsequent mixing and entrainment of the Nordic Seas overflow downstream of the GSR provides a significant fraction to the volume transport of the AMOC's lower limb (e.g. Hansen and Østerhus, 2000), thus maintaining a strong AMOC. In contrast, during stadials the presence of sea ice in the Nordic Seas and northern North Atlantic would have reduced ocean-atmosphere heat loss, and deep-water formation shifted to the south of the GSR (Dokken and Jansen, 1999). Consequently, the outflow from the Nordic Seas may have ceased (e.g., Rasmussen and Thomsen, 2004), which likely contributed to a reduced heat transport across the GSR as well (Sadatzki et al., 2019a). Furthermore, this may have lead to a weakening of the AMOC during the stadial phase. However, the connection between the Nordic Seas overflow and AMOC strength remains heavily debated, and at present no conclusive evidence linking the two exists (e.g. Lozier et al., 2017; Moffa-Sanchez et al., 2015). Alternatively, changes in wind-stress induced by displacements in sea ice may also affect large-scale ocean circulation through interactions with the subpolar gyre (Li and Born, 2019).

Several other mechanisms for triggering the abrupt sea ice retreat in the Nordic Seas have been proposed including for example; changes in the subpolar gyre circulation triggered by stochastic atmospheric forcing from the tropical Pacific (Kleppin et al., 2015); wind stress changes (Li et al., 2005); a salt-oscillator in the North Atlantic (Broecker et al., 1990; Peltier and Vettoretti, 2014) and ice-shelf instabilities induced by subsurface ocean warming (Petersen et al., 2013). In addition, recent numerical modeling studies by Vettoretti and Peltier (2016, 2018) have shown, that the rapid retreat of sea ice at the onset of the D-O warming phase may be initialized by large openings within the extensive North Atlantic sea ice cover, known as open-ocean polynyas. These studies indicate that open-ocean polynyas could be an integral part of glacial climate variability. Hence, understanding how and why these polynyas form in the present day ocean can provide useful insight to the dynamics of the abrupt sea ice changes, that occurred during the last glacial period.

1.3.2 Polynyas and abrupt climate change

A polynya is defined as an ice-free area surrounded by sea ice and typically ranges in size from 10 to 10^5 km^2 (Morales Maqueda et al., 2004). Generally, we differentiate between two types of polynyas; latent heat (coastal) polynyas and sensible heat (open-ocean) polynyas, illustrated in Fig. 1.4.

Latent heat polynyas are mechanically driven and are typically found along the coast of the Antarctic continent, mainly in the Weddell and Ross Seas and over the continental shelves in the Arctic (Martin et al., 1998; Skogseth et al., 2004). They are created by local offshore (i.e. katabatic) winds pushing newly formed sea ice away from coast, resulting in more sea ice formation and brine rejection associated with freezing of sea ice. In Antarctica, the cold and saline waters formed within coastal polynyas descend over the continental slope as gravity currents, entraining the ambient warm deep waters along the way. This process, known as continental shelf slope convection, is the dominant contributor to the formation of AABW in the present climate (Killworth, 1983; Orsi et al., 1999). In the Arctic, the brine release in coastal polynyas are important for maintaining the Arctic halocline and stratification (e.g., Cavalieri and Martin, 1994), and may have played a central role for the stability of the Nordic Seas ice cover during

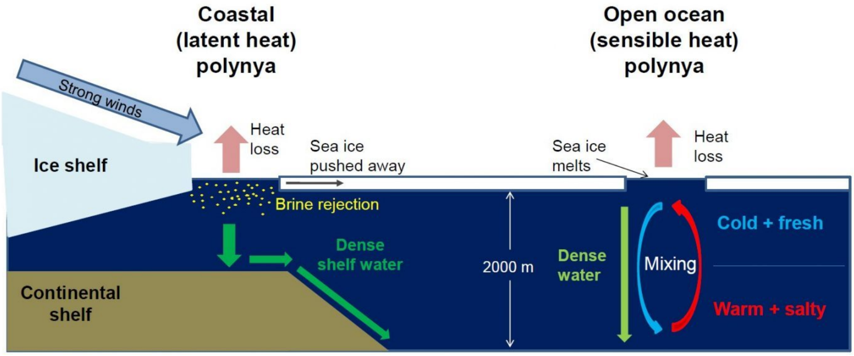

Figure 1.4: Schematic showing the two types of polynyas; latent heat (*coastal*) polynyas and sensible heat (*open-ocean*) polynyas and the processes that causes them to form. Credit: Celine Heuze (Heuze, 2016)

stadial times (Singh et al., 2014). In addition, coastal polynyas are important for Arctic and Antarctic ecosystems as well (e.g., Deibel and Daly, 2007; Labrousse et al., 2018; Morales Maqueda et al., 2004).

Sensible heat polynyas, on the other hand, form away from the continental shelf in open-ocean regions mainly around Antarctica. These so-called open-ocean polynyas are formed by thermodynamic processes, when relatively warm subsurface water (which originates from the NADW) is injected into the surface layer causing sea ice to melt or preventing it from forming (Fig. 1.4). In the absence of the protective sea ice cover, the intense cooling at the air-sea interface causes surface waters to sink, forming deep convective plumes that extend into the abyssal ocean. This provides a highly effective way of ventilating the deep and bottom waters in the Southern Ocean (Hirabara et al., 2012; Wang et al., 2016; Zanowski et al., 2015), which plays an important role in maintaining the global thermohaline circulation (Marotzke, 2000; Rahmstorf, 2002). The processes of open-ocean polynya formation can be summarized as follows: 1) preconditioning due to subsurface heat build-up below the sea ice and weak stratification; 2) destabilization of the water column; 3) polynya formation due to upwelling of relatively warm deep water; 4) open-ocean deep convection driven by intense surface cooling; and 5) cessation of deep convection and closing of the polynya (Cheon et al., 2017; Gordon, 1982; Martinson et al., 1981).

Open-ocean polynyas are a relatively unusual feature in the present climate system. A persistent, large-scale open-ocean polynya has only been observed once during the mid-1970's in the Weddell Sea (Gordon and Comiso, 1988). This is known as the Weddell Polynya (250,000 - 300,000 km^2 in size), which persisted from 1974 to 1976 and triggered deep-reaching convection down to ~3000 m depth with significant impact on Weddell Sea water mass properties and AABW (Gordon, 1982; Robertson et al., 2002; Zanowski and Hallberg, 2017; Zanowski et al., 2015). Subsequently, a polynya of the same size has not been observed, although smaller and short-term polynyas have occurred over Maud Rise (a seamount located in the eastern Weddell Sea) latest in 2016 and 2017 (e.g., Francis et al., 2019; Smedsrud, 2005; Swart et al., 2018).

In a recent modeling study, de Lavergne et al. (2014) suggested that the cessation of open-ocean deep convection in the Weddell Sea since the 1970's can be attributed to enhanced surface freshening of the Southern Ocean due to anthropogenic climate change. This, in turn, implies that open-ocean polynyas would have been more frequent in the past under pre-industrial conditions and may even have been the dominant mode of AABW formation (Gordon, 2014). Increased surface freshening acts to strengthen the stratification (i.e. the pycnocline) that separates the relatively warm and saline deep water from the cold and fresh surface layer, and prevents polynyas from forming. Projections of climate models suggest that this effect will increase in the future due to increased melt from the Antarctic ice sheet as well as an enhanced hydrological cycle (de Lavergne et al., 2014).

Several mechanisms have been proposed for triggering the upwelling of warm deep water leading to the formation of the Weddell Polynya including; wind-driven upwelling of warm water in the Weddell Gyre through changes in the Southern Hemisphere westerlies (Campbell et al., 2019; Cheon et al., 2017, 2015; Francis et al., 2019), topographic induced eddy activity at Maud Rise (Cheon and Gordon, 2019; Holland, 2000), and changes in atmospheric conditions affecting freshwater budget and sea ice formation (de Lavergne et al., 2014; Gordon et al., 2007). In addition, a number of ocean and fully-coupled climate models have demonstrated that open-ocean polynyas can arise from internal variability of the ocean-sea ice system occurring on a range of different timescales (Dufour et al., 2017; Martin et al., 2013; Reintges et al., 2017). In these models, subsurface heat slowly accumulates at intermediate depths and eventually destabilizes the water column triggering spontaneous open-ocean convection. Convection remains active until the subsurface heat reservoir is depleted, after which the polynya closes and heat starts accumulating again, thus reflecting a cycle between convective and non-convective phases of Southern Ocean deep ventilation. However, observational records remain too short to asses if these convective cycles are part of a natural oscillation of the climate system (Campbell et al., 2019).

The mechanism described above has many similarities with the Dokken et al. (2013) hypothesis, in which warm Atlantic waters accumulate below the Nordic Seas ice cover until it is subsequently released, triggering rapid sea ice loss, surface warming and enhanced deep-ocean ventilation (i.e. Fig. 1.3). Until recently, however, research on polynyas in the context of glacial climate variability was relatively unexplored. Using the Community Earth System Model version 1 (CESM1) with Last Glacial Maximum (LGM) boundary conditions, Vettoretti and Peltier (2016) showed that unforced D-O like variability occurs spontaneously in the model, and found that the initial phase of the D-O oscillation (i.e. abrupt warming), is characterized by the formation of a massive "super polynya" in the North Atlantic. The polynya forms due to a thermohaline convective instability closely linked to a build-up of subsurface heat below the ice cover, similar to (Dokken et al., 2013; Sadatzki et al., 2019a), leading to a large-scale retreat of sea ice in the North Atlantic (Vettoretti and Peltier, 2016, 2018). In the Southern Ocean, Martin et al. (2015) find that deep convection events, associated with large open-ocean polynyas in the Weddell Sea, can drive variations in the AMOC on multi-centennial time-scales: episodes of enhanced deep convection leads to a stronger AABW transport, which is compensated by a weaker southward flow of NADW (i.e. the bipolar see saw, Broecker (1998)). This suggest a potential link between Southern Ocean polynyas and AMOC variability, which may in turn explain the out-of-phase relationship between Antarctic warming events of the last glacial period and abrupt D-O events recorded in Greenland ice cores (Pedro et al., 2016).

Chapter 2

Motivation and objectives

There is now an emerging consensus from paleoproxy data and numerical models, that abrupt climate change of the last glacial involves basin-scale reorganizations of ocean circulation as well as rapid and large displacements in the Northern Hemisphere sea ice cover. In addition, a growing number of climate models point to the possibility, that the D-O events may be spontaneous oscillations of the glacial climate system, and can be triggered without invoking large inputs of freshwater. Despite these significant advancements, some major challenges remain providing the basis for this thesis.

First, the mechanism causing rapid sea ice retreat in the Northern Hemisphere is missing. In particular, how a build-up of heat beneath the ice cover can trigger abrupt changes in sea ice, and how it might be related to open-ocean polynyas. Secondly, the role of the AMOC in transporting heat to the high-latitudes has recently been brought into question (e.g., Li and Born, 2019; Wunsch, 2006). Naturally, the question arises whether the AMOC is the primary driver for abrupt changes in high-latitude climate, or just a passive response. Finally, it remains to be understood why some climate models exhibit unforced and self-sustained DO-like oscillations, while others do not. Recent studies have suggested that their existence may depend on the distribution of diapycnal mixing in the glacial ocean (e.g., Peltier and Vettoretti, 2014). However, the physical mechanism linking changes in ocean vertical mixing to abrupt glacial climate change remains elusive, which calls for dedicated sensitivity studies testing the impact of vertical mixing on glacial ocean circulation and sea ice.

2.1 Introduction to the papers

In this thesis, I present three papers that address each of the issues outlined above. Rather than trying to give a complete explanation of the D-O events in particular, the overall goal of the papers is to improve understanding of the dynamics of the coupled climate system and highlight potential drivers of abrupt climate change observed in the paleoclimate record.

Paper I, explores the dynamics of abrupt sea ice changes by studying the occurrence of open-ocean polynyas in the Southern Ocean simulated in a coupled ocean-sea ice model and discusses its implications for global ocean circulation. The main objective

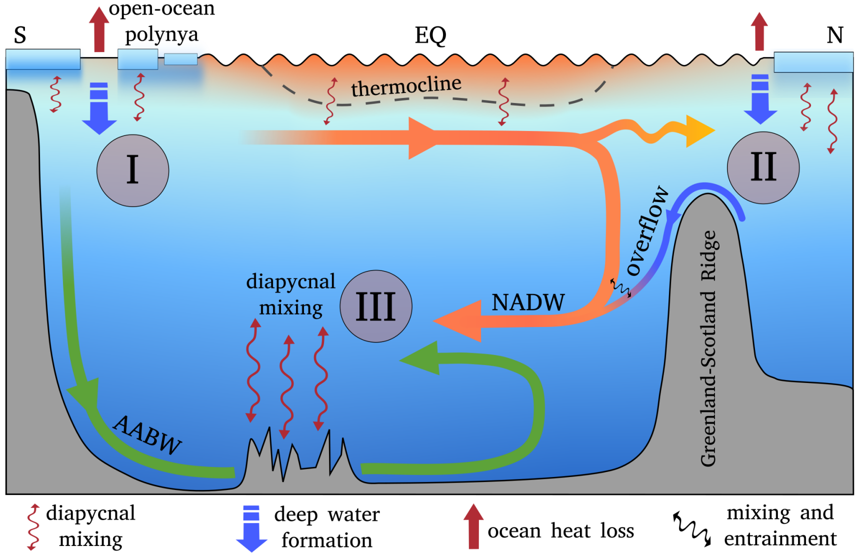

Figure 2.1: Schematic summarizing the three papers presented in this study and how they connect to each other.

of this paper is to attain a deeper insight into the physical mechanisms that precondition polynya formation and ultimately causes the polynya to open. Thus, the paper centers on the following question:

- *How can internal ocean-sea ice dynamics, associated with a gradual build-up of subsurface heat (below the ice cover), trigger abrupt changes in sea ice?*

Paper II looks at the role of ocean basin geometry in shaping ocean circulation and climate, providing useful insights into the dynamics of the coupled climate system. Through a set of idealized experiments with a coupled atmosphere-ocean-sea ice model, this paper explores how the Greenland-Scotland Ridge (GSR) influences the structure and strength of the AMOC and ocean heat transport. This modeling approach allows us to address the question:

- *What is the role of the AMOC in controlling ocean heat transport and high latitude climate?*

Finally, *Paper III* looks at the impact of ocean vertical mixing on glacial climate stability and aims to improve our understanding of the conditions necessary to obtain self-sustained oscillations in climate. The aim of this study is to understand the possible link between the D-O events and the distribution and strength of diapycnal mixing in the glacial ocean through its impact on the AMOC and Northern Hemisphere sea ice. Hence, Paper III addresses the question:

- *Under which conditions of vertical mixing can self-sustained oscillations of the coupled climate system occur?*

Together, these papers provide important insights into the dynamics of abrupt climate change, and are summarized schematically in Fig. 2.1.

Chapter 3

Summary of results

Paper I: *Internal ocean dynamics as a driver for open-ocean polynyas in the Weddell Sea,* ***In revision, Tellus A: Dynamic Meteorology and Oceanography***

We investigate the dynamics of open-ocean polynyas in the Weddell Sea, focusing on the role of internal ocean-sea ice dynamics in preconditioning and triggering open-ocean polynyas and evaluate their potential impact on deep water formation and large-scale ocean circulation. We employ a free-running 1300-year climate simulation with the ocean-sea ice version of the Norwegian Earth System Model (NorESM-OC1.2) where the atmospheric forcing is kept constant.

During the 1300-year simulation, two large open-ocean polynyas form in the Weddell Sea. As opposed to being triggered by changes in atmospheric forcing (e.g. surface winds or freshwater fluxes), the polynyas form due to internal ocean-sea ice dynamics, driven by a gradual build-up of subsurface heat and salt. Eventually, the water column becomes unstable, triggering enhanced mixing of warm and saline waters into the surface layer which melts sea ice causing the polynya to occur. Deep convection is triggered after the polynya opens, driving a rapid sea ice retreat by upwelling of warm deep water and leads to enhanced bottom water formation and changes in overturning circulation.

We show that vertical mixing plays a key role in the polynya formation, by controlling vertical fluxes of heat and salt to the sea ice: strong stratification and weak vertical mixing is necessary for building the subsurface heat reservoir, while enhanced mixing, triggered by convective instabilities at mid-depth, can erode the halocline from below. Our results further emphasize the role of salinity, and the subsurface salt reservoir, in controlling Weddell Sea stratification and polynya formation.

The timescale of Southern Ocean deep-convective events in the model is determined by the size of the previous polynya and stratification strength: large polynyas leave the heat reservoir more depleted and the subsequent recharge process occurs on a slow, centennial timescale determined by advective and diffusive processes in the ocean. A stronger stratification (and reduced mixing) tends to suppress polynya formation and prolongs the duration of the non-convective phase.

Finally, the results demonstrate that open-ocean polynyas cannot form when the subsurface waters become too cold and fresh, implying that the ocean-sea ice system can only sustain open-ocean convection due to polynyas within a relatively narrow window of boundary conditions.

Paper II: *Topological constraints by the Greenland-Scotland Ridge on AMOC and climate, **Submitted to Journal of Climate***

This study focuses on the Greenland-Scotland Ridge (GSR) and investigates its impact on climate, including global circulation, heat transport, and water mass properties. To this end, we use a coupled atmosphere-ocean-sea ice model with idealized Earth-like geometry (MITgcm Aquaplanet), comprising two wide strips of land set 90° apart extending from the North Pole to 40°S. This separates the global ocean into a small «Atlantic-like» and a large «Pacific-like» basin. In our experiment, we consider the effect of introducing a submarine ridge, mimicking the GSR, in the Atlantic-like basin, thereby presenting a zonal barrier constricting the water exchange between the North Atlantic and high-latitude ocean (i.e. the Nordic Seas).

Without the ridge, deep water formation occurs close to the North Pole contributing to a strong and deep overturning circulation in the Atlantic basin (i.e. an AMOC). This drives a strong northward ocean heat transport, and the northern high latitudes are warm. When the ridge is introduced, the high latitude overturning transport weakens substantially and the main location of deep water formation shifts south of the ridge, dramatically changing the structure of the AMOC. However, the maximum AMOC strength at 26°N does not change significantly.

In the absence of a zonal barrier in the Atlantic basin, the poleward heat transport is large, and mainly driven by the deep overturning cell extending into the polar region. When the ridge is present, the high-latitude heat transport is weaker and dominated by the shallow gyre circulation. These results show, that the AMOC plays a relatively small role in transporting heat into the high latitudes: despite a 64% reduction in AMOC transport across the GSR, ocean heat transport only decreases by 30%. The reduced transport across the GSR leads to cooling and freshening north of the ridge. Outside the northern high latitudes, the surface climate response is small and the GSR has no impact on global climate.

Our results highlight the possible disconnect between changes in the localization of deep-water formation, the structure of the AMOC and changes in Northern Hemisphere surface climate. They also underscore the necessary caution in interpreting paleoproxies in terms of AMOC and its impact on high latitude climate.

Paper III: *The impact of vertical mixing on glacial ocean circulation and sea ice, **Manuscript in preparation for Paleoceanography and Paleoclimatology***

In this study, we explore the sensitivity of a glacial climate model simulation to changes in the background diapycnal mixing, focusing in particular on the impact on Northern Hemisphere sea ice and the meridional overturning circulation. This builds on the findings in Paper I; showing that vertical mixing is a central element in both preconditioning and driving abrupt changes in sea ice. In Paper III, we test this hypothesis in a glacial setting, assessing the role of vertical mixing in controlling glacial climate variability.

Using a coupled ocean-atmosphere-sea ice model with idealized geometry (the same as in Paper II) and glacial-like boundary conditions, we consider three different configurations for vertical mixing: one with enhanced abyssal mixing and two experiments where mixing is either enhanced or decreased throughout the water column, thus mainly reflecting changes in thermocline mixing.

The imposed changes in diapycnal mixing lead to large changes in the overturning circulation, in line with previous theoretical and model studies. When abyssal mixing is increased, the abyssal overturning cell is strongly enhanced, while the strength of the AMOC cell, poleward ocean heat transport, and surface climate is largely unaffected. As a consequence, changes in abyssal mixing are not likely to play a role in abrupt climate changes, such as D-O events, during the glacial.

Conversely, changes in thermocline mixing greatly affects the overturning circulation and surface climate; enhanced thermocline mixing strengthens the AMOC, drives a larger poleward ocean heat transport, and leads to a retreat of Northern Hemipshere sea ice. Reduced thermocline mixing, on the other hand, leads to a weaker and shallower AMOC, reduced heat transport and sea ice advance.

When thermocline mixing and the AMOC is weak, the coupled ocean-sea ice system is unstable and internal oscillations occur, associated with a gradual build-up and release of subsurface heat beneath an extensive Northern Hemisphere sea ice cover. This is only possible because weak thermocline mixing allows the development of a shallow subsurface current transporting warm subtropical water under sea ice; while high thermocline mixing prevents the build-up of the necessary subsurface heat. This implies that weak vertical mixing in the upper ocean, and a reduced overturning transport, are critical for preconditioning abrupt transitions in Northern Hemisphere sea ice, such as those observed in the paleoclimate record over the last glacial period.

3.1 Main conclusions

Based on the findings in the three papers outlined above, the main conclusions of this thesis are:

- The formation of open-ocean polynyas provide a mechanism to trigger large and abrupt changes in sea ice, release oceanic heat to the atmosphere and enhance deep water formation through open-ocean deep convection (Paper I). Polynyas are therefore likely to play a fundamental role in the dynamics of abrupt changes in sea ice, including the Dansgaard-Oeschger events of the last glacial.

- Open-ocean polynyas and rapid sea ice retreat can be triggered by internal ocean-sea ice dynamics without the need of an external trigger (e.g. freshwater or atmospheric forcing), but relies on weak diapycnal mixing, a build-up of subsurface heat and salt beneath the ice cover, destabilizing the water column and triggering enhanced fluxes of heat and salt to the surface.

- The presence of the Greenland-Scotland Ridge plays a fundamental role in shaping the structure of the AMOC, the location of deep water formation, and high-latitude climate (Paper II). However, changes in the height of the GSR have little impact on maximum AMOC strength, and its effect on global climate is small.

- The AMOC plays a relatively small role in transporting heat across the Greenland-Scotland Ridge and into the northern high latitudes. This questions the role of the AMOC as the main driver of abrupt changes in high latitude climate, as often inferred from paleoclimate records.

- The vertical distribution of turbulent mixing in the glacial ocean plays a central role in glacial climate stability: unforced and self-sustained «DO-like» oscillations can occur when thermocline mixing is low and overturning circulation is weak (Paper III). These conditions allow subsurface heat to accumulate beneath the extensive Northern Hemisphere sea ice cover, which is critical for preconditioning abrupt transitions (Paper I and III).

- Abyssal mixing leads to a stronger abyssal ocean circulation, but does not contribute to the overall strength of the overturning circulation or the ocean's meridional heat transport. We conclude, that it is unlikely that changes in abyssal mixing alone played an important role in the D-O oscillations as indicated by previous studies (e.g., Peltier and Vettoretti, 2014).

Chapter 4

Perspectives and outlook

This section discusses some of the implications of the model results presented in this thesis in the context of abrupt climate changes recorded in the paleoclimate record, and its potential relevance for future climate.

4.1 The impact of the GSR on abrupt changes in the past

Paper II is in part motivated by the paleoclimate record indicating that changes in ocean bathymetry has played a critical role in driving large and potentially abrupt changes in climate throughout Earth's history. Based on the model results, the following section discusses the possibility that small, gradual changes in the height of the Greenland-Scotland Ridge (GSR), may have triggered abrupt changes in global climate.

Note that, the aquaplanet model used in *Paper II* (and *III*) lacks some important aspects of the North Atlantic-Nordic Seas circulation, e.g. the complex bathymetry, continental shelves, presence of an Arctic Ocean, sea ice dynamics, and the complex overflow across the GSR. Despite these limitations, the model reproduces the general features of the ocean (and atmosphere) circulation, providing important insights to the dynamics of the coupled climate system in response to changes in bathymetry.

Although changes in sill-depth of the GSR occur on very slow timescales (over millions of years due to plate tectonics), these gradual changes have been shown to trigger non-linear and rapid changes in ocean circulation (Stärz et al., 2017). This idea has been invoked in several proxy-based studies (e.g., Davies et al., 2001; Via and Thomas, 2006; Wright and Miller, 1996), relating large and abrupt shifts in global climate over the past 50 million years to small variations in sill-depth. For example, Abelson and Erez (2017) argue that the onset of a modern-like AMOC at the Eocene-Oligocene transition (EOT), which marks the shift from a greenhouse to an icehouse Earth ∼33.7 Ma ago (including the glaciation of Antarctica), may be triggered by deepening of the GSR. While it is very likely that a reorganization of the AMOC was involved in the EOT, *Paper II* suggest that the GSR might not be the main driver.

In our simulations, introducing the sill does not trigger large changes in AMOC, and as a consequence the global climate response is small. We note, although not tested in our model, that the overturning response might be more non-linear, when considering a gradual lowering from subaerial conditions (with virtually no connection between the North Atlantic and Nordic Seas) to deeper sill-depths (e.g., Stärz et al., 2017). Results from Stärz et al. (2017), however, show that even for very shallow sill-depths ($<$50 m), there is substantial NADW formation and the AMOC remains relatively strong (11.3 Sv versus the pre-industrial 16.8 Sv; Supplementary Information in Stärz et al. (2017)). This supports our conclusion that the height of the GSR does not control the maximum AMOC strength.

We speculate, that the Southern Ocean might play a bigger role controlling AMOC strength in our model (by surface momentum and buoyancy fluxes), as opposed to deep water formation in the North Atlantic (Marshall and Speer, 2012). This favors the hypothesis that the global cooling at the EOT is linked to tectonic gateway changes in the Southern Ocean (e.g., Toggweiler and Samuels, 1995; Yang et al., 2014). Therefore, in future studies we would like to test the sensitivity of the AMOC in the aquaplanet model to changes in e.g. Southern Hemisphere winds.

The height of the GSR has important consequences for ocean heat transport, water mass properties and surface climate at high northern latitudes. We speculate that the height of the GSR could play a role for the D-O events. However, considering that bathymetric changes are driven by geological processes that are much slower compared to the timescales of the D-O events (centennial to millenial), it can be assumed that the GSR sill-depth has been relatively stable throughout the last glacial period. It is therefore unlikely that changes in the sill-depth have played a role in the D-O cycle. On the other hand, other factors, such as sea level lowering in the last glacial could have contributed to changing ocean basin geometry, affecting the background climate state (e.g., Peltier and Fairbanks, 2006). For example, closing of the Bering Strait has been shown to impact AMOC hysteresis and glacial climate stability (Hu et al., 2012). Similarly, reduced water depth over the GSR (by up to $\sim$120 m at the LGM) as well as a narrower Denmark Strait may have affected water exchange between the North Atlantic and Nordic Seas in the glacial (e.g., Kösters et al., 2004).

Furthermore, in the context of D-O events, the GSR experiments offer a perspective on the role of the Nordic Seas and its impact on deep water formation and AMOC strength. Proxy-data from the Nordic Seas and North Atlantic show that stadial and interstadial conditions are associated with latitudinal shifts in the location of NADW formation (Dokken and Jansen, 1999; Rasmussen and Thomsen, 2004). Such changes are often linked to major changes in overturning circulation strength (see Fig. 1.2). The result from *Paper II*, however, show that despite a shift in deep water formation from the polar basin (i.e. the "Nordic Seas") to the subpolar North Atlantic, the maximum AMOC strength remain relatively unchanged. Nevertheless, there is a substantial cooling of the northern high latitudes, associated with the different modes of deep water formation and changes in ocean heat transport. Therefore, our findings suggest that more work is needed to understand the link between Nordic Seas deep water formation and past variations in AMOC strength and its potential impact on climate. New data from ocean monitoring systems such as the *Overturning in the Subpolar North Atlantic Program* (OSNAP) will help answering these questions (Lozier et al., 2017, 2019).

4.2 The role of vertical mixing for D-O events

The results from *Paper I* and *III*, suggest that vertical mixing, particularly in the thermocline, is important for glacial climate variability. First of all, it has a direct impact on sea ice by controlling vertical fluxes of heat and salt (*Paper I*), and secondly it plays a fundamental role in determining the strength and structure of the overturning circulation (Wunsch and Ferrari, 2004), which in turn has an indirect effect on sea ice by affecting ocean heat transport (*Paper III*). What remains less clear is whether changes in interior diapycnal mixing changes over the timescales of the Dansgaard-Oeschger events, and what mechanisms would be responsible.

It is widely accepted that the distribution of diapycnal mixing was different at the last glacial compared to present day, owing primarily to a $\sim$120 m drop in sea level, causing enhanced tidal energy dissipation in the deep ocean (e.g., Egbert et al., 2004; Green et al., 2009). Meanwhile, sea level fluctuations between stadials and interstadials (i.e. during MIS 3) are relatively modest ($<$50 m) (Siddall et al., 2008), suggesting that the energy dissipation rate and the vertical mixing profile remained relatively constant. Note, however, that LGM boundary conditions differ significantly from MIS 3 boundary conditions in a number of other ways, e.g. the LGM had larger ice-sheets and different orbital forcing and greenhouse gas concentrations (e.g., Van Meerbeeck et al., 2009). Hence, the large changes in vertical mixing applied in *Paper III* are not likely to occur on such short timescales, and should not be seen as a mechanism for triggering transitions between stadials and interstadials. Rather, the experiments mainly reflect how diapycnal mixing can affect the background climate state, thus preconditioning the glacial climate system for abrupt transitions. Based on the results in *Paper III*, we find that a low thermocline mixing is most likely to produce such "DO-like" oscillations, because it allows the development of a subsurface heat reservoir at high latitudes, preconditioning rapid changes in sea ice and AMOC.

That being said, there are at least two possible reasons why vertical mixing in the interior could have influenced stadial-interstadial cycles. First, changes in the geometry of the AMOC, i.e. switching between "cold" (stadial) and "warm" (interstadial) modes, could affect vertical mixing between deep water masses in the Atlantic by shifting the boundary between the NADW and AABW cells away from regions of topographically induced mixing in the deep ocean (Ferrari et al., 2014; Polzin et al., 1997). This could have had a significant impact on the AMOC strength and the poleward OHT (e.g., Jansen, 2017); shoaling of the NADW cell could help sustain the weak AMOC mode during stadials, and facilitating the development of an extensive sea ice cover.

Alternatively, changes in deep ocean stratification could affect the rate of diapycnal mixing, as the vertical diffusivity is inversely proportional to the buoyancy frequency (N^2) (e.g., Osborn, 1980). This is demonstrated in *Paper I*, where enhanced vertical mixing is triggered internally by a thermohaline convective instability at depth induced by changes in stratification. This leads to an abrupt and extensive retreat of sea ice and depletion of the subsurface heat reservoir. In the context of stadial-interstadial transitions, this feedback mechanism (between stratification and vertical mixing) is therefore likely to play a fundamental role in the abruptness of the D-O event. In comparison, for

Paper III changes to the vertical diffusivity are imposed on the model and do not occur spontaneously (except perhaps for the oscillations in the reduced mixing scenario). Because the vertical mixing profile was changed globally, the simulated sea ice changes are mostly dominated by advective processes associated with changes in ocean circulation (by the AMOC and the gyre circulation). We speculate, that this might lead to a slower, and perhaps smaller sea ice retreat, compared to the convective heat release seen in *Paper I*. On that note, the climate response might be fundamentally different, if changes to the vertical mixing are only applied at high latitudes, e.g. under sea ice, where its effect on the overturning circulation is likely to be small (e.g., Scott and Marotzke, 2002). Indeed, several studies have shown that changes in diapycnal mixing under sea ice can have a profound impact on water column stability, subsurface heat content and sea ice thickness (e.g., Heuzé et al., 2015; Liang and Losch, 2018; Zhang and Steele, 2007) and may even trigger remote changes in the AMOC (Kim et al., 2015).

What can these results tell us about the role of vertical mixing for the D-O oscillations? Both *Paper I* and *III* point to the fact that in order to sustain a large sea ice cover, upper ocean mixing (i.e. in the thermocline) should be low, which also facilitates a build-up of subsurface heat and salt. This is also supported by modern observations from the Arctic (Fer, 2009), showing that weak mixing in the upper ocean stabilizes the halocline and prevents sea ice melt. These results support the notion of a mixing-deprived and less ventilated Nordic Seas during stadial times (e.g., Dokken and Jansen, 1999; Dokken et al., 2013; Rasmussen and Thomsen, 2004; Sadatzki et al., 2019a). Under such quiescent conditions, it is likely that vertical mixing (below the halocline) is governed by the background diffusivity (see also Singh et al., 2014). Based on our findings in *Paper I*, we hypothesize that a slow upward mixing of warmer and saltier waters could erode the halocline, thus preconditioning the sea ice cover for an abrupt retreat. However, it may take several decades, or more, before the halocline is weak enough to initiate deep convection and sea ice retreat; a similar response is also evident in Martin et al. (2013); Vettoretti and Peltier (2016); Zanowski et al. (2015). The timescale would depend on the sea ice thickness, stratification strength, as well as the subsurface heat (and salt) content (i.e. *Paper I*).

This concept is supported by unpublished sedimentological data from the eastern Nordic Seas (Sadatzki et al., 2019b), showing that each stadial phase is characterized by a strong aging of intermediate depth waters with benthic reservoir ages of up to 2500 years. These ages are too old to be explained by reduced ventilation by deep convection during the stadial (the duration of the stadial phase is only a couple of hundred years on average). Rather, the observed pattern is interpreted as a slow interior upward mixing of very old, radiocarbon-depleted deep water (cold and salty) which helps to erode the stratification from below, and contributes to the abrupt sea ice retreat at the interstadial transition. This implies an important role of ocean mixing in the abrupt warming on Greenland. However, the trigger mechanism for this deep ocean mixing still remains unclear. Recently, Vettoretti and Peltier (2016) suggested that double-diffusive mixing (related to the different diffusive properties of temperature and salinity respectively) and thermobaric instabilities arising from the nonlinearity of the equation of state could be potential mechanisms for instigating vertical mixing at depth. Similarly, Adkins et al. (2005) suggested that accumulation of geothermal heat in the deep ocean (due to a strong salt-stratification in the glacial ocean) can trigger such thermobaric effects and cause a catastrophic release of heat. Note that these processes are not included in any of the models used in this thesis. Rather, the instability leading to the polynya in *Paper I* is related to changes in deep stratification through a positive feedback between vertical mixing and stratification (see also Dufour et al., 2017).

To summarize, the discussion presented here demonstrates that small-scale turbulent mixing in the ocean interior could play a key role in many aspects of abrupt climate change during the glacial period. In particular, setting the timescale and magnitude of the D-O events. Meanwhile, it implies that the parameterization of turbulent mixing in numerical models can in principle be "tuned" to produce a timescale that is consistent with the proxy-data (e.g., Peltier and Vettoretti, 2014). However, such experiments require careful consideration and must be based on physical arguments.

4.3 The role of polynyas in glacial climate variability

Recent studies by Vettoretti and Peltier (2016) and Vettoretti and Peltier (2018) have suggested that the occurrence of "super polynyas" in the glacial North Atlantic is central to the D-O cycle, underlying the abrupt sea ice retreat at the stadial-interstadial transitions. Despite the fact that the polynyas described in *Paper I* occur in the Southern Ocean, the dynamics are qualitatively consistent with the ones described in Vettoretti and Peltier (2016), where the polynya forms in response to a thermohaline instability. On a cautionary note, several studies have suggested that the formation of large open-ocean polynyas in current climate models is unrealistic (e.g., Heuze et al., 2013), reflecting inaccurate sensitivity to surface forcing conditions or missing physics (Dufour et al., 2017). Others show that polynya formation can be sensitive to the mixing parameterization in the models (Heuzé et al., 2015; Kjellsson et al., 2015; Timmermann and Beckmann, 2004).

An interesting perspective, is that Southern Ocean deep convection events may actually impact North Atlantic climate remotely by affecting the strength of the AMOC (e.g., Martin et al., 2015; Pedro et al., 2016) and also evident in *Paper I* although the AMOC response is mostly confined to the South Atlantic. This mechanism is closely related to the concept of the bipolar see-saw, which proposes a competition between the relative strength of the NADW and AABW circulation cells (Broecker, 1998). Based on a climate model simulation, Martin et al. (2015) demonstrated that the enhanced AABW production, associated with large open-ocean polynyas in the Weddell Sea, leads to a decrease in the southward export of NADW (i.e. AMOC weakening), which consequently reduces NADW formation and vice versa. This implies a southern "push" that may help explain the changes in the geometry of the glacial AMOC between stadials and interstadials (Fig. 1.2). Furthermore, this idea is supported by proxy-data from the Weddell Sea indicating that open-ocean polynyas occurred repeatedly during the glacial period (Smith et al., 2010) and may have been the dominant mode of AABW formation when the continental shelf was covered by grounded ice (e.g., Evans et al., 2005), thereby shifting the production of dense water into the open ocean. Since open-ocean deep convection is highly effective in producing bottom waters, it is likely that the volume of AABW was increased in the glacial, consistent with an expansion of Antarctic-sourced waters in the Atlantic at the LGM (e.g., Curry and Oppo, 2005). While this mechanism remains highly speculative, it demonstrates that the Southern Ocean exerts a major control on the AMOC (see also Buizert and Schmittner, 2015) and implies that Dansgaard-Oeschger events may in fact be driven from the south, although the relative timing of Northern and Southern Hemisphere climate changes are still debated (e.g., Blunier and Brook, 2001; Buizert et al., 2015).

4.4 Outlook

This thesis has demonstrated that abrupt climate change can occur within the natural and unforced climate system and underscores the importance of coupled atmosphere-ice-ocean dynamics in driving such changes. However, this study has focused primarily on the abrupt changes in glacial climate and it is less clear if the same mechanisms are valid under non-glacial boundary conditions, questioning whether abrupt climate change may occur in the future due to human-induced global warming. In particular, we have shown that sea ice plays a key role in preconditioning large and abrupt changes in high latitude climate with potential implications for large-scale ocean circulation.

Could the dramatic decline of Arctic sea ice seen in recent decades trigger such abrupt changes in the future? While some models show that Arctic sea ice decline can in fact induce AMOC slowdown (e.g., Liu et al., 2019; Sévellec et al., 2017), the impact is likely to be less dramatic due to the fact that the present day sea ice extent is much smaller compared to in glacial times (Gildor and Tziperman, 2003). On the other hand, as the AMOC is projected to weaken under global warming (e.g., Schmittner et al., 2005), the likelihood of an AMOC collapse may increase (Liu et al., 2017), although most climate model projections only show moderate reductions in AMOC for the 21st century (Collins et al., 2013). However, as shown here an AMOC weakening does not necessarily imply weaker ocean heat transport to the northern high latitudes (see also Årthun et al., 2019) , suggesting that high latitude climate can be disconnected from changes in the AMOC (*Paper II*). Nevertheless, given the large consequences of such abrupt changes, future research should aim to improve our understanding of the underlying physical processes, in order to develop appropriate strategies for adaptation and mitigation.

As a concluding remark, I would like to present my recommendations for the direction of future research in the context of the work presented in this thesis:

- More work is required to understand the role of ocean turbulent mixing for the existence of the D-O events. In particular, how different mixing parameterizations in climate models may or may not lead to unforced and abrupt transitions. Future experiments should try to isolate the direct effect of vertical mixing on sea ice (i.e. by changing vertical mixing only under the ice cover) from the indirect changes in ocean circulation, as this may help constrain the Dansgaard-Oeschger dynamics. Proxy-data might be able to constrain the magnitude and distribution of diapycnal mixing in the past and should be integrated in future paleo-climate model simulations. Furthermore, additional sensitivity studies should consider the relative role of vertical mixing on glacial climate stability to changes in other boundary conditions, such as e.g., CO_2, or ice-sheet configuration.

- The connection between open-ocean polynyas and millenial-scale glacial climate variability remains relatively unexplored. The question remains if open-ocean polynyas were a common feature of glacial climate and whether they played a role in the D-O events. While the results presented in this thesis demonstrate, that a build-up of subsurface heat alone is not enough to trigger polynyas, the triggering mechanism is still not completely understood. More work is needed exploring the relative role of ocean versus atmospheric forcing on the formation of polynyas, as well as the long-term consequences for deep water formation and ocean circulation. Employing fully hydrostatic models could provide additional insight to the dynamics.
- Finally, a climate model intercomparison project focusing specifically on MIS 3 climate variability and D-O events should be initiated. This will be critical for constraining potential mechanisms for the D-O events, and guiding future research. This should include models that produce self-sustained D-O-like oscillations as well as forced models (e.g. by freshwater), which could help isolate the effect of freshwater forcing on stadial and interstadial durations.

Chapter 5

Scientific results

Bibliography

Abelson, M. and Erez, J. (2017). The onset of modern-like Atlantic meridional overturning circulation at the Eocene-Oligocene transition: Evidence, causes, and possible implications for global cooling. *Geochemistry, Geophysics, Geosystems*, 18(6):2177–2199. 4.1

Adkins, J. F., Ingersoll, A. P., and Pasquero, C. (2005). Rapid climate change and conditional instability of the glacial deep ocean from the thermobaric effect and geothermal heating. *Quaternary Science Reviews*, 24(5-6):581–594. 4.2

Årthun, M., Eldevik, T., and Smedsrud, L. H. (2019). The role of Atlantic heat transport in future Arctic winter sea ice loss. *Journal of Climate*, 32(11):3327–3341. 4.4

Barbante, C., Barnola, J.-M., Becagli, S., Beer, J., Bigler, M., Boutron, C., and Others (2006). One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature*, 444(7116):195–198. 1.1

Barker, S., Chen, J., Gong, X., Jonkers, L., Knorr, G., and Thornalley, D. (2015). Icebergs not the trigger for North Atlantic cold events. *Nature*, 520(7547):333–336. 1.2

Blunier, T. and Brook, E. J. (2001). Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. *Science (New York, N.Y.)*, 291(5501):109–12. 4.3

Bond, G. C., Lotti, R., and Weaver, A. J. (1995). Iceberg Discharges into the North Atlantic on Millennial Time Scales During the Last Glaciation. *Science*, 267(5200):1005–1010. 1.2

Broecker, W. S. (1994). Massive iceberg discharges as triggers for global climate change. *Nature*, 372(6505):421–424. 1.2

Broecker, W. S. (1997). Thermohaline circulation, the achilles heel of our climate system: will man-made CO2 upset the current balance? *Science (New York, N.Y.)*, 278(5343):1582–8. 1

Broecker, W. S. (1998). Paleocean circulation during the last deglaciation: a bipolar seesaw? *Paleoceanography*, 13(2):119–121. 1.3.2, 4.3

Broecker, W. S. (2000). Abrupt climate change: causal constraints provided by the paleoclimate record. *Earth-Science Reviews*, 51(1–4):137–154. 1.3.1

Broecker, W. S., Bond, G., Klas, M., Bonani, G., and Wolfli, W. (1990). A salt oscillator in the glacial Atlantic? 1. The concept. *Paleoceanography*, 5(4):469–477. 1.3, 1.3.1

Bryan, F. (1987). Parameter Sensitivity of Primitive Equation Ocean General Circulation Models. *Journal of Physical Oceanography*, 17(7):970–985. 1.2.1

Buckley, M. W. and Marshall, J. (2015). Observations, inferences, andmechanisms of Atlantic Meridional Overturning Circulation variability: A review. *Reviews of Geophysics*, 54. 1.2

Buizert, C., Adrian, B., Ahn, J., Albert, M., Nature, R. A., and 2015, U. (2015). Precise interpolar phasing of abrupt climate change during the last ice age. *Nature*, 520:661–665. 4.3

Buizert, C. and Schmittner, A. (2015). Southern Ocean control of glacial AMOC stability and Dansgaard-Oeschger interstadial duration. *Paleoceanography*, 30(12):1595–1612. 4.3

Campbell, E. C., Wilson, E. A., Moore, G. W. K., Riser, S. C., Brayton, C. E., Mazloff, M. R., and Talley, L. D. (2019). Antarctic offshore polynyas linked to Southern Hemisphere climate anomalies. *Nature*, 570(7761):319–325. 1.3.2

Cavalieri, D. J. and Martin, S. (1994). The contribution of Alaskan, Siberian, and Canadian coastal polynyas to the cold halocline layer of the Arctic Ocean. *Journal of Geophysical Research*, 99(C9):18,343—-18,362. 1.3.2

Centre for Ice and Climate (2008). The Glacial - a period of instability. 1.1

Cheng, W., Bitz, C. M., and Chiang, J. C. (2007). Adjustment of the Global Climate to an Abrupt Slowdown of the Atlantic Meridional Overturning Circulation. In *Ocean Circulation: Mechanisms and Impacts - Past and Future Changes of Meridional Overturning*, pages 295–313. American Geophysical Union (AGU). 1.2

Cheon, W. G., Cho, C.-B., Gordon, A. L., Kim, Y. H., and Park, Y.-G. (2017). The Role of Oscillating Southern Hemisphere Westerly Winds: Southern Ocean Coastal and Open-Ocean Polynyas. *Journal of Climate*, pages JCLI–D–17–0237.1. 1.3.2

Cheon, W. G. and Gordon, A. L. (2019). Open-ocean polynyas and deep convection in the Southern Ocean. *Scientific Reports*, 9(1):6935. 1.3.2

Cheon, W. G., Lee, S. K., Gordon, A. L., Liu, Y., Cho, C. B., and Park, J. J. (2015). Replicating the 1970s' Weddell Polynya using a coupled ocean-sea ice model with reanalysis surface flux fields. *Geophysical Research Letters*, 42(13):5411–5418. 1.3.2

Clark, P. U., Pisias, N. G., Stocker, T. F., and Weaver, A. J. (2002). The role of the thermohaline circulation in abrupt climate change. *Nature*, 415(6874):863–869. 1.2

Clement, A. C. and Peterson, L. C. (2008). Mechanisms of Abrupt Climate Change of the Last Glacial Period. *Reviews of Geophysics*, 46(2006):1–39. 1.1, 1.2

Collins, M., Knutti, R., . . . , J. A. C. C., and 2013, U. (2013). Long-term climate change: projections, commitments and irreversibility. In Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., editors, *Climate Change 2013 - The Physical Science Basis*, pages 1029–1136. Press., Cambridge University, New York. 4.4

Curry, W. B. and Oppo, D. W. (2005). Glacial water mass geometry and the distribution of δ13C of ΣCO 2 in the western Atlantic Ocean. *Paleoceanography*, 20(1):n/a–n/a. 4.3

Davies, R., Cartwright, J., Pike, J., and Line, C. (2001). Early Oligocene initiation of North Atlantic Deep Water formation. *Nature*, 410(6831):917–920. 4.1

de Lavergne, C., Palter, J. B., Galbraith, E. D., Bernardello, R., and Marinov, I. (2014). Cessation of deep convection in the open Southern Ocean under anthropogenic climate change. *Nature Climate Change*, 4(4):278–282. 1.3.2

de Verdière, A. C. and Raa, L. T. (2010). Weak oceanic heat transport as a cause of the instability of glacial climates. *Climate Dynamics*, 35(7):1237–1256. 1.2, 1.3

Deibel, D. and Daly, K. (2007). Chapter 9 Zooplankton Processes in Arctic and Antarctic Polynyas. *Elsevier Oceanography Series*, 74:271–322. 1.3.2

Dokken, T. M. and Jansen, E. (1999). Rapid changes in the mechanism of ocean convection during the last glacial period. *Nature*, 401(6752):458–461. 1.2, 1.3.1, 4.1, 4.2

Dokken, T. M., Nisancioglu, K. H., Li, C., Battisti, D. S., and Kissel, C. (2013). Dansgaard-Oeschger cycles: Interactions between ocean and sea ice intrinsic to the Nordic seas. *Paleoceanography*, 28(3):491–502. 1.3.1, 1.3, 1.3.2, 4.2

Dufour, C. O., Morrison, A. K., Griffies, S. M., Frenger, I., Zanowski, H., and Winton, M. (2017). Preconditioning of the Weddell Sea polynya by the ocean mesoscale and dense water overflows. *Journal of Climate*, 30(19):7719–7737. 1.3.2, 4.2, 4.3

Egbert, G. D., Ray, R. D., and Bills, B. G. (2004). Numerical modeling of the global semidiurnal tide in the present day and in the last glacial maximum. *Journal of Geophysical Research: Oceans*, 109(C3). 4.2

Eisenman, I. and Wettlaufer, J. S. (2009). Nonlinear threshold behavior during the loss of Arctic sea ice. *Proceedings of the National Academy of Sciences of the United States of America*, 106(1):28–32. 1

Eldevik, T., Nilsen, J. E. Ø., Eldevik, T., and Nilsen, J. E. Ø. (2013). The Arctic–Atlantic Thermohaline Circulation*. *Journal of Climate*, 26(21):8698–8705. 1.2

Evans, J., Pudsey, C., ÓCofaigh, C., . . . , P. M. Q. S., and 2005, U. (2005). Late Quaternary glacial history, flow dynamics and sedimentation along the eastern margin of the Antarctic Peninsula Ice Sheet. *Elsevier*, 24:741–774. 4.3

Ezat, M. M., Rasmussen, T. L., and Groeneveld, J. (2014). Persistent intermediate water warming during cold stadials in the southeastern Nordic seas during the past 65 k.y. *Geology*, 42(8):663–666. 1.3.1

Fer, I. (2009). Weak Vertical Diffusion Allows Maintenance of Cold Halocline in the Central Arctic. *Atmospheric and Oceanic Science Letters*, 2(3):148–152. 4.2

Ferrari, R., Jansen, M. F., Adkins, J. F., Burke, A., Stewart, A. L., and Thompson, A. F. (2014). Antarctic sea ice control on ocean circulation in present and glacial climates. *Proceedings of the National Academy of Sciences*, 111(24):8753–8758. 1.2.1, 4.2

Ferreira, D., Marshall, J., Ito, T., and McGee, D. (2018). Linking Glacial-Interglacial States to Multiple Equilibria of Climate. *Geophysical Research Letters*, 45(17):9160–9170. 1.3

Ferreira, D., Marshall, J., and Rose, B. (2011). Climate determinism revisited: Multiple equilibria in a complex climate model. *Journal of Climate*, 24(4):992–1012. 1.3

Francis, D., Eayrs, C., Cuesta, J., and Holland, D. (2019). Polar cyclones at the origin of the reoccurrence of the Maud Rise Polynya in austral winter 2017. *Journal of Geophysical Research: Atmospheres*, page 2019JD030618. 1.3.2

Furevik, T., Mauritzen, C., and Ingvaldsen, R. (2007). The flow of Atlantic water to the Nordic Seas and Arctic Ocean. *Arctic Alpine Ecosystems and People in a Changing Environment*, pages 123–146. 1.2

Ganopolski, A. and Rahmstorf, S. (2001). Rapid changes of glacial climate simulated in a coupled climate model. *Nature*, 409(6817):153–158. 1.2

Gildor, H. and Tziperman, E. (2003). Sea-ice switches and abrupt climate change. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, 361(1810):1935–1944. 1.3.1, 4.4

Gordon, A. (1982). Weddell deep water variability. *J. Mar. Res*. 1.3.2

Gordon, A. L. (2014). Southern Ocean polynya. *Nature Climate Change*, 4(April):249–250. 1.3.2

Gordon, A. L. and Comiso, J. C. (1988). Polynyas in the Southern Ocean. *Scientific American; (USA)*, 258:6. 1.3.2

Gordon, A. L., Visbeck, M., and Comiso, J. C. (2007). A possible link between the Weddell Polynya and the southern annular mode. *Journal of Climate*, 20(11):2558–2571. 1.3.2

Green, M. J. A., Green, C. L., Bigg, G. R., Rippeth, T. P., Scourse, J. D., and Uehara, K. (2009). Tidal mixing and the meridional overturning circulation from the Last Glacial Maximum. *Geophysical Research Letters*, 36(15):n/a–n/a. 1.2.1, 4.2

Hansen, B. and Østerhus, S. (2000). North Atlantic-Nordic Seas exchanges. *Progress in Oceanography*, 45(2):109–208. 1.2, 1.3.1

Heinrich, H. (1988). Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130,000 years. *Quaternary Research*, 29(2):142–152. 1.2, 1.2

Henry, L. G., McManus, J. F., Curry, W. B., Roberts, N. L., Piotrowski, A. M., and Keigwin, L. D. (2016). North Atlantic ocean circulation and abrupt climate change during the last glaciation. *Science*, 353(6298). 1.2

Heuze, C. (2016). Image of the Week – What an ice hole! [blog post]. 1.4

Heuze, C., Heywood, K. J., Stevens, D. P., and Ridley, J. K. (2013). Southern Ocean bottom water characteristics in CMIP5 models. *Geophysical Research Letters*, 40(7):1409–1414. 4.3

Heuzé, C., Ridley, J. K., Calvert, D., Stevens, D. P., and Heywood, K. J. (2015). Increasing vertical mixing to reduce Southern Ocean deep convection in NEMO3.4. *Geoscientific Model Development*, 8(10):3119–3130. 4.2, 4.3

Hirabara, M., Tsujino, H., Nakano, H., and Yamanaka, G. (2012). Formation mechanism of the Weddell Sea Polynya and the impact on the global abyssal ocean. *Journal of Oceanography*, 68(5):771–796. 1.3.2

Hoff, U., Rasmussen, T. L., Stein, R., Ezat, M. M., and Fahl, K. (2016). Sea ice and millennial-scale climate variability in the Nordic seas 90 kyr ago to present. *Nature Communications*, 7(1):12247. 1.3.1

Holland, D. M. (2000). Transient sea-ice polynya forced by oceanic flow variability. *Progress in Oceanography*, 48(4):403–460. 1.3.2

Holland, M. M. and Bitz, C. M. (2003). Polar amplification of climate change in coupled models. *Climate Dynamics*, 21(3-4):221–232. 1

Holland, M. M., Bitz, C. M., and Tremblay, B. (2006). Future abrupt reductions in the summer Arctic sea ice. *Geophysical Research Letters*, 33(23):L23503. 1

Hu, A., Meehl, G. A., Han, W., Timmermann, A., Otto-Bliesner, B., Liu, Z., and Others (2012). Role of the Bering Strait on the hysteresis of the ocean conveyor belt circulation and glacial climate stability. *Proceedings of the National Academy of Sciences of the United States of America*, 109(17):6417–22. 4.1

Jansen, E., Christensen, J. H., Dokken, T., Nisancioglu, K. H., Vinther, B. M., Capron, E., and Others (2019). A new era of abrupt climate change - perspectives from the past. *Submitted to: Nature Climate Change*. 1

Jansen, M. F. (2017). Glacial ocean circulation and stratification explained by reduced atmospheric temperature. *Proceedings of the National Academy of Sciences*, 114(1):45–50. 4.2

Jansen, M. F. and Nadeau, L.-P. (2016). The Effect of Southern Ocean Surface Buoyancy Loss on the Deep-Ocean Circulation and Stratification. *Journal of Physical Oceanography*, 46(11):3455–3470. 1.2.1

Jayne, S. R. (2009). The Impact of Abyssal Mixing Parameterizations in an Ocean General Circulation Model. *Journal of Physical Oceanography*, 39(7):1756–1775. 1.2.1

Kageyama, M., Merkel, U., Otto-Bliesner, B., Prange, M., Abe-Ouchi, A., Lohmann, G., Ohgaito, R., Roche, D. M., Singarayer, J., Swingedouw, D., and Zhang, X. (2013). Climatic impacts of fresh water hosing under last glacial Maximum conditions: A multi-model study. *Climate of the Past*, 9(2):935–953. 1.2

Killworth, P. D. (1983). Deep convection in the World Ocean. *Reviews of Geophysics*, 21(1):1. 1.3.2

Kim, S. Y., Lee, H. J., Park, J. H., and Kim, Y. H. (2015). Effects of reduced vertical mixing under sea ice on Atlantic meridional overturning circulation (AMOC) in a global ice-ocean model. *Ocean Science Journal*, 50(2):155–161. 4.2

Kjellsson, J., Holland, P. R., Marshall, G. J., Mathiot, P., Aksenov, Y., Coward, A. C., Bacon, S., Megann, A. P., and Ridley, J. (2015). Model sensitivity of the Weddell and Ross seas, Antarctica, to vertical mixing and freshwater forcing. *Ocean Modelling*, 94:141–152. 4.3

Kleppin, H., Jochum, M., Otto-Bliesner, B., Shields, C. A., and Yeager, S. (2015). Stochastic Atmospheric Forcing as a Cause of Greenland Climate Transitions. *Journal of Climate*, 28(19):7741–7763. 1.3, 1.3.1

Klockmann, M., Mikolajewicz, U., Marotzke, J., Klockmann, M., Mikolajewicz, U., and Marotzke, J. (2018). Two AMOC States in Response to Decreasing Greenhouse Gas Concentrations in the Coupled Climate Model MPI-ESM. *Journal of Climate*, 31(19):7969–7984. 1.2

Kösters, F., Käse, R., Fleming, K., and Wolf, D. (2004). Denmark Strait overflow for Last Glacial Maximum to Holocene conditions. *Paleoceanography*, 19(2):n/a–n/a. 4.1

Kuhlbrodt, T., Griesel, A., Montoya, M., Levermann, A., Hofmann, M., and Rahmstorf, S. (2007). On the driving processes of the Atlantic meridional overturning circulation. *Reviews of Geophysics*, 45(2):RG2001. 1.2, 1.2.1, 1.2.1

Labrousse, S., Williams, G., Tamura, T., Bestley, S., Sallée, J.-B., Fraser, A. D., and Others (2018). Coastal polynyas: Winter oases for subadult southern elephant seals in East Antarctica. *Scientific reports*, 8(1):3183. 1.3.2

Landais, A., Barnola, J. M., Masson-Delmotte, V., Jouzel, J., Chappellaz, J., Caillon, N., and Others (2004). A continuous record of temperature evolution over a sequence of Dansgaard-Oeschger events during Marine Isotopic Stage 4 (76 to 62 kyr BP). *Geophysical Research Letters*, 31(22):1–4. 1.1

Lang, C., Leuenberger, M., Schwander, J., and Johnsen, S. (1999). 16 deg. C Rapid Temperature Variation in Central Greenland 70,000 Years Ago. *Science*, 286(5441):934–937. 1.1

Li, C., Battisti, D. S., and Bitz, C. M. (2010). Can North Atlantic sea ice anomalies account for Dansgaard-Oeschger climate signals? *Journal of Climate*, 23(20):5457–5475. 1.3.1

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(19):1–4. 1.3.1

Li, C. and Born, A. (2019). Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger events. *Quaternary Science Reviews*, 203:1–20. 1.2, 1.3.1, 2

Liang, X. and Losch, M. (2018). On the Effects of Increased Vertical Mixing on the Arctic Ocean and Sea Ice. *Journal of Geophysical Research: Oceans*, 123(12):9266–9282. 4.2

Liu, W., Fedorov, A., and Sévellec, F. (2019). The Mechanisms of the Atlantic Meridional Overturning Circulation Slowdown Induced by Arctic Sea Ice Decline. *Journal of Climate*, 32(4):977–996. 4.4

Liu, W., Xie, S.-P., Liu, Z., and Zhu, J. (2017). Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances*, 3(1). 4.4

Loving, J. L. and Vallis, G. K. (2005). Mechanisms for climate variability during glacial and interglacial periods. *Paleoceanography*, 20(4):n/a–n/a. 1.2

Lozier, M. S., Bacon, S., Bower, A. S., Cunningham, S. A., De Jong, M. F., De Steur, L., and Others (2017). Overturning in the Subpolar north Atlantic program: A new international ocean observing system. *Bulletin of the American Meteorological Society*, 98(4):737–752. 1.3.1, 4.1

Lozier, M. S., Li, F., Bacon, S., Bahr, F., Bower, A. S., Cunningham, S. A., and Others (2019). A sea change in our view of overturning in the subpolar North Atlantic. *Science*, 363(6426):516–521. 4.1

Lynch-Stieglitz, J. (2016). The Atlantic Meridional Overturning Circulation and Abrupt Climate Change. *Annual Review of Marine Science*, 9(1):83–104. 1.2, 1.2

MacAyeal, D. R. (1993). Binge/purge oscillations of the Laurentide Ice Sheet as a cause of the North Atlantic's Heinrich events. *Paleoceanography*, 8(6):775–784. 1.2

Manabe, S., Stouffer, R. J., and Others (1995). Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. *Nature*, 378(6553):165–167. 1.2

Marcott, S. A., Clark, P. U., Padman, L., Klinkhammer, G. P., Springer, S. R., Liu, Z., and Others (2011). Ice-shelf collapse from subsurface warming as a trigger for Heinrich events. *Proceedings of the National Academy of Sciences*, 108(33):13415–13419. 1.2

Marotzke, J. (2000). Abrupt climate change and thermohaline circulation: mechanisms and predictability. *Proceedings of the National Academy of Sciences of the United States of America*, 97(4):1347–50. 1.3.2

Marshall, J. and Speer, K. (2012). Closure of the meridional overturning circulation through Southern Ocean upwelling. *Nature Geosci*, 5(3):171–180. 1.2.1, 4.1

Martin, S., Drucker, R., and Yamashita, K. (1998). The production of ice and dense shelf water in the Okhotsk Sea polynyas. *Journal of Geophysical Research: Oceans*, 103(C12):27771–27782. 1.3.2

Martin, T., Park, W., and Latif, M. (2013). Multi-centennial variability controlled by Southern Ocean convection in the Kiel Climate Model. *Climate Dynamics*, 40(7-8):2005–2022. 1.3.2, 4.2

Martin, T., Park, W., and Latif, M. (2015). Southern Ocean forcing of the North Atlantic at multi-centennial time scales in the Kiel Climate Model. *Deep Sea Research Part II: Topical Studies in Oceanography*, 114(0):39–48. 1.3, 1.3.2, 4.3

Martinson, D. G., Killworth, P. D., and Gordon, A. L. (1981). A Convective Model for the Weddell Polynya. *Journal of Physical Oceanography*, 11(4):466–488. 1.3.2

Moffa-Sanchez, P., Hall, I. R., Thornalley, D. J., Barker, S., and Stewart, C. (2015). Changes in the strength of the Nordic Seas Overflows over the past 3000 years. *Quaternary Science Reviews*, 123:134–143. 1.3.1

Morales Maqueda, M. A., Willmott, A. J., and Biggs, N. R. T. (2004). Polynya Dynamics: a Review of Observations and Modeling. *Reviews of Geophysics*, 42(1):RG1004. 1.3.2, 1.3.2

Munk, W. (1966). Abyssal recipes. *Deep-Sea Research and Oceanographic Abstracts*, 13(4):707–730. 1.2.1

Munk, W. and Wunsch, C. (1998). Abyssal recipes II: Energetics of tidal and wind mixing. *Deep-Sea Research Part I: Oceanographic Research Papers*, 45(12):1977–2010. 1.2.1

National Research Council (2002). *Abrupt Climate Change*. The National Academies Press, Washington, D.C. 1

Nilsson, J., Broström, G., and Walin, G. (2003). The Thermohaline Circulation and Vertical Mixing: Does Weaker Density Stratification Give Stronger Overturning? *Journal of Physical Oceanography*, 33(12):2781–2795. 1.2.1, 1.2.1

Orsi, A. H., Johnson, G. C., and Bullister, J. L. (1999). Circulation, mixing, and production of Antarctic Bottom Water. *Progress in Oceanography*, 43(1):55–109. 1.3.2

Osborn, T. R. (1980). Estimates of the Local Rate of Vertical Diffusion from Dissipation Measurements. *Journal of Physical Oceanography*, 10(1):83–89. 4.2

Pedro, J. B., Jochum, M., Buizert, C., He, F., Barker, S., and Rasmussen, S. O. (2018). Beyond the bipolar seesaw: Toward a process understanding of interhemispheric coupling. *Quaternary Science Reviews*, 192:27–46. 1.1

Pedro, J. B., Martin, T., Steig, E. J., Jochum, M., Park, W., and Rasmussen, S. O. (2016). Southern Ocean deep convection as a driver of Antarctic warming events. *Geophysical Research Letters*, 43(5):2192–2199. 1.3.2, 4.3

Peltier, W. and Fairbanks, R. (2006). Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. *Quaternary Science Reviews*, 25(23-24):3322–3337. 4.1

Peltier, W. R. and Vettoretti, G. (2014). Dansgaard-Oeschger oscillations predicted in a comprehensive model of glacial climate: A "kicked" salt oscillator in the Atlantic. *Geophysical Research Letters*, 41(20):7306–7313. 1.3, 1.3.1, 2, 3.1, 4.2

Petersen, S. V., Schrag, D. P., and Clark, P. U. (2013). A new mechanism for Dansgaard-Oeschger cycles. *Paleoceanography*, 28(1):24–30. 1.3.1

Polzin, K. L., Toole, J. M., Ledwell, J. R., and Schmitt, R. W. (1997). Spatial variability of turbulent mixing in the abyssal ocean. *Science*, 276(5309):93–96. 1.2.1, 4.2

Rahmstorf, S. (2002). Ocean circulation and climate during the past 120,000 years. *Nature*, 419(6903):207–214. 1.2, 1.2, 1.2.1, 1.3.2

Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B., and Others (2014). A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews*, 106:14–28. 1.1

Rasmussen, T. L. and Thomsen, E. (2004). The role of the North Atlantic Drift in the millennial timescale glacial climate fluctuations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 210(1):101–116. 1.3.1, 4.1, 4.2

Reintges, A., Martin, T., Latif, M., and Park, W. (2017). Physical controls of Southern Ocean deep-convection variability in CMIP5 models and the Kiel Climate Model. *Geophysical Research Letters*, 44(13):6951–6958. 1.3.2

Robertson, R., Visbeck, M., Gordon, A. L., and Fahrbach, E. (2002). Long-term temperature trends in the deep waters of the Weddell Sea. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 49(21):4791–4806. 1.3.2

Rose, B. E., Ferreira, D., and Marshall, J. (2013). The role of oceans and sea ice in abrupt transitions between multiple climate states. *Journal of Climate*, 26(9):2862–2879. 1

Sadatzki, H., Dokken, T. M., Berben, S. M., Muschitiello, F., Stein, R., Fahl, K., Menviel, L., Timmermann, A., and Jansen, E. (2019a). Sea ice variability in the southern norwegian sea during glacial dansgaard-oeschger climate cycles. *Science Advances*, 5(3):eaau6174. 1.3.1, 1.3.2, 4.2

Sadatzki, H., Simon, M., Muschitiello, F., Berben, S. M., Friedrich, T., Jansen, E., Hajdas, I., Wacker, L., and Dokken, T. M. (2019b). Leading role of ocean mixing in the Norwegian Sea for Dansgaard-Oeschger events. *Geophysical Research Abstracts*, 21. 4.2

Schmittner, A., Green, J. A., and Wilmes, S. B. (2015). Glacial ocean overturning intensified by tidal mixing in a global circulation model. *Geophysical Research Letters*, 42(10):4014–4022. 1.2.1

Schmittner, A., Latif, M., and Schneider, B. (2005). Model projections of the North Atlantic thermohaline circulation for the 21st century assessed by observations. *Geophysical Research Letters*, 32(23):L23710. 4.4

Schmittner, A., Saenko, O. A., and Weaver, A. J. (2003). Coupling of the hemispheres in observations and simulations of glacial climate change. *Quaternary Science Reviews*, 22(5–7):659–671. 1.2

Scott, J. R. and Marotzke, J. (2002). The Location of Diapycnal Mixing and the Meridional Overturning Circulation. *Journal of Physical Oceanography*, 32(12):3578–3595. 1.2.1, 4.2

Seager, R. and Battisti, D. S. (2007). The Global Circulation of the Atmosphere. In Schneider, T. and Sobel, A. H., editors, *Challenges to our understanding of the general circulation: Abrupt climate change*, pages 331–371. Princeton University Press. 1, 1.1, 1.2

Serreze, M., Holland, M., Science, J. S., and 2007, U. (2007). Perspectives on the Arctic's shrinking sea-ice cover. *Science*, 315(5818):1533—-1536. 1

Sévellec, F., Fedorov, A. V., and Liu, W. (2017). Arctic sea-ice decline weakens the Atlantic Meridional Overturning Circulation. *Nature Climate Change*, 7(8):604–610. 4.4

Shaffer, G., Olsen, S. M., and Bjerrum, C. J. (2004). Ocean subsurface warming as a mechanism for coupling Dansgaard-Oeschger climate cycles and ice-rafting events. *Geophysical Research Letters*, 31(24). 1.2

Siddall, M., Rohling, E. J., Thompson, W. G., and Waellbroeck, C. (2008). Marine isotope stage 3 sea level fluctuations: Data synthesis and new outlook. *Reviews of Geophysics*, 46(4):RG4003. 4.2

Singh, H. A., Battisti, D. S., and Bitz, C. M. (2014). A heuristic model of dansgaard-oeschger cycles. part i: Description, results, and sensitivity studies. *Journal of Climate*, 27(12):4337–4358. 1.3.2, 4.2

Skogseth, R., Haugan, P. M., and Haarpaintner, J. (2004). Ice and brine production in Storfjorden from four winters of satellite and in situ observations and modeling. *Journal of Geophysical Research*, 109(C10):C10008. 1.3.2

Smedsrud, L. H. (2005). Warming of the deep water in the Weddell Sea along the Greenwich meridian: 1977–2001. *Deep-Sea Research I*, 52:241–258. 1.3.2

Smedsrud, L. H., Sorteberg, A., and Kloster, K. (2008). Recent and future changes of the Arctic sea-ice cover. *Geophysical Research Letters*, 35(20):10–13. 1

Smith, J. A., Hillenbrand, C.-D., Pudsey, C. J., Allen, C. S., and Graham, A. G. (2010). The presence of polynyas in the Weddell Sea during the Last Glacial Period with implications for the reconstruction of sea-ice limits and ice sheet history. *Earth and Planetary Science Letters*, 296(3-4):287–298. 4.3

Stärz, M., Jokat, W., Knorr, G., and Lohmann, G. (2017). Threshold in North Atlantic-Arctic Ocean circulation controlled by the subsidence of the Greenland-Scotland Ridge. *Nature Communications*, 8. 1, 1.2, 4.1

Stommel, H. (1961). Thermohaline convection with two stable regimes of flow. *Tellus*, 13(2):224–230. 1.2

Stommel, H. and Arons, A. B. (1959). On the abyssal circulation of the world ocean—I. Stationary planetary flow patterns on a sphere. *Deep Sea Research (1953)*, 6:140–154. 1.2.1

Stouffer, R. J., Yin, J., Gregory, J. M., Dixon, K. W., and Spelman, M. J. (2006). Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. *Journal of Climate*, 19:1365–1387. 1.2

Stroeve, J. C., Serreze, M. C., Holland, M. M., Kay, J. E., Malanik, J., and Barrett, A. P. (2012). The Arctic's rapidly shrinking sea ice cover: a research synthesis. *Climatic Change*, 110(3-4):1005–1027. 1

Swart, S., Campbell, E., Heuze, C., Johnson, K., Lieser, J., Massom, R., Mazloff, M., Meredith, M., Reid, P., Sallee, J.-B., and Stammerjohn, S. (2018). Return of the Maud Rise Polynya: climate litmus or sea ice anomaly? [in "State of the Climate in 2017"]. *Bulletin of the American Meteorological Society*, 99(9):188–189. 1.3.2

Swingedouw, D., Fichefet, T., Goosse, H., and Loutre, M. F. (2009). Impact of transient freshwater releases in the Southern Ocean on the AMOC and climate. *Climate Dynamics*, 33(2-3):365–381. 1.2

Timmermann, R. and Beckmann, A. (2004). Parameterization of vertical mixing in the Weddell Sea. *Ocean Modelling*, 6(1):83–100. 4.3

Toggweiler, J. R. and Samuels, B. (1995). Effect of Drake Passage on the global thermohaline circulation. *Deep Sea Research Part I: Oceanographic Research Papers*, 42(4):477–500. 1.2.1, 4.1

Tziperman, E. (1997). Inherently unstable climate behaviour due to weak thermohaline ocean circulation. *Nature*, 386(6625):592–595. 1.2

Uenzelmann-Neben, G. and Gruetzner, J. (2018). Chronology of Greenland Scotland Ridge overflow: What do we really know? *Marine Geology*, 406:109–118. 1.2

Van Meerbeeck, C. J., Renssen, H., and Roche, D. M. (2009). How did Marine Isotope Stage 3 and Last Glacial Maximum climates differ? - Perspectives from equilibrium simulations. *Climate of the Past*, 5(1):33–51. 1.2, 4.2

Vettoretti, G. and Peltier, W. R. (2016). Thermohaline instability and the formation of glacial North Atlantic super polynyas at the onset of Dansgaard-Oeschger warming events. *Geophysical Research Letters*, 43(10):5336–5344. 1.3.1, 1.3.2, 4.2, 4.3

Vettoretti, G. and Peltier, W. R. (2018). Fast physics and slow physics in the nonlinear Dansgaard-Oeschger relaxation oscillation. *Journal of Climate*, 31(9):3423–3449. 1.3.1, 1.3.2, 4.3

Via, R. K. and Thomas, D. J. (2006). Evolution of Atlantic thermohaline circulation: Early Oligocene onset of deep-water production in the North Atlantic. *Geology*, 34(6):441–444. 4.1

Voelker, A. H. (2002). Global distribution of centennial-scale records for Marine Isotope Stage (MIS) 3: A database. *Quaternary Science Reviews*, 21(10):1185–1212. 1, 1.1

Wang, Z. and Mysak, L. A. (2006). Glacial abrupt climate changes and Dansgaard-Oeschger oscillations in a coupled climate model. *Paleoceanography*, 21(2):n/a–n/a. 1.2

Wang, Z., Wu, Y., Lin, X., Liu, C., and Xie, Z. (2016). Impacts of open-ocean deep convection in the Weddell Sea on coastal and bottom water temperature. *Climate Dynamics*, pages 1–15. 1.3.2

Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O., and Svensson, A. (2010). Millennial-scale variability during the last glacial: The ice core record. *Quaternary Science Reviews*, 29(21):2828–2838. 1.1

Wright, J. D. and Miller, K. G. (1996). Control of North Atlantic deep water circulation by the Greenland-Scotland Ridge. *Paleoceanography*, 11(2):157–170. 4.1

Wunsch, C. (2006). Abrupt climate change: An alternative view. *Quaternary Research*, 65(2):191–203. 1.2, 1.2.1, 2

Wunsch, C. and Ferrari, R. (2004). Vertical mixing, energy, and the general circulation of the oceans. *Annual Review of Fluid Mechanics*, 36(1):281–314. 1.2.1, 4.2

Yang, S., Galbraith, E., and Palter, J. (2014). Coupled climate impacts of the Drake Passage and the Panama Seaway. *Climate Dynamics*, 43(1-2):37–52. 4.1

Zanowski, H. and Hallberg, R. (2017). Weddell Polynya Transport Mechanisms in the Abyssal Ocean. *Journal of Physical Oceanography*, 47(12):2907–2925. 1.3.2

Zanowski, H., Hallberg, R., and Sarmiento, J. L. (2015). Abyssal Ocean Warming and Salinification after Weddell Polynyas in the GFDL CM2G Coupled Climate Model. *Journal of Physical Oceanography*, 45(11):2755–2772. 1.3.2, 4.2

Zhang, J. and Steele, M. (2007). Effect of vertical mixing on the Atlantic Water layer circulation in the Arctic Ocean. *Journal of Geophysical Research: Oceans*, 112(4):C04S04. 4.2

Graphic design: Communication Division, UiB / Print: Skipnes Kommunikasjon AS

uib.no

ISBN: 9788230857793 (print)
9788230848470 (PDF)