Clim. Past, 8, 1011–1021, 2012
www.clim-past.net/8/1011/2012/
doi:10.5194/cp-8-1011-2012

Climate of the Past

Role of CO_2 and Southern Ocean winds in glacial abrupt climate change

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Received: 4 October 2011 – Published in Clim. Past Discuss.: 20 October 2011
Revised: 11 May 2012 – Accepted: 14 May 2012 – Published: 1 June 2012

Abstract. The study of Greenland ice cores revealed two decades ago the abrupt character of glacial millennial-scale climate variability. Several triggering mechanisms have been proposed and confronted against growing proxy-data evidence. Although the implication of North Atlantic deep water (NADW) formation reorganisations in glacial abrupt climate change seems robust nowadays, the final cause of these reorganisations remains unclear. Here, the role of CO_2 and Southern Ocean winds is investigated using a coupled model of intermediate complexity in an experimental setup designed such that the climate system resides close to a threshold found in previous studies. An initial abrupt surface air temperature (SAT) increase over the North Atlantic by 4 K in less than a decade, followed by a more gradual warming greater than 10 K on centennial timescales, is simulated in response to increasing atmospheric CO_2 levels and/or enhancing southern westerlies. The simulated peak warming shows a similar pattern and amplitude over Greenland as registered in ice core records of Dansgaard-Oeschger (D/O) events. This is accompanied by a strong Atlantic meridional overturning circulation (AMOC) intensification. The AMOC strengthening is found to be caused by a northward shift of NADW formation sites into the Nordic Seas as a result of a northward retreat of the sea-ice front in response to higher temperatures. This leads to enhanced heat loss to the atmosphere as well as reduced freshwater fluxes via reduced sea-ice import into the region. In this way, a new mechanism that is consistent with proxy data is identified by which abrupt climate change can be promoted.

1 Introduction

The last glacial period (ca. 110–10 kyr BP) was characterised by remarkable climatic instability on millennial timescales, mainly associated with so-called Dansgaard-Oeschger (D/O) events (Alley et al., 1999). These are considered to be the most abrupt, i.e. large and rapid, climate changes of the past 110 kyr, repeatedly manifested as warming in Greenland by more than 10 K on decadal timescales (e.g. Lang et al., 1999) with widespread global climatic effects (Voelker et al., 2002).

Both modelling and reconstruction efforts have contributed to increase our understanding of these glacial abrupt climate changes. The current paradigm is that these were caused by reorganisations of North Atlantic deep water (NADW) formation (Alley et al., 1999; Ganopolski and Rahmstorf, 2001). This is supported by the close agreement between results of climate simulations involving variations in NADW formation and the Atlantic meridional overturning circulation (AMOC), and the evidence from paleoclimate reconstructions. Models are in this way able to reproduce the so-called bipolar seesaw behaviour between Greenland and Antarctica (Blunier and Brook, 2001; EPICA-Project, 2006). The idea is that an intensification of the AMOC translates into an increase in northward heat transport at the expense of the southernmost latitudes; conversely, a weakening of the AMOC reduces northward heat transport, thereby warming the south (Crowley, 1992; Stocker, 1998). The different timescale between northern and southern latitudes can be explained by the fact that the Southern Ocean acts as a heat reservoir, that dampens and integrates in time the more rapid North Atlantic signal (Stocker and Johnsen, 2003).

However, the causes of NADW formation reorganisations remain yet unknown. Model studies generally employ freshwater forcing in the North Atlantic to mimic D/O-like fluctuations (e.g. Ganopolski and Rahmstorf, 2001), but the ultimate source of such a forcing has not been identified. Alternatively, a Southern Ocean origin of abrupt climate changes has also been proposed. Enhanced surface freshwater fluxes (Weaver et al., 2003) and slowly varying background climate conditions in the Southern Ocean (Knorr and Lohmann, 2003) have been shown to be able to trigger an AMOC intensification leading to an abrupt warming in the North Atlantic. The same result was found when applying gradual background climate changes from glacial to interglacial climate conditions on a global scale, including temperature and wind stress (Knorr and Lohmann, 2007). As suggested by the latter study, fluctuations in atmospheric CO_2 concentration are a potential candidate to generate such gradual climate variations. Ice core data and marine sediment proxies furthermore suggest atmospheric CO_2 levels rose during the last glacial period, coinciding with periods of halted NADW formation and reduced stratification in the Southern Ocean (Ahn and Brook, 2008). Such CO_2 variations are strongly correlated with Antarctic temperature and predate abrupt warmings in Greenland associated with the largest D/O events. Taken together, these results led Knorr and Lohmann (2007) to suggest CO_2 increases could have contributed to rapid AMOC intensification after Heinrich events, corresponding with the largest DO events.

The close correspondence between atmospheric CO_2 variations and Antarctic temperature variability on millennial timescales suggests an important role of the Southern Ocean in controlling the carbon cycle during the last glacial period. Recently, biogenic opal reconstructions have suggested that during deglaciation, as well as throughout the last glacial period, CO_2 rises were preceded by an increase in deep upwelling in the Southern Ocean (Anderson et al., 2009). Denton et al. (2010) and Toggweiler and Lea (2010) have proposed that the increase of both Southern Ocean upwelling and CO_2 levels was the consequence of a shift in atmospheric circulation patterns in response to a reduction of the AMOC through the bipolar seesaw effect. Southern Ocean winds indeed appear to have strengthened and shifted southward at the end of the last glacial period as well as during extreme cold periods in the Northern Hemisphere (Toggweiler, 2009). Recent model studies suggest that a southward shift of the intertropical convergence zone (ITCZ) and Southern Ocean winds intensification can also take place via atmospheric teleconnections, that is, without involving the bipolar seesaw, in response to a cooling in the North Atlantic, and leading to a rise in atmospheric CO_2 by 20–60 ppmv, consistent with proxy records (Lee et al., 2011).

These results indicate several mechanisms by which a decrease in the AMOC strength leading to northern cooling would have translated into a southward shift and/or intensification of Southern Ocean westerlies, which through enhanced deep upwelling would have contributed to increase the atmospheric CO_2 concentration.

Southern Ocean winds are one of the main driving factors of the AMOC (Kuhlbrodt et al., 2007). Thus, increased Southern Ocean westerlies could have contributed to an AMOC strengthening through the so-called Drake Passage effect (Toggweiler and Samuels, 1995). On the other hand, the concomitant effect of increasing atmospheric CO_2 levels on the glacial AMOC has not yet been assessed. Here, the evidence from all the former studies is taken together to investigate the effect of CO_2 and Southern Ocean winds variations on the glacial AMOC.

2 Model and experimental design

The model used in this study is CLIMBER-3α (Montoya et al., 2005). Its atmospheric component is a 2.5-dimensional statistical-dynamical model based on the assumption of a universal vertical structure of temperature and humidity in the atmosphere, with a horizontal resolution of $7.5° \times 22.5°$ (Petoukhov et al., 2000). Its oceanic component contains the state-of-the-art Geophysical Fluid Dynamics Laboratory (GFDL) MOM-3 ocean general circulation model, with a horizontal resolution of 3.75° and 24 variably spaced vertical levels, and the ISIS thermodynamic-dynamic snow and sea-ice model (Fichefet and Maqueda, 1997). CLIMBER-3α satisfactorily describes the large-scale characteristics of the atmosphere, ocean and sea-ice on seasonal and longer timescales.

The present study builds upon a previous climate simulation of the Last Glacial Maximum (LGM, ca. 21 kyr BP; Montoya and Levermann, 2008). Boundary conditions followed the specifications of the Paleoclimate Modeling Intercomparison Project Phase II (PMIP2), namely: changes in insolation; a reduced equivalent atmospheric CO_2 concentration of 167 ppmv to account for the lowered CH_4, N_2O and CO_2 concentrations; the ICE-5G ice sheet reconstruction (Peltier, 2004); and land-sea mask changes plus a global increase of salinity by 1 PSU to account for the $\sim$120 m sea-level lowering. Montoya and Levermann (2008) investigated the sensitivity of the glacial AMOC to wind stress strength by integrating the CLIMBER-3α model to equilibrium with the Trenberth et al. (1989) surface wind stress climatology multiplied globally by varying factors $\alpha \in [0.5,2]$. At $\alpha = 1.7$ a threshold, associated with a drastic AMOC increase of more than 10 Sv and a northward shift of NADW formation north of the Greenland-Iceland-Scotland (GIS) ridge, was found. We hypothesise herein that the glacial AMOC is close to this threshold. However, because D/O events take place within marine isotopic stage (MIS) 3 (ca. 60–27 kyr BP) rather than at the LGM, an equivalent atmospheric CO_2 level of 200 ppmv, resulting from the higher CH_4, N_2O and atmospheric CO_2 concentrations registered during the former period (Schilt et al., 2010), has been imposed to mimic MIS3

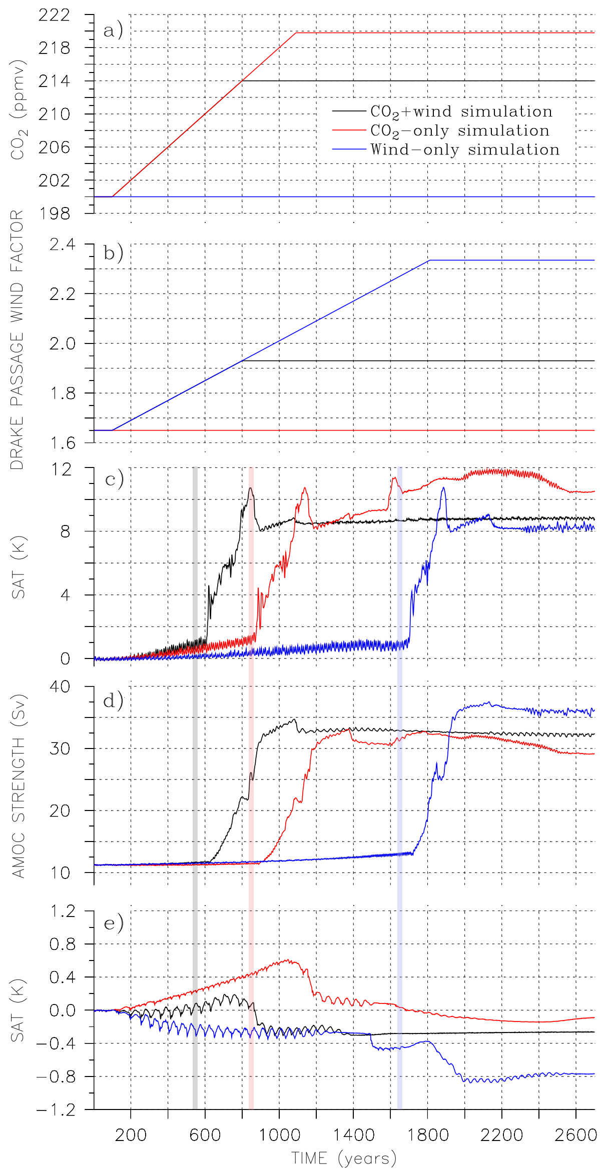

Fig. 1. Time series of forcings and relevant climatic variables: **(a)** CO_2 forcing in ppmv; **(b)** wind amplification factor over the Drake Passage (no units); **(c)** anomalies of North Atlantic SAT (67.5° N 11° W, in the Nordic Seas) with respect to the stadial state in K; **(d)** AMOC strength in Sv; **(e)** anomalies of Antarctic SAT (86.2° S 11° E) with respect to the stadial state in K. Black, red and blue lines show the simulation combining CO_2 and wind forcings, the CO_2-only experiment, and the wind-only forced run, respectively. Black, red and blue shaded bars indicate the transition stages for the simulation combining CO_2 and wind forcings, the CO_2-only experiment and the wind-only forced run, respectively.

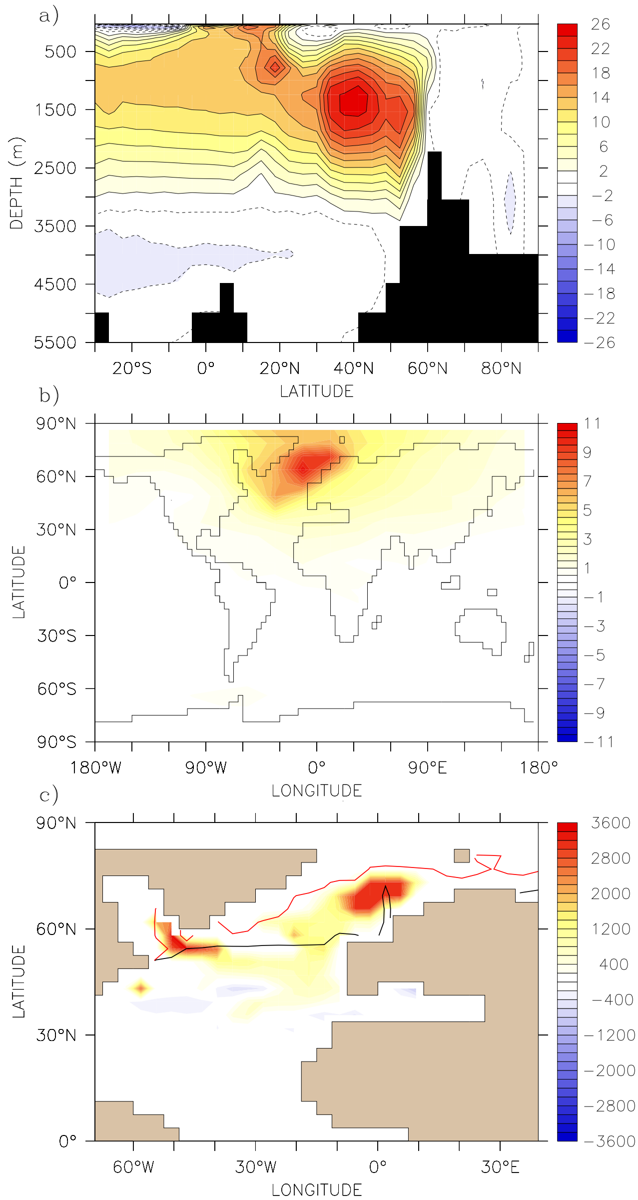

Fig. 2. Climatic patterns describing the interstadial state: **(a)** AMOC stream-function in Sv; **(b)** SAT anomalies with respect to the stadial state in K; **(c)** interstadial minus stadial maximum convective depth differences in m. Black and red lines show the locations of the 90 % northern summer (June–August) average sea ice concentration for the stadial and the interstadial regime, respectively.

climatic conditions. Consequently, the starting point for the experiments shown herein is the final equilibrium state of a control climate simulation with $\alpha = 1.65$ and an equivalent atmospheric CO_2 level of 200 ppmv, hereafter our stadial state.

Three transient experiments have been performed to test the AMOC sensitivity to CO_2 and wind forcings: a simulation combining both factors; a scenario considering CO_2 forcing only; and, finally, a wind-only forced experiment (Fig. 1a and b). CO_2 forcing consists of a linear increase in CO_2 levels by 20 ppmv in 1000 yr, thus at the highest end of the CO_2 increase rates suggested by Ahn and Brook (2008) and recent climate carbon cycle simulations (Bouttes et al., 2011). Wind forcing implies wind stress over the latitudinal

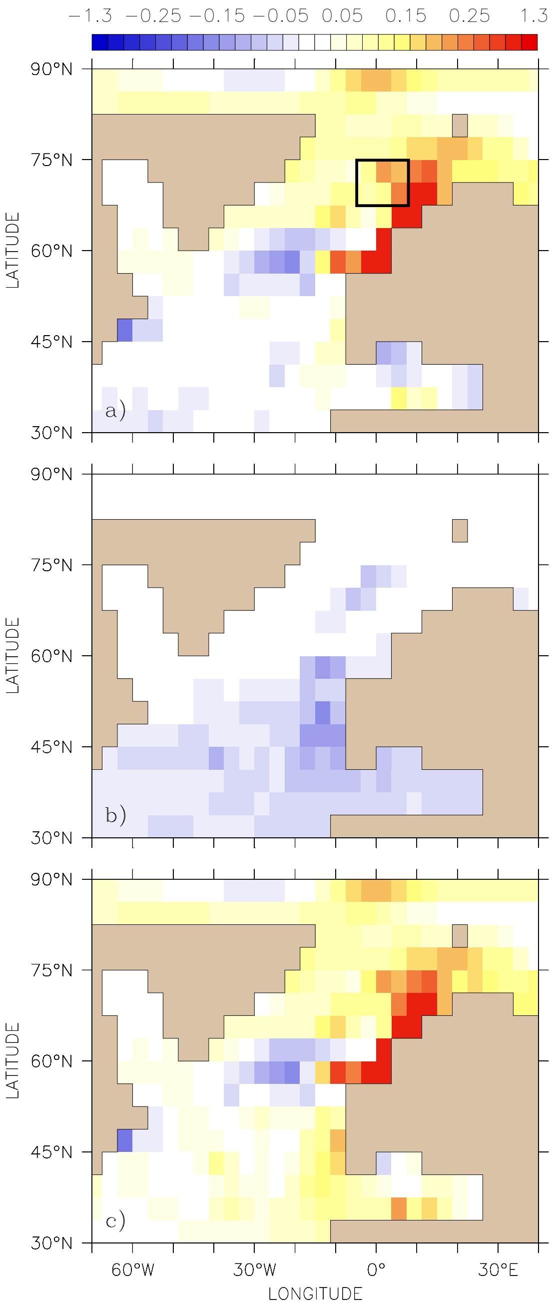

Fig. 3. (a) Surface density anomalies at the transition stage relative to the stadial regime for the CO_2-only experiment and contribution to the latter by **(b)** temperature and **(c)** salinity in $kg\,m^{-3}$, assuming a linear equation of state. The black box in panel **(a)** indicates the region where the surface freshwater flux balance was calculated.

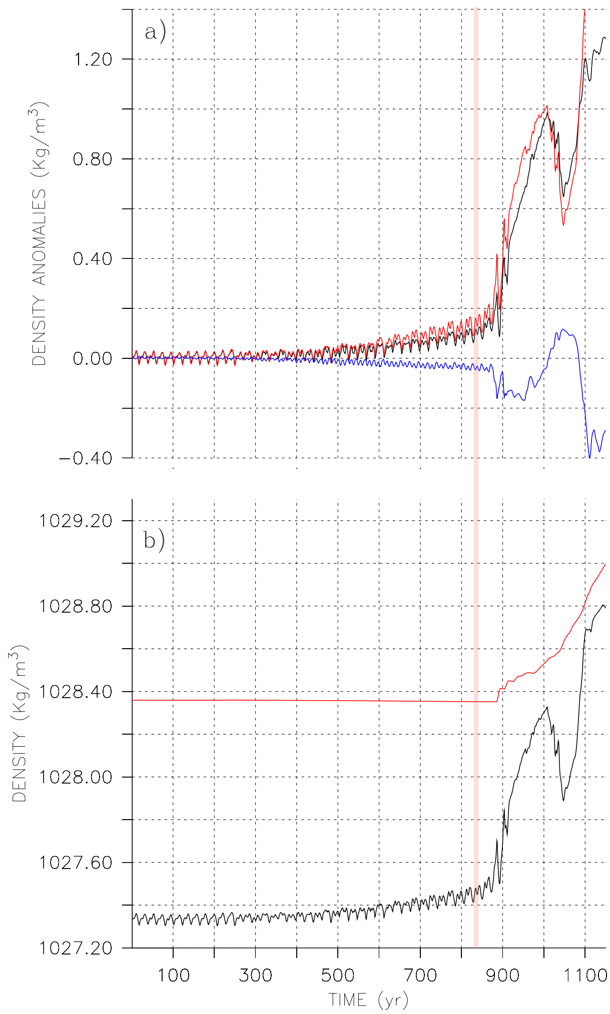

Fig. 4. (a) Surface anomalies with respect to the stadial state of density (black), together with salinity (red) and temperature (blue) contributions to density changes in $kg\,m^{-3}$ over the Nordic Seas area (67.5° N–75° N, 4° W–7.5° E; black box in Fig. 3a), assuming a linear equation of state for density for the CO_2-only experiment; **(b)** density evolution in $kg\,m^{-3}$ over the same region at the surface (0–87.5 m; black line) and depth (2800 m; red line). The red shaded bar indicates the transition stage for the CO_2-only experiment.

band of Drake Passage is linearly increased with a wind amplification rate of 0.4 in 1000 yr. This increase is roughly consistent with results of a recent atmospheric model study, in which cold conditions in the North Atlantic were shown to lead to an intensification of Southern Ocean winds by ∼25 % (Lee et al., 2011).

3 Stadial to interstadial transition

Increasing CO_2 levels and wind strength lead to a gradual warming in the Nordic Seas area (Fig. 1c, black). After about 700 yr the system is found to cross a critical point leading to an abrupt temperature increase in the North Atlantic sector, which is accompanied by a strong AMOC strengthening by more than 20 Sv (Fig. 1d). The simulated interstadial state is thus characterised by a more vigorous AMOC, deeper convective areas together with reduced sea ice in the Nordic Seas, and a temperature increase of up to 10 K in the North Atlantic relative to the stadial state (Fig. 2).

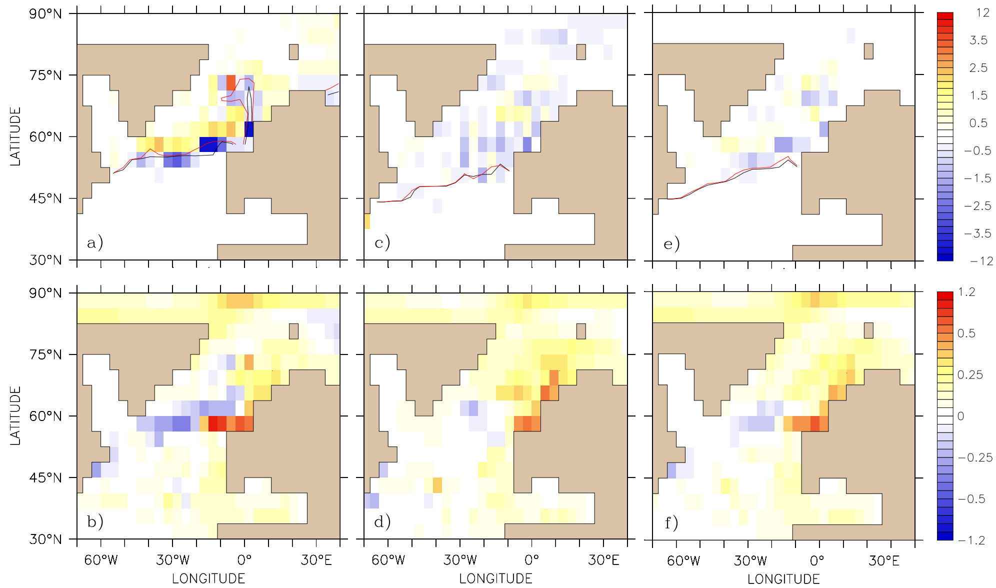

Fig. 5. Anomalies at the transition stage relative to the stadial regime under CO_2-only forcing conditions of **(a)** surface freshwater fluxes in m yr^{-1} and **(b)** surface salinity during summer months (June–August) in PSU; **(c–d)** and **(e–f)** same fields during winter (January–February) and for the annual mean, respectively. Black and red lines show the locations of the 90 % northern average sea ice concentration for the stadial and the transition stage, respectively.

In order to elucidate the mechanism behind this abrupt climate shift, we assess the precursors of the interstadial state. To this end, we analyse the climate system 30 yr before the jump into the interstadial (450, 750, and 1550 yr after switching on the forcing for the CO_2-plus-wind, CO_2-only, and wind-only experiments, respectively), hereafter the transition stage (see Fig. 1c and d). We furthermore assess separately those simulations in which only CO_2 and only Southern Ocean winds were changed, respectively.

Under CO_2-only forcing conditions, an abrupt surface air temperature (SAT) increase of up to 4 K in less than a decade occurs in the Nordic Seas once CO_2 reaches a level of ca. 215 ppmv (Fig. 1c). At this point the AMOC remains almost unchanged (Fig. 1d). This first abrupt warming is related to widespread loss of sea ice in the Nordic Seas and the resumption of NADW formation.

Density variations in the Nordic Seas are thus analysed as a precursor for triggering the AMOC recovery. Surface density anomalies at the transition stage reveal significant changes over the North Atlantic with respect to the stadial state, notably over the Nordic Seas and Fennoscandian coast (Fig. 3a). Temperature and salinity contributions to density variations indicate the major density anomalies are related to changes in salinity (Fig. 3). The surface density evolution, which results in a gradual erosion of vertical stratification previous to the jump into the interstadial state, indeed strongly correlates with surface salinity contribution to density changes (Fig. 4).

To understand the causes behind these salinity changes, surface freshwater fluxes over the Nordic Seas region have been analysed. Northern summer freshwater flux anomalies closely correlate with surface salinity anomalies at the transition stage (Fig. 5a and b). The latter persist throughout the year, explaining the less clear relationship in winter and in the annual mean (Fig. 5c–f). The ultimate causes of the northern summer surface freshwater flux change have been unravelled through a detailed analysis of its balance (precipitation, evaporation and sea ice changes) over the Nordic Seas region (Fig. 3a, black box) at the transition and stadial states (Table 1). The net northern summer surface freshwater flux in the area is found to be reduced by 0.59 m yr^{-1} (25 %) relative to the stadial state. This is partly due to a reduction in precipitation minus evaporation by 0.06 m yr^{-1}, but mostly due to a reduction in sea ice melting by 0.53 m yr^{-1}. Although rising temperatures due to increased CO_2 levels result in local widespread freshening, a northward shift of the northern summer polar front takes place north of the Fennoscandian coast (Fig. 5a). As a consequence, summer sea ice import into the region, most notably in the northeastern North Atlantic and north of the Fennoscandian coast, and thus melting there, is strongly reduced (Fig. 6). This counteracts the effect of sea ice melting and eventually results in local net negative freshwater flux anomalies.

To summarise, increased CO_2 levels translate into a modest radiative forcing of about 0.35 W m^{-2}, which leads to warming in the Nordic Seas by about 1 K (Fig. 1c) and, thereby, impacts the sea ice distribution in this region, especially its southernmost margins, by leading to a northward retreat of the summer polar front. This allows for increased heat loss in this region that contributes to foster convection

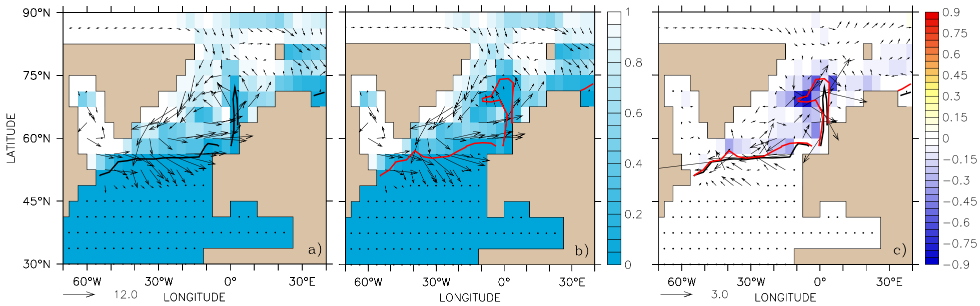

Fig. 6. Sea-ice fraction (shaded) and sea-ice velocities (vectors) in cm s^{-1} during summer (June–August) for the CO_2-only scenario in **(a)** the stadial state; **(b)** the transition state; **(c)** transition minus stadial state. Black and red lines show the locations of the 90 % northern summer (June–August) average sea ice concentration for the stadial and the transition stage, respectively.

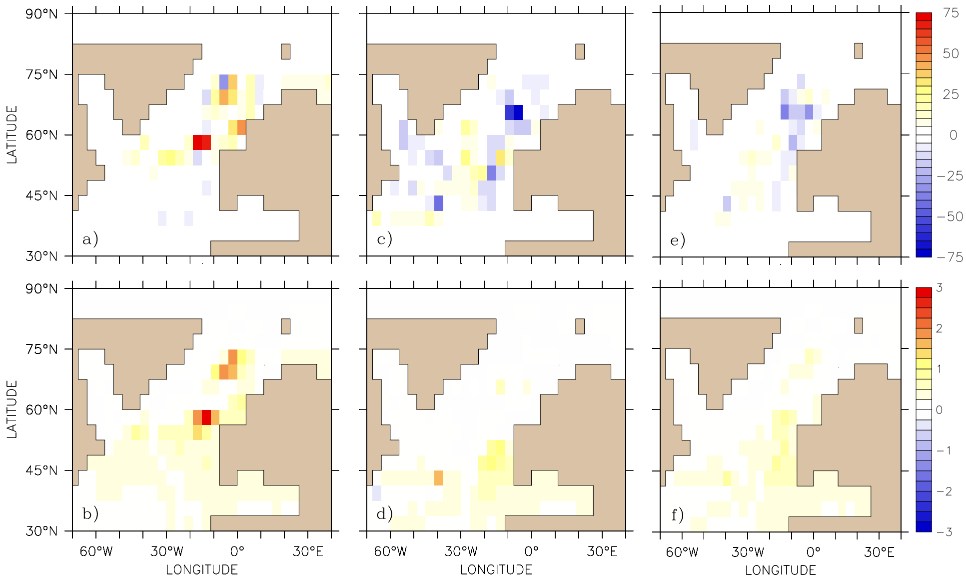

Fig. 7. Anomalies at the transition stage relative to the stadial regime under CO_2-only forcing conditions of **(a)** surface heat flux in W m^{-2} (negative values indicate heat loss by the ocean to the atmosphere) and **(b)** sea surface temperature during summer months (June–August) in K; **(c–d)** and **(e–f)** same fields during winter (January–February) and for the annual mean, respectively.

(Fig. 7) and leads to enhanced surface salinity and thereby denser surface waters in the vicinity of the Fennoscandian coast. This results in a resumption of NADW formation in open-water areas that were previously capped by sea ice during the stadial state. The onset of convection in the Nordic Seas contributes to increase the density of NADW, while South Atlantic densities barely change. This translates into a substantial increase in the meridional density gradient, which eventually leads to a strong AMOC strengthening (Fig. 8).

Note that the SAT evolution over Antarctica exhibits a behaviour that resembles the bipolar seesaw (Fig. 1e). The simulated gradual warming over Antarctica precedes the abrupt temperature increase in the North Atlantic. Nordic and Antarctic SATs reach peak warming roughly at the same time. The system subsequently switches into the interstadial state in centennial timescales at the expense of a more gradual cooling of the Southern Ocean. Note that the initial warming in Antarctica here is exclusively caused by the increase in atmospheric CO_2 rather than by a previous AMOC weakening. Yet, the final state is characterised by high AMOC and northern SAT values, and cold southern SATs, as expected according to the bipolar seesaw. In the latter case the Antarctic cooling is indeed the response to the redistribution of heat by the reactivation of the AMOC.

Within the wind-only forcing scenario, an abrupt SAT increase by 4 K in less than a decade is also found in the North Atlantic about 1650 yr after switching on the forcing. In this case, however, the increased temperatures at the transition stage over the area result from a significant AMOC intensification (Fig. 1c and d). Enhanced winds over the Southern

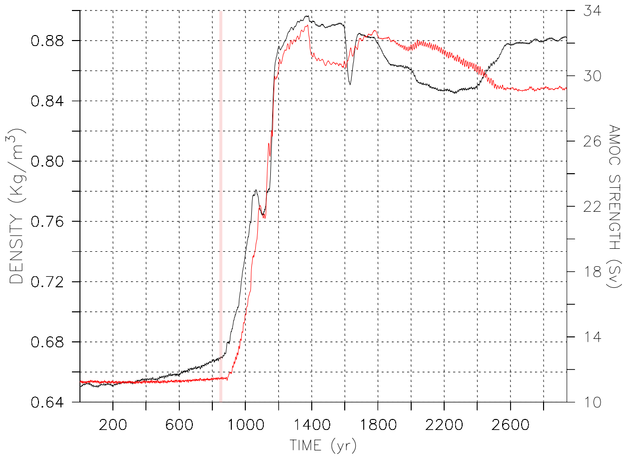

Fig. 8. Temporal evolution of the meridional north-south density contrast in $\mathrm{kg\,m^{-3}}$, estimated as the density difference between the North Atlantic (35° N–80° N, 60° W–10° E) and the South Atlantic (40° S, 60° W–10° E) at 750 m depth (black line) and AMOC strength in Sv (red line), for the CO_2-only experiment. The red shaded bar indicates the CO_2-only transition stage.

Table 1. Surface freshwater fluxes balance in $\mathrm{m\,yr^{-1}}$ over the Nordic Seas (67.5° N–75° N, 4° W–7.5° E) for the stadial and the transition state, and for the difference between them (transition minus stadial) during summer months (June–August) for the CO_2-only and wind-only experiments (left and right, respectively). SFF: total vertical freshwater flux, decomposed in precipitation (P), evaporation (E) and sea ice melting or formation (SI): SFF = P-E + SI; positive values indicate freshwater flux into the ocean.

		CO_2-only		Wind-only	
	Stadial	Transition	Transition minus stadial	Transition	Transition minus stadial
SFF	2.35	1.76	−0.59	1.82	−0.53
P	0.22	0.23	0.01	0.23	0.01
E	0.11	0.18	0.07	0.18	0.07
P-E	0.11	0.05	−0.06	0.05	−0.06
SI	2.24	1.71	−0.53	1.77	−0.47

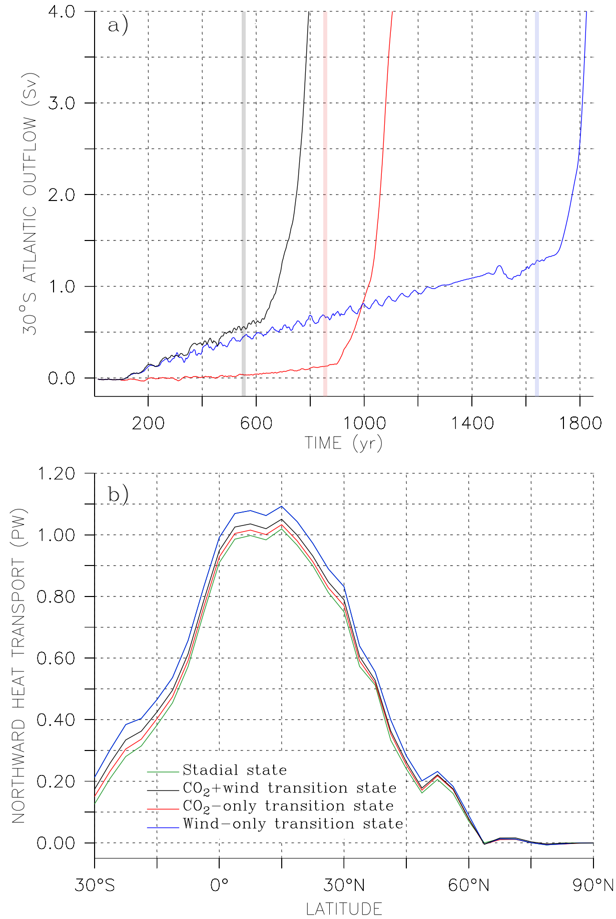

Fig. 9. (a) Evolution of AMOC outflow at 30° S in Sv for the CO_2-plus-wind simulation (black), CO_2-only (red) and wind-only (blue) forced experiments; **(b)** northward oceanic heat transport (0–1000 m depth) in PW for the stadial state (green) and transition stages for the CO_2-plus-wind (black), CO_2-only (red) and wind-only (blue) forced experiments. Black, red and blue shaded bars indicate the transition stage for the simulation combining CO_2 and wind forcings, the CO_2-only run and the wind-only experiment, respectively.

Ocean lead to an increase in deep upwelling over the latitudinal band of Drake Passage. This results in stronger outcropping of isopycnals in the Southern Ocean, and thereby a reduction of the density of Antarctic Intermediate Water (AAIW, not shown), which translates into an increase of the Atlantic outflow (Schewe and Levermann, 2010) by nearly 2 Sv (Fig. 9a). As a result, northward heat transport by the Atlantic Ocean is intensified at almost all latitudes (Fig. 9b). This suggests the AMOC is initially reactivated from southern latitudes in contrast with the CO_2-only run, in which virtually no changes in the AMOC and heat transport are found prior to the onset of the interstadial state (Fig. 9). As a result, North Atlantic waters become warmer in response to a slightly more vigorous AMOC. Increased North Atlantic SATs, related to enhanced northward heat transport driven by the AMOC, result in melting of the Nordic sea-ice cover. The summer sea ice polar front retreats to the north, which translates into enhanced heat loss and reduced freshwater fluxes and thereby increased surface salinity in critical convective areas in the North Atlantic. Again, sea ice changes related to surface salinity increase dominate the freshwater flux balance over this area (Table 1). In this case the reduction in freshwater flux over the Fennoscandian coast is of $0.53\,\mathrm{m\,yr^{-1}}$, of which $0.47\,\mathrm{m\,yr^{-1}}$ (∼90 %) are due to the sea ice reduction and, again, only $0.06\,\mathrm{m\,yr^{-1}}$ to a reduction in precipitation minus evaporation. The resulting salinity anomalies and the enhanced density gradient between both hemispheres are considered to be the precursors of NADW formation recovery and the AMOC reactivation, respectively, leading to the interstadial state. Note in this case, in the transient stage, the bipolar seesaw effect is less evident than in the CO_2-only forcing scenario. However, the final state clearly evidences the cold Antarctica state associated with the strong AMOC and high northern temperatures.

Finally, combining CO_2 and wind forcings translates into a prompter climate response, suggesting both forcings work in the same sense to trigger an abrupt climate shift (Fig. 1).

4 Conclusions and discussion

We have investigated the climatic response to increasing atmospheric CO_2 levels and Southern Ocean winds when the glacial climate state is close to a threshold. Both are found to lead to an initial abrupt SAT increase on decadal timescales over the Nordic Seas followed by further warming on centennial timescales, resembling the large and rapid warmings associated with D/O events that occurred during the last glacial period. The initial simulated abrupt warming is caused by reduced seasonal sea-ice cover in the North Atlantic within all forcing scenarios.

Despite the similarities in the Nordic Seas temperature response between these three scenarios, the mechanism behind the transition to the interstadial in the CO_2-only run is quite different from the experiment considering exclusively the wind amplification factor. In the CO_2-only simulation, the sea ice retreat is mainly due to the increased temperatures following the enhanced CO_2. In contrast, in the wind-only run it is caused by higher temperatures due to a more vigorous heat transport from southern latitudes in response to enhanced Southern Ocean winds.

Our results are consistent with previous studies suggesting an important role of sea ice in abrupt warming (Gildor and Tziperman, 2003; Li et al., 2005). Yet, in our simulations sea ice retreat causes the initial abrupt SAT increase in response to the onset of convection in the Nordic Seas, but it is the AMOC intensification that helps to sustain the system in the warm state. Note that despite the abruptness of the initial SAT increase, the AMOC response is more gradual, lasting several decades until the interstadial state is reached. Thus, the fact that an abrupt response of the AMOC is not found does not preclude the latter playing an important role in abrupt climate change.

Our results support those of Knorr and Lohmann (2003, 2007), who found that, starting from glacial conditions, slowly varying background climate conditions in the Southern Ocean, as well as globally, are able to trigger rapid climate change. Note that in our case global warming was achieved by incorporating increasing atmospheric CO_2 levels rather than prescribing gradually warmer conditions as in Knorr and Lohmann (2007). This result might seem contradictory with future projections, which suggest an increase in atmospheric CO_2 levels leads to North Atlantic warming and freshening, both of which weaken NADW formation. The question as to how abrupt climate change can be promoted in a context of global warming was investigated by Knorr and Lohmann (2007), who specifically assessed this issue in the context of deglaciation, which involves surface warming and freshening associated with melting ice sheets. In that case the mechanism responsible for the transition was found to be the preconditioning by an increase in ventilation of the warm subsurface water in the northern North Atlantic, which resulted in an increase in the meridional transport of salt to the northern high latitudes, leading to a resumption of convection and a rapid intensification of the AMOC. In our case an increase in atmospheric heat loss, together with a reduction in freshwater fluxes, is found in response to enhanced CO_2 mainly through sea ice changes at its margins. Because the CO_2 change is small, the response of atmospheric freshwater fluxes is minor. However, the reduction in sea ice allows for a non-linear response of the system. Thus, in our view, the background climate, and particularly the North Atlantic sea ice configuration, plays an important role in setting the climate sensitivity and its stability properties. This view is supported by Weaver et al. (2007), who found that the North Atlantic sea ice distribution of the initial mean climate determines the amplitude of the thermal response as well as the sign of the freshwater flux forcing associated with increasing greenhouse gases. For cold climates, freshwater flux forcing acted to reduce the transient AMOC decrease, whereas for warmer climates it reinforced the transient AMOC decrease.

The freshwater flux mechanism found herein is different from the salinity advection mechanism in the North Atlantic leading to a rapid AMOC switch-on described by Montoya and Levermann (2008). Note that in the latter study the model was integrated to the equilibrium by changing globally the oceanic wind stress in different simulations. Within this context, enhanced surface wind stress in the North Atlantic was found to increase the horizontal gyre circulation both in the subtropics and the subpolar regions, leading to enhanced salinity transport from the tropics to the North Atlantic in the upper ocean layers. This mechanism is initially absent here, where only the Southern Ocean wind stress and/or the CO_2 concentration are varied. Note that the precursors are analysed at the transition state, thus prior to the interstadial. By contrast, once a relatively large change in the AMOC is accomplished (i.e. once the interstadial state is fully reached), the northward salinity transport does increase considerably, as found by Montoya and Levermann (2008).

Although the abrupt warming simulated in the North Atlantic resembles those reported for D/O events, the comparison against the paleorecord is not fully satisfactory. The simulated rapid warming in the Nordic Seas in our case takes place in two steps: a sudden increase by 4 K in less than a decade, followed by more gradual warming greater than 10 K on centennial timescales, rather than warming by more than 10 K in only a few years found in proxy records (Steffensen et al., 2008). The difficulty to simulate climate changes as abrupt as those registered in the paleorecord is a common feature to many models, and the possible reasons are yet unclear. Recent studies point out the necessity to improve the ability of state-of-the-art models to simulate abrupt climate changes within the context of threshold values. This highlights the necessity to explore new research lines of past forcing factors which may help to understand the ensuing climate response (Valdes, 2011; Stocker and Marchal, 2000). Yet, up to now glacial abrupt climate change has almost exclusively been investigated from a modelling perspective using intermediate or simpler complexity models. Interestingly, it would be desirable to reassess our results with more comprehensive models in the future when this is computationally affordable. In this line, the current model setup was chosen so that the system resides close to a threshold associated with drastic changes in the oceanic circulation. The existence and location of such thresholds are model dependent. In addition, it is conceivable that small perturbations of a different origin could cause such a transition, assuming such perturbations are able to significantly affect density in the Nordic Seas area. Here, we have identified a mechanism that is consistent with proxy records, by which abrupt climate change can be promoted through the idealised experiments exhibited. Up to now climate simulations focusing on abrupt climate changes have mainly been based on imposing freshwater fluctuations in the North Atlantic, as reviewed by Kageyama et al. (2010). However, the sources of these freshwater fluxes have not yet been identified. Here, we propose such freshwater flux variations could be connected with rearrangements in the Nordic Seas sea-ice extent in response to CO_2 and Southern Ocean wind intensifications.

Our results confirm a recent study by Oka et al. (2012) suggesting that if the glacial climate were close to a threshold, small perturbations leading to a reduction in the sea-ice cover could have pushed the system across the latter. Through the sea-ice cover control of deep water formation, this provides an explanation for the different stability of the glacial AMOC compared to the present one, and thereby the different variability of glacial and interglacial periods (Marotzke, 2012).

Reconstructions suggest that during deglaciation, as well as throughout the last glacial period, CO_2 rises were primarily caused by the increase in deep upwelling in the Southern Ocean (Anderson et al., 2009). Models furthermore indicate that wind and CO_2 increases could themselves be the response to a previous North Atlantic cooling leading to a southward shift of the ITCZ and/or strengthening of the westerlies over the Southern Ocean (Chiang and Bitz, 2005; Lee et al., 2011; Timmermann et al., 2007). The oceanic explanation is that during stadial conditions, northward oceanic heat transport is strongly diminished in response to a weak overturning. As a consequence, the Southern Hemisphere warms at expense of the Northern Hemisphere through the bipolar seesaw effect. The temperature asymmetry is thereby reduced, and the ITCZ and the westerlies shift to the south and/or possibly strengthen. In this situation Southern Ocean westerlies are better aligned with the Antarctic Circumpolar Current (ACC). Within these conditions, atmospheric CO_2 levels increase in response to an oceanic upwelling intensification (Denton et al., 2010; Toggweiler and Lea, 2010). Alternatively, atmospheric models also indicate cooling in the North Atlantic (as would follow from a decrease in NADW formation and AMOC strength) leads to a southward shift of the ITCZ and Southern Ocean winds intensification, with a marginal southward shift, via atmospheric teleconnections leading to a rise in atmospheric CO_2 by 20–60 ppmv, consistent with proxy records (Lee et al., 2011). The upper limit is obtained when taking into account exclusively the physical process of increased outgassing of CO_2 due to enhanced upwelling; the lower limit includes as well the biological response to the increased upwelling. This results in an increase in surface nutrients, which fuels biological productivity, thereby damping the atmospheric CO_2 rise and accounting for the smaller increase found previously by Menviel et al. (2008) and Tschumi et al. (2008).

According to our results, higher atmospheric CO_2 concentration and enhanced westerlies act to promote NADW formation over the Nordic Seas region through vital sea ice variations, which eventually enhance the meridional density gradient. Thus, the AMOC is intensified and thereby its associated northward oceanic heat transport. At this point, in light of the above studies, the ITCZ would shift northward again and southern westerlies progressively weaken, decreasing upwelling and atmospheric CO_2. This constitutes a negative feedback that favours the return into stadial conditions through an AMOC weakening, which would lead to enhanced westerlies and higher atmospheric CO_2 concentration. As a conclusion this suggests that D/O events could be part of an internal oscillation that involves changes in CO_2, surface winds and AMOC on millennial timescales.

Acknowledgements. This work was funded by the Spanish Ministries for Environment (MARM) and Science and Innovation (MCINN) under the 200800050084028 and CGL08-06558-C02-01 projects. Research by J. Álvarez-Solas was also supported by a PICATA postdoctoral fellowship of the Moncloa Campus of International Excellence (UCM-UPM). The model simulations were performed at the Spanish Environmental Research Centre (CIEMAT) in Madrid. We are also grateful to the PalMA group for useful comments and suggestions as well as to G. Knorr and to three anonymous reviewers whose recommendations have contributed to improve the manuscript.

Edited by: G. Lohmann

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