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Simulation of Holocene cooling events in a coupled climate model

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Abstract

Three potential mechanisms behind centennial-scale Holocene cooling events are studied in simulations performed with the coupled climate model ECBilt–CLIO: (1) internal variability, (2) solar forcing, and (3) freshwater forcing. In experiments with constant preindustrial forcings, three centennial-scale cooling events occur spontaneously in 15,000 years. These rare events represent an unstable internal mode of variability that is characterised by a weaker thermohaline circulation, a more southward location of the main site of deep-water formation, expanded sea-ice cover and cooling of 10 °C over the Nordic Seas. This mode is visited more frequently when the climate is cooled by abruptly reducing the solar constant by 5 or 3 $W m^{-2}$. Prescribing a solar forcing of the same magnitude, but following a sinusoidal function with a period of 100 or 1000 years, does not result in any centennial-scale cooling events. The latter forcing does however result in more frequent individual cold years in the North Atlantic region that are related to local weakening of the deep convection and sea-ice expansion. Adding realistic freshwater pulses to the Labrador Sea is also able to trigger centennial-scale cooling events with temperature anomalies resembling proxy evidence for the cooling event at 8.2 kyr BP, suggesting that freshwater forcing is a valid explanation for early Holocene cooling events.

1. Introduction

In recent years it has become evident that the Holocene climate in the North Atlantic region experienced centennial-scale cooling events that are superimposed on the long-term orbitally forced trend. These events have been registered in a variety of proxy archives, e.g., glaciers (Denton and Karlén, 1973; Nesje and Dahl, 1993; Nesje et al., 2001), European lake sediments (Magny, 1993a, b, 1998), Atlantic Ocean sediments (Bond et al., 1997) and peat bogs (e.g., van Geel et al., 1996; Mauquoy et al., 2002). According to Bond et al. (1997, 1999), anomalous cooling occurred in the North Atlantic region around 11.1, 10.3, 9.4, 8.1, 5.9, 4.2, 2.8, 1.4 and 0.4 kyr cal BP. However, the exact timings are still under debate due to uncertainties in the age control (e.g., Rohling and Pälike, 2005). The duration of most events appears to be in the order of 100–200 years (e.g., Alley et al., 1997; van der Plicht et al., 2004; Booth et al., 2005). The magnitude of the cooling phases in the North Atlantic region was generally modest (about 0.5–1 °C), with the exception of the event just before 8 kyr BP (the '8.2 k' event) for which temperature depressions of 5 °C and 1.5 °C have been reconstructed in Greenland (Alley et al., 1997) and Central Europe (von Grafenstein et al., 1998), respectively. In this paper we present results of climate model experiments that shed light on the mechanisms behind these events.

It is important to gain a good understanding of the underlying mechanism for these climatic anomalies, as this may hold clues to the climate system's sensitivity, which is crucial in the context of the rapidly warming climate of the 21st century. Several different forcing mechanisms have been proposed. Most authors appear to favour reductions in solar irradiance as the main trigger (e.g., Denton and Karlén, 1973; Magny, 1993a, b; van Geel and Renssen, 1998; Bond et al., 2001; van der Plicht et al., 2004), except for some events early in the Holocene that have been linked to meltwater releases associated with the final deglaciation stages (e.g., the events around 10.3 and 8.2 kyr cal BP, von Grafenstein et al., 1998; Barber et al., 1999; Renssen et al., 2001; Nesje et al., 2004). A third possibility raised by model studies is that abrupt climatic cooling events could occur in the North Atlantic region without an external trigger,

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implying that they are part of the internal variability of the coupled climate system (Hall and Stouffer, 2001; Goosse et al., 2002).

The underlying mechanisms may be studied with numerical climate models (e.g., Schmidt et al., 2004). In particular, the thermohaline circulation (THC) can be easily perturbed in models by adding freshwater to the ocean surface, leading to a lower surface density and weakened deepwater formation, which results in reduced northward heat transport by the North Atlantic Ocean and significant surface cooling over adjacent continents (e.g., Maier-Reimer and Mikolajewicz, 1989; Stocker and Wright, 1991; Manabe and Stouffer, 1995; Rahmstorf, 1995, 1996; Cai et al., 1997; Schiller et al., 1997; Rind et al., 2001; Seidov et al., 2001; Renssen et al., 2002). However, most of these studies involve the perturbation of a modern climate state and only a few (Renssen et al., 2001, 2002; Bauer et al., 2004) have specifically considered the freshwater impact on the early Holocene climate.

Model simulations have also been performed to study the impact of solar forcing on climate, with many studies (e.g., Cubasch et al., 1997; Bertrand et al., 1999; Rind et al., 1999; Shindell et al., 2001a, b) focusing on the well-documented Maunder sunspot minimum (~1650–1700 AD, Eddy, 1976). For instance, Shindell et al. (2001a) used a state-of-the-art coupled general circulation model (GCM) to show that reduced solar irradiance during the Maunder Minimum could have resulted in changes in atmospheric circulation that enhanced the cooling over the Northern Hemisphere continents. In addition, models indicate that solar irradiance variations could significantly influence the behaviour of the thermohaline circulation (Cubasch et al., 1997; Goosse et al., 2002; van der Schrier et al., 2002; Weber et al., 2004).

The objective of this paper is to give an overview of the various experiments that have been performed with the ECBilt–CLIO coupled atmosphere-ocean model (Opsteegh et al., 1998; Goosse and Fichefet, 1999) to study centennial-scale climate variability. This model has a less complex atmospheric component than full-scale coupled GCMs, making it feasible to run multiple millennial-scale runs within a reasonable amount of time but without the requirement of super computing facilities. Over the past few years, a range of experiments have been performed with ECBilt–CLIO to explore the different aspects of Holocene cooling events, i.e., long-term internal variability (Goosse et al., 2002, 2003), the impacts of freshwater forcing (Renssen et al., 2001, 2002) and solar forcing (Goosse et al., 2002; Goosse and Renssen, 2004). The fact that all these simulations have been carried out with one model, gives us the opportunity to get a consistent picture of the connection between these different aspects. This enables us to present here a comprehensive 'model view' of the mechanisms behind Holocene cooling events, which has not been discussed in our previous individual papers. The discussed mechanisms could be helpful for the palaeodata community, as it gives the opportunity to place observed climatic anomalies in a physical context.

2. Model and experimental design

2.1. The model

The discussed simulations were performed with version 2 of the ECBilt–CLIO model, which describes the global coupled atmosphere-ocean system in three dimensions. The oceanic component CLIO is a primitive equation, free-surface oceanic GCM coupled to a state-of-the-art thermodynamic-dynamic sea-ice model (Goosse and Fichefet, 1999). The oceanic GCM has a horizontal resolution of 3° latitude by 3° longitude and includes 20 unevenly spaced levels in the vertical, while the sea ice model has 3 layers (Fichefet and Morales Maqueda, 1999). The atmosphere is represented by ECBilt, a quasi-geostrophic model with T21 resolution and 3 levels (Opsteegh et al., 1998). ECBilt contains a full hydrological cycle, including a simple model for soil moisture over continents, and computes synoptic variability associated with weather patterns. Cloud cover is prescribed according to modern climatology. ECBilt–CLIO includes realistic topography and bathymetry. To obtain a reasonable ocean circulation, a weak flux correction is applied, consisting of an artificial reduction of precipitation by 10% over the Atlantic Ocean and by 50% over the Arctic Ocean, and a homogeneous distribution of this removed amount over the Pacific Ocean. Further details about the model are available at http://www.knmi.nl/onderzk/CKO/ecbilt.html.

2.2. Experimental design

We discuss here the results of a range of experiments, of which the experimental design is summarised in Table 1. Two control experiments were performed in which all forcings were kept constant (i.e. equilibrium experiments). First, a 15,000-year long simulation was run with preindustrial forcings (experiment EPI1750, Goosse et al., 2002; Goosse and Renssen, 2004). Second, a 550-yr experiment was performed with 8.5 kyr cal BP conditions (experiment EHOL, Renssen et al., 2002), which include changes in orbital parameters (Berger, 1978), trace gas concentrations (Raynaud et al., 2000) and land surface characteristics such as vegetation (Adams and Fauré, 1997) and the remnant Laurentide ice sheet (Peltier, 1994). During the last 50 years of EHOL (i.e. from year 500 to 550), this simulation is very close to a quasi-equilibrium state as, for instance, the global mean ocean temperature experienced only a minor temperature trend of −0.007 °C per century (Renssen et al., 2002). The experiments EPI1750 and EHOL form the basis of the other simulations, i.e. the control states were perturbed by changing various forcings.

To study the impact of changes in solar irradiance, the preindustrial climate of EPI1750 was perturbed by adjust-

Table 1
Summary of the experiments discussed in this paper

Name	Length (years)	Description
EPI1750	15,000	Control simulation with constant pre-industrial forcing (1750 AD)
TDEC	$1\times15{,}000$, 8×1200	Transient response of the system to an abrupt decrease of solar constant of 1, 3 and $5\,\mathrm{Wm}^{-2}$ (3 members in each case, one $5\,\mathrm{Wm}^{-2}$ case is run for 15,000 years)
MIL	5000	Response to an idealised sinusoidal solar forcing with an amplitude of $3\,\mathrm{Wm}^{-2}$ and a period of 1000 years
CEN	3000	Response to an idealised sinusoidal solar forcing with an amplitude of $3\,\mathrm{Wm}^{-2}$ and a period of 100 years
EHOL	550	Control simulation with constant early Holocene forcing (8.5 kyr cal BP)
FW500	500	Response to 500-year FW pulse
FW50	5×500	Response to 50-year FW pulse (5 members)
FW20	3×500, 2×1500	Response to 20-year FW pulse (5 members)
FW10	4×500, 1×1500	Response to 10-year FW pulse (5 members)

ing the solar constant (Goosse et al., 2002; Goosse and Renssen, 2004). In the group of simulations labelled TDEC, the solar constant was abruptly reduced by 5, 3 or $1\,\mathrm{Wm}^{-2}$ during at least 1200 years. The latter experiments were repeated three times with different initial conditions (i.e. 3 ensemble members for each perturbation) to study the robustness of the results. The initial conditions for these TDEC ensemble members were taken from three states of EPI1750 separated by 250 years. One ensemble member with a $5\,\mathrm{Wm}^{-2}$ solar constant reduction was continued until a total duration of 15,000 years was reached (i.e. equivalent to EPI1750). In a second set of experiments, the solar constant was periodically varied following an idealised sinusoidal function with an amplitude of $3\,\mathrm{Wm}^{-2}$ and a period of either 100 (CEN) or 1000 years (MIL). An anomaly of $3\,\mathrm{Wm}^{-2}$ is comparable to the estimate of $-2.6\,\mathrm{Wm}^{-2}$ (or -0.2%) by Lean (2000) for the Maunder Minimum, although recent estimates for this period are more in the order of $-1\,\mathrm{Wm}^{-2}$ (or -0.08%, Lean et al., 2002; Fröhlich and Lean, 2004).

The effect of meltwater influxes was studied in the group of experiments labelled FW, in which freshwater perturbations were added to the early Holocene climate state of EHOL. The released volume of freshwater was fixed at $4.67\times10^{14}\,\mathrm{m}^3$; a value at the higher end of estimates of meltwater releases reconstructed for the 8.2 kyr cal BP event (e.g., von Grafenstein et al., 1998). The freshwater pulses were released in the Labrador Sea, which is consistent with the hypothesis that the 8.2 kyr cal BP event is associated with the final stages of the Laurentide ice sheet (e.g., Barber et al., 1999; Nesje et al., 2004). In separate experiments, the volume $4.67\times10^{14}\,\mathrm{m}^3$ freshwater was released at four different constant rates: (1) 0.03 Sv during 500 years (1 Sv is $10^6\,\mathrm{m}^3\mathrm{s}^{-1}$), (2) 0.3 Sv during 50 years, (3) 0.75 Sv during 20 years and (4) 1.5 Sv during 10 years. The experiments with 50, 20 and 10-year pulses were repeated four times (i.e. 5 ensemble members each) with different initial conditions derived from EHOL. For these 5 ensemble members, the initial conditions were obtained by taking samples at 5 year intervals from a continuation of EHOL (i.e. at years 550, 555, 560, 565 and 570).

3. Results

3.1. Internal variability under preindustrial conditions

In ECBilt–CLIO simulations with constant forcing (e.g., EPI1750), two low-frequency modes of variability have been described (Goosse et al., 2002, 2003). Both modes involve a strong increase in sea-ice cover in the Nordic Seas, anomalous cooling in the North Atlantic region and reduced northward atmospheric and oceanic transport at high northern latitudes. In addition, deep convection in the Nordic Seas is temporarily reduced. The two modes of variability can be distinguished on the basis of the duration of the anomalies and the severity of the change in deep convection. In the first mode, the deep convection in the Nordic Seas is only locally weakened during a few years to up to 3 decades (Goosse et al., 2003). In the second mode, on the other hand, an important southward shift in the main convection site occurs from the location close to Svalbard to a site near the Norwegian coast, leading to a new meta-stable state that survives between 50 and 500 years (Goosse et al., 2002). As the Holocene cooling events appear to have a duration in the order of one or two centuries, we focus in the remainder of this paper on low-frequency variability of the second type.

In experiment EPI1750, three anomalies of the mode 2 type are simulated in 15,000 years (Fig. 1, Goosse and Renssen, 2004). Consequently, under constant preindustrial forcings, this low-frequency mode of variability is spontaneously—but rarely—visited. The associated temperature anomaly has a characteristic pattern, with cooling in the Northern Hemisphere with a core of more than -10°C over the Nordic Seas, and relatively modest warming

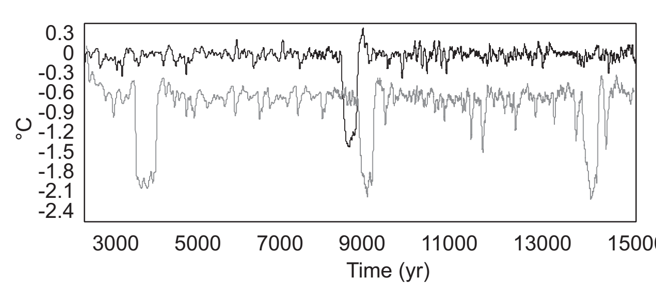

Fig. 1. Annual mean surface temperature anomaly averaged over the area North of 45°N in experiments EPI1750 (black) and TDEC5_1 (grey) (from Goosse and Renssen, 2004).

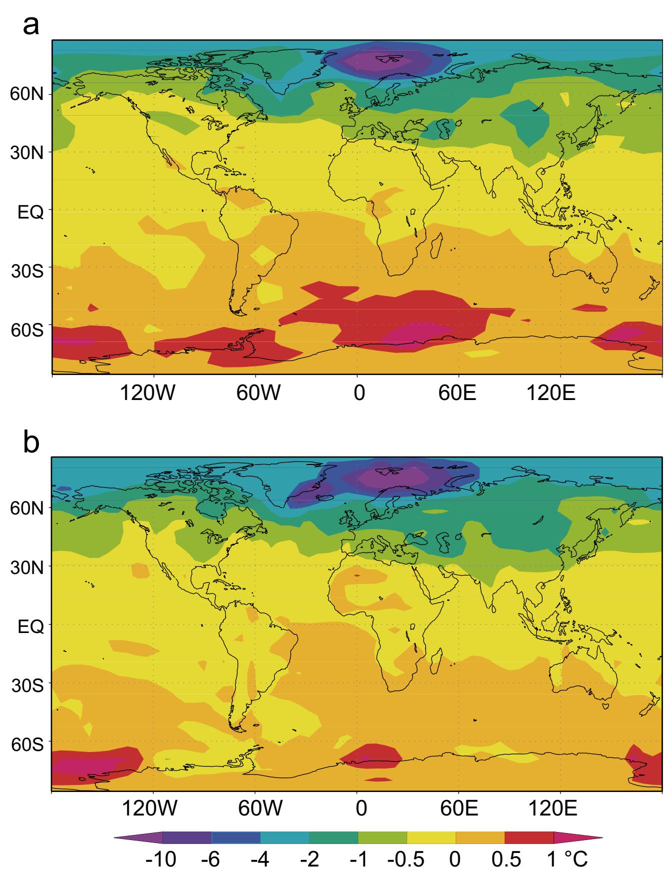

Fig. 2. (a–b) Anomaly of the annual mean surface temperature (in °C, see colour bar). Fig. 2a (top): the first large cooling event in experiment EPI1750. Shown is the difference between years 6750–6800 and 6000–6500 (From Goosse et al., 2002). Fig. 2b (bottom): cooling event triggered by freshwater forcing representative for the 8.2 k event (FW20_a). Shown is the difference between years 600-650 from FW20_a and 450–550 from EHOL.

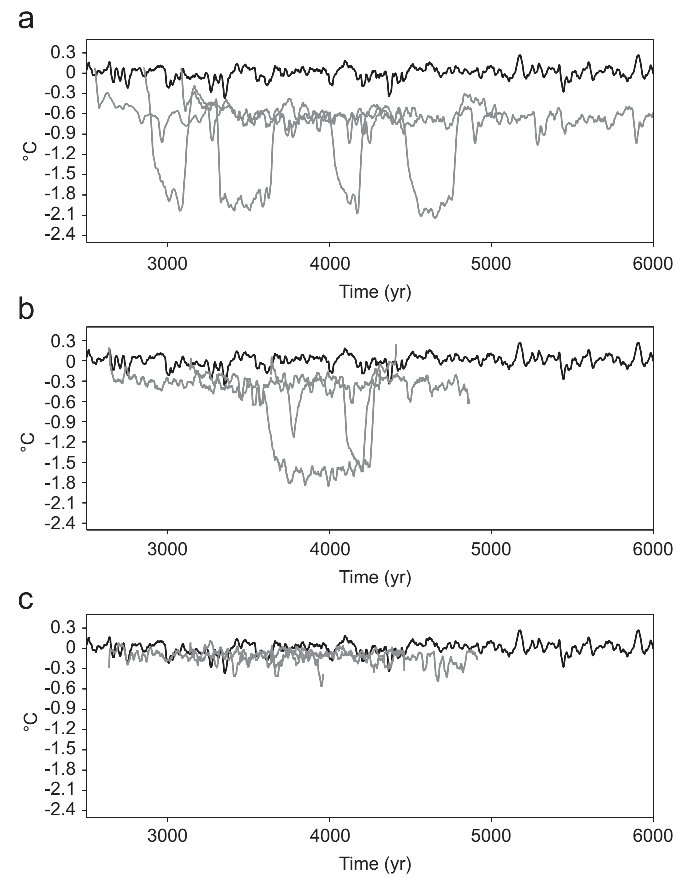

Fig. 3. (a–b) Annual mean surface temperature anomaly averaged over the area North of 45°N in experiments TDEC5 (a), TDEC3 (b) and TDEC1 (c) (from Goosse and Renssen, 2004). The black line represents the EPI1750 control experiment, while the grey lines depict the results of the 3 ensemble members for each experimental setup.

(mostly less than +1 °C) in the Southern Hemisphere (Fig. 2a, Goosse et al., 2002). The strong cooling over the Nordic Seas is associated with a local shutdown of deep convection just South of Svalbard, leading to an important reduction in the ocean-to-atmosphere heat flux in this region (by more than 100 W m^{-2}) and major expansion of the sea-ice cover. The extensive ice cover amplifies the initial cooling by two positive feedbacks, viz. the ice-albedo and ice-insulation feedbacks. The temperature reduction over land ranges from −4 °C close to the Nordic Seas over Greenland and Northern Scandinavia, to −2 to −0.5 °C over most of mid-latitude Eurasia, and −1 to −0.5 °C over Canada and Alaska.

3.2. *The impact of solar forcing*

In our model, cooling the global climate by reducing the solar constant by 5 W m^{-2} leads to a considerable increase in the frequency of centennial-scale cooling events (i.e. 7 in 15,000 years compared to 3 in EPI1750, Fig. 1). The TDEC experiments show that a 3 W m^{-2} reduction is also sufficient to trigger the events, while this is not the case with 1 W m^{-2} (Fig. 3). The events are triggered by a modification of the vertical density profile in the area where deepwater formation takes place under 'normal' conditions, i.e. South of Svalbard. At depth the density increase due to cooling is larger than at the surface. This change in the vertical density profile has been attributed to two factors (Goosse et al., 2002). First, because the region is close to the sea-ice limit, the ocean surface is not far from the freezing point, implying that the upper level temperature cannot decrease as much as at the lower levels. Second, the thermal expansion coefficient is smaller at surface than at depth because of the lower temperature. As a consequence of these processes, the water column near Svalbard becomes more stratified, preconditioning it for a local shutdown of deep convection. It is noteworthy that the time between the reduction in solar constant and the start of the cooling events varies considerably from case to case (between about 50 and 1200 years).

Although the TDEC simulations show that a reduction in solar irradiance can trigger centennial-scale cooling events in our model, it must be realised that these experiments are far from realistic, as in reality solar irradiance has not been reduced by a constant quantity for the duration of multiple centuries. Rather, proxy evidence shows that solar irradiance varies on multiple time-scales (e.g., Beer et al., 2000; Solanki et al., 2004). To study the impact of centennial and millennial-scale solar variations, Goosse and Renssen (2004) performed the CEN and MIL experiments, in which the solar constant was varied according to a sinusoidal function with an amplitude of 3 Wm^{-2}. Thus, in contrast to the TDEC experiments, in CEN and MIL the coupled system is continuously adjusting to changes in solar forcing. Goosse and Renssen (2004) find in CEN and MIL no shifts to the meta-stable state that is characteristic of centennial-scale cooling events (i.e. 2nd mode). However, CEN and MIL revealed that, during periods of reduced solar irradiance, the probability of short-lived (i.e. up to decades, 1st mode) phases with weakened deep convection in the Nordic Seas increases substantially. These short-lived events are further characterised by relatively extensive sea-ice cover and particularly cold conditions in the Nordic Seas region (Goosse and Renssen, 2004).

3.3. The impact of freshwater forcing

The FW-series of simulations show that realistic freshwater perturbations can also trigger centennial-scale cooling events in our model. This is not surprising, as an influx of freshwater in the North Atlantic reduces the surface density, leading to stratification of the surface ocean, reduced deep convection, and a weakened THC. However, the relation between freshwater forcing and THC response is complex, as the duration of this response is non-linearly related to the rate of freshwater release. In all experiments in which the fixed amount of $4.67 \times 10^{14}\,m^3$ was released in 10, 20 or 50 years, a shift to the meta-stable state (see Section 3.1) was simulated (Fig. 4). Only in the experiment with a relatively slow release rate (FW500), no significant response of the ocean circulation was found. In the set of simulations labelled FW50, the THC recovered within 200 years in all 5 ensemble members (Fig. 4). In FW20 and FW10, however, the duration of the simulated events varied between 200 and more 1200 years in individual ensemble runs, with the average duration being significantly longer in FW10 than in FW20.

In the FW simulations, the temperature response is slightly different from the events in the EPI1750 and TDEC experiments (Fig. 2b). The main difference in the spatial pattern is the cool anomaly between Iceland and Greenland in the FW experiments that is absent in the spontaneous event shown in Fig. 2a. This cooling near Iceland is caused by a cessation of deep convection here (i.e. it is a secondary site of convection in the model) due to the freshwater perturbation, combined with an expansion of sea ice in this area. In the spontaneous events only the deep convection site south of Svalbard is involved. A second difference is a cold-warm-cold fluctuation in the first decades after the freshwater pulse that is lacking in the simulated events without freshwater forcing. The warm phase in this fluctuation has been linked to a temporary influx of relatively warm and saline water, which is due to the low density of the injected anomaly, preventing it from sinking at a relatively southerly latitude (Manabe and Stouffer, 1995; Renssen et al., 2002). After the recovery of the event, the temperature evolution (Fig. 5) shows a slight 'overshoot' to anomalous warm conditions (+0.5 °C above the EHOL mean) that is also visible after the events in the EPI1750 and TDEC simulations. This overshoot is due to the release of heat that accumulated in the Atlantic Ocean at depth. The overall model response in the FW experiments is in good agreement with proxy records for the 8.2 k event (Wiersma and Renssen, 2006), showing widespread cooling in the Northern Hemisphere and relative dry conditions, especially in areas at low latitudes. The cooler North Atlantic climate in the FW experiments is in better agreement with available terrestrial data for the 8.2 ka event than the spontaneous events. For instance, over central Greenland, the FW experiments (Fig. 2b) suggest 2–4 °C cooling, while the spontaneous events only show 1–2 °C cooling (Fig. 2a), compared to about −5 °C suggested by Alley et al. (1997). This agreement supports the hypothesis that this event reflects a perturbation of the THC due to a freshwater release associated with the drainage of Laurentide Lakes.

4. Discussion

In our model, all three considered potential mechanisms (i.e. internal variability, solar forcing, and freshwater forcing) can cause centennial-scale cooling events with characteristics (duration, magnitude and distribution) that are in agreement with proxy records. However, there are important differences between the three mechanisms. By definition, the events caused by internal variability cannot be linked to any external forcing, making the timing of the events truly unpredictable. The spontaneous events require a rare concurrence of specific conditions that involve an interplay between atmosphere, sea ice and ocean. In the case of solar forcing, the reduction of solar irradiance increases the probability of a local shutdown of convection through the cooling of the atmosphere and ocean, which leads to a slow density adjustment and stratification in the main convection area. In all TDEC experiments with a 3 or 5 Wm^{-2} reduction in the solar constant, a centennial-scale cooling event occurred within 1250 years of the perturbation. Hence, the beginning of the event can be significantly delayed relative to the external forcing. In the case of freshwater forcing, on the other hand, the meltwater influx immediately reduces the surface density of the Atlantic Ocean, leading to a perturbation of the THC within two decades of the external forcing. In addition, the magnitude of the cooling is somewhat larger in the freshwater-induced events.

The spontaneous events in EPI1750 (Fig. 1) show some resemblance to the event simulated by Hall and Stouffer

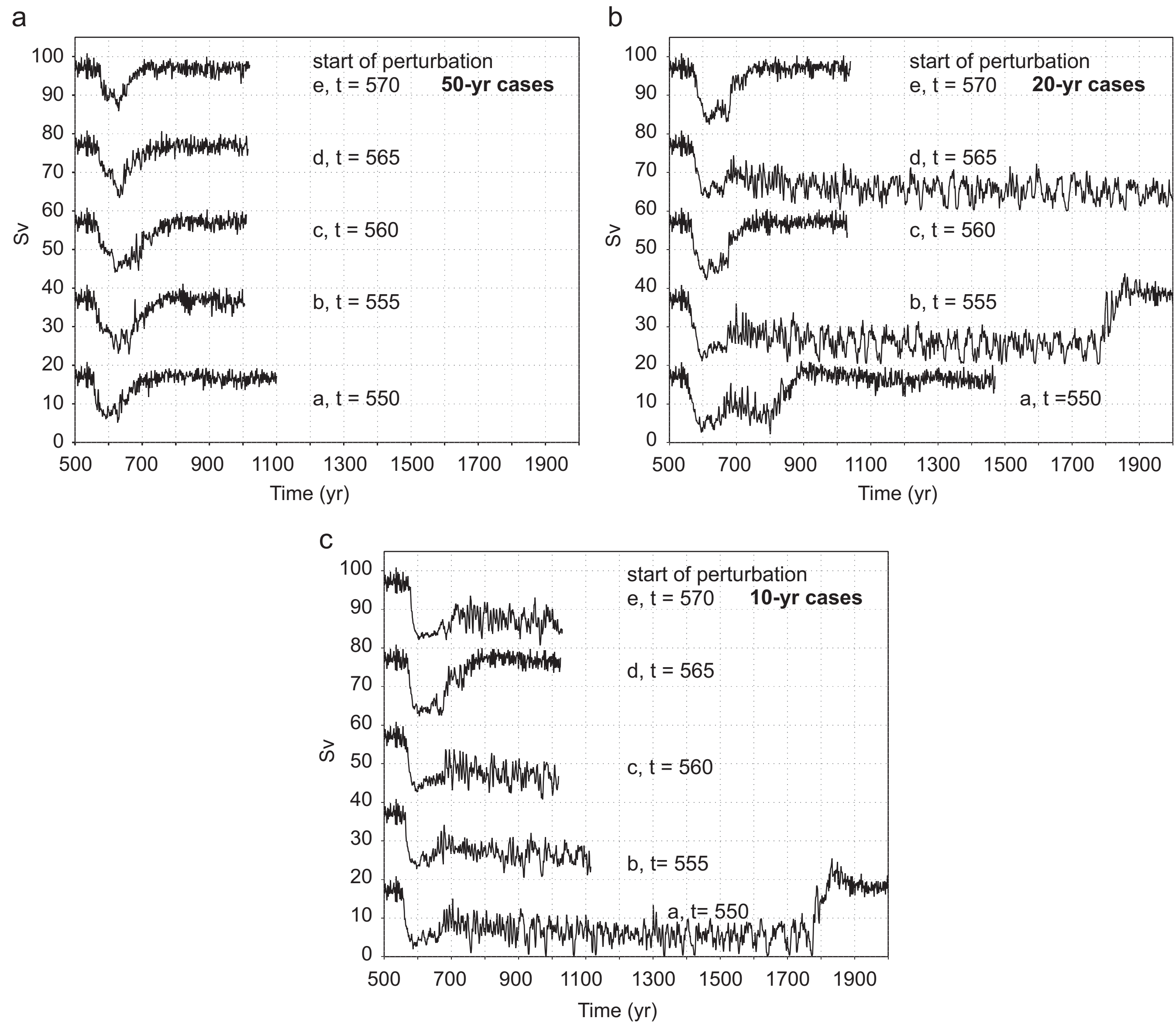

Fig. 4. Maximum meridional overturning rate (Sv) in the Nordic seas (i.e., between 60° and 80°N) plotted against time (years) for the FW experiments. (a) FW50, (b) FW20, and (c) FW10. The timing of the freshwater releases (labeled 'a' to 'e') are indicated. Note that, for convenience, values of the upper 4 curves have been elevated by 20, 40, 60, and 80 Sv (from Renssen et al., 2002).

(2001) in a 15,000-year long present-day control experiment performed with the GFDL coupled GCM. In both cases, deep convection in the North Atlantic Ocean is temporarily eliminated due to an extremely rare combination of ideal conditions in the atmosphere and ocean. Moreover, the spontaneous cold event of Hall and Stouffer (2001) lasts about 40 years (i.e. comparable to our shortest spontaneous event) and the maximum surface cooling is also more than 10 °C as in our events. However, compared to Hall and Stouffer (2001), sea ice plays a much more prominent role in our events, with northerly winds inducing a strong southward ice export out of the Barents Sea towards the main deep convection site South of Svalbard (74°N). Here it increases the stratification of the water column, preventing deep convection. In addition, the expansion of sea ice amplifies the surface cooling through the ice-albedo and ice-insulation positive feedbacks. In the model of Hall and Stouffer (2001) the main deep convection site is located in the Denmark Strait at ~63°N, implying that it is too far away from the ice margin for sea ice to play a direct role during the event. The more prominent role of sea ice expansion in our model explains why the cooling of our spontaneous events is much more widespread than reported by Hall and Stouffer (2001). In our case cooling exceeds −0.5 °C over most of the Northern Hemisphere mid- and high latitudes (Fig. 2a), while in Hall and Stouffer (2001) the cold anomaly of less than −0.5 °C is restricted to the North Atlantic region.

Regarding solar forcing, it is important to note that centennial-scale cooling events were only triggered in

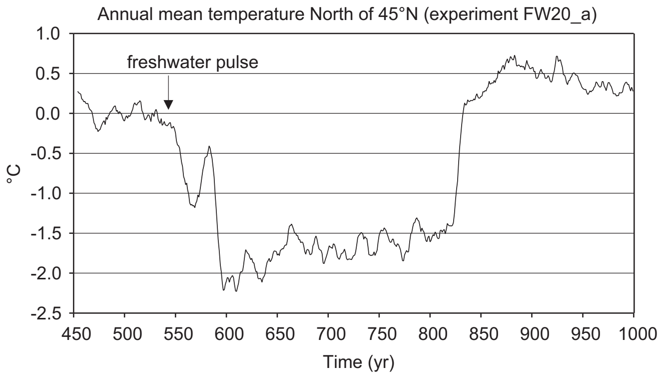

Fig. 5. Annual mean surface temperature anomaly averaged over the area North of 45°N in experiment FW20_a. Shown is the 10-year running mean result. Note the arrow for the timing of the freshwater pulse. The first 100 years represent the climate in quasi-equilibrium with early Holocene forcings (EHOL).

experiments with a highly unrealistic set-up, i.e. the solar constant reduced abruptly for several centuries. In multi-millennia simulations in which the solar forcing was varied according to a sinusoidal function with a 100-yr or 1000-yr period (CEN and MIL), no such events were simulated. This most likely implies that the probability to get a local convection shutdown (i.e. shift to mode 2) does not increase when the solar forcing varies at centennial to millennial time-scales. However, in the CEN and MIL simulations the frequency of extremely cold years with a particularly large sea-ice extent in the Nordic Seas and weakening of convection (i.e. mode 1) increased compared to EPI1750. A relatively small delay was found between the forcing and the response, as in CEN the maximum cold lagged the minimum in forcing by 23 years on average.

Besides the link between solar irradiance and climate variability discussed so far, there are several other possibilities of solar forcing of climate at centennial time-scales. As discussed in detail by Goosse and Renssen (2006), a negative correlation between solar forcing and overall THC strength has been found in modelling studies (e.g., Cubasch et al., 1997; Weber et al., 2004). When solar irradiance increases, the overall THC strength declines due to a decrease in surface density in the North Atlantic Ocean that results from a warmer surface ocean and/or higher freshwater fluxes. The high-latitude negative salinity anomalies are in turn advected southwards by the THC through the deep ocean, modifying the meridional density contrast with a delay of up to a few centuries, which amplifies the THC weakening (i.e. positive salinity-advection feedback). When solar irradiance variations have a similar time-scale (about 200 years) as this delay, they can further amplify the THC response. This was shown by Weber et al. (2004) in a 10 000-year simulation performed with the atmospheric model ECBilt coupled to a flat bottom ocean model. Consequently, part of the centennial-scale THC variability could be due to solar irradiance changes. This could not only influence the climate of the North Atlantic region, but also much further away through advection of temperature anomalies by ocean currents as shown in experiments with ECBilt–CLIO reported by Goosse et al. (2004) and Goosse and Renssen (2006). In response to an increase in solar irradiance, relatively warm deepwater could be formed in the North Atlantic Ocean, which is subsequently advected southward through the deep ocean, followed by upwelling in the Southern Ocean, causing a surface warming that is delayed in this region by 150–200 years (Goosse et al., 2004; Goosse and Renssen, 2006).

Another possibility is the modification of the atmospheric circulation by solar irradiance changes, which could in turn modify the surface ocean currents. For instance, van der Schrier and Barkmeijer (2005) applied an assimilation technique in ECBilt–CLIO to show that the specific winter sea level pressure pattern reconstructed for the Dalton Sunspot Minimum (around 1800 AD) leads to southward advection of polar waters into the north-eastern North Atlantic Ocean. In their model, this results in a lowering of the sea surface temperatures by 0.3–1.0 °C. If the reduced solar irradiance was responsible for the used sea level pressure anomaly, this would indicate that a feedback involving an interaction between atmosphere and surface ocean might amplify the climate response to solar forcing in certain regions, but this remains to be tested.

Our simulations show that freshwater perturbations of the THC offer a good explanation for early Holocene cooling events that coincide with major meltwater pulses. The best example is the 8.2 k event, for which good proxy evidence is available for both the meltwater release and the climatic response (Alley et al., 1997; von Grafenstein et al., 1998; Barber et al., 1999, Gasse, 2000; Alley and Agustdottir, 2005; Wiersma and Renssen, 2006). In addition, two earlier cooling phases around 11.1 kyr cal BP (Preboreal Oscillation) and 10.3 kyr cal BP (Erdalen event) have been linked to outbursts of meltwater into the Atlantic Ocean (e.g., Nesje et al., 2004). The magnitude of the reconstructed cooling for the 8.2 k event is larger than for later Holocene climatic anomalies, which is consistent with our simulation results that show a relatively strong cooling in response to freshwater forcing compared to the cooling in spontaneous events or those triggered by reduced solar forcing (compare Fig. 2a and 2b). As discussed by Wiersma and Renssen (2006), both proxy-data and our model results show for the 8.2 k event a cooling that is mainly concentrated in the North Atlantic region, ranging from more than 5 °C cooling in the Nordic Seas to about 0.5–1 °C over Europe and less than 0.5 °C over the subtropical North Atlantic.

Two other modelling groups have published model experiments on the 8.2 k event that confirm the idea that this event is caused by a meltwater-perturbation of the THC. First, Bauer et al. (2004) used the CLIMBER-2 coupled atmosphere-ocean-biosphere model of intermediate complexity to perform experiments with a similar setup as our simulations. However, compared to our experiments, the released freshwater pulse was considerably smaller ($1.6\times10^{14}\,m^3$ compared to $4.67\times10^{14}\,m^3$) and shorter (2 years compared to 10–500 years). With this freshwater perturbation, Bauer et al. (2004) simulate a cool event (−3.6 °C cooling) over the North Atlantic region with a duration varying between 15 and 150 years. Second, LeGrande et al. (2006) applied the coupled GCM of the Goddard Institute for Space Studies that includes a module for water isotopes and an atmosphere-only version that calculates aerosol deposition and wetland methane emissions. They were thus able to perform a multi-proxy model-data comparison for the 8.2 k event and found that a model state with a ~50% reduction in North Atlantic deepwater production provides a good match with a variety of palaeoclimate data (i.e. $\delta^{18}O$, dust, methane).

The performed solar forcing experiments do not confirm the idea that temporary reductions in solar irradiance could cause centennial-scale shifts in the THC as proposed by several authors (e.g., van Geel and Renssen, 1998; Bond et al., 2001). However, it should be noted that our model does not account for stratospheric processes. This could be important, as the impact of variations in solar irradiance on climate is thought to be amplified through the effect of UV changes on stratospheric ozone concentrations, which could modify the heat budget and circulation in the stratosphere. The resulting stratospheric anomalies could be propagated downwards to affect surface climate (Haigh, 1996; van Geel and Renssen, 1998; Shindell et al., 1999, 2001a, b). Shindell et al. (2001a), for instance, used an GCM with a complete stratosphere (including ozone-related chemistry) to show that the reduced solar irradiance during the Maunder Minimum caused a shift in the atmospheric circulation towards a more negative phase of the Arctic Oscillation, resulting in colder conditions over Northern Hemisphere continents (−1 to −2 °C in winter) in agreement with proxy data. In their model, this response was weaker in experiments without interactive ozone. Hence, possibly this stratospheric feedback is an essential element of the mechanism behind Holocene cooling events that are linked to solar forcing (e.g., the event at 2.8 kyr cal BP, van Geel et al., 1996, 1998, 2000; or the ‘Little Ice Age’, Shindell et al., 2001a; Mauquoy et al., 2002).

Alternatively, cooling events that are linked to periods of reduced solar activity do not reflect a centennial-scale THC shift (i.e. mode 2), but rather a ‘bundle’ of cold years associated with extended sea-ice cover in the Nordic Seas (i.e. mode 1). It would thus be very interesting to check if some proxy records are more sensitive to changes in the frequency of extreme events or to low frequency changes of the climate state in order to determine if the simulated changes in mode 1 provide a reasonable interpretation. This appears especially a valid option for events that are not very pronounced in proxy records, such as those dated by Bond et al. (2001) at 9.4 and 5.9 kyr cal BP. Another possibility could be that some of these events have occurred spontaneously without any link to external forcing.

It is intriguing that Bond et al. (2001) found a correlation between periods of reduced solar irradiance, as inferred from cosmogenic isotope records, and the timing of centennial-scale Holocene anomalies, including those events that coincide with a meltwater pulse (i.e. at 11.1, 10.3 and 8.2 kyr cal BP, Nesje et al., 2004). This could imply that the meltwater outbursts were actually triggered by anomalous climatic conditions related to a decrease in solar irradiance. In proxy records there are indications that this might have happened. For instance, around 10.3 kyr BP cosmogenic isotopes suggest a reduced solar radiation (Björck et al., 2001) and a general decrease in temperature has been inferred for the period before the cold spike associated with the 8.2 k event (Rohling and Pälike, 2005).

A possibility not considered so far here is that explosive volcanic eruptions may have played an important role in forcing centennial-scale climate variability. From recent events like the eruption of Mt. Pinatubo in 1991 it is well-known that single eruptions of which the plume reaches the stratosphere can have a significant effect on temperature in 2 years following an eruption (e.g., Robock and Mao, 1995). The annual mean temperature declines by 0.1–0.2 °C in the global mean (Robock and Mao, 1995). The seasonal signal, however, is more complicated. In the 2 winters following a major eruption, surface conditions tend to be warmer over Eurasia, but cooler over the Mediterranean, which is associated with a positive phase of the Arctic Oscillation. This has been observed in both data and models (e.g., Robock and Mao, 1995; Stenchikov et al., 2002; Shindell et al., 2003). The time-scale of this response makes it unlikely that single eruptions are solely responsible for Holocene centennial-scale variability. However, on a global scale, major volcanic eruptions are important to amplify the effect of other forcings (e.g., solar forcing) and the impact of clusters of explosive volcanic eruptions can extend the time-scale of their impact significantly (e.g., Crowley, 2000; Bertrand et al., 2002; Goosse et al., 2005).

5. Conclusions

We performed simulations with a coupled global climate model to explore the mechanism behind centennial-scale Holocene cooling events. Three potential mechanisms were considered: (1) solar forcing, (2) freshwater forcing and (3) internal variability. Our results suggest the following.

Our model includes a low-frequency mode of variability that has mean climatic characteristics that resemble the features reconstructed for Holocene cooling events, viz. cool conditions in the Northern Hemisphere mid- and high latitudes, drought particularly in low latitudes. This mode is associated with a local shutdown of deep convection in the Nordic Seas. With constant preindustrial forcing, this mode is visited spontaneously, but rarely (three times in 15,000 years), resulting in climatic cooling events with a duration of several decades to two centuries. Accordingly, it is possible that some of the Holocene cooling events found in proxy records occurred spontaneously and cannot be linked to any external forcing.

Shifts to the mode of low-frequency variability can be triggered by freshwater influxes into the North Atlantic Ocean. Perturbations of the thermohaline circulation by freshwater outbursts provide a sensible mechanism to explain centennial-scale cooling events in the early Holocene such as the 8.2 k event. The simulated climate response was in agreement with available proxy evidence with respect to the duration (few hundred years), distribution and magnitude.

Our solar forcing experiments cannot provide decisive support for the hypothesis that temporary reductions in solar forcing caused centennial-scale cooling events during the Holocene. We found that it is in principle possible to trigger a local convection shutdown by reducing the radiative forcing, but only when using an experimental set-up that is highly unrealistic (i.e. with an abrupt, prolonged reduction in solar constant). More realistic experiments with idealised time-varying solar forcing did not produce centennial-scale cooling events. This could be related to the fact that our model lacks representation of stratospheric processes. An alternative explanation is that cooling events that have been associated with reduced solar activity reflect an increase in the frequency of particularly cold years rather than a centennial-scale shift in the mode of the ocean circulation.

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References

Adams, J.M., Fauré, H. (Eds.), 1997. Review and atlas of palaeovegetation: preliminary land ecosystem maps of the world since the Last Glacial Maximum. Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Alley, R.B., Agustdottir, A.M., 2005. The 8 k event: cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews 24, 1123–1149.

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability—a prominent, widespread event 8200 yr ago. Geology 25, 483–486.

Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M.D., Gagnon, J.-M., 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. Nature 400, 344–348.

Bauer, E., Ganopolski, A., Montoya, M., 2004. Simulation of the cold climate event 8200 years ago by meltwater outburst from Lake Agassiz. Paleoceanography 19, PA3014, doi:10.1029/2004PA001030.

Beer, J., Mende, W., Stellmacher, R., 2000. The role of the sun in climate forcing. Quaternary Science Reviews 19, 403–415.

Berger, A.L., 1978. Long-term variations of caloric insolation resulting from the earth's orbital elements. Quaternary Research 9, 139–167.

Bertrand, C., van Ypersele, J.-P., Berger, A., 1999. Volcanic and solar impacts on climate since 1700. Climate Dynamics 15, 355–367.

Bertrand, C., Loutre, M.-F., Crucifix, M., Berger, A., 2002. Climate of the last millennium: a sensitivity study. Tellus 54A, 221–244.

Björck, S., Muscheler, R., Kromer, B., Heinemeier, J., Johnsen, S.J., Andresen, C.S., Conley, D., Koc, N., Spurk, M., Veski, S., 2001. High-resolution analyses of an early Holocene climate event may imply decreased solar forcing as an important climate trigger. Geology 29, 1107–1110.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates. Science 278, 1257–1266.

Bond, G.C., Showers, W., Elliot, M., Evans, M., Lotti, R., Hajdas, I., Bonani, G., Johnsen, S., 1999. The North Atlantic's 1–2 kyr climate rhythm: relation to Heinrich events, Dansgaard/Oeschger cycles and the Little Ice Age. AGU Geophysical Monograph 112, 35–58.

Bond, G.C., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 2130–2133.

Booth, R.K., Jackson, S.T., Forman, S.L., Kutzbach, J.E., Bettis III, E.A., Kreig, J., Wright, D.K., 2005. A severe centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages. The Holocene 15, 321–328.

Cai, W., Sytkus, J., Gordon, H.B., O'Farrell, S., 1997. Response of a global coupled ocean-atmosphere-sea ice climate model to an imposed North Atlantic high-latitude freshening. Journal of Climate 10, 929–948.

Crowley, T.J., 2000. Causes of climate change over the last 1000 years. Science 289, 270–277.

Cubasch, U., Voss, R., Hegerl, G.C., Waszkewitz, J., Crowley, T.J., 1997. Simulation of the influence of solar radiation variations on the global climate with an ocean-atmosphere general circulation model. Climate Dynamics 13, 757–767.

Denton, G.H., Karlén, W., 1973. Holocene climatic variations-Their pattern and possible causes. Quaternary Research 3, 155–205.

Eddy, J.A., 1976. The Maunder minimum. Science 192, 1189–1202.

Fichefet, T., Morales Maqueda, M.A., 1999. Modelling the influence of snow accumulation and snow-ice formation on the seasonal cycle of the Antarctic sea-ice cover. Climate Dynamics 15, 251–268.

Fröhlich, C., Lean, J., 2004. Solar radiative output and its variability: evidence and mechanisms. Astronomy and Astrophysics Review 12, 273–320.

Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. Quaternary Science Reviews 19, 189–211.

Goosse, H., Fichefet, T., 1999. Importance of ice-ocean interactions for the global ocean circulation: a model study. Journal of Geophysical Research 104, 23,337–23,355.

Goosse, H., Renssen, H., Selten, F.M., Haarsma, R.J., Opsteegh, J.D., 2002. Potential causes of abrupt climate events: a numerical study with a three-dimensional climate model. Geophysical Research Letters 29, 1860.

Goosse, H., Selten, F.M., Haarsma, R.J., Opsteegh, J.D., 2003. Large sea-ice volume anomalies simulated in a coupled climate model. Climate Dynamics 20, 523–536.

Goosse, H., Masson-Delmotte, V., Renssen, H., Delmotte, M., Fichefet, T., Morgan, V., van Ommen, T., Khim, B.K., Stenni, B., 2004. A late medieval warm period in the Southern Ocean as a delayed response to external forcing? Geophysical Research Letters 31, L06203.

Goosse, H., Renssen, H., Timmermann, A., Bradley, R.S., 2005. Internal and forced climate variability during the last millennium: a model-data comparison using ensemble simulations. Quaternary Science Reviews 24, 1345–1360.

Goosse, H., Renssen, H., 2004. Exciting natural modes of variability by solar and volcanic forcing: idealized and realistic experiments. Climate Dynamics 23, 153–163.

Goosse, H. and Renssen, H., 2006. Regional response of the climate system to solar forcing: the role of the ocean. Space Science Reviews 125, 227–235.

Hall, A., Stouffer, R.J., 2001. An abrupt climate event in a coupled ocean-atmosphere simulation without external forcing. Nature 409, 171–174.

Haigh, J.D., 1996. The impact of solar variability on climate. Science 272, 981–984.

Lean, J., 2000. Evolution of the Sun's Spectral Irradiance since the Maunder Minimum. Geophysical Research Letters 27, 2425–2428.

Lean, J.L., Wang, Y.M. and Sheeley, N.R., 2002. The effect of increasing solar activity on the Sun's total and open magnetic flux during multiple cycles: Implications for solar forcing of climate. Geophysical Research Letters 29, Art. No. 2224.

LeGrande, A.N., Schmidt, G.A., Shindell, D.T., Field, C.V., Miller, R.L., Koch, D.M., Faluvegi, G., Hoffmann, G., 2006. Consistent simulations of multiple proxy responses to an abrupt climate change event. Proceedings of the National Academy of Sciences 103, 837–842.

Magny, M., 1993a. Solar influences on Holocene climatic changes illustrated by correlations between past lake-level fluctuations and the atmospheric ^{14}C record. Quaternary Research 40, 1–9.

Magny, M., 1993b. Holocene fluctuations of lake levels in the French Jura and sub-Alpine ranges, and their implications for past general circulation patterns. The Holocene 3, 306–313.

Magny, M., 1998. Reconstruction of Holocene lake-level changes in the French Jura: methods and results. In: Harrison, S., Frenzel, B., Huckriede, U., Weiss, M.M. (Eds.), Palaeohydrology as reflected in lake level changes as climatic evidence for Holocene times. Gustav Fischer Verlag, Stuttgart, pp. 67–85.

Maier-Reimer, E. and Mikolajewicz, U., 1989. Experiments with an OGCM on the cause of the Younger Dryas. Max Planck Institut für Meteorologie report no. 39, Hamburg, 13 pp.

Manabe, S., Stouffer, R.J., 1995. Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. Nature 378, 165–167.

Mauquoy, D., van Geel, B., Blaauw, M., van der Plicht, J., 2002. Evidence from northwest European bogs shows 'Little Ice Age' climatic changes driven by variations in solar activity. The Holocene 12, 1–6.

Nesje, A., Dahl, S.O., 1993. Lateglacial and Holocene glacier fluctuations and climate variations in Western Norway: a review. Quaternary Science Reviews 12, 255–261.

Nesje, A., Matthews, J.A., Dahl, S.O., Berrisford, M.S., Andersson, C., 2001. Holocene glacier fluctuations of Flatebreen and winter-precipitation changes in the Jostedalsbreen, western Norway, based on glaciolacustrine sediment records. The Holocene 11, 267–280.

Nesje, A., Dahl, S.O., Bakke, J., 2004. Were abrupt Lateglacial and early-Holocene climate changes in NW Europe linked to freshwater outbursts to the North Atlantic and Arctic Oceans? The Holocene 14, 299–310.

Opsteegh, J.D., Haarsma, R.J., Selten, F.M., Kattenberg, A., 1998. ECBILT: A dynamic alternative to mixed boundary conditions in ocean models. Tellus A 50, 348–367.

Peltier, W.R., 1994. Ice age paleotopography. Science 265, 195–201.

Rahmstorf, S., 1995. Bifurcations of the Atlantic thermohaline circulation in reponse to changes in the hydrological cycle. Nature 378, 145–149.

Rahmstorf, S., 1996. On the freshwater forcing and transport of the Atlantic thermohaline circulation. Climate Dynamics 12, 799–811.

Raynaud, D., Barnola, J.-M., Chappellaz, J., Blunier, T., Indermühle, A., Stauffer, B., 2000. The ice record of greenhouse gases: a view in the context of future changes. Quaternary Science Reviews 19, 9–17.

Renssen, H., Goosse, H., Fichefet, T., Campin, J.-M., 2001. The 8.2 kyr BP event simulated by a global atmosphere–sea-ice–ocean model. Geophysical Research Letters 28, 567–570.

Renssen, H., Goosse, H., Fichefet, T., 2002. Modeling the effect of freshwater pulses on the early Holocene climate: the influence of high frequency climate variability. Paleoceanography 17, 1020, doi:10.1029/2001PA000649.

Rind, D., Lean, J., Healy, R., 1999. Simulated time-dependent climate response to solar radiative forcing since 1600. Journal of Geophysical Research 104, 1973–1990.

Rind, D., Demenocal, P., Russell, G.L., Sheth, S., Collins, D., Schmidt, G.A., Teller, J., 2001. Effects of glacial meltwater in the GISS coupled atmosphere-ocean model: Part I: North Atlantic Deep Water Response. Journal of Geophysical Research 106, 27335–27353.

Robock, A., Mao, J., 1995. The volcanic signal in surface temperature observations. Journal of Climate 8, 1086–1103.

Rohling, E.J., Pälike, H., 2005. Centennial-scale climate cooling with a sudden cold event around 8200 years ago. Nature 434, 975–979.

Schiller, A., Mikolajewicz, U., Voss, R., 1997. The stability of the North Atlantic thermohaline circulation in a coupled ocean-atmosphere general circulation model. Climate Dynamics 13, 325–347.

Schmidt, G.A., Shindell, D.T., Miller, R.L., Mann, M.E., Rind, D., 2004. General circulation modelling of Holocene climate variability. Quaternary Science Reviews 23, 2167–2181.

Seidov, D., Barron, E., Haupt, B.J., 2001. Meltwater and the global conveyor: northern versus southern connections. Global and Planetary Change 30, 257–270.

Shindell, D., Rind, D., Balachandran, N., Lean, J., Lonergan, P., 1999. Solar cycle variability, ozone, and climate. Science 284, 305–308.

Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., Waple, A., 2001a. Solar forcing of regional climate change during the Maunder Minimum. Science 294, 2149–2152.

Shindell, D.T., Schmidt, G.A., Miller, R.L., Rind, D., 2001b. Northern Hemisphere winter climate response to greenhouse gas, ozone, and volcanic forcing. Journal of Geophysical Research 106, 7193–7210.

Shindell, D.T., Schmidt, G.A., Miller, R.L., Mann, M.E., 2003. Volcanic and solar forcing of climate change during the Preindustrial era. Journal of Climate 16, 4094–4107.

Solanki, S.K., Usoskin, I.G., Kromer, B., Schüssler, M., Beer, J., 2004. Unusual activity of the sun during recent decades compared to the previous 11,000 years. Nature 431, 1084–1087.

Stenchikov, G., Robock, A., Ramaswamy, V., Schwartzkopf, M.D., Hamilton, K., and Ramachandran, S., 2002. Arctic Oscillation response to the 1991 Pinatubo eruption: effect of volcanic aerosols and ozone depletion. Journal of Geophysical Research 107, paper no. 4803, doi:10.1029/2002JD002090.

Stocker, T.F., Wright, D.G., 1991. Rapid transitions of the ocean's deep circulation induced by changes in surface water fluxes. Nature 351, 729–732.

van der Plicht, J., van Geel, B., Bohncke, S.J.P., Bos, J.A.A., Blaauw, M., Speranza, A.O.M., Muscheler, R., Björck, S., 2004. The Preboreal climate reversal and a subsequent solar-forced climate shift. Journal of Quaternary Science 19, 263–269.

van der Schrier, G., Barkmeijer, J., 2005. Bjerknes' hypothesis on the coldness during AD 1790–1820 revisited. Climate Dynamics 25, 537–553.

van der Schrier, G., Weber, S.L., Drijfhout, S.S., 2002. Sea level changes in the North Atlantic by solar forcing and internal variability. Climate Dynamics 19, 435–447.

van Geel, B., Buurman, J., Waterbolk, H.T., 1996. Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatological teleconnections around 2650 BP. Journal of Quaternary Science 11, 451–460.

van Geel, B., van der Plicht, J., Kilian, M.R., Klaver, E.R., Kouwenberg, J.H.M., Renssen, H., Reynaud-Farrera, I., Waterbolk, H.T., 1998. The sharp rise of ^{14}C around 800 cal BC: possible causes, related climatic teleconnections and the impact on human environments. Radiocarbon 40, 535–550.

van Geel, B., Heusser, C.J., Renssen, H., Schuurmans, C.J.E., 2000. Climate change in Chile at around 2700 BP and global evidence for solar forcing. The Holocene 10, 659–664.

van Geel, B., Renssen, H., 1998. Abrupt climate change around 2650 BP in North-West Europe: evidence for climatic teleconnections and a tentative explanation. In: Issar, A.S., Brown, N. (Eds.), Water, environment and society in times of climatic change. Kluwer, Dordrecht, pp. 21–41.

von Grafenstein, U., Erlenkeuser, H., Müller, J., Jouzel, J., Johnsen, S., 1998. The cold event 8200 years ago documented in oxygen isotope records of precipitation in Europe and Greenland. Climate Dynamics 14, 73–81.

Weber, S.L., Crowley, T.J., van der Schrier, G., 2004. Solar irradiance forcing of centennial climate variability: linear and nonlinear responses in a coupled model. Climate Dynamics 22, 539–553.

Wiersma, A.P., Renssen, H., 2006. Model-data comparison for the 8.2 ka BP event: confirmation of a forcing mechanism by catastrophic drainage of Laurentide Lakes. Quaternary Science Reviews 25, 63–88.