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Amplification of Holocene multicentennial climate forcing by mode transitions in North Atlantic overturning circulation

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[1] Using a three-dimensional global climate model, we show that mode-transitions in North Atlantic deep-water production can provide an amplifying mechanism of relatively weak climate perturbations during the Holocene. Under pre-industrial boundary conditions, a freshwater forcing in the Labrador Sea pushes the North Atlantic overturning circulation into a deterministically bistable regime, characterized by stochastic "on" and "off" switches in Labrador Sea convection. On a multicentennial time-scale these stochastic mode-transitions can be phase-locked by a small (subthreshold) periodic freshwater forcing. The local small periodic forcing is effectively amplified with the assistance of noise, to have a large-scale impact on North Atlantic overturning circulation and climate. These results suggest a stochastic resonance mechanism that can operate under Holocene boundary conditions and indicate that changes in the three-dimensional configuration of North Atlantic deep-water formation can be an important component of multicentennial climate variability during interglacials.
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1. Introduction

[2] During the Holocene, the North Atlantic climate has experienced pronounced variability at multicentennial time-scales. Important evidence comes from drift-ice deposits measured in deep ocean cores, showing multicentennial-scale fluctuations that have been interpreted as a series of southward shifts of Labrador Sea surface waters, accompanied by cooler ocean surface temperatures [*Bond et al.*, 2001; *Bond et al.*, 1999]. The drift-ice proxy correlates with reconstructed production rates of cosmogenic isotopes, which in turn has been taken as evidence of persistent solar influence on the North Atlantic Holocene climate [*Bond et al.*, 2001]. However, the direct effect of solar irradiance variations is considered too small to explain the observed climate variability in the Holocene [*Rind*, 2002]. Accordingly, an amplifying mechanism is required to explain multicentennial Holocene climate variability driven by a solar forcing.

[3] Here we test the hypothesis [*Bond et al.*, 2001] that changes in North Atlantic deep-water production can provide an amplifying mechanism of relatively weak climate perturbations during interglacials. We will show that under Holocene boundary conditions there exists a regime where noise-assisted state-transitions between modes of Atlantic overturning can be phase-locked by a small (subthreshold) multicentennial periodic forcing, leading to an amplified hemispheric-scale response.

2. Experimental Design

[4] ECBilt-Clio is a three-dimensional fully coupled atmosphere-ocean model. It consists of a $3^\circ \times 3^\circ$-resolution, 20 level, primitive equation, free-surface ocean general circulation model coupled to a thermodynamic-dynamic sea-ice model [*Goosse and Fichefet*, 1999] and a spectral T21 three level quasi-geostrophic atmospheric model [*Opsteegh et al.*, 1998]. For a more extensive description of ECBilt-Clio see www.knmi.nl/onderzk/CKO/ecbiltdescription.html. The intrinsic high-frequency noise [*Hasselmann*, 1976] of this coupled climate model results from the interactions of deterministic processes and in general is neither white nor independent of the climate state. As such it cannot be modified, which would allow for a more traditional approach to demonstrate stochastic resonance behavior [*Gammaitoni et al.*, 1998]. For pre-industrial boundary conditions this model captures the two main deep convection sites in the modern North Atlantic. Consistent with observations, stable deep convection occurs in the Labrador Sea and in the Nordic Seas [*Schulz et al.*, 2007, Figure 2a].

[5] When a weak, constant freshwater flux is added to the surface of the Labrador Sea, the stable Atlantic meridional overturning circulation gives way to bistable behavior on a centennial to millennial timescale [*Schulz et al.*, 2007]. In these sensitivity experiments (Figure 1), the Atlantic meridional overturning circulation shows state transitions with random timing upon constant Labrador Sea freshwater forcings of 5 mSv, 7.5 mSv and 10 mSv respectively ($1\ \mathrm{Sv} \equiv 10^6\ \mathrm{m}^3\ \mathrm{s}^{-1}$, for comparison: Greenland's largest glacier roughly discharges 1 mSv [*Thomas et al.*, 2003]). Transitions between the strong state and the weak state in Figure 1 are characterized by "on"/"off" switches in Labrador Sea convection [*Schulz et al.*, 2007, Figure 2].

[6] Neither 5 mSv nor 10 mSv freshwater fluxes are strong enough to force the Labrador Sea convection into a continuous "off"-mode (Figures 1a and 1c). With increasing magnitude of the freshwater forcing the probability for the system to occupy the weak state rises. However, in each experiment both the strong and weak overturning states are at some point occupied over a prolonged period of time on

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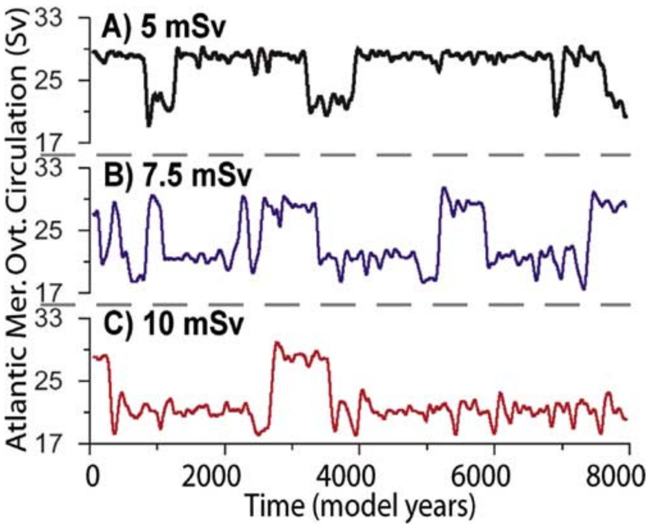

Figure 1. A constant Labrador Sea freshwater forcing of 5 mSv, 7.5 mSv, and 10 mSv, respectively, pushes the Atlantic meridional overturning circulation (AMOC) into a bistable regime, leading to random switches between a strong (29 Sv) and a weak (21 Sv) state. The weak state is associated with lack of convection in the Labrador Sea [cf. *Schulz et al.*, 2007, Figure 2]. With increasing magnitude of the freshwater forcing, the probability for the system to occupy the weak state rises, but apparently the system remains in the deterministically bistable regime over the whole range of applied forcings. (The time series shown are smoothed with a 101-year Hanning filter).

the order of 1000 years. Therefore we presume that the system remains in a deterministically bistable regime over the whole range of the applied forcings.

[7] To investigate whether these multicentennial state transitions are susceptible to small external forcings, we applied a periodically fluctuating freshwater forcing to the Labrador Sea instead of a constant forcing. This freshwater flux was varied sinusoidally between 5 and 10 mSv with a period of 500 years, corresponding to the salient 400–500 year timescale of observed drift ice fluctuations in the Holocene [*Bond*, 2005; *Bond et al.*, 2001]. This forcing is of the same order of magnitude as the yearly precipitation over that area [*Schulz et al.*, 2007]. More importantly, we note that the amplitude of the periodic forcing is sufficiently small to keep the system always in the bistable regime (Figure 1). Accordingly, we consider the periodic forcing as "small" since additional noise is required to trigger the individual state switches. For technical details on the model set-up, the experimental design and the statistical analysis, see the auxiliary material.[1]

3. Noise-Assisted Amplification of External Forcing

[8] In 12,000 model-years, the Atlantic meridional overturning circulation made 10 transitions to the weaker mode (Figure 2). A Rayleigh test (see auxiliary material) shows that the timing of the mode-transitions is significantly ($p < 0.05$) phase-locked with the periodic forcing (Figure 3). Accordingly the response of the system to the forcing occurs approximately at integer multiples of the forcing period. Effectively the local small periodic forcing is amplified to a hemispheric scale. In this sense the response of the climate system is deterministic. However, since the system remains in the bistable regime, it is the inherent noise that triggers the individual state switches.

[9] Intuitively, noise might be expected to weaken or obscure regular signals. However, in non-linear systems such as the climate system the presence of noise can provide a crucial mechanism for the system to explore its possible states [*Nicolis and Nicolis*, 1981]. Consequently, the timing of the state switches has a stochastic component, reflected by the spread of the vectors in Figure 3 and by the fact that not every extreme of the forcing leads to a state switch (Figure 2). The response of the Atlantic meridional overturning circulation to the periodic forcing is both deterministic and stochastic (i.e., "quasi-deterministic" [*Freidlin and Wentzell*, 1998]).

[10] Noise-assisted amplification of a small periodic forcing is a stochastic resonance phenomenon [*Benzi et al.*, 1981]. It has been shown that on an "interval of resonance" (a set of scale parameters for which chaotic or trivial behavior of the system is excluded), there must exist a stochastic resonance point [*Herrmann and Imkeller*, 2005]. The lower limit of this interval of resonance, below which the system remains practically in one of the states, coincides with a minimum exponential timescale for quasi-deterministic behavior [*Freidlin and Wentzell*, 1998; *Freidlin*, 2000]. The upper limit of this interval refers to a situation where the system switches chaotically between states. By showing prolonged but finite noise-assisted mode transitions that are significantly deterministic we argue that the modeled climate system operates on this interval of resonance, implying that a stochastic resonance mechanism can be operational during the Holocene.

4. Paleoclimatic Context

[11] As shown above, the modeled transitions of the large-scale ocean circulation follow the beat of the forcing (Figure 3), but sometimes one or more beats are "skipped" (Figure 2). Based on such characteristic skipping of beats in paleoclimatic records of the last glacial, it has been argued [*Alley et al.*, 2001] that stochastic resonance in the North Atlantic could be responsible for the millennial-scale regularity of abrupt glacial climate fluctuations. Such a mechanism has been simulated by *Ganopolski and Rahmstorf* [2002], involving state-switches in the Atlantic Ocean circulation causing warm ("interstadial") climate excursions under glacial climate conditions. However, the 2-dimensional zonally averaged Atlantic Ocean in their model did not exhibit stochastic resonance under Holocene climate conditions. In contrast, using a 3-dimensional model that captures the main convection sites we infer that a different stochastic resonance mechanism, involving both "on" and "off" switches of a bistable Labrador Sea convection, can be operational during the Holocene.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL030642.

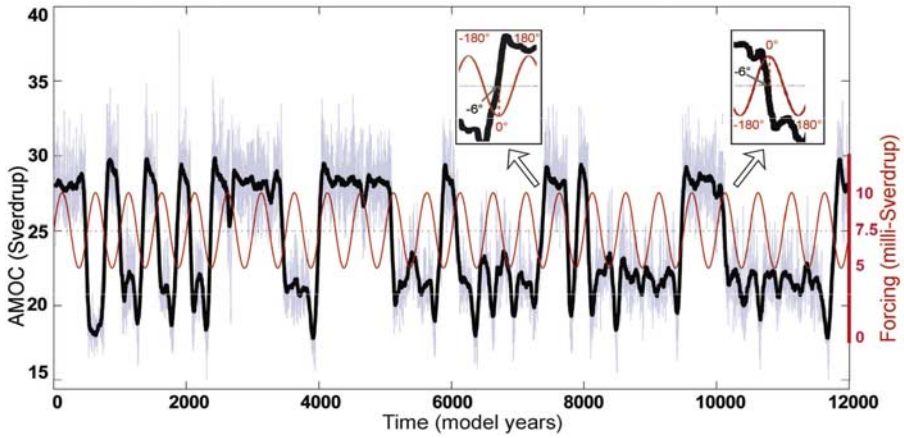

Figure 2. State transitions in Atlantic meridional overturning circulation (AMOC) with periodic freshwater forcing in the Labrador Sea. The 73-year running mean (black) of the AMOC (light blue) shows multicentennial state transitions. The superimposed sine function (red) represents the external small periodic freshwater forcing in the Labrador Sea (note 1000 times amplified, scale on the right). The absolute timing of a state switch is defined as the model-year in which the running mean of the Atlantic meridional overturning circulation crosses the 25 Sv line (dashed). The state switches, associated with "on" and "off" modes in Labrador Sea convection, follow the beat of the forcing, but sometimes beats are skipped. In order to evaluate whether this phase locking is statistically significant (Figure 3), the relative timing of each "off"-switch is defined as a phase difference with the nearest forcing-maximum. (right inset) For example, the event at year 10,116 has a phase lag of $-6°$ with the forcing that peaks at year 10,125 ((-9 yr/500 yr) $\times$ 360°). (left inset) Likewise the timing of each "on"-switch is defined as a phase difference with the nearest forcing-minimum (see auxiliary material for details).

[12] Although we have demonstrated noise-assisted phase locking between external forcing and transitions of the large-scale ocean circulation state, we can not conclude that the system preferentially responds to a forcing with a 500 year period. However, finding the stochastic resonance point (i.e., the timescale at which the system response is maximum) is not our intention here. Rather, the purpose of our study is to illustrate that the climate system is capable of amplifying a weak external forcing at a multicentennial timescale, as proposed by *Bond et al.* [2001].

[13] The relationship between fluctuations in solar activity, cosmogenic isotope production, and global climate is still under discussion [*Braun et al.*, 2005] and has been studied previously using the same model [*Goosse and Renssen*, 2006; *Renssen et al.*, 2006]. There is no evidence for a strong effect on the hydrologic cycle, whereas subtle fluctuations cannot be ruled out. The small periodic forcing has a 7.5 mSv constant baseline, which shifts the system into the bistable regime. Although this value might be model-dependent, several modeling studies [cf. *Kuhlbrodt et al.*, 2001; *Wood et al.*, 1999] suggest that the Labrador Sea operates robustly close to the border between the bistable and the monostable regime. We note that a 10-mSv fresh water flux into the Labrador Sea would be a very conservative estimate of what might be expected from a shrinking Greenland ice sheet [*Gregory and Huybrechts*, 2006].

[14] Paleoceanographic data also suggests that the Labrador Sea operates in or close to the bistable regime and exhibits state-switching behavior on a multicentennial timescale during the Holocene. *Hillaire-Marcel et al.* [2001] report pervasive millennial scale oscillations in Labrador Sea surface water density. Even though the resolution of the record is insufficient to capture the variability in Labrador Sea deep-water formation found in the model, the data suggest 11 state-switches (5 centennial-scale convection

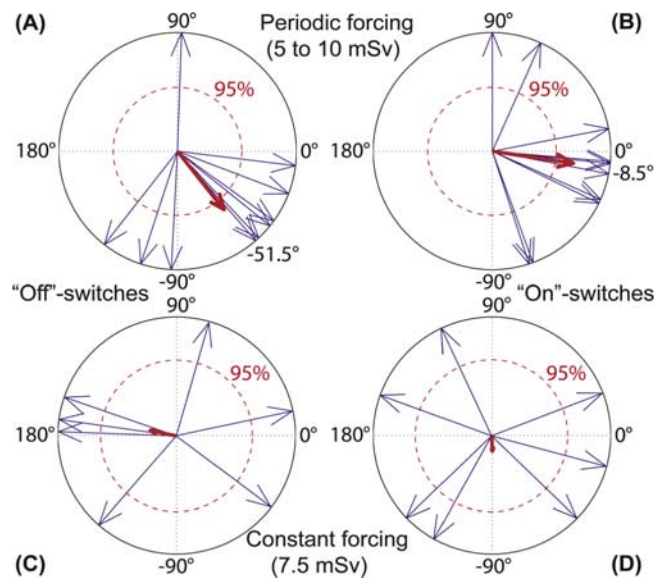

Figure 3. Statistical significance of the phase locking between the periodic forcing and the state-transitions in overturning circulation. The timing of the "off"- and "on"-switches relative to the phase of the forcing can be mapped as vectors in a unit circle (see Figure 2 (insets) and auxiliary material). For random timing of the transitions, the lengths of the averaged vectors (bold arrows) would tend to zero. In the (top) periodically forced run the average vectors of both (left) the "off"-switches and (right) the "on"-switches exceed a critical length (dashed circles), indicating a significant ($p <$ 0.05, n = 10) phase locking between the periodic forcing and the timing of the events. In the (bottom) control experiment with 7.5 mSv constant forcing (see Figure 1b) the lengths of the mean vectors stay well below the significance level, indicating that the timing of the state-switches cannot be predicted.

"on" states) during the Holocene [*Hillaire-Marcel et al.*, 2001, Figure 4g]. The magnitudes of the surface salinity and density variations in the Labrador Sea [*Hillaire-Marcel et al.*, 2001, Figure 4] are similar to the changes accompanying a state-shift in the model [*Schulz et al.*, 2007, Figures 4 and 6].

[15] On the other hand *Hillaire-Marcel et al.* [2001] deduce that similar oscillations in sea-surface salinity were not accompanied by Labrador Sea convection during the previous interglacial [*Hillaire-Marcel et al.*, 2001, Figure 4h]. This would mean that state-switches in Labrador Sea convection could not be the cause but at best the result of the "pervasive sea-surface salinity oscillations" which they link to the millennial-scale cyclicity described by *Bond et al.* [1999, 2001]. This would imply yet another, unknown, amplifying mechanism would be responsible for these oscillations. However, given the limitations of dinoflagellate cyst transfer functions in regards to sea-surface salinity reconstructions [*Telford*, 2006], this inference requires further scrutiny. Exploring the model behavior under previous interglacial boundary conditions could be the subject of future study.

5. Conclusions

[16] Our results indicate that under Holocene climate conditions there exists a regime were plausibly small (subthreshold) periodic freshwater forcings can lead to a phase-locked response in both "off" and "on" switches. In this regime, small climatic perturbations operating on a multicentennial timescale can be amplified into hemispheric-scale climate cycles. This noise-assisted amplification mechanism involves a reorganization of deep-water formation sites, characterized by local strengthening or weakening of deep convection. Hence our results support Bond et al.'s [*Bond*, 2005; *Bond et al.*, 2001] hypothesis on the existence of a multicentennial scale amplifying mechanism involving ocean-atmosphere interactions that can operate under interglacial (Holocene) conditions.

References

Alley, R. B., et al. (2001), Stochastic resonance in the North Atlantic, *Paleoceanography*, *16*, 190–198.

Benzi, R., et al. (1981), The mechanism of stochastic resonance, *J. Phys. A Math. Gen.*, *14*, L453–L457.

Bond, G. (2005), Are Dansgaard-Oeschger cycles and multicentennial cycles of the Holocene and the last glacial interconnected?, *Geophys. Res. Abstr.*, *7*, 06038.

Bond, G., et al. (1999), The North Atlantic's 1–2 kyr climate rhythm: Relation to Heinrich events, Dansgaard/Oeschger cycles and the Little Ice Age, in *Mechanisms of Global Climate Change at Millennial Time Scales*, *Geophys. Mongr. Ser.*, vol. 112, edited by P. U. Clark, R. S. Webb, and D. Lloyd Keigwin, pp. 35–58, AGU, Washington, D. C.

Bond, G., et al. (2001), Persistent solar influence on North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136.

Braun, H., et al. (2005), Possible solar origin of the 1,470-year glacial climate cycle demonstrated in a coupled model, *Nature*, *438*, 208–211.

Freidlin, M. I. (2000), Quasi-deterministic approximation, metastability and stochastic resonance, *Phys. D*, *137*, 333–352.

Freidlin, M., and A. D. Wentzell (1998), *Random Perturbations of Dynamical Systems*, Springer, Berlin.

Gammaitoni, L., et al. (1998), Stochastic resonance, *Rev. Mod. Phys.*, *70*, 223–287.

Ganopolski, A., and S. Rahmstorf (2002), Abrupt glacial climate changes due to stochastic resonance, *Phys. Rev. Lett.*, *88*, 038501, doi:10.1103/PhysRevLett.88.038501.

Goosse, H., and T. Fichefet (1999), Importance of ice-ocean interactions for the global ocean circulation: A model study, *J. Geophys. Res.*, *104*, 23,337–23,355.

Goosse, H., and H. Renssen (2006), Regional response of the climate system to solar forcing: The role of the ocean, *Space Sci. Rev.*, *125*, 227–235.

Gregory, J. M., and P. Huybrechts (2006), Ice-sheet contributions to future sea-level change, *Philos. Trans. R. Soc. Ser. A*, *364*, 1709–1731.

Hasselmann, K. (1976), Stochastic climate models. Part I: Theory, *Tellus*, *28*, 473–485.

Herrmann, S., and P. Imkeller (2005), The exit problem for diffusions with time-periodic drift and stochastic resonance, *Ann. Appl. Probab.*, *15*, 39–68.

Hillaire-Marcel, C., et al. (2001), Absence of deep-water formation in the Labrador Sea during the last interglacial period, *Nature*, *410*, 1073–1077.

Kuhlbrodt, T., et al. (2001), A simple model of seasonal open ocean convection. Part II: Labrador Sea stability and stochastic forcing, *Ocean Dyn.*, *52*, 36–49.

Nicolis, C., and G. Nicolis (1981), Stochastic aspects of climatic transitions: Additive fluctuations, *Tellus*, *33*, 225–234.

Opsteegh, J. D., et al. (1998), ECBILT: A dynamic alternative to mixed boundary conditions in ocean models, *Tellus Ser. A*, *50*, 348–367.

Renssen, H., et al. (2006), Coupled climate model simulation of Holocene cooling events: Oceanic feedback amplifies solar forcing, *Clim. Past*, *2*, 79–90.

Rind, D. (2002), The Sun's role in climate variations, *Science*, *296*, 673–677.

Schulz, M., et al. (2007), Low-frequency oscillations of the Atlantic Ocean meridional overturning circulation in a coupled climate model, *Clim. Past*, *3*, 97–107.

Telford, R. J. (2006), Limitations of dinoflagellate cyst transfer functions, *Quat. Sci. Rev.*, *25*, 1375–1382.

Thomas, R. H., et al. (2003), Investigation of surface melting and dynamic thinning on Jakobshavn Isbrae, Greenland, *J. Glaciol.*, *49*, 231–239.

Wood, R., et al. (1999), Changing spatial structure of the thermohaline circulation in response to atmospheric CO_2 forcing in a climate model, *Nature*, *399*, 572–575.

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