GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L03703, doi:10.1029/2004GL021564, 2005

Testing the influence of the Central American Seaway on orbitally forced Northern Hemisphere glaciation

A. Klocker, M. Prange, and M. Schulz

DFG Research Center Ocean Margins (RCOM) and Department of Geosciences, University of Bremen, Bremen, Germany

Received 20 September 2004; revised 17 November 2004; accepted 8 December 2004; published 1 February 2005.

[1] Utilizing a climate model of intermediate complexity, we test the hypothesis that the Pliocene closure of the Central American Seaway was a necessary precondition for orbitally triggered Northern Hemisphere glaciation. We conduct a series of sensitivity experiments in order to analyze the isolated and combined effects of Panama closure and orbital forcing on Northern Hemisphere perennial snow cover. While orbital forcing efficiently controls the extension of perennial snow cover, the model results suggest that the closure of the Central American Seaway did not intensify orbitally forced glaciation in high northern latitudes. **Citation:** Klocker, A., M. Prange, and M. Schulz (2005), Testing the influence of the Central American Seaway on orbitally forced Northern Hemisphere glaciation, *Geophys. Res. Lett.*, *32*, L03703, doi:10.1029/2004GL021564.

1. Introduction

[2] One of the most significant climate transitions during the Neogene was the pronounced intensification of Northern Hemisphere glaciation, which culminated in a synchronous ice-sheet development between Greenland, Scandinavian and North American regions around 2.7 Myr (million years) ago [e.g., *Kleiven et al.*, 2002]. Various hypotheses—invoking terrestrial as well as extraterrestrial mechanisms – have been proposed to explain the sudden appearance of major ice sheets in the Northern Hemisphere [see *Raymo*, 1994]. One hypothesis, which has received much attention, relies on the combined effects of the closure of the Central American Seaway and favorable orbital forcing [*Haug and Tiedemann*, 1998]. According to this hypothesis, the Pliocene closure of the Panama gateway promoted the formation of North Atlantic deepwater by intensifying the northward transport of warm and saline water in the North Atlantic starting 4.6 Myr ago. Evaporative cooling of surface waters during deepwater formation introduced moisture to the high-latitude atmosphere leading to enhanced snowfall. A progressive increase in obliquity amplitudes between 3.1 and 2.5 Myr is postulated as the final trigger for the major intensification of Northern Hemisphere glaciation. Extremely small obliquity angles would cause low Northern Hemisphere summer insolation. This would allow snow and ice to persist throughout summer and, hence, to accumulate over the years, eventually forming major ice sheets. In order to test this 'Panama hypothesis' we analyze the isolated and combined effects of Panama closure and extreme orbital forcing on Northern Hemisphere perennial snow cover in a coupled climate model.

0094-8276/05/2004GL021564$05.00

2. Experimental Design

[3] We perform a series of sensitivity experiments using the intermediate-complexity coupled atmosphere-ocean model ECBILT-CLIO version 3 [*Opsteegh et al.*, 1998; *Goosse and Fichefet*, 1999; *Goosse et al.*, 2002]. Beside a 5000 years control run (experiment CTL), simulating the modern (preindustrial) climate, five sensitivity experiments with open and closed Central American Seaway and different orbital configurations are carried out. The orbital parameters are set to produce modern, cold and warm Northern Hemisphere summers. The cold and warm orbital configurations are achieved by applying extreme values for obliquity (based on *Berger and Loutre* [1991]) and by changing the angle between perihelion and vernal equinox (ω) such that the Earth is at its farthest (closest) position to the sun during Northern Hemisphere summer. Since Earth's orbital eccentricity 2.7 Myr ago was similar to today [*Berger and Loutre*, 1991], the present-day value for eccentricity (0.0167) is used in all experiments. Therefore, the total annual solar insolation received by the Earth is identical in all model runs.

[4] For each sensitivity experiment, the model is integrated at least another 2000 years to reach a new equilibrium, using the control run as initial condition. All other boundary conditions are the same as in CTL. Table 1 gives a survey of the experiments. In those experiments, in which the Isthmus of Panama is open, the seaway is defined on three velocity grid points, corresponding to a width of approximately 1000 km with a depth of 700 m.

3. The 'Panama Hypothesis' Put to Test

[5] In the control run, maximum meridional overturning in the North Atlantic amounts to 27 Sv (1 Sv = 10^6 m^3 s^{-1}) (see *Prange and Schulz* [2004] for details and overturning plots). This vigorous circulation is associated with a large northward heat transport in the Atlantic Ocean. Maximum heat fluxes of about 0.9 PW are found between 15°N and 35°N. These values are within the range of results from inverse and constrained modeling [*Ganachaud and Wunsch*, 2000; *Stammer et al.*, 2003].

[6] Introducing an open Central American Seaway in experiments OM, OC and OW (Table 1) results in a transport of tropical water masses from the Pacific into the Atlantic Ocean. In these experiments, the annual mean total volume transport through the gateway is ~14 Sv and the flow is directed from the Pacific to the Atlantic over the entire depth of the strait. Intensity and vertical profile of the throughflow are very similar to the results from a recent study with an ocean-only model [*Nisancioglu et al.*, 2003, experiment CAS1000]. The eastward Central American

Table 1. Parameters for the Control Run (CTL) and the Sensitivity Experiments[a]

	CTL	OM	CC	OC	CW	OW
ω	102.04°	102.04°	90°	90°	270°	270°
obliquity	23.5°	23.5°	22.2°	22.2°	24.5°	24.5°
Panama	closed	open	closed	open	closed	open
AMOC [Sv]	27	15	19/29	14/18	27	19
AMHT [PW]	0.91	0.65	0.78/0.94	0.63/0.67	0.91	0.72

[a]The first letter of the abbreviations stands for closed (C) and open (O) Central American Seaway, the second letter for modern (M), cold (C) and warm (W) Northern Hemisphere summers. ω denotes the longitude of perihelion relative to the moving vernal equinox minus 180 degrees. The present-day value for eccentricity (0.0167) is used in all experiments. Atlantic meridional overturning circulation (AMOC) and Atlantic meridional heat transport (AMHT) refer to maximum annual mean values in the North Atlantic. Experiments CC and OC exhibit millennial-scale oscillations such that AMOC and AMHT switch between two states. The values for both states are given.

throughflow of relatively fresh Pacific water masses leads to a reduction of North Atlantic salinities. As a result, mean deepwater formation and mean meridional heat transport in the North Atlantic decrease by 8–12 Sv and 0.19–0.26 PW, respectively, compared to the corresponding experiments CTL, CC and CW with closed Panamanian Seaway (see Table 1).

[7] Changes in mean deepwater formation due to changes in orbital configuration are much smaller than the changes caused by the closure of the Central American Seaway. The mean oceanic meridional heat transport is very similar in all experiments with closed Panamanian Seaway and different orbital configurations. The same holds for the set of experiments with open seaway (Table 1). We note, however, that experiments CC and OC with cold orbital forcing exhibit millennial-scale oscillations of the Atlantic meridional overturning circulation, which are associated with switches between 'strong' and 'weak' overturning states. The nature of these oscillations, which have periods between 600 and 1300 years, will be the subject of a forthcoming study. In the following analyses, only the 'strong' overturning states are considered. We emphasize, however, that our conclusions are independent of the state which is considered, since the 'strong' overturning state generally leads to less snow accumulation in high northern latitudes than the 'weak' state.

[8] In order to assess the possibility of an intensification of glaciation in the conducted experiments, we analyze Northern Hemisphere perennial snow cover for all cases. Figure 1 shows the regions which are snow-covered throughout each month of a climatological year, calculated from the last 50 years of model integration. In experiment CTL, the snow cover in winter (December–February) is slightly overestimated, especially along the Arctic coast of Eurasia (not shown here). However, we do not expect that this model shortcoming significantly affects the differences in perennial snow cover between the conducted experiments.

[9] Comparing snow cover between the experiments with open and closed Central American Seaway, but identical orbital configurations, we notice a minor decrease in perennial snow cover upon closing the gateway (Figure 1), even though the snowfall increases over Greenland, the Canadian Arctic Archipelago, Alaska, northern Scandinavia and vast areas of Siberia (Figure 2a). In terms of snow accumulation, however, the increased snowfall is overcompensated by elevated summer temperatures (Figure 2b). An important reason for the increased atmospheric temperatures in the North Atlantic region is the onset of convection in the Labrador Sea after closure of the Central American Seaway. This model result is in line with isotope records from the western North Atlantic, which suggest that the Panama closure established today's general pattern of Atlantic Ocean circulation [*Burton et al.*, 1997, 1999]. South of Iceland, the closure of the Central American Seaway leads to an increase in modelled annual-mean sea-surface temperature by ~2°C, while surface salinity rises by ~0.5 psu (not shown). Both anomalies are in good agreement with recent reconstructions at Ocean Drilling Program Site 984 [*Bartoli et al.*, 2004].

[10] Between the experiments with different orbital configurations and identical Central American geometry, major changes in snow cover occur in the Northern Hemisphere (Figure 1). Perennial snow cover is substantially extended in the experiments with cold Northern Hemisphere summers, even in regions where snowfall rates decrease (e.g., Siberia in Figure 3a). This advance of the perennial snow cover is associated with lower atmospheric summer temperatures which decrease by up to 5°C over the

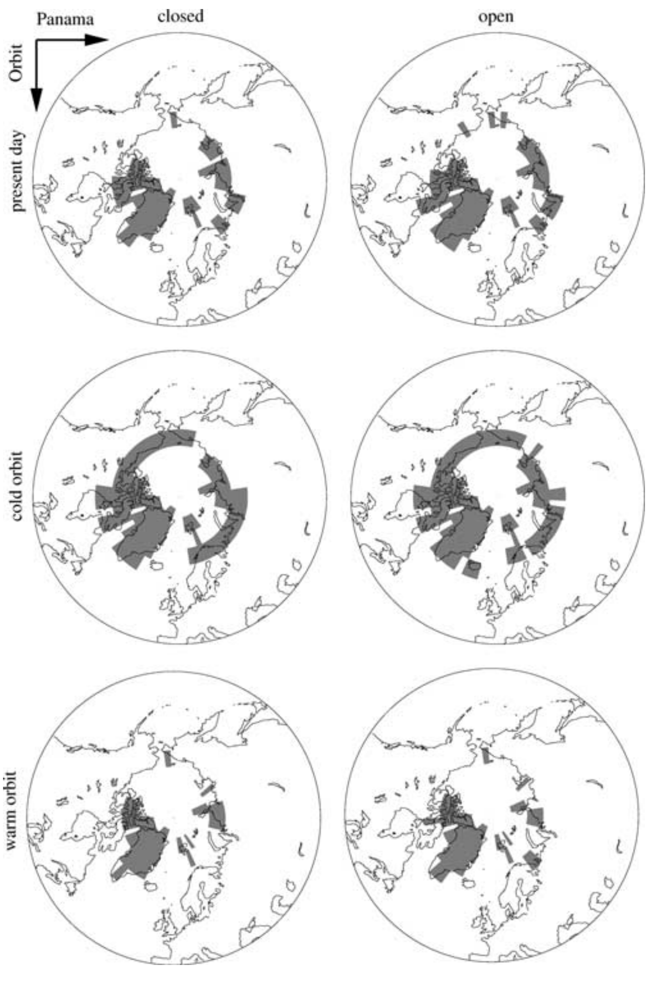

Figure 1. Perennial snow cover in all six experiments. Shaded areas show regions which are snow-covered throughout each month of a climatological year, calculated from the last 50 years of each model integration.

Canadian Arctic Archipelago (Figure 3b). Comparable impacts are observed in the experiments with warm Northern Hemisphere summers, in which perennial snow cover strongly diminishes (Figure 1). Therefore, the effect of a different distribution of solar insolation through changes in the orbital configuration appears to have a much greater influence on perennial snow cover than changes in snowfall rate.

4. Conclusions

[11] Our model results do not support the 'Panama hypothesis'. For a given set of orbital parameters, the closure of the Central American Seaway does not intensify

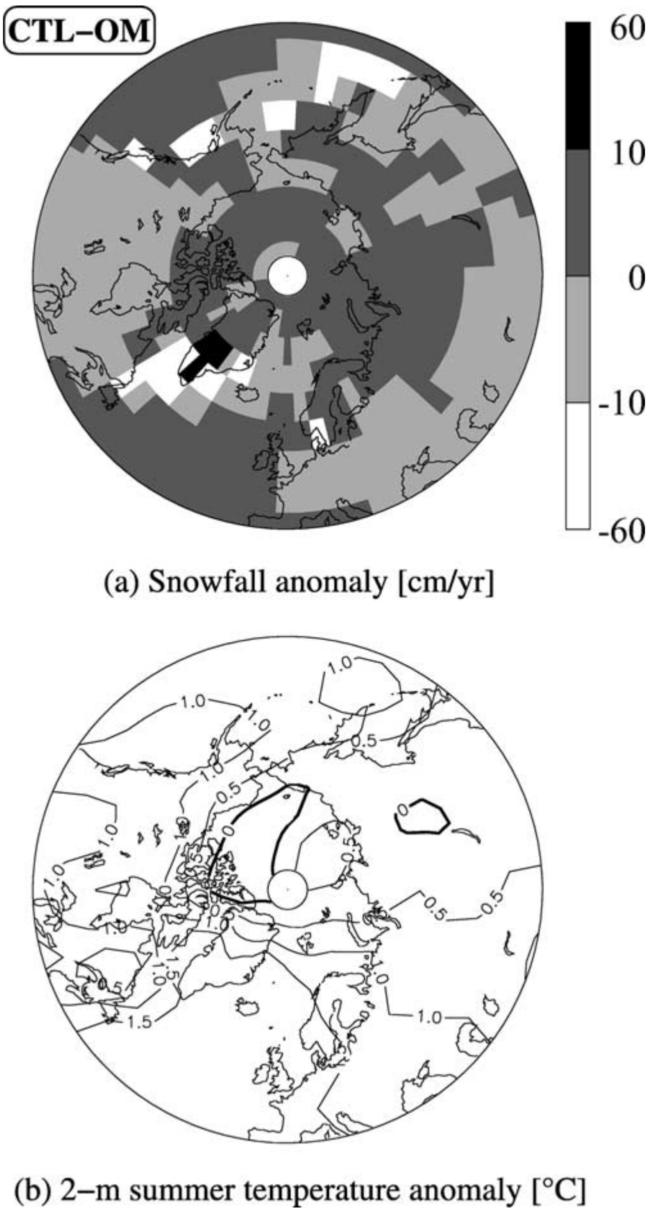

Figure 2. (a) Annual snowfall anomaly [cm/yr] and (b) 2-m summer temperature anomaly [°C] for CTL minus OM (i.e., anomaly in temporal direction of geological events). Averages over the last 50 years of model integrations are considered.

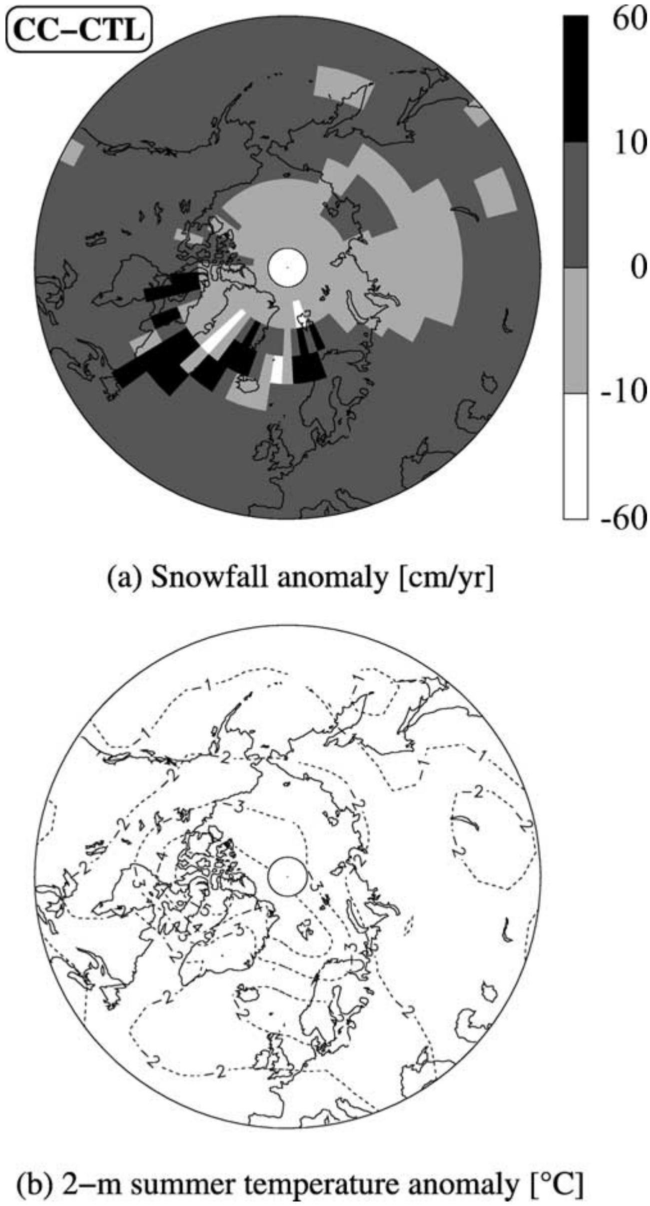

Figure 3. (a) Annual snowfall anomaly [cm/yr] and (b) 2-m summer temperature anomaly [°C] for CC ('strong' overturning state) minus CTL. Averages over the last 50 years of model integrations are considered.

snow accumulation in high northern latitudes. Rather, an increased northward heat transport in the Atlantic Ocean results in higher Arctic and sub-Arctic air temperatures, leading to a slight retreat of perennial snow cover. This finding is in line with the reasoning of *Berger and Wefer* [1996], who discussed the possibility that increased oceanic heat transport due to the closure of the Central American Seaway actually postponed the formation of major ice sheets in the Northern Hemisphere (their 'Panama Paradox'). We do not rule out the possibility that North Atlantic sea-surface temperatures increased due to the Panama closure, while at the same time, but in another region, ice sheets were growing.

[12] In our model experiments, orbital forcing efficiently controls the extension of the perennial snow cover. This

points to a key role for Earth's orbital obliquity and precession in causing Northern Hemisphere glaciation during the late Pliocene. However, similar orbital configurations occurred well before that time. This suggests that the climate system must have been preconditioned by some other process than enhanced atmospheric moisture transport due to the closure of Panama. One potential candidate is a decrease in atmospheric CO_2 concentration [see *Pearson and Palmer*, 2000] that might have brought the climate system to a critical threshold before favorable orbital parameters triggered the glaciation [*Maslin et al.*, 1998; *Li et al.*, 1998]. In terms of proxy-CO_2 reconstructions, however, a considerable amount of data is still needed for a reliable insight into trends and variability of atmospheric CO_2 concentration during the late Neogene.

[13] **Acknowledgments.** We thank A. Paul and A. Schmittner for stimulating discussions. Comments by G. Haug and an anonymous reviewer helped to improve the manuscript. ECBILT-CLIO is available from the Royal Netherlands Meteorological Institute (www.knmi.nl/onderzk/CKO/ecbilt.html). This research was funded by the Deutsche Forschungsgemeinschaft through the DFG Research Center 'Ocean Margins' at the University of Bremen (No. RCOM0238).

References

Bartoli, G. B., M. Weinelt, M. Sarnthein, H. Erlenkeuser, and D. Lea (2004), Enhanced North Atlantic heat transport, late Pliocene build-up of Greenland ice sheet, and the final closure of Panama, paper presented at 8th International Conference on Paleoceanography, Environ. et Paloenviron. Oceaniques, Biarritz, France.

Berger, A., and M.-F. Loutre (1991), Insolation values for the climate of the last 10 million years, *Quat. Sci. Rev.*, *10*, 297–317.

Berger, W., and G. Wefer (1996), Expeditions into the past: Paleoceanographic studies in the South Atlantic, in *The South Atlantic: Present and Past Circulation*, edited by G. Wefer et al., pp. 363–410, Springer, New York.

Burton, K. W., H.-F. Ling, and K. O'Nions (1997), Closure of the Central American Isthmus and its effect on deep-water formation in the North Atlantic, *Nature*, *386*, 382–385.

Burton, K. W., D.-C. Lee, J. N. Christensen, A. N. Halliday, and J. R. Hein (1999), Actual timing of neodymium isotopic variations recorded by Fe-Mn crusts in the western North Atlantic, *Earth Planet. Sci. Lett.*, *171*, 149–156.

Ganachaud, A., and C. Wunsch (2000), Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data, *Nature*, *408*, 453–457.

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., H. Renssen, F. M. Selten, R. J. Haarsma, and J. D. Opsteegh (2002), Potential causes of abrupt climate events: A numerical study with a three-dimensional climate model, *Geophys. Res. Lett.*, *29*(18), 1860, doi:10.1029/2002GL014993.

Haug, G. H., and R. Tiedemann (1998), Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation, *Nature*, *393*, 673–676.

Kleiven, H. F., E. Jansen, T. Fronval, and T. M. Smith (2002), Intensification of Northern Hemisphere glaciations in the circum Atlantic region (3.5–2.4 Ma)—Ice-rafted detritus evidence, *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, *184*, 213–223.

Li, X.-S., A. Berger, M.-F. Loutre, M. A. Maslin, G. H. Haug, and R. Tiedemann (1998), Simulating late Pliocene Northern Hemisphere climate with the LLN 2-D model, *Geophys. Res. Lett.*, *25*, 915–918.

Maslin, M. A., X.-S. Li, M.-F. Loutre, and A. Berger (1998), The contribution of orbital forcing to the progressive intensification of Northern Hemisphere Glaciation, *Quat. Sci. Rev.*, *17*, 411–426.

Nisancioglu, K. H., M. E. Raymo, and P. H. Stone (2003), Reorganization of Miocene deep water circulation in response to the shoaling of the Central American Seaway, *Paleoceanography*, *18*(1), 1006, doi:10.1029/2002PA000767.

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

Pearson, P. N., and M. R. Palmer (2000), Atmospheric carbon dioxide concentrations over the past 60 million years, *Nature*, *406*, 695–699.

Prange, M., and M. Schulz (2004), A coastal upwelling seesaw in the Atlantic Ocean as a result of the closure of the Central American Seaway, *Geophys. Res. Lett.*, *31*, L17207, doi:10.1029/2004GL020073.

Raymo, M. E. (1994), The initiation of Northern Hemisphere glaciation, *Annu. Rev. Earth Planet. Sci.*, *22*, 353–383.

Stammer, D., C. Wunsch, R. Giering, C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, C. N. Hill, and J. Marshall (2003), Volume, heat, and freshwater transports of the global ocean circulation 1993-2000, estimated from a general circulation model constrained by World Ocean Circulation Experiment (WOCE) data, *J. Geophys. Res.*, *108*(C1), 3007, doi:10.1029/2001JC001115.

A. Klocker, M. Prange, and M. Schulz, DFG Research Center Ocean Margins (RCOM), University of Bremen, Klagenfurter Str., D-28334 Bremen, Germany. (mprange@palmod.uni-bremen.de)