Large-scale instabilities of the Laurentide ice sheet simulated in a fully coupled climate-system model

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[1] Heinrich events, related to large-scale surges of the Laurentide ice sheet, represent one of the most dramatic types of abrupt climate change occurring during the last glacial. Here, using a coupled atmosphere-ocean-biosphere-ice sheet model, we simulate quasi-periodic large-scale surges from the Laurentide ice sheet. The average time between simulated events is about 7,000 yrs, while the surging phase of each event lasts only several hundred years, with a total ice volume discharge corresponding to 5–10 m of sea level rise. In our model the simulated ice surges represent internal oscillations of the ice sheet. At the same time, our results suggest the possibility of a synchronization between instabilities of different ice sheets, as indicated in paleoclimate records. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1620 Global Change: Climate dynamics (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 5416 Planetology: Solid Surface Planets: Glaciation. **Citation:** Calov, R., A. Ganopolski, V. Petoukhov, M. Claussen, and R. Greve, Large-scale instabilities of the Laurentide ice sheet simulated in a fully coupled climate-system model, *Geophys. Res. Lett.*, *29*(24), 2216, doi:10.1029/2002GL016078, 2002.

1. Introduction

[2] Heinrich events (HEs), discovered in the North Atlantic sediments as layers of ice-rafted debris [*Heinrich*, 1988], are associated with episodes of massive iceberg discharge from the Laurentide ice sheet (LIS) into the Atlantic ocean [*Broecker et al.*, 1992]. Each of these events lasted between several hundred and a thousand years, with recurrence intervals of about ten thousand years. There is a growing body of evidence that indicates that HEs not only represent catastrophic glaciological events, but also that they are closely related to abrupt climate changes [*Bard et al.*, 2000] via considerable slowdown of the Atlantic thermohaline circulation [*Elliot et al.*, 2002]. Although from the outset HEs were recognized as catastrophic glaciological events, the total amount of ice discharge during HEs is still poorly constrained [*Dowdeswell et al.*, 1995]. Recent analysis of sea level changes during the last glacial cycle [*Chappell*, 2002] shows a rapid increase of sea level by 10 m or more occurring synchronously with HEs. Such changes in sea level would require a freshwater flux of 0.1 Sv over one thousand years, which agrees with previous estimates [*MacAyeal*, 1993]. At the same time, a value of 0.1 Sv is just the right amount of additional freshwater flux needed for considerable reduction or even total collapse of the Atlantic thermohaline circulation for glacial climate states [*Ganopolski and Rahmstorf*, 2001].

[3] There is still no generally accepted explanation of the physical mechanism behind HEs. *MacAyeal* [1993] proposed a "binge/purge" free oscillatory mechanism, explaining HEs as transitions between two modes of operation of ice sheets: slow movement of ice over a frozen base and a fast sliding mode when the ice bed is at melting point. This type of self-sustained multi-millennial oscillation has been simulated in two-dimensional (one vertical and one horizontal direction) ice sheet models [*Payne*, 1995; *Greve and MacAyeal*, 1996; *Hindmarsh and Le Meur*, 2001], but in realistic 3-D models only small-scale instabilities restricted to the area of the mouth of the Hudson Strait have been simulated so far [*Marshall and Clarke*, 1997]. Here we report on what is to our knowledge the first simulation of large-scale instabilities of the LIS resembling HEs in periodicity, amplitude and spatial extent by using a more realistic 3-D ice sheet model.

2. Model and Experimental Design

[4] For this study we use the CLIMBER-2 Earth system model of intermediate complexity, which includes all major components of the Earth system: atmosphere, hydrosphere, biosphere, cryosphere and lithosphere [*Petoukhov et al.*, 2000]. CLIMBER-2 has been used for a variety of studies [*Ganopolski et al.*, 1998; *Claussen et al.*, 1999]. In the present study CLIMBER-2 includes the 3-D polythermal ice sheet model SICOPOLIS [*Greve*, 1997]. SICOPOLIS has been extensively tested for modern ice sheets [*Greve*, 1997; *Calov et al.*, 1998] and used for paleoclimate simulations [*Greve et al.*, 1999]. For this study SICOPOLIS is operated at a resolution of 1.5° longitude and 0.75° latitude, and its time step is half a year. The atmosphere components of CLIMBER-2 and SICOPOLIS are coupled bi-directionally [*Calov et al.*, 2002].

[5] Compared to the standard version of SICOPOLIS, one important modification related to the parameterization of the sliding law was made. In the standard version of the model, sliding of an ice sheet is parameterized by using a power law [*Calov and Hutter*, 1996], which describes sliding over a hard bed (rock) and yields relatively small velocities of 10–100 m/yr. Over soft water-saturated sedi-

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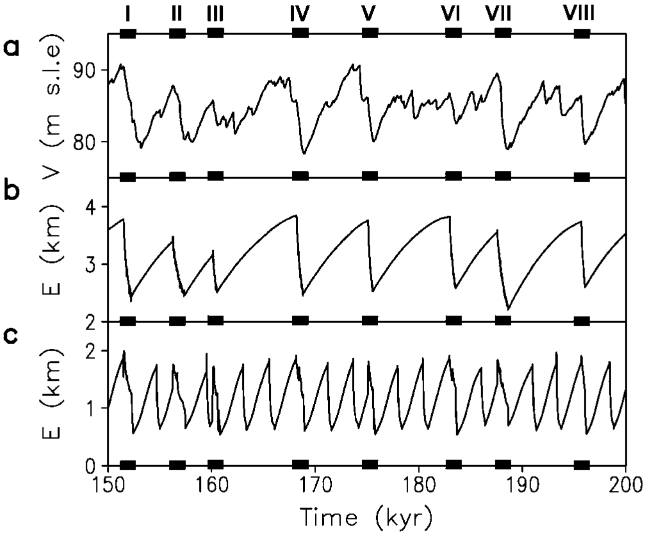

Figure 1. Time series of the baseline experiment. (a) Ice volume of the LIS measured in m sea-level equivalent (s.l.e.). The time averaged ice volume of the LIS is 85 m s.l.e. (b) Elevation over the center of the Hudson Bay (85.5°W, 61.5°N). (c), Elevation at the ice margin near the mouth of the Hudson Strait (67.5°W, 60.75°N). The thick horizontal lines on the time axes denote the time intervals of appearance of different simulated HEs.

ments, like those in the Hudson Bay, a much higher sliding velocity can arise [*Clarke*, 1987]. The sediment-sliding velocity u_s is computed using the simple linear parameterization $u_s = C\tau$, where C is the sediment-sliding coefficient, and $\tau = \rho g H \nabla h$ is the so-called basal shear stress with the ice thickness H, the ice-surface gradient ("slope") ∇h, the Earth's gravity acceleration $g = 9.81$ m s^{-2} and the density of ice $\rho = 910$ kg m^{-3}. This parameterization applies only if the base is covered by sediment and the basal ice temperature is at pressure melting point, otherwise the no-slip condition is applied. In our baseline experiment we use a value of $C = 0.1$ yr^{-1} m Pa^{-1} for the sediment-sliding coefficient. The geographical distribution of our rock/sediment mask is derived from a global compilation of sediment thickness [*Laske and Masters*, 1997].

[6] In the present study, we restrict our attention to the problem of sub-Milankovitch scale. For this end, similar to many previous studies, we performed experiments with constant external forcing, corresponding to the Last Glacial Maximum (LGM, about 21,000 yrs before present): orbital parameters were kept constant, and CO_2 concentration was set to 200 ppm. Such permanent LGM conditions are used in order to isolate the internal dynamics of ice sheets from variable climate forcing. We used the LGM reconstruction after *Peltier* [1994] to prescribe the initial ice sheet distribution. We allowed the ice sheets in North America to vary, keeping all other ice sheets constant, since our interests are focused on the LIS. The simulated LIS is relatively close to the reconstructed one with respect to the spatial extent. In all experiments described below we ran the model for 200,000 years. During the first 150,000 years the North American ice sheets reach statistically quasi-equilibrium state. Our analysis was therefore carried out for the last 50,000 years of each experiment.

3. Dynamics of Heinrich Events

[7] Our baseline experiment reveals persistent multi-millennial oscillations in the LIS volume with an amplitude corresponding to 5–10 m of global sea level change (Figure 1a), a value close to empirical estimates [*Chappell*, 2002]. The ice surges over the sediment-covered area of the Hudson Bay make a major contribution to these variations. The amplitude of these surges is 0.1–0.2 Sv (Figure 2a), which is much larger than the time-averaged ice flux of 0.05 Sv of the entire LIS. During each HE, the elevation drops by more than one kilometer over the Hudson Bay, and the LIS changes from a one-dome to a two-dome structure (Figure 3b). These resemble the equilibrium "maximum" and "minimum" reconstructions of the LIS [*Liccardi et al.*, 1998].

[8] Each Heinrich cycle consists of four distinct phases. The first and longest one represents a slow recovery of the ice sheet after the previous surge. The temperature at the ice bed over the Hudson Bay is well below pressure melting point (Figure 3d) and the ice flows by slow deformation movement. After the ice sheet over the Hudson Bay has become sufficiently thick, the second, most peculiar phase begins. This phase corresponds to a rapid expansion of the temperate basal area from the mouth of the Hudson Strait towards the Hudson Bay. Following *Fowler and Schiavi* [1998] we call this process an "activation wave". This wave represents a rapid upstream migration of a sharp gradient of the ice sheet elevation, caused by a large divergence of ice flow within the area of discontinuity in bottom boundary conditions. The sharp gradient itself creates an intensified flow of ice adjacent to the front and causes a large increase of dissipation of mechanical energy, which warms the bottom of the ice sheet to pressure melting point. As a result, the temperate basal area spreads upstream. The propagation of the activation wave from the mouth of the Hudson Strait to the center of the LIS takes less than a hundred years, and a

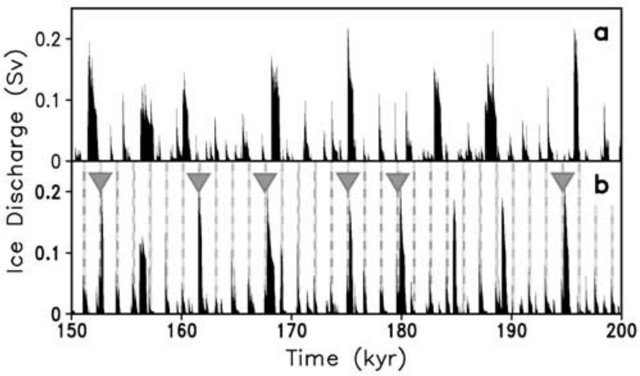

Figure 2. Ice discharge (in terms of freshwater flux in Sv = 10^6 m^3/s) via the Hudson Strait (a) in the baseline experiment and (b) in the experiment with imposed external 1500-year perturbations. The gray shaded vertical lines show the timing of the external perturbation. The gray triangles indicate HEs synchronous with these perturbations.

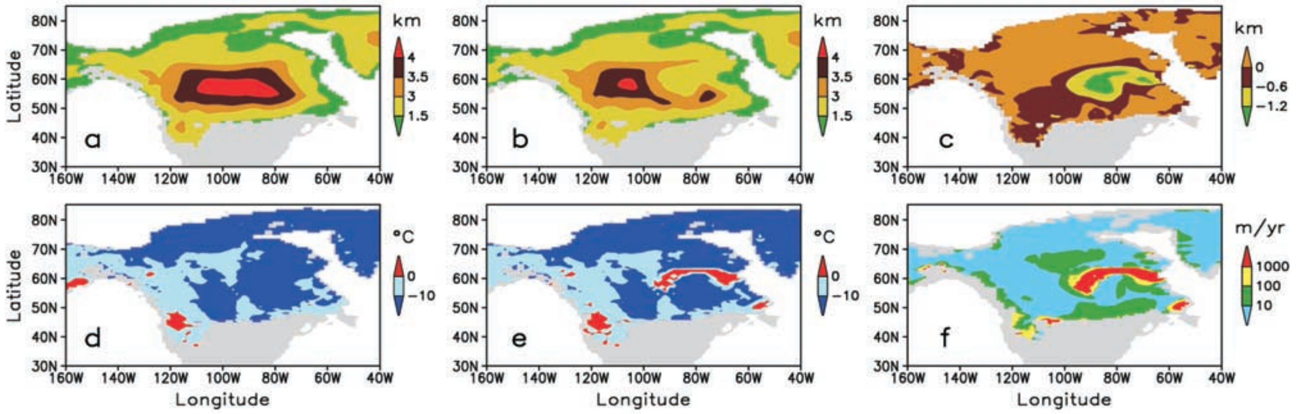

Figure 3. Heinrich event VI (in Figure 1) is shown here. Elevation of the LIS (a) before and (b) after that HE. (c) Difference between the elevations before and after the same HE. Basal temperature corrected for pressure melting (d) before and (e) during that HE. (f) Ice-surface velocity during the same HE.

pronounced ice stream of a few hundred kilometers in width and a thousand kilometers long is developed (Figures 3e and 3f). Thus the ice sheet enters the third, the surging phase of the cycle, which lasts between several hundred and a thousand years. The fast movement of ice with velocities of 1–10 km yr^{-1} causes a large dissipation of mechanical energy at the bottom of the ice sheet and helps to keep the basal temperature at melting point in spite of the increased downward advection of cold ice. During the surging phase, the ice sheet becomes thinner and its slope towards the Hudson Strait decreases. Eventually, the rate of energy dissipation becomes insufficient to sustain melting at the base and the basal temperature rapidly drops below melting point. This causes a rapid retreat of the temperate basal area downstream. Finally, the surge ceases completely. This fourth phase of the event ("deactivation wave") terminates the Heinrich cycle. HEs are simulated in our model as aperiodic internal oscillations. The recurrence time between surges varies between four and eight thousand years with an average recurrence time of about 7,000 years. Each HE is triggered by small-scale instabilities of the ice sheet at the mouth of the Hudson Strait. These small-scale instabilities have their own periodicity of about 2500 yrs (Figure 1c). Only each second or third such instability provokes large-scale surges of the LIS. The existence of ice-rafting events in the area of the Labrador Sea with similar periodicity was recently reported [*Andrews and Barber*, 2002].

[9] While the mechanism of simulated HEs is physically plausible, it is important to assess the role of uncertainties related to the parameterization of basal sliding, since its mechanisms are still poorly understood. To this end, we performed a series of sensitivity experiments with different numerical coefficients in the sliding parameterization (Figure 4). If the sediment-sliding coefficient reaches a critical value, here 0.3 times (Figure 4c) that of the baseline experiment (Figure 4a), then HEs start to develop. Further increase of the sediment-sliding coefficient varies the amplitude and periodicity of the HEs only marginally. For smaller sediment-sliding coefficients, the ice surges become irregular and their amplitude rapidly decreases (Figures 4d and 4e). Furthermore, we found that HEs also develop if sliding laws with a quadratic and cubic [*Payne*, 1995; *Hindmarsh and Le Meur*, 2001] dependence of the basal shear stress are used.

[10] To study the role of climate feedbacks and the temporal variation of the mass balance, we performed an ice-sheet-only experiment with prescribed temporal constant surface temperature and mass balance using time averaged fields from the baseline experiment. The HEs in this run are almost identical to those in the baseline experiment. These results demonstrate that, although other components of the climate system (atmosphere, ocean, biosphere) are important for the shaping of the climate background of the HEs, the large-scale instability of LIS is an intrinsic and robust feature of the ice-sheet component.

4. Synchronization of Glaciological Events

[11] In spite of some ambiguity, empirical data suggest almost synchronous discharges of icebergs from the North American and European [e.g. *Grousset et al.*, 2000] ice sheets during HEs. These findings have been used as evidence against the idea that HEs and other ice surges are internal oscillations of ice sheets [*Bond and Lotti*, 1995], since in this case, surges from different ice sheets should be

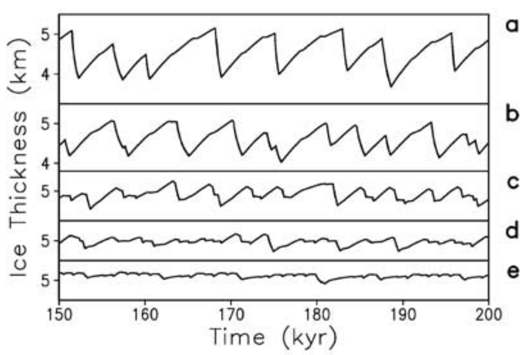

Figure 4. Time series of ice thickness averaged over the Hudson Bay (a) in the baseline experiment; experiments with a (a) 0.5, (c) 0.3, (d) 0.2 and (e) 0.1 times smaller sediment-sliding parameter than that of the baseline experiment.

independent of each other. However, in a strongly nonlinear system, such as the climate system, at least under some conditions different processes can be readily synchronized by a very weak interaction or external forcing — a mechanism which can resolve the apparent contradiction. For example, it was shown that millennial-scale Dansgaard-Oeschger oscillations, which are triggered by random freshwater forcing, can be synchronized with a very weak periodic 1500-year forcing via a mechanism called stochastic resonance [*Alley et al.*, 2001; *Ganopolski and Rahmstorf*, 2002].

[12] To address the question of whether the timing of HEs can be synchronized by a weak external forcing, we performed an additional experiment identical to our baseline experiment except that we added a small external perturbation to the system: at two grid points at the outlet of the LIS in the mouth of the Hudson Strait we switched on sediment-sliding conditions of 10 yrs duration every 1500 yrs. Such a weak perturbation might represent a small-scale instability of the ice shelf caused by a sea level rise due to iceberg discharge from other ice sheets. The choice of a 1500-year periodicity is not only justified by the existence of such climate cycles during the glacial age [e.g. *Dansgaard et al.*, 1993], but also because such periodicity is absent in the internal dynamics of the LIS in our model. This means that the synchronization with an external 1500-year cycle can be easily detected in the model results.

[13] The prescribed weak perturbations induce as a direct result only small-scale surges restricted to a few neighboring grid points, but on average each second of these "micro-events" provokes a more extended instability of the ice sheet in the eastern part of the Hudson Strait, similar to those which occur spontaneously and quasi-periodically in the baseline experiment. Further on, each second or third of the surge events in the eastern half of the Hudson Strait triggers large-scale instabilities over the Hudson Bay and Strait (HEs). In this way more than one half of the HEs are synchronized with the imposed 1500-year pulses (Figure 2b). Thus, although the mechanism and the periodicity (about 6,000 yrs) of the HEs in this experiment are similar to those in the baseline experiment, the timing of the ice surges can indeed be controlled by a weak external forcing. This experiment illustrates the possibility of a synchronization between ice surges from different ice sheets.

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