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Simulation of large-scale surges of the glacial Laurentide Ice Sheet: the simplified ISMIP HEINO experiments

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1. INTRODUCTION

Heinrich Events (HEs), which have been discovered in North Atlantic sediments as layers of ice-rafted debris, are associated with episodes of massive iceberg discharge from the Laurentide Ice Sheet into the Atlantic Ocean during the Weichselian glacial. The discharge events are likely caused by quasi-periodic collapses of the ice sheet over Hudson Bay and Hudson Strait, which occur when the basal temperature reaches the pressure melting point, so that very rapid basal sliding on a lubricating sediment layer develops. Besides representing catastrophic glaciological events, HEs are also closely related to abrupt climate changes via their impact on the Atlantic thermohaline circulation.

2. ISMIP HEINO

Calov et al. (2002) demonstrated for the first time that large-scale instabilities of the Laurentide Ice Sheet resembling HEs in periodicity, amplitude and spatial extent can be simulated with a 3-D dynamic/thermodynamic ice-sheet model (SICOPOLIS) coupled to an Earth system model (CLIMBER-2). In order to further investigate the dependence of these instabilities on atmospheric and basal conditions and compare the results of different ice-sheet models, the ISMIP HEINO [Ice Sheet Model Intercomparison – Heinrich Event INtercOmparison; see Calov and Greve (2005) and http://www.pik-potsdam.de/~calov/heino.html] experiments have been designed. A simplified geometry resembling that of the EISMINT Phase 2 Simplified Geometry Experiments (Payne et al. 2000) is employed. It consists of a flat, horizontal square with 4000 km side length, in which a circle of 2000 km radius defines the land area prone to glaciation. It is distinguished between hard rock and soft sediment, and the soft-sediment area has been chosen in order to resemble Hudson Bay and Hudson Strait (Fig. 1).

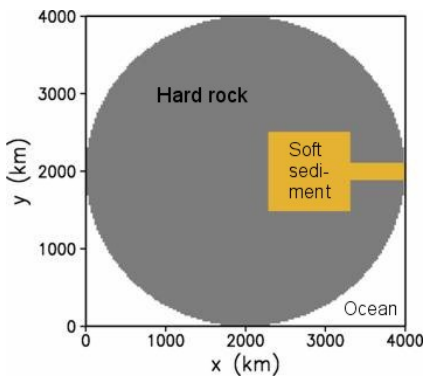

Figure 1: Model domain of ISMIP HEINO (Calov and Greve 2005). The sediment area mimics Hudson Bay (square) and Hudson Strait (channel towards the right).

Since the objective of ISMIP HEINO is to study internal ice-sheet dynamics, a *temporally constant* glacial climate is assumed. For the standard set-up ("ST"), the surface mass balance over the land area increases linearly from 0.15 m ice equiv. a^{-1} at the center to 0.3 m ice equiv. a^{-1} at the margin, and the surface temperature increases with the third power of distance from −40°C at the center to −20°C at the margin.

Rapid basal sliding is assumed for the sediment area ("Hudson Bay" and "Hudson Strait") if the basal temperature reaches the

pressure melting point. The sliding velocity v_b is then computed by using the linear sliding law $v_b = -C\tau/(\rho g)$, where C is the sediment-sliding parameter (standard value $500\,a^{-1}$). $\tau = \rho g H \nabla h$ denotes the basal drag (shear stress), with the ice thickness H, the ice-surface gradient ("slope") ∇h, the acceleration due to gravity $g = 9.81\,m\,s^{-2}$ and the ice density $\rho = 910\,kg\,m^{-3}$. By contrast, slow hard-bed sliding is assumed for the rock area, given by the Weertman-type sliding law $v_b = -C_R\tau^3/(\rho g\, p^2)$, where $C_R = 10^5\,a^{-1}$ is the rock-sliding parameter and $p = \rho g H$ the basal pressure. Note that for both cases no-slip conditions ($v_b = 0$) are assumed when the basal temperature is below the pressure melting point.

3. ICE-SHEET MODEL SICOPOLIS

For this study, we use the ice-sheet model SICOPOLIS, which simulates the large-scale dynamics and thermodynamics (ice extent, thickness, velocity, temperature, water content and age) of ice sheets three-dimensionally and as a function of time (Greve 1997). It is based on the shallow-ice approximation (e.g. Hutter 1983) and the rheology of an incompressible, heat-conducting power-law fluid [Glen's flow law, see Paterson (1994)]. Boundary conditions (surface temperature, surface mass balance, basal sliding, geothermal heat flux) are prescribed according to the HEINO set-up (see Sect. 2). For all simulations, the resolution is 50 km, and the model time is from $t = 0$ until $t = 200$ ka, starting from ice-free initial conditions. The time-step is 0.25 a, and the model parameters are those given by Calov and Greve (2005).

4. RESULTS

4.1 Standard run

The standard run ST, defined by the above set-up, shows very strong oscillations of the simulated ice sheet. The average ice thickness over the sediment area varies with a mean period of approx. 7500 years and an amplitude of about 1 km (Fig. 2, top panel).

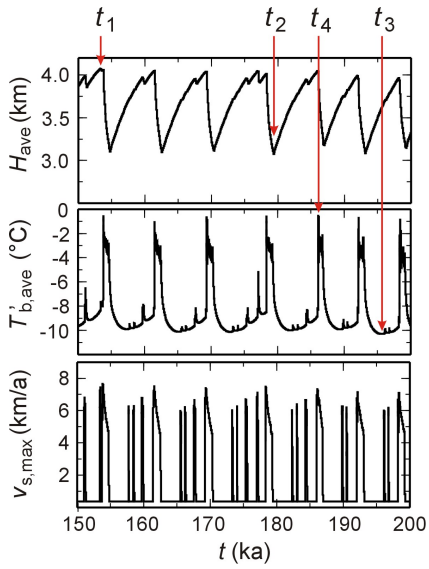

Figure 2: Time series of run ST (for the last 50 ka only): average ice thickness, H_{ave}, average basal temperature relative to pressure melting, $T'_{b,ave}$, and maximum surface velocity, $v_{s,max}$. Quantities refer to the sediment area shown in Fig. 1. For times t_1–t_4 see main text.

One full cycle consists of a gradual growth phase, followed by a massive surge. During the growth phase, basal temperatures are below pressure melting for most of the sediment area (Fig. 2, middle panel), and the ice flows slowly by internal deformation only (Fig. 2, bottom panel). Owing to increasing thermal insulation against the cold surface, basal temperatures rise gradually, until the pressure melting point is reached at the mouth of "Hudson Strait". At that time, rapid basal sliding sets in, which leads to increased strain heating. As a consequence, a thermal wave ("activation wave") develops, which travels upstream very quickly until almost the entire sediment area is at pressure melting. The surge starts, develops flow velocities of up to $8\,km\,a^{-1}$, and the ice sheet suffers a strong collapse, which goes on until the reduced thermal insulation and the enhanced downward advection of cold surface ice causes the basal temperatures to fall below pressure melting again. Then the surge comes to a halt, and the next growth phase begins.

In addition to the main oscillations, the signal of the maximum surface velocity (Fig. 2, bottom panel) shows a number of additional, higher-frequency peaks, which are only slightly

reflected in the signals of the ice thickness and the basal temperature. In this case, rapid sediment sliding remains limited to the mouth of "Hudson Strait", because the increased strain heating is not strong enough to initiate an activation wave. This behaviour was already reported by Calov et al. (2002). It is also visible in the power spectrum of the average ice thickness (Fig. 3), which shows clearly that the main oscillation, which manifests itself as a double peak centered around approx. 7500 years, is accompanied by some minor peaks at periods between 1000 and 5500 years.

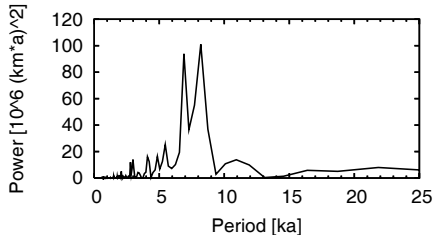

Figure 3: Power spectrum of the average ice thickness H_{ave} of run ST (see Fig. 2, top panel).

According to the ISMIP HEINO description (Calov and Greve 2005), the times t_1–t_4 are defined as the times of maximum (t_1) and minimum (t_2) average ice thickness, minimum average basal temperature (t_3) and maximum basal area at pressure melting (t_4) for the sediment region during the period from $t = 150$ to 200 ka. These times are indicated in Fig. 2, and snapshots of the state of the ice sheet at t_1 (before surge), t_2 (after surge) and t_4 (during surge) are shown in Fig. 4. Comparison of panels (a) and (d) shows very impressively the different topographies of the ice sheet before and after a surge. While before a surge the surface is essentially axially symmetric with respect to the center, after the surge the part over the sediment region has lowered by about 1 km and leaves a huge surface depression. The different distributions of the basal temperature and surface velocity before and during a surge are illustrated by the pairs of panels (b), (e) and (c), (f), respectively. Before a surge, basal temperatures are low and flow velocities are small ($< 100\,\mathrm{m\,a^{-1}}$) for the entire sediment area. This contrasts strongly with the high basal temperatures and flow velocities ($> 1000\,\mathrm{m\,a^{-1}}$) during the surge.

4.2 Parameter studies

In addition to the standard run ST discussed above, the ISMIP HEINO description (Calov and Greve 2005) defines a number of simulations with changed surface temperature, mass balance and sediment sliding. Here, we confine ourselves to reporting briefly the effect of a variation of the sediment-sliding parameter C. Results for the average ice thickness are shown in Fig. 5. For all values of C, significant oscillations occur. However, the amplitude increases with increasing C, and the shape of the oscillations is influenced significantly. In particular, the surge phases change from rather gradual surface lowerings to very abrupt collapses.

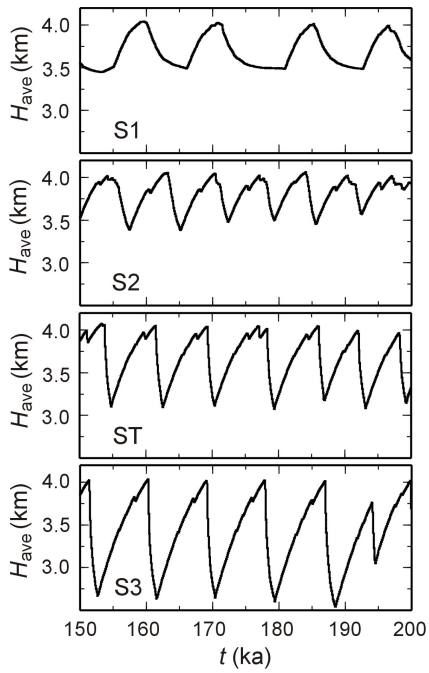

Figure 5: Time series of average ice thickness, H_{ave}, for runs S1, S2, ST and S3 (sediment-sliding parameter $C = 100$, 200, 500 and $1000\,\mathrm{a^{-1}}$, respectively).

5. CONCLUSION

The ice-sheet model SICOPOLIS operated at the Institute of Low Temperature Science, Hokkaido University, has successfully provided large-scale ice-sheet surges for the ISMIP HEINO set-up. This supports the idea that Heinrich Events are essentially the result of internal ice-sheet dynamics and thermodynamics

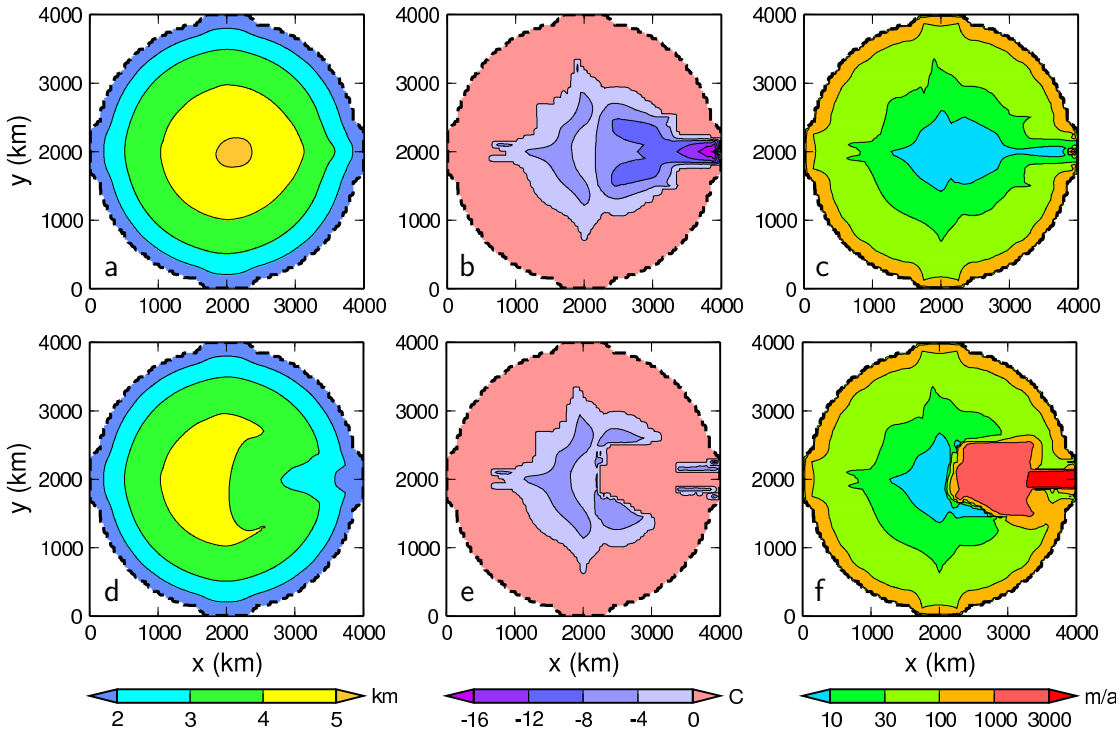

Figure 4: Phases of a Heinrich Event (HE). (a) Ice thickness at time t_1, (b) basal temperature relative to pressure melting at time t_1, (c) surface velocity at time t_1 (before a HE). (d) Ice thickness at time t_2 (after a HE). (e) Basal temperature relative to pressure melting at time t_4, (f) surface velocity at time t_4 (during a HE).

and do not depend crucially on external climate variability. We hope and expect that results from other working groups doing the same exercise with different models will corroborate this statement.

This study is part of the pending master thesis by Takahama (2006). A PDF version of the paper with colour figures will be made available online at R.G.'s website (http://hgxpro1.lowtem.hokudai.ac.jp/~greve/) under the item "Publications".

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