Simulation of Large-Scale Instabilities of the Laurentide Ice Sheet with a 3-D polythermal Ice-Sheet Model

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Large-scale instabilities of the Laurentide ice sheet (Heinrich events, HEs) are simulated with the 3-D polythermal ice-sheet model SICOPOLIS which is coupled bi-directional with the climate component of the Earth-system model CLIMBER-2. Our simulations explain Heinrich events as internal mechanism of the ice sheet due to quasi-periodical rapid sliding over Hudson Bay and Hudson Strait. The results are robust under different boundary conditions and sliding parameter.

The ice sheet model

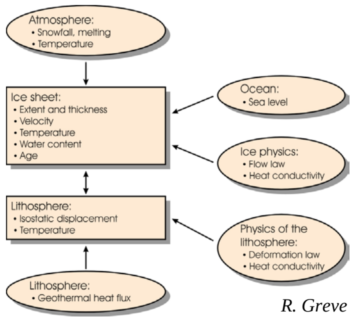

Figure 1: Block diagram of the polythermal ice sheet model SICOPOLIS.

The polythermal ice sheet model SICOPOLIS (SImulation COde for POLythermal Ice Sheets) was developed by Ralf Greve at the Technical University in Darmstadt, Germany. The model distinguishes between cold ice with a temperature below the pressure melting point and temperate ice with a temperature at the pressure melting point, the latter being considered as a binary mixture of ice and small amounts of water. The model computes three-dimensionally the temporal evolution of ice thickness, velocity, temperature and water-content for grounded ice sheets. In our version the snowfall, melting and the surface temperature are simulated in the climate component of the Earth system model CLIMBER-2. Here, SICOPOLIS resolves the northern Hemisphere with 1.5° longitude and 0.75° latitude, and its time step is half a year.

Sediment Sliding

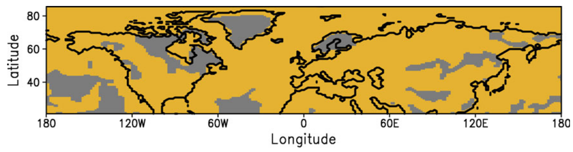

Figure 2: Sediment areas derived from observation of sediment thickness. Colours indicate assigned areas of bare rock (grey) and of sediment (dark yellow).

The sliding velocity over sediment reads

$$\boldsymbol{v}_S = -\,c_S\,H\,\boldsymbol{\nabla}_H h, \quad c_S = 1000\ \mathrm{yr}^{-1},$$

which applies if the basal ice is temperate and underlain by soft sediment (Figure 2).

Heinrich Events

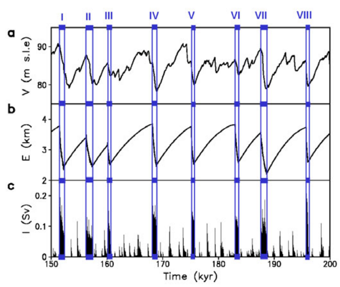

*Figure 3: Time series in the baseline run with the sliding parameter of equation (1) **a** Ice volume of the Laurentide ice sheet in m sea-level equivalent (s.l.e). **b** Elevation over the centre of Hudson Bay. **c** Ice discharge in Sv (=10^6 m^3/s) at the mouth of Hudson Strait. The blue lines indicate the simulated HEs.*

In our model, a HE lasts between 300 and 1200 years. The recurrence time is between 5000 and 10,000 years (Figure 3). This is mainly determined by the amount of snowfall. Only if the ice sheet is sufficiently thick and has with this a high surface gradient at the mouth of Hudson Strait, perturbations at the ice margin develop and cause a fast upstream migration of temperate basal area over Hudson Strait and Hudson Bay - a so-called activation wave. There is a sharp gradient in the ice surface over the front of the activation wave, which causes a large increase of dissipational heating there and drives its movement. If the basal ice over Hudson Bay and Hudson Strait has become temperate (see Figure 4d,e), fast basal sliding appears leading to a discharge of ice into the Labrador Sea. The warm base now is sustained by the basal frictional heating caused by the high sliding velocities. After several 100 years the advection of cold ice cools the base and causes a "deactivation wave". This terminates the Heinrich cycle and the ice sheet starts to rebuild. The simulated HEs affect large areas of the Laurentide ice sheet. Up to 15 percentage of ice volume can discharge during a HE (Figure 4c).The sliding velocities have the order of several kilometers per year (Figure 4f). The Laurentide ice sheet changes between a single-dome and a multi-dome complex during the Heinrich cycles (Figure 4a,b).

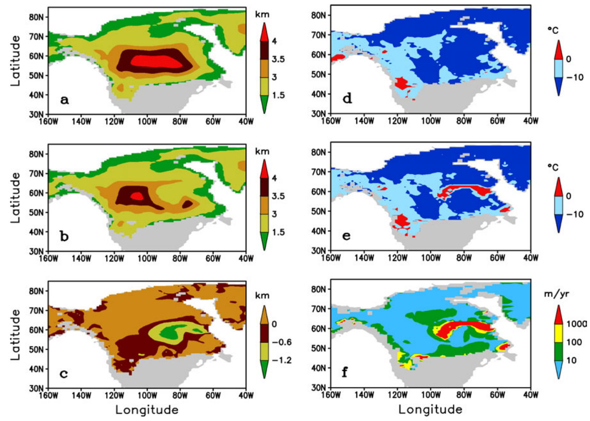

*Figure 4: Heinrich event VI in (figure 3). Elevation of the Laurentide ice sheet **a** before and **b** after that HE. **c** Difference between the elevations before and after the same HE. Basal temperature corrected for pressure melting **d** before and **e** after that HE. **f** Ice-surface velocity during the same event.*

Sliding Threshold

We performed simulations with different sliding parameters (Figure 5). We found that the sliding parameter has a threshold of $c_S = 300\ \mathrm{yr}^{-1}$ after which crossing HEs start to appear (Figure 5c). Further increase of the sliding parameter varies the amplitude and periodicity only slightly (Figure 5a,b). For smaller sliding coefficients, the ice surges become more and more irregularly and their amplitude rapidly decreases (Figure 5d,e). Additionally, these simulations show that, if the threshold has been crossed, the Heinrich oscillations are robust with respect to the sliding parameter which is poorly constrained by observations.

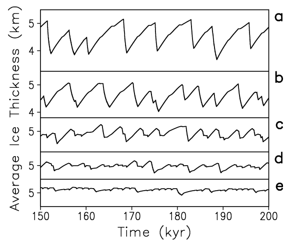

*Figure 5: Time series of ice thickness averaged over Hudson Bay **a** in the baseline run; simulations with a **b** 0.5, **c** 0.3 **d** 0.2 **e** 0.1 times smaller sliding parameter than in the baseline run.*

Robustness of the Oscillation

Although HEs can be modelled for a broad range of boundary conditions, their periodicity is not independent from them. For values in the range of natural variation, there is a strong dependence on the snowfall, while there is a weak one on the surface temperature (Figure 6). It is clearly demonstrated here that the snowfall controls the recovering time of the ice sheet.

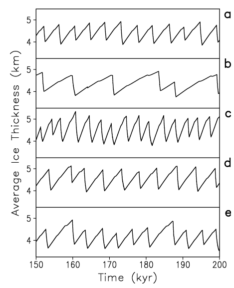

*Figure 6: Time series of ice thickness averaged over Hudson Bay. **a** Using temporarily averaged snowfall and ice-surface temperature from the baseline run as forcing; **b** 0.5 times lower snow fall, **c** 2 times higher snow fall, **d** 5 °C lower ice-surface temperature and **e** 5 °C higher ice-surface temperature as in the run in panel **a**.*

Schematic model setup for intercomparison

The sediment mask in Figure 7 together with a flat bedrock and simple parameterisations of the snowfall and the surface temperature might be useful for an intercomparison with other ice sheet models. Beside, such a setup shows the minimum requirements to model HEs with a thermomechanical ice-sheet model, or in our case a polythermal one. We propose the channalizing sediment region in Hudson Strait (Figures 2 and 7) and that the sliding velocity has an order of magnitude of kilometer per year as important key factors.

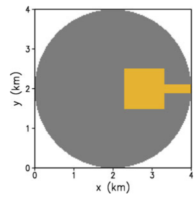

Figure 7: Schematic sediment area. Colours as in Figure 1.

Reference

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, GRL, 29 (24): art. no. 2216, 2002.