

A mass balance model for the Eurasian Ice Sheet for the last 120,000 years

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Abstract

We present a mass balance model for Eurasia which is based on the calculation of accumulation from a moisture balance concept. The model is forced with 500 hPa temperatures from GCM time slices at LGM and present day. The model simulates key characteristics, such as control on the size of ice sheets through the advection of moisture, asymmetric ice sheets due to advection of moisture and orography, and the drying of ice sheets when they grow. A simulation of the Eurasian Ice Sheet through a full glacial cycle shows that the model reproduces realistic ice sheets that compare well with geomorphological data. During the Middle Weichselian and the Late Weichselian, the model picks up the trend that the Scandinavian part of the ice grows towards the south and east whilst the ice sheet covering the Barents and Kara Seas remains relatively stable. However, the model seriously underestimates the observed ice extent in the Baltic area. Uncertainties in the temperature and the wind field limit the reliability of regional modelling results.

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1. Introduction

The simulation of ice sheets throughout ice ages is very sensitive to the description of past climate conditions, and the conversion of the climatological variables into ice melt or accumulation, i.e. the mass balance. Methods to prescribe the mass balance in ice flow models are very diverse and range from simplified parameterizations to complicated procedures to calculate snowfall and ice melt. Simple methods, such as prescribing a dependence on location or altitude work fine for synthetic experiments, but are difficult to apply in realistic situations. The geometry of the Eurasian Ice Sheet, for example, is strongly affected by the availability of moisture sources and wind direction (e.g. Velichko et al., 1997).

A calculation of the mass balance therefore usually consists of two steps; (1) the calculation of the ice mass melt or accumulation from the temperature and precipitation, and (2) prescribing the historic variations in temperature and precipitation. In step (1) the accumulation is generally determined from the total precipitation with a simple relation between temperature

and snow fraction. Several methods exist to estimate the amount of melt from an ice sheet, for example a Positive Degree Day (PDD) method, which models the ablation only as a function of temperature (Reeh, 1991; Braithwaite, 1995; Fabre et al., 1997; Charbit et al., 2002; Forsström and Greve, 2004; Huybrechts et al., 2004; Zweck and Huybrechts, 2005). As an alternative a parameterization as a function of both surface temperature and insolation can be used (Pollard, 1980; Oerlemans, 2001; Bintanja et al., 2002). Both methods produce equally good results, but have different sensitivities to temperature changes. In this paper we focus on step (2); the description of temperature and precipitation as a function of time.

In regions currently covered with ice (e.g. Greenland and Antarctica) the observations are both spatially and temporally sparse. As such, prevailing climate conditions must be estimated with models. Recent attempts to force ice sheets with results from General Circulation Models (GCMs) are promising (e.g. Fabre et al., 1997; Bintanja et al., 2002; Charbit et al., 2002; Forsström and Greve, 2004; Huybrechts et al., 2004; Zweck and Huybrechts, 2005). These studies either dynamically couple the GCM for a short model run or steady state experiment, or they use one or more time slices of precipitation and temperature fields. In addition, temperature series deduced

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from ice cores as GRIP and Vostok or inverse experiments (Bintanja et al., 2005) are used to describe the transient changes from one climate state to the next. It is computationally impossible to dynamically couple a GCM to an ice flow model at sufficiently fine grid throughout a transient run for an entire ice age.

Despite this limitation, GCM runs at LGM, such as performed in the Paleoclimate Modelling Intercomparison Project (PMIP) 1 and 2 experiments, provide useful information on climate changes during the ice ages. Nevertheless, there are some severe drawbacks. A major issue is the sensitivity of the precipitation and surface temperatures to the ice distribution prescribed in the GCM. Another problem is resolution; local precipitation and temperature are not well resolved in areas such as Norway where the topography is highly variable and the land–sea contrast is large. Hence, it is problematic to interpolate and extrapolate the climatological fields from time slices.

Instead of prescribing the precipitation field, we propose to calculate the precipitation from a moisture balance as a function of temperature, wind and altitude (e.g. Sanberg and Oerlemans, 1983). Since altitude is directly coupled to ice sheet geometry, we can explicitly calculate changes in the precipitation pattern caused by changes in the configuration of the ice sheet. Hence, the ice sheet and calculation of the precipitation field are dynamically coupled. The precipitation model is tuned to present day conditions only, and otherwise evolves freely together with the ice sheet. Key characteristics of the model include (1) the advection of moisture governing the dimensions of ice sheets, (2) the drying effect as ice sheets grow larger and higher, and (3) the generation of asymmetric mass balance profiles in the direction of the wind as a result of orography. These are generally believed to be essential features in modelling large ice sheets like the Eurasian Ice Sheet. A limitation of the model is

that we do not calculate the general circulation. Hence, we cannot calculate changes in precipitation related to changes in the large scale circulation. Since the only variable is temperature, the model is ideally suited for sensitivity experiments to assess the important processes in the development of ice sheets.

Instead of forcing the mass balance model with surface temperatures from GCM time slices at present day and LGM conditions, we force the model with 500 hPa temperatures. This pressure level is outside the boundary layer even when ice sheets grow very thick and as such, these temperatures are far less sensitive to the ice distribution used in the GCM than 850 hPa or surface temperatures. Hence, they represent a more robust parameter to incorporate in a dynamical ice sheet model. Moreover, 500 hPa temperatures are better representative for the calculation of the precipitation as this is close to the level that dominates large scale background circulation. In addition, the 500 hPa temperatures are still representative when surface properties change in time, whereas for surface temperatures this is not the case.

A similar precipitation model was successfully used to simulate present day climate in the UK and Patagonia (Hulton and Sugden, 1995; Purves and Hulton, 2000). In addition, Hulton and Sugden (1995) also studied the Patagonian climate under glacial conditions. These studies did not use a coupled ice flow model to directly model the response of an ice sheet. Letréguilly and Ritz (1993) did couple a similar precipitation model to an ice flow model, but only performed some sensitivity tests in Eurasia, hence not a full glacial run with representative temperature changes. Fabre et al. (1997) concluded that a similar precipitation model coupled to an ice flow model for the entire Northern Hemisphere did not produce accurate results, which suggests that the model should be tuned locally. Moreover, Fabre et al. (1997) did not study a full glacial cycle.

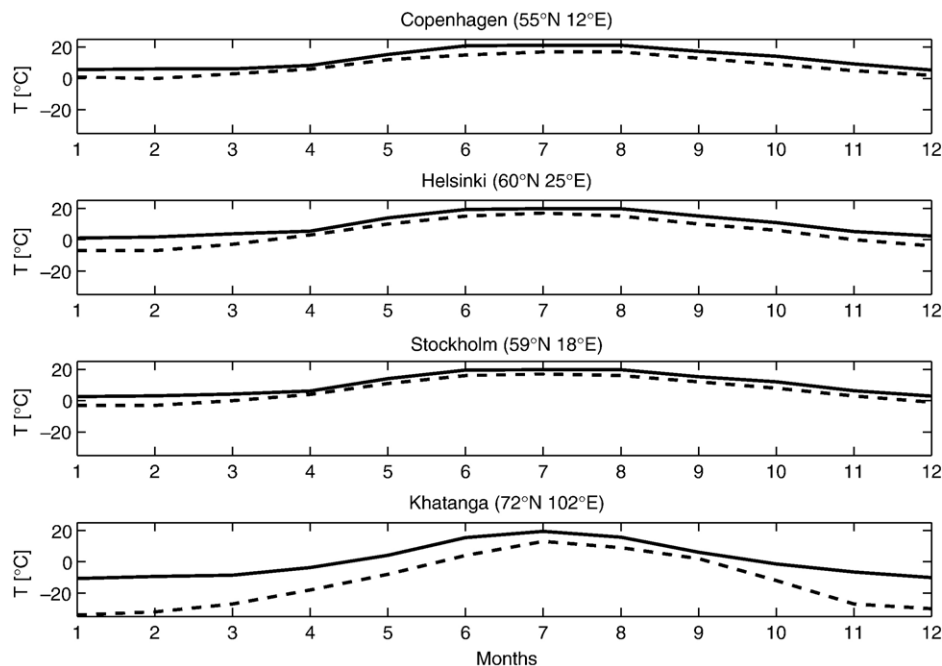


Fig. 1. Monthly present day surface temperatures for several locations. The dashed line is the actual surface temperature, the solid line is the extrapolated 500 hPa temperature from HADCM3M2.

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