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Calibrating a glaciological model of the Greenland ice sheet from the Last Glacial Maximum to present-day using field observations of relative sea level and ice extent

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ABSTRACT

We constrain a three-dimensional thermomechanical model of Greenland ice sheet (GrIS) evolution from the Last Glacial Maximum (LGM, 21 ka BP) to the present-day using, primarily, observations of relative sea level (RSL) as well as field data on past ice extent. Our new model (Huy2) fits a majority of the observations and is characterised by a number of key features: (i) the ice sheet had an excess volume (relative to present) of 4.1 m ice-equivalent sea level at the LGM, which increased to reach a maximum value of 4.6 m at 16.5 ka BP; (ii) retreat from the continental shelf was not continuous around the entire margin, as there was a Younger Dryas readvance in some areas. The final episode of marine retreat was rapid and relatively late (c. 12 ka BP), leaving the ice sheet land based by 10 ka BP; (iii) in response to the Holocene Thermal Maximum (HTM) the ice margin retreated behind its present-day position by up to 80 km in the southwest, 20 km in the south and 80 km in a small area of the northeast. As a result of this retreat the modelled ice sheet reaches a minimum extent between 5 and 4 ka BP, which corresponds to a deficit volume (relative to present) of 0.17 m ice-equivalent sea level. Our results suggest that remaining discrepancies between the model and the observations are likely associated with non-Greenland ice load, differences between modelled and observed present-day ice elevation around the margin, lateral variations in Earth structure and/or the pattern of ice margin retreat.

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1. Introduction

Since the Last Glacial Maximum (LGM, 21 ka BP), the Earth has seen the decay of the great ice sheets covering North America and Eurasia, ice mass loss in Greenland and Antarctica and the reduction of mountain glaciers. Over this time, global mean sea level has risen c. 120 m (e.g. Fairbanks, 1989; Yokoyama et al., 2000). This large ice–ocean mass exchange together with rapid climate change in Greenland (e.g. Cuffey et al., 1995) has played a part in the evolution of the Greenland ice sheet (GrIS) over this period. At the LGM, the GrIS is thought to have extended to cover parts of the continental shelf (Funder and Hansen, 1996) and reached an excess volume (compared to present) of 2–3 m ice-equivalent sea level (Clark and Mix, 2002). The retreat of the GrIS is hypothesised to have occurred in two key stages (Funder, 1989); initial retreat was driven by sea-level rise, causing the calving of ice grounded below sea-level and break up of the marine portions of the ice sheet. By c. 10 ka BP the GrIS was essentially at or inland of the present-day coastline (Funder and Hansen, 1996; Bennike and Björck, 2002). The second phase of retreat during the Holocene (10 ka BP to present) was slower and driven, primarily, by surface melting. Of particular interest is the reaction of the GrIS to the peak warming period known as the Holocene Thermal Maximum (HTM). The response of the ice sheet to this forcing may be a useful analogue for its future behaviour in a warming climate. The HTM occurred, broadly, between 9 and 5 ka BP in Greenland (Kaufman et al., 2004) causing the ice sheet to retreat behind its present-day position and reach a minimum post-LGM volume. It is not clear where and how far the ice margin retreated inland of its current position, as subsequent to reaching this minima the GrIS experienced a neoglacial readvance (Kelly, 1980), and so all geological and geomorphological evidence of the minimum configuration was overridden by advancing ice.

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Today the GrIS holds enough ice volume to raise mean global sea level by c. 7 m (Bamber et al., 2001). Recent mass balance estimates based on geodetic observations generally indicate an accelerated mass loss from Greenland over the last decade (Lemke et al., 2007). Due to the short time span of these observations, however, it remains contested if these changes are the beginning of a sustained response of the ice sheet to recent warming. The interpretation of these data is further complicated by the ongoing vertical motion of the solid Earth to past ice sheet changes. This contaminant signal is predicted using models of glacial isostatic adjustment (GIA) and removed from the measured signal. It is clear that a good understanding of past GrIS evolution is required if present-day observations are to be interpreted correctly.

The overall aim of this work is to calibrate a glaciological model of GrIS evolution since the LGM using inferences of relative sea level (RSL) and past ice extent from field data. The analysis has three primary motivations: (i) such a model can provide important insight into how the GrIS reacted to past sea-level and climate change and thus inform us how the ice sheet might behave in the future; (ii) as stated above, such a model can be adopted to predict the pattern of present-day solid Earth deformation in Greenland to more accurately correct and interpret the growing quantity and variety of geodetic data; and (iii) calibrating a model to field data will highlight any particular weaknesses in the ice and Earth model adopted and can therefore guide future research into model development.

Three approaches can be employed to reconstruct the deglaciation history of ice sheets: (1) three-dimensional ice sheet models that are forced by prescribed climatic conditions and freely simulate past ice sheet evolution (e.g. Huybrechts, 1990); (2) observations of GIA-induced sea-level change in the near-field of past or presently glaciated regions that are used to quantitatively infer the loading history of grounded ice sheets (e.g. Peltier, 1994); and (3) directly constraining the lateral and/or height extent of past ice from field observations (e.g. Dyke and Prest, 1987; Bentley et al., 2006). Previous studies have, in general, combined only two of these approaches; normally (1) and (3) (e.g. Marshall et al., 2002) or (2) and (3) (e.g. Tushingham and Peltier, 1991). The Greenland GrB model of Tarasov and Peltier (2002) first demonstrated that by adopting (1) a 3-D ice sheet model with (2) a GIA forward model is a powerful tool that reduces the uncertainty of past ice sheet evolution. In this study we combine and apply all three methods (e.g. Tarasov and Peltier, 2004) to the Greenland ice sheet. Using, primarily, observations of RSL complemented by geological and geomorphological data we constrain the millennial-scale spatial changes of a 3-D thermomechanical ice sheet model (Huybrechts, 2002) from the LGM to the present-day.

Two previous studies have constrained the evolution (LGM to present-day) of the GrIS using RSL data. First, as mentioned above, Tarasov and Peltier (2002) presented their GrB model which forms the Greenland component of the global ice sheet reconstruction ICE-5G (Peltier, 2004). Second, Fleming and Lambeck (2004) presented their GREEN1 model which has a deglaciation history based on several stages of linear interpolation between an LGM reconstruction (Denton and Hughes, 1981) and the observed present-day ice sheet (Ekholm, 1996). We extend these previous studies in two main respects: (i) we make use of an RSL and ice extent dataset that is significantly improved over those used in these past two analyses. In particular, previous models were constrained primarily using sea-level observations derived from molluscan assemblages which have a large age and altitude uncertainty. We focus on the growing number of RSL observations reconstructed from isolation basins (e.g. Long et al., 2006, 2008, in press; Sparrenbom et al., 2006a, b) which are more precise and consequently provide a more powerful model constraint (see Section 2.1); (ii) we provide a more detailed sensitivity analysis which targets key Earth and ice model parameters.

The work is structured as follows; in Section 2.1 we describe the nature of the data employed to calibrate the ice model and provide an overview of the observed sea-level history of Greenland. We start our modelling (Section 3) by comparing predictions generated using the ice model published by Huybrechts (2002). Adopting this as our preliminary ice model, we consider the sensitivity of sea-level predictions to wide ranges in the more important Earth model parameters and identify an optimal set of values. Based on this Earth model sensitivity study, we are able to isolate data-model misfits that are due to limitations in the ice model. We then explore key aspects of the ice history that might explain the misfits of our starting ice model (Section 3.2). A central element of our analysis is the careful examination of trade-offs between ice and Earth model parameters. In Section 3.3 we show fits to the RSL data for our new calibrated ice model, before discussing the key aspects of our new model (Section 4.1) and possible sources for any remaining data-model residuals (Section 4.2). The conclusions are listed in Section 5.

2. Data and description of the model

2.1. Nature of the data

In our modelling analysis we use data on past RSL and past ice extent. The primary focus is upon RSL data, the locations and source references of which are shown in Fig. 1 and Table 1, respectively. All RSL data used in this investigation are categorised as either sea-level index points or limiting dates. In total there are 214 observations used for RSL reconstruction; 73 of which have a well defined height and age relationship to former sea level and a further 141 that provide limiting constraints. Sea-level index points are derived from field evidence that has a defined (c. ±50 cm) vertical relationship to past mean sea level. This height relationship is referred to as the 'indicative meaning' (e.g. Shennan, 1986). In Greenland, the most precise sea-level index points are derived from dating the sediments preserved in isolation basins (e.g. Bennike, 1995; Long et al., 1999; Sparrenbom et al., 2006a) and thus provide a precise measure of past sea level in both time and height. By analysing a staircase of basins that occur below the marine limit, a well constrained RSL reconstruction can be produced (e.g. Fig. 2).

A variety of other field evidence lack an indicative meaning (a defined height relationship to a former tidal datum) and so provide a less precise height constraint on past sea level; these are referred to as limiting dates. Radiocarbon dates from marine shells within raised beaches or deltas are typical examples of limiting dates. It is often uncertain how far below past sea level the shells lived and in most instances they provide only a lower height limit for RSL reconstructions (Gotfredsen and Møberg (2004) detail the height relationship to mean sea level for specific molluscan species). However, for a number of shell dates plotted on a time–height diagram the upper height envelope of these observations can often tentatively be interpreted as past mean sea level. Fig. 2 shows a comparison of limiting dates (Rasch and Jensen, 1997) with index point data from an isolation basin study from Innaarsuit (Inn, Fig. 1) in southern Disko Bugt. We select limiting dates that are close to the isolation basins to keep spatial differences in RSL small. Using only the isolation basin data as a guide we reconstruct past sea level on the time–height diagram (dashed line, Fig. 2) and on top of which the limiting dates are also plotted. Mostly we find the upper height envelope of the shell dates corresponds (within age error) to the past sea-level reconstruction. With more and better time–height coverage of the data we can have increasing confidence that the

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