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A model of Greenland ice sheet deglaciation constrained by observations of relative sea level and ice extent

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ABSTRACT

An ice sheet model was constrained to reconstruct the evolution of the Greenland Ice Sheet (GrIS) from the Last Glacial Maximum (LGM) to present to improve our understanding of its response to climate change. The study involved applying a glaciological model in series with a glacial isostatic adjustment and relative sea-level (RSL) model. The model reconstruction builds upon the work of Simpson et al. (2009) through four main extensions: (1) a larger constraint database consisting of RSL and ice extent data; model improvements to the (2) climate and (3) sea-level forcing components; (4) accounting for uncertainties in non-Greenland ice. The research was conducted primarily to address data-model misfits and to quantify inherent model uncertainties with the Earth structure and non-Greenland ice. Our new model (termed Huy3) fits the majority of observations and is characterised by a number of defining features. During the LGM, the ice sheet had an excess of 4.7 m ice-equivalent sea-level (IESL), which reached a maximum volume of 5.1 m IESL at 16.5 cal ka BP. Modelled retreat of ice from the continental shelf progressed at different rates and timings in different sectors. Southwest and Southeast Greenland began to retreat from the continental shelf by ~16 to 14 cal ka BP, thus responding in part to the Bølling-Allerød warm event (c. 14.5 cal ka BP); subsequently ice at the southern tip of Greenland readvanced during the Younger Dryas cold event. In northern Greenland the ice retreated rapidly from the continental shelf upon the climatic recovery out of the Younger Dryas to present-day conditions. Upon entering the Holocene (11.7 cal ka BP), the ice sheet soon became land-based. During the Holocene Thermal Maximum (HTM; 9-5 cal ka BP), air temperatures across Greenland were marginally higher than those at present and the GrIS margin retreated inland of its present-day southwest position by 40–60 km at 4 cal ka BP which produced a deficit volume of 0.16 m IESL relative to present. In response to the HTM warmth, our optimal model reconstruction lost mass at a maximum centennial rate of c. 103.4 Gt/yr. Our results suggest that remaining data-model discrepancies are affiliated with missing physics and sub-grid processes of the glaciological model, uncertainties in the climate forcing, lateral Earth structure, and non-Greenland ice (particularly the North American component). Finally, applying the Huy3 Greenland reconstruction with our optimal

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Earth model we generate present-day uplift rates across Greenland due to past changes in the ocean and ice loads with explicit error bars due to uncertainties in the Earth structure. Present-day uplift rates due to past changes are spatially variable and range from 3.5 to −7 mm/a (including Earth model uncertainty).

1. Introduction

Between 26.5 and 19 thousand years before present (ka BP) global ice volume reached and maintained a maximum value resulting in global mean sea-level being 120–135 m below present (Clark and Mix, 2002; Lambeck et al., 2002; Milne et al., 2002; Clark et al., 2009; Austerman et al., 2013). During this period, known as the Last Glacial Maximum (LGM), there was large-scale glaciation across North America and Eurasia as well as more extensive ice in Greenland and Antarctica. The subsequent deglaciation and transition to a warmer interglacial climate saw the disappearance of the North American and Eurasian ice complexes, glaciers and ice caps shrank and withered away, and the mass of the Antarctic and Greenland ice sheets was significantly reduced. This change in the distribution of ice has left its mark on the landscape. Resultant features such as recessional moraines provide a direct means of reconstructing ice extent (e.g. Dyke and Prest, 1987). The transfer of water to oceans that accompanied these changes lead to a global-scale visco-elastic response of the solid Earth (e.g. Peltier and Andrews, 1976; Clark et al., 1978). Vertical land motion in previously glaciated areas resulted in raised marine deposits and landforms which provide valuable indirect information on changes in ice extent (e.g. Lambeck et al., 1998). Information from ice core records has also been used to constrain past ice thickness changes (Vinther et al., 2009). In this study, we apply a range of direct and indirect observations of ice extent and relative sea-level (RSL) to reconstruct the Greenland ice sheet (GrIS) during its most recent deglaciation.

The rapid change in global RSL and climate following the LGM had dramatic consequences for the evolution of the GrIS. Geological observations suggest that during the LGM the GrIS extended across large portions of the continental shelf and, in some areas, extended as far as the shelf break (e.g. Larsen et al., 2010; O'Cofaigh et al., 2013). This LGM maximum for the GrIS has been affiliated with an increase in volume of 2–3 m ice equivalent sea level (IESL) relative to present (Clark and Mix, 2002). In this study the term IESL refers to barystatic sea level, which is defined as the global mean sea-level change associated with the change of mass in the ocean (Gregory et al., 2013), additionally we account for a changing ocean area since the LGM (It is important to note, however, that this definition of IESL does not account for the increase in ocean basin volume associated with the retreat of marine-based ice. It is used here only to provide an additional measure of ice volume). During the subsequent deglaciation, the GrIS retreated initially through the calving of its marine-based ice as sea levels rose (Funder and Hansen, 1996; Kuijpers et al., 2007). By approximately 10 cal ka BP, the GrIS was mainly land-based with the exception of some outlet glaciers (e.g. Funder et al., 2011a), after which time, retreat slowed and was dominated by surface melt. During the Holocene Thermal Maximum (HTM), between about 9 and 5 cal ka BP, air temperatures across Greenland were warmer than present (Kaufman et al., 2004). It has been suggested that, in some areas, the GrIS retreated inland of its present-day margin in response to the HTM. It attained a post-LGM ice volume minimum around 4 cal ka BP (Simpson et al., 2009). During the subsequent Neoglacial readvance (Kelly, 1980), all direct geomorphological evidence pertaining to the minimum configuration was overridden. Thus, the ice sheet's minimum configuration can only be inferred from RSL and ice-core records.

The motivation of this research is to more accurately understand the response of the GrIS to past climate change to better predict its future. For example, better constraining the response of the ice sheet to the HTM (a part analogue for future regional climate) is one clear application of using the past behaviour of the ice sheet to assess and inform how it will respond in the future. The necessity to understand the current state of the GrIS is becoming increasingly evident. The GrIS is in dynamic and thermodynamic disequilibrium (on millennial and longer time-scales). This must be accounted for to accurately predict its future behaviour. Furthermore, future projection of GrIS mass loss for a given climate scenario relies on accurate estimates of contemporary mass loss. In this regard, satellite altimetry, interferometry, and gravimetry data sets have been applied to estimate the mass balance of the GrIS (Shepherd et al., 2012; Wouters et al., 2013); the results indicate that the GrIS lost mass at an accelerated rate with a total loss of 142 ± 49 Gt/yr between 1992 and 2011. However, prior to extracting mass loss using these data sets, it is necessary to correct them for the present-day vertical motion of the solid Earth due to past load changes. The glacial isostatic adjustment (GIA) model presented here, including uncertainties in the ice chronology and Earth structure, can be used directly for this purpose.

Several distinct approaches have previously been used to reconstruct the most recent GrIS deglaciation (Huybrechts, 2002; Tarasov and Peltier, 2002; Fleming and Lambeck, 2004; Peltier, 2004; Simpson et al., 2009), each having advantages and disadvantages. The disadvantages include a lack of glaciological self-consistency (Peltier, 2004) to the use of a small set of observational constraints (Huybrechts, 2002). The current study builds upon the work of Simpson et al. (2009) (henceforth referenced as the Simpson study). They employed a three-dimensional ice sheet model forced by prescribed climatic conditions (e.g. Huybrechts, 2002). Output from the glaciological model was constrained to ice extent observations and RSL observations.

In this study, we initially adopt the Simpson model reconstruction of GrIS evolution (termed Huy2) and then improve it. The Huy2 reconstruction was achieved by simultaneously tuning/calibrating a 3-D thermomechanical ice sheet model in series with a GIA model of sea-level change. The ice sheet model was tuned through its ensemble parameters to generate hundreds of GrIS evolution histories, while the GIA model of RSL change was calibrated to yield a probability distribution based on data-model fits with respect to model parameters. As in the Simpson study, this procedure is herein referred to as simply calibrating the model. Our new reconstruction adopts this methodological approach but with four extensions. Firstly, we employ additional RSL and ice extent constraints, which are detailed in Section 2. Key additions are an up-to-date Greenland-wide marine limit data base (K. Kjeldsen and S. Funder, personal communication) and ice-core derived thinning curves (from GRIP, NGRIP, Dye-3, and Camp Century), which constrain elevation changes of the ice surface for the period 8 cal ka BP to present (Vinther et al., 2009; Lecavalier et al., 2013). We also employ two improvements in the ice model: these are (1) a better parameterization of the positive degree day (PDD) algorithm for computing surface mass balance changes (Wake and Marshall,