Quaternary Science Reviews 169 (2017) 148–172

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Deglaciation of the Eurasian ice sheet complex

Henry Patton [a,*], Alun Hubbard [a], Karin Andreassen [a], Amandine Auriac [b], Pippa L. Whitehouse [b], Arjen P. Stroeven [c,d], Calvin Shackleton [a], Monica Winsborrow [a], Jakob Heyman [e], Adrian M. Hall [c]

[a] CAGE—Centre for Arctic Gas Hydrate, Environment and Climate, Department of Geosciences, UiT The Arctic University of Norway, 9037 Tromsø, Norway
[b] Department of Geography, Durham University, South Road, Durham, DH1 3LE, UK
[c] Geomorphology and Glaciology, Department of Physical Geography, Stockholm University, Stockholm, Sweden
[d] Bolin Centre for Climate Research, Stockholm University, Sweden
[e] Department of Earth Sciences, University of Gothenburg, Sweden

ARTICLE INFO

Article history:
Received 11 March 2017
Received in revised form
17 May 2017
Accepted 22 May 2017

Keywords:
Eurasian ice sheet complex
Barents sea
Fennoscandian ice sheet
Late Weichselian
Deglaciation
Glacio-isostatic adjustment
Subglacial lakes
Proglacial hydrology
Younger Dryas
Fleuve Manche

ABSTRACT

The Eurasian ice sheet complex (EISC) was the third largest ice mass during the Last Glacial Maximum with a span of over 4500 km and responsible for around 20 m of eustatic sea-level lowering. Whilst recent terrestrial and marine empirical insights have improved understanding of the chronology, pattern and rates of retreat of this vast ice sheet, a concerted attempt to model the deglaciation of the EISC honouring these new constraints is conspicuously lacking. Here, we apply a first-order, thermo-mechanical ice sheet model, validated against a diverse suite of empirical data, to investigate the retreat of the EISC after 23 ka BP, directly extending the work of Patton et al. (2016) who modelled the build-up to its maximum extent. Retreat of the ice sheet complex was highly asynchronous, reflecting contrasting regional sensitivities to climate forcing, oceanic influence, and internal dynamics. Most rapid retreat was experienced across the Barents Sea sector after 17.8 ka BP when this marine-based ice sheet disintegrated at a rate of ~670 gigatonnes per year (Gt a^{-1}) through enhanced calving and interior dynamic thinning, driven by oceanic/atmospheric warming and exacerbated by eustatic sea-level rise. From 14.9 to 12.9 ka BP the EISC lost on average 750 Gt a^{-1}, peaking at rates >3000 Gt a^{-1}, roughly equally partitioned between surface melt and dynamic losses, and potentially contributing up to 2.5 m to global sea-level rise during Meltwater Pulse 1A. Independent glacio-isostatic modelling constrained by an extensive inventory of relative sea-level change corroborates our ice sheet loading history of the Barents Sea sector. Subglacial conditions were predominately temperate during deglaciation, with over 6000 subglacial lakes predicted along with an extensive subglacial drainage network. Moreover, the maximum EISC and its isostatic footprint had a profound impact on the proglacial hydrological network, forming the *Fleuve Manche* mega-catchment which had an area of ~2.5×10^6 km^2 and drained the present day Vistula, Elbe, Rhine and Thames rivers through the Seine Estuary. During the Bølling/Allerød oscillation after c. 14.6 ka BP, two major proglacial lakes formed in the Baltic and White seas, buffering meltwater pulses from eastern Fennoscandia through to the Younger Dryas when these massive proglacial freshwater lakes flooded into the North Atlantic Ocean. Deglaciation temporarily abated during the Younger Dryas stadial at 12.9 ka BP, when remnant ice across Svalbard, Franz Josef Land, Novaya Zemlya, Fennoscandia and Scotland experienced a short-lived but dynamic re-advance. The final stage of deglaciation converged on present day ice cover around the Scandes mountains and the Barents Sea by 8.7 ka BP, although the phase-lagged isostatic recovery still continues today.

1. Introduction

Northern Eurasia was covered by three semi-independent ice sheets that between 26 and 19 ka BP (Clark et al., 2009) coalesced to form a single Eurasian ice sheet complex (EISC) during the last

* Corresponding author.
E-mail address: henry.patton@uit.no (H. Patton).

http://dx.doi.org/10.1016/j.quascirev.2017.05.019

glacial maximum (LGM) (Svendsen et al., 2004). This complex had an impressive latitudinal and longitudinal coverage, with continuous ice cover spanning over 4500 km extending southwest of the Isles of Scilly (50°N, 6°W) on the Atlantic seaboard to beyond Franz Josef Land (81°N, 56°E) in the Russian High Arctic (Fig. 1). It was the third largest ice mass after the North American and Antarctic ice sheets, and, with a combined volume three times the present Greenland ice sheet, accounted for at least 20 m of eustatic sea-level lowering (Patton et al., 2016). Growth of the EISC initiated from three main nucleation centres located over Britain and Ireland, Fennoscandia, and the Barents-Kara seas, with contrasting styles of glaciation and associated conditions and processes reflecting these settings, from marine-terminating, fast-flowing ice streams in maritime regions to extensive frozen-based glaciation in inter-ice-stream and upland areas.

Knowledge of the maximum extent, chronology, and patterns of retreat of the EISC has improved greatly in the last decade, particularly in offshore sectors where marine geophysical surveys have addressed a number of notable gaps in understanding (e.g., Landvik et al., 2005; Ottesen et al., 2005; Bradwell et al., 2008; Dunlop et al., 2010; Winsborrow et al., 2010; Andreassen et al., 2014; Sejrup et al., 2016). Moreover, developments in cosmogenic exposure dating, as well as refinement of radiocarbon and other dating techniques, has enabled detailed onshore deglaciation chronologies to be developed (Rinterknecht et al., 2006; Linge et al., 2007; Ballantyne, 2010; Stroeven et al., 2011; Briner et al., 2016). Subsequent publication of data-rich compilations and review studies has thus set in place a strengthened empirical framework against which modelling investigations of the EISC can be made and tested (Napieralski et al., 2007; Clark et al., 2012; Hormes et al., 2013; Hughes et al., 2014, 2016; Patton et al., 2015; Auriac et al., 2016; Cuzzone et al., 2016; Stroeven et al., 2016), although the utility of such empirical datasets for modelled reconstruction comparisons must be considered in light of the quality of legacy data they incorporate (e.g., Small et al., 2017).

Since the early numerical modelling undertaken as part of the QUEEN programme (cf. Siegert and Dowdeswell, 2004), progress on modelling the Late Glacial retreat of the EISC has been limited to a number of regional reconstructions (Holmlund and Fastook, 1993; Boulton et al., 2001; Boulton and Hagdorn, 2006; Hubbard et al., 2009) or otherwise focussed primarily on process dynamics (Arnold and Sharp, 2002; Forsström and Greve, 2004; Näslund et al., 2005; van den Berg et al., 2008a, 2008b, Clason et al., 2014, 2016). An alternative to these process-based models are EISC reconstructions developed through glacial isostatic adjustment modelling (Peltier, 2004; Lambeck et al., 2010; Peltier et al., 2015). These inverse models are calibrated using empirically determined ice extents and relative sea-level data, but the resulting reconstructions are static and do not provide insight into the dynamics of ice sheet retreat, nor do they inform the climatic/oceanic forcing that drove it.

In this paper, we apply a first-order, thermomechanical ice sheet model to investigate the dynamic retreat of the EISC after 23 ka BP. The primary aims are twofold: i) to present a robust, 4D high-resolution, synoptic reconstruction of EISC deglaciation from 23 to 8 ka BP, from its local LGM extent, through the Younger Dryas stadial (12.9–11.7 ka BP), and into the Early Holocene; and, ii) to validate and discuss model output against a suite of empirical data that constrain both the pattern and rate of retreat of the EISC, including its glacial-isostatic footprint, chronological data for the timing of deglaciation, flowset vectors, and its sub- and pro-glacial hydrological legacy.

The study extends the work of Patton et al. (2016) who previously explored the asynchronous and asymmetric growth of the EISC to its maximum LGM extent from 37 to 19 ka BP. A variety of geomorphological, geophysical and geochronological data are used to constrain and validate the broad-scale dynamics of the retreating ice mass. In particular though, where terrestrial constraints are notably lacking across the relatively data-sparse Barents and Kara seas, we utilise glacial isostatic adjustment modelling to test transient ice loading and retreat rates.

2. Methods

2.1. The ice flow model

The 3D thermomechanical model and associated initial boundary condition data applied are of the same derivation as that used to previously model the pre-LGM build-up of the EISC by Patton et al. (2016), where a more complete description of the model setup and implementation can be found. In brief, the ice flow model is a first-order approximation of the Stokes equations, adapted from Blatter (1995), Hubbard (1999, 2000), Marshall et al. (2005), and Pollard and DeConto (2007). The approach to solving the three dimensional stress/strain field equates to the L1L2 classification of higher-order models defined by Hindmarsh (2004), and includes longitudinal (membrane) stresses that become increasingly important across steep gradients in topography and motion. The model is integrated forward through time on a finite-difference grid with a resolution of 10 km through perturbations in climate and eustatic sea level (Fig. 2A–B). Isostatic loading is implemented using an elastic lithosphere/relaxed asthenosphere scheme described by Le Meur and Huybrechts (1996), which provides a computationally pragmatic solution in the absence of a full spherical earth model. Gridded output is projected under an equal area Lambert Azimuthal projection, with a central meridian of 73°E.

Surface mass balance is determined by a positive degree-day scheme, applied according to Laumann and Reeh (1993), and derives total melt from integrated monthly positive temperatures. Both temperature and precipitation adjust to the evolving ice sheet surface through applied lapse rates derived from multiple-regression analyses of meteorological observations at a resolution of 1 km from the WorldClim database (Hijmans et al., 2005; Version 1.4). To account for the large variations in climate regime across the Eurasian domain, regional reference climates and associated forcing are tuned independently for each of the three major accumulation centres (Fig. 2C–D). An additional mass balance term incorporated is the net water vapour flux to and from the ice sheet surface – a predominant component of ablation in cold continental settings where humidity can be very low (e.g., Fujii and Kusunoki, 1982; Kameda et al., 1997).

Calving losses at marine-terminating margins are coupled to relative sea level (RSL) (Waelbroeck et al., 2002) using a standard empirical function relating the calving flux to ice thickness and water depth (Brown et al., 1982; van der Veen, 1999). The sensitivity of calving to, for example, variations in ocean temperature (Luckman et al., 2015) and sea-ice buttressing (Hoff et al., 2016) is controlled spatially and temporally through a depth-scaled calving parameterisation (Hubbard, 2006) (Fig. 2D). In the absence of explicit calculations of such external feedbacks, this depth-related calving coefficient provides a pragmatic and computationally efficient parameterisation for determining mass loss at marine terminating margins of the ice complex. The model is applied to a 10 km finite-difference mesh with the inclusion of grounding-line dynamics based on the analytical boundary-treatment of Schoof (2007) and adapted in 2D by Pollard and DeConto (2007), which defines the ice flux at the grounding line as a function of ice thickness linearly interpolated between the adjacent node that bracket floating and grounded ice (Hubbard et al., 2009).