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Relative sea-level changes and crustal movements in Britain and Ireland since the Last Glacial Maximum

Ian Shennan [a, *], Sarah L. Bradley [b], Robin Edwards [c]

[a] *Sea-Level Research Unit, Department of Geography, Durham University, Durham, UK*
[b] *Department of Geoscience and Remote Sensing, Delft University of Technology, Delft, The Netherlands*
[c] *School of Natural Sciences, Trinity College Dublin, Dublin 2, Republic of Ireland*

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ABSTRACT

The new sea-level database for Britain and Ireland contains >2100 data points from 86 regions and records relative sea-level (RSL) changes over the last 20 ka and across elevations ranging from ~+40 to −55 m. It reveals radically different patterns of RSL as we move from regions near the centre of the Celtic ice sheet at the last glacial maximum to regions near and beyond the ice limits. Validated sea-level index points and limiting data show good agreement with the broad patterns of RSL change predicted by current glacial isostatic adjustment (GIA) models. The index points show no consistent pattern of synchronous coastal advance and retreat across different regions, ~100–500 km scale, indicating that within-estuary processes, rather than decimetre- and centennial-scale oscillations in sea level, produce major controls on the temporal pattern of horizontal shifts in coastal sedimentary environments.

Comparisons between the database and GIA model predictions for multiple regions provide potentially powerful constraints on various characteristics of global GIA models, including the magnitude of MWP1A, the final deglaciation of the Laurentide ice sheet and the continued melting of Antarctica after 7 ka BP.

1. Introduction

Four factors combine to make coastal Britain and Ireland a unique laboratory to determine the global, regional and local drivers of sea-level change. First, the sediment archives and landforms of coastal sites spread across the islands of Britain and Ireland produce more than two thousand quantitative constraints on the age and elevation of sea level since the Last Glacial Maximum (LGM). Second, the glacial isostatic response created by the growth and decay of the Celtic Ice Sheet (Patton et al., 2017), which covered the whole of Ireland and most of Britain at its maximum extent, produces radically contrasting records of relative sea-level (RSL) change across the region (Brooks et al., 2008; Shennan et al., 2012). Third, marine terminating ice streams facilitated rapid deglaciation and therefore the potential of field-based research to produce RSL records more than 15,000 years in length (Shennan et al., 2006). Finally, the region lies peripheral to the much larger Fennoscandian ice sheet and subject to proglacial forebulge collapse. In quantitative modelling of glacial isostatic adjustment (GIA), the small Celtic Ice Sheet situated on the Fennoscandian forebulge produces a distinctive combination to help constrain Earth model parameters (Bradley et al., 2011; Peltier et al., 2002). In combination, these factors should allow us to constrain the varying importance, through space and time, of the different processes which control relative sea-level change and coastal evolution. These processes range spatially from local, to regional, to global and temporally from a few seconds to millennia.

In order to better understand the driving mechanisms of sea-level change at different scales since the LGM, compilation and screening of sea-level data from Britain and Ireland commenced during International Geological Correlation Programme (IGCP) Project 61 (1974–1982) using an internationally agreed format (Preuss, 1979; Tooley, 1982) and many of the original principles remain central to the current protocol for a geological sea-level database (Hijma et al., 2015). Studies using the first compilations of radiocarbon-dated sea-level index points considered the interplay between GIA and global ice-volume equivalent (also known as eustatic) sea-level change (Flemming, 1982) and the landward and

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* Corresponding author.

E-mail addresses: ian.shennan@durham.ac.uk (I. Shennan), d80ngv@gmail.com (S.L. Bradley), robin.edwards@tcd.ie (R. Edwards).

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seaward shifts in sedimentary environments as evidence of decimeter-scale oscillations of sea level (Shennan, 1982a; b). The growing volume and quality of the data, coupled with the very different sea-level histories between sites beneath the thickest parts of the Celtic Ice sheet and those beyond the LGM ice limits, drew the attention of GIA modelling groups (e.g. Lambeck, 1991; Peltier, 1998) and led to much collaborative research (e.g. Bradley et al., 2011; Kuchar et al., 2012; Milne et al., 2006; Peltier et al., 2002; Shennan et al., 2000; Shennan et al., 2002), improved modelling of changes in tidal range (Neill et al., 2010; Shennan et al., 2003; Uehara et al., 2006; Ward et al., 2016) and new field-based research to test research questions arising from the existing model-data comparisons (e.g. Barlow et al., 2014; Edwards et al., 2017; Massey et al., 2008). With the last major revisions of the databases from Britain (Shennan and Horton, 2002) and Ireland (Brooks and Edwards, 2006) more than a decade ago, our objective here is update and integrate these databases and address outstanding research questions.

In the first section below we provide a brief synopsis of the physical characteristics of the region which lead to the contrasting records of relative sea-level change evident in both modelled and field data. Next we describe the characteristics of the database and the methods employed to evaluate relative sea-level change for 86 regions across Britain and Ireland. In section 4 we present the updated database and a series of analyses to consider four outstanding research questions:

- How predictable is relative sea-level change across Britain and Ireland?
- Is relative sea-level change a primary driver of coastal advance and retreat on centennial timescales?
- How does the relative importance of local and regional controls on sea-level change vary?
- To what extent can near-field records constrain GIA models of global sea-level change since the Last Glacial Maximum?

Each of these questions involves, to varying degrees, comparisons between the sea-level database and RSL predictions from GIA models. We make comparisons with two published sets of predictions (Bradley et al., 2011; Kuchar et al., 2012) and a new variant of one of them. These simulations represent the current state of the art and provide a robust framework within which the field data can be assembled and evaluated. GIA model development in the region is an ongoing, iterative process that extends back over 20 years. The combined sea-level database for Britain and Ireland presented here will play a critical role in the next iteration, with the development of a new generation of Celtic ice sheet models developed as part of the BRITICE Project (Clark et al., 2017).

We conclude by suggesting opportunities for future research which we have identified from our present unknowns or uncertainties.

2. Regional setting

At the regional scale, ~1300 km from the Shetland Isles in the north to the Scilly Isles in the south, glacio-isostatic response to varying ice loads is a key driver of RSL change. Between 26 and 19 ka BP, the LGM, three semi-independent ice sheets coalesced to produce continuous ice cover from the edge of the continental shelf west of Ireland (Fig. 1) to beyond Franz Joseph Land (81°N, 56°E) in the high Arctic, a distance of more than 4500 km (Patton et al., 2017). Collectively, these three, the Celtic, Fennoscandian, and Barents Sea ice sheets, accounted for more than 20 m of eustatic sea-level lowering. The Celtic ice sheet was the smallest of the three, accounting for a little over 10% of their combined maximum volume. These differences in ice sheet size are important for GIA modelling as Earth model parameters obtained from regions beneath large ice sheets, such as the Laurentide, show RSL predictions are sensitive to the deeper Earth properties, especially lower mantle viscosity (Lambeck, 1995, 1996; Peltier, 1998, 2004). In contrast, the much smaller Celtic ice sheet produced a glacio-isostatic response that is highly sensitive to shallow Earth model parameters, especially lithospheric thickness and upper mantle viscosity (Lambeck et al., 1996; Peltier et al., 2002).

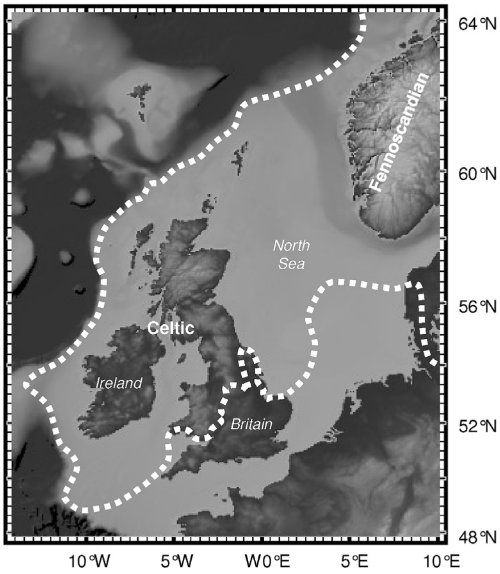

Fig. 1. Approximate maximum extent (dotted line) of the Celtic Ice Sheet, across Britain and Ireland, and the western part of the Fennoscandian Ice sheet between 25 and 23 ka BP (Patton et al., 2017).

Because of their similar magnitudes, global meltwater influx and glacio-isostatic rebound in northern Britain and Ireland result in RSL change that is highly non-monotonic in time as these processes dominate at different periods. Importantly, many coastal areas close to the centres of ice dispersal in northern Britain and Ireland were ice free relatively early, some perhaps by 20 ka BP (Clark et al., 2012), and more widely by 17 to 16 ka BP (Small et al., 2017). Landforms and sediments from these areas provide critical constraints on RSL reconstructions.

We see radically different patterns of RSL as we move to areas near to and beyond the LGM ice limits, with gradual sea-level rise dominating for most of the record. In these locations, early evidence of former RSL is more challenging to obtain, as it is typically deeply buried beneath thick sedimentary sequences or located on the submerged continental shelf. Nevertheless, a significant corpus of precise RSL data cover the entire Holocene, constituting one of the most comprehensive sea level datasets from anywhere in the world.

Once described as probably the most exotic region on Earth from the perspective of GIA (Peltier, 1998), the factors outlined above combine to make the region particularly suited to analysing and modelling the varying contributions of different processes to RSL change and the links between climate change, ice sheets, oceans, and the solid Earth. With the potential of long records, more than 15,000 years, RSL index points from Britain and Ireland combine with those from far-field locations to produce a particularly rigorous test for quantitative GIA models, ice sheet history and patterns of global ice-volume equivalent sea level, in addition to more local-scale studies of coastal sensitivity and change.