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

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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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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).

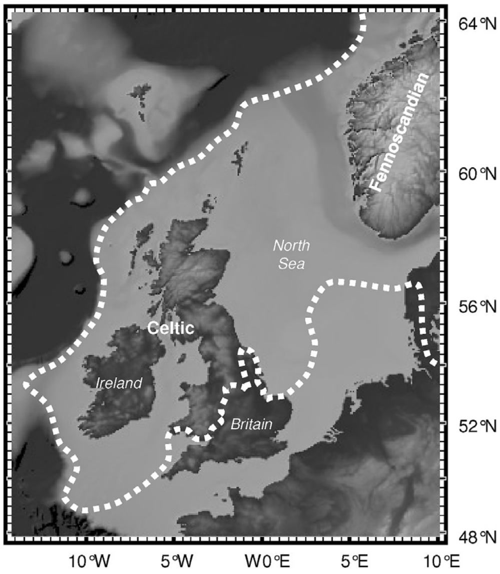

Fig. 1. Approximate maximum extent (dotted line) of the Celtic Ice Sheet, across Britain and Ireland, and the western part of the Fennoscandian Ice sheet between 25 and 23 ka BP (Patton et al., 2017).

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.

3. Database properties and methods

The original database was rather basic, comprising only details of age, altitude, co-ordinates, material sampled, site and laboratory code (Flemming, 1982; Shennan, 1982a; Tooley, 1982). The first major update (Shennan, 1989) produced an increase in the number of data points (Fig. 2) and the addition of more than sixty separate fields of information to allow reproducible, conditional filters to determine those index points considered reliable. The next update (Shennan and Horton, 2002), retaining essentially the same structure, significantly increased the number of sea-level index points. The database structure maps directly to the current protocol (Hijma et al., 2015).

The 2002 update contained two new elements. It introduced samples from freshwater peat that do not show a direct relationship to a contemporaneous tide level. These could have formed at a water level directly or indirectly controlled by tides, or at an unknown height above high tide level. Therefore they act as terrestrial or freshwater limiting data, in that RSL must have been at or below the elevation at which they are found. It also set out a methodology to align field-based investigations with the quantitative evaluation of GIA model predictions of RSL. Incremental adoption and enhancement of this approach, illustrated in section 4, encourages a hypothesis-testing approach to determine the drivers of sea-level change at different temporal and spatial scales (Shennan, 2015).

The database for Ireland developed semi-independently (Brooks and Edwards, 2006), following the same broad principles to define sea-level index points and terrestrial or freshwater limiting data. It also included marine limiting data, comprising radiocarbon ages on calcareous marine molluscs or foraminifera. In the absence of a quantifiable intertidal or subtidal position, each marine limiting data point took the upper limit of formation as highest astronomical tide, and indicates that RSL must have been at or above the elevation at which the sample was taken.

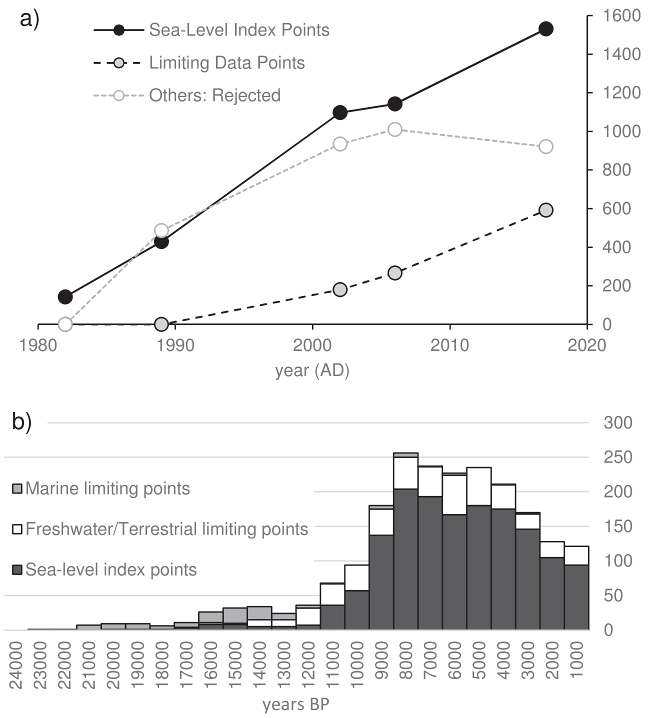

Fig. 2. a) Number of sea-level index points, limiting data points and rejected data points within the database 1982 to 2017, including intervening updates (Brooks and Edwards, 2006; Shennan, 1989; Shennan and Horton, 2002); b) frequency distribution, in 1000 year intervals, of sea-level index points and limiting data points in the 2017 database.

3.1. Key enhancements in the 2017 update

For this update we set out to include new sea-level index points from papers published since 2002 for Britain and since 2006 for Ireland. We also found a few papers missing from the earlier versions. We have merged the previously separate databases and aligned all the fields to meet the current agreed protocol (Hijma et al., 2015), as detailed in the supplementary files. We identified and corrected a few, <30, errors in the previous versions. We extracted many samples previously rejected in the 2002 database for Britain (Fig. 2a) by assessing further details in the original literature. These are mainly limiting dates, either peat or wood samples indicating terrestrial or freshwater maximum RSL elevations, or marine mollusc or foraminifera samples indicating minimum RSL elevations. Major advances in applying microfossil-based transfer methods to RSL reconstructions (summaries include Barlow et al., 2013; Kemp and Telford, 2015) and how these advances promoted radiocarbon-dating sampling strategies through whole units rather than concentrating on the boundaries between units led us to refine and expand the number of indicative meanings (Table 1). We have revised the age calibrations for all samples, using the latest downloadable version of CALIB (Stuiver et al., 2017) and the IntCal13 or Marine13 calibration curve option as relevant to each sample.

3.2. Key factors not quantified

Two critical processes complicate RSL reconstructions, changes in tidal range through time (Griffiths and Hill, 2015) and sediment compaction (Brain, 2015). Estimates of both of these require a range of assumptions and modelling approaches which are external to the database. We consider the effects of each in section 4 but stress that the choice of quantitative corrections to each index point is the responsibility of individual users of this database.

Previous investigations illustrate the importance of changes in tidal range around Britain and Ireland (Neill et al., 2010; Shennan et al., 2003; Uehara et al., 2006; Ward et al., 2016). For this paper we have revised the estimates of tidal range changes in eastern England (Shennan et al., 2003) based on the updated calibrated ages for each index point and introduced an uncertainty estimate based on the spatial variation of the predicted tidal range change. The uncertainty ranges from ±0.02 to ±0.20 m (95% range), depending upon age and location. Estimates for all index points from Britain and Ireland, building on recent advances (Ward et al., 2016), remain a future goal.

To illustrate and consider the potential influence of sediment compaction, in section 4, the RSL reconstructions show 5 types of data points, the marine limiting and terrestrial/freshwater limiting data points as described above, and three classes of sea-level index points: those from basal peat, those from within unconsolidated sediment sequences, termed intercalated data points, and those from lake basins, commonly call isolation basins. We hypothesise that the intercalated data are more susceptible to compaction than the basal peat data, whilst the isolation basin data have no compaction effect as the elevation is defined by the rock sill, not the elevation of the sediment sample.

4. Results and discussion

Age-elevation plots of the complete database (Fig. 3) summarise the regional-scale variation in RSL. The scatter reflects the total isostatic effect of the glacial rebound process, including the ice load,

Table 1
Summary of the indicative meanings used to calculate the relative sea levels for different types of index point. Mean high water of spring tides (MHWS), mean low water of spring tides (MLWS), mean tide level (MTL) and highest astronomical tide (HAT). *Indicative range may be greater than the number given where authors present additional evidence to indicate this.

Sample type	Evidence	Reference Water Level	Indicative Range*
Freshwater to high marsh transition	Fen wood peat directly below *Phragmites* peat or tidal marsh deposit	MHWS	±0.2 m
High marsh environment	Herbaceous or *Phragmites* peat directly above fen wood peat	MHWS-0.1 m	±0.2 m
High marsh environment	Herbaceous or *Phragmites* peat directly below tidal marsh deposit	MHWS-0.2 m	±0.2 m
Freshwater to high marsh transition	Fen wood peat directly above *Phragmites* peat or tidal marsh deposit	(MHWS + HAT)/2	±0.2 m
High marsh environment	Herbaceous or *Phragmites* peat directly below fen wood deposit	((MHWS + HAT)/2)-0.1 m	±0.2 m
High marsh environment	Herbaceous or *Phragmites* peat directly above tidal marsh deposit	((MHWS + HAT)/2)-0.2 m	±0.2 m
Freshwater/ Terrestrial limiting	Freshwater peat or wood that do not show a direct relationship to a contemporaneous tide level.	(MTL + HAT)/2	MTL to HAT
Isolation basins	Stage of isolation determined from lithology and microfossil assemblages	Uniquely defined, ranging from MTL to HAT	Uniquely defined, ranging from 0.2 to 0.6 m
Marine limiting	Marine shells or calcareous foraminifera in clastic sediment	MTL	<MLWS to MHWS
User defined	Quantitative estimate of reference water level based on proxy evidence, e.g. microfossil-based transfer function; or freshwater peat with eroded contact	Uniquely defined	Uniquely defined
Freshwater to high marsh transition	Herbaceous, *Sphagnum* or wood peat with supporting microfossil evidence to determine HAT	HAT	Uniquely defined

water load and rotational contributions to the redistribution of ocean mass. It shows a maximum measured differential of ~65 m around 13 ka BP. This differential would be greater prior to 13 ka BP but there are few data points constraining pre-Holocene RSL minima due to the challenges in accessing deeply buried or offshore material outlined above. The cone-shaped scatter of index points narrowing from 6 to 0 ka BP indicate differential motions continuing to the present day. These provide a first-order maximum range of RSL change prior to any effect from anthropogenic-driven 20th and 21st century climate change. The upper limit suggests a maximum rate of RSL fall in the order of 1.3 mm/a, averaged over millennia. The lower limit of the scatter, indicates RSL rise in the order of 2.0 mm/a. Because many of these index points come from intercalated peat, sediment compaction contributes to this rate of RSL rise.

In order to identify the separate driving mechanisms reflected in the regional-scale scatter (Fig. 3) we need to structure our analyses around testable hypotheses, first outlining the temporal and spatial dependency of potential controlling variables (Shennan, 2015). For each geographical location, and for each sea-level index point, we consider RSL to vary with time and location and to be a function of five factors (Shennan, 2015): (1) the time-dependent eustatic sea level, derived from a global GIA model, that would result by distributing any meltwater evenly across a rigid, non-rotating planet and neglecting self-gravitation in the surface load; (2) the total isostatic effect of the glacial rebound process including the ice load (glacio-isostatic), water load (hydro-isostatic) and rotational contributions to the redistribution of ocean mass; (3) the tectonic effect, which includes processes operating over long timescales such as plate motions and mountain building and dynamic topography, and short term such as uplift and subsidence during earthquakes; (4) the total effect of local processes within the coastal system, which include first, the total effect of tidal regime changes and any other influences, such as dynamic oceanographic and atmospheric effects, that may change the reference water level of a sea-level index point, and second, the total effect of sediment consolidation since the time of deposition; (5) the sum of other unspecified factors, either not quantified or not thought of. Implicitly most studies assume the total effect of the unspecified factors close to zero and random. Except for the eustatic factor, all the other factors, along with RSL, vary with time and location.

Therefore to proceed with further analyses we may split the database into smaller regions (Fig. 4 and Table 2) to summarise spatial variations, although we must keep in mind that there will be some variation within these smaller regions.

4.1. *How predictable is relative sea-level change across Britain and Ireland?*

Quantitative GIA models provide a basis for investigating the contribution of the five factors outlined above. Typically a GIA model has three key inputs: a model of the Late Quaternary ice history commencing at ~120 ka BP, an Earth model to reproduce the solid earth deformation resulting from surface mass redistribution between ice sheets and oceans, and a model of sea-level change to calculate the redistribution of ocean mass (which includes the influence of GIA-induced changes in Earth rotation). We use the terms eustasy/eustatic sea-level change in the sense of the ice-equivalent sea-level change, defined as the uniform shift of the height of the ocean surface that takes place in the absence of gravitational and rotational effects, ocean dynamics and solid Earth deformation, due to the input of meltwater to the ocean (Whitehouse and Bradley, 2013). We evaluate the predictability of RSL across Britain and Ireland with reference to two previously published GIA models for the region, supplemented by a third, new variant illustrating one of the ongoing research efforts. All three regional models share the same global GIA model (Bradley et al., 2016) which determines the far-field signal driven by the melting of the larger global ice sheets, predominantly Laurentide and Antarctica.

The first model, referred to as BRADLEY2011, represents the final version (Bradley et al., 2011) of a series of models that developed over a decade along with the growth of the sea-level database and the synergies they brought. In common with other models during that decade (e.g. Brooks et al., 2008; Milne et al., 2006; Peltier et al., 2002; Shennan et al., 2006; Shennan et al., 2000) the regional-scale ice model in each study was rather crudely constructed from published geomorphological constraints on ice sheet extent and elevation. These ice models contained no quantitative model of climate-driven glaciological processes.

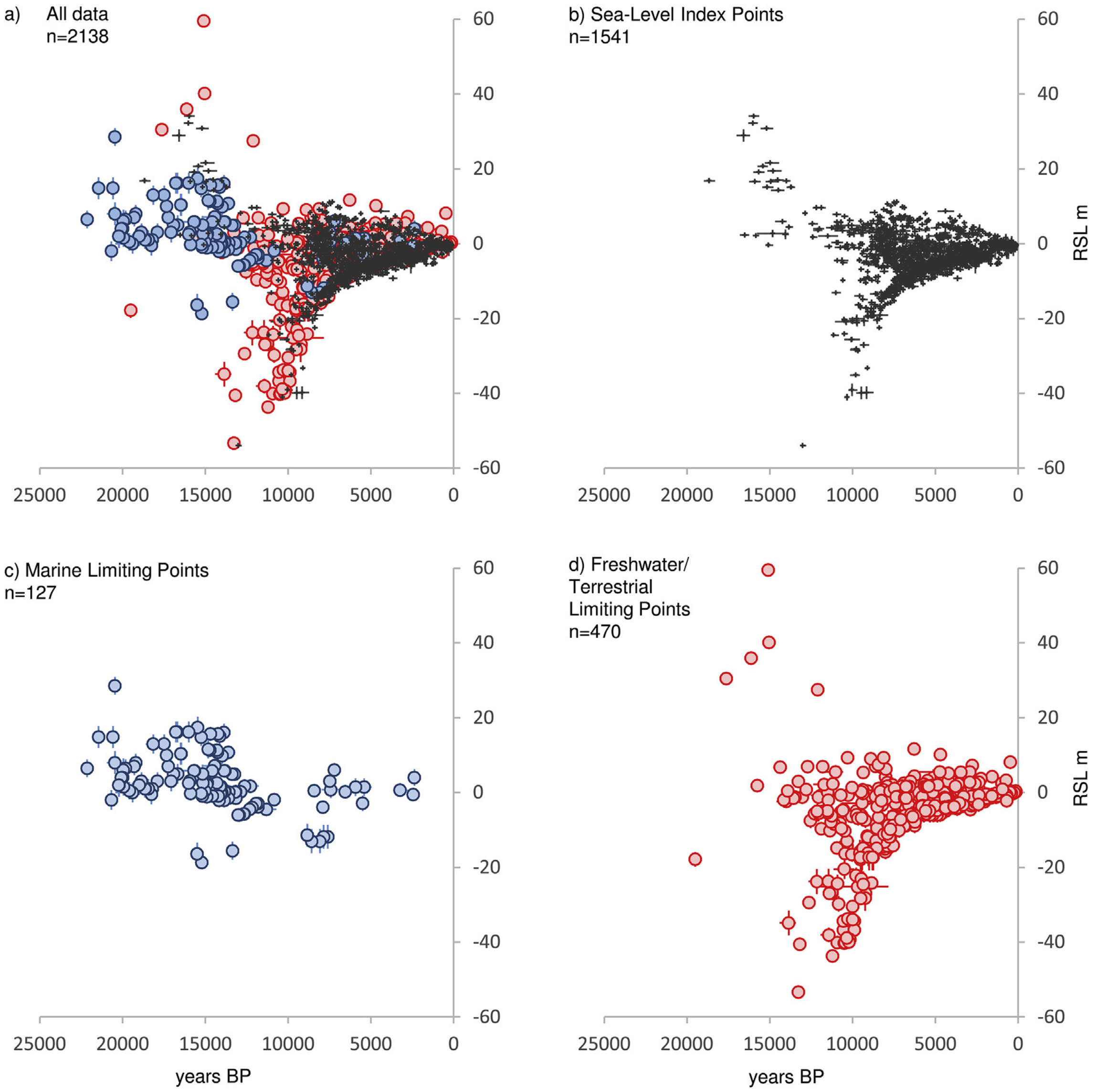

Fig. 3. Age-elevation plots of the data points. All data available in the Supplementary File.

Our second set of predictions, KUCHAR2012, represents one scenario from the first attempt to utilise quantitative models of climate-driven glaciological processes to reconstruct the Celtic ice sheet (Kuchar et al., 2012). The resulting ice sheet, whilst significantly thicker than the regional ice model employed in BRADLEY2011, was less laterally extensive than indicated by field data, particularly towards its south westerly margin.

The final set of predictions, BRADLEY2017, illustrate the impact of a higher grid resolution, ~35 km compared to ~70 km in the regional ice model, while keeping the same the Earth model parameters as BRADLEY2011. This high resolution approach is just one development that we anticipate will come to fruition in the future.

RSL predictions for 86 regions (Fig. 5a) illustrate the dramatic spatial variability in RSL history associated with the former Celtic ice sheet. In regions under the greatest ice load RSL change is non-monotonic, falling from well above present to a minimum in the early Holocene, rising to a mid-Holocene highstand, then falling to present (Fig. 4, group A regions). In contrast, regions at the ice sheet periphery record up to 120 m of predominantly continuous RSL rise (Fig. 4, group E regions). The 86 predictions cover the spectrum between these two extremes and reflect the spatial variation caused by GIA. The different ages for the start of RSL fall during the Dimlington Stadial (Fig. 5) primarily reflect the age at which the area became ice free in the model of the Celtic ice sheet.

Various characteristics of the eustatic sea-level changes appear as differences in rate or sign of RSL change dependent upon location (Fig. 5A). Two episodes of accelerated eustatic sea-level rise show distinct, predicted changes in RSL, the first between 14.5 and 13.5 ka BP, and a second from 11 to 10 ka BP. In the mid-to late Holocene, the abruptness of a predicted highstand at some sites and the inflection from relatively rapid rise to much slower rise at others reflect the final decay of the Laurentide ice sheet and the late Holocene contribution to global sea level from Antarctica.

Given the rigidity of the Earth's lithosphere, and assuming no significant active faulting, we can expect a spatial coherence in RSL, with nearby regions having similar patterns of RSL change (Fig. 6). Spatial variability of RSL change varies with respect to ice thickness. For example, across southern England, beyond the LGM ice limit, predicted RSL curves for the Thames Estuary and Cornwall, ~425 km apart, are very similar (Fig. 6B and C). Statistical measures

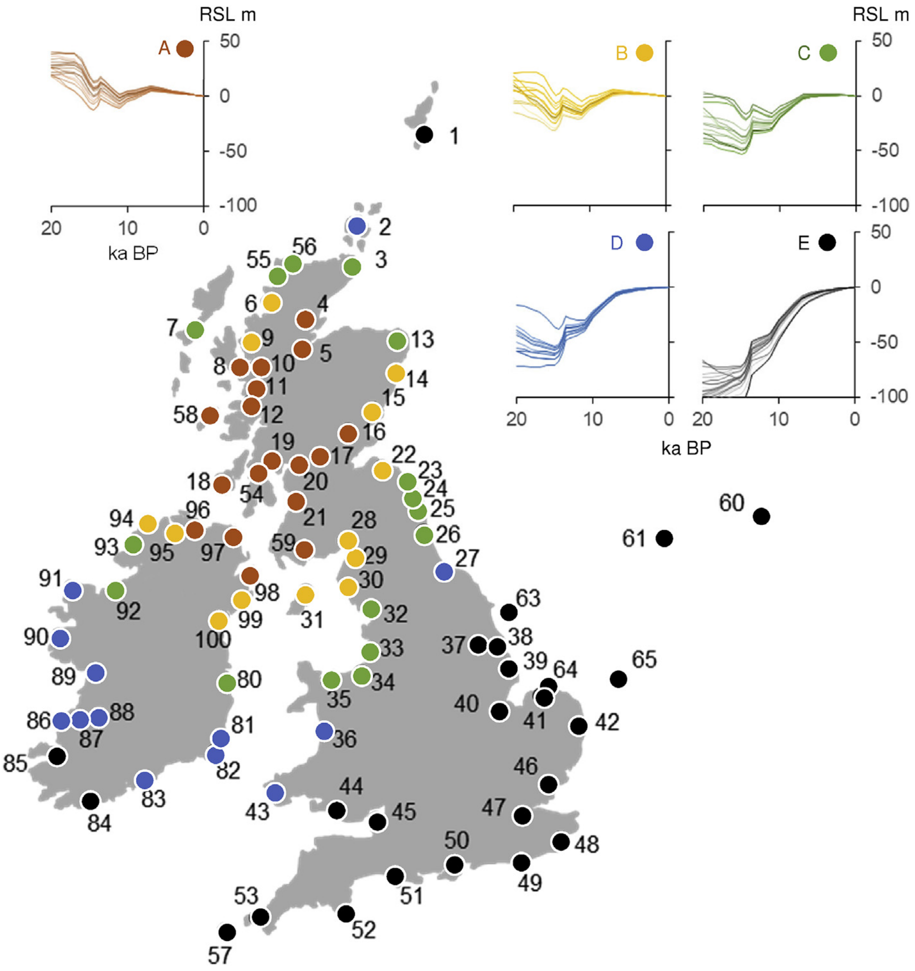

Fig. 4. Locations used for analysing the spatial variability of relative sea-level changes across Britain and Ireland (numbers, names and coordinates in Table 2). Regions sub-divided into 5 groups, A to E, to aid discussion, based on the broad pattern of predicted RSL change using the BRADLEY2011 model. Same colour scheme used for RSL graphs and locations on the map.

of similarity of RSL predictions for each pair of sites summarise the regional predictability of RSL change (Supplementary File contains the correlation matrix for all pairwise measures from the 86 sites) and we shall use this in section 4.2 to investigate whether RSL change is a primary driver of coastal advance and retreat.

In a similar fashion, the GIA predictions of RSL and their reflection of eustatic sea level allow us to investigate the relative importance of local and regional controls on RSL change, in section 4.3, and whether near-field records can constrain models of global sea-level change, in section 4.4. All of these require a comparison of the RSL reconstructions derived from the sea-level index points and limiting data with the GIA-predicted RSL curves.

4.1.1. *Comparison of sea-level reconstructions and predictions*

At the broadest scale, long records from regions around to the centre of the Celtic ice sheet clearly show a non-monotonic pattern of RSL fall prior to 10 ka BP, RSL rise in the early Holocene to a mid-Holocene highstand, and RSL fall to present (Fig. 7, regions 8, 9, 11, 12, 13, 14, 15, 16, 17, 20, 54, 95, 97, 98, 99, 100). Shorter records from sites nearby add further definition to the pattern of RSL rise to a mid-Holocene highstand and subsequent RSL fall (regions 4, 5, 6, 10, 18, 19, 21, 22, 23, 24, 25, 28, 29, 30, 31, 32, 33, 56, 59).

Immediately peripheral to these regions a number of other sites illustrate the gradual disappearance of any clear mid-Holocene highstand, in the north (regions 2, 3), along the east coast of England (south of region 25), the west coast of England and Wales (regions 34, 35), although weakly constrained in Ireland (regions 80, 81, 93).

Beyond these regions, RSL rise dominates. The longest records, with some index points ~10 ka BP or older, occur in a number of regions, frequently combining data from onshore and offshore sites (regions 36, 37, 38, 40, 41, 42, 44, 45, 47, 48, 49, 52, 60, 63, 65).

Virtually all of the regional plots of sea-level index points show a scatter of data points that do not overlap. This indicates one or more of the following: (1) underestimation of age and/or elevation error terms; (2) plotting data from a too large spatial extent, so incorporating differential GIA, even though we defined the extent of each region (Table 2) specifically to minimise this effect; (3) underestimation of factors that operate on the local scale, especially changes in tidal range and sediment compaction; (4) evidence of other unspecified factors, either not quantified or not thought of, including misinterpretation of field evidence for some index points. We can use scatter of sea-level index points and their degree of fit with RSL predictions from GIA models to address the series of research questions outlined in section 1, but first we should consider the fit of a particular GIA model. Indeed, using sea-level index points to constrain GIA model parameters is a key area of research, but not within the scope of this paper. Such efforts will follow publication of the new ice sheet constraints arising from the BRITICE Project. The KUCHAR2012 RSL predictions for the period

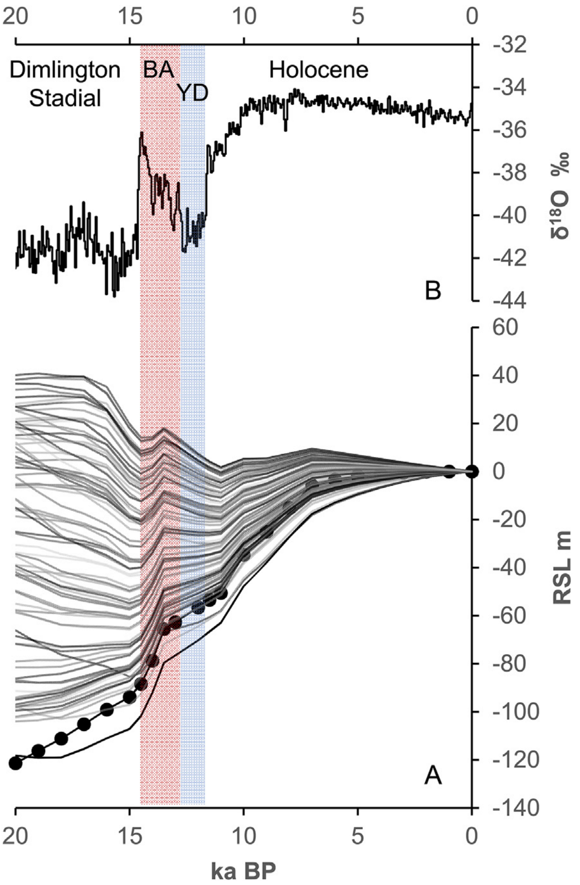

Fig. 5. A) Ice-equivalent (eustatic) sea level (black circles) and RSL predictions for 86 regions across Britain and Ireland (Fig. 4) based on the BRADLEY2011 GIA model; B) NGRIP Oxygen isotope record (Rasmussen et al., 2014) as a proxy for the major climate changes, including the first substantial warming at the start of the Bølling-Allerød (BA) and the return to cold conditions during the Younger Dryas (YD) during which an ice sheet developed across parts of Scotland.

prior to 10 ka BP lie well above index points or terrestrial limiting points in many regions around the centre of the Celtic ice sheet (8, 9, 11, 13, 16, 17, 20, 54). The predictions are also higher than the highest shorelines mapped in many regions. Although not directly dated, and therefore not in the database, they indicate the site was ice free when the shoreline formed, hence the oldest index point plotted for the region acts as a minimum age constraint. This model often provides the poorest fit during the Holocene (regions 6, 8, 10, 11, 12, 13, 14, 17, 18, 21, 37, 38, 54).

While KUCHAR2012 predicted too much isostatic rebound in regions around the centre of the Celtic ice sheet, the ice model used in both BRADLEY2011 and BRADLEY2017 produces too little rebound. This arose from a constraint used in developing the ice model. The ice model used the interpretation of glacial trimlines on mountains as the maximum surface elevation of the ice (Ballantyne et al., 1998). Changing this interpretation to indicating a thermal boundary within the ice (Ballantyne, 2010) removes this constraint on ice thickness and therefore the possibility to generate more rebound in future ice models (Edwards et al., 2017; Shennan et al., 2012). We see no systematic improvement in fit with respect to BRADLEY2011 or BRADLEY2017, although the latter does show a smaller mid-Holocene highstand, closer to the sea-level data points at some locations. For simplicity and clarity in the following sections we shall focus on comparisons between the sea-level data and the BRADLEY2011 predictions.

The most striking misfit occurs in N. Mayo (Region 91, Fig. 7) on the western coast of Ireland, where all RSL model variants plot several decametres below the marine limiting data points provided by radiocarbon-dated marine shells and foraminifera within raised glaciomarine muds at Belderg Pier and Fiddauntawnanoneen (McCabe et al., 2005). The mismatch between Lateglacial RSL elevations inferred from glaciosedimentary data and those predicted by GIA models remains a long-standing debate (Brooks et al., 2008; Edwards et al., 2008; Lambeck and Purcell, 2001; McCabe, 2008), with a tendency toward rather polarised views (Knight, 2017). Recently, Edwards et al. (2017) demonstrate that it is possible to simulate high Lateglacial RSL in western Ireland whilst fitting the field data that indicates RSL was below present for the duration of the Holocene. They conclude that a future GIA model with a thicker Irish Ice sheet component is required to resolve the current predicted RSL misfits in western Ireland.

4.2. Relative sea-level change as a primary driver of coastal advance and retreat on centennial timescales

One of the most hotly debated topics, since at least the 1940s, focusses on the existence of decimetre- and centennial-scale oscillations in sea level and whether they occur at global, regional or local scales (Gehrels and Shennan, 2015). One line of argument centres on the interpretation of field evidence of horizontal shifts of coastal sedimentary environments recorded by transgressive and regressive overlaps between peat and clastic units, often mapped across many 10s of kilometres. Transgressive and regressive overlaps are examples of the tendency of a sea-level indicator, describing the increase (positive sea-level tendency) or decrease (negative sea-level tendency) in marine influence recorded by that indicator. To identify sub-millenial scale changes we would expect to record changes both at a number of sites within the same region and across adjacent regions. The expression of the change in vegetation, stratigraphy, morphology or microfossils will be site specific, but a change in sea level of more than local significance should be recorded over the wider area. This change in sea level should be reflected in the mix of tendencies recorded in the system, reflecting whether or not sea-level change is the driving force for coastal evolution at that site at that time. While age-elevation plots of sea-level index points, with their associated errors, from multiple locations in the region are unlikely to reveal oscillations of sea level, analysis of the tendency for each index point, for example the lithostratigraphic and microfossil changes above and below each dated sample, could identify trends through time (Shennan, 2015). Initial attempts foundered due to insufficient numbers of index points (Shennan et al., 1983), but the much larger database now available allows a reappraisal.

Based on the predictability of predicted RSL change at nearby locations (section 4.1 and Fig. 6) we group regions together to test a working hypothesis that decimetre oscillations in sea level should produce a preponderance of positive sea-level tendencies during RSL rise and a preponderance of negative tendencies during RSL fall. The spatial scale of the groups ranges from ~100 to 500 km. The alternative working hypothesis is that the controls on sediment accumulation recording positive and negative tendencies, including transgressive and regressive overlaps are local-scale, within-estuary processes. We exclude regions with few data points and those with a strong isostatic influence, indicated by a distinct mid-Holocene highstand. Differential glacio-isostasy between regions leads to diachroneity in the start and end of oscillation, ranging from decades to a few centuries, depending on the wavelength and amplitude of the oscillation (Shennan, 2015). These exclusions leave us with two groups of regions covering the peripheral zone of a small to indistinct mid Holocene highstand,

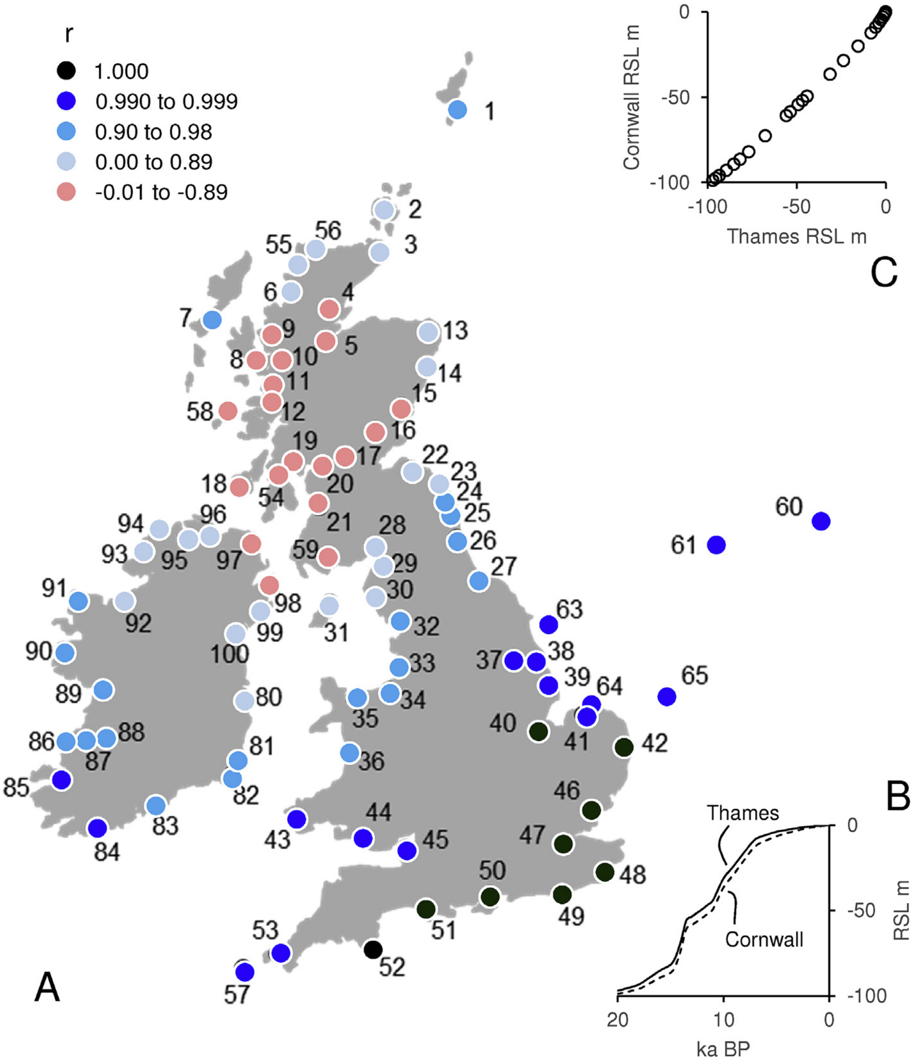

Fig. 6. A) Correlation coefficient (r) for RSL predictions from the BRADLEY2011 model for the Thames Estuary and the other 85 regions, B) RSL predictions 20 to 0 ka BP for the Thames Estuary and Cornwall and (C) their slightly non-linear relationship.

and four groups of regions dominated by RSL rise since 8 ka BP (Fig. 8).

Under millennial-scale RSL rise, typical of global ice-volume equivalent (eustatic) GIA models for the last 8 ka, RSL fall during shorter term oscillations should increase the occurrence of negative sea-level tendencies. We see no visible correlation in the peaks of negative tendencies across the regional groups (Fig. 8) and suggest within-estuary processes produce major controls on the temporal pattern of sea-level tendencies and horizontal shifts in coastal sedimentary environments.

4.3. The relative importance of local and regional controls on RSL change

Even for a best-fit RSL prediction we still expect to see a scatter of index points arising from a number of possible sources (section 4.1). In our assessment of any GIA model RSL prediction, assuming that we have not underestimated the uncertainty terms of the index points and the GIA prediction for a location close enough to ignore within-region differential GIA, we would define a best fit that lies through or below the terrestrial/freshwater limiting data, and through or above the marine limiting data. The best fit should also be through the data from isolation basins, as they are not affected by sediment compaction. Index points from basal peat and those intercalated within sediment sequences are likely to incorporate some effect of compaction, with the effect on intercalated likely greater. We are not in the position to model compaction for all index points (Brain, 2015) and have included no correction for this in the database, even where the original authors made an estimate. The numerical values for the estimated correction is often missing from the source papers (e.g. Devoy, 1982; Heyworth and Kidson, 1982). Future improvements would include modelling compaction using independently replicable methods and reporting the details. Therefore our current best fit solution should plot through the scatter of index points from basal peat and within or above the scatter of index points from intercalated peat. The scatter of index points below the GIA prediction, especially for estuaries in south and east England (Fig. 7, regions 37, 40, 41, 42, 45, 47, 48) indicate an average effect in the order of 0.4 mm a^{-1} (Horton and Shennan, 2009). Combining this at the local scale with the GIA RSL prediction more than doubles the estimated rate of relative land subsidence over the late Holocene (Shennan et al., 2012).

As outlined previously (section 3.2), modelling of changes in tidal regime for all regions of Britain and Ireland remains an

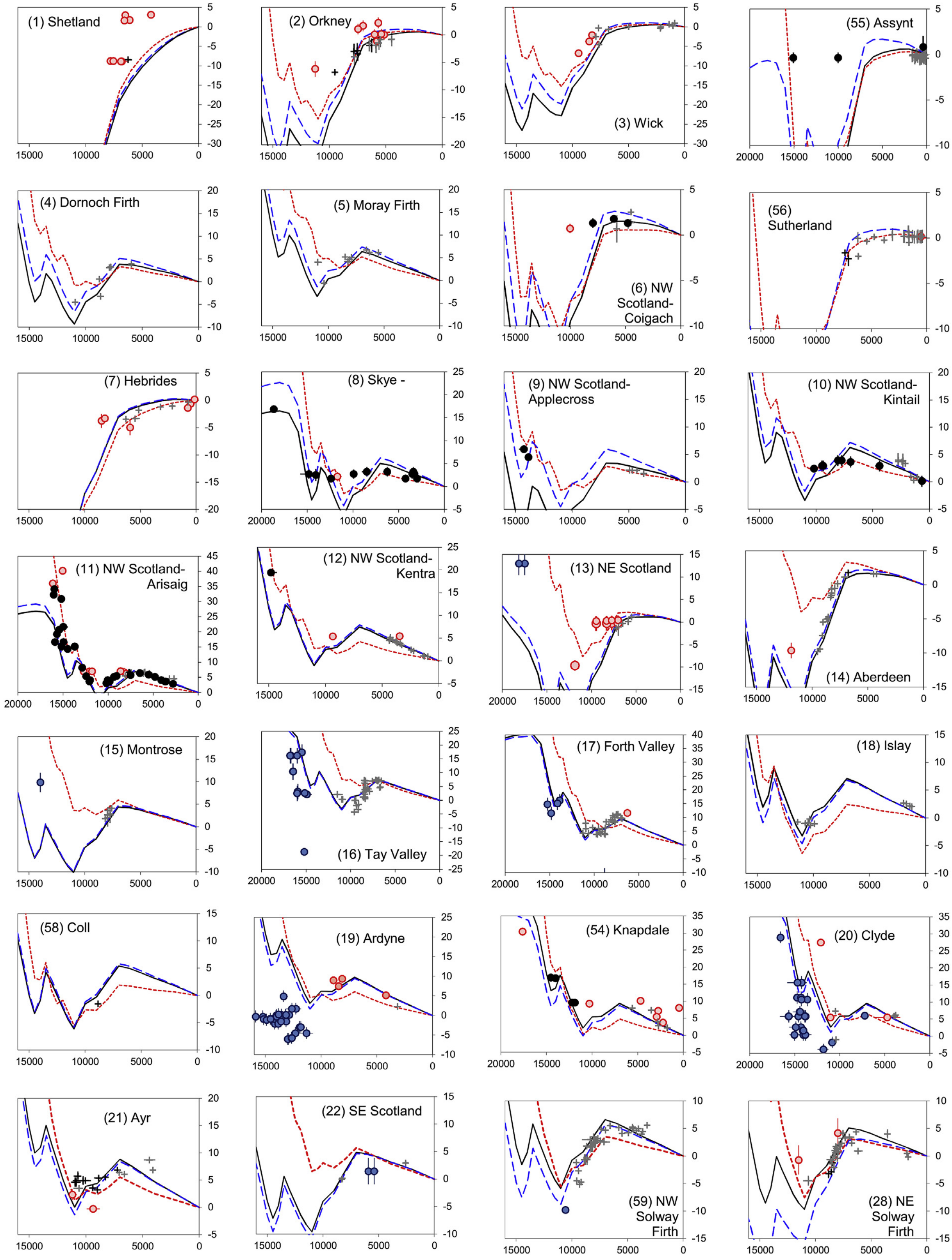

Fig. 7. Age – elevation plots for each region (Table 2) of sea-level index points, limiting data and RSL predictions for three GIA models. Note different scales for both age and elevation axes. 95% uncertainty terms visible where greater than the symbol size.

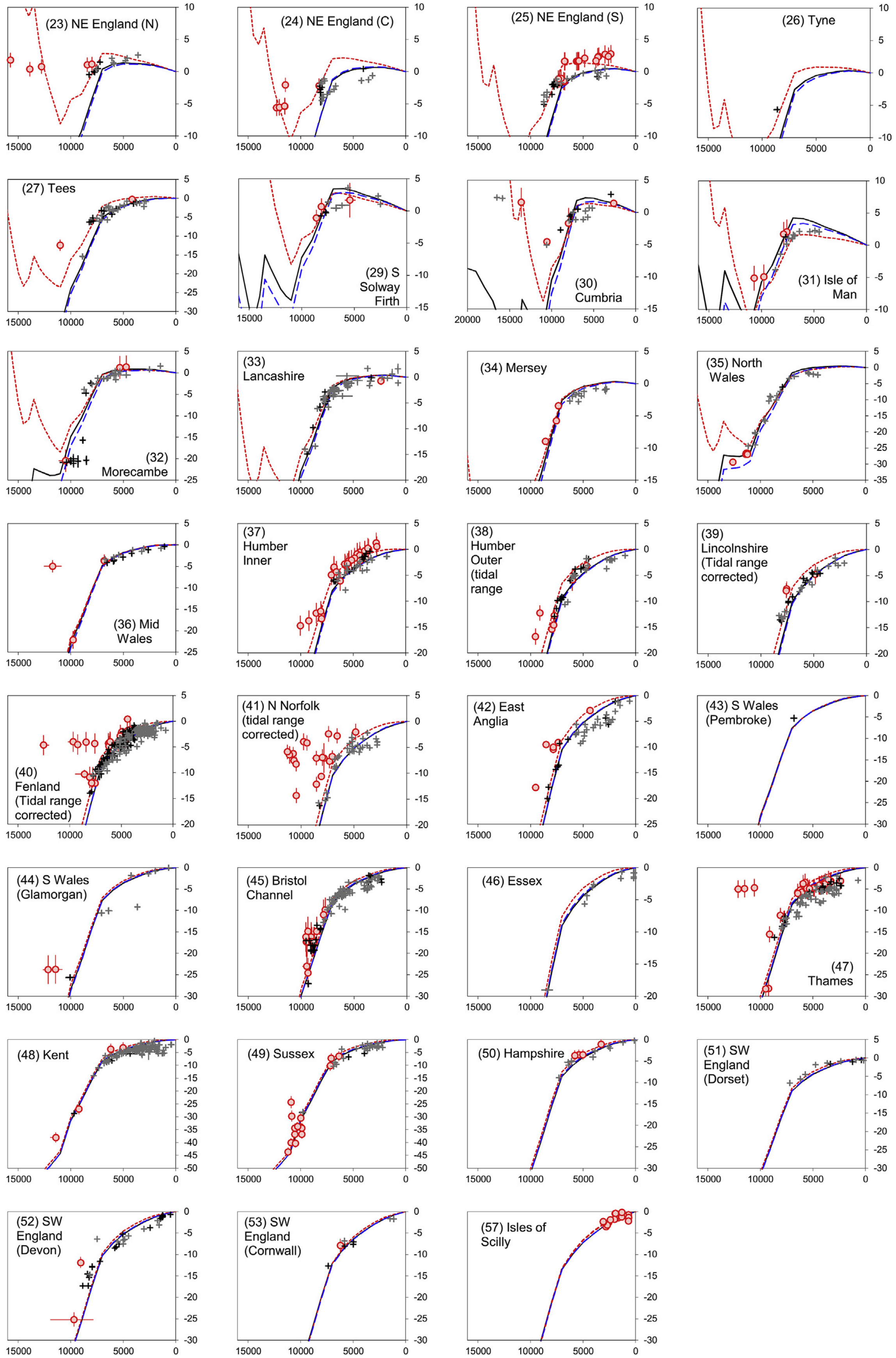

Fig. 7. (*continued*).

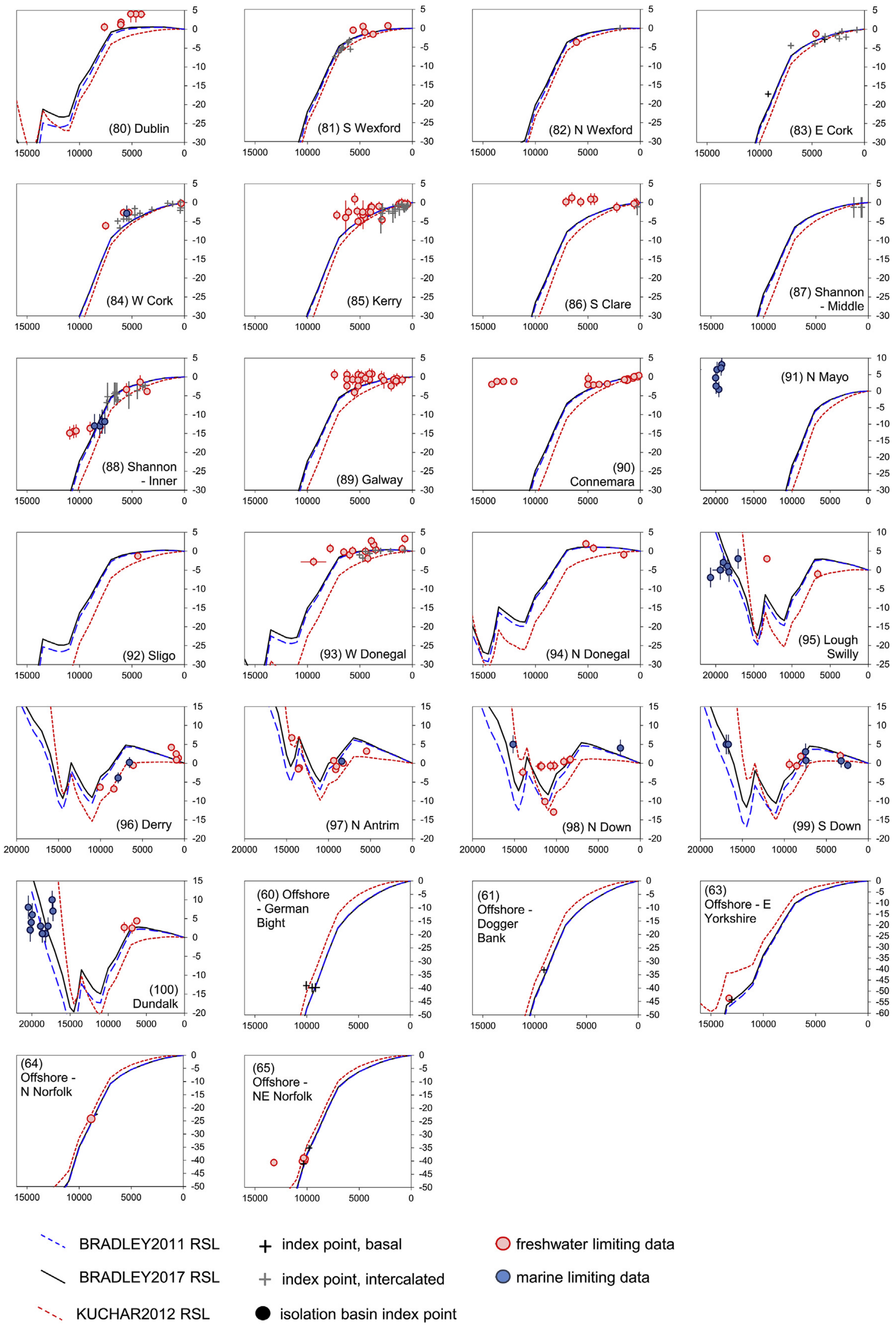

Fig. 7. (*continued*).

Table 2
Names and coordinates (decimal degrees latitude and longitude) for 86 regions from Britain and Ireland.

Original Regions							
1	Shetlands	60.34	−1.03	28	N Solway Firth	54.99	−3.59
2	Orkney	58.97	−2.96	29	S Solway Firth	54.9	−3.17
3	Wick	58.45	−3.12	30	Cumbria	54.38	−3.37
4	Dornoch Firth	57.86	−4.26	31	Isle of Man	54.39	−4.45
5	Moray Firth	57.49	−4.46	32	Morecambe Bay	54.12	−2.97
6	Coigach	58.05	−5.36	33	Lancashire	53.64	−2.97
7	Hebrides	57.77	−7.12	34	Mersey	53.4	−3.14
8	Skye	57.18	−6.04	35	N Wales	53.26	−3.98
9	Applecross	57.58	−5.81	36	Mid Wales	52.47	−4.06
10	Kintail	57.26	−5.49	37	Humber (Inner Estuary)	53.64	−0.69
11	Arisaig	56.91	−5.85	38	Humber (Outer Estuary)	53.68	−0.11
12	Kentra	56.76	−5.84	39	Lincolnshire Marshes	53.32	0.24
13	NE Scotland	57.63	−1.99	40	Fens	52.74	0.04
14	Aberdeen	57.34	−2.01	41	Norfolk	52.97	0.79
15	Montrose	56.71	−2.52	42	East Anglia	52.49	1.64
16	Tay Valley	56.38	−3.2	43	Pembrokeshire	51.66	−5.07
17	Forth Valley	56.12	−4.14	44	Glamorgan	51.59	−3.91
18	Islay	55.81	−6.34	45	Bristol Channel	51.33	−2.99
19	Ardyne	55.87	−5.04	46	Essex	51.68	0.81
20	Clyde	55.86	−4.49	47	Thames	51.48	0.18
21	Ayr	55.43	−4.73	48	Kent	51.01	0.89
22	SE Scotland	56.03	−2.69	49	Sussex	50.77	0.02
23	NE England (North)	55.69	−1.92	50	Hampshire	50.82	−1.37
24	NE England (Central)	55.51	−1.65	51	Dorset	50.63	−2.41
25	NE England (South)	55.32	−1.58	52	Devon	50.3	−3.74
26	NE England (Tyne)	54.96	−1.67	53	Cornwall	50.19	−5.39
27	Tees	54.63	−1.23				
New Regions				Offshore: North Sea			
54	Kintyre	55.88	−5.46	60	German Bight	55.07	6
55	Assynt	58.37	−5.05	61	Dogger Bank	55.02	2.98
56	Sutherland	58.46	−4.54	63	Offshore (E of Yorkshire)	53.99	0.17
57	Scilly Isles	49.92	−6.3	64	Offshore (N of Norfolk)	52.99	1.11
58	Coll	56.69	−6.47	65	Offshore (NE of Norfolk)	53.07	2.34
59	NW Solway	54.93	−4.4				
Ireland							
80	Dublin	53.14	−6.12	90	Connemara	53.68	−9.9
81	South Wexford	52.52	−6.23	91	North Mayo	54.32	−9.54
82	North Wexford	52.32	−6.41	92	Sligo	54.26	−8.61
83	East Cork	51.95	−7.94	93	West Donegal	54.89	−8.43
84	West Cork	51.61	−8.91	94	North Donegal	55.16	−7.98
85	Kerry	52.11	−9.92	95	Lough Swilly	55.12	−7.38
86	South Clare	52.6	−9.72	96	Derry	55.15	−6.85
87	Middle Shannon	52.6	−9.21	97	North Antrim	55.05	−6.01
88	Inner Shannon	52.66	−8.71	98	North Down	54.55	−5.66
89	Galway	53.24	−9.31	99	South Down	54.33	−5.77
				100	Dundalk	53.95	−6.34

ongoing effort. Some of the changes derive from regional scale factors including changing bathymetry and coastline position during the transgression of the continental shelf. Other result from local morphology and sediment infilling of large estuaries.

4.4. *Can near-field records constrain models of global eustatic sea-level change?*

We noted previously (Section 4.1 and Fig. 5) how the RSL predictions across Britain and Ireland collectively reflect certain characteristics of global ice-volume equivalent (eustatic) sea-level change. Inflections in the RSL predictions derive from rapid changes in the rate of rise of global sea level. In contrast, the isostatic component follows a damped response, reflecting the long timescale, >10 ka BP, of glacial rebound of the Earth's crust and a smaller, instantaneous redistribution of ocean mass due to gravitational and rotational contributions (Fig. 9). We can use these characteristics to examine the transfer of meltwater into the oceans from the global GIA model used to derive our RSL predictions.

First identified in the coral records of Barbados (Fairbanks, 1989; Peltier and Fairbanks, 2006), short-term periods of accelerated sea-level rise reflect rapid melting of continental ice sheets. Their duration, magnitude, and relationship to changes in climate, however, remain controversial (Deschamps et al., 2012). The most extreme of these meltwater pulses, MWP1A, occurred around the time of the Bølling warming ~14.6 ka BP (Fig. 5). Its representation in the global ice sheet reconstructions for BRADLEY2011, ~10 m equivalent global sea-level rise 14.5 to 14.0 ka BP and ~13 m rise 14.0 to 13.5 ka BP, leads to oscillations in RSL predicted for many regions in Britain and Ireland (Figs. 5 and 10). The global ice model in BRADLEY2011 (Bradley et al., 2016) is an extension of the Bassett et al. (2005) model.

Sea-level index points and limiting data from a number of sites provide a robust test of the predicted RSL changes driven by the representation of MWP1a in the BRADLEY2011, BRADLEY2017 and KUCHAR21012 models (Fig. 10). All three models have the same ice models for the distant ice sheets (Bradley et al., 2016), Antarctica, Laurentide and Greenland (AIS + LIS + GIS, Fig. 10) and the

Fig. 8. Proportion of negative and positive sea-level tendencies within each 250 year interval for regional groups; NW England to N Wales (regions 30, 32, 33,34, 35), NE England (23, 24, 25, 26), Mid Wales to Bristol Channel (36, 43,44,45), E England (27, 37, 37, 39, 40, 41, 42), Thames & Essex (46, 47), S England (48, 49, 50, 51, 52, 53). Age labels indicate upper limit of the 250 year class. Index points assigned by their median age with no consideration of their 95% age range.

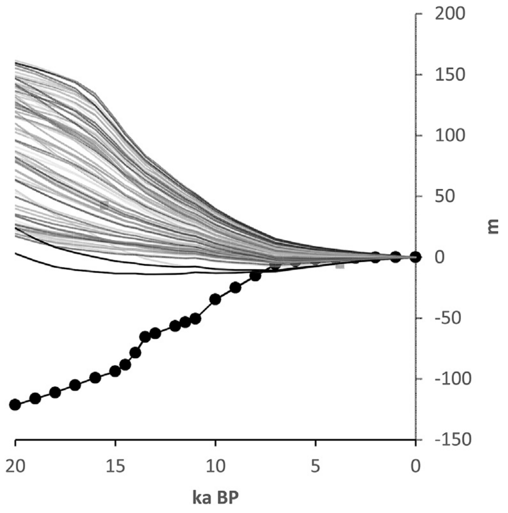

Fig. 9. Ice-equivalent (eustatic) sea level (black circles)) and net isostatic component at the 86 regions, calculated as difference between the BRADLEY2011 predicted RSL and eustasy. The net isostatic component includes glacial rebound and the redistribution of ocean mass due to gravitational and rotational contributions.

Fennoscandia and Barents Sea ice sheet (FIS + BSIS). The field evidence falls into three categories. First, marine limiting data from the Forth Valley (17) and Tay Valley (18) do not refute the predicted RSL changes. Other lines of evidence, however, provide additional constraints. Much of the first research in these two areas concentrated on the landforms associated with deglaciation and the morphology of raised shorelines. Although not dated directly, interpretations of the shoreline sequences and their tilting gave no suggestion of RSL oscillations at the predicted elevations (Cullingford, 1977; Sissons et al., 1966). Their maximum elevations also lie well below the KUCHAR2012 predictions pre-15ka BP. The second set of regions, Clyde (20), N Antrim (97) and N Down (98), have at least one marine or terrestrial/freshwater limiting data point incompatible with the RSL oscillation in the BRADLEY2011 and BRADLEY2017 predictions. The final category of constraints come from isolation basin evidence, Skye (8), Applecross (9), Arisaig (11) and Knapdale (54). In addition to providing an index point that dates the isolation of the basin, sediment lithology and biostratigraphy indicate that prior to isolation RSL was above the sill, the equivalent of marine limiting data, and after isolation, RSL was below the sill, the equivalent of terrestrial/freshwater limiting

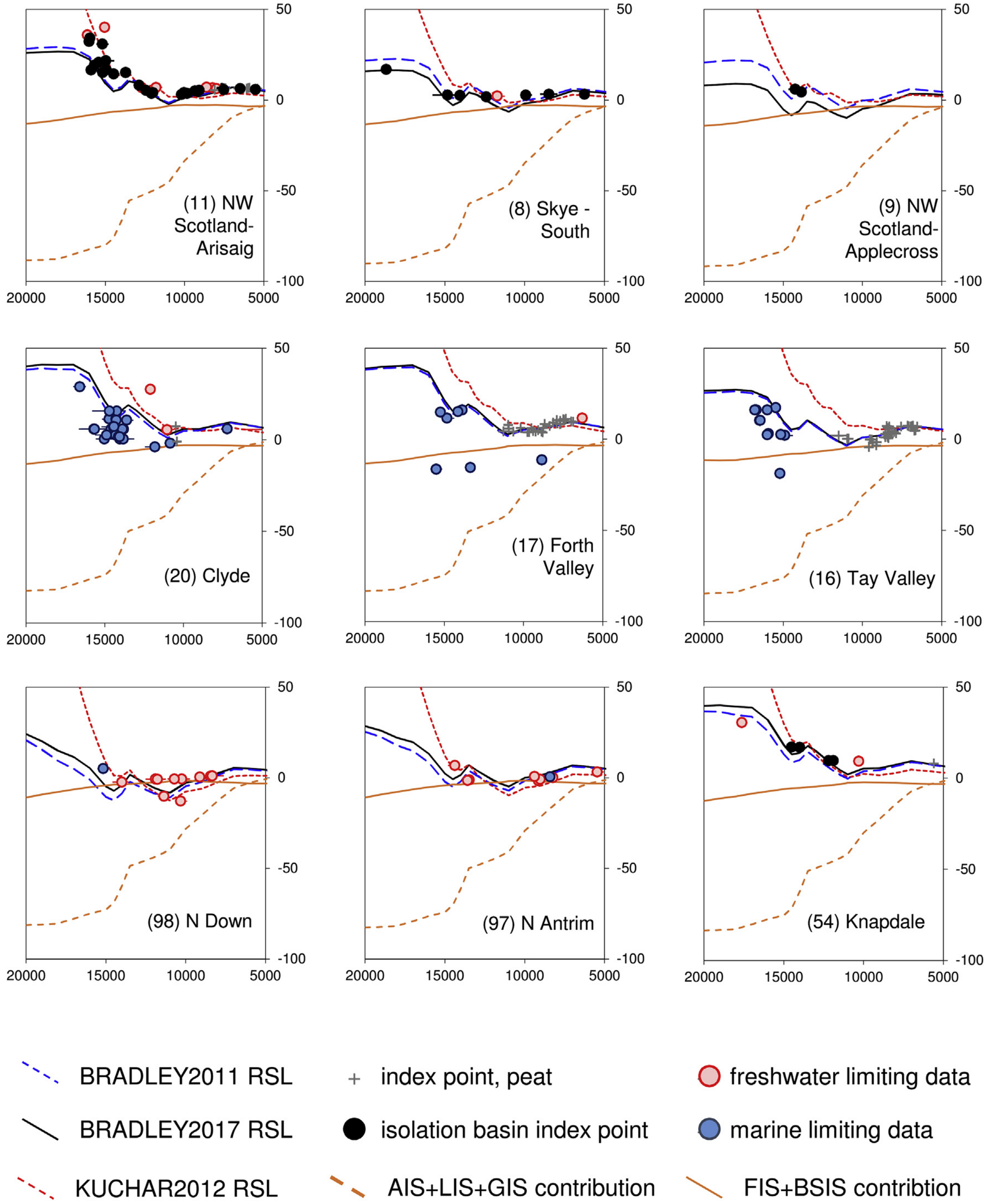

Fig. 10. Comparison of sea-level index points and the BRADLEY2011, BRADLEY2107 and Kuchar2012 RSL predictions around the timing of MWP1a and the contributions of distant ice sheets to the RSL predications, for Antarctica, Laurentide and Greenland (AIS + LIS + GIS) and the Fennoscandia and Barents Sea ice sheet (FIS + BSIS).

data. The index points and limiting values are strong evidence against the predicted RSL oscillation.

The data from these regions indicate that MWP1A should be smaller than its depiction in BRADLEY2011 and BRADLEY2017. KUCHAR2012 shows no RSL oscillation but is rejected because it has RSL too high at all sites pre-15 ka BP. Given the predictability of the isostatic component (Fig. 9) and the contributions from the different ice sheets (Fig. 10), we can make a crude estimate that the magnitude of MWP1A should be reduced in the order of 1–5 m, giving a smaller RSL oscillation to fit with the data, or for there to be no oscillation, just a reduction in the rate of RSL fall.

We stress, however, that the differences between the BRADLEY2011, BRADLEY2017 and KUCHAR2012 RSL predictions, with the same global ice models, reveal GIA model dependency. Modelled changes in tidal range across the time interval of MWP1a suggest a contribution of less than 0.5 m (Neill et al., 2010; Ward et al., 2016). We conclude that the sea-level index points and limiting data from Britain and Ireland provide potentially powerful constraints on MWP1A but require a thorough analysis of GIA model parameters along with a new ice model based on the forthcoming BRITICE project results, and more paleo-tidal modelling. These near-field constraints could then be incorporated with those from tropical locations, which also indicate a smaller MWP1A (Liu et al., 2016).

We see the potential for similar approaches to investigate other debates about global sea-level change. These include MWP1B, ~11.3 ka BP, although it is not represented in the global GIA model used here, and a ~1–3 m sea-level jump around 8.2 ka BP (Hijma and Cohen, 2010; Lawrence et al., 2016; Smith et al., 2013; Tornqvist and Hijma, 2012).

The good fit between index points, limiting data and RSL predictions from the early Holocene to present in southern locations (Fig. 7, regions 36, 37, 38, 40, 41, 42, 44, 45, 47, 48, 49, 52, 60, 63, 65) give good support to the global ice-melt (eustatic) component in BRADLEY2011, which includes >5 m rise since 7 ka BP and reaching zero at 1 ka BP, but the poor fit with KUCHAR2012 reinforces the point that we require a thorough, new analysis of the model parameter space using all the new sea-level data and ice-model constraints. The nature of the mid-Holocene highstand also supports the hypothesis of post 7 ka BP ice melt. An abrupt end of melting ~7 ka BP produces a too sharp, distinct RSL peak (Peltier et al., 2002), rather than the broad, flatter highstand evident in many regions (Fig. 7, regions 3, 5, 6, 8, 10, 11, 16, 23, 28, 31, 32, 56, 59). The quality and number of late Holocene index points from the southern regions may also be used in a similar fashion to those from far-field locations to constrain eustatic sea-level rise over this time (Bradley et al., 2016), addressing important questions on the amount and timing of Antarctic melting.

As a preliminary assessment of model performance during the Holocene, we perform a comparison of all sea-level index points, excluding the limiting data, in the new database with the RSL predictions for the period 11ka to present produced by BRADLEY2011. We partition the data into five groups based on the similarity of predicted Holocene RSL and plot the mean residual (1ka bins) between the reconstructed RSL for each index point and the sample-specific predicted RSL (Fig. 11). Negative residuals indicate that reconstructed RSL is lower than modelled RSL and may reflect model over-prediction or lowering of sea-level index points by processes such as sediment compaction or tidal amplification. Conversely, positive residuals indicate reconstructed RSL is higher than modelled RSL and may reflect model under-prediction or processes that can elevate reconstructed RSL such as tidal dampening. Negative residuals are a pervasive feature of the post 6ka interval in regions peripheral to the Celtic ice sheet and are most striking in Group E, with the greatest RSL rise during the Holocene. This is most plausibly explained as a consequence of sediment compaction, with its impact most pronounced where sedimentary sequences are thickest and non-basal index points are most deeply buried. In contrast, closer to the centres of ice sheet loading, where RSL fall from a mid-Holocene highstand characterises the last 6ka, Group A, we see a slight tendency for modelled RSL to plot beneath reconstructed RSL. Similar positive residuals characterise all regions prior to 7ka with a general tendency for these residuals to increase with age. Some of this misfit could plausibly arise from increases in tidal range in the early Holocene, indicated by palaeotidal modelling but not incorporated in RSL reconstructions except for eastern England (section 3.2). Conversely, other regions see modelled tidal range decreasing during the early Holocene (Neill et al., 2010; Shennan et al., 2003; Ward et al., 2016). Alternatively, they could be linked to systematic under-prediction by the GIA models, either linked to the Celtic ice sheet loading history or the choice of global GIA model and their representation of the final deglaciation of the Laurentide ice sheet and the continued melting of Antarctica. Different global GIA models show substantial differences around this time, ~11 to 8 ka BP (e.g. Bassett et al., 2005; Fleming et al., 1998; Peltier, 1998; Peltier, 2004) but the large volume of data for this period across a 50 m elevation rage (Fig. 3) should encourage new analyses to disentangle and test these scenarios.

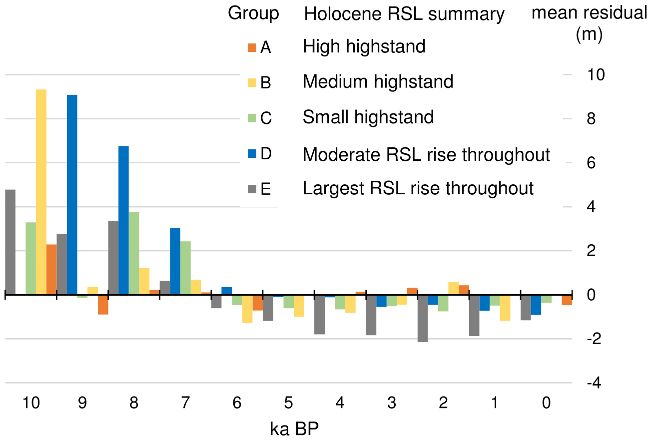

Fig. 11. Mean residual (1 ka bins, 0–999 BP … … 10,000–10,999) for five groups of regions (same groups as Fig. 4). Residuals calculated for each index point, excluding limiting data, as the difference between the reconstructed RSL and the sample-specific predicted RSL, based on the calibrated median age of the index point and the BRADLEY2011 GIA model.

5. Conclusions

The new, updated sea-level database for Britain and Ireland contains >2100 data points from 86 regions and records RSL changes the last 20 ka and across elevations ranging from ~+40 to −55 m. We see radically different patterns of RSL as we move from regions under the thickest part of the Celtic ice sheet to areas near to and beyond the LGM ice limits. The sea-level index points and limiting data show good agreement with the broad patterns of RSL change predicted by current GIA models, although KUCHAR2012 predicts too much isostatic rebound in regions around the centre of the Celtic ice sheet and both BRADLEY2011 and BRADLEY2017 produce too little rebound. The updated sea-level database will play a critical role in the next iteration of GIA modelling, with the development of a new generation of Celtic ice sheet models developed as part of the BRITICE Project.

Irrespective of the goodness of fit with model predictions, the sea-level index points show no consistent pattern of synchronous coastal advance and retreat across different regions. We suggest within-estuary processes, rather than decimetre- and centennial-scale oscillations in sea level, produce major controls on the temporal pattern of sea-level tendencies and horizontal shifts in coastal sedimentary environments.

Comparisons between the RSL database and GIA model predictions for multiple regions provide potentially powerful constraints on various characteristics of global GIA models, including the magnitude of MWP1A, a sea-level jump around 8.2 ka BP, the final deglaciation of the Laurentide ice sheet and the continued melting of Antarctica after 7 ka BP. We anticipate that such efforts will need a revised reconstruction of the Celtic ice sheet and sample-specific estimates of changes in tidal range for all index points.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2018.03.031.

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