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Two Centuries of Relative Sea-Level Rise in Dublin, Ireland, Reconstructed by Geological Tide Gauge

RESEARCH PAPER

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ABSTRACT

We demonstrate the utility and reproducibility of the saltmarsh foraminifera-based 'geological tide gauge' (GTG) approach by developing two independent records of relative sea-level (RSL) change for Dublin, Ireland. Our records, recovered from two different saltmarshes, indicate that RSL rose at a century-scale rate of 1.5 ± 0.9 mm yr^{-1} over the last 200 years. This compares favourably with the shorter, but more precise, mean sea level (MSL) record from the Dublin Port tide gauge, which indicates long-term (1953–2016 CE) rise at a rate of 1.1 ± 0.5 mm yr^{-1}. When corrected for the influence of glacio-isostatic adjustment our saltmarsh-based reconstruction suggests sea levels in Dublin rose at a rate of 1.6 ± 0.9 mm yr^{-1} since the start of the 19th century, which is in excellent agreement with the regional value of MSL rise over the same period (1.5 ± 0.2 mm yr^{-1}) calculated from a compilation of tide gauge records around Britain. Whilst our record has decadal-scale temporal resolution (1 sample every 8 years), we are currently unable to resolve multidecadal-scale variations in the rate of sea-level rise which are masked by the size of the vertical uncertainties (± 20 cm) associated with our reconstruction of palaeomarsh-surface elevation. We discuss the challenges of applying the GTG approach in the typically minerogenic saltmarshes of the NE Atlantic margin and outline potential solutions that would facilitate the production of Common Era RSL reconstructions in the region.

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1. INTRODUCTION

Spatial patterns of relative sea level (RSL) provide critical insight into the drivers of sea-level change (Fox-Kemper et al., 2021 and references therein). The development of techniques to extract RSL data from saltmarsh sediments has produced a suite of near continuous reconstructions spanning several centuries to millennia, supplementing and extending the records provided by instrumental tide gauges (Gehrels et al., 2005; Kemp et al., 2009; Barlow et al., 2013). These saltmarsh-based 'geological tide gauge' (GTG) records have been used in combination with spatiotemporal modelling to extract global temperature-related sea-level changes over the Common Era (Kopp et al., 2016), quantify sea-level budgets (Walker et al., 2021) and identify the onset of accelerated RSL rise linked with global warming (Walker et al., 2022). However, spatial bias in the distribution of RSL reconstructions limits the questions that can be addressed by this approach. For example, the availability of multiple GTG records along the eastern seaboard of North America has identified spatial patterns of RSL that may be linked with changes in atmospheric and oceanic circulation over the North Atlantic region (e.g., Kemp et al., 2011, 2013, 2018). In contrast, whilst similar signals may be detectable along other Atlantic margins (e.g., Saher et al., 2015), there are comparatively few GTG records from north-western Europe with which to explore the relative influence of these mechanisms (Barlow et al., 2014; Walker et al., 2022).

The GTG technique utilises sequences of saltmarsh sediments and the microfossils preserved within them to build reconstructions of past RSL change (e.g., Gehrels et al., 2005; Kemp et al., 2009; Barlow et al., 2013). Saltmarsh foraminifera are vertically zoned, as individual species have a different tolerance to the frequency and duration of tidal inundation (Scott and Medioli, 1978; Horton and Edwards, 2006; Kemp et al., 2012). The modern relationships among elevation and different foraminifera species can be used to produce transfer functions that predict palaeomarsh surface elevation (PME) from down-core fossil foraminifera assemblages that are extracted from sequences of saltmarsh sediments (Gehrels, 1999, 2000; Horton et al., 1999; Edwards et al., 2004; Horton and Edwards, 2005; Massey et al., 2006; Cahill et al., 2016). In this way, the former position of RSL is calculated by subtracting the PME from the modern sample elevation which, when combined with information on sample age, can be used to reconstruct RSL change.

Ireland's location on the Atlantic seaboard of Europe means it is ideally placed to improve our understanding of sea-level variability in the North Atlantic region. In this study, we test the application of the saltmarsh-based GTG approach in Ireland by reconstructing two centuries of RSL change in Dublin. We validate this reconstruction against the instrumental tide gauge record from Dublin Port, Ireland's longest time series extending back to 1938. We conclude that the GTG approach accurately quantifies the century-scale RSL trend which, when corrected for the influence of glacio-isostatic adjustment (GIA), reproduces the mean sea-level trend for the last 200 years identified in a recent analysis of historical and instrumental data from Great Britain (Hogarth et al., 2021). We discuss the implications of our results for the production of longer GTG records from Ireland and similar European contexts.

2. STUDY AREA

Dublin is located on the eastern coast of Ireland (Figure 1) where the rivers Liffey and Tolka drain into the Irish Sea. The area is mesotidal with a spring tidal range of around 3.5 m. We investigate two saltmarshes adjacent to Dublin City, that historical mapping indicate have the potential to provide near-continuous accumulations of sediment spanning the last two centuries (Figure 1).

The first saltmarsh, located in Baldoyle estuary, formed in the lee of the large sand spit of Portmarnock and is separated from Dublin Bay by a low-lying tomobolo extending to the Howth Peninsula. The saltmarshes at Portmarnock were identified in an Ordnance Survey Ireland (OSI) survey dated to 1836 (Historic 6" First Edition; sheet DN015; published 1843) and today comprise a thin mature marsh of *Festuca rubra*, *Glaux maritima* and *Scirpus maritimus* flanked seaward by extensive meadows of the invasive species *Spartina anglica* (Craven et al., 2013). Whilst a small drain cuts through the rear of the marsh, a progressive transition from saltmarsh to upland is evident along the landward margin flanking the road.

The second saltmarsh is located on the landward side of North Bull Island (hereafter 'Bull Island'), a sand spit situated in the northern part of Dublin Bay which grew rapidly from the early 19th century following construction of two tidal walls to improve navigation in the Port of Dublin (Harris, 1973). Saltmarshes have existed at this site since at least 1907 (Historic 25"; Sheet DN019-06; published 1910), with the construction of a causeway between 1964 and 1970 splitting the back barrier environment into two separate lagoons (Figure 1). Saltmarsh vegetation includes *Salicornia* spp., *Spartina anglica, Halimione portulacoides* and *Puccinellia maritima* (Grey et al., 2021). Embanking and fencing associated with two golf courses on Bull Island has caused significant disturbance at the rear of the marsh, so surface sampling for modern analogues was conducted toward the eastern end of the spit beyond the limit of the golf courses where the saltmarsh to upland transition is preserved (Figure 1d).

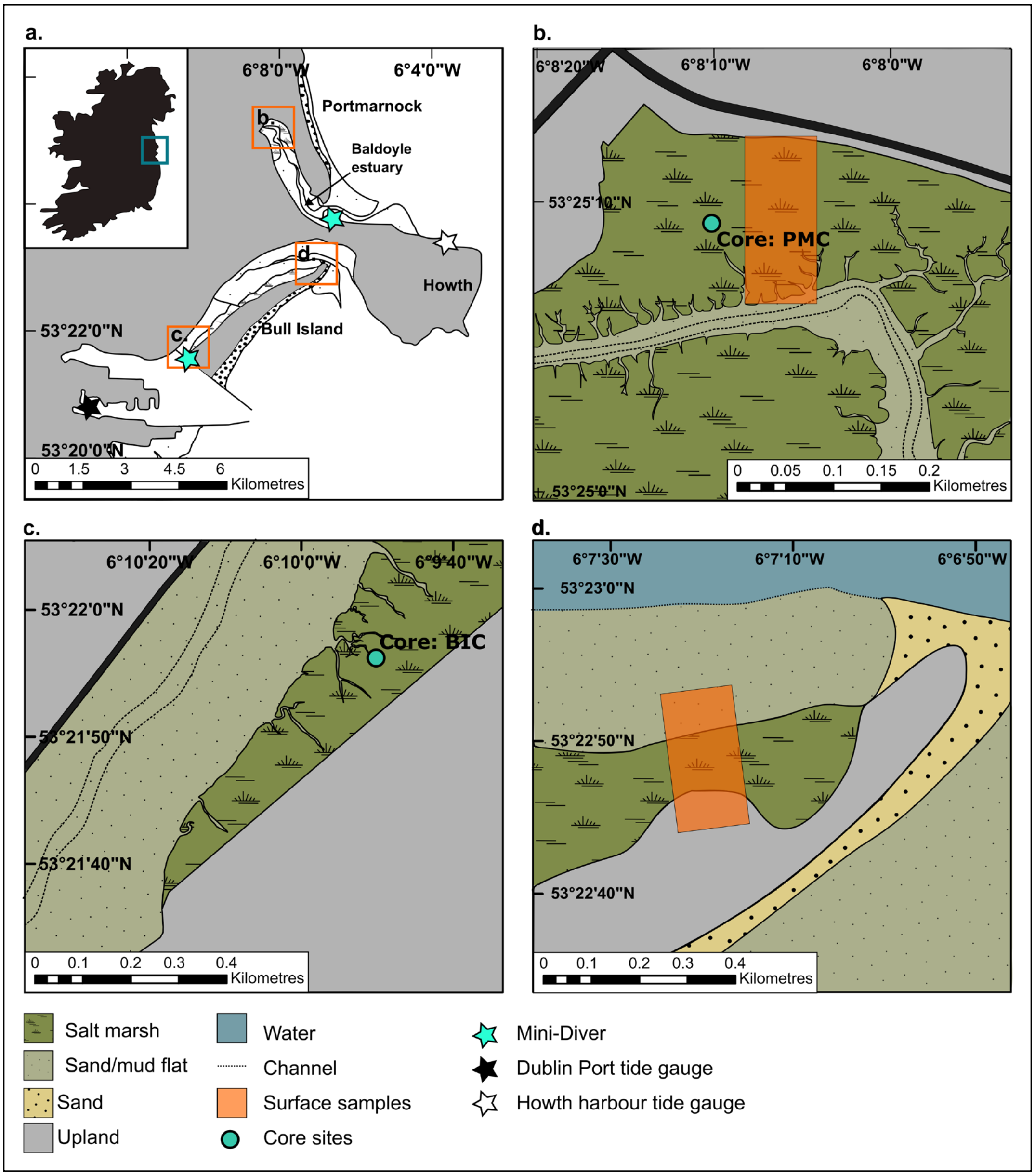

Figure 1 (a) Map of County Dublin indicating the location of our study sites; Portmarnock **(b)**, Bull Island West **(c)** and Bull Island East **(d)**. Core sites (green circle), locations of Mini-Divers (green star), Dublin Port tide gauge (black star), Howth Harbour tide gauge (white star) and surface sampling locations (orange box) are indicated.

3. METHODS

3.1 SURFACE SAMPLING AND TIDAL ELEVATION

We quantify the modern relationships among saltmarsh foraminiferal taxa and tidal elevation by collecting multiple transects of surface foraminifera from Bull Island and Portmarnock, extending across the vegetated marsh platform to the adjacent upland (Edwards & Wright, 2015). Each site was sampled four times in 2007 to account for any seasonal fluctuations in the foraminiferal distributions (Horton and Edwards, 2006; Walker et al., 2020). Samples comprising approximately 10 cm^2 of the uppermost centimetre of sediment were recovered at 5–10 cm vertical intervals, with sample height measured by a Trimble R8s GNSS system and expressed relative to Ordnance Datum Malin (ODM), the Irish national levelling datum.

On return to the laboratory surface sediments were washed through 500 and 63 µm sieves and stained with a buffered solution of ethanol and rose Bengal to identify foraminifera that were living at the time of collection (Walton, 1952; Murray and Bowser, 2000). Sediment samples were sub-divided using a wet splitter (Scott and Hermelin, 1993) and complete aliquots counted in suspension under a binocular microscope until a minimum of 100 dead foraminifera were recorded, which is regarded as conservative for this kind of study (Kemp et al., 2020). We use the death assemblage for the palaeoenvironmental reconstructions, as this is more representative of the material recovered from sediment cores (Horton, 1999; Murray, 2000; Horton and Edwards, 2003; Horton et al., 2005; Horton and Edwards, 2006).

Local tidal elevation was measured by on-site data loggers (Eijelkamp Mini-Divers) for 4 months at Bull

Island and 6 months at Portmarnock, capturing seven and eleven spring-neap cycles respectively (Figure 1). As the data loggers were exposed at low tide, local mean tide level (MTL) was calculated by comparing the logger time series with the corresponding measurements (mean high water; MHW) at the nearby tide gauge in Howth Harbour and applying the vertical offset to the Howth datum (Table 1). MHW and MTL are identical at both study marshes and within 3 cm of the MTL recorded by the Dublin Port tide gauge.

We use the highest occurrence of foraminifera (HOF) in combination with the tidal data to define sample elevation in terms of a standardised water level index (SWLI) following Wright et al. (2011) where:

$$SWLI = \left(\left(\frac{Elev - MTL}{HOF - MTL}\right) \times 100\right) + 100$$

The organic content of surface sediments was measured using loss on ignition (LOI). Approximately 5g of wet sediment was weighed, oven dried at 65°C for 48 hours and re-weighed to obtain the dry weight. The oven-dried sediment was placed in a furnace at 550°C for four hours and, following this, weighed to obtain the ash residue weight. Percentage LOI was calculated following Plater et al. (2015). These data were collected to further characterise the different marsh environments as, typically, LOI values decrease from the high marsh to the tidal mudflats (Horton and Edwards, 2006; Plater et al., 2015).

3.2 CORE SAMPLING AND CHRONOLOGY

Reconnaissance coring using a narrow chamber gouge auger confirmed a simple lithostratigraphy at both sites comprising a thin saltmarsh peat overlying stiff grey silty sands. In 2009, the uppermost 50 centimetres of the sequence at Portmarnock (PMC) and Bull Island (BIC) was sampled using a monolith tin, with additional material recovered using a closed-chamber Eijkelkamp flap gouge auger (Figure 1). Coring site altitude was measured by a Trimble R8s GNSS system and expressed relative to Ordnance Datum Malin (ODM). Sediments were described using the Troels-Smith scheme of stratigraphic notation (Troels-Smith, 1955).

On return to the laboratory the sediments were processed for foraminifera and organic content (LOI) using the methods outlined in Section 3.1, with additional material being extracted for dating. ^{137}Cs, ^{214}Pb and ^{210}Pb activity were measured at 2 cm intervals in the University of Plymouth Consolidated Radio-isotope Facility (CORIF), following the analytical procedure outlined by Appleby (2001). Spheroidal carbonaceous fly-ash particles (SCPs) were counted at 2 cm intervals with sample preparation following Rose (1990, 1994). SCPs are by-products of industrial fossil fuel combustion and can be used to establish chronohorizons given knowledge of atmospheric pollution history (Marshall, 2015). The R programme 'rplum' was used to develop a model to reconstruct ^{210}Pb accumulation histories using Bayesian statistics, combine the different dating techniques into an age-depth model and estimate ages for sample-specific depths within the cores (Aquino-López et al., 2018). Radiocarbon dating is not utilised in this study because previous work has demonstrated that ^{14}C dating of saltmarsh sediments in Dublin Bay produces erroneously old ages, presumably due to the reworking of 'old' allochthonous carbon (Southall, unpubl. data).

In addition, we applied optically stimulated luminescence (OSL) dating to the Bull Island core. One sediment sample (BIC-33) was recovered at 33cm depth by inserting an opaque, light-resistant plastic tube into the sediment. Once removed, the tube was sealed in a light-tight container. In the laboratory the sample was prepared using standard procedures for 150–200 mm quartz grains settled on 8 mm large aliquots. A single-aliquot regeneration protocol was employed involving a single regenerative and test dose of 2.35 Gy for determining the equivalent dose and applying standard rejection criteria (Murray and Wintle 2003). The dose rate was determined using standard gamma-spectrometric procedures (Mauz et al. 2022) and factors adopted for converting activity concentration to dose (Guérin et al., 2011), attenuation of beta- and gamma-rays in quartz grains (Mejdahl, 1979)

BULL ISLAND MINI-DIVER (02/07/08 TO 17/09/08)	LEVEL RELATIVE TO ODM (m)
Mean High Water	1.48
Mean tide level	0.01
Highest occurrence of foraminifera	2.01
SUTTON MINI-DIVER (07/03/2009 TO 24/06/2009)	**LEVEL RELATIVE TO ODM (m)**
Mean High Water	1.48
Mean tide level	0.01
Highest occurrence of foraminifera	2.05

Table 1 Tidal datums and standardisation of elevation data across tide gauge sites.

and attenuation of radiation in the presence of water (Guérin et al., 2012).

3.3 DATA ANALYSIS AND RELATIVE SEA-LEVEL RECONSTRUCTION

We use partitioning around medoids (PAM) to identify distinct assemblages of foraminifera following screening of the dataset to remove samples with low counts (<50 tests) and minor taxa (<5% of any sample). PAM was performed using the 'cluster' package in R (Maechler et al., 2012), with the number of clusters informed by the 'NbClust' package (Charrad et al., 2014).

We quantify the modern relationship between surface foraminifera and elevation using a Bayesian transfer function (BTF) for tide level based on count data (Cahill et al., 2016). Whereas traditional transfer functions typically apply a single response form to all species of foraminifera (e.g., unimodal gaussian), the Bayesian model allows for a multi-modal and non-gaussian species response to environmental conditions and better reflects true ecological variability (Cahill et al., 2016). We use this transfer function to predict PME for our core samples, based on their foraminifera assemblage, with a sample specific 95% uncertainty interval. RSL is calculated by subtracting the PME from the sample elevation. Down-core measurements of RSL and age, with associated error terms, are then combined within an Errors in Variables Integrated Gaussian Process (EIV-IGP) model to estimate RSL and rates of RSL change over time while accounting for both vertical and chronological uncertainties (Cahill et al., 2015).

4. RESULTS

4.1 SURFACE FORAMINIFERA DISTRIBUTION AND TRANSFER FUNCTION DEVELOPMENT

We identified 15 foraminifera species across our two study sites (Figure 2). Of the 21,700 tests counted from 148 samples, *Entzia macrescens* (also known as *Jadammina macrescens*) was the dominant species (15,404 tests), followed by *Miliamina fusca* (2,649 tests) and *Trochammina inflata* (2,035 tests). We use cluster analysis to divide the Dublin surface data into three assemblages (Figure 3). Cluster 1 (mean SWLI = 182; standard deviation = 11) is characterised by high relative abundances of *E. macrescens* (mean = 60%) and *T. inflata* (mean = 31%). Cluster 2 (mean SWLI = 177; standard deviation = 11.5) is dominated by *E. macrescens* (mean = 88%), with lower abundances of *T. inflata* (mean = 7%), whilst Cluster 3 (mean SWLI = 156; standard deviation = 11) is characterised by a high relative abundance of *M. fusca*

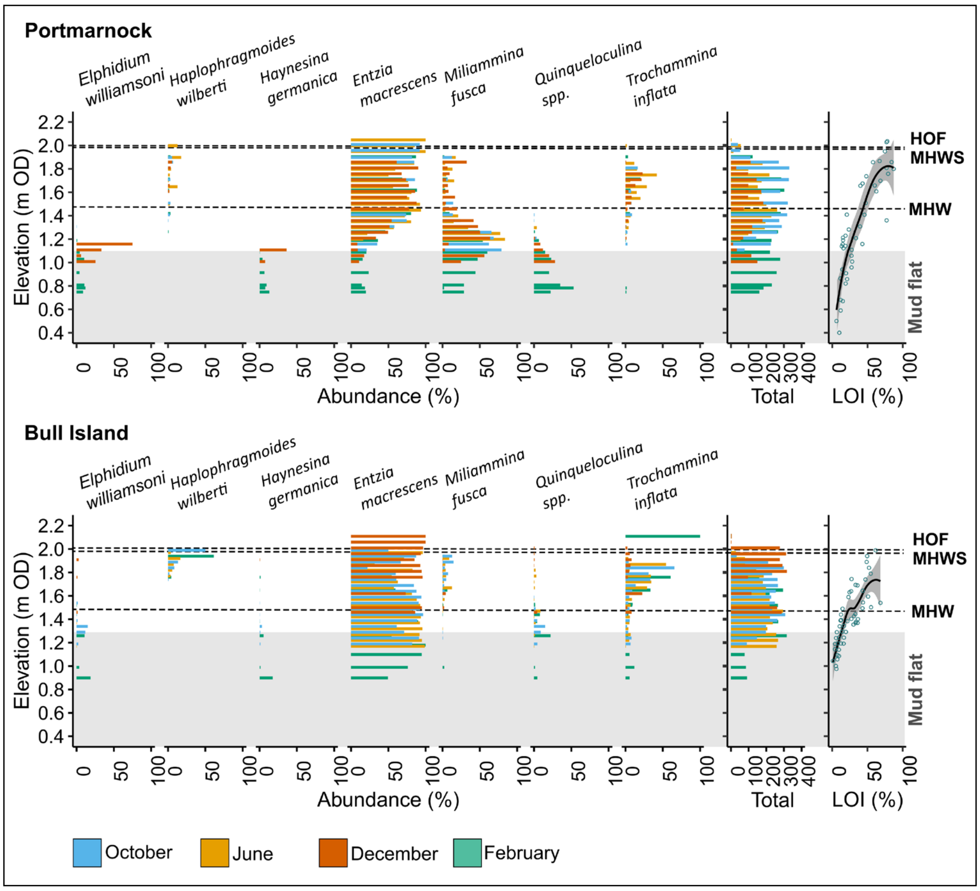

Figure 2 Raw foraminifera data (dominant species expressed as relative abundance and colour coded based on month of collection), total number of foraminifera identified and total organic matter (loss on ignition; LOI) against elevation (m OD) for Portmarnock and Bull Island. HOF = Highest occurrence of foraminifera, MHWS: Mean high water springs, MHW = Mean high water.

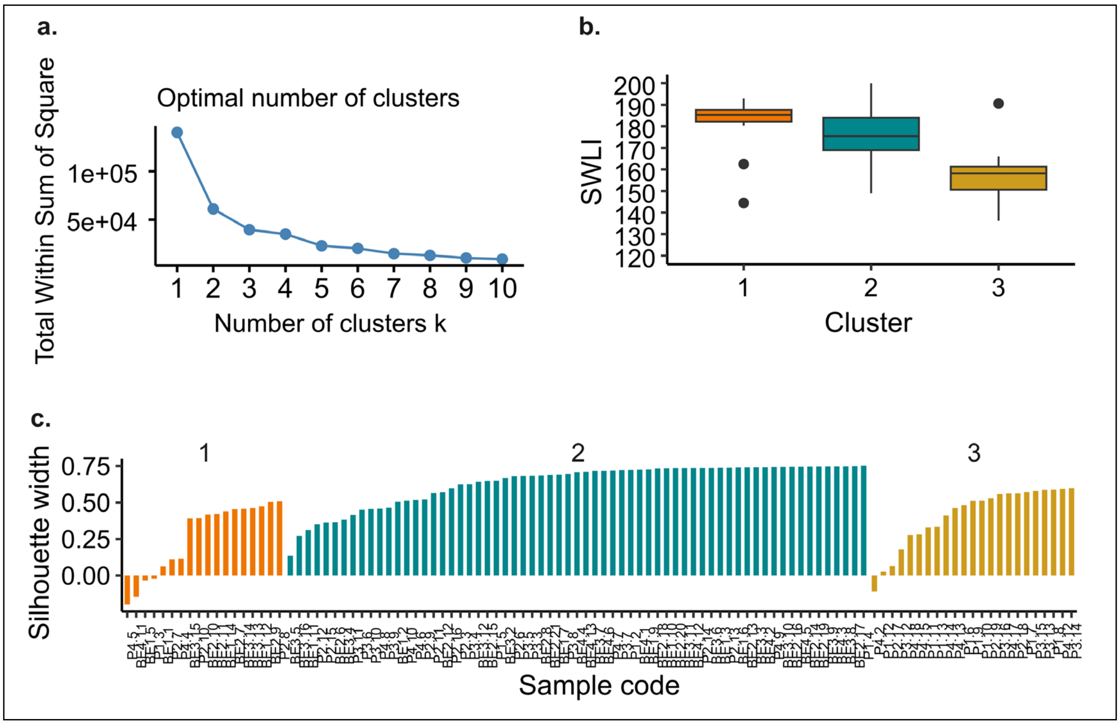

Figure 3 Partitioning around medoids (PAM) analysis on screened and combined surface foraminifera data set. This includes samples from Bull Island and Portmarnock. **(a)** Optimal number of clusters for our dataset, guided by 'NbClust' (Charrad et al., 2014). **(b)** Box and whisker diagram showing standardised elevation (SWLI) range of clusters. **(c)** Silhouette plot showing silhouette widths for samples from Bull Island and Portmarnock.

(54%), with smaller contributions from *E. macrescens* (mean = 36%) and *Quinqueloculina* spp. (mean = 7%).

Modern foraminifera distributions indicate that *E. macrescens* and *T. inflata* are middle to high saltmarsh species (e.g., Coles, 1977; Coles and Funnell, 1981; Murray, 1991; Boomer, 1998; Funnell and Boomer, 1998; Gehrels and van de Plassche, 1999; Horton et al., 1999; Edwards et al., 2004; Horton and Edwards, 2006; Armynot du Châtelet et al., 2009; Milker et al., 2015). In addition, *E. macrescens* can sometimes be found in monospecific assemblages towards the landward limit of the saltmarsh (Scott, 1976; Scott and Medioli, 1978, 1980; Edwards et al., 2004). The relative abundance of *M. fusca* is typically elevated within low marsh to tidal flat environments (Scott and Medioli, 1980; Smith et al., 1984; Scott et al., 1990; Horton and Edwards, 2006; Milker et al., 2015), whilst calcareous taxa, including *Quinqueloculina* spp., frequently characterise tidal flat foraminifera assemblages (Phleger, 1970; Horton and Edwards, 2006; Horton and Culver, 2008). These distributions are broadly consistent with the results of our cluster analysis which divides the samples into a high marsh assemblage (Cluster 1) characterised by high relative abundances of *E. macrescens* and *T. inflata*, a high to middle-marsh assemblage (Cluster 2), characterised by abundant *E. macrescens*, and a low-marsh to tidal flat assemblage (Cluster 3), with abundant *M. fusca* and *Quinqueloculina* spp. (Figure 3).

Collectively, the foraminiferal assemblages populating the vegetated saltmarsh platforms above MHW in Bull Island and Portmarnock are very similar in composition to each other and are typical of upper saltmarsh assemblages reported elsewhere in the literature (e.g., Horton et al., 1999; Gehrels & van de Plassche, 1999; Hawkes et al., 2010; Wright et al., 2011; Kemp et al., 2012; Milker et al., 2015). At Portmarnock, the common faunal turnover from high marsh taxa, such as *E. macrescens* and *T. inflata*, to characteristic lower elevation taxa, such as *M. fusca*, *Quinqueloculina* spp., and *Elphidium williamsoni*, occurs just below MHW, a pattern that is broadly replicated across sites in Britain, Ireland and adjacent regions (e.g., Horton & Edwards, 2006; Müller-Navarra et al., 2017; Rush et al. 2021). Unusually, the lower elevation (below MHW) distributions at Bull Island do not follow this pattern and are dominated by *E. macrescens* with only minor contributions from *M. fusca* and calcareous taxa. This appears to be a robust feature of the distributions at this site, as it is replicated in transects sampled four times over the course of twelve months.

Post-mortem modification of low elevation assemblages can occur via the dissolution of calcareous tests leading to an artificially elevated relative abundance of the residual agglutinated component (Murray & Alve, 1999; Edwards & Horton, 2000). Whilst this kind of taphonomic process would contribute to the very high relative abundance of *E. macrescens* in low marsh to mudflat environments, it does not explain the extremely low abundance of the agglutinated taxon *M. fusca*. Similarly, the transport of high marsh foraminifera into depauperate low marsh and mudflat sediments would be expected to result in an increase in both *E. macrescens* and *T. inflata* which is not observed. Müller-Navarra et al. (2017) report high relative abundances of *E. macrescens* in low elevation samples from the tidal creek marsh at Sønderho in the Danish North Sea region. However, *M. fusca* is abundant at the site and the contrasting tidal and salinity conditions are associated with a very different high marsh assemblage, dominated by *Balticammina pseudomacrescens*. The semi-enclosed nature of the lagoon at Bull Island, coupled with nutrient-rich runoff from the surrounding land, promotes extensive algal blooms that coat the tidal flats for part of the year. Whilst it is possible that that this may contribute to the unusual faunal character of the lagoon, further work will be required to explain the low elevation distributions at the site.

We develop a BTF from a training set comprising the combined surface foraminiferal data from Portmarnock and Bull Island. We remove samples recovered from the intertidal flats at Bull Island with an assemblage comprised almost exclusively of *E. macrescens*, as these samples are strongly influenced by an unknown secondary environmental control. The resulting species response curves describing the vertical distribution of the major taxa reproduce the general patterns described in the cluster analysis (Figure 4c). The agglutinated species *T. inflata* has optimum occurrence above MHW (174 SWLI) at a SWLI of 186. *E. macrescens* has a bimodal distribution, with an optimum occurrence at the landward limit of the marsh (200 SWLI) and a second peak close to MHW (171 SWLI). Lower elevation taxa have their optima below MHW, with the maximum occurrence of *M. fusca* occurring at 153 SWLI, and peaks in the calcareous taxa *E. williamsoni* and *Quinqueloculina* spp. at 136 SWLI. Ten-fold cross validation indicates that the transfer function performs well, with the true value of SWLI falling within the modelled 95% credible intervals 95% of the time and a root mean squared error of 9.91 SWLI units (0.2 m at our study sites).

4.2 CORE DATA AND PALAEOMARSH SURFACE ELEVATIONS

We analysed the lithostratigraphy and biostratigraphy of the core material recovered from Portmarnock (PMC) and Bull Island (BIC) to produce two independent records of PME change from neighbouring sites (Figures 5 and 6). PMC is 50 cm long and comprises 10 cm of brown saltmarsh silty peat which grades progressively downwards into a brown-grey organic clayey-silt with abundant roots extending to a depth of 30 cm. Below 30 cm sediments are clay-rich with black mottling and occasional fine humified rootlets, grading into a basal unit of well sorted sand with rare, fine humified rootlets. The down-core foraminiferal assemblage is dominated by *E. macrescens* (>60%), with elevated abundances of *T. inflata* (~30%) at 1.5 cm, 17.5 cm and 31.5 cm depth. *M. fusca* is present in low abundances of up to 6% between 0 and

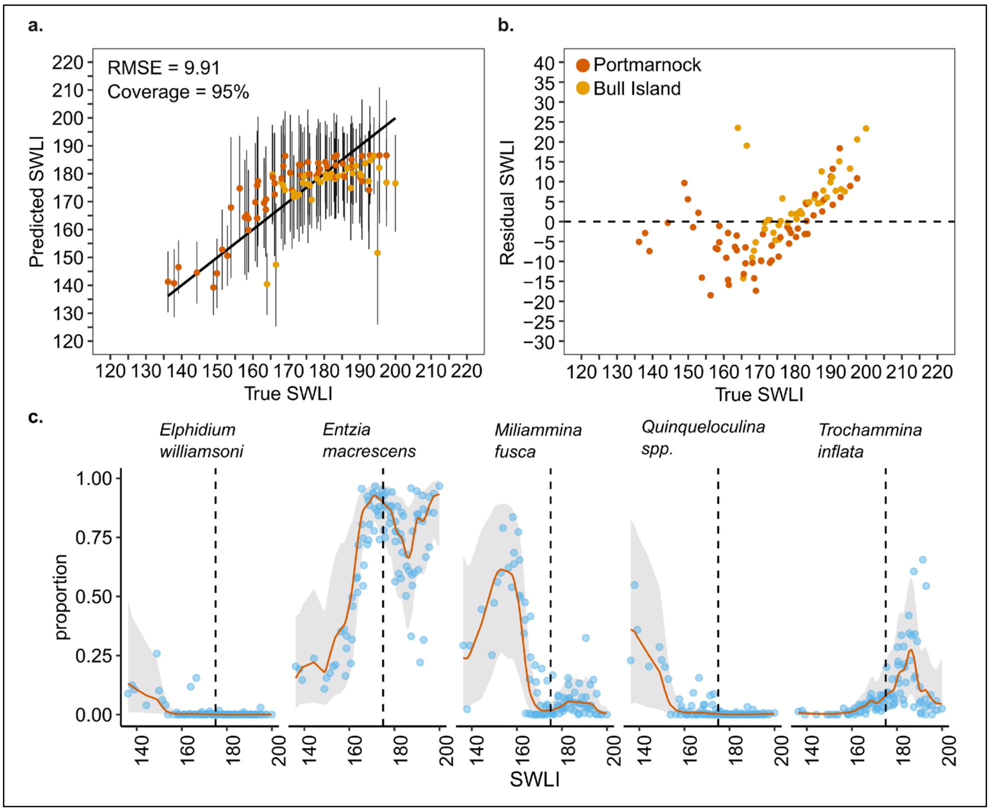

Figure 4 (a) Bayesian transfer function (BTF) 10-fold cross validation. Modern sample SWLI plotted against predicted SWLI predicted by the BTF. 95% of the time the True SWLI falls within the model 95% credible intervals. Prediction of error is 9.91, as measured by the Root Mean Squared Error (RMSE). **(b)** Observed-predicted residuals. **(c)** Species response curves for our screened, combined dataset (red line), with 95% confidence intervals (grey area). This incorporates surface samples from Bull Island and Portmarnock (blue circles). The proportion of each species is plotted against standardised elevation (SWLI). MHW is shown as a vertical dashed line.

35 cm depth. Below 35 cm, *E. macrescens* has a relative abundance >90%. Organic content decreases with depth from around 50% in the saltmarsh silty peat to less than 10% in the basal unit below 32 cm depth.

BIC is 34 cm long and comprises an upper unit of grey-brown silty peat with clay and humified organic matter, extending to 23 cm depth. Below 23 cm, sediments are grey silty clay with occasional fine humified rootlets, with a basal unit (30.5 cm to base) of fine to medium sand (0.06–0.6 mm) with rare fine humified rootlets. The downcore foraminiferal assemblage is similar to PMC and is dominated by *E. macrescens* (>80%). *T. inflata* is also present, with an elevated relative abundance (~13%) at 5.5 cm and 9.5 cm depth and between 20 and 25 cm. *H. wilberti* and *M. fusca* are present at very low relative abundances (1–2%). Organic content decreases with depth from around 74% at the top of the core to less than 5% in the basal sediments.

Calibration of the fossil foraminiferal assemblages with the BTF produces PME estimates for the two sediment cores, suggesting relatively uniform accumulation in a high marsh environment at or above MHW (Figures 5e and 6e). Whilst a high marsh interpretation is consistent with the uppermost, organic-rich portions of the sequences, it is incompatible with the minerogenic nature of the units underlying the saltmarsh. The performance statistics indicate that this is not an intrinsic problem with the BTF (Figure 4) but rather it reflects the general absence of *M. fusca* and calcareous taxa from the minerogenic sediments of both cores, resulting in an assemblage that is indistinguishable from that of the high marsh. Such a situation could arise from post-depositional processes that selectively remove the diagnostic components of the lower elevation assemblages (e.g., dissolution or preferential degradation of *M. fusca* tests). Alternatively, this could be the product of similar processes to those operating today in the lagoon at Bull Island which have produced low elevation, minerogenic sediments with apparently high elevation foraminiferal assemblages (Section 4.1). In either case, this mismatch violates the basic premise of reasoning by analogy that underpins the transfer function approach and so we do not attempt to reconstruct PME from samples with a low organic content similar to that of the modern tidal flats (<15%) and sedimentological characteristics that indicate deposition in a tidal flat setting.

The resulting reconstructions of PME encompass the top 30 cm of PMC and the top 23 cm of BIC. In both cores the marsh surface accumulated around 180 SWLI with minor fluctuations primarily reflecting the varying

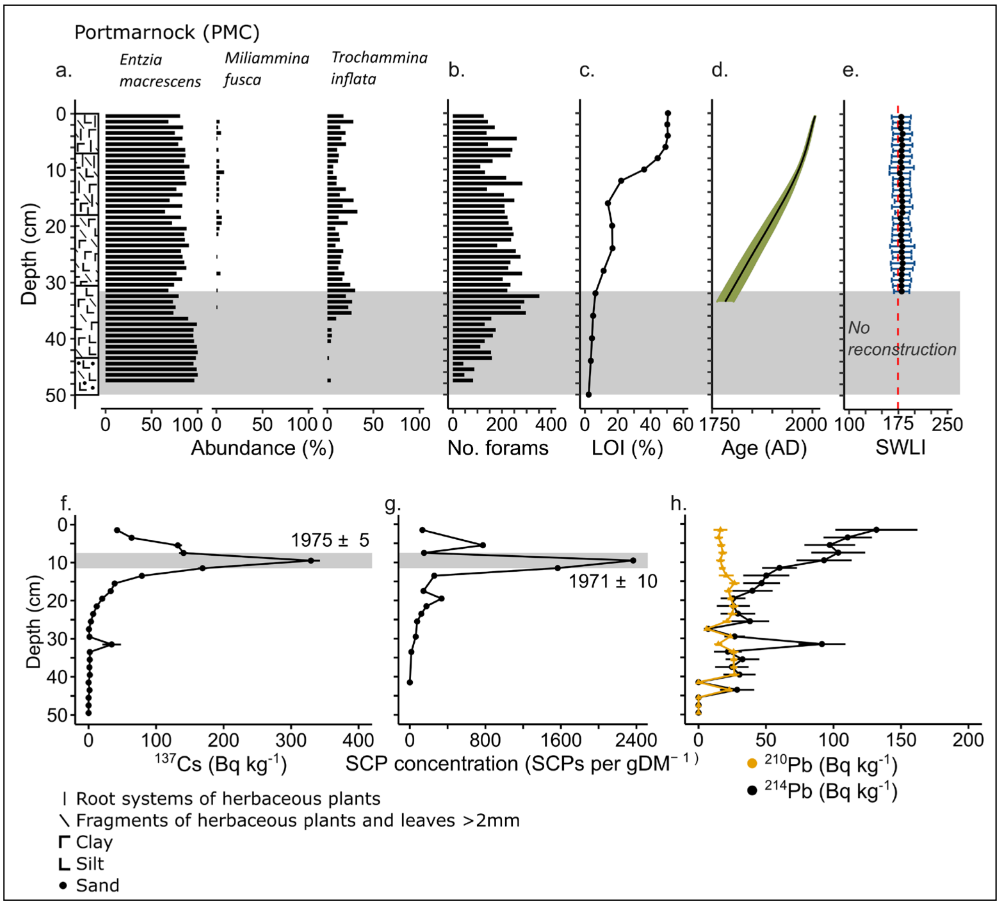

Figure 5 (a) Core log and relative abundance of foraminifera, **(b)** number of foraminifera counted, **(c)** percentage total organic matter (LOI), **(d)** age depth model obtained from R package 'rplum' with 95% confidence interval and **(e)** palaeomarsh elevation predicted by the Bayesian transfer function, expressed as standardised water level index (SWLI) with 95% confidence interval. The red dashed line indicates the core top SWLI. PMC is cropped (a–e) to only include saltmarsh sediments. **(f)** ^{137}Cs, **(g)** Spheroidal carbonaceous particle (SCP) concentration and **(h)** ^{210}Pb and ^{214}Pb results for Portmarnock core PMC.

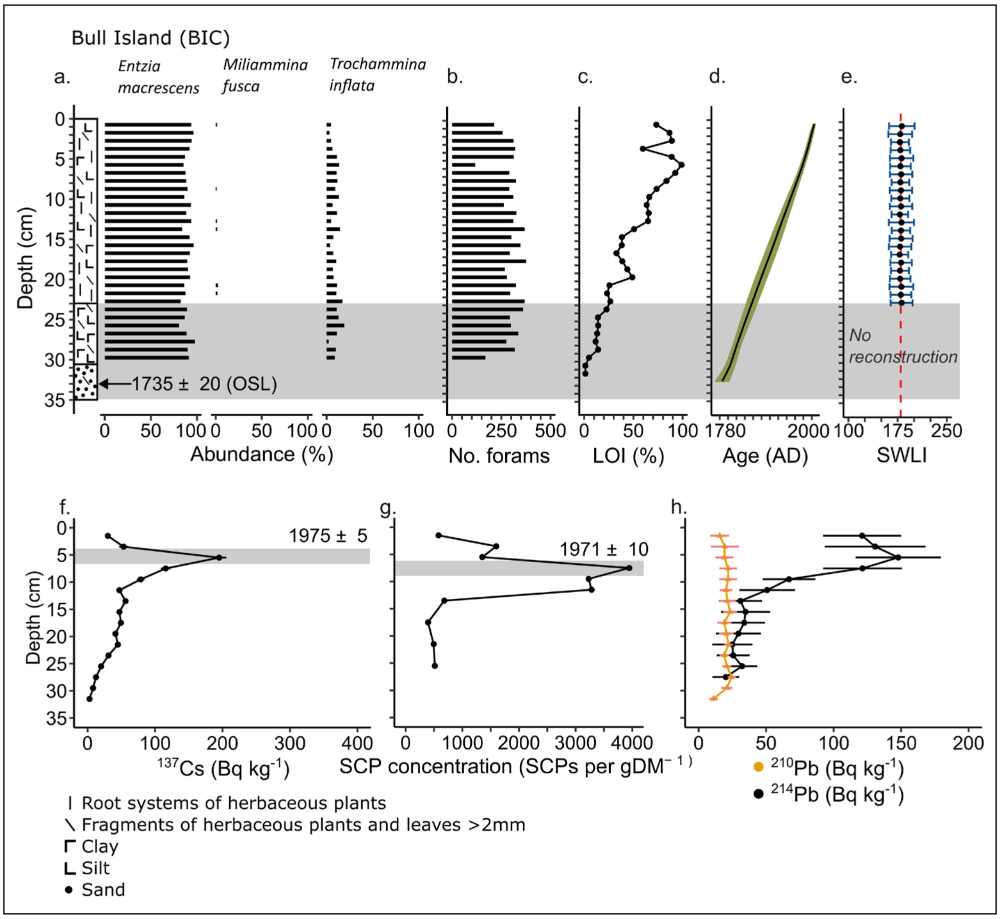

Figure 6 **(a)** Core log and relative abundance of foraminifera, **(b)** number of foraminifera counted, **(c)** percentage total organic matter (LOI), **(d)** age depth model obtained from R package 'rplum' with 95% confidence interval and **(e)** palaeomarsh elevation predicted by the Bayesian transfer function, expressed as standardised water level index (SWLI) with 95% confidence interval. The red dashed line indicates the core top SWLI. BIC is cropped (a–e) to only include saltmarsh sediments. **(f)** ^{137}Cs, **(g)** Spheroidal carbonaceous particle (SCP) concentration and **(h)** ^{210}Pb and ^{214}Pb results for Bull Island core BIC.

abundance of *T. inflata.* At both sites, the reconstructed elevations inferred from the topmost foraminiferal assemblage match the measured core top elevations within error.

4.3 CHRONOLOGY AND AGE-DEPTH MODELLING

We combine the age information provided by ^{210}Pb, ^{137}Cs and SCPs in rplum to produce composite chronologies for each of our sedimentary sequences (Figures 5d and 6d). In addition, at Bull Island, the age of the basal sand unit is constrained by the single OSL date of 1735 ± 20 CE. Excess ^{210}Pb was interpreted using rplum (Aquino-López et al., 2018). ^{210}Pb-based ages are supported by a chronostratigraphic marker based on ^{137}Cs activity.

^{137}Cs contamination at our sample sites is likely derived from global fallout (late 1950s to early 1960s), discharge from nuclear fuel processing (e.g., Sellafield, UK) and from the Chernobyl incident (1986). Previous coastal studies in Britain have found that down-core ^{137}Cs specific activity reaches levels that cannot be explained by Northern Hemisphere ^{137}Cs fallout alone, and that waterborne discharges from Sellafield are a key contributor (Tsompanoglou et al., 2010). As such, peak ^{137}Cs is frequently attributed to maximum authorised discharges from Sellafield into the Irish Sea in 1975 (Gray et al., 1995; Tsompanoglou et al., 2010; Rahman et al., 2013; Swindles et al., 2018) and we assign an age of 1975 ± 5 years to the ^{137}Cs peak in our cores.

Peak SCP concentration in the UK and Ireland is variable, occurring in 1979 ± 6 years in the northwest UK (north Wales, northwest England, Northern Ireland, northern and southwest Scotland), 1994 ± 2 years in southeast Scotland and northeast England and in 1970 ± 5 years in south and central England (Rose and Appleby, 2005). Our sedimentary sequences are also likely to be strongly overprinted by local sources of SCPs from electricity generation in Dublin, with a series of oil and coal-fired power stations operating within 5–10 km of our study sites from 1903 onward. The Pigeon House oil-powered station operated between 1903 and 1976; the oil and coal fired Ringsend A and B commenced operation in 1955 and 1965 respectively, before being decommissioned in 1988; whilst the Poolbeg station operated between 1971 and 2010, with a second chimney being added in 1978. On this basis we date the peak SCP concentration to 1971 ± 10 years, coinciding with increased electricity production at Poolbeg but prior to the decommissioning of the adjacent station at Pigeon House.

4.4 RELATIVE SEA-LEVEL RECONSTRUCTIONS

We combine the PME and age-depth data to produce two, independent RSL reconstructions from neighbouring sites. These duplicate records allow us to informally assess inter-site variability and evaluate the consistency of the GTG approach.

Our reconstruction indicates RSL at Portmarnock rose by 30 ± 8 cm between 1785 and 2009 (Figure 7a). Whilst subtle variations in RSL are hinted at in the PME reconstructions, the record lacks the resolution to distinguish decadal-scale changes in the model. Instead, the EIV-IGP model indicates RSL rose at a long term (century-scale) rate of 1.5 ± 1.0 mm yr^{-1} (Figure 7a).

The record from Bull Island is slightly shorter than that from Portmarnock, indicating RSL rose by 20 ± 10 cm between 1840 and 2009 (Figure 7b). As at Portmarnock, some decadal-scale variation is hinted at but is too subtle to be distinguished by the model. The EIV-IGP model indicates RSL at Bull Island rose at a long term (century-scale) rate of 1.3 ± 1.5 mm yr^{-1} (Figure 7b).

The RSL records from our two sites indicate a consistent pattern of RSL rise since the middle of the 19th Century. In light of this consistency, we combine the data from both sites to produce a single, composite RSL record for Dublin spanning 1785–2009 (Figure 7c). This record indicates that RSL rose at a long-term rate of 1.5 ± 0.9 mm yr^{-1}.

5. DISCUSSION

5.1 COMPARING THE GTG RECORD WITH THE DUBLIN PORT TIDE GAUGE

The Dublin Port tide gauge record, extending back to 1938, is Ireland's longest sea-level time series and provides a useful reference against which to assess the most recent portion of our saltmarsh-based RSL reconstructions. When recalibrated to adjust for biased high-water measurements, the tide gauge indicates RSL in Dublin Bay rose at a rate of 1.1 ± 0.5 mm yr^{-1} between 1953 and 2016 (Shoari Nejad et al., 2022). Although covering different time intervals, this instrumental rate of RSL rise overlaps with the longer-term rate inferred from our GTG-based approach, and the Dublin tide gauge record plots within the 95% confidence interval of the reconstruction for much of its length (Figure 7c).

The annually resolved Dublin Port tide gauge exhibits substantial decadal-scale variability with two intervals of unusually low MSL, centred around 1980 and the mid-1990s, which fall outside of the modelled 95% confidence interval of our RSL reconstruction. Shoari Nejad et al. (2022) note that these intervals of lower sea level are not apparent in the tide gauge records from Newlyn (UK) or Brest (France), and their precise cause is currently unknown.

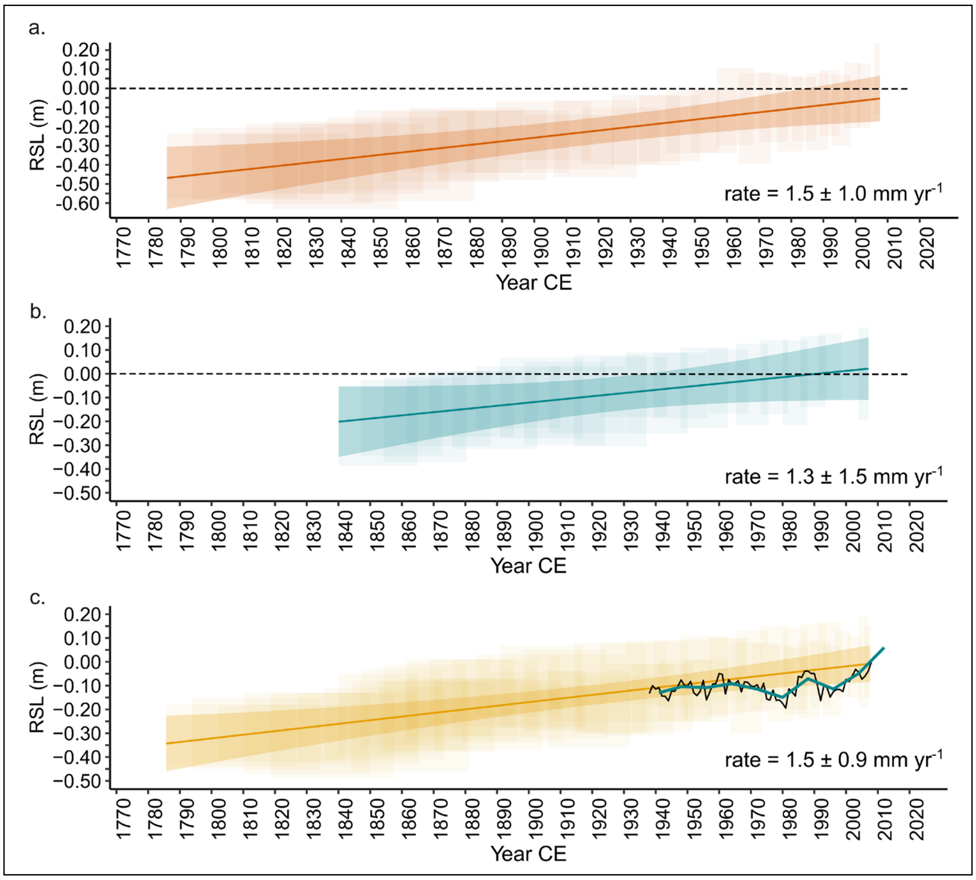

Figure 7 Errors in Variables Integrated Gaussian Process model results for County Dublin sites **(a)** Portmarnock (orange), **(b)** Bull Island (blue) and **(c)** a combined record including results from Portmarnock and Bull Island (yellow) showing mean with 95% confidence interval. Dublin Port tide gauge RSL data is also shown as annual (black line) and 8-year (turquoise) averages.

To evaluate whether such a signal is theoretically detectable in our saltmarshes, in which a 1 cm thick sample equates to sediment accumulation over approximately c. 8 years, we replot the Dublin Port tide gauge record as the average of consecutive 8-year bins (Figure 7c). The results indicate that whilst the two reductions in RSL would be resolvable in the time domain, their small magnitude (c. 10 cm) is only half the size of the vertical uncertain represented by the EIV-IGP 95% confidence interval, and so would not be detectable in the foraminifera-based reconstructions. Whilst unresolved in the biostratigraphic data, we note that two intervals of elevated LOI are evident in BIC at 5.5 cm depth (1978) and 1.5 cm depth (2000), separated by a marked reduction in organic content at 3.5 cm depth (1991) (Figure 6c). It is therefore possible that the supply of minerogenic sediment onto the saltmarsh platform at Bull Island also varied in conjunction with the unusual pattern of sea-level change recorded by the Dublin Port tide gauge. However, we note that a similar signal is absent in the Portmarnock core which indicates that whatever was responsible for this decadal-scale variability is expressed as a local process within Dublin Bay itself. We suggest that this could be an anthropogenic signal related to the development or dredging of the port, which would have significantly affected the tidal amplitude locally.

5.2 TWO CENTURIES OF DUBLIN RSL CHANGE IN A REGIONAL CONTEXT

We compare our new RSL record from Dublin with the regional pattern of MSL change inferred from a recent compilation of tide gauge data from Britain (Hogarth et al., 2021). In order to place local records of MSL rise into a regional context, it is necessary to correct RSL records for vertical land movement and changes in the geoid associated with the ongoing process of glacio-isostatic adjustment (GIA). RSL data from Britain and Ireland have featured extensively in GIA model development, with several different models available for the region (e.g., Lambeck, 1996; Brooks et al., 2008; Bradley et al., 2011, 2023; Kuchar et al., 2012). As the choice of model will influence the final GIA-corrected value of MSL change, we use the ICE-6G (VM5a) model of Peltier et al. (2015) for consistency with the results presented by Hogarth et al. (2021).

After correction for GIA, the GTG record from Dublin indicates that over the past two centuries, MSL rose at a long-term rate of 1.6 ± 0.9 mm yr^{-1}. This rate is in agreement with a regional value of 1.5 ± 0.2 mm yr^{-1} calculated by the EIV-IGP model from the Hogarth et al. (2021) instrumental dataset (Figure 8). Whilst both approaches indicate the same amount of MSL rise since the start of the 19th century, the greater precision and sampling density of the tide gauge compilation allows the EIV-IGP model to extract the time-evolving rate of change, indicating that sea-level rise accelerated over the past 200 years. This trajectory of MSL rise lies within the 95% confidence interval of our reconstruction, but the magnitude of the vertical uncertainties associated with the PME estimates mean that analysing multidecadal-scale variability is beyond the resolution of our saltmarsh-based reconstruction.

5.3 APPLICATIONS AND CHALLENGES FOR THE GTG APPROACH

The reproducibility of the saltmarsh-based RSL reconstructions from Dublin, and their close agreement with the century-scale rates of MSL change inferred from tide gauge records, demonstrates the utility of the GTG approach in the minerogenic saltmarshes of Ireland. The capacity to develop RSL reconstructions spanning the last few centuries from locations where tide gauge records are short, or absent, provides a means of augmenting the information provided by existing instrumental datasets (Kopp et al., 2016). For example, in Ireland, only two tide gauges outside of Dublin have records of sufficient length to analyse long period MSL changes and both of these gauges (Malin Head and Belfast Harbour) are located in the northern part of the country where directions and

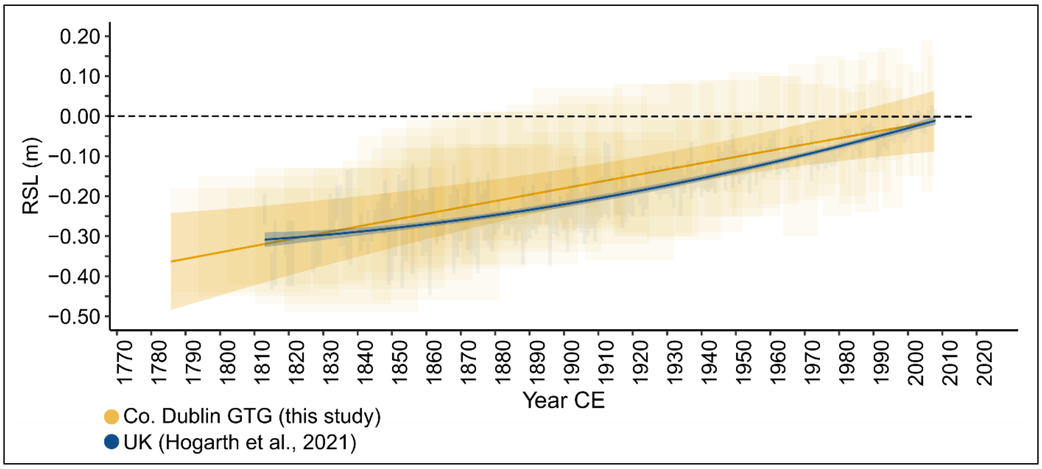

Figure 8 Errors in Variables Integrated Gaussian Process model results for County Dublin (yellow) and the UK (blue; Hogarth et al., 2021) with 95% confidence interval.

rates of GIA differ significantly from those experienced further to the south and west (e.g., Bradley et al., 2011, 2023). GIA in the northeast reduces RSL rise, whereas GIA in south and west increases RSL rise. The GTG approach has the potential to greatly increase the spatial and temporal coverage of RSL data, filling the gaps where instrumental measurements are not available, and extending record duration where gauges have only been operating for a limited period of time. In addition to quantifying local scale background rates of RSL change, a more densely sampled network of sea-level reconstructions will help constrain spatial patterns of GIA and refine existing models, both of which are key components for accurately projecting future regional sea-level change (e.g., Edwards et al., 2017; Palmer et al., 2018; Kirby et al., 2023). The GTG approach has the potential to improve data coverage in other regions where similar minerogenic saltmarsh deposits are both available and suitable.

Whilst our GTG reconstruction accurately reproduces the long-term rate of regional MSL rise over the past two centuries, the Dublin record highlights several limitations in the application of this approach in a NW European context. The size of the vertical uncertainty in our reconstructions effectively precludes the identification of (multi)decadal-scale changes in rate, such as those observed in the tide gauge compilation of Hogarth et al. (2021) and in the Dublin Port record (Shoari Nejad et al., 2022). The vertical error term primarily reflects the precision with which PME can be reconstructed which, in turn, is determined by the tidal range and the detail with which this vertical range can be sub-divided into discrete elevation zones. In the case of the Dublin record, our vertical uncertainty is around 6% of the tidal range which compares favourably with the performance of saltmarsh foraminifera-based reconstructions elsewhere in the Atlantic region (Barlow et al., 2013). As tidal range is dictated by study site location, increasing the precision of a given record will depend upon improvements in the estimation of PME from proxy data.

Further work to better understand the factors controlling modern foraminifera distributions in Ireland is required to isolate the assemblages and components that carry the strongest elevation signals, but this will not resolve some of the limitations inherent with the use of this individual proxy (Edwards and Wright, 2015). The use of Bayesian models offers one way of improving vertical precision by incorporating prior information from complementary data to help constrain the plausible bounds of elevation zones. The potential of this approach has been demonstrated by Kemp et al. (2012) who used carbon isotopes in combination with foraminiferal data to refine PME estimates in New Jersey, USA. The marked difference between the organic content of saltmarsh and tidal flat sediments identified in our cores, and noted in previous studies (e.g., Plater et al., 2015), indicates that organic content in general could be used to formally constrain the lower bound of saltmarsh deposits, although the influence of post-depositional processes such as decomposition should be considered (Plater et al., 2015).

Similarly, resolution in the upper marsh could be improved by incorporating a terrestrial ‘end member’ that would be restricted to the highest elevation contexts around the upper limit of marine influence. Testate amoebae have the potential to fulfil this role as they exhibit distinctive vertical assemblage zones around the high marsh to upland transition which directly complement the information provided by saltmarsh foraminifera (Barnett et al., 2017; Kemp et al., 2017a). For example, a double peak in the relative abundance of *E. macrescens* is evident in our surface foraminiferal dataset, with the upper peak located at the top of the intertidal zone and a lower peak evident around MHW (Figure 2). The incorporation of testate amoebae into our training set could help discriminate between these peaks and improve the precision of PME reconstructions above MHW. At present, little is known about the distribution of testate amoebae in Irish saltmarshes, but their occurrence at sites across the North Atlantic region suggests the development of this multi-proxy approach has great potential, especially in the region of Ireland where high rainfall results in saltmarshes with typically lower salinity regimes than elsewhere (Cott et al., 2012).

Further limitations of our record are its comparatively short duration, reflecting the fact that the saltmarsh sequences in Dublin are thin, and recovering reliable RSL information from minerogenic tidal flat sediments is problematic. The GTG approach works best where near continuous sequences of organic-rich, high-marsh sediments accumulate, as illustrated by the large number of records that have been developed from these contexts along the Atlantic coast of North America (e.g., Gehrels, 2000; Gehrels et al., 2002; Kemp et al., 2009, 2012, 2017b, 2018). The utility of these deposits stems from an abundance of material easily dateable by ^{14}C for developing detailed chronologies, coupled with rich microfossil assemblages from which to infer PME. Finding comparable material in the minerogenic saltmarshes of NW Europe is challenging, with many coastal sequences characterised by intercalated deposits of peat and silty-clay, and a general paucity of organic saltmarsh units in the late Holocene (e.g., Allen, 2000; Long et al., 2000). Where longer saltmarsh units are present, they are typically less organic than their North American counterparts, often lack recognisable plant macrofossils, and are generally less suitable for the production of detailed, radiocarbon-based chronologies (Edwards, 2023). In these settings, researchers often rely on dating bulk sediment samples which incorporate carbon from multiple sources. This results in reduced precision of sample-specific age ranges and also potentially increases the risk of erroneous age estimates (e.g., Barlow et al., 2014). The development of Ramped Pyrolysis Oxidation (RPyOx) radiocarbon dating, which separates carbon fractions thermally, may assist in correcting bulk radiocarbon dates for contamination and improve the resulting chronologies (Rosenheim et al., 2008; Rosenheim et al., 2013; Suzuki et al., 2021) as would further utilisation of luminescence techniques for dating the minerogenic sediment fraction (Plater et al., 2000; Edwards, 2004; Bateman, 2015; Pannozzo et al., 2022).

Our study sites were selected on the basis of their proximity to the long Dublin Port tide gauge record and are not optimally located for the development of longer records of change. However, thicker saltmarsh deposits are likely to be recovered from other parts of the Irish coastline, especially in regions to the south and west where models suggest more rapid subsidence linked to GIA resulting in greater accommodation space for the accumulation of intertidal deposits. The development of longer records with improved resolution would provide a useful input for the analysis of spatial trends in RSL change around the North Atlantic margin (Walker et al., 2022), which can ultimately be used to test the relative importance of processes driving RSL change (e.g., Kopp et al., 2016; Kemp et al., 2018; Walker et al., 2022).

6. CONCLUSIONS

We present new surface and core data from two sites in Dublin, Ireland, to test the applicability and reproducibility of the saltmarsh foraminifera-based GTG approach to RSL reconstruction. Our data demonstrate that saltmarsh foraminifera in Ireland are vertically zoned and contain similar assemblages to those reported elsewhere in the region. We combine these foraminifera assemblages to produce a Bayesian transfer function for tide level capable of reconstructing PME with an RMSEP of 20 cm.

When applied to coastal sediment cores from two different saltmarshes, the GTG approach produces RSL records that are essentially identical to each other with long-term (century-scale) rates that overlap with the longest tide gauge record available. Following correction for GIA, the saltmarsh-based rates of RSL for the last two centuries are comparable with the long-term rate of MSL rise derived from a regional compilation of tide gauge data from Britain spanning the same time period. On this basis, we conclude that the GTG approach is robust, reproducible and accurate within the defined limits of uncertainty.

Our relatively short Dublin record is currently incapable of resolving the (multi)decadal-scale changes required to detect any acceleration in the rate of RSL rise during the study period or evaluate the timing of the onset of current rates of change. Future applications should focus on improving record resolution and duration by refining PME estimates and identifying longer sequences of saltmarsh sediment. Improving our understanding of the spatial variability and controls on modern saltmarsh foraminifera distributions will assist in accurately quantifying PME, as will the incorporation of informative priors (e.g., organic content, testate amoebae data) into the Bayesian transfer function framework. Attention should now focus on producing longer records of RSL from the region to compare with the extensive dataset that has been developed along the Atlantic margin of North America.

Ireland is unusual in a European context in that its network of tide gauge observations was established relatively recently in the 2000s (Cámaro García et al. 2021). Ongoing data archaeology efforts provide intermittent estimates of sea-level rise (Pugh et al. 2021) but these require continuous estimates to fill the blanks. Therefore, the GTG approach naturally complements these estimates of RSL change and plays a key role in delivering the information necessary for understanding Ireland's vulnerability to rising sea levels in a changing climate.

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **Roseby-et-al_Supp-Info.xlsx.** Surface and core foraminifera data from Portmarnock and Bull Island. DOI: https://doi.org/10.5334/oq.121.s1

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

ZR: statistical analysis of the foraminiferal dataset, chronology building, RSL reconstructions and writing the manuscript; KS: data collection in the field and laboratory analysis; FA: statistical analysis of surface foraminifera; NC: Bayesian transfer function and EIV-GP modelling; GM: Dublin Port tidal data; RE: project conception and design, data collection in the field, writing the manuscript. All authors provided comments on drafts of the manuscript.

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REFERENCES

Allen, JRL. 2000. Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. *Quaternary Science Reviews*, 19: 1155–1231. DOI: https://doi.org/10.1016/S0277-3791(99)00034-7

Appleby, P. 2001. Chronostratigraphic techniques in recent sediments, Tracking environmental change using lake sediments. *Springer*, 171–203. DOI: https://doi.org/10.1007/0-306-47669-X_9

Aquino-López, MA, Blaauw, M, Christen, JA and **Sanderson, NK.** 2018. Bayesian Analysis of 210Pb Dating. *Journal of Agricultural. Biological and Environmental Statistics*, 23: 317–333. DOI: https://doi.org/10.1007/s13253-018-0328-7

Armynot du Châtelet, E, Degre, D, Sauriau, P-G and **Debenay, JP.** 2009. Distribution of living benthic foraminifera in relation with environmental variables within the Aiguillon cove (Atlantic coast, France): Improving knowledge for paleoecological interpretation. *Bulletin De La Societe Geologique De France*, 180: 131–144. DOI: https://doi.org/10.2113/gssgfbull.180.2.131

Barlow, NLM, Long, AJ, Saher, MH, Gehrels, WR, Garnett, MH and **Scaife, RG.** 2014. Salt-marsh reconstructions of relative sea-level change in the North Atlantic during the last 2000 years. *Quaternary Science Reviews*, 99: 1–16. DOI: https://doi.org/10.1016/j.quascirev.2014.06.008

Barlow, NLM, Shennan, I, Long, AJ, Gehrels, WR, Saher, MH, Woodroffe, SA and **Hillier, C.** 2013. Salt marshes as late Holocene tide gauges. *Global and Planetary Change*, 106: 90–110. DOI: https://doi.org/10.1016/j.gloplacha.2013.03.003

Barnett, RL, Newton, TL, Charman, DJ and **Gehrels, WR.** 2017. Salt-marsh testate amoebae as precise and widespread indicators of sea-level change. *Earth-Science Reviews*, 164: 193–207. DOI: https://doi.org/10.1016/j.earscirev.2016.11.002

Bateman, MD. 2015. The application of luminescence dating in sea-level studies. In: Shennan, I, Long, AJ and Horton, BP (eds.), *Handbook of Sea-Level Research*. Chichester: J. Wiley and Sons Ltd. pp. 404–417. DOI: https://doi.org/10.1002/9781118452547.ch27

Boomer, I. 1998. The relationship between meiofauna (Ostracoda, Foraminifera) and tide levels in modern intertidal environments of North Norfolk: A tool for palaeoenvironmental reconstruction. *Bulletin of the Geological Society of Norfolk*, 46: 17–29.

Bradley, SL, Milne, GA, Shennan, I and **Edwards, R.** 2011. An improved glacial isostatic adjustment model for the British Isles. *Journal of Quaternary Science*, 26: 541–552. DOI: https://doi.org/10.1002/jqs.1481

Bradley, SL, Ely, JC, Clark, CD, Edwards, RJ and **Shennan, I.** 2023. Reconstruction of the palaeo-sea level of Britain and Ireland arising from empirical constraints of ice extent: Implications for regional sea level forecasts and Laurentide ice volume. *Journal of Quaternary Science*. DOI: https://doi.org/10.1002/jqs.3523

Brooks, AJ, Bradley, SL, Edwards, RJ, Milne, GA, Horton, B and **Shennan, I.** 2008. Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. *Journal of Quaternary Science*, 23: 175–192. DOI: https://doi.org/10.1002/jqs.1119

Cahill, N, Kemp, AC, Horton, BP and **Parnell, AC.** 2015. Modeling sea-level change using errors-in-variables integrated Gaussian processes. *The Annals of Applied Statistics*, 9: 547–571. DOI: https://doi.org/10.1214/15-AOAS824

Cahill, N, Kemp, AC, Horton, BP and **Parnell, AC.** 2016. A Bayesian hierarchical model for reconstructing relative sea level: from raw data to rates of change. *Clim. Past*, 12: 525–542. DOI: https://doi.org/10.5194/cp-12-525-2016

Camaro Garcia, W, Dwyer, N, Barrett, F, Berry, A, Cronin, M, Cusack, C, Gallagher, S, Gault, J, Gill, M, Gleeson,

E, Hanley, J, Kane, P, Lambkin, K, Lawlor, R, Lydon, K, Lyons, K, Martin, D, McCarthy, G, McGovern, E, Murphy, C, Nolan, G, Nugent, C, O'Dwyer, B, Ovadnevaite, J, Quinlan, C, Saunders, M, Silke, J, Smith, G, Thomas, R, Walsh, S, Westbrook, G, Eoin, W and **Wilkes, R.** 2021. Climate Status Report for Ireland, Tech. rep., EPA. https://www.epa.ie/publications/research/climate-change/Research_Report_386.pdf.

Charrad, M, Ghazzali, N, Boiteau, V and **Niknafs, A.** 2014. NbClust: An R Package for Determining the Relevant Number of Clusters in a Data Set. *Journal of Statistical Software*, 61: 1–36. DOI: https://doi.org/10.18637/jss.v061.i06

Coles, BPL. 1977. The Holocene foraminifera and palaeogeography of central Broadland. Unpublished thesis (PhD), University of East Anglia.

Coles, BPL and **Funnell, BM.** 1981. Holocene Palaeoenvironments of Broadland, England. In: Nio, S-D, Shüttenhelm, RTE and Van Weering, TjCE (eds.), *Holocene Marine Sedimentation in the North Sea Basin*. pp. 123–131. DOI: https://doi.org/10.1002/9781444303759.ch9

Cott, GM, Jansen, MAK and **Chapman, DV.** 2012. Salt-Marshes on Peat Substrate: Where Blanket Bogs Encounter the Marine Environment. *Journal of Coastal Research*, 28: 700–706. DOI: https://doi.org/10.2112/JCOASTRES-D-11-00108.1

Craven, KF, Edwards, RJ, Goodhue, R and **Rocha, C.** 2013. Evaluating the influence of selected acid pre-treatment methods on C/N and $\delta^{13}C$ of temperate inter-tidal sediments for relative sea level reconstruction. *Irish Journal of Earth Sciences*, 31: 25–42. DOI: https://doi.org/10.3318/IJES.2013.31.5

Edwards, R, Gehrels, WR, Brooks, A, Fyfe, R, Pullen, K, Kuchar, J and **Craven, K.** 2017. Resolving discrepancies between field and modelled relative sea-level data: lessons from western Ireland. *Journal of Quaternary Science*, 32: 957–975. DOI: https://doi.org/10.1002/jqs.2969

Edwards, R and **Horton, B.** 2000. Reconstructing relative sea-level change using UK salt-marsh foraminifera. *Marine Geology*, 169: 41–56. DOI: https://doi.org/10.1016/S0025-3227(00)00078-5

Edwards, RJ. 2004. Constructing chronologies of sea-level change from salt-marsh sediments. In Buck, CE and Millard, AR (eds.), *Tools for Constructing Chronologies: Crossing Disciplinary Boundaries*. London: Springer Verlag. pp. 191–213. DOI: https://doi.org/10.1007/978-1-4471-0231-1_9

Edwards, RJ. 2023. Sedimentary indicators of relative sea-level changes—Low energy. *Encyclopedia of Quaternary Science*, 3rd Edition. Elsevier. DOI: https://doi.org/10.1016/B978-0-323-99931-1.00017-9

Edwards, RJ and **Wright, A.** 2015. Foraminifera. In: *Handbook of sea-level research*. pp. 191–217. DOI: https://doi.org/10.1002/9781118452547.ch13

Edwards, RJ, Wright, AJ and **van de Plassche, O.** 2004. Surface distributions of salt-marsh foraminifera from Connecticut, USA: modern analogues for high-resolution sea level studies. *Marine Micropaleontology*, 51: 1–21. DOI: https://doi.org/10.1016/j.marmicro.2003.08.002

Fox-Kemper, B, Hewitt, HT, Xiao, C, Aðalgeirsdóttir, G, Drijfhout, SS, Edwards, TL, Golledge, NR, Hemer, M, Kopp, RE, Krinner, G, Mix, A, Notz, D, Nowlicki, S, Nurhati, IS, Ruis, L, Sallée, J-B, Slangen, ABA and **Yu, Y.** 2021. Ocean, Cryosphere and Sea Level Change. In: Masson-Delmotte, V, Zhai, P, Pirani, A, Connors, SL, Péan, C, Berger, S, Caud, N, Chen, Y, Goldfarb, L, Gomis, MI, Huang, M, Leitzell, K, Lonnoy, E, Matthews, JBR, Maycock, TK, Waterfield, T, Yelekçi, O, Yu, R and Zhou, B (eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. pp. 1211–1362.

Funnell, BM and **Boomer, I.** 1998. Microbiofacies tidal-level and age deduction in Holocene saltmarsh deposits on the North Norfolk Coast. *Bulletin of the Geological Society of Norfolk*, 46: 31–55.

Gehrels, WR. 1999. Middle and Late Holocene Sea-Level Changes in Eastern Maine Reconstructed from Foraminiferal Saltmarsh Stratigraphy and AMS 14C Dates on Basal Peat. *Quaternary Research*, 52: 350–359. DOI: https://doi.org/10.1006/qres.1999.2076

Gehrels, WR. 2000. Using foraminiferal transfer functions to produce high-resolution sea-level records from salt-marsh deposits, Maine, USA. *Holocene*, 10: 367–376. DOI: https://doi.org/10.1191/095968300670746884

Gehrels, WR, Kirby, JR, Prokoph, A, Newnham, RM, Achterberg, EP, Evans, H, Black, S and **Scott, DB.** 2005. Onset of recent rapid sea-level rise in the western Atlantic Ocean. *Quaternary Science Reviews*, 24: 2083–2100. DOI: https://doi.org/10.1016/j.quascirev.2004.11.016

Gehrels, WR and **van de Plassche, O.** 1999. The use of Jadammina macrescens (Brady) and Balticammina pseudomacrescens Brönnimann, Lutze and Whittaker (Protozoa: Foraminiferida) as sea-level indicators. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 149: 89–101. DOI: https://doi.org/10.1016/S0031-0182(98)00194-1

Gehrels, WR, Belknap, DF, Black, S and **Newnham, RM.** 2002. Rapid sea-level rise in the Gulf of Maine, USA, Since AD 1800. *The Holocene*, 12: 383–389. DOI: https://doi.org/10.1191/0959683602hl555ft

Gray, J, Jones, S and **Smith, AD.** 1995. Discharges to the environment from the Sellafield site, 1951–1992. *Journal of Radiological Protection*, 15: 99. DOI: https://doi.org/10.1088/0952-4746/15/2/001

Grey, A, Cunningham, A, Lee, A, Monteys, X, Coveney, S, McCaul, MV, Murphy, BT, McCloughlin, T, Hidaka, B and **Kelleher, BP.** 2021. Geochemical mapping of a blue carbon zone: Investigation of the influence of riverine input on tidal affected zones in Bull Island. *Regional Studies in Marine Science*, 45: 101834. DOI: https://doi.org/10.1016/j.rsma.2021.101834

Guérin, G, Mercier, N and **Adamiec, G.** 2011. Dose-rate conversion factors: update. *Ancient TL*, 29: 5–8.

Guérin, G, Mercier, N, Nathan, R, Adamiec, G and **Lefrais, Y.** 2012. On the use of the infinite matrix assumption and associated concepts: A critical review. *Radiation Measurements*, 47: 778–785. DOI: https://doi.org/10.1016/j.radmeas.2012.04.004

Harris, CR. 1973. The evolution of North Bull Island, Dublin Bay. Unpublished thesis (MSc), Trinity College Dublin.

Hawkes, AD, Horton, B, Nelson, A and **Hill, D.** 2010. The application of intertidal foraminifera to reconstruct coastal subsidence during the giant Cascadia earthquake of AD 1700 in Oregon, USA. *Quaternary International*, 221: 116–140. DOI: https://doi.org/10.1016/j.quaint.2009.09.019

Hogarth, P, Pugh, DT, Hughes, CW and **Williams, SDP.** 2021. Changes in mean sea level around Great Britain over the past 200 years. *Progress in Oceanography*, 192: 102521. DOI: https://doi.org/10.1016/j.pocean.2021.102521

Horton, BP, Edwards, R and **Lloyd, J.** 1999. Reconstruction of former sea levels using a foraminiferal-based transfer function. *Journal of Foraminiferal Research*, 29: 117–129. DOI: https://doi.org/10.2113/gsjfr.29.2.117

Horton, BP. 1999. The distribution of contemporary intertidal foraminifera at Cowpen Marsh, Tees Estuary, UK: implications for studies of Holocene sea-level changes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 149: 127–149. DOI: https://doi.org/10.1016/S0031-0182(98)00197-7

Horton, BP and **Culver, SJ.** 2008. Modern intertidal foraminifera of the Outer Banks, North Carolina, USA, and their applicability for sea-level studies. *Journal of Coastal Research*, 24: 1110–1125. DOI: https://doi.org/10.2112/08A-0004.1

Horton, BP and **Edwards, RJ.** 2003. Seasonal distributions of foraminifera and their implications for sea-level studies, Cowpen Marsh, UK. In: Olson, HC and Lecjie, M (eds.), *Micropaleontologic Proxies for Sea-Level Change and Stratigraphic Discontinuities*. DOI: https://doi.org/10.2110/pec.03.75.0021

Horton, BP and **Edwards, RJ.** 2005. The application of local and regional transfer functions to the reconstruction of Holocene sea levels, north Norfolk, England. *The Holocene*, 15: 216–228. DOI: https://doi.org/10.1191/0959683605hl787rp

Horton, BP and **Edwards, RJ.** 2006. Quantifying Holocene sea level change using intertidal foraminifera: lessons from the British Isles. *Departmental Papers (EES)*, 50.

Horton, BP, Whittaker, JE, Thomson, KH, Hardbattle, MI, Kemp, A, Woodroffe, SA and **Wright, MR.** 2005. The development of a modern foraminiferal data set for sea-level reconstructions, Wakatobi Marine National Park, Southeast Sulawesi, Indonesia. *The Journal of Foraminiferal Research*, 35: 1–14. DOI: https://doi.org/10.2113/35.1.1

Kemp, AC, Horton, BP, Culver, SJ, Corbett, DR, van de Plassche, O, Gehrels, WR, Douglas, BC and **Parnell, AC.** 2009. Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). *Geology*, 37: 1035–1038. DOI: https://doi.org/10.1073/pnas.1015619108

Kemp, AC, Horton, BP, Donnelly, JP, Mann, ME, Vermeer, M and **Rahmstorf, S.** 2011. Climate related sea-level variations over the past two millennia. *Proceedings of the National Academy of Sciences*, 108: 11017–11022. DOI: https://doi.org/10.1073/pnas.1015619108

Kemp, AC, Horton, BP, Vann, DR, Engelhart, SE, Grand Pre, CA, Vane, CH, Nikitina, D and **Anisfeld, SC.** 2012. Quantitative vertical zonation of salt-marsh foraminifera for reconstructing former sea level; an example from New Jersey, USA. *Quaternary Science Reviews*, 54: 26–39. DOI: https://doi.org/10.1016/j.quascirev.2011.09.014

Kemp, AC, Telford, RJ, Horton, BP, Anisfeld, SC and **Sommerfield, CK.** 2013. Reconstructing Holocene sea level using salt-marsh foraminifera and transfer functions: lessons from New Jersey, USA. *Journal of Quaternary Science*, 28: 617–629. DOI: https://doi.org/10.1002/jqs.2657

Kemp, AC, Wright, AJ and **Cahill, N.** 2020. Enough is Enough, or More is More? Testing the Influence of Foraminiferal Count Size on Reconstructions of Paleo-Marsh Elevation. *Journal of Foraminiferal Research*, 50: 266–278. DOI: https://doi.org/10.2113/gsjfr.50.3.266

Kemp, AC, Wright, AJ, Edwards, RJ, Barnett, RL, Brain, MJ, Kopp, RE, Cahill, N, Horton, BP, Charman, DJ, Hawkes, AD, Hill, TD and **van de Plassche, O.** 2018. Relative sea-level change in Newfoundland, Canada during the past ~3000 years. *Quaternary Science Reviews*, 201: 89–110. DOI: https://doi.org/10.1016/j.quascirev.2018.10.012

Kemp, AC, Wright, AJ, Barnett, RL, Hawkes, AD, Charman, DJ, Sameshima, C, King, AN, Mooney, HC, Edrwards, RJ, Horton, BP and **van de Plassche, O.** 2017a. Utility of salt-marsh foraminifera, testate amoebae and bulk-sediment $\delta^{13}C$ values as sea-level indicators in Newfoundland, Canada. *Marine Micropaleontology*, 130: 43–59. DOI: https://doi.org/10.1016/j.marmicro.2016.12.003

Kemp, AC, Hill, TD, Vane, CH, Cahill, N, Orton, PM, Talke, SA, Parnell, AC, Sanborn, K and **Hartig, EK.** 2017b. Relative sea-level trends in New York City during the past 1500 years. *The Holocene*, 27: 1169–1186. DOI: https://doi.org/10.1177/0959683616683263

Kirby, JR, Garrett, E and **Gehrels, RW.** 2023. Holocene relative sea-level changes in northwest Ireland: An empirical test for glacial isostatic adjustment models. *The Holocene*. DOI: https://doi.org/10.1177/09596836231169992

Kopp, RE, Kemp, AC, Bittermann, K, Horton, BP, Donnelly, JP, Gehrels, WR, Hay, CC, Mitrovica, JX, Morrow, ED and **Rahmstorf, S.** 2016. Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences*, 113: E1434–E1441. DOI: https://doi.org/10.1073/pnas.1517056113

Kuchar, J, Milne, G, Hubbard, A, Patton, H, Bradley, S, Shennan, I and **Edwards, R.** 2012. Evaluation of a numerical model of the British–Irish ice sheet using relative sea-level data: implications for the interpretation of trimline observations. *Journal of Quaternary Science*, 27: 597–605. DOI: https://doi.org/10.1002/jqs.2552

Lambeck, K. 1996. Glaciation and sea-level change for Ireland and the Irish Sea since Late Devensian/Midlandian time. *Journal of the Geological Society, London*, 153: 853–872. DOI: https://doi.org/10.1144/gsjgs.153.6.0853

Long, AJ, Scaife, RG and **Edwards, RJ.** 2000. Stratigraphic architecture, relative sea-level, and models of estuary development in southern England: new data from Southampton Water. In: Pye, K and Allen, JRL (eds.), *Coastal and Estuarine Environments: Sedimentology, Geomorphology and Geoarchaeology*. London: Geological Society, Special Publications, 175: 253–279. DOI: https://doi.org/10.1144/GSL.SP.2000.175.01.19

Maechler, M, Rousseeuw, P, Struyf, A, Hubert, M and **Hornik, K.** 2012. Cluster: cluster analysis basics and extensions. *R package version*, 1: 56.

Marshall, W. 2015. Chronohorizons: indirect and unique event dating methods for sea-level reconstructions. In: *Handbook of Sea-Level Research*. Hoboken, NJ: Wiley. pp. 373–385. DOI: https://doi.org/10.1002/9781118452547.ch25

Massey, AC, Gehrels, WR, Charman, DJ and **White, SV.** 2006. An intertidal foraminifera-based transfer function for reconstructing Holocene sea-level change in southwest England. *Journal of Foraminiferal Research*, 36: 215–232. DOI: https://doi.org/10.2113/gsjfr.36.3.215

Mauz, B, Nolan, PJ and **Appleby, PG.** 2022. Technical note: Quantifying uranium-series disequilibrium in natural samples for dosimetric dating – Part 1: gamma spectrometry. *Geochronology*, 4: 213–225. DOI: https://doi.org/10.5194/gchron-4-213-2022

Mejdahl, V. 1979. Thermoluminescence dating: beta-dose attenuation in quartz grains. *Archaeometry*, 21: 61–72. DOI: https://doi.org/10.1111/j.1475-4754.1979.tb00241.x

Milker, Y, Horton, B, Nelson, A, Engelhart, S and **Witter, R.** 2015. Variability of intertidal foraminiferal assemblages in a salt marsh, Oregon, USA. *Marine Micropaleontology*, 118. DOI: https://doi.org/10.1016/j.marmicro.2015.04.004

Murray, AS and **Wintle, AG.** 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. *Radiation Measurements*, 37: 377–381. DOI: https://doi.org/10.1016/S1350-4487(03)00053-2

Murray, JW. 1991. Ecology and Palaeoecology of Benthic Foraminifera. Harlow, England: Longman Scientific and Technical.

Murray, JW. 2000. The enigma of the continued use of total assemblages in ecological studies of benthic foraminfera. *Journal of Foraminiferal Research*, 30: 244–245. DOI: https://doi.org/10.2113/0300244

Murray, JW and **Bowser, SS.** 2000. Mortality, protoplasm decay rate, and reliability of staining techniques to recognize 'living'foraminifera: a review. *The Journal of Foraminiferal Research*, 30: 66–70. DOI: https://doi.org/10.2113/0300066

Murray, JW and **Alve, E.** 1999. Taphonomic experiments on marginal marine foraminiferal assemblages: how much ecological information is preserved? *Palaeogeography, Palaeoclimatology, Palaeoecology*, 149: 183–197. DOI: https://doi.org/10.1016/S0031-0182(98)00200-4

Müller-Navarra, K, Milker, Y and **Schmiedl, G.** 2017. Applicability of transfer functions for relative sea-level reconstructions in the southern North Sea coastal region based on salt-marsh foraminifera. *Marine Micropaleontology*, 135: 15–31. DOI: https://doi.org/10.1016/j.marmicro.2017.06.003

Palmer, M, Howard, T, Tinker, J, Lowe, J, Bricheno, L, Calvert, D, Edwards, T, Gregory, J, Harris, G and **Krijnen, J.** 2018. UKCP18 marine report.

Pannozzo, N, Smedley, RK, Chiverrell, RC, Carnacina, I and **Leonardi, N.** 2022. An integration of numerical modeling and paleoenvironmental analysis reveals the effects of embankment construction on long-term salt marsh accretion. *Journal of Geophysical Research: Earth Surface*, 127. DOI: https://doi.org/10.1029/2021JF006524

Peltier, WR, Argus, D and **Drummond, R.** 2015. Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research: Solid Earth*, 120: 450–487. DOI: https://doi.org/10.1002/2014JB011176

Phleger, FB. 1970. Foraminiferal populations and marine marsh processes. *Limnology and Oceanography*, 15: 522–534. DOI: https://doi.org/10.4319/lo.1970.15.4.0522

Plater, A, Ridgway, J, Rayner, B, Shennan, I, Horton, B, Haworth, EY, Wright, MR, Rutherford, MM and **Wintle, AG.** 2000. Sediment provenance and flux in the Tees Estuary: The record from the Late Devensian to the present. *Geological Society, London, Special Publications*, 166: 171–195. DOI: https://doi.org/10.1144/GSL.SP.2000.166.01.10

Plater, AJ, Kirby, JR, Boyle, JF, Shaw, T and **Mills, H.** 2015. Loss on ignition and organic content. In: Shennan, I, Long, AJ and Horton, BP (eds.), *Handbook of Sea-Level Research*. Chichester: J. Wiley and Sons Ltd. pp. 312–330. DOI: https://doi.org/10.1002/9781118452547.ch21

Pugh, DT, Bridge, E, Edwards, R, Hogarth, P, Westbrook, G, Woodworth, PL and **McCarthy, GD.** 2021. Mean sea level and tidal change in Ireland since 1842: A case study of Cork. *Ocean Sci*, 17: 1623–1637. DOI: https://doi.org/10.5194/os-17-1623-2021

Rahman, R, Plater, AJ, Nolan, PJ, Mauz, B and **Appleby, PG.** 2013. Potential health risks from radioactive contamination of saltmarshes in NW England. *Journal of Environmental Radioactivity*, 119: 55–62. DOI: https://doi.org/10.1016/j.jenvrad.2011.11.011

Rose, NL. 1990. A method for the extraction of carbonaceous particles from lake sediment. *Journal of Paleolimnology*, 3: 45–53. DOI: https://doi.org/10.1007/BF00209299

Rose, NL. 1994. A note on further refinements to a procedure for the extraction of carbonaceous fly-ash particles from sediments. *Journal of Paleolimnology*, 11: 201–204. DOI: https://doi.org/10.1007/BF00686866

Rose, NL and **Appleby, PG.** 2005. Regional Applications of Lake Sediment Dating by Spheroidal Carbonaceous Particle Analysis I: United Kingdom. *Journal of Paleolimnology*, 34: 349–361. DOI: https://doi.org/10.1007/s10933-005-4925-4

Rosenheim, BE, Day, MB, Domack, E, Schrum, H, Benthien, A and **Hayes, JM.** 2008. Antarctic sediment chronology by programmed-temperature pyrolysis: Methodology and data treatment. *Geochemistry, Geophysics, Geosystems*, 9. DOI: https://doi.org/10.1029/2007GC001816

Rosenheim, BE, Santoro, JA, Gunter, M and **Domack, EW.** 2013. Improving Antarctic Sediment 14C Dating Using Ramped Pyrolysis: An Example from the Hugo Island Trough. *Radiocarbon*, 55: 115–126. DOI: https://doi.org/10.2458/azu_js_rc.v55i1.16234

Rush, G, McDarby, P, Edwards, R, Milker, Y, Garrett, E and **Gehrels, WR.** 2021. Development of an intertidal foraminifera training set for the North Sea and an assessment of its application for Holocene sea-level reconstructions. *Marine Micropaleontology*, 169: 102055. DOI: https://doi.org/10.1016/j.marmicro.2021.102055

Saher, MH, Gehrels, WR, Barlow, NLM, Long, AJ, Haigh, ID and **Blaauw, M.** 2015. Sea-level changes in Iceland and the influence of the North Atlantic Oscillation during the last half millennium. *Quaternary Science Reviews*, 108: 23–36. DOI: https://doi.org/10.1016/j.quascirev.2014.11.005

Scott, DB. 1976. Brackish-water foraminifera from southern California and description of Polysaccammina ipohalina n. gen, n. sp. *Journal of Foraminiferal Research*, 6: 312–321. DOI: https://doi.org/10.2113/gsjfr.6.4.312

Scott, DB and **Hermelin, JOR.** 1993. A Device for Precision Splitting of Micropaleontological Samples in Liquid Suspension. *Journal of Paleontology*, 67: 151–154. DOI: https://doi.org/10.1017/S0022336000021302

Scott, DB and **Medioli, FS.** 1980. Quantitative Studies of Marsh Foraminiferal Distributions in Nova Scotia: Implications for Sea Level Studies. *Cushman Foundation for Foraminiferal Research*.

Scott, DB, Schnack, EJ, Ferrero, L, Espinosa, M and **Barbosa, CF.** 1990. Recent marsh foraminifera from the east coast of South America: comparison to the northern hemisphere, Paleoecology, biostratigraphy, paleoceanography and taxonomy of agglutinated foraminifera. *Springer*. 717–737. DOI: https://doi.org/10.1007/978-94-011-3350-0_25

Scott, DS and **Medioli, FS.** 1978. Vertical zonations of marsh foraminifera as accurate indicators of former sea-levels. *Nature*, 272: 528–531. DOI: https://doi.org/10.1038/272528a0

Shoari Nejad, A, Parnell, AC, Greene, A, Thorne, P, Kelleher, BP, Devoy, RJN and **McCarthy, G.** 2022. A newly reconciled dataset for identifying sea level rise and variability in Dublin Bay. *Ocean Sci*, 18: 511–522. DOI: https://doi.org/10.5194/os-18-511-2022

Smith, DA, Scott, DB and **Medioli, FS.** 1984. Marsh foraminifera in the Bay of Fundy: modern distribution and application to sea-level determinations. *Atlantic Geoscience*, 20. DOI: https://doi.org/10.4138/1581

Suzuki, K, Yamamoto, M, Rosenheim, BE, Omori, T and **Polyak, L.** 2021. New radiocarbon estimation method for carbonate-poor sediments: A case study of ramped pyrolysis 14C dating of postglacial deposits from the Alaskan margin, Arctic Ocean. *Quaternary Geochronology*, 66: 101215. DOI: https://doi.org/10.1016/j.quageo.2021.101215

Swindles, GT, Galloway, JM, Macumber, AL, Croudace, IW, Emery, AR, Woulds, C, Bateman, MD, Parry, L, Jones, JM, Selby, K, Rushby, GT, Baird, AJ, Woodroffe, SA and **Barlow, NLM.** 2018. Sedimentary records of coastal storm surges: Evidence of the 1953 North Sea event. *Marine Geology*, 403: 262–270. DOI: https://doi.org/10.1016/j.margeo.2018.06.013

Troels-Smith, J. 1955. Karakterisering af løse jordarter. Danmarks Geologiske Undersøgelse IV. *Række*, 3: 1–73. DOI: https://doi.org/10.34194/raekke4.v3.6989

Tsompanoglou, K, Croudace, IW, Birch, H and **Collins, M.** 2010. Geochemical and radiochronological evidence of North Sea storm surges in salt marsh cores from The Wash embayment (UK). *The Holocene,* 21: 225–236. DOI: https://doi.org/10.1177/0959683610378878

Walker, JS, Cahill, N, Khan, NS, Shaw, TA, Barber, D, Miller, KG, Kopp, RE and **Horton, BP.** 2020. Incorporating temporal and spatial variability of salt-marsh foraminifera into sea-level reconstructions. *Marine Geology*, 429: 106293. DOI: https://doi.org/10.1016/j.margeo.2020.106293

Walker, JS, Kopp, RE, Shaw, TA, Cahill, N, Khan, NS, Barber, DC, Ashe, EL, Brain, MJ, Clear, JL, Corbett, DR and **Horton, BP.** 2021. Common Era sea-level budgets along the US Atlantic coast. *Nature Communications*, 12(1): 1841. DOI: https://doi.org/10.1038/s41467-021-22079-2

Walker, JS, Kopp, RE, Little, CM and **Horton, BP.** 2022. Timing of emergence of modern rates of sea-level rise by 1863. *Nature Communications*, 13: 966. DOI: https://doi.org/10.1038/s41467-022-28564-6

Walton, WR. 1952. Techniques for recognition of living foraminifera. *Cushman Found, Foram. Res. Contr*, 3: 56–60.

Wright, AJ, Edwards, RJ and **van de Plassche, O.** 2011. Reassessing transfer-function performance in sea-level reconstruction based on benthic salt-marsh foraminifera from the Atlantic coast of NE North America. *Marine Micropaleontology*, 81: 43–62. DOI: https://doi.org/10.1016/j.marmicro.2011.07.003

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