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Review paper

Salt marshes as late Holocene tide gauges

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ABSTRACT

Understanding late Holocene to present relative sea-level changes at centennial or sub-centennial scales requires geological records that dovetail with the instrumental era. Salt marsh sediments are one of the most reliable geological tide gauges.

In this paper we review the methodological and technical advances that promoted research on 'high resolution' late Holocene sea-level change. We work through an example to demonstrate different pathways to quantitative reconstructions of relative sea level based on salt marsh sediments. We demonstrate that any reconstruction is in part a result of the environment from which the record is taken, the modern dataset used to calibrate the fossil changes, statistical assumptions behind calibrating microfossil assemblages and choices made by the researchers. With the error term of typical transfer function models ~10–15% of the tidal range, micro-tidal environments should produce the most precise sea-level reconstructions. Sampled elevation range of the modern dataset also has a strong influence on model predictive ability. Model-specific errors may under represent total uncertainty which comes from field practices, sedimentary environment, palaeotidal changes and sediment compaction as well as statistical uncertainties. Geological tide gauges require a detailed chronology but we must be certain that apparent relative sea-level fluctuations are not simply a consequence of an age–depth model.

We make six suggestions to aid the development and interpretation of geological tide gauge records.

Contents

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1. Introduction

Comparisons of secular trends in sea level from the twentieth century and late Holocene period (determined from instrumental tide gauge and geological data respectively) from the North Atlantic region, reveal that the instrumental tide gauge measured trends of mean sea-level are systematically larger than the long-term sea-level trends (Shennan and Woodworth, 1992; Woodworth et al., 1999; Shennan and Horton, 2002; Gehrels et al., 2004; Engelhart et al., 2009). Additional analyses incorporating continuous GPS and absolute gravity estimates reinforce these observations in Britain (Teferle et al., 2009). Around the UK, instrumental tide gauge trends for 1901 onwards are ~1.4 ± 0.2 mm yr^{-1} larger than those inferred from geology or geodetic methods (Woodworth et al., 2009), suggesting a regional sea-level rise of climate change origin several tenths of mm per year lower than Church and White's 1.7 ± 0.2 mm yr^{-1} global estimate of 20th century sea-level rise. These observations highlight the importance of a regional approach to understanding past and present sea-level changes and the need for regional-scale predictions of future sea-level rise (Milne et al., 2009).

Understanding the regional patterns of sea level provides knowledge not only of the mechanisms and dynamics of sea-level change, but also of the mass–balance changes of ice sheets and glaciers in response to climate change (Milne et al., 2002). Melting of continental ice sheets increases the volume of water in the oceans, which is distributed non-uniformly around the globe due to the change in the mass and gravitational attraction of the ice sheets (Mitrovica et al., 2001; Tamisiea et al., 2001). Detailed understanding of these processes and the 'fingerprint' of sea level which results from changes in ice sheet and mountain glacier mass balance requires geological records of past sea level from the near-, intermediate- and far-field sites that dovetail with the instrumental and geodetic era (Fig. 1A).

Tide gauges or sea level recorders (WOCE, 2002) come in many different forms, and simply aim to determine the level of the sea at a point in time for one location. Modern instruments provide four to ten readings per hour to the nearest centimetre but for some scientific questions they are limited by either their length of record, as noted above, or spatial coverage. Different types of geological measurements of coastal environments provide quantitative measures of relative sea-level change over timescales of millennia and centennial (e.g. Kemp et al., 2011) through to instantaneous, in the case of tectonic relative sea-level change where they also provide better spatial detail (Plafker, 1969; Farías et al., 2010). By seeking to quantify the vertical and temporal resolutions of different types of geological tide gauges we can extend the spatial coverage and length of record of past sea-level change and therefore address new, important scientific questions.

In this paper we aim to review the developments in using one type of geological tide gauge, salt marshes, to produce records of late Holocene relative sea-level change, with particular emphasis on the methodological and technical advances that promoted research on finer resolution, in some cases sub-decadal and less, relative sea-level changes over the last millennium. We work through an example to demonstrate the consequences of different assumptions and decisions required during different stages of analysis in producing quantitative estimates of relative sea-level change. Finally, we examine how to extract trends in RSL from what are inherently 'noisy' proxy reconstructions.

2. The background: reconstructing RSL changes using coastal sediments

The non-uniform distribution of meltwater from continental ice sheets to the oceans means that any particular coastal location will only record relative sea-level change, defined as change relative to present (Mitrovica et al., 2001; Tamisiea et al., 2001; Mitrovica and Milne, 2002; Mitrovica and Milne, 2003; Peltier, 2004; Plag, 2006; Shennan et al., 2012). The glacial isostatic modelling studies that led advances in understanding these processes required quantitative reconstructions of age and elevation of past sea level from different regions, with records covering several millennia. Low energy coastal sediment sequences, from the high latitudes to the tropics, provided many of these records, starting with the pioneering work of Godwin (1940) followed by numerous studies from the 1960s onwards (as summarised by Pirazzoli, 1991). Sediment cores or outcrops that contained beds of peat overlain or underlain by intertidal minerogenic sediments provide ideal samples for reconstructing past sea level. Radiocarbon dating allows dating of organic material to give the age parameter, and the stratigraphic association with a tidal deposit provided the elevation relationship with palaeo sea level.

Reconstructing RSL requires four attributes for each sea-level indicator or index point: location, age, elevation (both the measured elevation of the sample and the modern relationship to the tide level at which such an indicator would form today), and tendency (van de Plassche, 1986). The tendency of a sea-level indicator describes the increase (positive sea-level tendency) or decrease (negative sea-level tendency) in marine influence recorded by the indicator. The age-elevation plot of individual sea-level index points (Fig. 1B) gives a suitable summary over a 10,000 year timescale and represents the primary method by which we use such data to test glacial isostatic adjustment (GIA) models (Lambeck et al., 1998; Peltier, 2004; Brooks et al., 2008; Bradley et al., 2011). While the age-elevation plot comprises just the radiocarbon dated index points (Fig. 1C) it does not reveal more subtle, though recognisable, changes in vegetation and lithology revealed during the analysis of coastal sediments which may help differentiate between different models of RSL (Fig. 1D). The expression of the change in vegetation, stratigraphy or microfossils will be site specific, but the change in sea level of more than local significance should be recorded over a wider area. Unlike instrumental tide gauge data (Fig. 1E), where we know the exact position of each observation on the time axis, unless the radiocarbon dated samples come from the same core or section we cannot define their precise sequence, and sub-millennial RSL changes in many cases may lie within the error terms and scatter of data points (Shennan, 1982; Tooley, 1982; Shennan et al., 1983). To identify sub-millennial scale changes it is necessary to analyse the stratigraphic and microfossil changes above and below each dated sample to identify trends through time (tendency) along with quantified error terms for age and elevation (Tooley, 1978, 1982; Shennan, 1982).

Technical developments in the 1990s: such as AMS radiocarbon dating, short lived radionuclide chronology and quantitative environmental reconstruction methods developed in ecology and palaeoceanography, provided the stimulus for further developments in studying sub millennial RSL change. AMS, ^{210}Pb and ^{137}Cs methods allowed analysis of small samples, in some case contiguous 0.5–1 cm slices, through organic and