Quaternary Science Reviews 173 (2017) 20–39

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Relative sea-level variability during the late Middle Pleistocene: New evidence from eastern England

N.L.M. Barlow [a, b, *], A.J. Long [a], W.R. Gehrels [c], M.H. Saher [c, d], R.G. Scaife [e], H.J. Davies [c, f], K.E.H. Penkman [g], D.R. Bridgland [a], A. Sparkes [h], C.W. Smart [i], S. Taylor [g]

[a] Department of Geography, Durham University, South Road, Durham, DH1 3LE, UK
[b] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
[c] Environment Department, University of York, Heslington, York, YO10 5NG, UK
[d] School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, LL59 5AB, UK
[e] Department of Geography and Environment, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
[f] School of Geography, Earth and Environmental Sciences (GEES), University of Birmingham, Birmingham, B15 2TT, UK
[g] BioArCh, Department of Chemistry, University of York, Heslington, York, YO10 5DD, UK
[h] School of Earth & Ocean Sciences, Cardiff University, Cardiff, CF10 3XQ, UK
[i] School of Geography, Earth and Environmental Sciences, Plymouth University, Plymouth, PL4 8AA, UK

ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form
21 July 2017
Accepted 11 August 2017
Available online 18 August 2017

Keywords:
Sea-level changes
Quaternary
Pleistocene
Hoxnian
Dating
Micropaleontology
Ice sheets
Western Europe

ABSTRACT

Unravelling patterns of relative sea-level change during previous interglacials enhances our understanding of ice sheet response to changing climate. Temperate-latitude estuarine environments have the potential to preserve continuous records of relative sea level from previous interglacial (warm) periods. This is important because, currently, we typically only have snapshots of sea-level highstands from low-latitude corals and raised palaeoshoreline indicators while the (continuous) deep-sea oxygen isotope record only provides indirect evidence of sea-level changes. Here, we focus on the Nar Valley in eastern England, in which is preserved evidence of a late middle-Pleistocene marine transgression more than 20 vertical metres in extent. By applying a model of coastal succession and sea-level tendencies, as used in Holocene sea-level studies, we assess the mode (abrupt versus gradual) of sea-level change recorded by the interglacial Nar Valley sequences. Compiled palaeo-stratigraphic evidence comprising foraminifera, pollen and amino acid racemization dating, suggests that the mode of sea-level change in the Nar Valley interglacial sequence was gradual, with potentially two phases of regional transgression and relative sea-level rise occurring at two separate times. The first phase occurred during the latter part of marine Oxygen Isotope Stage (MIS) 11 from ~8 to 18 m OD; and, the second phase potentially occurred during early MIS 9 from ~-3 to 3 m OD (with long-term tectonic uplift included in these estimates). We cannot conclusively preclude an alternative MIS 11 age for these lower sediments. The lack of indicators for rapid sea-level oscillations in the Nar Valley adds weight to an argument for steady melt of the ice sheets during both MIS 11 and 9.

1. Introduction

To achieve an improved understanding of the relationship between climate, ice-sheet behaviour and sea level, we need to examine geological archives. Previous interglacials are often used to assess changes in past sea level during warm-climate episodes (Dutton et al., 2015) and inform predictions of future sea-level change (Church et al., 2013; Lowe et al., 2009). A key component of this work is understanding how the ice sheets may respond to future climate change, which presents the largest uncertainty in future predictions (Grinsted et al., 2015). Reconstructing direct evidence of ice-sheet behaviour during previous interglacials is challenging, with many archives (e.g., proximal marine sediments and geomorphological features) removed by subsequent glaciations. Ice cores provide the best insight into past ice sheet accumulation (e.g., Dansgaard et al., 1993; Petit et al., 1999), but are typically drilled on stable ice domes in order to provide the most

* Corresponding author. School of Earth and Environment, The University of Leeds, Leeds, LS2 9JT, UK.
E-mail address: n.l.m.barlow@leeds.ac.uk (N.L.M. Barlow).

http://dx.doi.org/10.1016/j.quascirev.2017.08.017

complete records, whereas the peripheries of ice sheets are the regions where mass is potentially lost during interglacial warming. As a result, observations of changes in past sea level are the most commonly used method to infer past ice-sheet changes (e.g., Dutton et al., 2015).

Evidence for modes of sea-level variability during MIS 11 and 9 is relative sparse, although they are interglacials of particular interest. MIS 11 is the longest interglacial of the late Quaternary (27 ka, Tzedakis et al., 2012) with global atmospheric CO_2 at 286 ppm, and is considered a potential analogue of the current interglacial due to similarities in orbital configuration (McManus et al., 2013). MIS 9, although comparatively short in duration (11.6 ka), is the warmest interglacial recorded in Antarctica, with global atmospheric CO_2 at 300 ppm (Past Interglacials working group of PAGES, 2016). Yin and Berger (2012) demonstrate that MIS 11c, MIS 9e and MIS 5e are the warmest interglacials of the last 800,000 years.

Evidence of MIS 11 and 9 sea level in low-latitude regions includes relict shorelines, marine terraces, tidal notches and coral reefs (e.g., Blakemore et al., 2015; Chen et al., 2014; Hearty and Kindler, 1995; Murray-Wallace, 2002; Raymo and Mitrovica, 2012; Schellmann and Radtke, 2004; Vezina et al., 1999). These features typically provide evidence for the elevation of the interglacial sea-level highstand at, or above present, although the calculated elevation is dependent on the assumed long-term uplift rate (e.g., Schellmann and Radtke, 2004). Based upon these relative sea-level (RSL) data, terrestrial ice extent during MIS 11 is assumed to be less than at present (Raymo and Mitrovica, 2012). However, little is known about stage MIS 9.

Marine oxygen isotope data can act as proxy for past sea level in the absence of coastal geomorphological features and the near-continuous time series may highlight any notable sea-level fluctuations (e.g., Siddall et al., 2007; Spratt and Lisiecki, 2016) (Fig. 1). These datasets suggest MIS 11 is typified by a single, long (~30 ka) duration highstand (Siddall et al., 2007). MIS 9 has a dominant single peak in sea level during the earliest substage (MIS 9e, Railsback et al., 2015), with a much smaller (~8–10 m lower) secondary peak during the next substage (MIS 9c) (Siddall et al., 2007). One or more sea-level oscillations during a highstand suggests dynamic behaviour of the ice sheets during the peak warm period with episodes of significant mass loss and gain, often in relatively short time intervals (a few thousand years or less), as has been reconstructed in MIS 5e (Kopp et al., 2009). The marine isotope records from MIS 11 and MIS 9 provide no evidence for abrupt, large scale oscillations in sea level that might be comparable to those seen in some MIS 5e records.

To achieve better understanding of the behaviour of ice sheets during MIS 11 and 9, there is a need for continuous records of RSL as found in temperate-latitude estuarine environments, similar to detailed study of the MIS 5e Netherlands record (Long et al., 2015; Zagwijn, 1983). There is evidence for marine inundation in northwest Europe in MIS 11 and 9, for example within the Thames, and along the south and east coasts of England (Bridgland et al., 1999, 2013; Roe et al., 2009; Roe et al., 2011; Roe and Preece, 2011; Schreve et al., 2002; White et al., 2013). Flexure of the North Sea Basin, tectonic uplift/subsidence, sediment compaction and glacial-isostatic adjustment (GIA) during repeated glacial-interglacial cycles (Busschers et al., 2008; Lambeck et al., 2012; Rose, 2009) mean that the elevations at which sea-level positions are observed may be different from their elevations at the time of formation. Notwithstanding, these records are important because they are often continuous for all or part of the interglacial highstand(s), and, therefore, offer the potential to reconstruct the mode (gradual versus abrupt) of sea-level change with a high degree of precision, especially if microfossil analyses – as developed and applied in Holocene sea-level studies (e.g., Barlow et al., 2013) – can be applied.

The study area for this paper, the Nar Valley in eastern England (Fig. 2) has evidence of Pleistocene interglacial marine transgression(s), preserved over ~20 vertical metres (Stevens, 1959). By applying methodological insight gained from Holocene sea-level reconstructions in estuarine settings, similar to that discussed by Long et al. (2015), this paper aims to assess the mode of sea-level change during the interglacial Nar Valley record, which we demonstrate as recording marine inundation during MIS 11 and 9. This archive from a temperate-latitude location may increase our knowledge of ice-sheet behaviour during warm periods and aid predictions of future responses.

2. Identifying modes of sea-level change in estuarine sediments

Assessing the mode of sea-level change in estuarine sediments requires consideration of three main lines of evidence which have been applied extensively in temperate-latitude, estuarine-based studies of Holocene sea level:

1. The tendency of the sea-level indicator;
2. The nature of the transgressive or regressive contact, i.e., abrupt or gradual;
3. The lateral extent of the transgressive or regressive contact and its representation in adjacent vertically stacked sequences.

The tendency of a sea-level indicator describes the stratigraphic or morphological evidence for an increase (positive sea-level

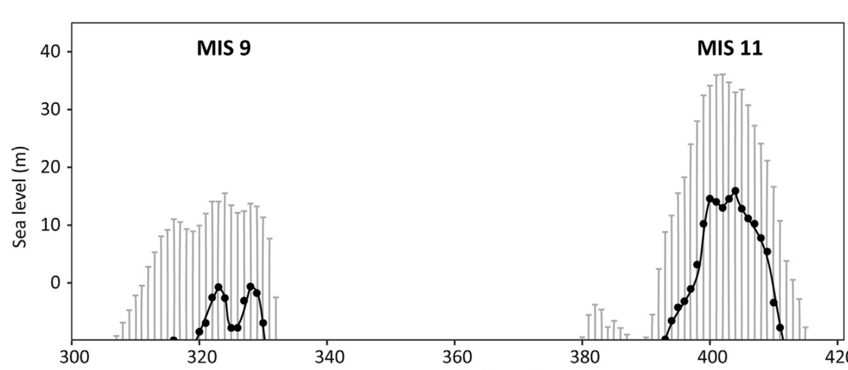

Fig. 1. MIS 9 and 11 global sea level highstands recorded by the Spratt and Lisiecki (2016) ocean core sea level stack (PC1) relative to present (0 m at 0 ka). Only vertical uncertainties shown, for clarity.