Quaternary Science Reviews 115 (2015) 1–16

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

New constraints on late Holocene eustatic sea-level changes from Mahé, Seychelles

Sarah A. Woodroffe [a,*], Antony J. Long [a], Glenn A. Milne [b], Charlotte L. Bryant [c], Alexander L. Thomas [d]

[a] Department of Geography, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE, UK
[b] Department of Earth Sciences, University of Ottawa, FSS Hall, Ottawa, K1N 6N5, Canada
[c] NERC Radiocarbon Facility (East Kilbride), Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride, Glasgow, G75 0QF, UK
[d] Department of Geosciences, University of Edinburgh, Grant Institute, The King's Buildings, West Mains Road, Edinburgh, EH9 3JW, UK

A R T I C L E I N F O

Article history:
Received 11 September 2014
Received in revised form
6 February 2015
Accepted 12 February 2015
Available online

Keywords:
Eustasy
Relative sea level
Mangroves
Seychelles
Late Holocene
Glacial-isostatic adjustment

A B S T R A C T

This study provides new estimates of globally integrated ice sheet melt during the late Holocene (since 4 ka BP) from Seychelles in the western Indian Ocean, a tectonically stable, far field location where the necessary Glacial-Isostatic Adjustment (GIA) correction is small and is relatively insensitive to predictions using different Earth viscosity profiles. We compare sea level data from Seychelles to estimates of eustasy from two GIA models, ICE-5G and EUST3, which represent end-members in the quantity of global melt during the late Holocene. We use data from a range of coastal environments including fringing reef, present day beaches, fossil plateau and mangrove deposits on the largest island of the Seychelles archipelago, Mahé to reconstruct relative sea-level changes. Our data suggest that extensive coastal deposits of carbonate-rich sands that fringe the west coast formed in the last 2 ka and the horizontal nature of their surface topography suggests RSL stability during this period. Mangrove sediments preserved behind these deposits and in river mouths date to c. 2 ka and indicate that RSL was between −2 m and present during this interval. Correcting the reconstructed sea level data using a suite of optimal GIA models based on the two ice models mentioned above and a large number (c. 350) of Earth viscosity models gives a result that is consistent with the sedimentological constraints. When uncertainties in both model results and data are considered, it is possible to rule out eustatic sea levels below c. 2 m and more than a few decimetres above present during the past two millennia. This uncertainty is dominated by error in the reconstructions rather than the model predictions. We note, however, that our estimates of eustasy are more compatible with the EUST3 model compared to the ICE-5G model during the late Holocene (2–1 ka BP). Our evidence from Seychelles shows that the timing of when eustatic sea level first rose close to present is between the predictions of the two end-member GIA models presented here (4 ka BP for ICE-5G and 1 ka BP for EUST3). Using all lines of evidence currently available from Mahé we suggest that the eustatic contribution during the last 2 ka has been less than 2 m . This conclusion is drawn from a tectonically stable, far-field region that is relatively insensitive to earth and ice model uncertainties, and implies that global eustasy has been relatively insensitive to climate fluctuations over the pre-industrial part of the last 2 ka.

1. Introduction

Relative sea-level (RSL) changes around the world since the Last Glacial Maximum (LGM) reflect the interaction of ice sheets, oceans and the solid earth. In locations far from the centres of former ice masses (far-field locations), the influx of glacial meltwater into the oceans dominates RSL and so reconstructions from such sites are commonly used to constrain volumetric changes in global grounded ice through time (Fleming et al., 1998; Yokoyama et al., 2000; Lambeck, 2002; Peltier, 2002; Milne et al., 2005; Peltier and Fairbanks, 2006; Bradley et al., 2011; Deschamps et al., 2012; Lambeck et al., 2014). Most far-field records of RSL from the LGM sea-level lowstand to present used by geophysical models are coral-based (Chappell and Polach, 1991; Bard et al., 1996; Peltier and

* Corresponding author. . Tel.: +44 191 334 1932.
E-mail address: s.a.woodroffe@durham.ac.uk (S.A. Woodroffe).

http://dx.doi.org/10.1016/j.quascirev.2015.02.011

Fairbanks, 2006), with a smaller number of sediment-based archives that focus on the LGM minimum (e.g. Hanebuth et al., 2000; Yokoyama et al., 2000). None of these records provide any observations and hence model constraints during the late Holocene. More recent studies by Bradley et al. (2011) and Lambeck et al. (2014) have tried to redress this focus on long, coral-based records by including evidence from coral and sediment-based archives in the mid to late Holocene.

Though many studies claim to record "eustatic" changes, i.e. the global mean change associated with meltwater addition only (e.g. Whitehouse and Bradley, 2013), there is in fact no single location on earth where we can directly measure eustasy through time. Even in far-field locations, isostatic, gravitational and rotational effects associated with Glacial-Isostatic Adjustment (GIA) can have a significant influence on regional RSL changes (Clark et al., 1978; Milne and Mitrovica, 2008; Lambeck et al., 2014). In addition to these regional changes, the globally uniform signal known as ocean syphoning (Mitrovica and Peltier, 1991; Mitrovica and Milne, 2002) also has a significant effect. These factors are less apparent during the deglacial and early Holocene periods because of rapid sea-level rise due to ice sheet melt. However during the mid to late Holocene when the rate of ice melt was reduced or eliminated, these ongoing GIA processes become more evident and can dominate the observed far-field RSL signal, leading to high stands or continued RSL rise. Of course, other processes such as tectonics can cause local RSL to deviate significantly from eustasy.

1.1. Mid to late-Holocene grounded ice melt

Several geophysical models suggest that global ice melt ceased in the mid Holocene. Milne et al. (2005) suggest that RSL data from the Caribbean and South America are compatible with no significant net melt (i.e. >1 m eustatic equivalent) of grounded ice since 6 ka BP. Peltier (2002) shows that RSL predictions for equatorial Pacific locations using the ICE-4G model do not match coral-based reconstructions of a mid Holocene highstand if global ice melt (at 0.25 or 0.5 mm/yr from Antarctica or Greenland) continues after 4 ka BP (thousand years before present), although they predict more than 2 m of global ice melt between 6 and 4 ka BP. However modelling studies that consider other mid to late Holocene RSL data from intermediate and far-field locations infer that some ice melt continued until more recently (Nakada and Lambeck, 1989; Lambeck, 2002; Lambeck and Purcell, 2005; Bradley et al., 2011; Lambeck et al., 2014). For example, the global ice model in Bradley et al. (2011), constrained using RSL data from China and the Malay-Thai Peninsula, includes approximately 1.5 m of grounded ice melt between 4 and 1 ka BP, and Lambeck et al. (2014) suggest a total contribution of up to 1 m in the past 4.2 ka constrained using a large suite of RSL data from across the far-field. The eustatic functions of the EUST3 (Bradley et al., 2011) and ICE-5G (Peltier, 2002) ice models therefore represent end members in the quantity of melt during the mid to late Holocene. Determining which is the more accurate is an important task towards producing improved GIA models and a better understanding of polar ice sheet response to climate during this period.

Despite different estimates of the magnitude and timing of any continued ice melt in the mid to late Holocene, most modelling studies agree that major melt finished during the mid Holocene. The Laurentide Ice Sheet had largely disappeared by 6.8 ka BP, with small ice caps in northern Canada contributing only a minor quantity to global sea-level until c. 5.5 ka BP (Carlson et al., 2008). In Greenland, parts of the western and southern sectors of the ice sheet reached their minimum extent in the mid Holocene before re-growing in the late Holocene during the cool neoglacial period (Kelly, 1980; Simpson et al., 2009). Small ice caps and alpine glaciers in the northern and southern hemispheres also grew during the neoglacial (e.g. Patagonia, Alaska, western USA; Konrad and Clark, 1998; Glasser et al., 2004, 2005; Barclay et al., 2009), and together these ice masses potentially caused a small (decimetre-scale) draw-down in global sea level. This leaves Antarctica as the main potential source of late Holocene eustasy (Nakada and Lambeck, 1988). A study of glacial retreat across the Ross Sea embayment in Antarctica suggests the ice shelf passed a grounding line c. 250 km beyond its present position only 3.2 ka BP (Conway et al., 1999) and there is evidence that ice in the Marie Byrd region of west Antarctica has melted steadily through the Holocene into recent times (Stone et al., 2003). However a general paucity of field observations on ice margin change during the late Holocene means debates remain about the potential contribution of Antarctica to any late Holocene eustatic sea-level rise (Whitehouse et al., 2012). The outstanding question is, therefore: has there been significant (>1 m global sea-level equivalent) ice melt during the mid to late Holocene (since c. 5 ka BP), and if so when did it occur, at what rate of change and from which source(s)?

2. RSL and eustasy in the far-field

In theory, RSL data from anywhere in the world can be used to constrain global grounded ice volume once the non-eustatic contributing factors are isolated. However, isolating these factors is a non-trivial exercise because uncertainties in GIA models are not uniform over time or space. For example, some sites are more or less sensitive to model assumptions regarding earth rheology and ice model parameters. Therefore, a sensible approach to this problem is to generate RSL data from sites where the non-eustatic (GIA) components tend to cancel (i.e. departures from eustasy are small) and where the sensitivity of the non-eustatic signal to uncertainties in the parameters of the GIA model are small.

Seychelles is in one of the few regions of the world where RSL is modelled to be within 1 m of eustasy during the last 6 ka, and where the GIA correction is relatively insensitive to predictions using different earth viscosity profiles (Milne and Mitrovica, 2008). It is also a tectonically stable region (Israelson and Wohlfarth, 1999). Previous Holocene studies here rely primarily on cored coral from coastal reefs, which provide relatively imprecise constraints on RSL during the early and mid Holocene but very little late Holocene data as RSL reached close to present. The region supports a range of mangrove environments and extensive beach sand deposits that provide potential alternative sources of RSL data. In this study we combine data from these different sources to reconstruct past sea-level changes and coastal evolution in Seychelles. We use our estimates of late Holocene RSL to estimate eustatic changes using two global ice models – ICE-5G (Peltier, 2004) and EUST3 (Bradley et al., 2011) – and a large suite of earth viscosity models. These two ice models were adopted as they include contrasting end-member estimates of ice volume changes during the late Holocene (see above) and so represent a conservative estimate of model uncertainty in this regard. We conclude that RSL in Seychelles had risen to within c. 2 m of present by 2 ka BP, and has been within c. −1 m of present since 1 ka BP. This estimate is then considered in the context of better constraining the eustatic function during the late Holocene, to address the questions highlighted above and to test which current ice sheet volume estimates are most accurate.

2.1. Field location

Seychelles is an archipelago of 115 islands, spread across the southwestern Indian Ocean between 56° 14′ and 46° 23′ E and 3° 43′ and 10° 13′ S (Fig. 1). The main granitic islands, which are