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Tectonic influences on late Holocene relative sea levels from the central-eastern Adriatic coast of Croatia

Timothy A. Shaw [a, *], Andrew J. Plater [b], Jason R. Kirby [c], Keven Roy [a], Simon Holgate [d], Pero Tutman [e], Niamh Cahill [f], Benjamin P. Horton [a, g]

[a] Asian School of the Environment, Nanyang Technological University, Singapore, 639798, Singapore
[b] Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Roxby Building, Liverpool, Merseyside, L69 7ZT, UK
[c] School of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool, Merseyside, L3 3AF, UK
[d] Sea Level Research Ltd, Studio D, Baltic Creative Campus, Liverpool, Merseyside, L1 0AH, UK
[e] Institute of Oceanography and Fisheries, Šetalište Ivana Meštrovića 63, 21000, Split, Croatia
[f] School of Mathematics and Statistics, University College Dublin, Dublin, Ireland
[g] Earth Observatory of Singapore, Nanyang Technological University, Singapore, 639798, Singapore

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ABSTRACT

Differential tectonic activity is a key factor responsible for variable relative sea-level (RSL) changes during the late Holocene in the Adriatic. Here, we compare reconstructions of RSL from the central-eastern Adriatic coast of Croatia with ICE-7G_NA (VM7) glacial-isostatic model RSL predictions to assess underlying driving mechanisms of RSL change during the past ~ 2700 years. Local standardized published sea-level index points (n = 23) were combined with a new salt-marsh RSL reconstruction and tide-gauge measurements. We enumerated fossil foraminifera from a short salt-marsh sediment core constrained vertically by modern foraminiferal distributions, and temporally by radiometric analyses providing sub-century resolution within a Bayesian age-depth framework. We modelled changes in RSL using an Errors-In-Variables Integrated Gaussian Process (EIV-IGP) model with full consideration of the available uncertainty. Previously established index points show RSL rising from −1.48 m at 715 BCE to −1.05 m by 100 CE at 0.52 mm/yr (−0.82-1.87 mm/yr). Between 500 and 1000 CE RSL was −0.7 m below present rising to −0.25 m at 1700 CE. RSL rise decreased to a minimum rate of 0.13 mm/yr (−0.37-0.64 mm/yr) at ~1450 CE. The salt-marsh reconstruction shows RSL rose ~0.28 m since the early 18th century at an average rate of 0.95 mm/yr. Magnitudes and rates of RSL change during the twentieth century are concurrent with long-term tide-gauge measurements, with a rise of ~1.1 mm/yr. Predictions of RSL from the ICE-7G_NA (VM7) glacial-isostatic model (−0.25 m at 715 BCE) are consistently higher than the reconstruction (−1.48 m at 715 BCE) during the Late Holocene suggesting a subsidence rate of 0.45 ± 0.6 mm/yr. The new salt-marsh reconstruction and regional index points coupled with glacial-isostatic and statistical models estimate the magnitude and rate of RSL change and subsidence caused by the Adriatic tectonic framework.

1. Introduction

Significant efforts have been made towards understanding Holocene relative sea-level (RSL) changes in the Mediterranean (e.g., Flemming, 1969; Pirazzoli, 1976, 1991; 1996; Flemming and Webb, 1986; Zerbini et al., 1996, 2017; Woodworth, 2003; Lambeck et al., 2004a; Marcos and Tsimplis, 2008; Vacchi et al., 2016). During the Holocene, geological records illustrate eustatic and glacio-hydro-isostatic changes (e.g., Lambeck and Purcell, 2005; Stocchi and Spada, 2007, 2009; Roy and Peltier, 2018) superposed by tectonic and local processes (e.g., Pirazzoli, 2005; Antonioli et al., 2009, 2011; Vacchi et al., 2016). Indeed, tectonic effects on late Holocene RSL histories in the northern Adriatic are particularly important, attesting to variable subsidence and uplift rates (e.g., Benac et al., 2004, 2008; Furlani et al., 2011; Surić et al., 2014; Fontana et al., 2017). The effect of tectonics on RSL histories in the central-eastern Adriatic is, however, less well constrained (e.g. Faivre et al., 2013). Anthropogenic forcings since the mid to late 19th

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* Corresponding author.
E-mail address: tshaw@ntu.edu.sg (T.A. Shaw).

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century have contributed towards sea-level changes (e.g. Jevrejeva et al., 2009; Dangendorf et al., 2015; Kopp et al., 2016). In the Adriatic and wider Mediterranean region, tide-gauge stations document coherent RSL trends, simultaneously recording large inter-annual and inter-decadal variability (Orlić and Pasarić, 2000; Tsimplis and Baker, 2000; Tsimplis and Josey, 2001; Tsimplis et al., 2012). Comparing independent RSL datasets with differing resolution and time periods is, therefore, problematic and restricts our understanding of RSL changes in the Adriatic.

Here, we reconstruct late Holocene RSL using geological and tide-gauge data coupled with a new salt-marsh based reconstruction from the central-eastern coast of Croatia that bridges the gap between late Holocene and modern sea-level data. Salt-marsh environments afford a unique ability providing near continuous, decimeter vertical (Scott and Medioli, 1978, 1980; Horton and Edwards, 2006) and sub-century temporal resolution (Törnqvist et al., 2015; Corbett and Walsh, 2015; Marshall, 2015). Their use in reconstructing RSL is well established across regions in Northern (Gehrels et al., 2005; Kemp et al., 2013a; Barlow et al., 2014; Saher et al., 2015) and Southern Hemispheres (Gehrels et al., 2008, 2012; Strachan et al., 2014). Salt-marsh based reconstructions have aided our understanding of climate-sea-level connections (Kemp et al., 2011; Kopp et al., 2016); the onset of increases in the rate of RSL rise in the mid to late 19th century (Kopp et al., 2016); and tectonic (Van De Plassche et al., 2014), compaction (Brain et al., 2017) and tidal range (Horton et al., 2013) influences on local RSL change. The Adriatic and wider Mediterranean region, however, have evaded similar high-resolution RSL studies.

To better understand driving mechanisms of RSL change in the central-eastern Adriatic, we compare the composite RSL record with ICE-7G_NA (VM7) glacio-isostatic model predictions (Roy and Peltier, 2017) for the last ~ 2700 years. We show the magnitude of RSL change during this period is offset to model predictions by more than 1 m, implying an overarching influence of tectonic subsidence on RSL changes. We demonstrate the utility of the salt-marsh reconstruction in deriving similar magnitudes and rates of RSL change to long-term tide-gauges.

2. Study area

2.1. Tectonic setting

Tectonism in the western Mediterranean region is the consequence of the collision boundary between the major tectonic plates of Africa and Eurasia (Fig. 1). This convergence zone results in a number of microplates, including the Adriatic (McKenzie, 1972; Anderson and Jackson, 1987; D'Agostino et al., 2008). The Adriatic microplate, which shows movements independent to Africa and Eurasia (Grenerczy et al., 2005; Altiner et al., 2006; Serpelloni et al., 2013), is subdivided into northern and southern sectors with the southern sector moving counterclockwise in a N-NW direction at 5–10 mm/yr (Oldow et al., 2002; Herak et al., 2005; Marjanović et al., 2012). Tectonic activity predominately occurs along the coasts and a through a number of fault lines that pass through the region (Herak et al., 1996, 2017; Korbar, 2009). The distribution of earthquake epicenters in the Adriatic between the Ancona-Zadar and Gargano-Dubrovnik lines (Fig. 2) suggests this region is seismically more intense compared to the north with four $M_L = \geq 5.5$ events recorded since the twentieth century (Herak et al., 2005). Most recently, a sequence of earthquakes peaking at $M_L = 5.5$ occurred in 2003 at Jabuka, some ~90 km west of Vis (Fig. 2) in the central Adriatic Sea (Herak et al., 2005).

Modern measurements from Global Positioning System (GPS) stations reveal both lateral and vertical land movements in the Adriatic region (Buble et al., 2010; Weber et al., 2010; Serpelloni et al., 2013; Devoti et al., 2017). Vertical velocities from GPS stations in the north-western Adriatic show significant subsidence rates up to ~8 mm/yr near the Po River Delta, reflecting crustal movements and also compaction of sediments (Carminati et al., 2003; Antonioli et al., 2009). While the density of observations along the eastern Adriatic are limited, vertical motions in northern and central Croatia are close to 0 mm/yr with minor subsidence up to 1 mm/yr recorded in the south near to Dubrovnik (Fig. 2).

2.2. Oceanographic setting

The Adriatic Sea is a relatively shallow elongated basin connecting with the Mediterranean Sea through the Strait of Otranto. The bathymetry is subdivided with a shallow (average ~ 35 m water depth) northern section near the Gulf of Trieste, progressively deepening to ~ 1200 m towards the south near Dubrovnik (Ciabatti et al., 1987; Orlić et al., 1992). Tidal ranges in the region are microtidal, increasing as water depth decreases to the north (Cushman-Roisin and Naimie, 2002). The influence of strong north-easterly Bora and south-easterly Sirocco winds can significantly alter the tidal regime (Orlić et al., 1994; Vilibić, 2006; Ferla et al., 2007) and meteorological tsunamis associated with prolonged low atmospheric pressure systems are a relatively common occurrence (Vilibić; Šepić, 2009; Vilibić et al., 2017).

Instrumental observations of RSL change from long-term (>50 years) tide-gauge stations in the Adriatic are restricted to the northern and eastern coastline (Fig. 2). The tidal station at Trieste provides an inference of RSL change since the late 19th century while Bakar extends (discontinuously) to 1930 CE. The tidal stations at Split and Dubrovnik extend to the mid-1950s. By comparison to the rest of the Adriatic, high rates of RSL change are observed in the north in Venice; however, this is attributable to anthropogenic influences exacerbating subsidence in the region (Woodworth, 2003) as illustrated by the GPS network.

2.3. Study site

We investigated the salt-marsh environments located near Jadrtovac, along the central-eastern Adriatic coastline of Croatia (Fig. 2). Our focus on this region was motivated by the availability of pristine salt marshes (Pandža et al., 2007) and nearby long-term tide-gauge stations. In this context, tide gauges can provide a means of self-evaluation for proxy-based reconstructions, permitting independent comparison of RSL changes (e.g. Donnelly et al., 2004; Gehrels et al., 2005; Kemp et al., 2009). Shaw et al. (2016) previously documented the vertical zonation of contemporary foraminiferal assemblages at Jadrtovac, underpinning their potential to reconstruct RSL change. The microtidal regime, with a mean tidal range of 0.23 m (Hydrographic Institute, 1955; Vilibić et al., 2005), also helps limit vertical uncertainties (Barlow et al., 2013). The salt-marsh environment is located at the head of a ~2.5 km channel in the Morinje Bay, northwest of Split and is a typical karstic environment with limited vegetation and poor soils on the surrounding slopes. The bay was infilled during the Holocene marine transgression, resulting in ~4.5 m of sediment (Bačani et al., 2004; Šparica et al., 2005). The main salt-marsh surface is ~130 m wide on the eastern side and gradually thins moving north around the bay.

3. Methodology

We investigated the depositional history of the salt-marsh environment, describing the underlying lithostratigraphy according to the Troëls-Smith (1955) classification of coastal sediments. Core transects were established capturing the full range of sub-