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

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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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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-

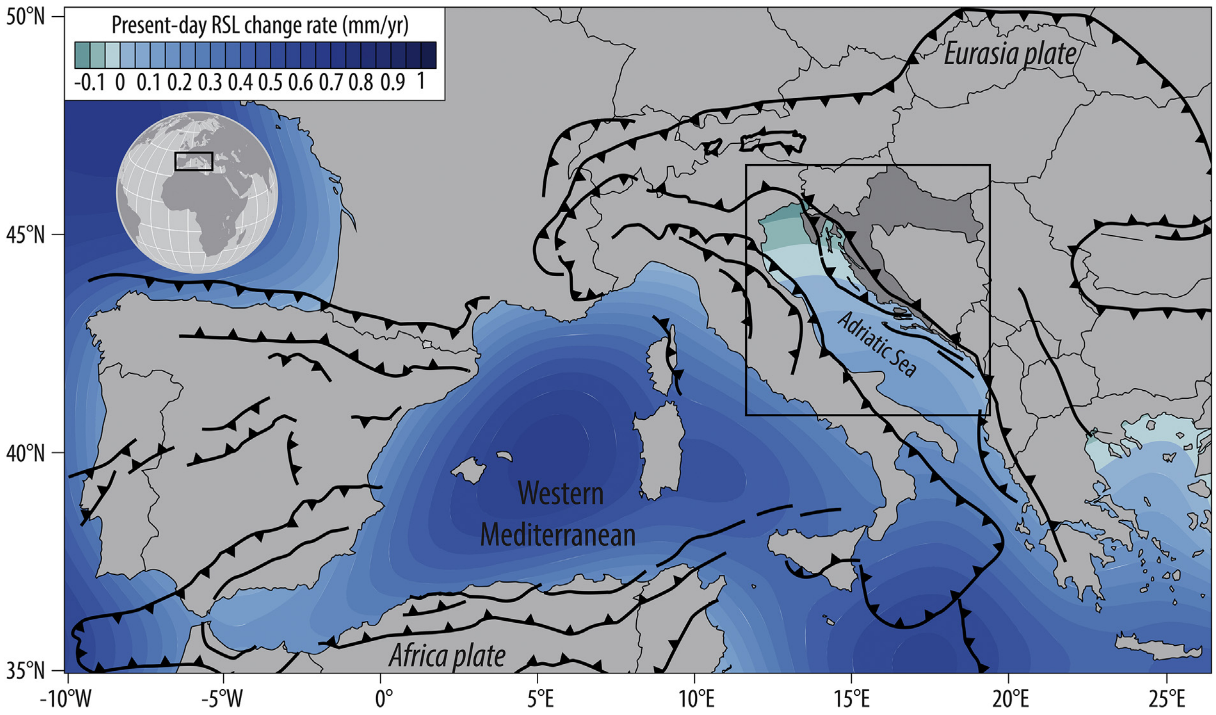

Fig. 1. Western Mediterranean showing location of major tectonic boundaries modified after Faccenna et al. (2014) with ICE-7G_NA (VM7) (Roy and Peltier, 2017) model predictions of present-day RSL change rate (mm/yr). Square outline depicts Adriatic study region presented in Fig. 2.

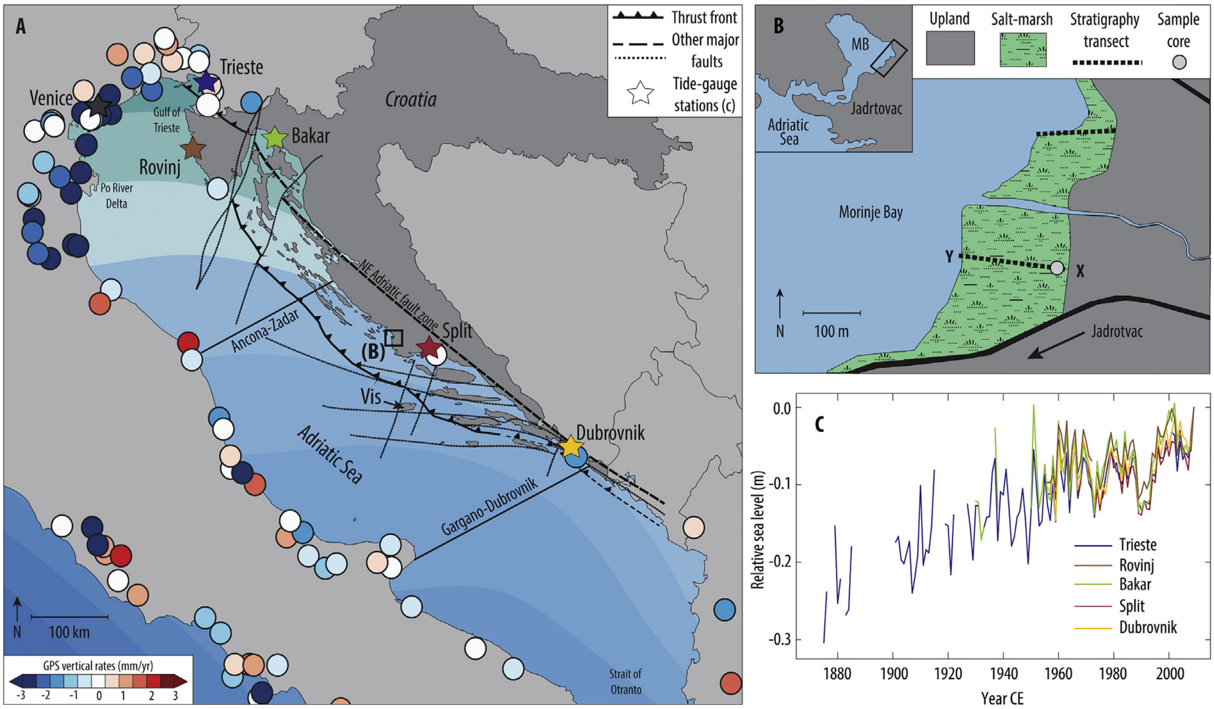

Fig. 2. (A) Adriatic study area showing the location of long-term (>50 years) tide-gauge stations (stars), the vertical land movements recorded by GPS stations (dots) modified after Serpelloni et al. (2013) and the simplified tectonic setting of the Croatian coastline modified after Korbar (2009), together with the location of Island of Vis and the Ancona-Zadar and Gargano-Dubrovnik lines (Herak et al., 2005) referred to in text. (B) Sample site at Jadrtovac within the Morinje Bay showing stratigraphic transects and sample core location. (C) Tide-gauge measurements of relative sea-level (RSL) change from stations highlighted in panel A.

environments from the landward high salt-marsh (hereafter termed 'high-marsh') edge to open water boundary. Following this, a short 42 cm core (43.6803 N, 15.9570 E) was selected from the high-marsh and extracted using a 1 m-long Eijkelkamp hand gouge corer with a diameter of 50 mm. The relative thinness of organic salt-marsh deposits in the Morinje Bay most likely reflects low biological productivity and suspended sediment concentrations in the tidal waters related to the impoverished soils in the limestone catchment area. Nonetheless, the shallow core depth helps minimize the effects of post-depositional lowering through sediment compaction (e.g. Brain et al., 2011) because of the limited depth of overburden (e.g. Törnqvist et al., 2008; Horton and Shennan, 2009) and was drilled onto the limestone bedrock. The outer surface of the core was carefully cleaned to prevent contamination prior to sub-sampling of the undisturbed internal section and samples were kept refrigerated until ready for analysis. We surveyed core sample altitudes using Real Time Kinetic (RTK) satellite navigation and Leica Na820 optical leveling equipment relative to Croatian national geodetic datum (m HVRS71).

Core samples were prepared at 1 cm intervals for all subsequent analyses. Samples for foraminiferal analysis followed procedures outlined in Horton and Edwards (2006), enumerating foraminiferal tests from sediments between sieve fractions 500 μm and 63 μm transferred to a wet splitter (Scott and Hermelin, 1993) and analyzed wet under a binocular microscope. Our taxonomic identification follows Shaw et al. (2016) where fossil foraminiferal assemblages mirrored those observed in the contemporary environments and are typical of intertidal environments (Edwards and Wright, 2015). Calcareous taxa *Ammonia*, *Elphidium* and *Quinqueloculina* were recorded as generic groups (Horton and Edwards, 2006) and followed contemporary studies (Shaw et al., 2016).

We determined the organic matter content of core sediments through Loss-On-Ignition (LOI) (Ball, 1964), combusting sediment samples at 450 °C for 4 h to provide supplementary evidence for intertidal environmental change (Plater et al., 2015).

3.1. Chronology

We established sedimentation rates for the salt-marsh core using a composite chronology combining Accelerator Mass Spectrometry (AMS) ^{14}C dating coupled with short-lived radionuclides (^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am) for sediments deposited in the past 100 years or so (Corbett and Walsh, 2015). Radionuclide activities were analyzed by direct gamma assay at the University of Liverpool Environmental Radioactivity Laboratory. Prior to gamma assay, we determined the dry bulk density of the sediment samples by freeze-drying and weighing. Samples were then lightly disaggregated before being stored for three weeks to allow radioactive equilibration. Samples were analyzed using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al., 1986). We corrected for the effect of self-absorption of low energy γ-rays within the sample (Appleby and Oldfield, 1992) and ^{210}Pb ages calculated using the Constant Rate of Supply (CRS) model (Appleby and Oldfield, 1978; Appleby et al., 1979). To further constrain ages obtained via ^{210}Pb dating, ^{137}Cs activities referenced to nuclear weapons testing and the Chernobyl disaster were used as a chronological marker (Appleby, 2001).

We selected plant macrofossils for AMS ^{14}C dating as opposed to bulk sediment dating for improved accuracy and reduced uncertainties (Törnquist et al., 2015). Following preparation methods outlined in Kemp et al. (2013b), we identified a varying abundance of *Scirpus holoschoenus* seeds, a common high-marsh plant of the eastern Adriatic seaboard (Pandža et al., 2007). Three, closely spaced intervals were selected for analysis by AMS ^{14}C at the NERC Radiocarbon Facility, U.K (Table 2). Using *a priori* knowledge of their stratigraphic position (i.e. the assumption that the lowest most sample was deposited before those above), conventional radiocarbon ages were calibrated using the INTCAL13 calibration curve (Reimer et al., 2013) within a Bayesian age-depth framework using Bchron (Haslett and Parnell, 2008; Parnell et al., 2008) to provide 2σ age distributions.

3.2. Reconstructing relative sea level

Our assessment of late Holocene RSL changes in the central-eastern Adriatic are derived from salt-marsh, tide-gauge and sea-level index points extracted from the quality controlled Mediterranean Holocene RSL database of Vacchi et al. (2016). Indicative meanings of the proxy RSL data are detailed in Table 1.

Our reconstruction of RSL changes from the salt-marsh environment uses indicative ranges from contemporary foraminiferal distributions (Shaw et al., 2016) to provide estimates of the paleomarsh elevation (PME) from fossil counterparts. We used stratigraphic markers of environmental change (e.g., sediments and organic matter content) as supporting evidence. In microtidal environments such as the Adriatic, using indicative ranges can derive an estimate of PME with equivalent or improved precision over statistically more vigorous techniques (e.g. transfer functions) (Kemp et al., 2017). We identified clusters in fossil foraminiferal assemblages using Partitioning Around Medoids (PAM) cluster analysis (Kaufman and Rousseeuw, 1990) and used contemporary distributions to provide an indicative range (i.e. vertical uncertainty) over which the sample formed relative to mean tide level (MTL). To determine the most statistically representative number of clusters, PAM produces silhouette widths providing a measure of the samples classification. Our RSL reconstruction is restricted to the agglutinated assemblages only within which chronologies and contemporary distributions are constrained. To attain RSL we

Table 1
Indicative meanings of proxy RSL data used in RSL reconstruction.

Sea level indicator	Description	Indicative meaning
Salt-marsh	Organic sediment dominated by salt-marsh plant macrofossils and agglutinated foraminifera (e.g. *Entzia macrescens*).	MTL-HAT
**Lithophyllum byssoides*	Fixed biological fossil rims of *Lithophyllum byssoides* recorded by Faivre et al. (2013).	MTL-HAT
*Archaeological	Functional interpretation of harbour structure (pier and dolia) recorded by Faivre et al. (2013).	MTL ±0.25

MTL = mean tide level; HAT = highest astronomical tide. **Lithophyllum byssoides* and archaeological evidence extracted from the Vacchi et al. (2016) Mediterranean RSL database.

Table 2
Results from AMS ^{14}C analyses.

Depth (cm)	Laboratory code	^{14}C Year BP (±)	δ^{13}C (‰)	Modelled (2σ) ^{14}C ages (CE)[a]	Material dated
25–26	SUERC45020	256 (37)	−25.3	1764–1805	*Scirpus holoschoenus* seeds
26–27	SUERC45021	213 (37)	−26.2	1742–1800	*Scirpus holoschoenus* seeds
28–30	SUERC45022	112 (37)	−26.8	1692–1784	*Scirpus holoschoenus* seeds

[a] ^{14}C ages calibrated within Bchron age-depth modelling software (Haslett and Parnell, 2008; Parnell et al., 2008).

subtracted PME from surveyed sample elevations related to MTL (Shennan and Horton, 2002), coupled with age estimations provided by the Bchron age-depth model.

We analyzed annual measurements from the Split Gradska tide-gauge spanning the period 1955 to 2009 CE. Tide-gauge measurements were analyzed relative to 2009 CE to directly compare RSL changes with the core extraction date of the salt-mash reconstruction. Vertical uncertainties of the tide gauge data were calculated from the standard deviation of annual measurements (±0.03 m) and a temporal uncertainty of ±0.5 years follows that of Kemp et al. (2015).

We extracted Holocene sea-level index points (n = 23) from Vacchi et al. (2016) for the nearby Island of Vis, central-eastern Adriatic (Fig. 2). These RSL data are based on fossil rims of *Lithophyllum byssoides* (a precise fixed biological indicator of past RSL) and archaeological evidence recorded by Faivre et al. (2013). Temporal uncertainties of the RSL data ranged from ±50–244 years with vertical uncertainties of ±0.3 m. No reinterpretation of the RSL data was applied after Vacchi et al. (2016).

We quantified RSL changes from the salt-marsh, instrumental and a composite RSL record using an Error-In-Variables Integrated Gaussian Process (EIV-IGP) model (Cahill et al., 2015). The EIV-IGP model takes an unevenly distributed RSL time series, prone to vertical and temporal uncertainties, as input and produces estimates of RSL and rates of RSL with 95% credible intervals. The EIV-IGP models rates of RSL change using a Gaussian process (GP) (Williams and Rasmussen, 1996) and models RSL as the integral of the GP (IGP) plus (measured and estimated) vertical uncertainty. Temporal uncertainties are accounted for by setting the IGP model in an errors-in-variables (EIV) framework (Dey et al., 2000).

3.3. Glacial-isostatic model predictions

The Adriatic and wider Mediterranean has been a region of great interest in the study of the glacial-isostatic adjustment (GIA) process. The large array of biological, archaeological and geological indicators of past sea level have provided an opportunity to tune, test and/or validate GIA models (e.g. Lambeck et al., 2004b; Lambeck and Purcell, 2005; Stocchi and Spada, 2009; Spada et al., 2009; Lambeck et al., 2011; Vacchi et al., 2016). The recent availability of a standardized Holocene RSL database covering the western Mediterranean basin (Vacchi et al., 2016) has enabled the community to further test global models of the GIA process against RSL data, such as the ICE-7G_NA (VM7) model (Roy & Peltier 2017, 2018).

Here, we compared the composite RSL record with glacial-isostatic model predictions in the central-eastern Adriatic using the ICE-7G_NA (VM7) model (Roy and Peltier, 2017). Our model choice is motivated by the ability of the ICE-7G_NA (VM7) model to explain a wide range of geophysical observables related to the GIA process coming from geographically disparate regions (covering formerly glaciated areas, forebulge regions and far-field sites) using a single, simple rheological structure. This independence is important to understand patterns of sea-level evolution in the context of complex local effects, such as tectonic activity (Antonioli et al., 2011). Indeed, the ICE-7G_NA (VM7) model has been shown to fit a large proportion of the geographically and temporally extensive RSL data set from Vacchi et al. (2016).

The ICE-7G_NA (VM7) model is an update to the precursor ICE-6G_C (VM5a) model of Peltier et al. (2015). It includes a modified spherically-symmetric viscosity structure and an updated North American ice-loading history, described in detail in Roy and Peltier (2017).

4. Results

4.1. Salt-marsh stratigraphy

Boreholes drilled across the salt-marsh showed an overall increase in sediment depth with distance towards open water (Fig. 3). The lithostratigraphy revealed five main stratigraphic units where sediment accumulation appeared relatively uniform across the site. An unrecoverable (i.e. overly saturated) unit was found between 40 m and 110 m along the transect and overlain by varying silt and clay units (often containing shells fragments) which become progressively more organic towards the surface. An organic salt-marsh peat was restricted to the landward 20 m of the transect where the

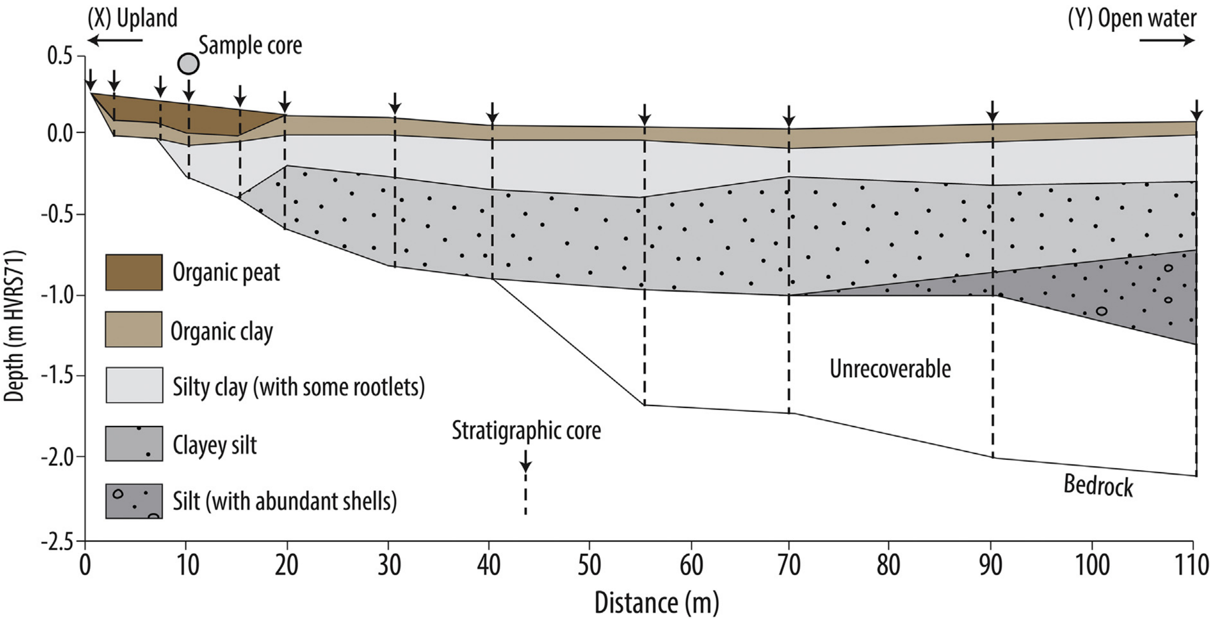

Fig. 3. Simplified cross-sectional profile of the salt-marsh stratigraphy at Jadrtovac showing location of sample core (see Fig. 2 for transect location).

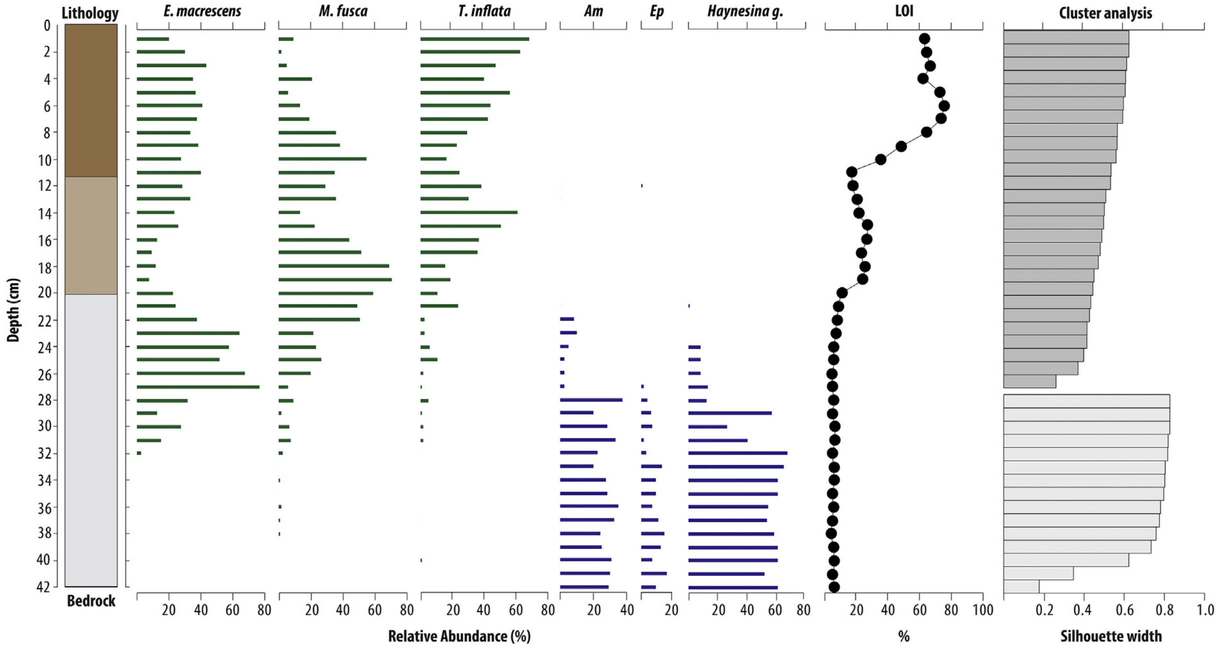

Fig. 4. Sample core sediment profile from Jadrtovac salt-marsh core showing lithology (following that displayed in Fig. 3), relative abundance (%) of the most abundant agglutinated (shaded green) and calcareous (shaded blue) foraminiferal taxa, organic matter content (LOI %) and results from cluster analysis. Foraminiferal taxa from left to right; *Entzia macrescens*; *Miliammina fusca*; *Trochammina inflata*; (*Am*) *Ammonia* spp., (*Ep*) *Elphidium* spp., *Haynesina germanica*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sample core was extracted. The sediments in the sampled core were comprised of a silty clay bottom unit with low organic content (LOI ~ 8%) between 42 cm and 20 cm. This was overlain by an increasingly organic clay (LOI 10–40%) up to 11 cm and an organic humified peat deposit towards the surface (LOI >50%) (Fig. 4).

4.2. *Indicative meaning based on foraminiferal assemblages*

The biostratigraphy shows fossil foraminifera preserved throughout the entire sediment core sequence (Fig. 4). An up-core transition from a calcareous-dominated assemblage to agglutinated types is broadly coincident with a shift in sedimentation regime with progressively increasing organic matter content at ~27 cm depth. Indeed, foraminiferal abundance was significantly higher in line with this sedimentation change, with a mean abundance of 1310 per 5 cm^3. Between 42 cm and 32 cm, *Ammonia* spp., *Elphidium* spp. and *Haynesina germanica* dominate before agglutinated types *Entzia macrescens*, *Miliamminia fusca* and *Trochammina inflata* increase in relative abundance. A decrease in the relative abundance of *M. fusca* from 19 cm (71%), corresponds with an increase in *E. macrescens* and *T. inflata* towards the surface within the organic peat deposits (LOI >40%).

Cluster analysis identified two foraminiferal assemblage groups in the fossil environment, essentially discriminating between agglutinated and calcareous dominated assemblages, reflecting the transition from intertidal muds and clays to organic salt-marsh sediments. Two broad indicative meanings are appropriate given the current understanding of contemporary foraminiferal distributions from the central-eastern Adriatic coast (e.g., Shaw et al., 2016). The fossil foraminiferal assemblages mirrored those dominating the contemporary environment. The contemporary distribution of agglutinated types (dominated by *E. macrescens* and *T. inflata*) across the salt-marsh platform extends from 0.17 m ± 0.12 m MTL. Current vertical uncertainties of ±0.12 m using salt-marsh sediments are comparable to other RSL studies adopting different sea-level indicators from the central-eastern Adriatic (Vacchi et al., 2016).

4.3. *Chronology*

We established age-depth relationships in the core through short-lived radionuclide analyses and AMS ^{14}C dating of three intervals between depths 25–30 cm where *Scirpus holoschoenus* seeds were observed within the calcareous-agglutinated foraminiferal assemblage transition (Table 2). The upper ~20 cm were constrained from downcore profiles of ^{210}Pb and ^{137}Cs, respectively (Fig. 5). Total ^{210}Pb activity reaches equilibrium with the supporting ^{226}Ra at ~20 cm depth. Unsupported ^{210}Pb concentrations record a minor discontinuity between 10 and 13 cm, below which they decline exponentially with depth. Analysis of ^{137}Cs activity shows a relatively well-defined maximum at 9–12 cm (69.9 Bq kg^{-1}). Its double peak reflects the same event that affected ^{210}Pb concentrations at this depth. As a result, the $^{137}Cs/^{210}Pb$ activity ratio can be a more accurate marker (Plater and Appleby, 2004) to show a well-defined peak between 10 and 12 cm that reflects peak fallout from the atmospheric testing of nuclear weapons (1963 CE). A second, more recent peak at 5–6 cm (57.1 Bq kg^{-1}), is interpreted as fallout from the Chernobyl reactor accident (1986 CE).

Peaks in ^{137}Cs broadly correspond to those found from previous research in the Morinje Bay environment where maximum ^{137}Cs activity occurs within the upper 20 cm (Mihelčič et al., 2006). The CRS dating model place 1963 at 11.5 cm and 1986 at 5.5 cm, in good agreement with the depths suggested by the ^{137}Cs record. The results are relatively unambiguous down to ~16 cm, dated to 1920 CE beyond which the uncertainty of age estimates increases. The stratigraphic position of ^{14}C ages was used to constrain calibrated age distributions within Bchron. The composite chronologies were modelled to provide age estimates with 95% credible intervals for sediments in the upper 30 cm, with an average temporal uncertainty of ±19 years (Fig. 5).

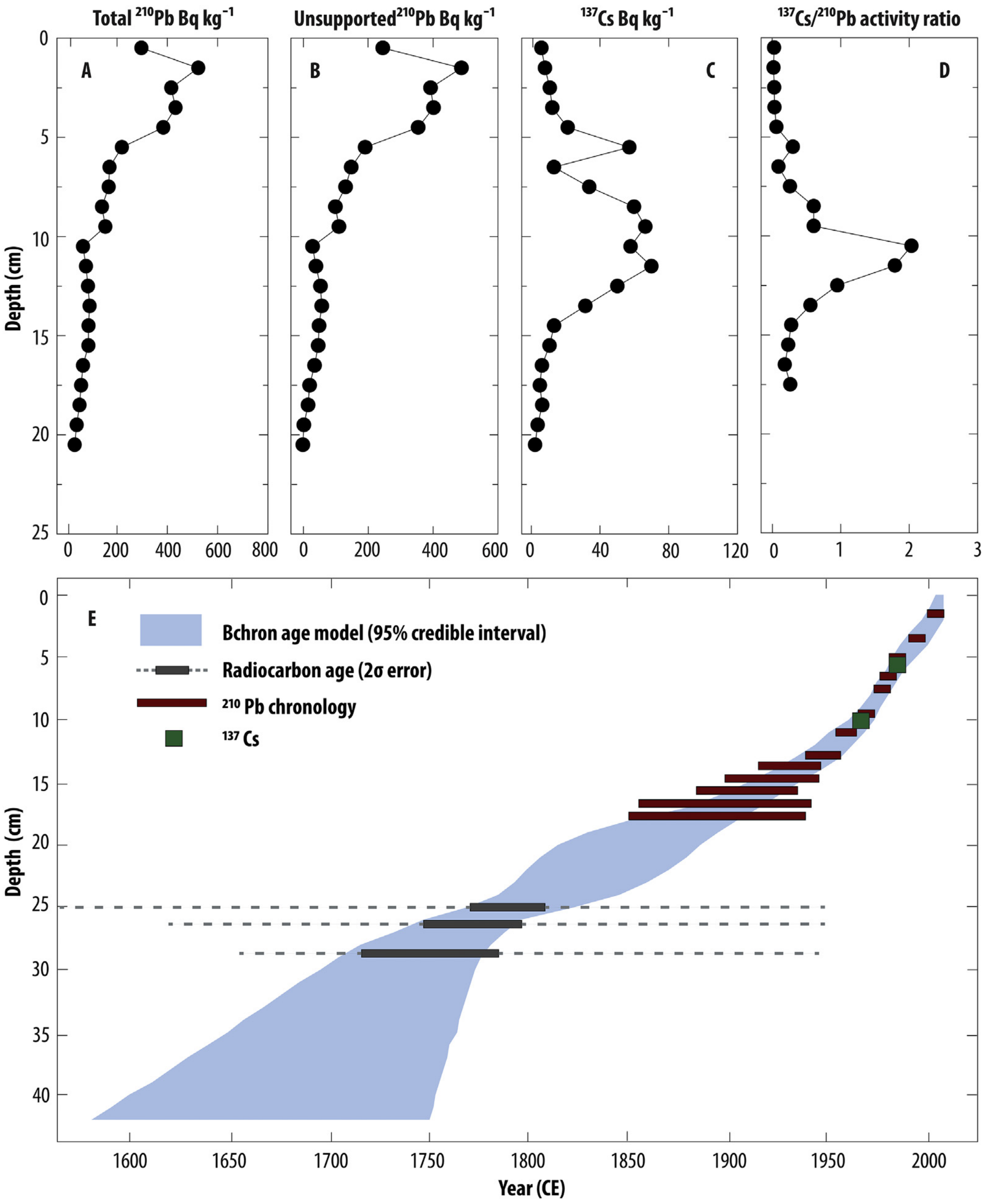

Fig. 5. Down-core profiles from short-lived radionuclide analyses (A–D) described in text. Error bars from analyses are smaller than data point symbols used. (E) Bchron age-depth model with 95% credible interval incorporating short-lived radionuclide and AMS ^{14}C dating.

4.4. Late Holocene relative sea-level trends

Application of the EIV-IGP model to the salt-marsh RSL reconstruction showed a magnitude of RSL change of ~0.28 m since 1733 CE (Fig. 6) with an average rate of RSL change of 0.95 mm/yr over the whole record. Rates of RSL increase from 0.71 mm/yr (−0.67-2.09 mm/yr) to 0.93 mm/yr (0.39–1.47 mm/yr) at 1850 CE when RSL was at −0.19 m below present level. Since 1900 CE, RSL rose ~0.14 m at an average rate of 1.09 mm/yr, increasing to 1.16 mm/yr (−0.08-2.42 mm/yr) at 2009 CE.

Annual measurements from the Split tide-gauge since 1955 CE show a magnitude RSL change of ~0.09 m (Fig. 7), concurrent with that recorded by salt-marsh sediments for the same period (~0.08 m; Fig. 6). The average rate of RSL change was 0.60 mm/yr increasing from 0.52 mm/yr (−0.15-1.2 mm/yr) at 1955 CE to 0.67 mm/yr (0.01–1.33 mm/yr) at 2009 CE.

Late Holocene RSL data from the Island of Vis show a magnitude of RSL change from −1.48 m since 715 BCE increasing to −1.05 m by 100 CE at 0.52 mm/yr (−0.82-1.87 mm/yr) (Fig. 8). Between 500 and 1000 CE, RSL was at around −0.7 m below present increasing to −0.25 m at 1700 CE, similar to that recorded by the salt-marsh reconstruction for the same time period (−0.28 m). Acknowledging temporal paucity of earlier data, rates of RSL are relatively stable up to 800 CE increasing to 0.77 mm/yr (−0.02-1.57 mm/yr) and then decreasing to 0.13 mm/yr (−0.37-0.64 mm/yr) at 1450 CE. The inclusion of the salt-marsh reconstruction and tide-gauge measurements shows the gradual increase in RSL change towards the present.

Comparison of the late Holocene composite RSL record with ICE-7G_NA (VM7) model predictions for the central-eastern Adriatic

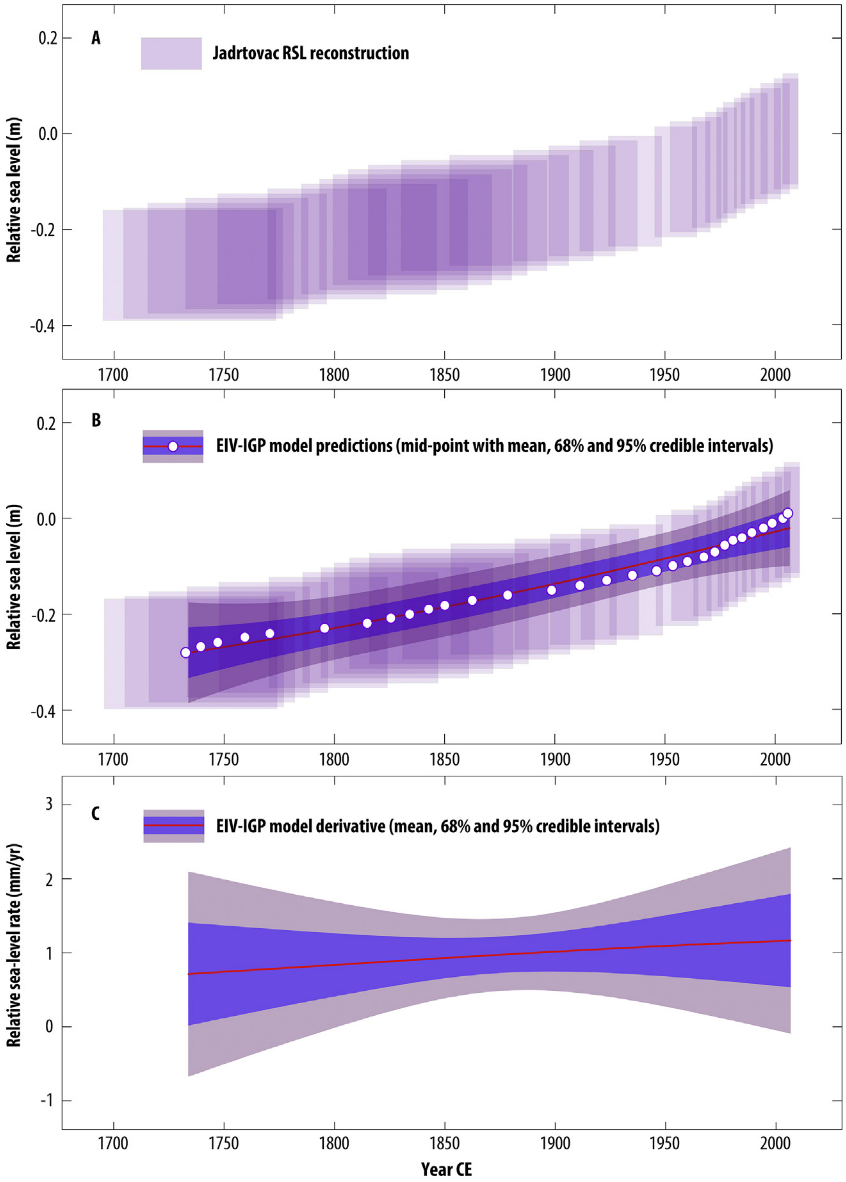

Fig. 6. (A) Reconstruction of relative sea-level (RSL) from salt-marsh core at Jadrtovac. (B) Error-In-Variables Integrated Gaussian Process (EIV-IGP) model showing mid-points from the RSL reconstruction with mean, 68% and 95% credible intervals. (C) Rates of RSL (mm/yr) with mean, 68% and 95% credible intervals.

coast reveals a significant offset between the RSL data and predicted results (Fig. 8d). At ~700 BCE, the ICE-7G_NA (VM7) model predicts RSL at −0.25 m below present, compared to −1.48 ± 0.3 m suggested by the RSL data. Indeed, this offset is manifest throughout the late Holocene towards the present, with the GIA model predicting magnitudes of RSL changes lower than RSL reconstructions in the central-eastern Adriatic.

5. Discussion

Eustatic and glacio-hydro-isostatic processes have been important driving mechanisms of RSL change in the Mediterranean (e.g., Lambeck and Purcell, 2005; Stocchi and Spada, 2007, 2009; Roy and Peltier, 2018). At more local scales, particularly in the northern Adriatic, geological evidence from geomorphological, sedimentological and archeological sea-level indicators have been utilized to illustrate the importance of differential tectonic movements and local processes (e.g. sediment compaction) affecting late Holocene RSL histories (e.g., Pirazzoli, 2005; Antonioli et al., 2009, 2011; Marriner et al., 2014; Surić et al., 2014; Benjamin et al., 2017; Fontana et al., 2017). Furthermore, understanding RSL changes from the late Holocene to the modern period have been restricted by the temporal offset between geological and tide-gauge RSL records (Vacchi et al., 2016), which record large inter-annual and inter-decadal variability (Tsimplis et al., 2012). Our salt-marsh RSL reconstruction overcomes this limitation.

5.1. Late Holocene relative sea levels in the Adriatic

In the northwestern Adriatic, geomorphological and geoarchaeological evidence shows RSL was at −2.0 ± 0.6 m between 1250 and 1110 BCE, increasing to −1.1 ± 0.3 m at ~50 BCE (Fontana et al., 2017). In the northeastern Adriatic, archeological evidence shows RSL was between −1.75 and −1.4 m–0 CE (Vacchi et al., 2016). More recent RSL data from the Venice and Fruili lagoons shows RSL was at −0.4 ± 0.6 m at ~1350 CE and below −0.3 m at

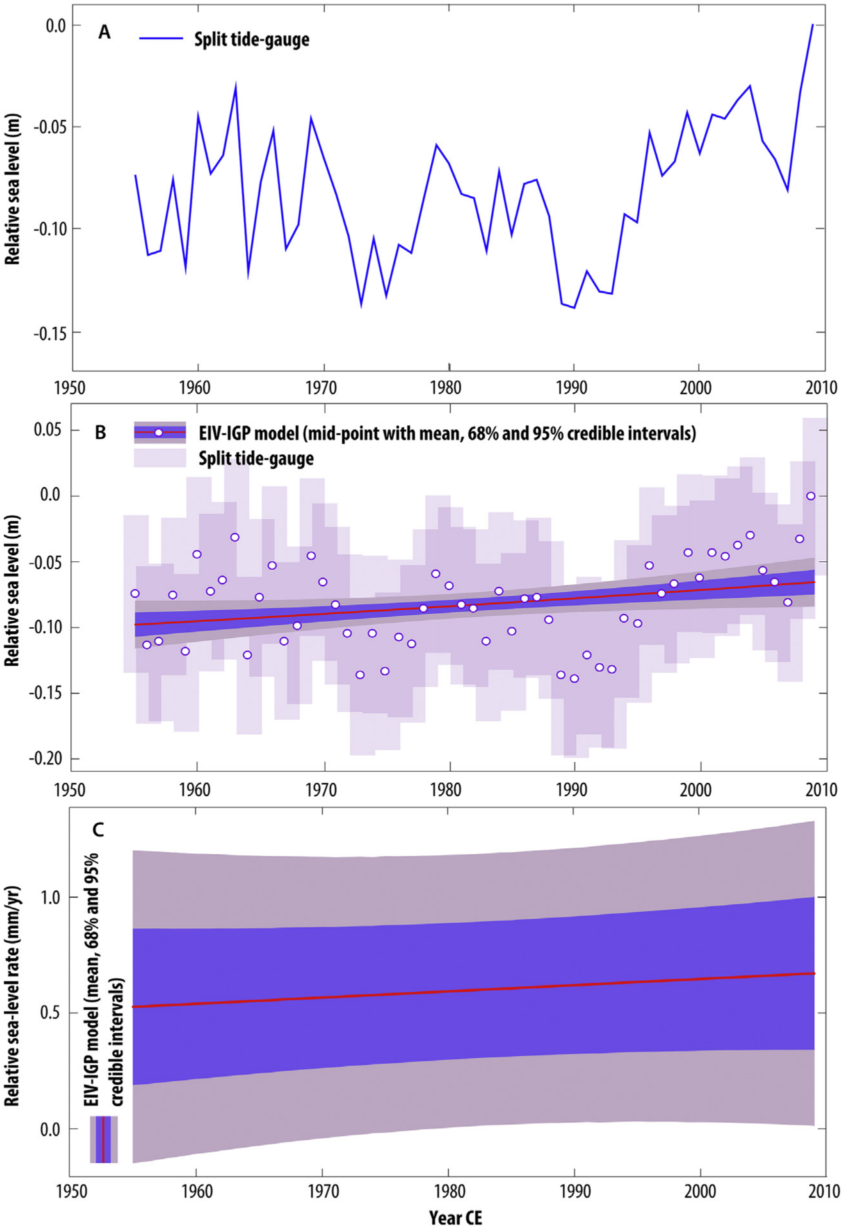

Fig. 7. (A) Annual mean relative sea-level (RSL) trends from the Split Gradska tide-gauge (see Fig. 2 for location). (B) EIV-IGP model showing mid-points from tide-gauge measurements with mean, 68% and 95% credible intervals. (C) Rates of RSL (mm/yr) with mean, 68% and 95% credible intervals. Annual RSL data accessed from the Permanent Service for Mean Sea Level on 13/11/2017 (http://www.psmsl.org/products/trends/trends.txt).

1650 CE (Vacchi et al., 2016). These results compare well with our RSL data from the central-eastern Adriatic (Faivre et al., 2013), which show a magnitude of RSL change of -1.48 ± 0.3 m since 715 BCE increasing to -1.05 ± 0.3 m by ~ 100 CE and at -0.3 ± 0.3 m between 1350 and 1750 CE.

We compared the composite RSL record for the central-eastern Adriatic with glacio-isostatic model predictions from ICE-7G_NA (VM7) (Roy and Peltier, 2017) (Fig. 8). The magnitude of RSL change from the RSL data (1.48 ± 0.3 m), however, is significantly greater than ICE-7G_NA (VM7) model predictions (0.25 m). If we assume the viscosity profile in the GIA model to be accurate, the disparity between the RSL reconstructions and model predictions of RSL could be due to eustatic input and/or tectonics in the absence of local processes (e.g., sediment compaction). For example, the eustatic contribution to sea-level change during the late Holocene from the Antarctic ice sheet may be underestimated in the ICE-7G_NA (VM7) model. Reconstructions of RSL from the Mediterranean basin can play a crucial role in understanding the response of the cryosphere to deglacial warming, in particular with respect to the late melting history of the Antarctic ice sheet (Stocchi et al., 2009; Roy and Peltier, 2018). Indeed, one of the key distinctions between various reconstructions of ice sheet deglaciation history lies in the late Holocene eustatic component of sea-level change largely driven by the Antarctic and Greenlandic ice sheets. Whereas the ICE-6G_C and ICE-7G_NA models of ice sheet loading history show around 2 m of global mean sea level (GMSL) rise since 7ka, with no substantial increase after 4ka, other models have inferred up to 6 m of GMSL rise since 7ka, with more than 80 cm of this change having occurred after 4ka (Lambeck et al., 2014). It is important to place this observation in the broader context of the

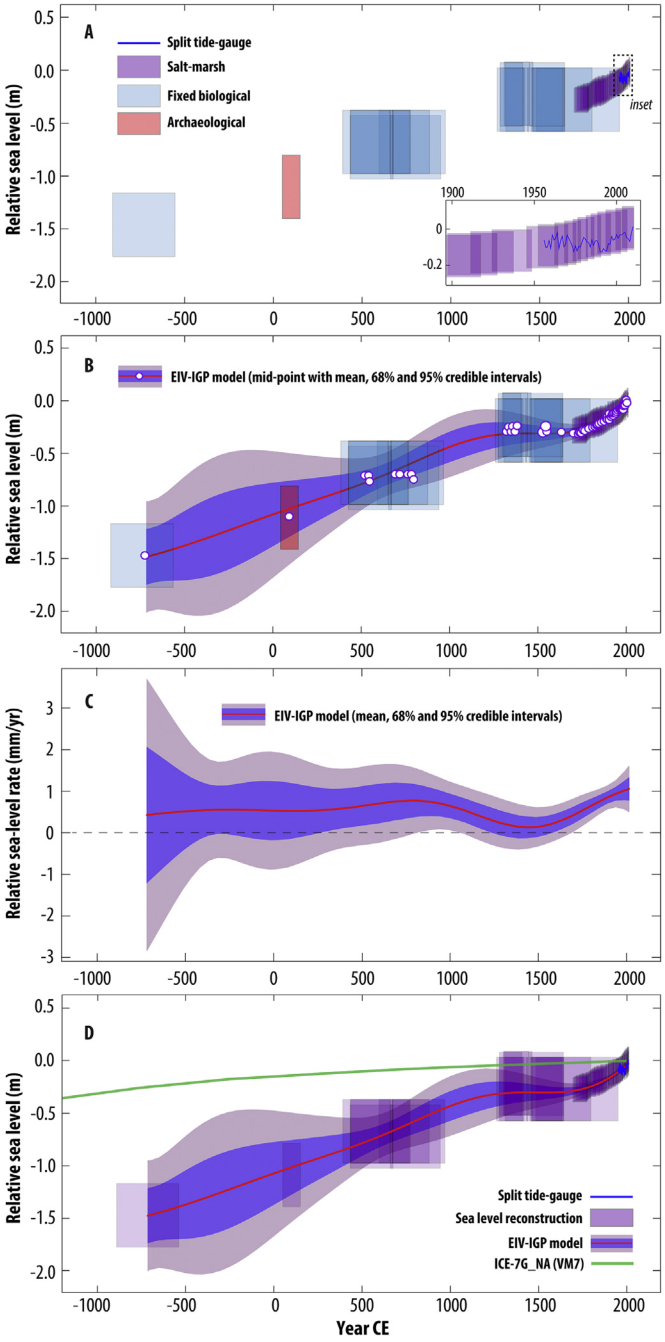

Fig. 8. (A) Late Holocene relative sea-level (RSL) change from fixed biological (*Lithophyllum*) littoral rims and archaeological evidence from the Island of Vis recorded by Faivre et al. (2013), the salt-marsh RSL reconstruction from Jadrtovac and Split Gradska tide-gauge measurements. (B) Application of EIV-IGP model to the composite RSL showing mid-points with mean, 68% and 95% credible intervals. (C) Rate of RSL (mm/yr) with mean, 68% and 95% credible intervals. (D) Comparison of the composite RSL reconstruction against glacial-isostatic adjustment model predictions of RSL from ICE-7G_NA (VM7) for the study region.

quality of the fit provided by the ICE-7G_NA (VM7) to RSL data in the rest of the western Mediterranean basin (Fig. 9). Roy and Peltier (2018) found their model to perform very well in France, around the Ligurian Sea, in Corsica and in Sardinia. However, the authors identified regions of sustained misfits between the model predictions and the Vacchi et al. (2016) database, notably in central Spain, southwest Italy and in the Adriatic (Fig. 9). The GIA model is able to fit the majority of RSL reconstructions between 3ka and 1ka in the western Mediterranean basin to within two standard deviations. However, the RSL data that misfit with model predictions by greater than two standard deviations are concentrated in the Adriatic.

The misfit between RSL data and model predictions provide support for the existence of tectonic effects in the Adriatic, rather than an issue in the rate of GMSL rise included in the ICE-7G_NA model. The difference between the reconstruction and the model suggest a tectonic subsidence of 0.45 ± 0.6 mm/yr. Although a full assessment of the influence of tectonics operating in the region is challenging, the large variations in GPS vertical velocities (Fig. 2) observed around the Adriatic Sea (Serpelloni et al., 2013) supports the idea of substantial tectonic motion. It should also be noted that the presence of a complex tectonic setting should also be studied in the context of potential local lateral heterogeneity in the viscosity of the mantle. Due to the small scale of the Adriatic Sea, any sensitivity to such variations would be expected to be limited to the uppermost layers of the mantle. Nonetheless, any rigorous determination of the geological evolution throughout the region will need to consider these effects.

The influence of local processes including paleotidal-range change and sediment compaction to Holocene RSL histories (e.g. Horton et al., 2013) may also contribute to differences between glacial-isostatic model predictions and RSL data. A lack of Mediterranean based studies currently restricts the assessment of paleotidal-range changes (e.g. Hill et al., 2011; Griffiths and Hill, 2015) to Mediterranean Holocene RSL data (e.g. Vacchi et al., 2016). However, given the local micro tidal range and time period involved, we can consider the influence of paleotidal-range changes to be negligible. Furthermore, the influence of sediment compaction, is also negligible due to the limited depth of overburden (e.g. Törnqvist et al., 2008; Horton and Shennan, 2009) of the relatively thin organic salt-marsh peat deposits at Jadrtovac. Nonetheless, future RSL studies in the Adriatic and Mediterranean region accounting for these processes, would inherently provide more accurate predictions of RSL change.

5.2. Centennial scale relative sea-level variability

Climate-driven centennial sea-level variability superposed on late Holocene RSL are expressed at the global scale (Kopp et al., 2016) with the transition from the Medieval Climate Anomaly (MCA) to the Little Ice Age (LIA) coinciding with a reduction in air and ocean temperatures (Mann et al., 2009; Marcott et al., 2013; Rosenthal et al., 2017). Application of the EIV-IGP model to the geological data from Vis shows a (subtle) increase and decrease in RSL rate, occurring at 800 CE and 1450 CE, respectively. This broadly coincides with the MCA to LIA transition which Faivre et al. (2013) suggested a response of central-eastern Adriatic sea levels similar to the North Atlantic based on comparisons of RSL trends with salt-marsh based RSL reconstructions from North America (Kemp et al., 2011). While the temporal coverage and vertical resolution of late Holocene RSL data from the western Mediterranean currently restricts more local interpretations (e.g. Vacchi et al., 2016), variability of late Holocene RSL in the eastern Mediterranean has been reported (Sivan et al., 2004). Archaeological and biological proxy data from Israel support inferences for sea-level variability between 900 and 1300 CE (Toker et al., 2012). Indeed, the climatic deterioration during the LIA has also been associated with a period of increased storminess throughout the Mediterranean region (Marriner et al., 2017).

5.3. Modern sea-level rise

Empirical modelling of proxy and instrumental RSL records has

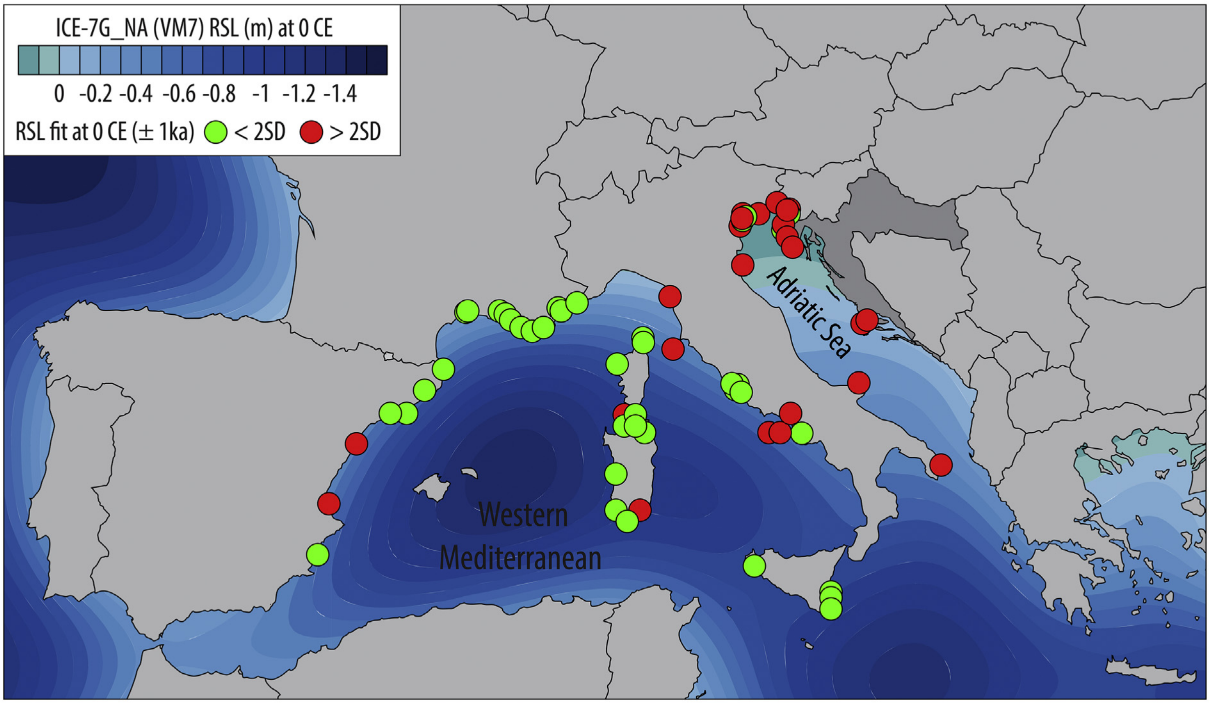

Fig. 9. Quality of the fit to the late Holocene RSL data from the western Mediterranean (Vacchi et al., 2016) provided by the model predictions of the ICE-7G_NA (VM7) model, centered on 0 CE (±1000 years). Green dots represent an agreement between the model prediction of RSL and the local RSL reconstruction within 2 standard deviations (SD), while red dots indicate locations where the difference between the model predictions and the RSL reconstruction is greater than 2 SD. Contours represent ICE-7G_NA (VM7) model predictions of RSL (m) at 0 CE. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

enabled inferences regarding timing the onset of modern sea-level rise (Kopp et al., 2016). At the global scale, sea levels began rising around 1860 CE (Kemp et al., 2011; Kopp et al., 2016), synchronous with sustained industrial-era warming of the tropical oceans and Northern Hemisphere continents (Abram et al., 2016). Here, we applied the EIV-IGP model to our salt-marsh reconstruction, which captures the dynamic evolution of sea-level change with robust consideration of sources of uncertainty (Cahill et al., 2015). Importantly, the EIV-IGP model shows a subtle but constant increase in the mean rate of RSL rise from 0.71 mm/yr (−0.67-2.09 mm/yr) to 1.16 mm/yr (−0.08-2.42 mm/yr) between 1733 CE and 2009 CE (Fig. 6c). Indeed, this subtle increase in mean RSL rate stems from the deviation of sea-level trends recorded up to ~1450 CE (Fig. 8c).

Uncertainties in constraining age-depth relationships in the salt-marsh reconstruction during the nineteenth century may preclude important inferences regarding timing of the onset of modern RSL rise in the Mediterranean. Records of RSL change from twentieth century tide-gauge stations in the Mediterranean show RSL rising at a rate of 1.1–1.3 mm/yr (Tsimplis and Baker, 2000; Orlić and Pasarić, 2000; Marcos and Tsimplis, 2008). Zerbini et al. (2017) also report a rising RSL trend of 1.2–1.3 mm/yr (±0.2–0.5 mm/yr) from their analyses. The salt-marsh RSL reconstruction supports these findings with an average RSL rate of ~1.1 mm/yr between 1900 and 2009. While a lower average rate of RSL change was recorded by the Split tide-gauge (0.60 mm/yr), this reflects a deviation of sea levels recorded by Adriatic and Mediterranean tide-gauge stations during the latter half of the twentieth century. A decrease in RSL rate between 1960 and 1993 (Tsimplis and Baker, 2000; Marcos and Tsimplis, 2008) coincided with a period of higher atmospheric pressure and evaporation over the basin driven by the high state of the North Atlantic Oscillation (Tsimplis and Josey, 2001).

6. Conclusions

Reconstructions of RSL change along the central-eastern coast of Croatia offer new insight to the late Holocene sea-level history of the central-eastern Adriatic region. We reconstructed RSL using salt-marsh sediments and foraminifera that underpins their underutilized potential to derive RSL changes in the Mediterranean. Fossil foraminifera enumerated from a short sediment core were constrained vertically by contemporary foraminiferal distributions, and temporally, by radiometric dating techniques within a Bayesian age-depth framework. The reconstruction shows RSL rose ~0.28 m since ~1733 CE, with a magnitude RSL change of ~0.14 m comparable to tide-gauge records during the twentieth century. We modelled RSL changes using the EIV-IGP model (Cahill et al., 2015) showing rates of RSL change increasing from 0.71 mm/yr (−0.67-2.09 mm/yr) at ~ 1733 CE to 0.93 mm/yr (0.39–1.47 mm/yr) at 1850 CE. Average rates of RSL during the twentieth century, rising at ~1.1 mm/yr, are analogous with the instrumental measurements.

We compared a composite RSL record combining the tide-gauge and salt-marsh reconstruction with local published sea-level index points (n = 23) (Faivre et al., 2013) against ICE-7G_NA (VM7) glacio-isostatic model predictions (Roy and Peltier, 2017) for the last ~ 2700 years. The magnitude of RSL change from the RSL reconstruction (1.48 m) differs from the glacio-isostatic model prediction by more than 1 m, supporting subsidence rates driven by the Adriatic tectonic framework of 0.45 ± 0.6 mm/yr. Application of the EIV-IGP model supports evidence for late Holocene sea-level variability with rates of RSL rise decreasing from 0.77 mm/yr (−0.02-1.57 mm/yr) at 800 CE to 0.13 mm/yr (−0.37-0.64 mm/yr) at ~ 1450 CE. The temporal coverage of the salt-marsh reconstruction bridging RSL changes from the late Holocene to the modern instrumental period shows the gradual increase in mean RSL rate towards the present.

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