Historical and recent sea level rise and land subsidence in Marina di Ravenna, northern Italy

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ABSTRACT

The regions facing the northern Adriatic Sea are particularly vulnerable to sea-level rise. Several trade ports are located there, and the area is important from social and economical viewpoints. Since tourism and cultural heritage are a significant source of income, an increase in sea-level could hinder the development of these regions. One of the longest sea-level time series in the northern Adriatic, which goes back to the late 1880s, has been recorded at Marina di Ravenna, in Emilia-Romagna region. The record is anomalous, showing a rate of increase that largely exceeds that observed in nearby stations. During the last few decades, geodetic campaigns based on geometric high precision leveling, SAR interferometry, and GPS have monitored the Ravenna area. In this work, tide gauge observations are merged with yet unpublished geodetic data, aiming at a coherent interpretation of vertical land movements. We confirm that land subsidence is the major cause of relative sea-level change at Marina di Ravenna, at least during the period allowing for a quantitative analysis (1990-2011). The rate of absolute sea-level change (2.2±1.3 mm yr^{-1} during the same time period), given by the difference between the rate of relative sea-level change and the rate of subsidence, is consistent with the rate of absolute sea-level change observed by altimetry in the northern Adriatic Sea.

1. Introduction

Sea-level change is one of the key indicators of global warming. According to the latest report of the Intergovernmental Panel on Climate Change (IPCC), global sea level rose at a rate in the range between 1.3 and 1.7 mm yr^{-1} between 1901 and 1990 [Church et al. 2013], with an acceleration of ~0.01 mm yr^{-2} [Spada et al. 2015]. However, satellite data [Wunsch and Stammer 1995] and hydrographic observations [Roemmich and Owens 2000], in agreement with climate models [Spada et al. 2013], show that sea level has not been rising uniformly across the oceans. In some regions, rates are even several times larger than the global mean sea-level rise, while in others sea level is falling [Cazenave and Llovel 2010]. Globally, sea-level rise is mainly driven by the thermal expansion of water masses and by the melting of glaciers and ice sheets [Lombard et al. 2005, Plag 2006, Cazenave and Remy 2011], but both factors also imply significant local and regional variations [Spada and Galassi 2016]. These are also controlled by changes of atmospheric pressure and, in the case of semi-enclosed basins like the Mediterranean Sea, by the forcing exerted from nearby ocean masses driving variations of relative sea level [Umgiesser et al. 2011]. Other causes are significantly contributing, such as the deposition and compaction of sediments, tectonic movements, the soil reaction to fluid or gas withdrawal, and the response of the Earth to changes in surface loading [Milne et al. 2009]. Understanding the mechanisms driving sea-level changes is important to promote mitigation measures, when these are possible [McGranahan et al. 2007, Nicholls and Cazenave 2010].

It has long been recognised that the northern Adriatic Sea is particularly vulnerable to sea-level rise. This stems from the combined effect of low elevation coastlines, subsidence and intense urbanization [Armaroli et al. 2012, Perini et al. 2015]. The area is of great importance from the social and economical standpoints, mainly for several ports located here (e.g., Venice, Trieste, Ravenna, Dubrovnik, Split; see Figure 1), as well as for

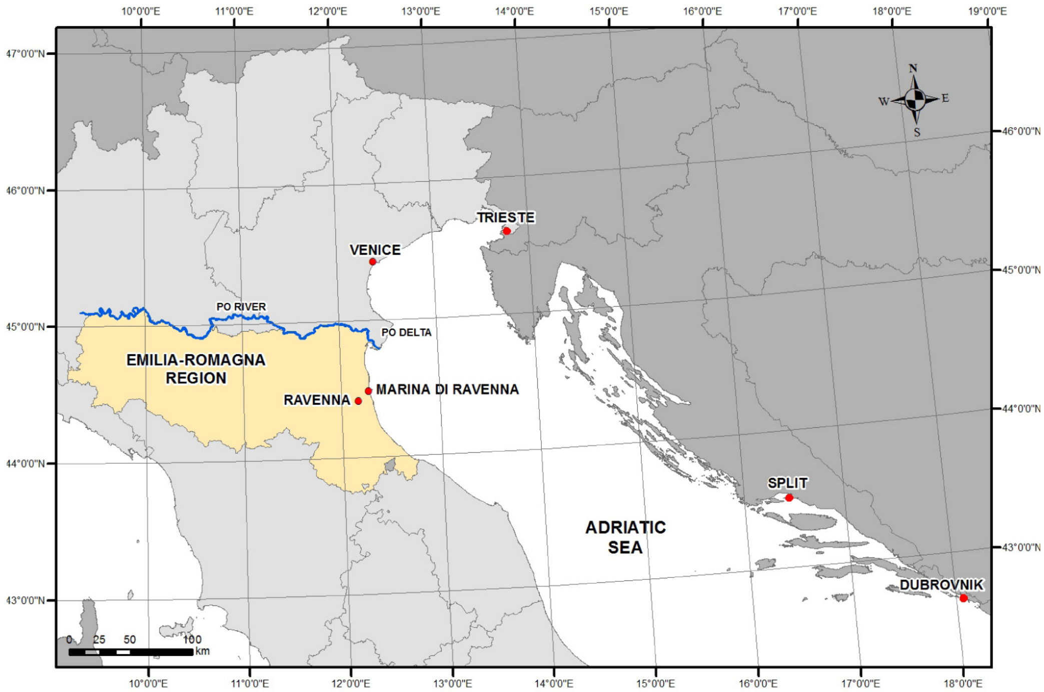

Figure 1. Map of the northern Adriatic Sea and surrounding regions, showing the toponyms of interest for this work. Italy and Emilia-Romagna region are coloured in light grey and yellow, respectively. A blue line marks the path of the Po River.

tourism and cultural heritage [e.g. Cori 1999, Preti and De Nigris 2009]. An important cause of relative sea-level change in some parts of this area facing the northern Adriatic Sea is land subsidence [Bitelli et al. 2010], of both natural and anthropogenic origins [Brunetti et al. 1998, Carminati et al. 2003, Stright Jr et al. 2008, Baldi et al. 2009]. The effects of subsidence are particularly important in the area of Ravenna in Emilia-Romagna region, which belongs to the delta portion of the Po River plain (Figure 1). Due to its sedimentary origin, the Po valley is subject to natural subsidence, which is partly compensated by the transportation of sediments and by the advance of the coastline [Teatini et al. 2005]. Over the last century, the observed subsidence showed a significant increase in the area of Ravenna, with rates as large as tens of millimetres per year between 1972 and 1977 [Bertoni et al. 1973, Carbognin et al. 1978, Carbognin et al. 1984, Teatini et al. 2005]. A first cause of subsidence is the ground water withdrawal from subsurface aquifers, promoted by the economic growth after the end of World War II and by the development of tourism along the coast [Preti and De Nigris 2009, Bitelli et al. 2010]. Another source of subsidence is the gas extraction from deep on-shore and off-shore reservoirs, with the first producing a diffuse sinking along the coasts and the latter having much more localised effects [Gambolati et al. 1991, 1999]. In addition to these causes, sea-side processes as the steep drop in the sand transportation by rivers due to the overbuilding of the river banks, or the reclamation of wetlands and lagoons areas on the north, are playing a significant role [Teatini et al. 2005, Preti and De Nigris 2009].

For its vulnerability and for the high subsidence rates, the area of Ravenna has been intensively studied. On one hand, efforts from integrated modelling approaches [Gambolati et al. 1991, 1999] have allowed a quantitative evaluation of the main causes impacting the stability of the whole area. On the other hand, various geodetic surveys have provided new insights on the recent rates of subsidence. Over time, the surveys have been planned by the Italian Geographic Military Institute (IGM), the regional environmental service (ARPAE, formerly ARPA), the Consorzio di Bonifica di Ravenna, the Geological Service of the Ravenna Municipality, and the Italian oil company ENI-E&P. Furthermore, in the northern Adriatic Sea, the Porto Corsini tide gauge sited in Marina di Ravenna (formerly known as Porto Corsini) has collected a long record (1897-2014) of relative sea level, in a location that during last century has been particularly affected by land subsidence [Teatini et al. 2005]. No other comparatively long sea-level time series is available from instruments deployed along the coasts of Emilia-Romagna region. It has long been known (see e.g., Caputo [1971]) that long-term relative sea-level variations at the Porto Corsini tide gauge are strongly affected by the vertical land movements and possibly by pier instability. Consequently, the correlation with sea-level signals from other tide gauges deployed along the Adriatic and northern Mediterranean coast (Venice, Trieste and Genoa) is poor, as also pointed out by Raicich [2011] and Tsimplis et al. [2012]. Indeed, the mean rate of relative sea-level change shown by the Porto Corsini tide gauge record exceeds by 3-6 times the typical Mediterranean rates during the period 1897-2011 [Tsimplis et al. 2012]. Since they can help to assess the long-term subsidence, the relative sea-level data from the tide gauge of Porto Corsini are of remarkable importance.

In the framework outlined above, the present study aims at investigating how the sea-level rise observed at the Porto Corsini tide gauge is reflecting the observed local land subsidence. During the last few decades, this is accomplished by means of yet unpublished geodetic data, which allow for estimating the rate of change of absolute sea level. We believe that this study may improve the reliability of the Porto Corsini tide gauge observations, which are now included in the quality-controlled section of the Permanent Service for Mean Sea Level database (PSMSL, see Holgate et al. [2012]) only for a very limited time span (1969-1972).

The paper is organised as follows. In Section 2, we describe the data and the methods employed in our study, in Section 3 we first estimate the long-term relative sea level and subsidence at the Porto Corsini tide gauge, and then we focus on the last few decades. The results are discussed in Section 4 and the conclusions are drawn in Section 5.

2. Data and methods

2.1. Sea level measurements

The Porto Corsini tide gauge station (44.49° N, 12.28° E) is placed on the Italian Adriatic coastline in the municipality of Marina di Ravenna, east of the town of Ravenna in Emilia-Romagna region (see Figure 1). Here, instrumental sea-level observations are available since 1897, when the station became part of the newly born Italian tide gauge network.

The annual mean sea-level data of Porto Corsini used in this work come from several sources: (*i*) the Permanent Service for Mean Sea Level (PSMSL) archive (data retrieved on January 1, 2016, from http://www.psmsl.org/), for the time period 1897-1922 [Woodworth and Player 2003, Holgate et al. 2012], (*ii*) Annali Idrologici di Bologna (Hydrology Annals of Bologna) for the period 1934-1979 [Annali 1934-1979], and (*iii*) DSTN/APAT/ISPRA (Institute for Environmental Protection and Research) for the period 1980-2014 (data are available from http://www.mareografico.it). A plot of the annual mean sea-level record for Porto Corsini is shown in Figure 2. In order to obtain a coherent time series, the different datasets have been homogenised relying upon the information on benchmarks and data overlaps (see also Mosetti [1969]). A relocation of the tide gauge was, for example, necessary due to works for the re-construction of the dock next to the Marina di Ravenna lighthouse.

The sea-level measurements at the Porto Corsini tide gauge are historically referred to the IGM benchmark located in the Marina di Ravenna lighthouse, sited 150 m away from the tide gauge. The lighthouse was connected in 1885 to the first IGM Italian leveling network [Salvioni 1957], gathering at the time the main Italian harbours, with the establishment of the Porto Corsini tide gauge. However, this initial network resulted inadequate and after the end of World War II it was completely re-established. The first leveling of the lighthouse benchmark with respect to the national altimetric datum, defined by the tide gauge in Genoa in 1942, was accomplished in 1970. Subsequently, other

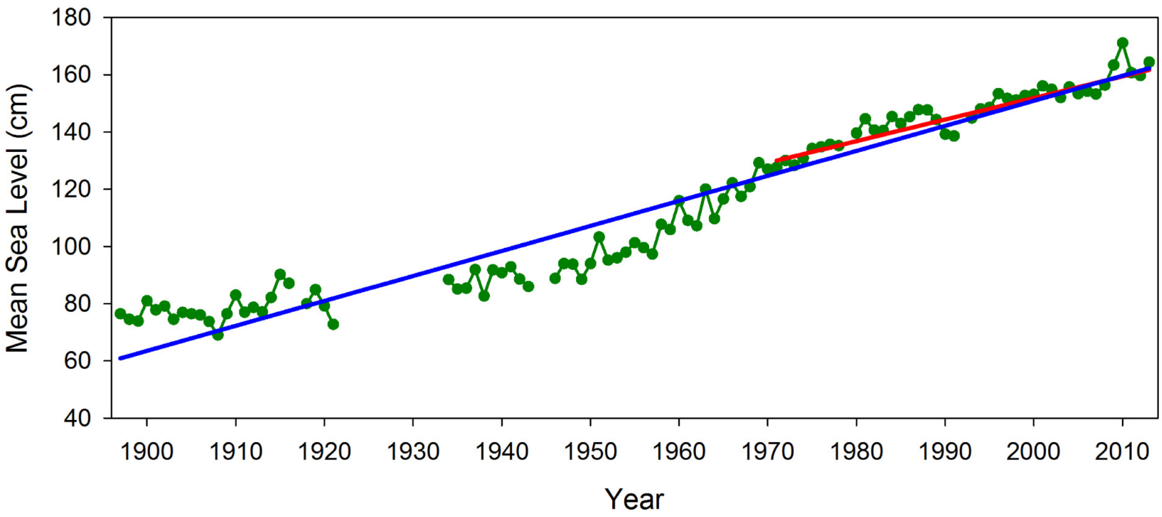

Figure 2. Annual values of mean sea-level at the Porto Corsini tide gauge in Marina di Ravenna during 1897-2013. The blue line represents the long-term trend obtained by applying the least squares regression method over the entire time series, while the red one shows the trend during 1970-2013.

level surveys were performed by IGM in 1977 and 1990, which provided a reference for the sea-level data collected by the Porto Corsini tide gauge since 1990. In 2012, the lighthouse benchmark was connected to the IGM network and since September 2013 the height observed in that occasion became the reference value used by the tide gauge.

2.2. Land subsidence measurements

In this work, different measurements of land altitude and of its rate of change are considered and compared, during different time periods. As mentioned in the Introduction, land subsidence in the Ravenna area has been monitored by several agencies. Here, we consider only locations geographically or historically related to the Porto Corsini tide gauge site. A summary of the monitoring campaigns is presented in Table 1.

Concerning the IGM measurements, points prior to World War II resulted inconsistent with respect to the rest of the period. Salvioni [1957] homogenized the 1897-1957 dataset by using a compensation approach and the same IGM datum. Other surveys were performed by the Consorzio di Bonifica di Ravenna in 1949 and 1972, with the establishment of a local leveling network in Ravenna Municipality. The elaboration in contour maps of these IGM and Consorzio di Bonifica di Ravenna surveys for the periods 1897-1957 and 1949-1972 [Salvioni 1957, Carbognin et al. 1984, Arca and Beretta 1985] was later georeferenced and gridded in GIS maps by Teatini et al. [2005], to which we refer to qualitatively characterise the land subsidence at Marina di Ravenna prior to 1970. First IDROSER SpA and afterwords the ARPAE agency, on behalf of Emilia-Romagna region, monitored the subsidence by using the high precision geometric leveling method, assuming as a stable reference the IGM benchmark at Sasso Marconi in the Apennine Mountains [Regione Emilia-Romagna - Arpa 2006]. Many sites along the Ravenna coast were monitored, including the Marina di Ravenna lighthouse and the tide gauge station on the dock (Table 1). The results from the 1993 survey campaign are not considered here, since doubts on their validity have been raised [Regione Emilia-Romagna - Arpa 2001]. Since 2005, ARPAE continued the land subsidence monitoring by the support of SAR Interferometry (PSInSAR^{TM} technique), to provide rates of subsidence [Regione Emilia-Romagna - Arpa 2007, 2012].

Two different calibration methods were used, providing rates of vertical movement for periods 1992-2000, 2003-2006, and 2006-2011 (see Table 1). For the first two periods SAR Interferometry was calibrated by 2005 leveling surveys [Regione Emilia-Romagna - Arpa 2007], while, for the last period, a network of 16 GPS-GNSS permanent stations located in the Emilia-Romagna plain [Bitelli et al. 2014, 2015] was used [Regione Emilia-Romagna - Arpa 2012]. Since none of these GPS stations is located in or near Marina di Ravenna, we did not include any GPS data in the present analysis. We consider the scatter points available in the vicinity of the tide gauge site, i.e., on the dock structure and on top of the lighthouse or in its neighbourhood (an example of these points is shown in Figure 3). When several scatter points were available on the same structure (this occurred during period 2003-2006), averaged values have been considered. Table 2 reports raw data for the height measurement and for the rate of vertical movement,

Agency	Date	Type of survey	Notes
IGM and Consorzio di Bonifica di Ravenna	1897, 1949, 1972	Geometric leveling	GIS maps in Teatini et al. [2005]
IGM	1970, 1977, 1990	Geometric leveling	Lighthouse benchmark
IDROSER	1984, 1987	Geometric leveling	Lighthouse benchmark and tide gauge benchmark on the dock
ARPAE	1999, 2005	Geometric leveling	Lighthouse benchmark and tide gauge benchmark on the dock
ARPAE	1992-2000	InSAR calibrated on 2005 geometric leveling	Two scatter points: one on the dock and one over the lighthouse
ARPAE	2003-2006	InSAR calibrated on 2005 geometric leveling	Four scatter points: two on the dock and two over the lighthouse
ARPAE	2006-2011	InSAR calibrated on GPS permament network	Two scatter points: one on the dock and one over the closest building to the lighthouse

Table 1. Main surveys carried out in the Marina di Ravenna area by various agencies, with data used in the present work.

Figure 3. Aerial view of Marina di Ravenna showing the Porto Corsini tide gauge station and the surroundings. The ARPAE benchmark is sited in the same place of the tide gauge. The altimetric reference is the benchmark of the lighthouse. Red dots mark the scatter points from the interferometric satellite considered in this work, for the period 2006-2011 (units are mm yr^{-1}).

collected on the dock structure and on to the lighthouse or in its neighbourhood from 1970 to 2011.

3. Results

3.1. Long-term relative sea level and land subsidence in Marina di Ravenna

The historical time series of relative sea level at the Porto Corsini tide gauge is shown in Figure 2 (the data sources are summarized in Section 2.1). Here, annual mean relative sea-level data are presented, over a period exceeding one century (1897-2014). By considering the whole time series, the total variation of relative sea-level is ~1.0 m. To assess the rate of relative sea-level change, we applied the least squares regression, which provided a value of 8.5±0.2 mm yr^{-1}. This trend, displayed as a blue line in Figure 2, is comparable to the one that can be obtained by applying the Theil-Sen estimator [Theil 1950, Sen 1968], i.e. 8.7 mm yr^{-1} (the 95% confidence interval for the rate ranges between 8.1 and 9.5 mm yr^{-1}). To obtain this statistically significant ($p < 0.001$) trend, we adopted the Theil-Sen implemen-

Date/Interval	Lighthouse		Dock	
	Level (m a.s.l.)	Rate (mm yr^{-1})	Level (m a.s.l.)	Rate (mm yr^{-1})
1970	0.9325			
1977	0.7896			
1984	0.6866		1.0688	
1987	0.6315		1.0187	
1990	0.6273			
1999	0.5205		0.9298	
2005	0.4639		0.8848	
1992-2000		−6.7±1.0		−5.9±1.0
2003-2006		−7.2±2.6		−5.7±2.6
2006-2011		−5.3±2.0		−3.1±2.0

Table 2. Direct and undirect height measurements at the lighthouse and at the dock of Marina di Ravenna from the subsidence surveys presented in Table 1. A distinction is made between data sampled as height a.s.l. (e.g. levelling data, column "Level") and as average rates during specific time intervals (e.g. InSAR, column "Rate").

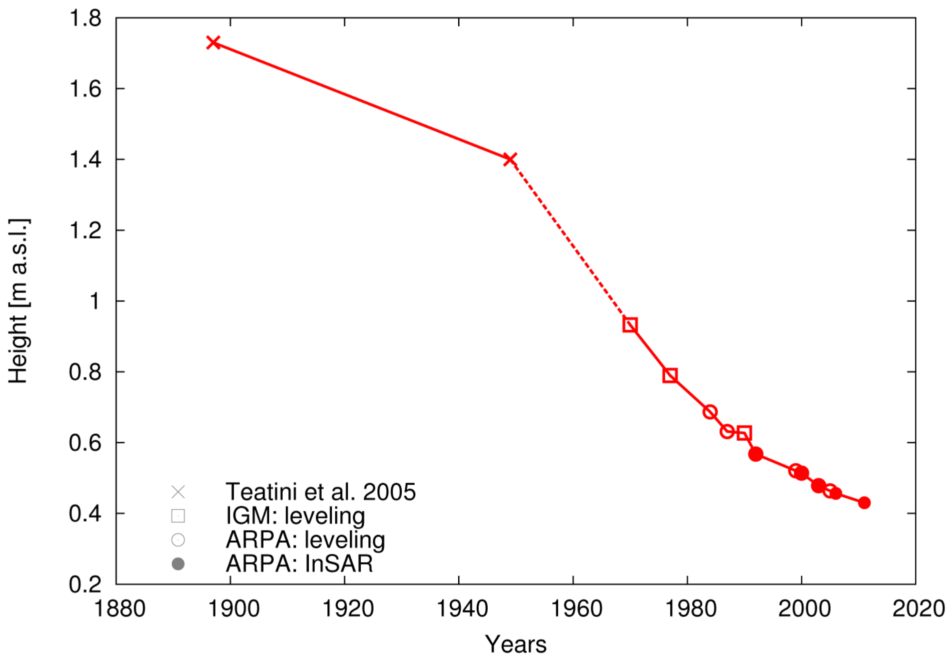

Figure 4. Altitude measurements in Marina di Ravenna at various epochs. Given the various elaborations applied to data before 1970 (see Section 2.2), the association with the 1970 IGM leveling is approximate (dashed line). Data after 1970 refer to different sources and survey methods, marked by various symbols (see legend). Further details are given in Tables 1 and 2.

tation in the *openair* software [Carslaw and Ropkins 2012], after having filled the gaps in the time series by applying a linear interpolation. Such rate of relative sea-level rise largely exceeds that obtained for other stations along the northern Adriatic and Mediterranean coasts over comparable time periods. According to Raicich [2011] and Tsimplis et al. [2012], the rates of relative sea level observed in Venice, Trieste and Genoa are 2.6, 1.3 and 1.2 mm yr^{-1}, respectively. By applying a quadratic (three-parameter) regression, we find that the value of the sea-level acceleration at Marina di Ravenna is 0.08 ± 0.02 mm yr^{-2}, which provides evidence for a significant increase in the long-term rate of relative sea-level change. Although existing estimates of global long-term sea-level acceleration are scattered (see review in Spada et al. [2015], and references therein), the value for Marina di Ravenna largely exceeds all of these.

The historical subsidence in the area of Marina di Ravenna is qualitatively inferred from the GIS slicing of the leveling surveys along the shoreline of Ravenna Municipality from the work of Teatini et al. [2005], by associating the subsidence between the intervals 1897-1949 and 1949-1972 with the benchmark elevation measured by IGM in 1970 at the Marina di Ravenna lighthouse (see Figure 14 in Teatini et al. [2005]). The time history of subsidence is plotted in Figure 4, where the observations are referred to the lighthouse of Marina di Ravenna. Coherently with the general trend in the Ravenna area (see the case study of Porta Adriana in the town of Ravenna [Carbognin et al. 1978]), the subsidence in the area of Marina di Ravenna experienced a marked increase during 1950-1970, with rates close to 24 mm yr^{-1}. These exceed the "natural trend" during 1897-1950 by about 6 mm yr^{-1}. In the ensuing years, the rate decreased, but still exceeding the natural trend. The last values obtained from the interferometric satellite analysis during 2006-2011 are close to 5.5 mm yr^{-1}. Overall, these data are consistent with the increase in the groundwater withdrawal between the 50s and late 70s and its subsequent decline. While the mainland appears to be substantially stable, many sites along the coast are still subsiding at rates exceeding the natural trend [Teatini et al. 2005]. Marina di Ravenna is coherent with this general behaviour, although the most recent interferometric analysis (2006-2011) has evidenced a recovering of the slower natural trend of subsidence. New data from the interferometric analysis scheduled for year 2016 will be useful to confirm or deny this trend.

3.2. Sea level at Marina di Ravenna since 1970

During the time period 1970-2013, monthly averaged values of relative sea level are available for Marina di Ravenna, characterised by a high degree of completeness. We have applied the least squares regression to this relatively short time series, obtaining a trend of 7.7 ± 0.3 mm yr^{-1}, displayed as the red line in Figure 2. Again, this trend resulted comparable to the significant ($p < 0.001$) trend obtained by the Theil-Sen method, i.e. 7.5 mm yr^{-1} (the 95% confidence interval for the rate ranges between 7.0 and 8.1 mm yr^{-1}). To analyse the sea-level variability coherently, seasonal cycles should

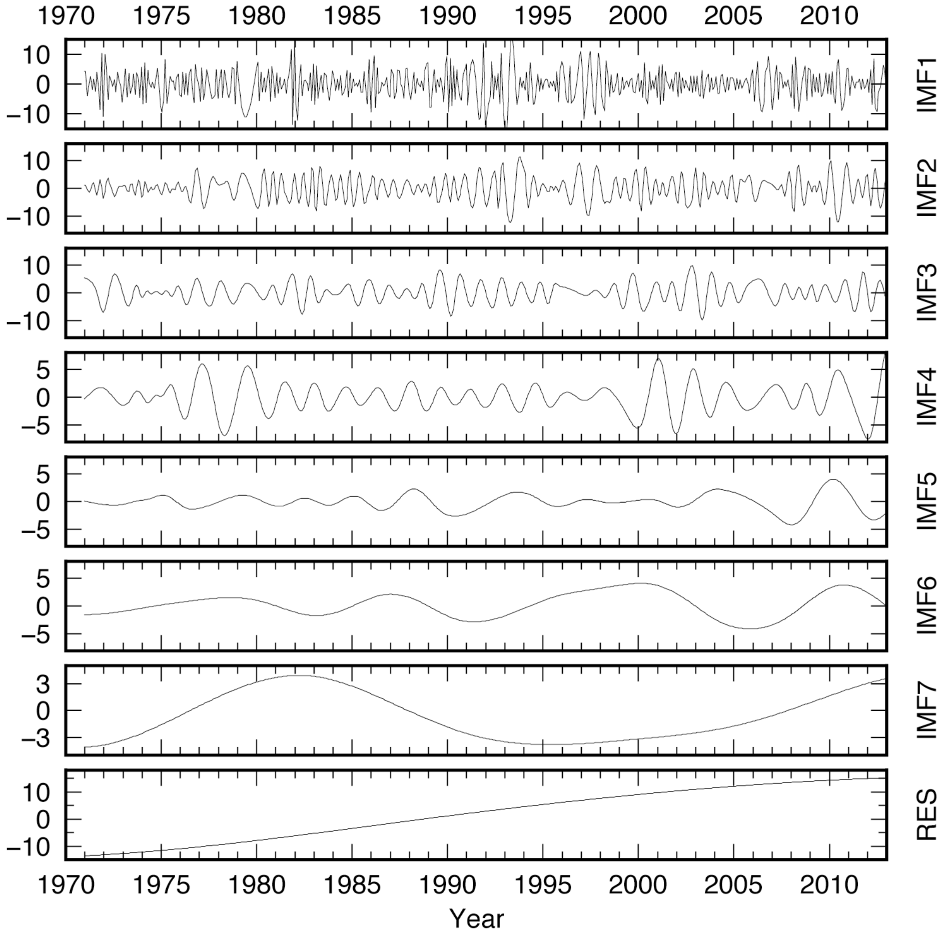

Figure 5. Results of the EMD analysis of the Marina di Ravenna relative sea-level time series since 1970, with the IMFs in the top frames and the residual (RES) in the bottom, respectively. Units are cm throughout.

be removed, since these derive from regional coastal effects. In many coastal areas, a large fraction of the seasonal cycle is associated with the steric component of sea-level change, induced by density variations in response to temperature and salinity fluctuations [Tsimplis et al. 2012]. However, due to the influence of regional hydrology, the non-steric component of the seasonal cycle of sea level was found to be important in some cases. The seasonal cycle and the amplitude of coastal sea-level height thus represent the local response to a seasonal pattern of large-scale sea-level variability and hydrology (see Bergant et al. [2005], and references therein). In Marina di Ravenna, we estimated the "climatological" annual variation considering monthly values, although the details of this analysis are not shown here. The minimum sea-level height was found in February (1.51±0.26 m), while two maxima were found in November (1.64±0.25 m) and June (1.55±0.22 m). This is consistent with with the results of Bergant et al. [2005], showing a minimum during the first months of the year, and two maxima in November and April. However, by a Mann-Whitney "U test" [Mann and Whitney 1947], we have found that the difference between the amplitude of the two peaks is not statistically significant ($p = 0.764$).

To detect possible cyclic components in the tide gauge time series of Porto Corsini since 1970, we have employed the empirical mode decomposition (EMD) method of Huang et al. [1998], in the improved version of Torres et al. [2011] (the Complete ensemble EMD with adaptive noise). The EEMD has been adopted by Breaker and Ruzmaikin [2011] to analyse the San Francisco tide gauge record and, more recently, by Spada et al. [2014] to study the Nuuk/Godthab (SW Greenland) time series, by Galassi and Spada [2014] to characterise the cyclic sea-level variations across the Adriatic Sea and by Vecchio et al. [2014] to study the transient effect of a tsunami in the Mediterranean Sea. The EEMD allows to split non-linear and non-stationary time series into a limited sequence of empirically orthogonal "intrinsic mode functions" (IMFs) that describe cyclic modes not necessarily characterised by a constant amplitude nor phase. Differently from traditional spectral methods, the EEMD is not requiring assumptions on the functional expression of the regression model. Figure 5 shows the seven IMFs that compose the non monotonic portion of the Porto Corsini tide gauge record. IMF2 and IMF3 capture the semi-annual and annual pe-

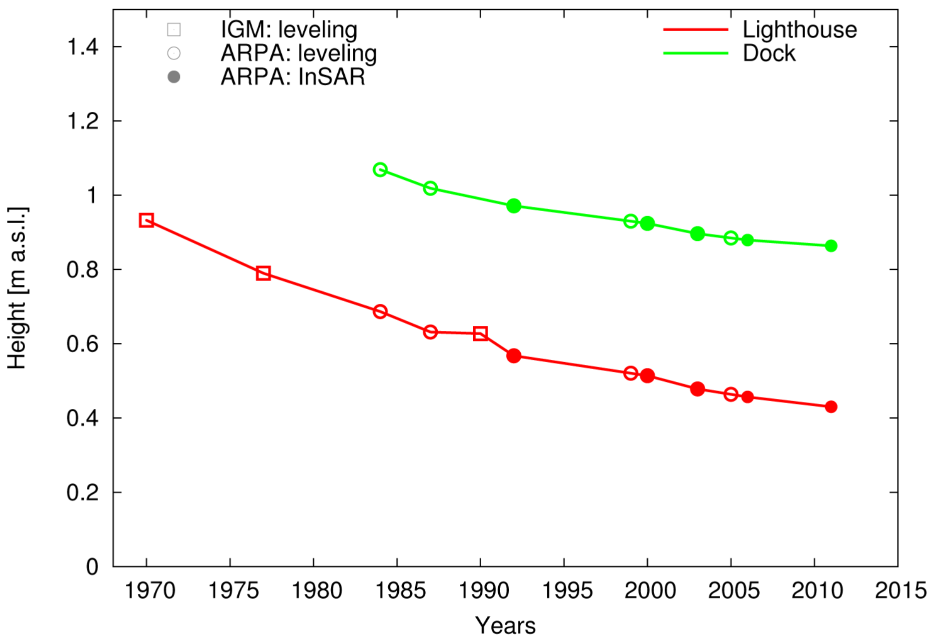

Figure 6. Elevation measurements at the Porto Corsini lighthouse (red) and dock (green) benchmarks at various epochs. The various data sources and sampling methods are denoted by different symbols, as indicated in the legend (see Tables 1 and 2 for details).

riodicities, respectively. IMF4 corresponds to an oscillation at about 1.7 years whereas the IMF5 reveals a period of about 3.6 years; this latter has been detected, adopting a similar approach, on the whole Adriatic Sea scale (see Galassi and Spada [2014]). IMF6 and IMF7 show longer periods, with 8.4 and 14.2 years, respectively. RES represents the non-cyclic residual, revealing the long-term natural trend of the time series [Huang et al. 1998] that remains once all the cyclic components have been sifted. The linear trend of RES since 1970 is 6.8 mm yr^{-1}, somewhat smaller than the one obtained above by the Theil-Sen method.

3.3. Land subsidence at Marina di Ravenna since 1970

To estimate the rate of subsidence in Marina di Ravenna since 1970, we have considered the full dataset from the IGM and ARPAE leveling surveys and the results of the interferometric analysis (see Tables 1 and 2). Values for years 1992, 2000, 2003, 2006 and 2011 have been derived from the three interferometric analyses, by computing the height variation corresponding to the interferometric velocity multiplied by the time difference from the previous or the following leveling datum. This has allowed to compute regression curves and to estimate the rates of subsidence of the ground settlement at the lighthouse and at the tide gauge scatter points located over the dock, separately. The data shown in Figure 6, clearly indicate that the rate of land subsidence at the lighthouse benchmark (v_l) has been significantly larger than the rate at the tide gauge point over the dock (v_d). Indeed, by two linear regressions we obtain

$$v_l = -13.0 \pm 0.7 \text{ mm yr}^{-1} \text{ (1970-2011)} \quad (1)$$

and

$$v_d = -8.3 \pm 0.4 \text{ mm yr}^{-1} \text{ (1984-2011)}, \quad (2)$$

for the two points, respectively. The different rates of subsidence may be explained as a local effect due to the weight of the structures on which the lighthouse and the dock are located, being the embankment lighter compared to the base of the building. The same conclusion can be reached only considering the level surveys data, available for the period 1984-2005, which provide the values $v_l = -10.3 \pm 0.7$ mm yr^{-1}, and $v_d = -8.3 \pm 0.7$ mm yr^{-1}, for the lighthouse and for the dock, respectively. This further motivates the choice of considering separately the rates observed on the dock structure and those observed close to the lighthouse. An acceleration in the rate of land settlement is found at both points, with comparable amplitudes. From a quadratic regression we obtain $a_l = 0.19 \pm 0.03$ mm yr^{-2} for period 1970-2011 and $a_d = 0.18 \pm 0.05$ mm yr^{-2} during 1984-2011.

4. Discussion

A simultaneous evaluation of the sea-level rise and land subsidence in Marina di Ravenna is possible during the time interval 1990-2011. In fact, the elevation of the dock structure was measured for the last time in 2011 and the reference altitude value used by the tide gauge was not recoverable before 1990, when the IGM level of 1990 was adopted. During 1990-2011, the dock structure subsided by 167±2 mm, where this value is derived from the linear regression of the dock time series that indicates a rate of subsidence of 7.6±0.1 mm yr^{-1}. During the same time span, in Marina di Ravenna, relative sea-level rose by 216±29 mm, a value obtained by a linear regression of the annual averaged time series between 1990 and 2013 that provides a rate of change of 9.8±1.3 mm yr^{-1}. On longer time periods, the analysis becomes more problematic, since the land movement is measured only at the Marina di Ravenna lighthouse since 1970 and in the previous years only one estimate across the whole Marina di Ravenna area was available. It is likely that the vertical movement at this site had a dominant role on the observed relative sea level, although the available data do not allow to obtain any quantitative estimate.

Our results firmly indicate that, during the period 1990-2011, local land subsidence was the major responsible for relative sea level rise observed at the site of Porto Corsini. Anthropogenic factors, as water extraction and soil compaction, are known to be the major causes of land subsidence, contributing to the relative sea-level variations observed, as explained in Teatini et al. [2005]. Other possible factors contributing to sea-level change in the Adriatic Sea are worth to be discussed, although their role appears to be less important. The modelled contribution of glacial isostatic adjustment (GIA) to the rate of relative sea-level change at the Porto Corsini tide gauge location only amounts to 0.1 mm yr^{-1}, according to the ICE-6G model (http://www.atmosp.physics.utoronto.ca/~peltier/data.php) [Peltier et al. 2015]. This implies that for the time period 1990-2011, only ~2 mm of the observed relative sea-level change can be attributed to the effects of GIA. The contribution of co-seismic and post-seismic vertical deformation to relative sea-level change at tide gauges has been assessed at global level by Melini et al. [2004] and Melini and Piersanti [2006]. Using data from the Seismic Moment Tensor catalogue, they have clearly shown that earthquakes have cumulatively the tendency to produce a positive sea-level trend of ~ 0.2 mm yr^{-1} at the tide gauges locations. The low level of seismicity along the coasts of the northern Adriatic Sea may suggest that this global value may represent an upper bound for the site of Marina di Ravenna. In addition, in their work on the effects of seismicity on subsidence in foreland basins with an application to the case study of Venice, Carminati et al. [2007] have suggested that accelerations in the rate of subsidence due to co-seismic displacements associated to earthquakes that occurred along active faults around and within the Po Plain are negligible.

According to the "sea-level equation" (see, e.g., Spada [2016]), the rate of absolute sea-level change at the Porto Corsini tide gauge can be estimated by subtracting the rate of subsidence from the rate of relative sea-level change. During the time period 1990-2011, we obtain a trend of 2.2±1.3 mm yr^{-1}. Therefore, despite the large influence of land vertical movement at Marina di Ravenna, the absolute sea-level increase can be recognised combining the rate of subsidence with the tidal record. Since the Porto Corsini tide gauge is not facing the open sea (see Figure 3), a direct comparison with the rate of absolute sea-level change observed by altimetry is not feasible. However, the satellite altimetry trend during 1993-2012 in the northern Adriatic Sea has been close to 3 mm yr^{-1} [Bonaduce et al. 2016], in fair agreement with the value obtained from *in situ* observations at the Porto Corsini tide gauge.

5. Conclusions

The analysis performed in our work has permitted, for the first time, the simultaneous evaluation of the sea-level rise and of land subsidence in Marina di Ravenna, along the North-Adriatic coast of Italy. Although long records exist for both the relative sea-level variations at the Porto Corsini tide gauge (1897-2014) and for the historical land movements in the Marina di Ravenna area (1897-2011), a quantitative analysis has been possible only for the period 1990-2011, due to missing information about tide gauge setup before 1990 and since the last useful data of height measurement dates 2011. We have enlightened the importance of studying land movements at the Porto Corsini tide gauge by relying upon measurements collected on the dock structure above which the tide gauge is located. Indeed, the analysis of the available geodetic data indicates that the reference point at which the tide gauge is usually connected (i.e., the lighthouse) has been subject to a rate of subsidence significantly exceeding that of the dock structure. In the time interval 1990-2011, the land subsided at a rate of 7.6±0.1 mm yr^{-1} while relative sea-level rose at a rate of 9.8±1.3 mm yr^{-1}. Therefore, our study confirms that land subsidence has been the major cause of relative sea-level change at Marina di Ravenna, at least during the period permitting a quantitative comparison (1990-2011) between relative sea level and vertical land motion signals. The residual (rate of relative sea-level change minus rate of land subsidence) of 2.2±1.3 mm yr^{-1} is found to be coherent with the altimetric observations in the northern Adriatic for the rate of change of absolute sea-level during the same time period.

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