

RESEARCH ARTICLE

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Key Points:

- We reconstructed the longest tide gauge record for the eastern Mediterranean Sea
- The merger offers ~75 years of composite and quality-checked tide gauge data in Antalya, Turkey
- Relative mean sea-level rise at Antalya was 2.2 ± 0.5 mm/year (1935–2008) and 6.0 ± 1.5 mm/year (1985–2008)

Supporting Information:

- Supporting Information S1
- Data Set S1

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A New Centennial Sea-Level Record for Antalya, Eastern Mediterranean

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Abstract Quantitative estimates of sea-level rise in the Mediterranean Basin become increasingly accurate thanks to detailed satellite monitoring. However, such measuring campaigns cover several years to decades, while longer-term sea-level records are rare for the Mediterranean. We used a data archeological approach to reanalyze monthly mean sea-level data of the Antalya-I (1935–1977) tide gauge to fill this gap. We checked the accuracy and reliability of these data before merging them with the more recent records of the Antalya-II (1985–2009) tide gauge, accounting for an eight-year hiatus. We obtain a composite time series of monthly and annual mean sea levels spanning some 75 years, providing the longest record for the eastern Mediterranean Basin, and thus an essential tool for studying the region's recent sea-level trends. We estimate a relative mean sea-level rise of 2.2 ± 0.5 mm/year between 1935 and 2008, with an annual variability (expressed here as the standard deviation of the residuals, $\sigma_{\text{residuals}} = 41.4$ mm) above that at the closest tide gauges (e.g., Thessaloniki, Greece, $\sigma_{\text{residuals}} = 29.0$ mm). Relative sea-level rise accelerated to 6.0 ± 1.5 mm/year at Antalya-II; we attribute roughly half of this rate (~ 3.6 mm/year) to tectonic crustal motion and anthropogenic land subsidence. Our study highlights the value of data archeology for recovering and integrating historic tide gauge data for long-term sea-level and climate studies.

Plain Language Summary We demonstrate how data archeology of tide gauge data contributes to completing the contemporary century sea-level record in the eastern Mediterranean Basin. It is important to rescue such data and to make them available for future research on sea-level rise that goes beyond modern and highly accurate satellite-based monitoring. In our particular case, the monthly mean sea-level records of Antalya-I (1935–1977), we merged them with the modern records of Antalya-II (1985–2009) located only ~5 km away. This merger offers a homogeneous composite time series of monthly and annual mean sea level of nearly 75 years, the longest record in the eastern Mediterranean Basin. We reviewed all previous work, metadata, and changes in the zero of tide gauges and datum. Major issues included obtaining the leveling information and to determine rates of tectonic vertical crustal movement. It is worth noting that nearly half of the observed sea-level rise in Antalya-II is driven by local vertical land motion, which might be influenced heavily by anthropogenic sources.

1. Motivation

Sea levels have risen globally by about 1.7 mm/year in the 20th century (Church et al., 2013), which is predicted to accelerate in the 21st century (Haigh et al., 2014). This global rate is subject to global water mass balance due to dams that store water (Fiedler & Conrad, 2010), extracted groundwater (Wada et al., 2012), and melting land ice (Antarctic Ice Sheet, Greenland Ice Sheet, and Glaciers; Jacob et al., 2012) besides the thermosteric expansion (Levitus et al., 2012). Local rates substantially deviate from this global trend (Sallenger et al., 2012) due to, for example, local tectonic effects or anthropogenic subsidence (Zerbini et al., 2017), so it is necessary to obtain robust and reliable data on variations in local and regional sea-level rise (SLR). The Mediterranean Sea is a semiclosed basin, where sea level primarily responds to mass changes from inflowing freshwater (Mariotti et al., 2008; Struglia et al., 2004), evaporation (Bethoux & Gentili, 1999), and the exchange of seawater with the Atlantic Ocean through the Strait of Gibraltar (Calafat et al., 2010, 2012; Fukumori et al., 2007; Pinardi et al., 2014). Sea levels refer to vertical changes in the ocean surface due to steric effects resulting in thermal expansion and density variations (Dangendorf et al., 2014; Levitus et al., 2012; Marcos & Tsimplis, 2007; Tsimplis & Rixen, 2002), which are mostly seasonal (Calafat et al., 2012; Landerer & Volkov, 2013). Large-scale atmospheric modes over the North Atlantic and Europe such

as the North Atlantic Oscillation (NAO) also influence sea level independent on seasons (Gomis et al., 2008; Martínez-Asensio et al., 2014; Tsimplis & Shaw, 2008; Tsimplis et al., 2013). Sea-level time series also need to be corrected for vertical surface displacements due to glacial isostatic adjustment (GIA; Peltier et al., 2015), and volcanic or tectonic uplift or subsidence (Bouin & Wöppelmann, 2010; Santamaría-Gómez et al., 2012; Wahl et al., 2013) to obtain absolute sea-level variations (Yildiz et al., 2013). GIA has a minor effect on geocentric sea levels in the Mediterranean Basin (Peltier, 2002; Spada & Galassi, 2012); the effect diminishes toward the southern and eastern coasts (Stocchi & Spada, 2009; Tsimplis et al., 2011). Thus, GIA models do not fully capture local tectonic motion (Fenoglio-Marc et al., 2012; Teferle et al., 2006), whereas the local vertical land motion (VLM) is driven by volcanic or tectonic activity, and natural or anthropogenic subsidence (Fenoglio-Marc et al., 2004; Zerbini et al., 2017), which dominate relative SLR in the eastern Mediterranean Basin in particular (Garcia et al., 2007). Although data on all these drivers of Mediterranean sea-level change are available, robust sea-level curves spanning multiple decades are rare. Yet reliable sea-level records are important diagnostics of climate change if adequately corrected for nonclimatic contributions (Wöppelmann et al., 2006).

Tide gauges have been the main source of data on local sea levels since the 17th century (Woodworth et al., 2011). However, the scarcity of records covering more than 60 years limits our understanding of how sea level varies in the long-term (Douglas, 2000; Zerbini et al., 2017). Long and reliable time series are available for the coasts of northern Europe (Holgate et al., 2013), and several studies rigorously evaluated historical time series worldwide (Araújo et al., 2013; Gouriou et al., 2013; Marcos et al., 2011; Raicich, 2007; Testut et al., 2010; Woodworth, 1999; Wöppelmann et al., 2006), partly including also coastal archeological data (Anzidei et al., 2011; Kayan, 1988; Lambeck et al., 2004; Toker et al., 2012). Unlike for the rest of Europe, it is difficult to obtain reliable long-term gauging data for the eastern Mediterranean Basin (Woodworth et al., 2009). The only >60-year series for Alexandria, Egypt (1944–2006), is considered unreliable because it does not refer to the Revised Local Reference (Marcos & Tsimplis, 2008), which is an arbitrary local datum used to avoid negative monthly and annual means. Instead this time series refers to the Land Survey Datum (Permanent Service for Mean Sea Level, 2013), a local leveling system that covers all parts of Egypt based on a fixed datum. The lack of reliable long-term tidal records in the eastern Mediterranean emphasizes the need for reconstructing regional sea-level trends using alternative methods.

We contribute to filling this gap by using historic records that we merged with modern measurements. We follow the principles of data archeology (Woodworth et al., 2010), which aims at recovering and systematically compiling predigital information for modern data analysis. Our objective is to recover and merge historical records of the Antalya-I (1935–1977) tide gauge, southwestern Turkey, with those of the nearby newer gauge of Antalya-II (1985–2009) referring to data documentations of the tide gauges and other published works. We hypothesize that both time series can be merged objectively despite an eight-year hiatus and a number of possible incorrect measurements. To test this, we quality-checked the observations, tied them to a common datum, checked their consistency, and compared the composite time series with nearby gauges in the eastern Mediterranean. The resulting sea-level record spans ~75 years (1935–2009) with a gap between 1977 and 1985, and thus offers a new nearly centennial record of contemporary SLR in the eastern Mediterranean.

The paper is structured as follows: First, we present the data set together with a detailed review of previous works and the routine data corrections. Then we describe methods to check the quality of the data, present and discuss our results, before concluding on the novelty of our contribution.

2. Data

We used sea-level data from two stations: Antalya-I (1935–1977) and Antalya-II (1985–2009), both located in the Gulf of Adalya (Figure 1). Station Antalya-I was established by the General Command of Mapping (GCM) during the setup of the Turkish National Vertical Control Network (TUDKA) in June 1935 (Alpar et al., 2012; Gürdal, 1998; Sezen et al., 2012). More information regarding the history of Antalya-I station can be found in the supporting information (Ayhan et al., 1995; Emery et al., 1988). In 1991, the records of Antalya-I were reviewed and digitized by GCM and published in condensed form featuring monthly minimum, maximum, and mean sea-level (MSL) values (General Command of Mapping [GCM], 1991). The second, modern tide gauge Antalya-II is part of the Turkish National Sea Level Monitoring System (TUSELS). Its hourly records

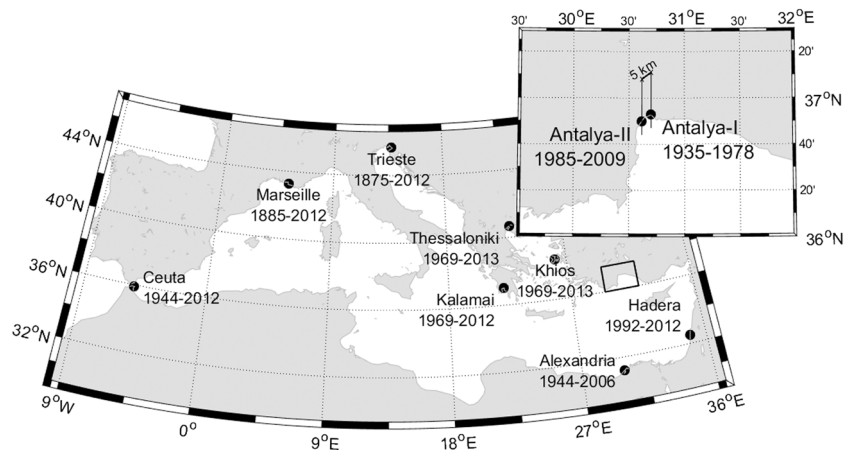


Figure 1. Location of selected tide gauges in the Mediterranean Basin with years of data coverage; we used these stations to cross validate the composite Antalya data that we combined from the Antalya-I (1935–1977) and the Antalya-II (1985–2009) tide gauges in the Gulf of Adalya (inset).

are published annually by GCM, and monthly averages of these records are available at the Permanent Service for Mean Sea Level (PSMSL, www.psmsl.org). The two stations are some 5 km away from each other and within the same bay. The tidal characteristics of the bay are assumed to be homogenous and internally consistent (Sezen & Baybura, 2010). Synthesizing sea-level time series from different locations is rare, and we assumed Antalya-I and Antalya-II to be a single station producing a single time series, following previous work (Marcos et al., 2011).

Various forcing factors of yearly sea-level fluctuations can bias short-term tide gauge records. Hence, Marcos and Tsimplis (2008) used the longest records in subbasins of the Mediterranean Sea as reference stations, namely, Trieste (1875–2012) for the Adriatic Sea, Marseille (1885–2012) for the Western Mediterranean, and Ceuta (1944–2012) at the Strait of Gibraltar for validating other gauges in the respective subbasins (Figures 1 and 4a). Following their work we adopted these time series, as there is no other tide gauge station within the eastern Mediterranean Basin except Alexandria (1944–2006), which is long enough to compare with Antalya. Marcos and Tsimplis (2008) also acknowledged sufficient quality for several short records by checking their consistency with cross correlation and trend comparison with these reference stations. Hence, we compiled ancillary monthly averaged sea-level data from Alexandria (1944–2006), Hadera (1992–2012), Kalamai (1969–2012), Khios (1969–2013), and Thessaloniki (1969–2013) in the eastern Mediterranean Basin (including the Aegean and Ionian Seas) for buddy checking from the archives of PSMSL (Figure 1; Woodworth & Player, 2003).

The PSMSL also provides the contemporary rate of change of relative sea level and crustal uplift at the stations as predicted by a GIA model based on ICE-6G (VM5a; Argus et al., 2014; Peltier et al., 2015). We subtracted the GIA estimates from all the gauge data that are referred in this study. We also obtained monthly mean sea surface pressure (sea-level pressure, SLP) data from the 20th Century Reanalysis V2 to account for inverse barometric effects (Compo et al., 2011). These data are available globally at 2°-grid resolution from 1871 to present, and updated annually. The inverse barometric effect is also removed from all the gauge data that are referred in this study.

2.1. Previous Work and Datum Continuity

The hourly sea-level data of Antalya-I were summarized in paper charts with weekly frequency until 13 October 1955, and daily afterward by GCM. We computed the mean for October 1955 based on weekly measurements between 1 and 13 October and daily measurements between 14 and 31 October. GCM (1991) reported that the gauge was lowered by 1,500 mm with respect to its benchmark on 13 October 1955. Tide gauge zero shifted several times during its period of operation (1935–1977), which was documented minutely by the operating organizations as January and March 1938, October 1955, May 1956, March 1957, and July 1963, and listed together with the raw data referenced to nearby benchmarks (Figure 2a; GCM,

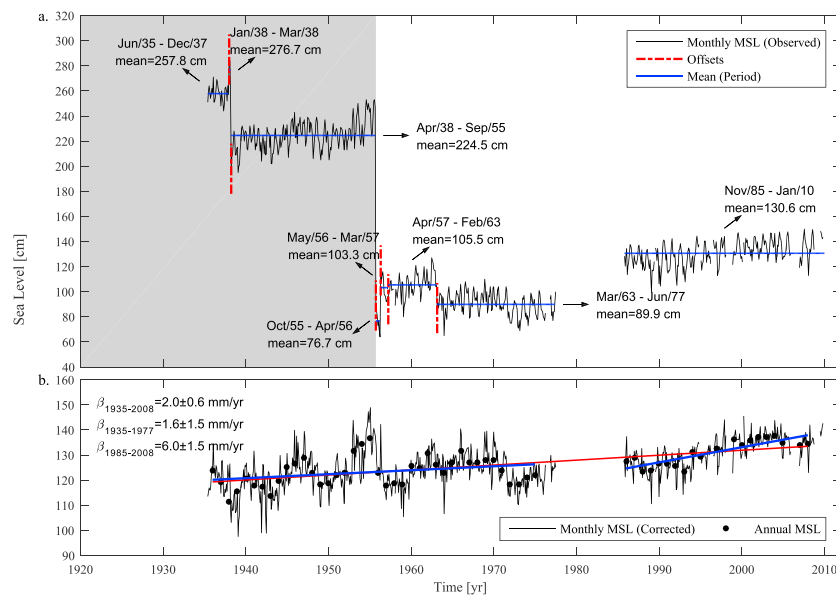


Figure 2. (a). Monthly mean sea level at Antalya (1935–2009) published by the GCM and PSMSL with the means of each period (blue) between reported offsets (red). (b) Composite time series of Antalya (1935–2009) after offsets and datum issues were resolved, inverse barometer effect corrected for, and seasonal cycles removed. The estimated trends are for Antalya-I (blue), Antalya-II (blue), and the entire period (red).

1991; GLOSS, 2006). Sezen (2006) and Sezen and Baybura (2010) used autoregressive models to reconcile the amplitude of these offsets (tide gauge zero) at those dates with the amplitude of the GCM (1991). Besides the shifts in the tide gauge zero, reported corrections were 742 mm between the inside benchmark and the tide gauge zero between October 1935 to October 1973, and 1,226 mm after October 1973, which were corrected by the operating organizations (GCM, 1991).

Several authors investigated surface subsidence at Antalya-II for different periods using different techniques. Yildiz et al. (2013) pointed out that the Global Positioning System (GPS)-derived subsidence rate was -3.6 ± 1.7 mm/year (1994–2009), agreeing with previous estimates of -3.6 ± 0.3 mm/year (1985–2001; Yildiz & Demir, 2002). Using satellite altimetry, vertical crustal deformation is estimated as the difference between measured land and sea surface heights at the tide gauge. Fenoglio-Marc et al. (2004) used this method to derive a surface subsidence of -3.0 ± 1.6 mm/year (1993–2001) at Antalya-II. Yildiz et al. (2013) obtained similar altimetry-derived VLM rates for 1993–2009. These decadal rates of surface subsidence are higher than the longer-term average (Seseogullari et al., 2007), and Anzidei et al. (2011) reconstructed that the mean tectonic subsidence rate of Turkey's southwestern coast between Cnidos and Kekova was -1.5 ± 0.3 mm/year over the past 2,300 years.

Sezen (2006) determined the datum difference between Antalya-I and Antalya-II using high precision leveling surveys based on the latest Turkish National Vertical Control Network (TUDKA) observations in 1999 (TUDKA-99; GCM, 2014). Although we fully adopted Sezen's (2006) work, we believe that the influence of vertical crustal motion between 1977 and 1999 might have been neglected when correcting the datum; at least no correction was documented. Additionally 30 earthquakes with $5.5 < M_S < 6.7$ occurred from 1977 to 1999 at an average depth of 42 km and 70–300 km from the Antalya stations (International Seismological Centre, 2014). We assumed no substantial vertical displacement resulting from these earthquakes, though provide theoretical coseismic displacements with our results. We subtracted the GPS VLM rate -3.6 ± 1.7 mm/year (1994–2009) and the GIA of -0.1 mm from the tide gauge data without any GPS or altimetry records for the period 1977–1985, which sums to -79.2 ± 37.4 mm for 1977–1999. We choose the GPS data starting in 1994 deliberately, considering questionable data quality in the 1980s before the establishment of International Global Navigation Satellite Systems Service (Dow et al., 2009). We thus assume that VLM, resulting from GIA, regional tectonic rates, and long earthquake return periods, remained roughly constant over decades (Bouin & Wöppelmann, 2010). However, this may not apply to local anthropogenic causes. Nonetheless, we cannot

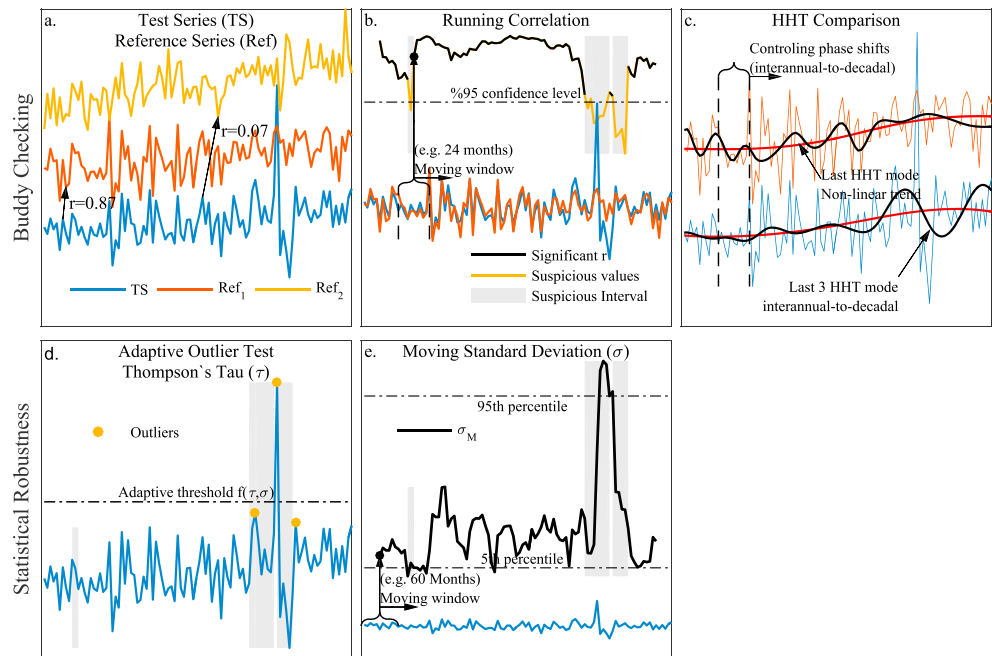


Figure 3. (a–c) Two-step data quality control of the Antalya tide gauge data, involving buddy checking, and (d and e) tests for statistical robustness. (a) Linear cross-correlation coefficient (r) with neighboring quality-checked data to select reference stations (i.e., Ref_1 and Ref_2) for further tests (b and c). (b) Linear cross correlations (r) in a moving window (i.e., 24 months), with monthly increments to localize suspicious intervals. (c) The time series are decomposed empirically following the Hilbert-Huang Transform (HHT) to control the phase shifts of the interannual-to-decadal signal (last three HHT modes) and the nonlinear trends. (d) Adaptive outlier test based on Thompson's Tau; we removed outliers from the data iteratively, resetting the threshold after removing each point (equation (2)). (e) Moving standard deviation σ_M computed within a monthly window for identifying intervals of suspicious observations. See text for explanation.

fully constrain surface subsidence due to plate tectonic motion in our trend calculations, as accurate data are missing for the early period (1935–1985), but we did consider land movements due to GIA in our calculations for all the stations in this study. We routinely removed the estimated GIA trends (linear monthly) that are provided for each station (e.g., $-0.10/12$ mm/month for Antalya-II and $-0.11/12$ mm/month for Alexandria) from the monthly tide gauge time series.

2.2. Routine Corrections

The inverted barometer effect assumes ~ 10 mm of SLR for each mbar drop in local atmospheric pressure. This effect is routinely removed in all sea-level curves using the nearest SLP data to the station referenced to a mean pressure of 1,013.3 mbar (AVISO & PODAAC, 2012). Sea levels are subject to seasonal variations due to natural forcing factors of ocean and atmosphere interactions, such as wind stress, steric changes, water mass changes, hydrostatic effect of the SLP (Marcos & Tsimplis, 2007), and the response of the Earth's crust to surface loads, such as hydrological, atmospheric, and nontidal ocean loadings (Van Dam & Wahr, 1998). Those seasonal effects are routinely removed from the monthly raw data (Dangendorf et al., 2013). We estimated the mean seasonal cycle from the detrended time series by taking monthly means (Pezzulli et al., 2005), thus removing seasonal effects from all the data (Figure 2b).

3. Method

Tide gauge records are prone to errors arising from surface waves and operator bias (Arns et al., 2013). Therefore, we conducted quality checks to detect and identify suspicious values (Figure 3), looking at the Antalya-I data both alone and together with those of Antalya-II. We applied two types of quality tests: (i) buddy checking (Intergovernmental Oceanographic Commission, 2002), that is, comparing the Antalya data with data from neighboring stations (Figures 3a–3c), and (ii) robustness tests (Figures 3d and 3e).

Buddy checking compares the MSL variability between nearby tide gauges to identify data errors (Shennan et al., 2015). PSMSL suggests that the buddy stations should be within 400 km to warrant sufficient similarity in oceanographic and meteorological controls. We had to violate this recommendation, since no station within this distance had long enough measurements. We compared the linear Pearson's correlation coefficients for the entire time series to determine potential reference stations for further tests. We expect low correlation with the selected reference stations owing to their long distances from Antalya in trying to locate changes in the correlation over time to find likely measurement errors. Thus, we computed 24-month running monthly MSL correlations to detect the time intervals of potential outliers in the Antalya data (Figure 3c). Twenty-four months were chosen arbitrarily as a trade-off between temporal resolution and averaging (Soper et al., 1917), thus reducing the size of the suspicious interval. If the correlation coefficient dropped below the 95th significance level (Student's t test) at least three times in an interval, we considered it suspicious in the Antalya-I time series. We also empirically decomposed the time series in oscillatory modes following the Hilbert-Huang Transform (HHT; Barnhart, 2011; Wu & Huang, 2009), which splits the time series into a finite sum of oscillatory modes of different periodicities and a nonoscillatory mode (nonlinear trend). We investigated the interannual-to-decadal variability using the last three HHT modes to check whether sea levels at different locations were in phase (Figure 3b; Ezer & Corlett, 2012).

Buddy checks are good for capturing suspicious intervals, but they do not provide any statistical significance to detect outliers. Thus, we also used Thompson's Tau test to identify potential outliers (Thompson, 1985) by checking each value and determining a zone of rejection (τ , equation (1)) based on the number of data n and Student's t value for a significance level $\alpha = 0.05$ and $n - 2$ degrees of freedom. This method iteratively removes outliers, using new values of t and n , until no further outlier is found (Figure 3d). We also used the running standard deviation σ_M to check the statistical stability of the data (Figure 3e), the change in the standard deviation in time. This standard deviation is based on 60 data points, for which the distribution is approximately Gaussian.

$$\tau = \frac{t \cdot (n - 1)}{\sqrt{n} \cdot \sqrt{n - 2 + t^2}} \quad (1)$$

The closest seismically active regions to Antalya are the Dinar fault zone and the Burdur graben system (Duman et al., 2016). Subduction of the African plate beneath the Anatolian block also provides seismicity at larger depths (>50 km; Figure 8a; Howell et al., 2017). We estimated the possible coseismic displacement in Antalya with EDGRN/EDCMP program (Wang, 2003). This program requires earthquake focal mechanisms to describe the location, orientation, and extent of ruptures that we took from the global centroid moment tensor catalog (Dziewonski et al., 1981; Ekström et al., 2012) for 1976–1996, and from the regional centroid moment tensor catalog (Pondrelli et al., 2002, 2004, 2007, 2011) for 1997–2017. The rupture area is calculated from the magnitude-dependent scaling relation by Strasser et al. (2010). We define interface earthquakes as those with positive rakes and intraslab earthquakes with negative rakes. The slip D on the earthquake rupture surface, the rupture area A , and the shear modulus μ define the seismic moment M_0 (e.g., Stein & Wysession, 2003),

$$M_0 = \mu \cdot A \cdot D \quad (2)$$

where the shear modulus μ is defined as

$$\mu = v_s^2 \cdot \rho \quad (3)$$

where v_s is the shear wave velocity and ρ is the density. We took both from the Earth structural model ak135 for continental crust (Kennett et al., 1995). We refined the parameters of the uppermost layer of the ak135 with velocities and densities from crust 1.0 (Laske et al., 2013) for Antalya to include the effect of local sedimentary rocks (Hall et al., 2014). The calculated slips are in the same range as reported slips for interface and intraslab earthquakes (Shaw & Scholz, 2001). Due to the nodal plane ambiguity of focal mechanisms, we considered both planes as rupture planes and calculated displacements, respectively, and used the mean of both displacements.

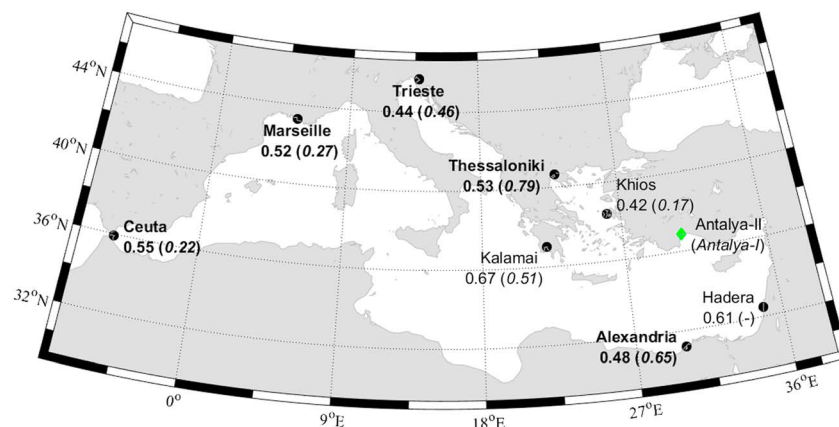


Figure 4. Correlation coefficients r of sea levels at Antalya-I (1935–1977, italic) and Antalya-II (1985–2009) data with other Mediterranean reference stations. We only considered reference stations (bold) for further analysis (Figure 5).

4. Results

We estimated a trend of relative SLR of 1.6 ± 1.5 mm/year (± 2 standard errors) at Antalya-I (1935–1977) after the routine corrections on the data (section 2.2). We estimated relative rates of 6.0 ± 1.5 mm/year at Antalya-II (1985–2008) and 2.0 ± 0.6 mm/year for the composite time series (1935–2008), based on the average GPS rate (-3.6 ± 1.7 mm/year, 1994–2009) of -79.2 mm from 1977 to 1999; if considering the error margins of ± 37.4 mm in GPS rate, the highest (lowest) SLR rate is 2.6 ± 0.6 (1.3 ± 0.6) mm/year. Autocorrelation was taken into account in standard error estimates.

4.1. Buddy Checking

Correlation is highest between Thessaloniki and Antalya-I ($r = 0.79$ in the period 1969–1977), though over a period too short for validating the entire time series. Alexandria ($r = 0.65$, 1944–1977) also correlates with Antalya-I, missing the first six years of operation. Western Mediterranean stations correlate less ($r = 0.25$) with Antalya-I, when compared with Antalya-II ($r = 0.54$). Sea levels at Antalya-II correlate with all potential reference stations ($0.4 < r < 0.7$ with a mean of 0.53; Figure 4). Distant stations such as Marseille have a weak but above 95th confidence level correlation with Antalya-II.

Antalya shows above average SLR trend (2.0 ± 0.6 mm/year, 1936–2008) compared to Trieste (1.4 ± 0.2 mm/year, 1935–2011) and Marseille (1.3 ± 0.3 mm/year, 1935–2011; Figure 5a). Although the larger error is suspicious for Antalya in all the comparisons, the consistent trends of Antalya (3.8 ± 1.2 mm/year) and Thessaloniki (3.7 ± 0.6 mm/year) for the period 1969–2009 indicate that data are more reliable after 1969. We expected to see similar trends at Alexandria (2.0 ± 0.2 mm/year) and Antalya (1.6 ± 0.8 mm/year) for period 1944–2005, but they differ from each other indicating potential errors.

We note large inconsistencies with sea-level trends in the Aegean basin (Marcos & Tsimplis, 2008). We thus excluded the Aegean stations in the trend comparison except for Thessaloniki, given its high correlation with Antalya-I (Figure 4). The differing lengths of records also limit the use of Hadera (1992–2012) for running correlations. We also excluded data from Ceuta (1969–2012), which correlate poorly with Antalya-I. All stations had moderate, but significant correlations ($r \geq 0.40$, 95% confidence interval) except for two different, approximately five-year intervals from the late 1940s to the early 1950s and around 1970 at Antalya-I (Figure 5b).

In our final buddy check we compared the interannual-to-decadal sea-level variability (last three HHT modes; Figure 6). The longest four time series, that is, Trieste (1875–2012), Marseille (1885–2012), Ceuta (1944–2012), and Alexandria (1944–2006), were in phase with Antalya (1935–2009), and so was a shorter record at Thessaloniki (1969–2013), which had the highest correlation with Antalya (Figure 4). This variability had similar patterns and periods of approximately five years (Figure 6), yet the amplitudes are larger for the Antalya-I data (Figure 6). We computed the standard deviation of the residuals of Antalya ($\sigma_{\text{residuals}} = 49.5$ mm) to

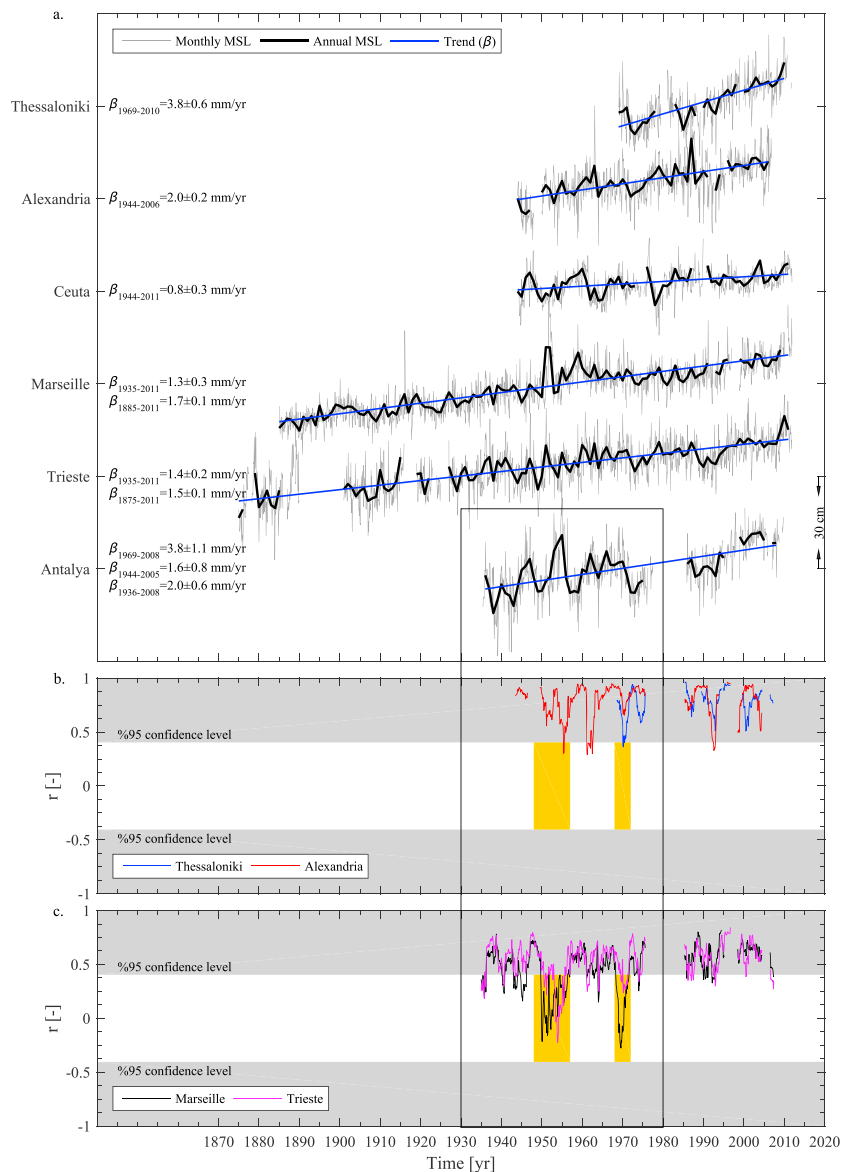


Figure 5. (a) Monthly and annual MSL of Mediterranean tide gauge records and their estimated trends. A second trend is given for Marseille and Trieste to compare them with Antalya; a second trend at Antalya allows comparison with Alexandria. (b) Twenty-four monthly MSL moving correlations of Antalya with the reference time series for the eastern Mediterranean Basin (c: outside the basin). We computed correlations only if both time series had 90% overlapping data. The yellow shaded rectangles show where the correlation drops below the 95% confidence level (gray shaded, Student's t test) in at least three curves. Interval of concern is marked with a black box.

compare with Thessaloniki ($\sigma_{\text{residuals}} = 28.7$ mm). We labeled a peak between 1952 and 1956 as suspicious given that it was strongly out of phase.

4.2. Detecting Outliers

One period of suspicious data at Antalya-I was between 1952 and 1956. The Thompson Tau method identified the annual means from 1953 to 1955 at Antalya and the monthly means of those years' winters as outliers. When ignoring the annual means of those years in the Antalya data, the trend increases by nearly 20% to 2.2 ± 0.5 mm/year (1935–2008; $\beta_{1935-1977} = 1.7 \pm 1.2$ mm/year) and the $\sigma_{\text{residuals}}$ decreases to 41.4 mm. To evaluate the statistical robustness of the data, we calculated the standard deviation of the Antalya time series in 60-month moving windows (Figure 7). Annual fluctuations of this standard deviation have similar trends in

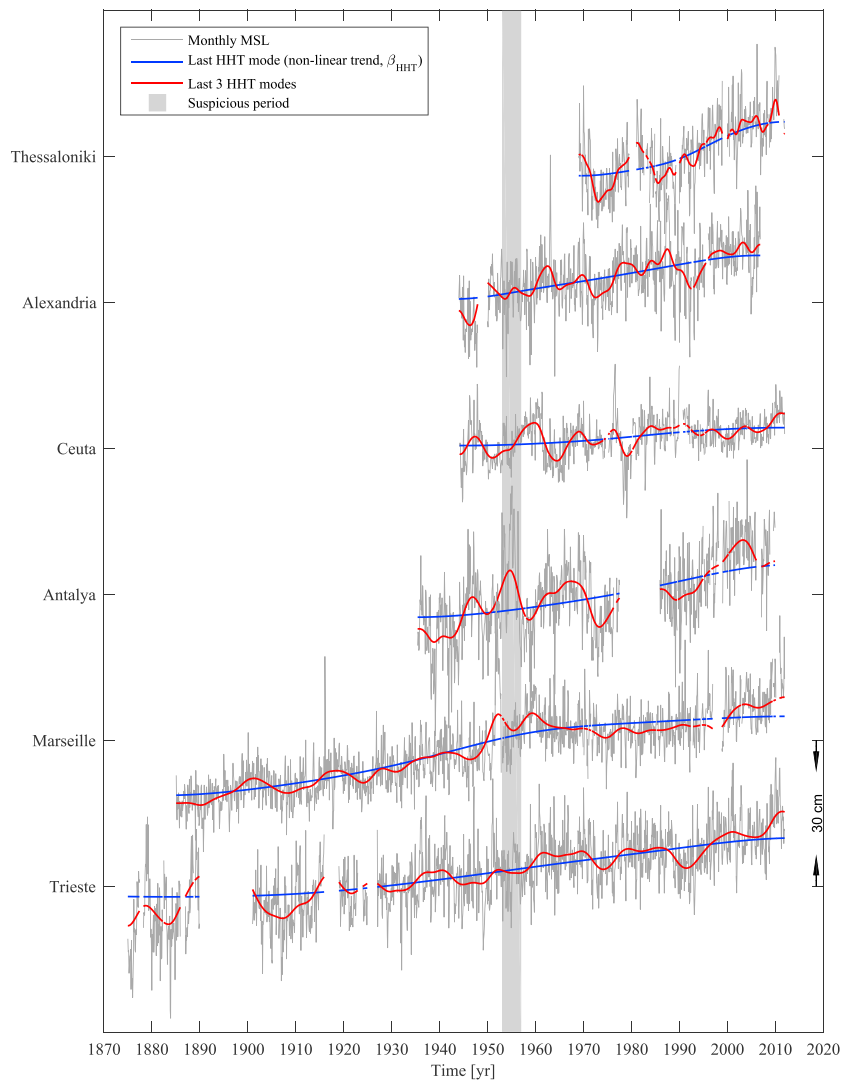


Figure 6. Monthly mean sea level at selected Mediterranean tide gauges with HHT analysis. The observed record is decomposed several modes with the “interannual-to-decadal” (last three) modes (red) and the remaining residual or “nonlinear trend” mode (blue). The shaded gray area marks a suspicious interval in the Antalya data.

the entire Mediterranean Basin. Between 1952 and 1956, however, the Antalya data had the highest spread of all stations considered. The measured sea levels at 1954 were above the 99th percentile and out of phase with the reference stations. A similar extreme value also occurs at Marseille between 1950 and 1954 (above the 99.9th percentile); at Antalya, this increase is rather smooth (Figure 7). Considering this strong contrast to all other sea-level data in the Mediterranean Basin, we do not recommend to use data from 1950 to 1954 for Marseille, and from 1953 to 1955 for Antalya for any further analysis.

4.3. Coseismic Displacement

The cumulative displacements of nearby earthquakes are negligible in Antalya, and the pattern of seismicity (Figure 8) shows that subsequent vertical displacements did not cancel each other out. None of the earthquakes since 1976 caused surface displacements due to their deep hypocenters. However, the distribution of seismicity did not change with time as indicated by the events ($M > 4$) of the ISC catalog (International Seismological Centre, 2014) from 1935 to 1975 (Figure 8a, filled black circles). We observed no coseismic displacement at the Antalya stations between 1935 and 2017.

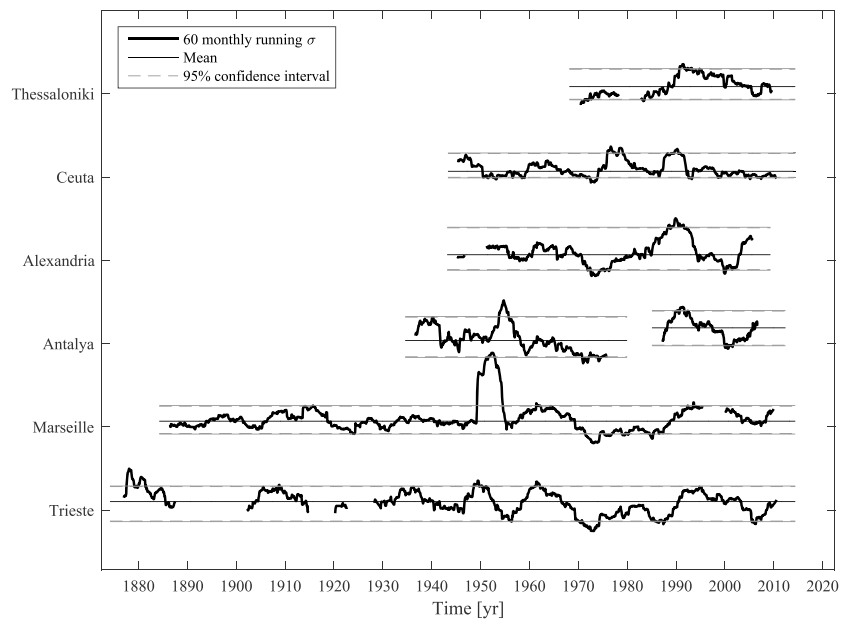


Figure 7. Moving standard deviations σ_M of 60-month moving windows of sea-level data at several Mediterranean tide gauges. Data from Antalya (1935–1978 and 1985–2009) are dealt separately to emphasize the abruptness of the Antalya-I.

5. Discussion

We offer a new composite time series of nearly 75 years of relative sea-level rise in the eastern Mediterranean. We eliminated most natural sources of periodicity (i.e., IB effect, GIA, and seasonality) in this record. Our tests showed that the Antalya time series was generally consistent with only two intervals of questionably high sea levels. We note a low correlation with nearby tide gauges (Figure 5b), and an abnormally high and out of phase interannual-to decadal variability (Figure 6) compared to reference stations around 1950. A similar pattern emerged in the Marseille data (1885–2012) two years earlier (Figure 7), so that we found these extremes reflect local measurement errors. Having checked the robustness of the time series, we found that the measurements of 1953 to 1955 were outliers according to the Thompson's Tau test. The same period was

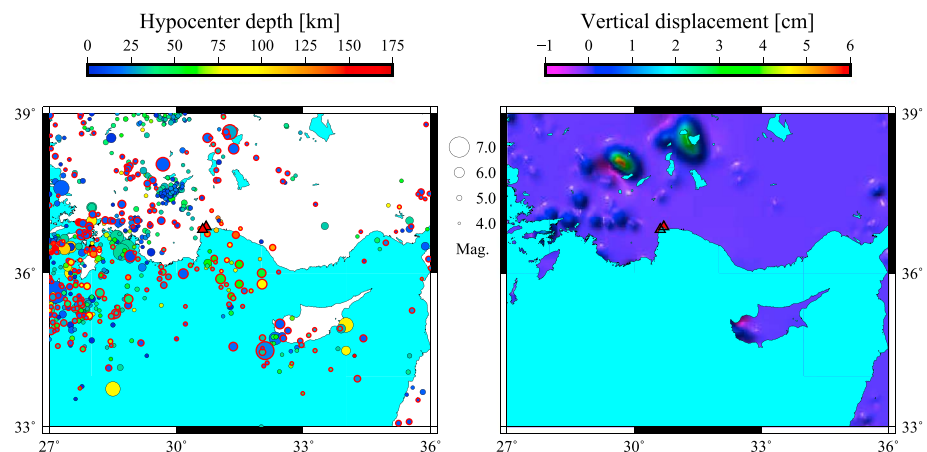


Figure 8. (a) Seismicity in Antalya and adjacent regions. The circles are earthquake locations scaled by magnitude and colored to depth. The black circles are from ISC catalog (1935–1975); the red circles are coseismic displacement for all earthquakes in the global centroid moment tensor/regional centroid moment tensor catalogs, which shows high displacement in the west, and negligible values at the gauge sites.

Table 1
Trend Estimates for Antalya Considering Different Crustal Subsidence Rates to Connect the Antalya-I (1935–1977) and Antalya-II (1985–2008)

Subsidence rates		Total offset	With 1953–1955 annual means	Without 1953–1955 annual means
1977–1985 (8 years)	1985–1999 (14 years)	mm	mm/year	mm/year
–3.6 mm/year GPS	–3.6 mm/year GPS	79.2	2.0 ± 0.6	2.2 ± 0.5
–3.6 mm/year GPS	–2.1 mm/year GPS-MCS	–58.2	1.6 ± 0.6	1.8 ± 0.5
–2.1 mm/year GPS-MCS	–2.1 mm/year GPS-MCS	–46.2	1.3 ± 0.6	1.5 ± 0.5
0	0	no offset	0.5 ± 0.7	0.7 ± 0.6

Note. MCS stands for the millennial crustal subsidence rate by Anzidei et al. (2011).

significantly different from the rest of the time series (above the 99th percentile and out of phase), as far as the moving standard deviation can reveal. Hence, we suggest excluding the annual means of 1953 and 1955 for further analysis. At Marseille the period of 1950 to 1954 was similarly spurious, and possibly faulty (Douglas, 1992). There, high sea levels in the early 1950s (1951–1953) are very similar to peaks at Antalya-I between 1953 and 1955. In the case of Marseille, high values of 1951–1953 were attributed “to bad operation of the instrument” and suggested for exclusion based on rigorous archive investigations (Marcos & Tsimplis, 2008; Wöppelmann et al., 2014); we suspect that something similar might have happened in Antalya-I.

Overall, we estimate an average SLR of 1.6 ± 1.5 mm/year at Antalya-I (1935–1977). The modern trend is much higher (6.0 ± 1.5 mm/year at Antalya-II, 1985–2008), and thus the average of 2.0 ± 0.6 mm/year for the composite data from 1935 to 2008. Ignoring the mean annuals of 1953 to 1955, this trend increases to 2.2 ± 0.5 mm/year from 1935 to 2008, while $\sigma_{\text{residuals}}$ of the monthly data falls to 41.4 mm ($\beta_{1935-1977} = 1.7 \pm 1.2$ mm/year). The trends of Alexandria (2.0 ± 0.2 mm/year) and Antalya (1.9 ± 0.8 mm/year) for the common period (1944–2005) are in good agreement.

Our results are consistent with previously estimates by Marcos and Tsimplis (2008), who observed that in the 1990s, Mediterranean sea levels were rising fastest in the eastern parts of the basin. Our findings also highlight the error margins tied to modern and rapid SLR from short and partly uncorrected records: Alpar (2009) reported a trend of 7.9 ± 1.0 mm/year (1986–2001), whereas Klein and Lichter (2009) proposed a trend as high as 10.6 mm/year (1986–2003) for the Antalya-II data.

The major natural contributor to relative SLR in Antalya is vertical crustal subsidence, similar to the trends recorded at other eastern Mediterranean Basin tide gauges (Ostanciaux et al., 2012). We did not consider the vertical crustal subsidence of -3.6 ± 1.7 mm/year (1994–2009) in our trend estimate for Antalya-II. When including this subsidence, the mean SLR is ~ 2.3 mm/year at Antalya-II, and in the range of other records in the eastern Mediterranean Basin (Figure 5a), though still higher than the climate-related SLR of 1.7 mm/year for the entire basin (Wöppelmann & Marcos, 2012). We used GPS record to connect the Antalya-I and Antalya-II assuming that the deformation rate remained constant between 1978 and 1985 up to their connection time in 1999 that sums to about -79.2 mm. It is questionable whether the GPS rate of $-3.6 + -1.7$ mm/year can be used for longer time scales, given an average millennial crustal subsidence of -1.5 ± 0.3 mm/year nearby (Anzidei et al., 2011). When this millennial rate is included, the relative difference between Antalya-I and Antalya-II would drop to about -2.1 mm/year ($-3.4 + 1.5$), that sums to about -46.2 mm instead of -79.2 . Table 1 presents also trends without any relative difference between the two stations besides these rates. Coseismic displacement apparently does not play an important role at Antalya (Figure 8), although frequent seismicity is a major contributor to the estimated trends in the Aegean basin. Hence, this high GPS rate may largely (~ 2 mm/year) reflect recent anthropogenic drivers, such as land use change, urbanization, and groundwater extraction (e.g., in Italy; Zerbini et al., 2017). Population of the Antalya Province reached ~ 2 million in 2010 from one million in 1990 and 240 thousand in 1935 (TUIK, 2017), and the city developed an infrastructure to host more than one million tourists in 2000.

6. Conclusion

We demonstrate how data archeology of tide gauge data contributes to completing the contemporary century sea-level record in the eastern Mediterranean Basin. It is important to rescue such data and make them

available for research on SLR before the times of satellite based monitoring. We merged monthly MSL records of Antalya-I (1935–1977) provided by the GCM with modern records of Antalya-II (1985–2009) ~5 km away. This merger offers a homogeneous composite time series of monthly and annual MSL of nearly 75 years, the longest record in the eastern Mediterranean Basin. Major issues arose from obtaining the leveling information and to determine rates of tectonic vertical crustal movement. We find that nearly half of the observed SLR in Antalya-II is driven by local VLM, likely dominated by human activity. The only available correction for tectonic motion comes from geological studies suggesting a millennial subsidence rate of -1.5 ± 0.3 mm/year (Anzidei et al., 2011), as detailed GPS coverage began in the mid-1980s. The final record is consistent with regional and global data, though collected over shorter periods. We estimate a relative SLR of 2.2 ± 0.5 mm/year (1935–2008), or about 1 mm/year if correcting for tectonic subsidence. Our estimate is in the range of a recent global estimate of about 1.2 ± 0.2 mm/year (Hay et al., 2015), which considers mainly high-latitude tide gauges (Hamlington & Thompson, 2015). We point out that there are some other historic sea-level records in the eastern Mediterranean Basin, which are still not available to the scientific community (e.g., Karsiyaka, Turkey). These observations should also be investigated and validated to contribute to sea-level research in the region. Any effort in this respect will be highly appreciated by those concerned with using SLR as a proxy of regional and global environmental change.

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