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Mazara del Vallo Tide Gauge Observations (1906–16): Land Subsidence or Sea Level Rise?

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ABSTRACT

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Tide gauge (TG) data constitute an invaluable tool for the interpretation of short- and long-term sea-level changes occurring in the Mediterranean Sea. The complex geophysical environment and the limited amount of sufficiently long records make the interpretation of local signals problematic because these are often affected by interlacing processes. Starting from newly disclosed TG records from the site of Mazara del Vallo (SW Sicily), we analyze simultaneously the time series available from other locations in Sicily across the beginning of the 20th century (Messina and Palermo). Despite the limited record length, we show that these observations provide new perspectives on the causes of the observed sea-level variations in the central Mediterranean region, and, in particular, they challenge previous tenets regarding the extent of land movements caused by the 1908 Messina Straits earthquake.

ADDITIONAL INDEX WORDS: *great Messina earthquake, climate change, postseismic deformations*.

INTRODUCTION

Tide gauge (TG) time series provide particular insights into a broad range of geophysical phenomena (*e.g*. local tide measurements, regional water circulation, tsunami recording, and postglacial rebound). Originally deployed for assisting navigation into and out of the harbors, TGs are currently useful for studying ocean circulation and its anomalies (Woodworth *et al*., 2002). On the secular time scale, TG observations are also used to detect footprints of ocean mass variations associated with climate changes (*e.g*. Mitrovica *et al*., 2001). Because the TGs record the local offset of the sea-surface elevation relative to the Earth's surface, they do not provide absolute sea-level variations. It is well known that relative sea-level observations are corrupted by various processes that span a broad range of time scales (*e.g*. Spada and Galassi, 2012). These include atmospheric pressure variations, decadal oscillations (Sturges and Hong, 2001), long-term glacial isostatic movements, and local site modifications. The latter can result from slow subsidence of the pier or instrumental drift but can also be the consequence of abrupt tectonic movements. First recognized by Omori (1913), large earthquakes occurring near the TG can induce permanent coseismic deformations and slow postseismic effects. The first stems from the direct consequence of the slip on the fault during the earthquake occurrence (see Okada, 1985 and references therein), while the second takes place after the earthquake; it is driven by the change in stress distribution in the vicinity of the fault and by mantle relaxation (Antonioli, Piersanti, and Spada, 1998; Piersanti *et al.,* 1995). Observations are rare but significant. Besides the 1908 Messina earthquake, evidence for coseismic and postseismic movements recorded at TGs has been reported for the 1964 Alaska earthquake (Brown *et al*., 1977; Larsen *et al*., 2003) and for the 1995 Jalisco (Mexico) earthquake (Melbourne *et al*., 1997).

This work focuses on the analysis of the sea-level record from the Mazara del Vallo TG (SE Sicily, henceforth abbreviated as MV, Figure 1). At the end of the 19th century, the Regia Marina Italiana deployed a Richard-type TG instrument at the harbor of the town of Mazara del Vallo, and this was operational until the end of 1916. Platania (1911) mentioned this installation, and a partial record (1909–16) is currently held at the Permanent Service for the Mean Sea Level (PSMSL; Woodworth and Player, 2003) in the form of unrevised ("metric") monthly data. As far as we know, the MV time series has not been used in geophysical investigations until the present. Additional monthly averaged sea-level observations (which also include daily minimum and maximum values) were transcribed from copies of the original logbook of the MV observatory and provided to the authors by the Istituto Geografico Militare (IGM). The resulting complete MV time series, reproduced in Figure 2, includes the period from January 1906 to October 1916.

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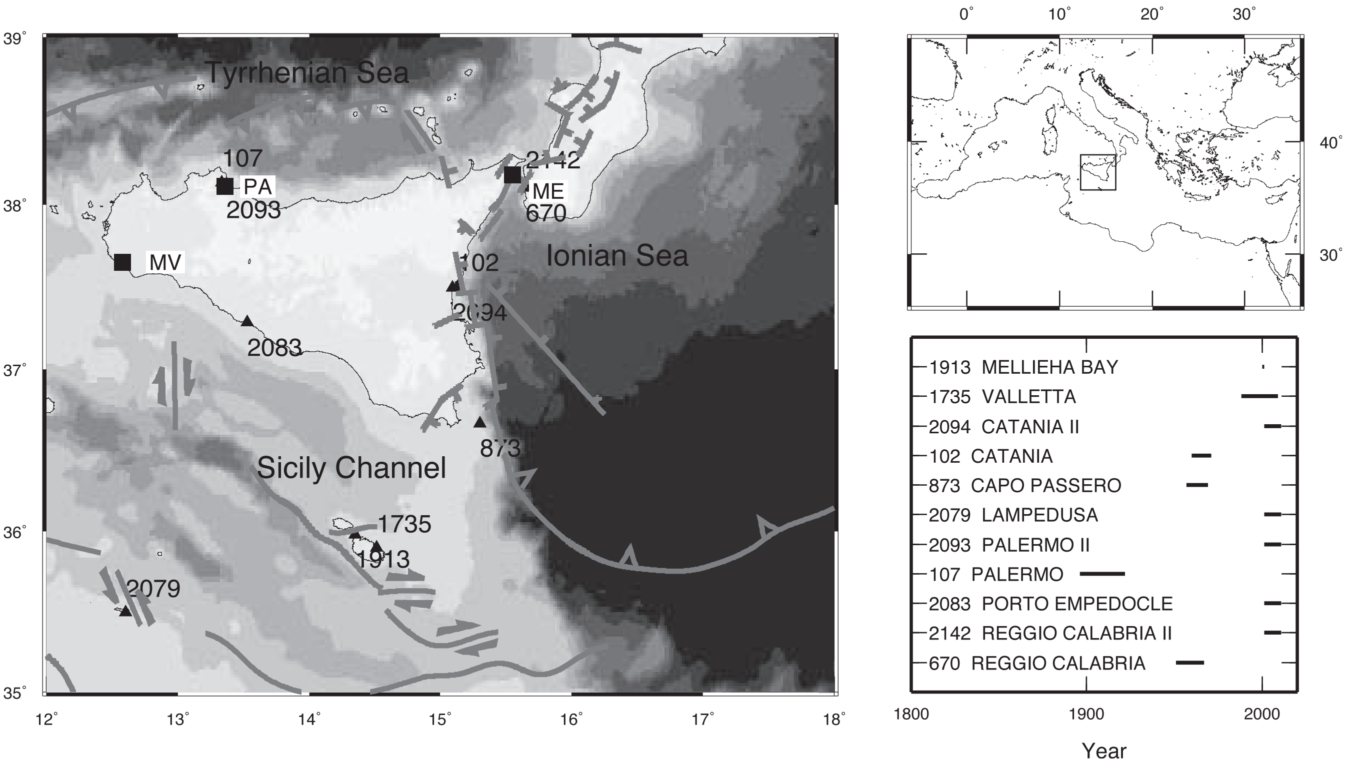

Figure 1. Summary of the available revised local reference (RLR) PSMSL sites and time series for TGs in Sicily since 1900. Left: map showing sites (black triangles) and PSMSL IDs. The grayscale color table shows the topography and the bathymetry of the region; gray lines are the most relevant faults from the Geodynamic Map of the Mediterranean (Barrier *et al*., 2005). Top right: map of Mediterranean Sea, where the box shows the region displayed in the left panel. Bottom right: data availability for TGs sited in Sicily and southern islands. The Messina and Mazara del Vallo TGs do not appear here because they do not belong to the RLR record. Labels MV, ME, and PA indicate the Mazara del Vallo, Messina, and Palermo TGs considered in this work.

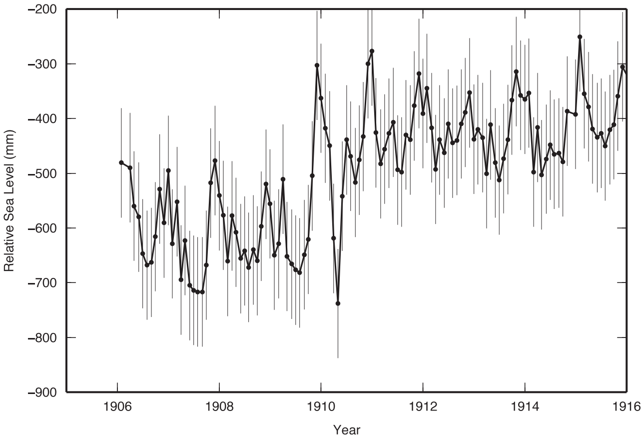

Figure 2. Monthly mean sea-level observations for the TG of Mazara del Vallo, southern Sicily, obtained from transcription of the original record held at the IGM. Error bars, in gray, represent the standard deviation of the average as discussed in the Results section.

In view of the geographical location of the TG and of the particular observation period, the MV record could potentially provide new insight into the sea-level changes along the coasts of Sicily and the Central Mediterranean Sea for an epoch between the late 19th century and early 20th century, in which relevant changes in the global sea-level trend have been observed (Church and White, 2006). The MV observations could also shed new light on the possible long-term effects of the 28 December 1908 Messina Straits earthquake (body-wave magnitude M_w 7.1), which occurred 270 km ENE of MV. The 1908 Messina earthquake was extensively investigated by several authors (see De Natale and Pingue, 1991; Pino *et al*., 2009 and references therein).

GEODYNAMICAL AND OCEANOGRAPHICAL CONTEXTS

Sicily, the triangle-shaped, largest island in the Mediterranean Sea, is bordered by the Ionian Sea to the E, by the Tyrrhenian Sea to the N, and by the Strait of Sicily to the SW (Figure 1). In the context of the continental collision between the Eurasian and the African plates, Sicily is the orogenic segment that joins the African Maghrebides with the Calabrian Arc and southern Apennines. Sicily can be divided into two domains: foreland and orogenic. The first domain includes the SW portion of the island and the Ionian basin, while the second domain encompasses most of the island and the main tectonic belts. The latter is bordered to the north by the Tyrrhenian Sea, and it belongs to the hinterland domain that also includes the Sardinia block (Finetti, 2005). Mount Etna, the largest active volcano in Europe, is located north of the town of Catania (Sicily).

The tectonic setting of the region is somewhat complex. The moment tensor catalog, which provides fault models for moderate and large earthquakes from 1977 to present (Pondrelli *et al*., 2002), shows a consistent NS compressional regime in the S part of the Tyrrhenian Sea with diffuse moderate seismicity, while seismicity is rare inland. Global positioning system (GPS) observations (Devoti *et al*., 2010, 2011) confirm the shortening of the NW side of Sicily, which also shows evidence of uplift (~1.2 mm/y) in contrast with the subsidence of the SE side connected to the Ibleo-Maltese plateau (–0.2 mm/y). Two major earthquakes hit the region in the last century. The aforementioned 1908 earthquake (M_w 7.1), characterized by a normal fault mechanism, was located offshore the town of Messina (ME in Figure 1). The most significant local effect, evidenced by inversion of leveling data (Capuano *et al*., 1988), was a permanent maximum subsidence of 70 cm, which generated a destructive tsunami that struck the coasts of Sicily and Calabria (Pino *et al*., 2009). In 1968, the Belice thrust earthquake (M_w 6.1) hit the W side of inland Sicily with an epicenter 45 km SW of Palermo (PA).

From an oceanographic viewpoint, the sea-level variability in the Mediterranean is strongly influenced by the state of the North Atlantic Oscillation, which affects the evaporation-precipitation balance (Tsimplis, 2001), while tidal motion is mainly an effect of local forces. The Atlantic tide effect could only account for 10% of the tidal motions in the Mediterranean basin (Candela, Winant, and Ruiz, 1990). In the last decades, steric sea-level changes, resulting from cooling and warming of shallow waters, have contributed significantly to the total sea-level rise (Marcos and Tsimplis, 2007; Tsimplis, 2002). The different driving mechanisms of sea-level change characterizing the Atlantic and the Mediterranean Sea have been examined by Marcos and Tsimplis (2007). From 1960–2000, the trends observed in the two regions were markedly different, with the Mediterranean trends dominated by the atmospherically forced component of sea-level change and a prominent role of glacial isostatic readjustment in the NW Atlantic. Sicily stands at the junction of the Tyrrhenian, the Ionian Sea, and the Sicily Channel. These subsystems are characterized by different behaviors both in terms of steric response and of the large-scale water circulation (Carillo *et al*., 2012; Millot, 1999; Pinardi *et al*., 1997). The observation that the three sides of the Sicilian coastlines can indeed experience different annual and decadal variations of sea level (Carillo *et al*., 2012) and that, given the complexity of the water circulation in the Mediterranean (Pinardi *et al*., 1997), large-scale or global phenomena can affect the different sides in different epochs are crucial for this work. These phenomena can indeed originate in specific regions and can be revealed by thorough examination of the TG signals. This is manifest, for instance, in the Adriatic Sea, where geographically coherent, sudden, local sea-level changes were observed from 1960–2000 (Tsimplis *et al*., 2012).

In view of the complex entanglement of geodynamical and oceanographical processes described previously, a full understanding of the sparse TG time series available for Sicily and the surrounding regions could hardly be obtained. We will address, however, that the new sea-level observations from the MV TG effectively allow valuable insight into the southern Mediterranean geophysical context. Furthermore, it unexpectedly discloses new aspects that are challenging traditional views regarding the spatial extent of the permanent effects of the Messina earthquake on the Sicilian TGs. This work aims to provide a comprehensive discussion of the problem.

RESULTS

The time series for most of the TGs deployed in Italy in the past (left frame of Figure 1) are neither continuous nor characterized by remarkably long observation periods when compared to records from other regions of the world (see, *e.g*. Spada and Galassi, 2012). Some of the Italian time series recently included in the revised local reference (RLR) PSMSL dataset, however, have been operating during overlapping periods and provide a satisfactory geographical coverage for Sicily and Malta. Figure 3 shows the monthly mean sea-level variations from five TGs in the region simultaneously operational from 2001–10. Three of them (Catania II, Palermo II, and Porto Empedocle) are located in Sicily, on the E, N, and SW sides, respectively; the others are relative to La Valletta (island of Malta) and to the island of Lampedusa, which is located in the middle of the Sicily Channel (see also Figure 1). The time series clearly show a temporal coherence in frequency and amplitude. From visual inspection, none of them exhibits anomalies in their trends or features that could suggest local ground subsidence or sudden variations in the rate of absolute sea-level variation (a possible exception is observed for Lampedusa for year ~2006, where anomalously large short-term fluctuations are detected).

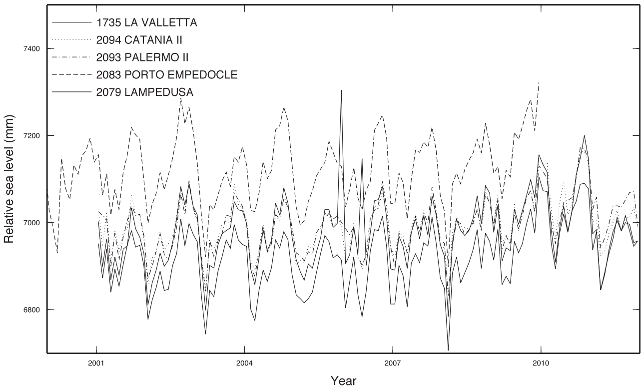

Figure 3. Time series (RLR PSMSL data) from 2000–10 for TGs in Sicily (Catania II, Palermo II, and Porto Empedocle) and for Lampedusa and La Valletta (Malta). Corresponding PSMSL IDs are marked on the map in Figure 1.

Figure 3 strongly suggests that, at least from 2001–10, Sicily and its surroundings have been subject to spatially coherent sea-level variations, unaltered by local anomalies related to land movements. This, however, was not the case at the beginning of the 20th century when only three TGs were operating in Sicily: ME, PA, and MV. Monthly records from these TGs are shown in Figure 4. The 1908 Messina earthquake, whose occurrence is marked by a vertical dashed segment in Figure 4, induced a ~57 cm relative local offset that was recorded at the TG of Messina earthquake, which also shows a slowly varying relative sea-level rise during the years that followed the main shock. Because this is not observed at the TG of PA, located ~190 km W of Messina and commonly used as a reference, this delayed response has been interpreted as the effect of postseismic relaxation in response to the main shock (Antonioli *et al.,* 2009; Braitenberg *et al.,* 2011). The jump and the following trend observed at ME matches the observations for the TG of Kodiak at the time of the big 1964 Alaska earthquake (see Figure 5 of Larsen *et al.*, 2003). Further sources of information are the two TGs of Oran (Algeria) and La Goulette (Tunisia), for which annual mean sea-level data for the same epoch (from the end of 19th century to the beginning of the 20th century) are available from the PSMSL repository of ancillary data. The corresponding time series, which are not reproduced here, show no evidence of trend variations at the time of the Messina earthquake; however, the coarse annual sampling and the poor quality of ancillary data could well prevent the detection of small coseismic signals.

Figure 4 shows that the MV time series is consistent with the PA and ME records for the time interval January 1906–December 1908 that precedes the 1908 Messina earthquake, although the record is not long enough to allow for a more quantitative comparison. From January 1909, an upward trend can be recognized in MV, coherent with the one observed at ME after the abrupt coseismic offset immediately following the earthquake. To provide a quantitative estimate of the error associated with monthly mean sea-level data for MV TG, the variance of the monthly average from daily minimum and maximum observations was computed for some months. The standard deviation of the mean was found to be about 100 mm, which is taken as an estimate of the uncertainty of the monthly mean for all the three time series. We then analyzed the TGs time series by using a bootstrap procedure (Horowitz, Härdle, and Kreiss, 2003) to account for normally distributed errors when estimating the best fitting linear ($y = a + bx$) or bilinear relation. The bilinear regression was preceded by the search for the most significant change point performing a statistical Chow test for each point in the time series (Chow, 1960; Hansen, 2001). A Fisher F-test was then applied to evaluate the significance of the resulting best fit.

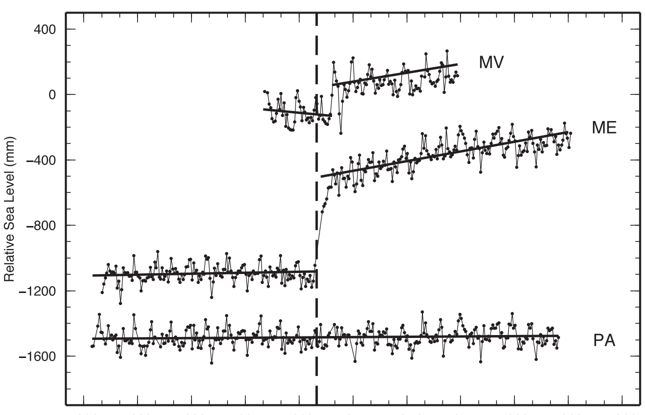

Figure 4. Time series of the monthly sea level as observed at Mazara del Vallo (MV), Messina (ME), and Palermo (PA). MV and PA data are shifted to better visualize the details of the time series. To be consistent with the tradition of sea-level data representation, time series are displayed as broken lines even though they represent single monthly observations. The vertical dashed line marks the date of occurrence of the 28 December 1908 Messina earthquake.

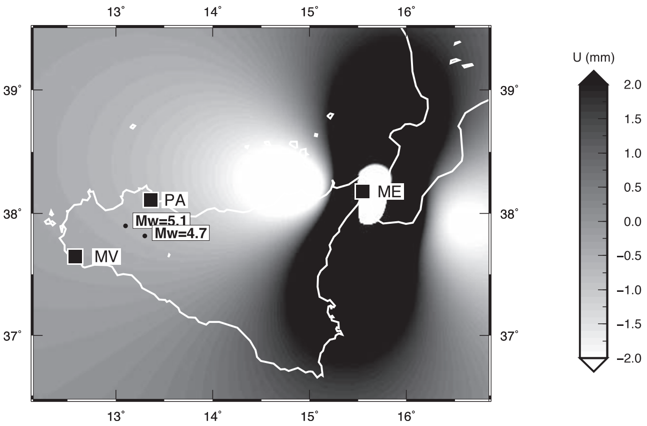

Figure 5. Postseismic vertical displacement induced by the 28 December 1908 Messina earthquake according to the solution by Amoruso, Crescentini, and Scarpa (2002), assuming a 0.9 m uniform slip on the fault plane. Displacement is grayscale color-coded in mm according to the grayscale color table shown on the right and superimposed to the map of the region, where black squares represent the locations of the ME, PA, and MV TGs. The two black circles represent the only two $M > 4.5$ earthquakes that occurred in the vicinity of MV during 1908–09, according to the CPTI11 catalogue (Rovida *et al.*, 2011).

As discussed by previous authors (see, *e.g.* Antonioli *et al.*, 2009), the ME time series shows a clear break point at the beginning of 1909 (mean values for January and February 1909 are, however, missing because of a failure of the TG system) when, according to our estimates, the best-fitting linear regression coefficient b jumps from 2.1 ± 2.0 mm/y before 1909 to 19.9 ± 2.0 mm/y after 1909. The same analysis for MV time series evidences a change point around October 1909 when the regression coefficient of the best fitting linear relation rises from $b = -10 \pm 14$ mm/y to 10.7 ± 5.0 mm/y. On the contrary, the PA TG time series does not evidence any significant change point, and the best-fitting model is a straight line with regression coefficient $b = 0.7 \pm 0.8$ mm/y.

The results of the regression analysis are summarized in Table 1 and shown in Figure 4. For the cases of the ME and the MV TGs, the poorly constrained regression coefficients before

Table 1. *Results for bilinear and linear regressions according to the methodology described in the text. The PA TG time series does not evidence the presence of a significant change point, and the reported regression coefficient is valid for the entire time series. The Messina earthquake occurred on 28 December 1908.*

Site	b coefficient (mm/y) before the CP	Ranges for the epoch of the change point (CP)	b coefficient (mm/y) after the CP
ME (Messina)	2.1 ± 2.0	December 1908–March 1909	19.9 ± 2.0
MV (Mazara del Vallo)	−10 ± 14	September 1909–October 1909	10.7 ± 5.0
PA (Palermo)	0.7 ± 0.8		

the occurrence of the change can be interpreted as the result of the short duration of the record and of the dominance of decadal oscillations.

DISCUSSION

The TG record observed in ME after the 1908 earthquake is usually interpreted as the effect of delayed postseismic relaxation (see, *e.g.* Antonioli *et al.*, 2009). It is well established that the relatively short time scale of relaxation that characterizes the postseismic deformations observed after large earthquakes (a few years) could be attributed to the response of low-viscosity layers in the crust or in the shallow upper mantle (see, *e.g.* Nostro *et al.*, 1999 and references therein). Indeed, the traditional interpretation is supported by inverse modeling efforts, indicating that the postseismic record observed in ME could be satisfactorily explained invoking viscosity values comparable to those inferred in other tectonic contexts (D. Melini, 2012, *personal communication*).

To assess the spatial pattern and the amplitude of the coseismic deformations across Sicily and the southern Mediterranean as a consequence of the Messina 1908 earthquake, we ran a standard model of coseismic deformation that assumes a homogeneous Earth in flat geometry and neglects gravitational effects (Okada, 1985; source parameters are from Amoruso, Crescentini, and Scarpa, 2002). The results for vertical displacement U, shown in Figure 5, show that a negligible vertical uplift (<1 mm) is predicted at the far-field PA TG. Indeed, the lack of any apparent elastic jump in the time series of PA at the epoch of the Messina earthquake has been put forward as a confirmation of the coseismic origin of the signal observed in ME (Antonioli *et al.*, 2009). According to Figure 5, the coseismic vertical displacements expected at the MV TG are small and comparable to those predicted for PA.

At first glance, the similar responses shown by the ME and MV TGs after the Messina earthquake (see Figure 4) could be interpreted as indicative of postseismic land uplift at MV. (We exclude that they were caused by an almost coincidental systematic drift of the two instruments in use: a "Mareografo Mati" in ME and a "Mareografo Richard" in MV.) If the MV observations are trusted, however, a seismic origin is hardly tenable. First, as shown in Table 1, application of the Chow test shows that MV response delays that of ME by ~6 months (this is also appreciated by visual inspection of the time series), which could not be easily explained in the context of the postseismic relaxation modeling. Second, because of the relatively short distance between PA and MV, both located in the far field of the Messina earthquake source, similar postseismic deformations should be expected in these two places (this is suggested by our elastic estimates in Figure 5 and is clearly proposed by more realistic, rheologically layered models; see Nostro *et al.*, 1999). Crustal or mantle rheological heterogeneity, which are generally not taken into account in postseismic rebound models, could justify, in principle, different responses for MV and PA. In this respect, lateral crustal heterogeneities below the Etna volcano are possible candidates; however, GPS observations for 2000–10 do not show evidence for a tectonic decoupling between MV and PA (Serpelloni *et al.*, 2007). Finally, no other significant earthquake occurred near MV that could justify the anomalous signal observed in MV in terms of coseismic displacement or its similarity with the one seen in ME. In fact, for 1909, the Catalogo Parametrico dei Terremoti Italiani 11 (CPTI11) of Rovida *et al.* (2011) reports only two moderate events in the study area with magnitudes M_w 5.1 and M_w 4.5, respectively (Figure 1).

As previously discussed, TGs record the time-dependent offset of the sea surface relative to the Earth's crust. Given that the change point and trend observed for the MV TG time series could hardly be explained in terms of coseismic or postseismic ground deformation, one possibility is that these signals are dominated by sea-surface variations occurring during a period that includes the Messina earthquake. Various authors have proposed, primarily based on qualitative analyses, that modern sea-level rise could correspond to the onset of the Industrial Revolution between the end of 18th and the middle of 19th century (see Spada and Galassi, 2012 and references therein). Long and complete TG records such as those of Brest (NE Atlantic Coast, France) and San Francisco (NE Pacific Coast, U.S.A.) support this view, but others do not. In particular, no similar sharp variations can be visually detected in the PA record (Figure 4) or apparently in records from other TGs facing the Tyrrhenian Sea, including Marseille (France) and Genova (Italy) (see Figures 3 and 4 of Spada and Galassi, 2012). Hence, if the "anomalous" record shown by MV and ME at the beginning of the century is indeed a manifestation of the inception of modern sea-level rise, this would point to a specific sensitivity, particularly of instruments facing only the southern Mediterranean Sea. This hypothesis is supported by previous studies, which have enlightened the regional and temporal variability of sea level in response to different forcing sources (*e.g.* Tsimplis, 2002).

CONCLUSIONS

The unveiling of new sea-level records from the site of Mazara del Vallo (MV) from 1906–16 provides clues about the sea-level change in the Mediterranean Sea and possible regional land movements in response to the large 1908 Messina earthquake. The MV time series indicates the existence of a change point (*i.e.* a variation of the regression coefficient of the best-fitting line) occurring between September and October 1909. After the change point, the observed regression coefficient is found to be approximately half of the one observed in ME, which shows a change point in early 1909. The latter was commonly interpreted as an effect of the postseismic relaxation; however, standard models for postseismic deformation cannot explain, in terms of land subsidence, the signal observed at MV and, at the same time, the lack of a comparable signal at the nearby site of PA.

Based on the arguments given in this work, our preferred interpretation is that land movements at the time of the Messina earthquake have not affected the MV TG time series significantly, and that the observed change point results from an ocean signal. This would suggest that the trend observed at the ME TG in the years following the 1908 earthquake has its origin not only in postseismic land movements, but that it could also result from a response to climatic variations affecting both MV and ME. This hypothesis could have different realistic interpretations: the inception of the global sea level acceleration (Church and White, 2006) that appears to be not simultaneous world wide; local sporadic acceleration, as for the case of the Adriatic Sea reported by Tsimplis *et al*. (2012); an effect of the complexity of the sea-water circulation in the Mediterranean, as described by Pinardi and Masetti (2000).

The quantity and the quality of the available observations do not suffice to fully clarify the origin of the signals detected in MV and ME; however, this study has shown that the importance of these records in the geophysical contexts of the southern Mediterranean Sea is possibly greater than previously thought. In this framework, the analysis of historical records from the Malta TG would be crucial. Even though analog records exist (the charts are preserved in the archive of the United Kingdom Hydrographic Office [UKHO] in Taunton), they are still waiting for quality assessment and digitalization (Christopher Jones, 2012, *personal communication*).

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