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A. Vecchio, M. Anzidei, V. Capparelli, V. Carbone and I. Guerra

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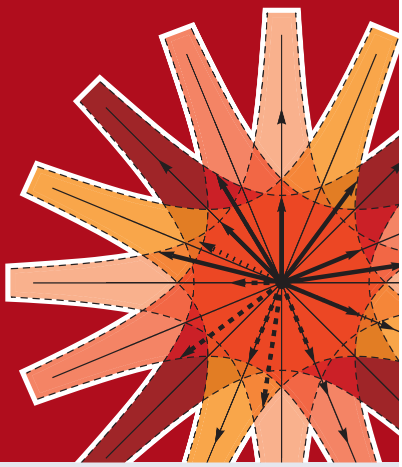

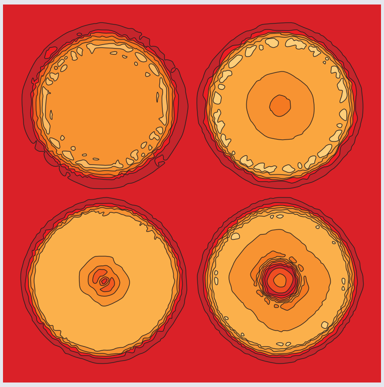

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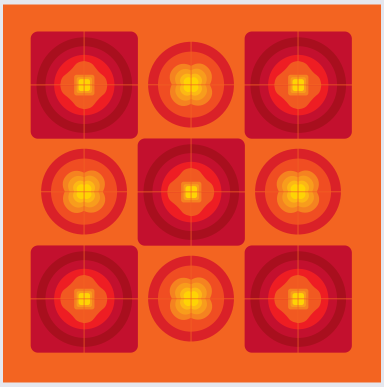

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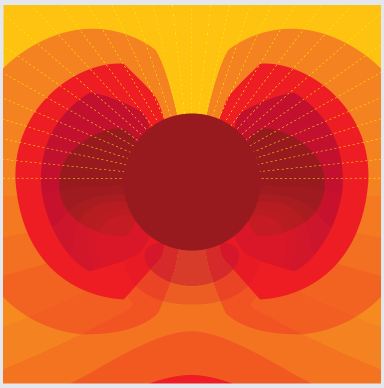

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# Has the Mediterranean Sea felt the March 11th, 2011, Mw 9.0 Tohoku-Oki earthquake?

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**Abstract** – The possibility that the tsunami, generated as a consequence of the large Mw 9.0 Tohoku-Oki earthquake of March 11th 2011, could be recorded by the tide gauge stations located in the Mediterranean Sea has been investigated. We find two kinds of transient signatures which should be attributed to the far-field destabilizing effect of the tsunami on the usual tidal components: 1) the excitation of a broad spectrum of frequency fluctuations, superimposed to the diurnal and semidiurnal tidal components, 2) the change of amplitude of the low-frequency tidal components in the Mediterranean, related to the sea surface fluctuation perhaps caused by the direct transmission of the tsunami across Gibraltar.



**Introduction.** – On March 11, 2011 at 05:46:23 UTC the NE coast of Honshu island (Japan) was struck by one of the largest earthquakes ever occurred in the world since historical times. The Mw 9.0 event released the tectonic stress accumulated over the last 700 years [1] and triggered a giant tsunami that caused an estimated loss of 200–300 billion US dollars and killed more than 10000 people living along the coasts of Japan and elsewhere in the Pacific region [1–3]. The period of a tsunami wave ranges from few minutes to several tens of minutes and generally it depends on the geographic location. At the same time, its amplitude is large enough to be identified within the normal tidal and nontidal spectrum of the sea level variability processes [4–6]. Recent studies showed that large tsunamis can propagate through the oceans up to very distant regions [7–11]. Small-amplitude sea level oscillations, superimposed to the normal tides, were recorded in connection with the eastern Indian ocean tsunami of December 26 2004, even along the coasts of the British Isles, thousand of km away from the Mw 9.3 earthquake epicenter, and up to the West coast of Africa. These results could explain the finding of the overall tendency of giant earthquakes to produce a global relative sea level variation [12].

The propagation of tsunamis in oceans is a topic largely investigated by means of fluid numerical simulations in shallow-water approximation (see, *e.g.*, [8,13] and references therein). This approach allowed to understand many properties of the propagation, such as the role of the orientation and intensity of the offshore seismic line source and the trapping effect of mid-ocean ridge topographic waveguides that influences wave amplitude, directionality, and global propagation patterns (see, *e.g.*, ref. [8]). On the other hand, the possibility that a tsunami wave, produced by a far seismic event, could affect in some way the Mediterranean Sea, has received less attention. This is mainly attributable to the irregular bathymetry of the Strait of Gibraltar, that is believed to produce a strong damping and multiple reflections of the wave thus decreasing the probability of penetration in the Mediterranean basin. After the large 2004 Indian Ocean tsunami, additional improvements to global tide gauge systems were performed for the monitoring of both tsunamis [8] and variations in sea level [11]. This allowed to achieve, also in the Mediterranean, real-time data with a quite homogeneous spatial coverage and high time resolutions, needed

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to reveal possible low-amplitude fluctuations due to the far-field destabilizing effect of tsunamis in this basin.

The present paper aims to investigate the occurrence of possible signatures in sea level data at high-quality tide gauge stations, after the megathrust Japan earthquake of March 2011, in the Mediterranean, a remote sea far from the earthquake epicenter. This investigation will support new insights on the physics of tsunami propagation across narrow straits, such as the one of Gibraltar, the transient effect on sea level, in remote basins in relationships with the Earth's free oscillations induced by high-magnitude earthquakes, and finally investigate the resonance effects in enclosed sea basins, such as the Mediterranean, in response to tsunami events.

**Data analysis.** – We focused on 31 sea level data in the period 9–15 March 2011. The sea level signals, having a time sampling of 10 minutes and an accuracy of better than 1 cm, have been retrieved from the IOC sea level station monitoring[1], from the Institute for Environmental Protection and Research (ISPRA)[2] and from the Permanent Service for Mean Sea Level (PSMSL)[3]. The geographic distribution of the tide gauge stations is reported in fig. 1. During the considered time window the weather situation around the stations was favorable (mainly calm sea, low and constant wind velocity), thus not inducing critical conditions of the sea surface for the quality of the sea level data set. Moreover, our analysis was restricted to the tidal stations located in sheltered positions; namely, the effects of both intensity and direction of the wind on the sea level recordings, based on the length of the fetch and the subsurface topography for the location[4], were negligible [5]. Sea level observations were first reduced for atmospheric pressure variations by applying an inverse barometric correction to the data [14]. As an example of raw data, in fig. 2 (row A) we show the sea level time series $L(t)$ at four stations. Time is measured as the lag from the earthquake occurrence. A sudden change of regime can be identified in all the signals after the earthquake. In fact, the regular tidal oscillation is broken, more frequencies appear, and the time behavior becomes more complex and highly nonstationary. This kind of dynamical behavior is common to all the records we investigated. In fig. 3 we report the sea level time series $L(t)$ for the Cagliari station (panel (a)), along with the 12 hours return map $L(t+\Delta)$ *vs.* $L(t)$, for $\Delta = 12$ hours (panel (b)). The figure roughly provides evidences that after the mainshock the Mediterranean Sea felt a strong phase and amplitude perturbation of the tidal oscillation. In fact, for $t \leqslant 0$ (blue line), the points of the return map are approximately sorted along a straight line, indicating that the oscillation amplitude and phase remain almost constant. On the contrary for $t > 0$ (red line), the points are distributed on irregular ellipses, indicating that the phase and amplitude are no more constant but change with time.

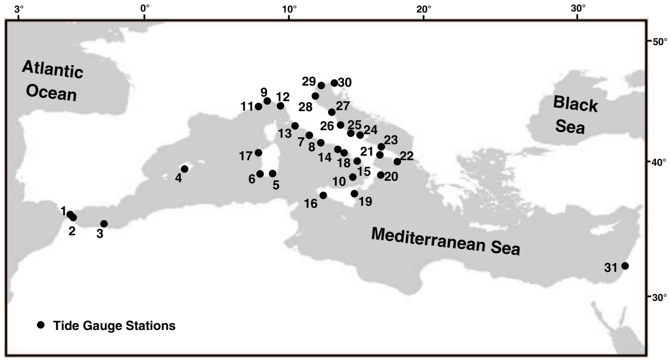


Fig. 1: Map of the tide gauge stations, in the Mediterranean, used in this study. Numbers refer to the following stations: 1) Gibraltar, 2) Ceuta, 3) Melilla, 4) Palma de Mallorca, 5) Cagliari, 6) Carloforte, 7) Civitavecchia, 8) Gaeta, 9) Genova, 10) Ginostra, 11) Imperia, 12) La Spezia, 13) Livorno, 14) Napoli, 15) Palinuro, 16) Porto Empedocle, 17) Porto Torres, 18) Salerno, 19) Catania, 20) Crotone, 21) Taranto, 22) Otranto, 23) Bari, 24) Vieste, 25) Ortona, 26) San Benedetto, 27) Ancona, 28) Ravenna, 29) Venezia, 30) Trieste, 31) Hadera.

In order to characterize the observed change of dynamical behavior, we use the Empirical Mode Decomposition (EMD) [15], a technique developed to analyze nonstationary time series and used in various contexts [16–18], including geophysical systems [19–22]. Each sea level time series $L(t)$ is decomposed into a finite number $n$ of Intrinsic Mode Functions (IMF) $\theta_j(t)$ as

$$L(t) = \sum_{j=0}^{n} \theta_j(t) + r_n(t). \quad (1)$$

The IMFs, contaning information about the local properties of the signal, are empirical, *i.e.* not given *a priori* but obtained from the data by following the "sifting" method [15]. This procedure starts by identifying local extrema of $L(t)$. The envelopes of maxima and minima are then obtained through cubic splines and the mean between them, $m_1(t)$, is calculated. The difference quantity $h_1(t) = L(t) - m_1(t)$ represents an IMF only if it satisfies two criteria: i) the number of extrema and zero-crossing does not differ by more than one; ii) at any point the mean value of the two envelopes is zero. If i) and ii) are not satisfied, the previous steps are repeated by using $h_1(t)$ as raw series and $h_{11}(t) = h_1(t) - m_{11}(t)$, where $m_{11}(t)$ is the mean of the envelopes in this case, is generated. This procedure is repeated $k$ times until $h_{1k}(t)$ satisfies the IMF's properties. Thus $\theta_1(t) = h_{1k}(t)$ represents the first IMF, associated with the shortest time scale of the process. To guarantee that the IMF components have enough physical sense with respect to both amplitude and frequency modulations, a criterion to stop the sifting

[1] www.ioc-sealevelmonitoring.org.
[2] www.mareografico.it.
[3] www.pol.ac.uk.
[4] Cf. the Fetch- and Depth-Limited Wave Calculations facilities at http://woodshole.er.usgs.gov/staffpages/csherwood/sedx_equations/RunSPMWave.html.

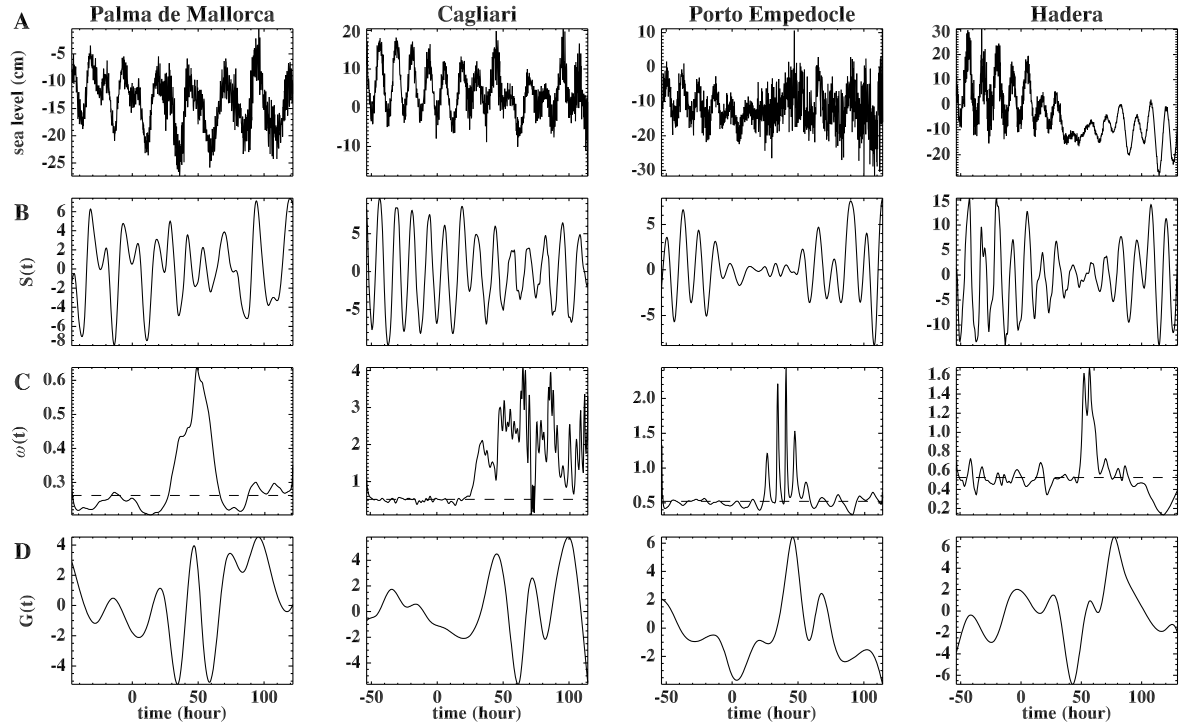


Fig. 2: Time evolution of the sea levels (line A), contribution of the high-amplitude components $S(t)$ (line B), instantaneous frequency of the highest-amplitude IMF (line C), low-frequency contribution $G(t)$ (line D) for the stations of Palma de Mallorca (4), Cagliari (5), Porto Empedocle (16) and Hadera (31). Time is counted from the origin time of the Tohoku-Oki earthquake. The dashed line corresponds to $(2\pi)/12\,\mathrm{hour}^{-1}$ for Cagliari, Porto Empedocle and Hadera and $(2\pi)/24\,\mathrm{hour}^{-1}$ for Palma.

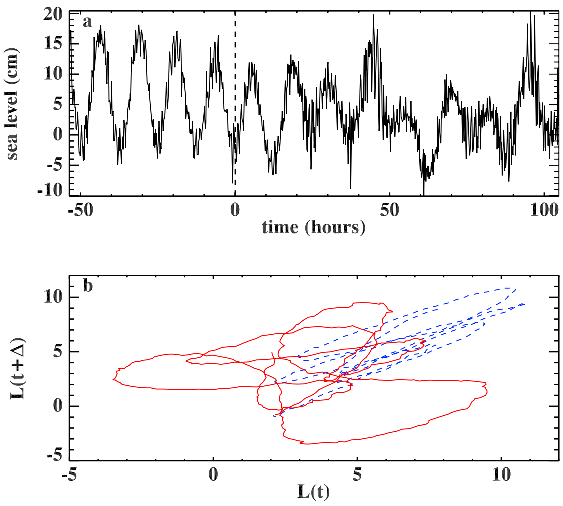


Fig. 3: (Colour on-line) Time evolution of the sea level $L(t)$ (panel (a)) and the 12 hours return map $L(t+\Delta)$ *vs.* $L(t)$ (panel (b)) for the Cagliari station ($\Delta = 12$ hours). Time is counted from the origin time of the Tohoku-Oki earthquake. The blue dashed line refers to times $t \leqslant 0$, the red full line refers to times $t > 0$.

process has been introduced [15]. A kind of standard deviation, calculated using two consecutive siftings, is defined $\sigma = \sum_{t=0}^{N}[(|h_{1(k-1)}(t)| - |h_{1k}(t)|)/h^2_{1(k-1)}(t)]$ and the iterative process is stopped when $\sigma$ is smaller than a threshold value, in our case chosen as 0.3 [15]. The function $r_1(t) = L(t) - \theta_1(t)$, the first residue, is analyzed in the same way as just described, thus obtaining a new IMF $\theta_2(t)$ and a second residue $r_2(t)$. The process continues until $\theta_j$ or $r_j$ are almost zero everywhere or when the residue $r_j(t)$ becomes a monotonic function from which no more IMF can be extracted. At the end of the procedure $n$ empirical modes, ordered with increasing characteristic time scale, and a residue $r_n(t)$, which describes the mean trend if any, are obtained. Each IMF has its own time scale, $\tau_j$, and represents a zero mean oscillation experiencing amplitude and frequency modulations; namely the $j$-th IMF can be written as $\theta_j(t) = A_j(t)\cos[\omega_j(t)\cdot t]$, where $A_j(t)$ and $\omega_j(t)$ are the time-dependent amplitude and frequency of the $j$-th mode, respectively. The IMF time scale is computed as the average time between local maxima and minima. The EMD allows to define, for each IMF, a meaningful instantaneous frequency calculated as follows. The Hilbert transform is applied on each IMFs, namely

$$\theta_j^*(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\theta_j(t')}{t-t'}\mathrm{d}t', \qquad (2)$$

where $P$ indicates the Cauchy principal value. $\theta_j(t)$ and $\theta_j^*(t)$ form the complex conjugate pair so that the instantaneous phase can be calculated as $\phi_j(t) = \arctan[\theta *_j(t)/\theta_j(t)]$. The instantaneous frequency follows as $\omega_j(t) = \mathrm{d}\phi_j/\mathrm{d}t$. This definition of $\omega(t)$ is quite general and in principle some limitations on the data are necessary in order to obtain instantaneous frequency as a single-value function of time. The latter property is fulfilled by the EMD basis functions which allow to obtain a meaningful instantaneous frequency consistent with the physics of the system under study [15].

The EMD represents a powerful tool for the time-frequency analysis of nonlinear and nonstationary data. Being based on an adaptive basis, it allows to overcome some disadvantages of the Fourier spectral analysis when applied to real nonperiodic and nonstationary data, such as the *a priori* definition of the Fourier modes, that are often far from being proper eigenfunctions of the phenomenon at hand. Moreover, when dealing with nonperiodic data, Fourier modes are mixed together in order to build up a solution corresponding to the fictitious periodic boundary conditions imposed by the analysis. On the other hand, the EMD does not introduce spurious harmonics, as in the case of Fourier analysis, in reproducing nonstationary data and nonlinear waveform deformations. The EMD frequency is derived by differentiation rather than convolution, as in the case of Fourier, and, therefore, there is not an uncertainty principle limitation on time or frequency resolution. The EMD decomposition is complete and orthogonal. The latter property, even if not theoretically guaranteed, is practically fulfilled [15] and should be checked numerically *a posteriori*. In our case, we verified that the obtained IMFs can be considered at a good approximation as orthogonal. The orthogonality ensures that each IMF captures the empirical dynamical behavior of a single independent mode of the system, namely each $j$-mode describes a single phenomenon within the complex dynamics. This allows to filter and reconstruct the signal through partial sums in eq. (1) in order to obtain independent contributions to the signal in different ranges of time scales [15,17,18].

**Results.** – When applied to the Mediterranean tide gauge data the EMD gives a number $n$ of modes which in general depends on the station under analysis. As obtained from the test of significance for the various IMFs [23], the first three modes, $j \leqslant 2$, represent high-frequency noise while higher-$j$ modes are associated with significant oscillations of the sea level at different time scales. For the majority of the stations the IMF with the highest amplitude has a period of $\tau \approx 12$ hours, corresponding to the well-known semidiurnal oscillation. However, in the analyzed data sets, the full semidiurnal component of the tide is split into two or three IMFs, depending on the station. This means that one IMF does not suffice to fully describe the temporal behavior of the 12 hours tidal component. The previous result follows from the high sensitivity of the EMD to local frequency fluctuations. The latter, still persisting when meteorological effects are removed, are strong enough to affect the regularity of the semidiurnal mode of oscillation. As mentioned before, since for the properties of the EMD decomposition each IMF is associated to a well-defined time scale of the signal at hand, a regular semidiurnal oscillation should be isolated in a single IMF. In the presence of localized frequency fluctuations new time scales arise and affect the regular oscillation of the high-energy tidal components. In this case, a single IMF is not able to account for the new time scales and the time evolution of the 12 hour oscillation is split into two or more IMFs. Of course, the sum of these EMD modes will describe the full contribution of the semidiurnal oscillation to the sea level. For Palma de Mallorca and the stations in the northern sector of the Adriatic Sea (stations 26–30), the simultaneous presence of both diurnal and semidiurnal components, as main tidal constituents, has been detected. This is a well-known phenomenon and it should depend, in the Adriatic Sea, on the basin characteristics, *i.e.*, the low sea depth and the semiclosed shape [24,25]. For these cases the previous considerations are also valid for the 24 hours component which is split into two IMF. By exploiting the orthogonality of the EMD decomposition, the signal $L(t)$ has been divided, by partial sum in eq. (1), into four contributions namely $L(t) = \eta(t) + S(t) + G(t) + r_n(t)$. The function $\eta(t)$ is associated with the high-frequency noise, $S(t)$, obtained as the sum of the high-amplitude components (semidiurnal and for some station also diurnal), represents the basic tidal mode and $G(t)$ describes the remaining low-frequency contribution. An example of the time behavior of $S(t)$ is reported in row B of fig. 2. Its dynamics is far from being regular and stationary since the waveforms abruptly change after $t = 0$. The variation of the main tidal contribution can be better appreciated by looking at the instantaneous frequency of the highest-amplitude IMF (row C of fig. 2) which is abruptly destabilized in correspondence of the change of the oscillating regime in $S(t)$ and departs from the constant value of $(2\pi)/12\,\text{hour}^{-1}$. Note that for Palma de Mallorca the reference frequency is $(2\pi)/24\,\text{hour}^{-1}$ since, in this case, the highest-amplitude mode is associated with the diurnal component.

EMD modes with longer periods describe low-frequency phenomena. The function $G(t)$, an example is reported in row D of fig. 2, is characterized by the increase of amplitude after $t = 0$. Figure 4 shows the contour plot of the functions $G(t)$, ordered according to the distance from Gibraltar. The figure clearly indicates that the time at which the increased amplitude regime is at its maximum absolute value is a function of the distance from the Strait of Gibraltar. This result is consistent with a traveling perturbation in the whole Mediterranean Sea propagating from Gibraltar. The Adriatic stations, for the sake of clarity, have been excluded from fig. 4. For these stations, due to the Adriatic basin geographic characteristics, the time-distance relation is inverted. In fact, the northernmost Adriatic stations are nearer to Gibraltar but the perturbation has to cover a longer path before reaching them. As shown in fig. 4 the majority of stations shows a peak (in red) after $t = 0$, which indicates

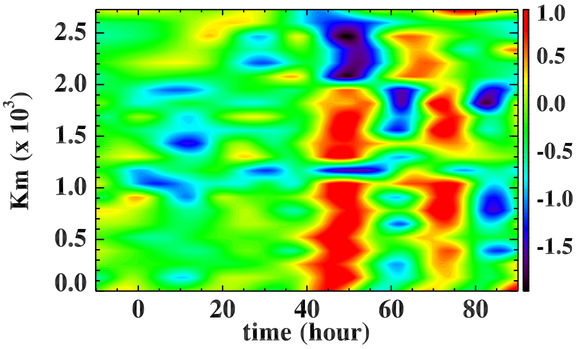


Fig. 4: (Colour on-line) Contours of $G(t)$ in the space-time plane. The $x$-axis reports the time counted from the Tohoku-Oki earthquake, while the $y$-axis reports the distance in km from Gibraltar.

a positive fluctuation of the sea level. On the other hand, some records, including Hadera and the stations in the Ionian Sea, are characterized by a drop (in blue) followed by the transient increase of the sea level. This behavior can be induced by the local seafloor topography and/or by the different paths taken by the tsunami waves and reflection effects [9]. The space-time representation allows to estimate the velocity of propagation of the perturbation, in the Mediterranean Sea, to be about $V_p \simeq$ 60 m/s. Note that, this perturbation is revealed in the whole Mediterranean Sea, being observed up to Hadera, the easternmost station, about 13 hours after Gibraltar.

We hypothesize that both the indirect perturbation of the tidal frequency and the direct transfer of small fluctuations beyond the Strait of Gibraltar, are generated from the tsunami triggered by the March 11th 2011, Tohoku-Oki earthquake. We remark that the timing of both these effects, varying between $\sim 45$ hours in Gibraltar and $\sim 58$ hours in Hadera, are in agreement with the results of theoretical models of tsunami propagation for which the perturbation should arrive at Gibraltar in a time of about 38 hours after the earthquake[5]. The obtained results have been tested by looking at the sea level records during the period 9–15 September 2011, in a time window which cannot be related with the Tohoku-Oki earthquake. We assume that, in this period, the possible transient effect of the tsunami is null and the system behaves according to the usual dynamics. As expected, we found that the principal tidal components show a regular behavior and are detected, by the EMD, in a single IMF. This indicates that the splitting of the principal tidal components into more IMFs along with the instantaneous frequency destabilization could be plausibly in connection with a transient effect, associated with the tsunami. As an example, the results for the Cagliari station are reported in fig. 5. The raw data are shown in panel (a), and panel (b) shows the regular semidiurnal component associated with the largest-amplitude IMF, whose characteristic time scale is 12.27 hours. Panel (c) shows the instantaneous frequency of the IMF reported in panel (b). The striking difference with fig. 2 is evident. As expected, the frequency is centered around the value $2\pi/12\,\text{hour}^{-1}$ with low-amplitude superimposed stochastic fluctuations.

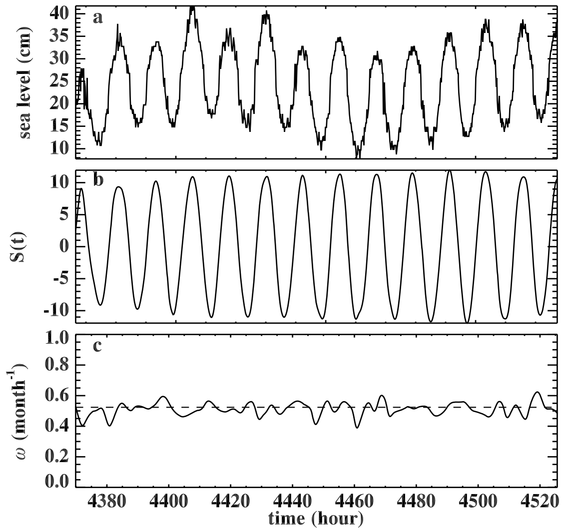


Fig. 5: Time evolution of the sea levels (a), semidiurnal IMF (b) and instantaneous frequency (c) for the Cagliari station. Time is counted from the origin time of the Tohoku-Oki earthquake.

**Conclusions.** – In this paper we investigated the anomalous sea level changes for 31 stations in the Mediterranean basin, due to a transient perturbation in the period 9–15 March 2011. Once the atmospheric pressure effects have been removed and the wind intensity and direction have been accounted for, with respect to the position of the individual tidal stations, we hypothesize that the perturbation is a consequence of the tsunami generated by the March 11th, 2011, Mw 9.0 Tohoku-Oki earthquake. Our analysis shows that the Mediterranean felt the effect of the tsunami 40–50 hours after the mainshock thus indicating that tsunamis generated by strong earthquakes are truly global events. In particular, we revealed two kinds of transient signatures. Firstly, the perturbation generates strong frequency fluctuations affecting the regular behavior of the high-amplitude tidal components, usually the semidiurnal and in some cases also the diurnal one. As a consequence of the perturbation, these components appear highly nonstationary and several IMFs are needed to reproduce their full contribution. In addition the instantaneous frequency shows abrupt destabilization after the earthquake occurrence. The physical mechanism causing these manifestations should be related to a resonant response to the tsunami at the strait entrance. Tides in enclosed basins, connected to the open sea by a narrow strait, can manifest amplified or damped response to a forcing action outside the basin [26]. Due to nonlinear effects the basin may exhibit chaotic modulation of the tidal amplitude and frequency. Since the Mediterranean

[5]`http://nctr.pmel.noaa.gov/honshu20110311/honshu2011-globalmaxplot.png`.

Sea is similar to a closed basin with respect to the oceans and is connected to Atlantic Ocean by a narrow strait, it could be affected by the forcing action of the fluctuations associated with the tsunami and could manifest nonlinear response leading to amplification and frequency destabilization. The second signature consists in a propagating perturbation manifesting itself with a weak increase of amplitude of the low-frequency EMD modes, after the occurrence of the Tohoku-Oki earthquake. This perturbation, significant with respect to the noise level, should be an evidence of the direct transmission of tsunami fluctuations, characterized by long periods, through the Strait of Gibraltar.

The timing of the detected tidal perturbations at the recording stations are in agreement with the prediction of the global models of tsunami propagation, for which the arrival at the Strait of Gibraltar is expected about 38 hours after the onset of the earthquake. Effects on sea levels due to post-seismic deformations [12], capable to cause global sea level raise of the order of a fraction of mm (`http://cires.colorado.edu/~bilham/Honshu2011/Honshu2011.html`) and direct propagation of surface seismic waves from the epicenter, arriving at the Mediterranean region 20–30 minutes after the mainshock (`www.emsc-csem.org`), have been excluded since they are not consistent with the observed sea level variations. Additionally, it is unlikely that free oscillations of the Earth, excited by the high-magnitude Tohoku-Oki earthquake, originated the detected fluctuations since the timing and period of the main mode of oscillation [27,28] are not in agreement with the timing and frequency of the sea level perturbations revealed by our observations. However, based on the available seismological and geophysical literature [27] the effects of free oscillations of the Earth on the sea level have not yet been investigated and the results presented in this paper provide new observational constraints for these studies. The physical mechanisms, briefly described above, need deeper investigations and will be tackled in a future paper.

* * *

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