Arab J Geosci (2015) 8:8969–8974
DOI 10.1007/s12517-015-1896-2

ORIGINAL PAPER

Nonlinear trend and seasonal signals in Mediterranean Sea level derived by multiresolution wavelet analysis of altimetry data

Sofiane Khelifa[1] · Ali Rami[1]

Received: 24 September 2014 / Accepted: 24 March 2015 / Published online: 7 April 2015

Abstract Using multiresolution wavelet analysis, the spectral content of monthly maps of sea level anomaly time series on the Mediterranean Sea derived from satellite altimetry over the period 1993 to 2013 is investigated in order to assess its seasonal changes and its nonlinear trend. The multiresolution decomposition has extracted useful the seasonal signals (annual and semi-annual) and nonlinear trend of the analyzed time series by means of its signals of "details" and "approximations," respectively. Details and approximations signals represent, respectively, the high-frequency and the low-frequency contained in the analyzed time series. The amplitude values for the annual signal are less than 10 cm with an average of 6.74 cm, while those for the semi-annual signal are mostly less than 4 cm with an average of 1.79 cm. However, the successive smoothing of the analyzed time series through the signals of approximations has allowed to better identify the rate and time spans of the increase and decrease of the Mediterranean Sea. The filtered trend has a slope about 2.30 mm/year compared to 2.46 mm/year of the original time series estimated by linear least squares regression.

Keywords Mediterranean Sea · Sea level anomaly · Time series analysis · Multiresolution analysis · Nonlinear trend · Seasonal variations

✉ Sofiane Khelifa
khelifa_sofiane@yahoo.fr

[1] Centre of Space Techniques, PO Box 13, 31200 Arzew, Algeria

Introduction

The variation of the Mediterranean Sea has been the object of many research studies in order to assess its trend and its seasonal changes, and to understand the mechanisms governing its spatial and temporal variability. Several results for the last years (1993–2013) (Cazenave et al. 2001, 2002; Vigo et al. 2005, 2011; Criado-Aldeanueva et al. 2008; Haddad et al. 2011a, b, 2013; Taibi et al. 2013), based on altimetry data using various tools (least squares method, empirical orthogonal function (EOF), singular spectrum analysis (SSA), etc.), indicate that the mean sea level in the Mediterranean Sea presents a very high interannual variability and does not rise uniformly. The sea level trend estimate is about 7 mm/year indicated by Cazenave et al. (2002) from 6 years (1993–1998), 2.2 mm/year from 8 years (1992–2000) reported by Fenoglio-Marc (2002), 2.1 mm/year from 13 years (1993–2005) obtained by Criado-Aldeanueva et al. (2008), 1.7 mm/year from 17 years (1993–2009), and 2.4 mm/year from 20 years (1993–2012) showed, respectively, by Haddad et al. (2011a, 2011b) and Haddad et al. (2013).

This paper is a contribution to these continuous researches on the Mediterranean Sea variability. We apply the wavelet transform method (Daubechies 1992), for time-scale analysis, to the time series of monthly maps of sea level anomaly over the Mediterranean Sea from 21 years (1993–2013) of altimetry data, in order to identify and extract its nonlinear trend and its seasonal signals. In particular, that this approach allows to simultaneously localize the sea level signal in both time and scale (frequency) domains, it works as a mathematical microscope that can focus on a specific part of the signal to extract local structures and singularities (Ghil et al. 2002). Various methods of wavelet transform (discrete wavelet transform, cross wavelet transform, wavelet coherence, wavelet-based multiresolution analysis, etc.) have been extensively used for time series analysis in a wide variety of applications, such as those of oceanography and climate (Meyers et al. 1993; Lau and Weng 1995; Mak 1995; Flinchem and Jay 2000; Jevrejeva et al. 2003, 2005, 2006; Barbosa et al. 2005, 2006; Rangelova et al. 2006; Bastos et al. 2013). This proposed study adds to the literature on the use of multiresolution wavelet analysis for the assessment of sea level variability from altimetry data for the region of the Mediterranean Sea. We also confront our results with those obtained via other filtering methods based on the phase space, such as EOF and SSA (Ghil et al. 2002), in order to study the convergence of the two approaches (frequency domain and phase space).

Methods

The wavelet transform (Daubechies 1992; Mallat 1999) is a well-known technique used in several geophysical contexts (Kumar and Foufoula-Georgiou 1994). It allows to decompose a signal into frequencies by preserving a temporal localization. The starting signal is projected on a set of basic functions called wavelets which vary in frequency and time and which therefore allow to have a well localization in time and frequency of the analyzed signal. The wavelets were initially introduced by Grossman and Morlet (1984) as a mathematical tool for analysis of seismic signals. Then, the theory was developed and formalized by several contributors (Lemarié and Meyer 1986; Mallat 1989; Daubechies 1990; Rioul and Vetterli 1991; Cohen et al. 1992). This section gives a brief overview on the mathematical definition of wavelet transform, for a more detailed description of this tool; the reader may refer to the works (Daubechies 1992; Meyer 1992; Holschneider 1998; Mallat 1999).

Wavelet transform

A wavelet ψ is a function of $L^2(R)$ (square integrable functions) with zero mean which can be expanded/contracted (scale factor s) and translated (localization parameter u), forming a set of basic functions called wavelets on which the signal $X(t)$ is projected (Mallat 1999):

$$\psi_{u,s}(t) = s^{-1/2}\psi((t-u)/s) \text{ with } s\in R_+^* \text{ and } u\in R \quad (1)$$

The continuous wavelet transform is defined by

$$WT(u,s) = s^{-1/2}\int_{-\infty}^{+\infty} X(t)\psi^*((t-u)/s)dt \quad (2)$$

where * denotes the complex conjugate function.

The signal $X(t)$ can be reconstructed from $WT(u,s)$ using the following equation (Chaux 2006):

$$X(t) = 1/C_\psi \int_0^{+\infty}\int_{-\infty}^{+\infty} WT(u,s)\psi_{u,s}(t)du\, ds/s^2 \quad (3)$$

with

$$C_\psi = \int_0^{+\infty} \left|\widehat{\psi}(\omega)\right|^2/\omega \; d\omega < +\infty \quad (4)$$

where $\widehat{\psi}(\omega)$ is the Fourier transform of $\psi(t)$ and the constant C_ψ must be finite; it is what one calls the condition of admissibility.

Multiresolution analysis

The multiresolution analysis, introduced by Mallat (1989), is a tool for signal processing which allows to decompose a signal on several scales (resolutions) and to reconstruct it from the elements of this decomposition. This can be realized by varying the scaling factor in dyadic way (i.e., powers of two), by choosing $s=2^j$, $j\in Z$ and $u=k\,2^j$, $k\in Z$. In this context, a multiresolution analysis is defined as a sequence of closed subspaces $(V_j)_{j\in Z}$ of $L^2(R)$ satisfying the four following properties (Chaux 2006):

1. $\forall j\in Z$, $V_{j+1}\subset V_j$
2. $\forall j\in Z$, $f(t)\in V_j \Leftrightarrow f(t/2)\in V_{j+1}$
3. $\cap_{j\in Z} V_j = \{0\}$ and $\overline{\cup_{j\in Z} V_j} = L^2(R)$
4. There exists a function Φ called scaling function, such as $\{\Phi(t-n), n\in Z)\}$ is an orthonormal basis of V_0.

We check then that $\{2^{-j/2}\ \Phi(2^{-j}\ t-k), k\in Z\}$ constitutes an orthonormal basis of V_j. The multiresolution analysis of a signal X consists to realize successive orthogonal projections of the signal on spaces V_j which leads to approximations increasingly coarse of signal X according the increase of j. The difference between two consecutive approximations represents the information of "detail" which is lost in the passage from one scale to another; this information is contained in the subspace W_j orthogonal to V_j such as (Chaux 2006):

$$V_{j-1} = V_j \oplus W_j$$

where $\oplus$ denotes the direct sum of spaces.

We show then that there exists a wavelet $\psi \in L^2(R)$ such as $\{2^{-j/2}\ \psi\ (2^{-j}\ t-k), k\in Z\}$ is an orthonormal basis of W_j. The decomposition by orthogonal wavelets of a signal X can be carried out in a very effective way (Mallat 1999). For this fact, one determines at each resolution level $j\in Z$ its approximations

$(C_{j,k})_{k\in Z}$ in the space V_j, and its detail coefficients $(d_{j,k})_{k\in Z}$ in the space W_j defined by (Chaux 2006):

$$C_{j,k} = 2^{-j/2} \int_{-\infty}^{+\infty} X(t)\Phi^*\left(2^{-j}t-k\right)dt \quad (5)$$

$$d_{j,k} = 2^{-j/2} \int_{-\infty}^{+\infty} X(t)\psi^*\left(2^{-j}t-k\right)dt \quad (6)$$

In the context of multiresolution analysis, the periodic components are represented by the high-frequency contained in signals of details, and the trends (long-term evolution of the signal) are represented by the low-frequency contained in signals of approximations.

The critical point in the analysis by wavelets resides in the choice of the appropriate wavelet function (Meyer, Daubechies, Haar, Shannon, Morlet, etc.) which remains dependent on the envisaged application (Meyer 1992; Holschneider 1998; Mallat 1999). In this work, we have employed the wavelet of Meyer (Meyer 1992) because it is symmetrical which allows to better identify the periodic signals, and it is regular which allows us to well localize the singularities of the analyzed signal.

Data used

Radar altimeters permanently transmit signals to Earth, and receive the reflected echo from the sea surface. The sea surface height (SSH) is the height of the sea surface above the reference ellipsoid. It is calculated by subtracting the measured distance between the satellite and the sea surface from the satellite precise orbit (Taibi et al. 2013). However, the sea level anomaly (SLA), as seen in Fig. 1, is defined as the difference between the sea surface height (SSH) and a priori mean sea level (MSL).

In this study, we use the averaged maps of sea level anomaly time series from measurements of several altimetric satellites: TOPEX/Poseidon (1992–2002), Jason-1 (2002–2008), and Jason-2 (2008 to present). The averaged SLA maps are generated by the SSALTO/DUACS (Segment Sol multi-missions d'ALTimétrie, d'Orbitographie et de localisation précise/Data Unification and Altimeter Combination System) near-real time and delayed-time altimeter data processing software; it processes data from all altimeter missions (see SSALTO/DUACS user handbook 2014 for more details). These time series were computed basing on the extended delayed-time maps in weekly/daily temporal resolution averaging month by month at 1/8°×1/8° on a regular grid from January 1993 to July 2013 over the Mediterranean Sea. These data are available from (ftp://ftp.aviso.oceanobs.com/pub/oceano/AVISO/SSH/climatology/mediterranean_sea/monthly_mean_dt_upd/).

All of the standard corrections (atmospheric, geophysical, and orbital corrections) to the altimeter range were applied to the SSH including ionosphere delay determined from the dual frequency measurements from the altimeter (Rummel 1993), dry tropospheric correction obtained from ECMWF (European Centre for Medium range Weather Forecasts) Model, wet tropospheric correction computed by TMR (TOPEX Microwave Radiometer) for TOPEX data (DAAC and NASA Physical Oceanography 2006) and JMR (Jason Microwave Radiometer) for Jason data (Brown et al. 2003), inverse barometer using low-frequency signals (Pascual et al. 2008), ocean tide estimated using GOT4.7 model (Ray 1999), solid tide computed as described by Cartwright and Edden (1973), pole tide easily computed as described in (Wahr 1985), sea state bias computed using CLS Collinear v. 2009 (Tran et al. 2010), orbital error is obtained by STD0905 model (Lemoine et al. 2010) and instrumental corrections.

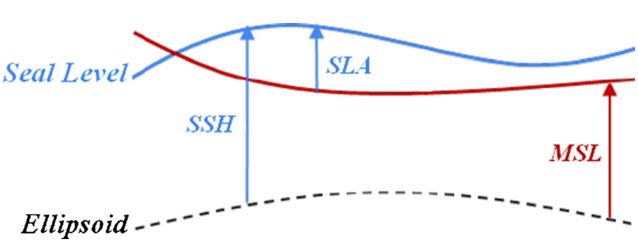

Fig. 1 Illustration of sea level anomaly (SLA) definition

Results

Seasonal signals

The seasonal variations in sea level are mainly due to changes in the heat content of the upper ocean and, by a lesser effect, to changes in atmospheric pressure and wind field (Lionello 2012).

The Fig. 2 represents the variation of the analyzed time series which clearly indicates a strong annual signal and a slope of about 2.46 mm/year obtained by least square fit.

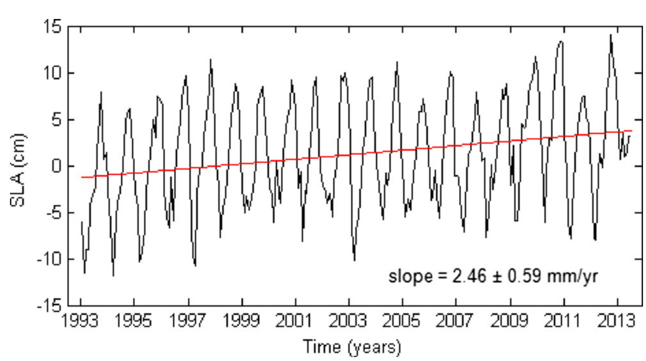

Fig. 2 Sea level anomaly (SLA) time series over the Mediterranean Sea from 1993 to 2013 and its linear trend obtained by least square fit

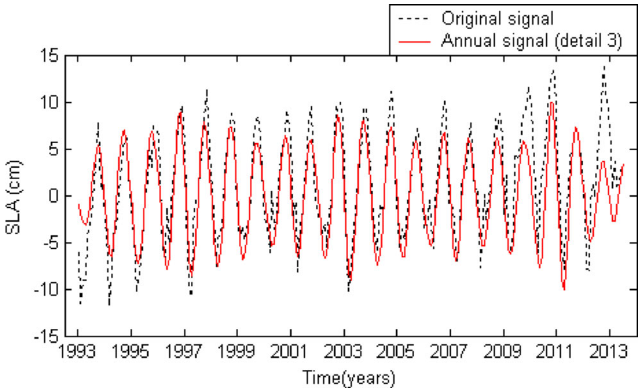

Fig. 3 SLA time series and its annual signal represented by the signal of detail 3

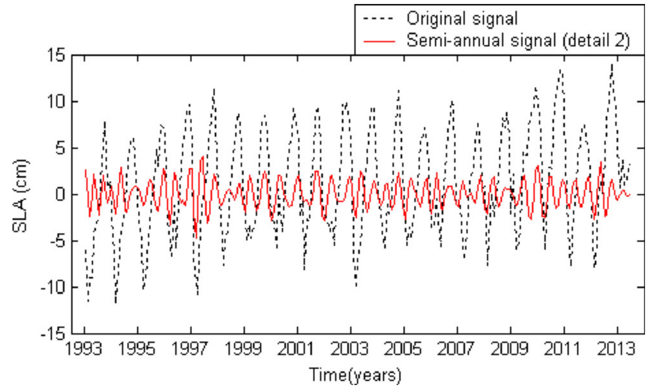

Fig. 5 SLA time series and its semi-annual signal represented by the signal of detail 2

Using the Meyer wavelet, the details signals which allow to extract the periodic signals contained in SLA time series show that this time series is dominated by two seasonal terms: annual and semi-annual. The annual and semi-annual signals are identified by details 3 and 2, respectively, as shown in Figs. 3 and 5 respectively.

The Fig. 3 shows that the analyzed SLA time series is dominated by a clear annual signal which following perfectly the variation of the original signal, its amplitudes vary from 4 to 10 cm with an average of 6.74 cm (from peak to peak), and its minimum and maximum are reached in April and October, respectively, as zoomed in Fig. 4. The highest maximum amplitude of 9.88 cm is found in October 2010, and the less pronounced minimum of −10.09 cm corresponds to April 2011. The lowest maximum of 3.57 cm is identified in October 2010, while the greatest minimum of –2.69 cm is observed in March 2013. However, the semi-annual signal (see Fig. 5) is less important than the annual signal. Indeed, its amplitude is smaller for most of the Mediterranean Sea, and it is less neatly defined; it varies from 0.4 to 4 cm with an average of 1.79 cm. These results are in agreement with previous results from altimetry data (Vigo et al. 2005, 2011; Criado-Aldeanueva et al. 2008).

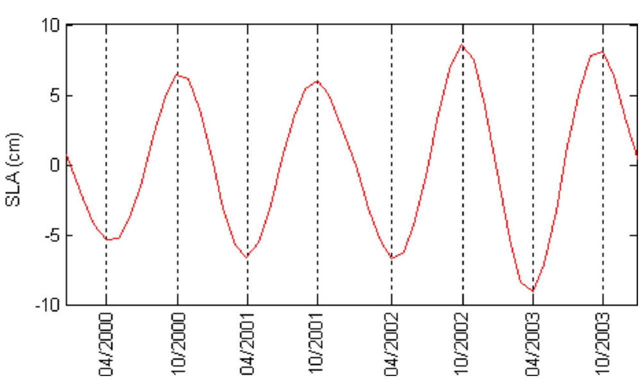

Fig. 4 Highlighted of the annual signal (detail 3) over the 4 years 2000–2003

Nonlinear trend

As mentioned previously, the multiresolution wavelet analysis can extract the trend of a signal. Successive approximations lose progressively more high-frequency information. Removing high frequencies, what remains is the slowest part of the signal, i.e., the overall trend of the signal.

Using the same wavelet of Meyer, Fig. 6 reveals the successive approximations of the fourth, fifth, sixth, and the seventh decomposition of the analyzed SLA time series. The successive approximations show, on the one hand, that the Mediterranean sea level rise is irregular and varies considerably over time, and on the other hand that the signal is smoothed progressively at each consecutive level of decomposition. The signal of approximation 4 shows a strongly increasing trend in winter 2009–2010. This high positive sea level anomaly in Mediterranean Sea has been indicated by Aviso Web site (http://www.aviso.oceanobs.com), explaining that this great change is probably associated to the negative NAO (North Atlantic Oscillation) index which is negatively correlated with variations in sea level observed in

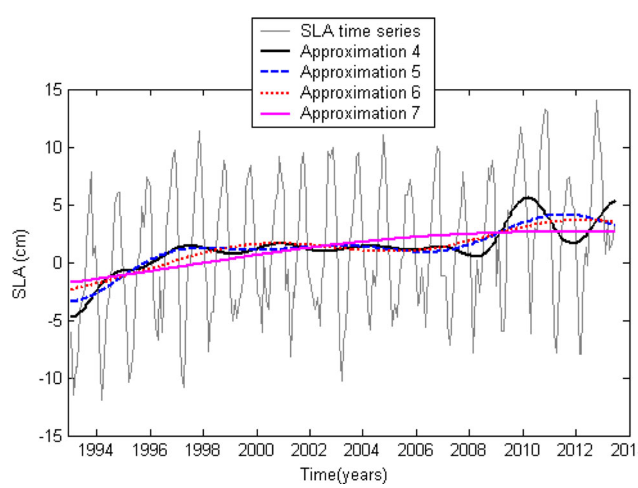

Fig. 6 Nonlinear trends of SLA time series represented by successive approximation signals from 4 to 7

Mediterranean Sea. In the approximation 5, the SLA signal has been more smoothed with the detection of the monotonous (ascendant or descendant) portions of the signal. The approximation 6 shows an evident three different apparent linear trends (increasing or decreasing) at different time periods. We clearly observe an ascendant trend of about 5.59±0.09 mm/year from 01/1993 to 12/2000, then a descendant trend of about −2.03±0.03 mm/year from 01/2001 to 11/2004 followed by an ascendant trend of about 4.28±0.08 mm/year from 12/2004 to 01/2013.

The observed sea level rise from 01/1993 to 12/2000 is probably linked with sea surface warming for that same time period (Cazenave et al. 2001; Fenoglio-Marc 2002). It should also be noted that the negative trend from 2001 onwards has been shown by several authors (Vigo et al. 2005; Criado-Aldeanueva et al. 2008; Del Rio-Vera et al. 2009). However, the approximation 7 reveals a well smoothed trend of the analyzed SLA time series with a slope of 2.30±0.04 mm/year computed from the first order polynomial fitted to the approximation at the 7th level of decomposition. This result is in good agreement with that of 2.44 mm/year estimated by Singular Spectrum Analysis (SSA) in a recent published study undertaken by Haddad et al. (2013) from altemetry data and covering the period 1993–2012. Our results are also in agreement with those of Criado-Aldeanueva et al. (2008) which indicate a positive sea level trend of 2.1 mm/year, estimated by least square method, in the Mediterranean Sea using altimetry data for the period 1992–2005.

There are several possible causes for the sea level trends in the Mediterranean Sea. The observed sea level trends are mainly related to the following: changes in seawater volume due to density changes in response to temperature and salinity variations, and changes in the mass content of the basin due to water exchange with atmosphere and land through precipitation, evaporation, and river runoff (Cazenave et al. 2001). Moreover, the exchange of water through the Gibraltar Strait (Ross et al. 2000; Fenoglio-Marc et al. 2013) and changes in atmospheric pressure and wind (Gomis et al. 2008) can also contribute to the Mediterranean long-term sea level variability.

Discussion and conclusion

In this paper, we have applied the multiresolution spectral analysis, based on the wavelet transform, on a long-term series of nearly 21 years (1993–2013) of sea level anomaly over the Mediterranean Sea from satellite altimetry in order to evaluate its seasonal signals and its nonlinear trend.

The multiresolution analysis has well extracted the seasonal signals and trends in the analyzed SLA time series through the signals of details and approximations, respectively. The annual and semi-annual signals have been estimated by the detail signals at the third and second level of decomposition, respectively. The obtained results show that the change in the Mediterranean Sea is mainly dominated by an annual signal. The semi-annual amplitudes are an order of magnitude smaller than annual signal; the amplitude average of the annual and semi-annual signals is about 6.74 cm and 1.79 cm, respectively. However, October 2010 and April 2011 exhibit stronger seasonality with a maximum amplitude of 9.88 cm and −10.09 cm, respectively.

Furthermore, the signals of approximations have shown clearly the rate and time spans of different acceleration/deceleration of the Mediterranean Sea. The trend is estimated at the seventh level of decomposition (approximation 7); it is about 2.30 mm/year compared to 2.46 mm/year of the original SLA time series estimated by linear least squares regression. Moreover, our results are in agreement with previously published results obtained by other smoothing methods (least squares method, EOF, and SSA).

Compared to the least squares method which is frequently used to calculate the sea level slope (linear trend), the multiresolution wavelet analysis assesses both the seasonal signals and trends contained in the time series. Furthermore, the determination of trends and seasonal signals through the multiresolution wavelet analysis is fast and direct without any initial assumptions on the time series properties. While, the SSA application requires that time series to be analyzed should be regular (gaps should be filled), and depends, firstly, on the choice of the adequate embedding dimension (M) with which the time series is embedded into a vector space of dimension M and, secondly, on the selection of the appropriate number of eigenvectors on which the time series is projected for its reconstruction in terms of trend, seasonal signals, and noise. Finally, we conclude that for the analysis of the sea level time series, this non parametric method offers more flexibility in extracting nonlinear trends at several resolutions (levels of decomposition) which allows a better localization in both time and frequency of trend changes.

References

Barbosa SM, Fernandes MJ, Silva ME (2005) Space-time analysis of sea level in the North-East Atlantic from T/P satellite altimetry. IAG Symp 129:248–253

Barbosa S, Silva ME, Fernandes MJ (2006) Wavelet analysis of the Lisbon and Gibraltar North Atlantic oscillation winter indices. Int J Climatol 26(5):581–593

Bastos A, Trigo RM, Barbosa SM (2013) Discrete wavelet analysis of the influence of the North Atlantic Oscillation on Baltic Sea level. Tellus A 65:20077

Brown S, Ruf C, Keihm S, Kitiyakara A (2003) Preliminary validation and performance of the Jason Microwave Radiometer. Int Geosci Remote Se (IGARSS '03) 2:1077–1079

Cartwright DE, Edden AC (1973) Corrected tables of tidal harmonics. J Geophys Res 33:253–264

Cazenave A, Cabanes C, Dominh K, Mangiarotti S (2001) Recent sea level changes in the Mediterranean Sea revealed by TOPEX/ Poseidon satellite altimetry. Geophys Res Lett 28(8):1607–1610

Cazenave A, Bonnefond P, Mercier F, Dominh K, Toumazou V (2002) Sea level variations in the Mediterranean Sea and Black Sea from satellite altimetry and tide gauges. Glob Planet Chang 34(1–2):59–86

Chaux C (2006) Analyse en ondelettes M-bandes en arbre dual; application à la restauration d'images. Thèse de doctorat soutenue à l'Université de Marne-la-Vallée, France

Cohen A, Daubechies I, Feauveau J (1992) Bi-orthogonal bases of compactly supported wavelets. Commun Pur Appl Math 45:485–560

Criado-Aldeanueva F, Del Rio-Vera J, García-Lafuente J (2008) Steric and mass-induced Mediterranean sea level trends from 14 years of altimetry data. Glob Planet Chang 60(3–4):563–575

DAAC, NASA Physical Oceanography (2006) TOPEX Microwave Radiometer Replacement product (http://podaac.jpl.nasa.gov/DATA_CATALOG/tmrinfo.html).

Daubechies I (1990) The wavelet transform, time-frequency localization and signal analysis. IEEE Trans Inf Theory 36(5):961–1005

Daubechies I (1992) Ten lectures on wavelets. Society for Industrial and Applied Mathematics (SIAM), USA, 357 pages

Del Rio-Vera J, Criado-Aldeanueva F, García-Lafuente J, Soto-Navarro FJ (2009) A new insight on the decreasing sea level trend over the Ionian basin in the last decades. Glob Planet Chang 68:232–235

Fenoglio-Marc L (2002) Long-term sea level change in the Mediterranean Sea from multi-satellite altimetry and tide gauges. Phys Chem Earth 27:1419–1431

Fenoglio-Marc L, Mariotti A, Sannino G, Meyssignac B, Carillo A, Struglia MV, Rixen M (2013) Decadal variability of net water flux at the Mediterranean Sea Gibraltar Strait. Glob Planet Chang 100:1–10

Flinchem EP, Jay DA (2000) An introduction to wavelet transform tidal analysis methods. Estuar Coast Shelf Sci 51:177–200

Ghil M, Allen MR, Dettinger MD, Ide K, Kondrashov D, Mann ME, Robertson AW, Saunders A, Tian Y, Varadi F, Yiou P (2002) Advanced spectral methods for climatic time series. Rev Geophys 40(1):3-1–3-41

Gomis D, Ruiz S, Sotillo MG, Álvarez-Fanjul E, Terradas J (2008) Low frequency Mediterranean sea level variability: the contribution of atmospheric pressure and wind. Glob Planet Chang 63:215–229

Grossman A, Morlet J (1984) Decomposition of Hardy functions into square integrable wavelets of constant shape. SIAM J Math 15: 723–736

Haddad M, Belbachir MF, Kahlouche S (2011a) Long-term global mean sea level variability revealed by singular spectrum analysis. Int J Acad Res 3(2-III):411–420

Haddad M, Belbachir MF, Kahlouche S, Rami A (2011b) Investigation of Mediterranean sea level variability by singular spectrum analysis. J Math Technol 2(1):45–53

Haddad M, Hassani H, Taibi H (2013) Sea level in the Mediterranean Sea: seasonal adjustment and trend extraction within the framework of SSA. Earth Sci Inform 6(2):99–111

Holschneider M (1998) Wavelets: an analysis tool. Oxford University Press, USA, p. 423

Jevrejeva S, Moore JC, Grinsted A (2003) Influence of the Arctic Oscillation and El Nino-Southern Oscillation (ENSO) on ice conditions in the Baltic Sea: the wavelet approach. J Geophys Res 108(D21):4677–4687

Jevrejeva S, Moore JC, Woodwoth PL, Grinsted A (2005) Influence of large-scale atmospheric circulation on European sea level: results based on the wavelet transform method. Tellus A 57(2):183–193

Jevrejeva S, Grinsted A, Moore JC, Holgate S (2006) Nonlinear trends and multiyear cycles in sea level records. J Geophys Res 111, C09012

Kumar P, Foufoula-Georgiou E (1994) Wavelet analysis in geophysics: an introduction. In: Foufoula-Georgiou K (ed) Wavelets in geophysics. Academic, New York, pp 1–43

Lau KM, Weng HY (1995) Climate signal detection using wavelet transform: how to make a time series sing. Bull Am Meteorol Soc 76: 2391–2402

Lemarié P, Meyer Y (1986) Ondelettes et bases hilbertiennes. Rev Mat Iberoam 2:1–18

Lemoine FG, Zelensky NP, Chinn DS, Pavlis DE, Rowlands DD, Beckley BD, Luthcke SB, Willis P, Ziebart M, Sibthorpe A (2010) Towards development of a consistent orbit series for TOPEX, Jason-1, and Jason-2. Adv Space Res 46:1513–1540

Lionello P (2012) The climate of the mediterranean region: from the past to the future. Elsevier edition, p 502

Mak M (1995) Orthogonal wavelet analysis: interannual variability in the sea surface temperature. Bull Am Meteorol Soc 76:2179–2186

Mallat S (1989) A theory for multiresolution signal decomposition: the wavelet representation. IEEE Trans Pattern Anal 11(7):674–693

Mallat S (1999) A wavelet tour of signal processing, 2nd edn. Academic, USA, 637 pages

Meyer Y (1992) Les Ondelettes: Algorithmes et Applications. Armand Colin, Paris, 172 pages.

Meyers SD, Kelly BG, O'Brien JJ (1993) An introduction to wavelet analysis in oceanography and meteorology: with application to the dispersion of Yanai waves. Mon Weather Rev 121:2858–2866

Pascual A, Marcos M, Gomis D (2008) Comparing the sea level response to pressure and wind forcing of two barotropic models: validation with tide gauge and altimetry data. J Geophys Res 113, C07011

Rangelova EV, Grebenitcharsky RS, Sideris MG (2006) Identifying sea-level rates by a wavelet-based multiresolution analysis of altimetry and tide gauge data. Bureau Gravimétrique International & International Geoid Service Joint Bulletin. Newton's Bull 3:104–115

Ray RD (1999) A global ocean tide model from TOPEX/Poseidon Altimetry: GOT99.2. NASA Tech Memo, NASA/TM-1999-209478, 58 pages.

Rioul O, Vetterli M (1991) Wavelet and signal processing. IEEE Signal Proc Mag 8(4):14–38

Ross T, Garett C, Le Traon PY (2000) Western Mediterranean sea level rise: changing exchange flow through the Strait of Gibraltar. Geophys Res Lett 27:2949–2952

Rummel R (1993) Satellite altimetry in geodesy and oceanography. Lect Notes Earth Sci 50:453–466

SSALTO/DUACS User Handbook (2014) (M)SLA and (M)ADT near-real time and delayed time products. CLS-DOS-NT-06-034, SALP-MU-P-EA-21065-CLS, Issue 4.2

Taibi H, Kahlouche S, Haddad M, Rami A (2013) Trends in global and regional sea level from satellite altimetry within the framework of Auto-SSA. Arab J Geosci 6(12):4575–4584

Tran N, Labroue S, Philipps S, Bronner E, Picot N (2010) Overview and update of the sea state bias corrections for the Jason-2, Jason-1 and TOPEX missions. Mar Geod 33(1):348–362

Vigo I, García D, Chao BF (2005) Change of sea level trend in the Mediterranean and Black seas. J Mar Res 63:1085–1100

Vigo I, Sanchez-Reales JM, Trottini M, Chao BF (2011) Mediterranean sea level variations: analysis of the satellite altimetric data, 1992–2008. J Geodyn 52(3–4):271–278

Wahr JW (1985) Deformation of the Earth induced by polar motion. J Geophys Res 90:9363–9368