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Estimating trends of the Mediterranean Sea level changes from tide gauge and satellite altimetry data (1993–2015)

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Abstract The impact of climate change on sea level has received a great deal of attention by scientists worldwide. In this context, the problem of sea levels on global and regional scales have been analyzed in a number of studies based on tide gauges observations and satellite altimetry measurements. This study focuses on trend estimates from 18 high-quality tide gauge stations along the Mediterranean Sea coast. The seasonal Mann-Kendall test was run at a 5% significance level for each of the 18 stations for the period of 1993–2015 (satellite altimetry era). The results of this test indicate that the trends for 17 stations were statistically significant and showed an increase (no significant trend was observed only at one station). The rates of sea level change for the 17 stations that exhibit significant trends, estimated using seasonal Sen's approach, range after correction for Vertical Land Motion (VLM) from 1.48 to 8.72 mm/a for the period 1993–2015. Furthermore, the magnitude of change at the location of each tide gauge station was estimated using the satellite altimetry measurements. Thus, the results obtained agree with those from the tide-gauge data analysis.

Keyword: sea level; tidal height; satellite altimetry; trend analysis; Mann-Kendall test; Sen's slope estimates

1 INTRODUCTION

The knowledge of sea level is a long-standing concern to the human being. The first motivation, which led man to focus closely on the observation of sea level changes, was probably navigation. This necessity has led man to imagine more and more sophisticated technical means to accurately measure sea level fluctuations; first, by simply installing tide board near the ports; then, by designing instruments of a high technical level, such as pressure sensors or acoustic tide gauges; finally, in recent years, by using artificial altimetry satellites. The tide gauge instruments are employed in coastal areas for the measurement of sea level changes relative to fixed benchmarks on the land, while the satellite altimetry allows measuring in the open ocean surfaces the absolute change of sea level with regard to the surface of the ellipsoid (geocentric reference frame). Therefore, the tide gauge records and space altimetry measurements are complementary for observing the sea level changes. It must be noted, that satellite altimetry is inadequate near the coastlines due to the bad spatial and temporal sampling of altimetry measurements (White et al., 2005) and also to the instability in the altimeter instrument during its passage from the land to the marine environment (Fenoglio-Marc, 2002).

Tide gauge being fixed to the ground provides a measure of the sea level relative to the coast: it records indeed such Vertical Land Motion (VLMs) of the coast, in addition, to the variations of the sea level. This relative character of the tide gauge compared to the coast is critical for the study of long-term sea level changes because the rates of these changes and the VLMs are of the same order of magnitude (a few millimeters per year). In contrast to tide gauges, altimeters directly measure the absolute sea level, relative to the Earth's center of mass.

Among the main phenomena causing vertical movements of the Earth's crust are: effects of Earth

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tides, tectonic effects (co and post seismic deformations), postglacial rebound, load effects (vertical crustal deformations under effect of air mass, oceanic and continental waters), subsidence effects related to sediment weight, pumping of groundwater, gas and oil, etc. (Wöppelmann, 1997). The best studied physical process causing VLM of the Earth's crust is certainly the postglacial rebound. This is the only geological process that can be modeled globally, even though large uncertainties remain. For example, Peltier's successive models, most recently: ICE-6G (Argus et al., 2014; Peltier et al., 2015) are the most commonly used to correct tide gauge measurements.

At present, sea level change draws much attention as it represents a significant consequence of global climate warming. Global Mean Sea Level (GMSL) is the object of clear increase since the late nineteenth century. More recently, GMSL increased at a rate close to 2 mm/a in the twentieth century (Douglas and Peltier, 2002; Bindoff et al., 2007; Nicholls and Cazenave, 2010; Church and White, 2011) and more recently, since 1993 (satellite altimetry era) by a rate near to 3.2 mm/a (Haddad et al., 2013a; Taibi et al., 2013). The regional variability in the GMSL trend is due to large-scale changes in ocean density in response to forcing factors (eg, wind forcing, heat, and freshwater exchange to the air-sea interface) and their consequences in the ocean circulation. Thus, the greatest regional variabilities of the sea level are mainly due to changes in ocean temperature (i.e. non-uniform thermal expansion), but in some regions, ocean salinity variations are also important. A recent study based on altimetry data has revealed the major contributions, to the GMSL rise during altimetry era, are from the Indian Ocean with (3.78±0.08 mm/a) (Taibi et al., 2013).

The Mediterranean Sea being a land-locked sea is one of the most vulnerable regions in the world to the impact of climate change, estimating an increase in average surface temperatures in the range of 2.2°C for the period of 1980–2000 and 5.1°C for the period of 2080–2100. That further indicates an increasing heat content of this basin that can directly translate into an increase in the mean sea level by the thermal expansion (IPCC, 2013). A possible impact of sea-level rise is enhanced further in the Mediterranean Sea by the presence, particularly along the coasts, of densely populated areas and a high-value economic activity. There are several studies focusing on sea-level variability and trends in the Mediterranean Sea based on tide-gauge and satellite altimetry data analysis (Vignudelli et al., 2005; Pascual et al., 2007; Fenoglio-Marc et al., 2012; Birol and Delebecque, 2014; Bonaduce et al., 2016). Analyzing satellite altimetry data reported that the Mediterranean Sea level has risen with an average trend of 2.44 mm/a for the period 1993–2013 (Haddad et al., 2013b; Bonaduce et al., 2016).

The aim of this study is to reveal the information stored in the Permanent Service of Mean Sea Level (PSMSL) published datasets of monthly sea level height of 18 tide gauge stations situated along the Mediterranean Sea coast: Tarifa, Malaga II, Barcelona, L'Estartit, Sete, Marseille, Toulon, Nice, Marsaxlokk (Formally Valletta), Preveza, Levkas, Katakolon, Kalamai, Piraievs, Khios, Siros, Leros and Ceuta stations. By means of statistical methods, we evaluate the presence or not of significant trends and their magnitude of change by year in these sea level time series. The used statistical methods in this study are the seasonal Mann-Kendall test (Mann, 1945; Kendall, 1975; Hirsch et al., 1982) and the seasonal Sen's method for slope estimates (Sen, 1968; Hirsch et al., 1982). We are motivated to use the Mann-Kendall test because it is a nonparametric test where data must not obey a particular distribution. The second advantage of this test is its low sensitivity to change-points or abrupt breaks in the time series (Tabari et al., 2011). To estimate the magnitude of trend change per unit time, Sen's method uses a linear model and the variance of the residuals should be constant in time (Salmi et al., 2002). These tests are incorporated in XLSTAT (2017) statistical analysis software that offers a wide variety of functions for data analysis. Prompted by this analysis, the rates of sea level changes from tide gauge measurements, corrected for VLM using the ICE-6G model, are compared with those obtained using satellite altimetry data. The main aim of this comparison is to check if the altimetry data are representative of a local sea level trend, as revealed by tide gauge measurements.

The rest of the paper is organized as follows. Section 2 describes the tide gauge and satellite altimetry data used in this study. The seasonal Mann-Kendall test used for trend detection and the Sen's slope approach used to estimate the magnitude of trends are explained briefly in Section 3. The obtained results are given in Section 4. These results are followed by a comparison between trends from tide gauge records and satellite altimetry measurements. Section 5 concludes.

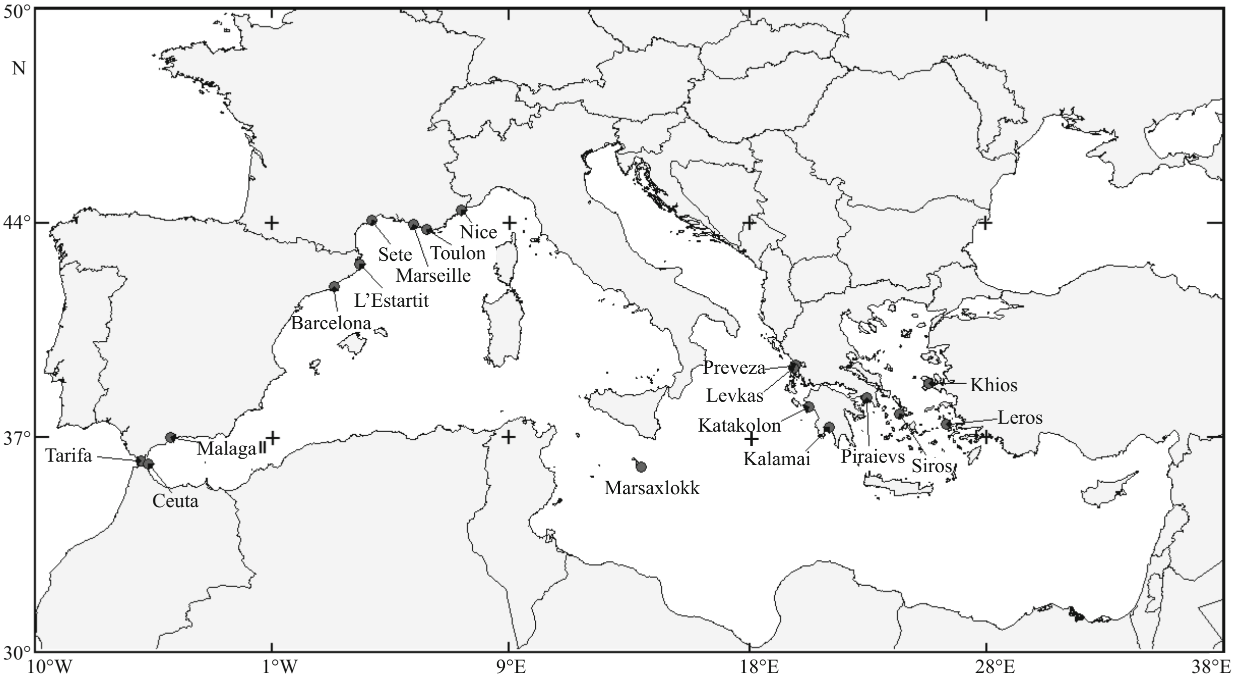

Fig.1 Tide-gauge stations distribution in the Mediterranean between January 1993 and December 2015

2 DATA

2.1 Tide gauge data

The study of the trend of sea level variability does not necessarily require direct manipulation of hourly tide gauge data. Indeed, the mechanism for calculating of average hourly data for one month or one year filters the fluctuations of short period observed in tide gauge records, that they are of irregular nature (waves of the storm, tidal wave…) or periodical (diurnal, tidal waves, tides…). The time series of monthly or annual averages are consequently suitable under investigation of the sea level variability. In this context, we have chosen within the framework of this study to analyze the available monthly averages sea level series. In the Mediterranean basin, there are nearly 100 tide gauge stations with Revised Local Reference (RLR) datasets covering the period from 1993 to 2015 (satellite altimetry era) (Holgate et al., 2013; PSMSL, 2018). Less than half of these have complete time series. Accordingly, we selected 18 tide gauge stations that have at least 80% monthly data present during the analysis period: Tarifa, Malaga II, Barcelona, L'Estartit, Sete, Marseille, Toulon, Nice, Marsaxlokk (Formally Valletta), Preveza, Levkas, Katakolon, Kalamai, Piraievs, Khios, Siros, Leros and Ceuta stations. Figure 1 shows the spatial distribution of these tide gauge stations over the Mediterranean Sea.

The corresponding monthly tidal heights series are obtained from the PSMSL. These data are of the "RLR" category, i.e., those checked in terms of quality, continuity, and local stability of the tide gauge reference. A description of data checks routinely made by the PSMSL is given in (Woodworth et al., 1990) and (IOC, 1992). Examination of sea level time series from these 18 stations is very important to perform and interpret the trend analysis. Table 1 presents the descriptive statistics of the considered series for the entire period of study (1993–2015) as well as their completeness expressed in a number of observations without missing data. The magnitude of change and its standard deviation for each tide gauge are estimated using the classical least squares method that finds the line of best fit for a dataset.

The RLR datum at each station is approximately 7 000 mm below mean sea level. This arbitrary choice was made by the PSMSL in order to avoid negative values in the resulting RLR monthly sea level time series (see Table 1, Columns from 7 to 9). The standard deviation in Column 10 of Table 1, that quantifies the dispersion of data, shows that the sea level at each station is object of strong variations due probably to the annual signal present in the Mediterranean Sea level variations (standard deviation from 56 to 95 mm) (Haddad et al., 2013a). As can be seen in Column 11 of Table 1, all the sea level series show a positive trend. However,

Table 1 Descriptive statistics of data from 18 tide gauge stations used in the study (1993–2015)

PSMSL station code	Station	Latitude (°N)	Longitude (°E)	Number of observation	Missing data	Min. (mm)	Max. (mm)	Mean (mm)	Std. (mm)	Slope (mm/a)
220/021	Tarifa	36.008 600	-5.602 600	276	3	6 858.00	7 189.00	7 030.52	62.94	4.70±0.51
220/032	Malaga II	36.711 840	-4.417 090	276	4	6 864.00	7 220.00	7 059.15	67.54	2.59±0.60
220/061	Barcelona	41.341 770	2.165 700	276	11	6 828.00	7 312.00	7 071.13	85.87	6.23±0.70
220/081	L'Estartit	42.050 000	3.200 000	276	0	6 859.00	7 275.00	7 049.37	74.34	3.51±0.64
230/021	Sete	43.397 598	3.699 100	276	48	6 715.00	7 224.00	6 931.19	86.46	4.78±0.81
230/051	Marseille	43.278 801	5.353 860	276	35	6 809.00	7 271.00	7 005.74	78.93	4.23±0.72
230/061	Toulon	43.112 898	5.914 720	276	17	6 838.00	7 231.00	7 021.67	73.36	3.60±0.66
230/081	Nice	43.695 599	7.285 500	276	49	6 872.00	7 250.00	7 047.88	72.11	3.68±0.71
265/001	Marsaxlokk	35.820 063	14.532 955	276	50	6 899.00	7 360.00	7 136.43	87.29	1.56±1.03
290/001	Preveza	38.959 078	20.756 628	276	35	6 904.00	7 298.00	7 087.25	76.92	5.17±0.63
290/004	Levkas	38.834 544	20.712 108	276	29	6 885.00	7 370.00	7 130.57	93.68	9.13±0.67
290/017	Katakolon	37.644 822	21.319 681	267	18	6 900.00	7 290.00	7 114.94	77.82	6.00±0.65
290/021	Kalamai	37.023 678	22.115 839	276	53	6 850.00	7 240.00	7 068.70	81.12	4.43±0.83
290/031	Piraievs	37.937 328	23.626 714	276	41	6 681.00	7 181.00	6 969.30	94.98	7.48±0.83
290/71	Khios	38.371 514	26.141 189	273	40	6 708.00	7 206.00	6 976.07	76.22	3.08±0.78
290/081	Siros	37.439 969	24.945 808	276	37	6 674.00	7 144.00	6 960.28	85.11	3.52±0.87
290/091	Leros	37.129 675	26.847 994	276	22	6 832.00	7 252.00	7 059.80	67.24	1.84±0.63
340/001	Ceuta	35.892 400	-5.315 890	276	4	6 838.00	7 154.00	6 999.32	56.23	1.90±0.50

concerning the Marsaxlokk (Formally Valletta) station, the reliability of its slope is rather suspicious in view of its error margin that is of the same order of magnitude (1.56±1.03 mm/a). This may be due to the multiple dysfunctions and repositioning of the float gauge thus inducing bias on the zero datum of the Marsaxlokk station. The history of this station is available from the Permanent Service for Mean Sea Level (PSMSL) web site (http://www.psmsl.org/data/obtaining/stations/1735.php). Here, we must take into account the problem of the presence or not of significant monotonic trends in time series before any estimation of the trend.

2.2 Satellite altimetry data

In this study, we also used the monthly gridded Maps of Sea Level Anomaly (MSLA) data that cover the Mediterranean basin. These data are produced by AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data) and are available through the website: http://www.aviso.oceanobs.com/. These maps cover the period from January 1993 to December 2015, with a spatial resolution of 1/8×1/8 degrees in latitude and longitude.

Sea Level Anomaly (SLA), that represents the variation of the sea surface height with respect to a several-year mean or a mean sea surface, is generally used as a precious and main indicator for the analysis of ocean variability. The main input data for processing MSLA grids are the Geophysical Data Records produced from different space altimetry missions that are therefore of the highest quality, notably in terms of satellite's orbit determination (position and altitude). All of the standard corrections to the altimeter data were applied including tropospheric and ionospheric corrections, removal of ocean tides, sea state bias correction, and inverted barometer correction (CLS, 2018). These maps of SLA are available in NetCDF format. This format is a generic format and multi-platform data storage. An exhaustive presentation of the NetCDF conventions is available on the Unidata website: http://www.unidata.ucar.edu/. The necessary routines for using the NetCDF are available on this website.

To highlight the spatial variations of the Mediterranean Sea level, a map (30°N–46°N, 6°W–37°E), showing the sea level variation rates (drift or velocity in mm/a), was performed from the monthly maps of SLA (1993–2015) by estimating the linear slopes for each cell of this map (Fig.2). As shown in Fig.2, the Mediterranean Sea level is characterized by an East-West differentiation. While the Eastern Mediterranean basin is the object of a clear increasing trend, an inverse situation occurs at

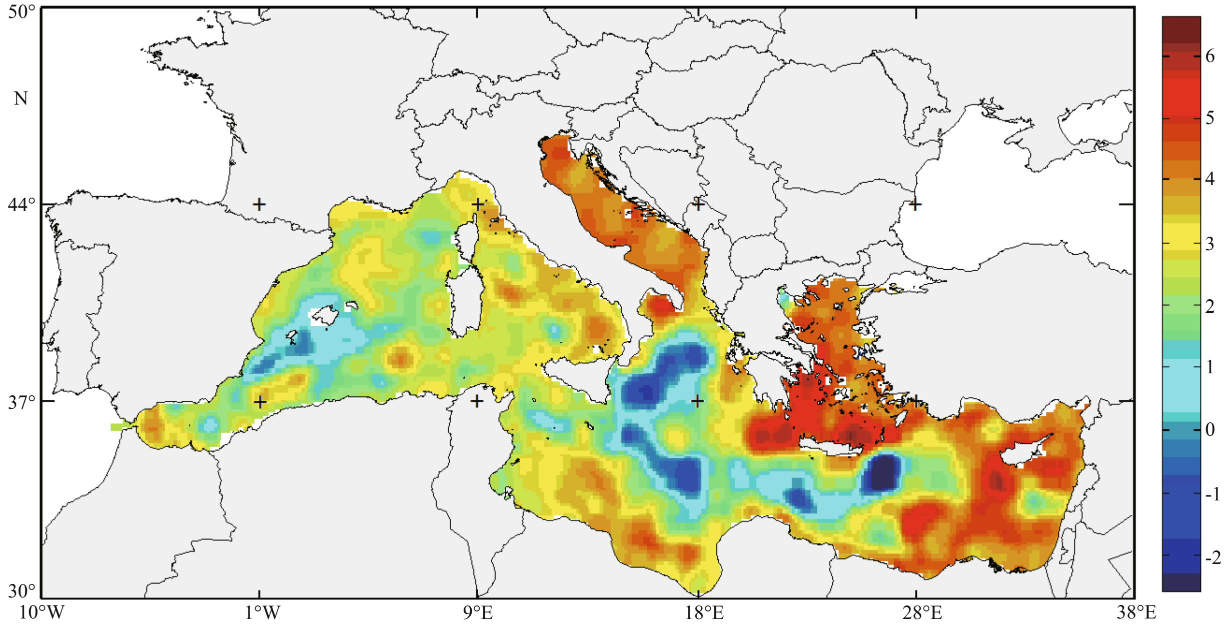

Fig.2 Rates of the Mediterranean Sea level change in mm/a between January 1993 and December 2015

Negative values (dark blue to dark green) to positive values (from green to dark red).

the Ionian Sea where the sea level is falling. The observed trends are in agreement with the results of Haddad et al. (2013b) obtained by performing a singular spectrum analysis (SSA) with satellite altimetry data to estimate the seasonal cycle and trend, in almost the same analysis period.

3 METHOD

3.1 Mann-Kendall test

The Mann-Kendall test (Mann, 1945; Kendall, 1975) is a nonparametric test that is used commonly to detect the presence or not of significant trends in environmental, climate, or hydrological time series. The null hypothesis, H_0, is that the data come from a population with independent realizations that does not follow any trend. The alternative hypothesis, H_1, is that the data follow a clear monotonic trend.

Considering a time series of n data points and t_i and t_j as two subsets of data where i=1,2,3,⋯, n−1 and j=i+1, i+2, i+3,⋯, n, the Mann-Kendall statistic S is calculated by analyzing all possible pairs of measurements in the dataset. If the earlier measurement is less in magnitude than a later one, S is incremented by one. On the other hand, if an earlier value is greater in magnitude than a later sample, S is decremented by one. For two equivalent measurement values, S remains unchanged:

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn(t_j-t_i), \tag{1}$$

with:

$$sgn(t_j-t_i)=\begin{cases}1 & \text{if } t_j-t_i>0\\ 0 & \text{if } t_j-t_i=0.\\ -1 & \text{if } t_j-t_i<0\end{cases} \tag{2}$$

The variance for the S-statistic is defined by:

$$\mathrm{Var}(S)=\left\{n(n-1)(2n+5)-\sum_{j=1}^{g}t_j(t_j-1)(2t_j+5)\right\}/18, \tag{3}$$

where n: size of the series, g: represents the number of groups of ties in the time series, and t_j: the number of ties in the j^{th} group of ties.

The statistic S is approximately normal distributed. The standardized Z-statistic for an increasing (or decreasing) trend is computed using the equation:

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S>0\\ 0 & \text{if } S=0.\\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S<0\end{cases} \tag{4}$$

The statistic Z is used as an indicator of the significance of the trend. If $|Z|$ is greater than $Z_{\alpha/2}$, where α represents the chosen significance level (eg: 5% with $Z_{0.025}$=1.96), then the null hypothesis H_0 is invalid implying that the trend is significant (Motiee and McBean, 2009). A positive value of Z indicates an increasing trend and a negative value indicates a decreasing trend. Using P-value calculated for Z, H_0 is rejected if $P<\alpha$.

The seasonal Mann-Kendall (Hirsch et al., 1982) is a simple modification to the Mann-Kendall test that accounts for apparent seasonal fluctuations in the series. It is suitable for seasonal data with a moderate level of autocorrelation between the different components of the series and may be used even in the case of presence of missing data in the series. This seasonal approach runs a separate Mann Kendall trend test on each of m seasons separately, where m is the number of separate seasons (Spring, Summer etc.). Seasonal can also refer to other time periods, like hours, days, or months.

The test consists of computing the Mann-Kendall statistic S_i and its variance $\mathrm{Var}(S_i)$ for each season with data collected over years. For monthly time series, January would only be compared with January and February would only be compared with February, etc. The overall seasonal Mann-Kendall statistic S' is calculated from summing each season's Kendall S statistic, and the Z' statistic is computed:

$$S'=\sum_{i=1}^{m}S_i, \tag{5}$$

$$\mathrm{Var}(S')=\sum_{i=1}^{m}\mathrm{Var}(S_i), \tag{6}$$

$$Z'=\begin{cases}\dfrac{S'-1}{\sqrt{\mathrm{Var}(S')}} & \text{if } S'>0\\ 0 & \text{if } S'=0.\\ \dfrac{S'+1}{\sqrt{\mathrm{Var}(S')}} & \text{if } S'<0\end{cases} \tag{7}$$

The hypothesis H_0 is rejected in favor of the alternative hypothesis of a downward trend if Z' is negative and If $|Z'|$ is greater than $Z'_{\alpha/2}$. Using P-value calculated for Z', H_0 is rejected if $P<\alpha$. For further information, the reader is referred to Hipel and McLeod (1994) and Hirsch et al. (1982).

3.2 Sen's slope estimator

Sen's slope estimation (Sen, 1968) is a non-parametric method that is used for analysis of the magnitude of the trend. The advantage of using Sen's slope is that it is not affected by the possible presence of outliers and data errors in the dataset (Salmi et al., 2002). This method assumes that the trend line is a linear function in the time series:

$$f(t)=Qt+\mathrm{B}, \tag{8}$$

where Q is the slope and B is a constant.

The slopes of all data pairs t_j and t_k for j and k times of a period, where $j>k$, are calculated as follow:

$$Q_i=\frac{t_j-t_k}{j-k}, i=1, 2, \cdots, n. \tag{9}$$

Median is computed from n observations of the slope to estimate the Sen's Slope estimator.

The simple Sen's Slope estimator can be modified to account for seasonality in the observations (Hirsch et al., 1982). It is calculated by the following formula:

$$Q_{ijk}=\frac{t_{ij}-t_{ik}}{j-k}. \tag{10}$$

For each (t_{ij}, t_{ik} pair i=1, 2,$\cdots$, m, where$1\le k\le j\le n_i$ and n_i is the number of known values in the i^{th} season. The seasonal slope estimator is the median of the Q_{ijk} values.

Software used in this study for performing the statistical seasonal Mann-Kendall test and seasonal Sen's slope estimator is Addinsoft's XLSTAT (2017).

4 RESULT AND DISCUSSION

The trend analysis of the sea level series has been done using the data of Tarifa, Malaga II, Barcelona, L'Estartit, Sete, Marseille, Toulon, Nice, Marsaxlokk (Formally Valletta), Preveza, Levkas, Katakolon, Kalamai, Piraievs, Khios, Siros, Leros and Ceuta tide gauge stations. Here, we used a P-value approach to test the null hypothesis, H_0, of no trend versus the alternative hypothesis, H_1, of either an upward or downward trend. Table 2 gives the results of the running of the seasonal Mann-Kendall test on tidal heights data for the considered 18 stations. The hypothesis H_0 is rejected when P-value is less than the considered significance level α of 0.05. The reject of the null hypothesis meaning the presence of a trend in the series is statistically significant. Table 2 indicates that acceptance of the null hypothesis (H_0) occurred only for the Marsaxlokk (Formally Valletta) station (the P-value of the test of 0.374 is greater than the significance level α of 0.05). For the remainder, the results show a significant positive trend (P-value$<\alpha$). We can conclude that relative sea level changes along the Mediterranean Sea coast are the object of increasing behavior during 1993–2015.

Using the seasonal Sen's approach, the rate of change over time (in mm per year) of each sea level time series, that exhibits a statistically significant monotonic trend, is computed as the median of all

Table 2 Trend analysis of tide gauge data 1993–2015 using seasonal Mann-Kendall test

PSMSL station code	Station	Statistics S'	Var S'	P value of the test	Null hypothesis (H_0)	Risk of rejecting the null hypothesis (%) while it is true	Direction of trend
220/021	Tarifa	1 367.000	16 657.000	<0.000 1	Rejected	<0.01	+
220/032	Malaga II	737.000	16 505.667	<0.000 1	Rejected	<0.01	+
220/061	Barcelona	1 421.000	15 316.333	<0.000 1	Rejected	<0.01	+
220/081	L'Estartit	1 081.000	17 191.000	<0.001	Rejected	<0.01	+
230/021	Sete	691.000	9 896.333	<0.001	Rejected	<0.01	+
230/051	Marseille	771.000	11 605.667	<0.001	Rejected	<0.01	+
230/061	Toulon	791.000	14 379.667	<0.001	Rejected	<0.01	+
230/081	Nice	625.000	9 709.000	<0.001	Rejected	<0.01	+
265/001	Marsaxlokk	74.000	9 616.667	0.450 5	Not rejected	45.05	+
290/001	Preveza	935.000	11 518.333	<0.001	Rejected	<0.01	+
290/004	Levkas	1 341.000	12 489.667	<0.001	Rejected	<0.01	+
290/017	Katakolon	1 121.000	12 219.667	<0.001	Rejected	<0.01	+
290/021	Kalamai	617.000	9 137.000	<0.001	Rejected	<0.01	+
290/031	Piraievs	894.000	10 648.667	<0.001	Rejected	<0.01	+
290/71	Khios	395.000	10 311.667	0.000	Rejected	<0.01	+
290/081	Siros	566.000	11 147.333	<0.001	Rejected	<0.01	+
290/091	Leros	355.000	13 347.667	<0.002	Rejected	<0.21	+
340/001	Ceuta	729.000	16 492.333	<0.001	Rejected	<0.01	+

H_0: there is no trend in the series; H_1: there is a trend in the series.

Table 3 Rates of change estimated from tide gauge measurements and satellite altimetry (1993–2015)

PSMSL station code	Station	Latitude (N°)	Longitude (E°)	Tide gauge (mm/a)	VLM (mm/a)	Tide gauge (VLM corrected) (mm/a)	Altimetry (mm/a)	Difference (mm/a)
220/021	Tarifa	36.008 600	-5.602 600	4.65	-0.27	4.92	2.35	2.57
220/032	Malaga II	36.711 840	-4.417 090	2.20	-0.21	2.41	3.37	-0.96
220/061	Barcelona	41.341 770	2.165 700	6.36	-0.37	6.73	2.74	3.99
220/081	L'Estartit	42.050 000	3.200 000	3.83	-0.39	4.22	2.80	1.42
230/021	Sete	43.397 598	3.699 100	4.72	-0.20	4.92	2.91	2.01
230/051	Marseille	43.278 801	5.353 860	3.82	-0.32	4.14	3.26	0.88
230/061	Toulon	43.112 898	5.914 720	3.28	-0.39	3.67	3.09	0.58
230/081	Nice	43.695 599	7.285 500	3.26	-0.29	3.55	2.43	1.12
290/001	Preveza	38.959 078	20.756 628	6.02	-0.13	6.15	2.85	3.30
290/004	Levkas	38.834 544	20.712 108	8.57	-0.15	8.72	3.15	5.57
290/017	Katakolon	37.644 822	21.319 681	5.68	-0.24	5.92	3.59	2.33
290/021	Kalamai	37.023 678	22.115 839	4.21	-0.28	4.49	3.52	0.97
290/031	Piraievs	37.937 328	23.626 714	7.24	-0.15	7.39	5.24	2.15
290/71	Khios	38.371 514	26.141 189	2.78	-0.09	2.87	3.92	-1.05
290/081	Siros	37.439 969	24.945 808	3.67	-0.23	3.90	4.59	-0.69
290/091	Leros	37.129 675	26.847 994	1.32	-0.16	1.48	4.37	-2.89
340/001	Ceuta	35.892 400	-5.315 890	1.63	-0.26	1.89	2.38	-0.49

slopes between data pairs within the same season. The obtained trend values are given in Table 3, Column 5. Corrections for VLM due to postglacial rebound (Table 3, Column 6) are derived from predictions of the ICE-6G model of Peltier et al. (2015), which is available from the University of Toronto web site:

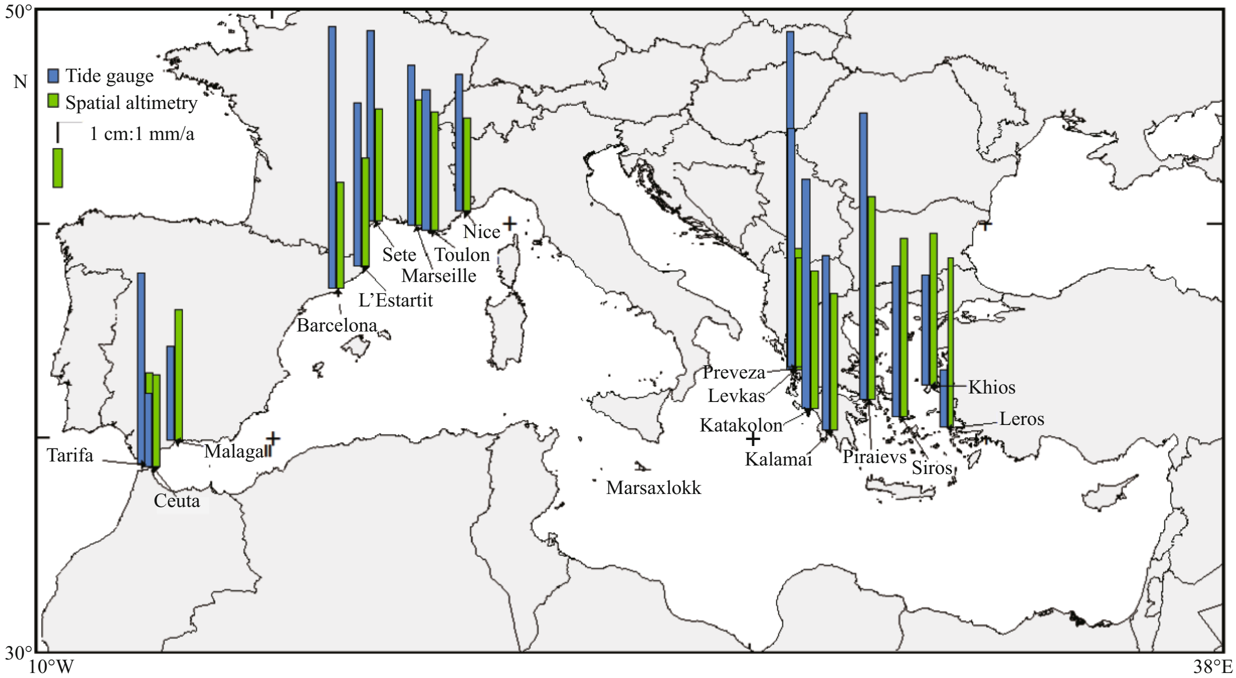

Fig.3 Geographical distribution of estimated magnitudes of change from tide gauges and satellite altimetry measurements (1993–2015)

www.atmosp.physics.utoronto.ca/~peltier/data.php.

An increasing annual trend is detected for all stations that exhibit a statistically significant trend. After VLM corrections, the largest annual trend is noticed for the Levkas station with a rate of change of 8.72 mm/a, whereas the low annual trend is observed for the Leros station with a value of 1.48 mm/a (Table 3, Column 7). These results provide further evidence, if needed, the rise in the costal Mediterranean Sea level.

With the aim to assess whether offshore altimetry signals were representative in term of temporal variability of the local sea level along the coasts of the Mediterranean basin, as seen from the tide gauges records, the magnitude of change at the location of each tide gauge station was estimated from the drift map (Fig.2) using the nearest-neighbor interpolation method.

The obtained rates of change, estimated from the analysis of in-situ tidal gauge and satellite altimetry data (Table 3, Columns 7 and 8), show positive linear trends during 1993–2015. These results are sufficient to admit the rise in the coastal sea level of the Mediterranean Sea. The differences between the estimated rates from in-situ and satellite measurements vary, in absolute value, from 0.49 to 5.57 mm/a in an average of 1.94 mm/a (Table 3, Column 9). These differences corroborate the agreement and the complementarity of the two techniques of measurement (satellite altimetry and tide gauge) to cover the Earth's ocean surfaces, just as well in the open ocean as in coastal areas.

Nevertheless, note that the main reasons for the difference between the trends estimated from these two techniques are due to the lack of altimetry data in the coastal areas of the fact that the observations are confined typically every 10 days along the ground tracks, which decreased the accuracy of the corrective terms within this dynamic environment operating between land and sea. Tide gauges are fundamentally different which measuring in situ sea level each second to hour accurately at selected coastal locations.

For illustrative purposes, the rates of change estimated from tide gauges and satellite altimetry measurements for the period from 1993 to 2015 are illustrated in Fig.3. The highest tide gauge sea-level trend is estimated at the Levkas station to 8.72 mm/a, on the Western coast of Greece. This value is 5.57 mm/a higher than the absolute trend estimated at the nearest satellite grid point, 3.15 mm/a (see Fig.2), suggesting a strong subsidence rate at this site.

5 CONCLUSION

The main objective of this study is to take advantage of tide gauge and satellite altimetry techniques to monitor sea level variability along the Mediterranean

Sea coast. To that end, we have analyzed 18 tidal height series that are available over the satellite altimetry era period (1993–2015). The seasonal Mann-Kendall test is performed to identify statistically significant trends of these series. The magnitudes of sea level change, estimated by the use of seasonal Sen's approach, show that there is an increase in sea level for all tide gauge stations that exhibit a significant trend. After correction for vertical land motions (VLM) due to postglacial rebound, the magnitudes of changes are from 1.48 to 8.72 mm/a during 1993–2015.

A second analysis was carried out in order to assess whether the altimetry data can be representative of the local sea level along the Mediterranean coast. For this purposes, monthly maps of sea level anomaly derived from different space altimetry missions at the Mediterranean scale were analyzed. The results indicate that there is a clear differentiation between the behavior of the Eastern and the Western parts of the Mediterranean Sea. While a greater rise was observed in the Eastern Mediterranean Sea, the Ionian Sea level fell during 1993–2015.

These rates from the altimetry measurements were exploited to provide the magnitude of change at the location of each tide gauge station, using the nearest-neighbor interpolation method. The differences between the estimated rates of sea level change from in-situ tide gauge and satellite measurements vary, in absolute value, from 0.49 to 5.57 mm/a with an average of 1.94 mm/a. One of the reasons for these differences can be attributed to the fact that the altimetry measurements are not accurate near the coasts. Nevertheless, all local trends, estimated from the set of in-situ tide gauge and satellite altimetry data, show positive rates during 1993–2015. This finding is sufficient to admit firstly the coastal sea level rise of the Mediterranean basin, and secondly, the complementarity of the two measurement techniques (satellite altimetry and tide gauges).

In the face of climate change phenomenon, this experimentation shows the efficacy of statistical tests in detecting the sea level trends derived from the tidal gauge measurements. The obtained results may appear primary; however, these trends are essential for climatologists to determine what correlations exist between climatic events that the Earth is undergoing. To conclude, evidence from this study confirms that the coastal Mediterranean Sea level has risen during the period of the altimetry era (1993–2015).

6 DATA AVAILABILITY STATEMENT

The tide gauge data that support this study are available from the Permanent Service of Mean Sea Level (PSMSL) Website: http://www.psmsl.org. The altimetry data that support this study are available from AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data) through the website: http://www.aviso.oceanobs.com/.

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