Sea level variability at Antalya and Menteş tide gauges in Turkey: atmospheric, steric and land motion contributions

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ABSTRACT

Sea level trends and interannual variability at Antalya and Menteş tide gauges are investigated during the 1985-2001 period, quantifying the roles of atmospheric, steric and local land motion contributions. Tide gauge sea level measurements, temperature/salinity climatologies and GPS data are used in the analyses and the results are compared with the output of a barotropic model forced by atmospheric pressure and wind. The overall sea level trends at two tide gauges collocated with GPS are in the range of 5.5 to 7.9 mm/yr during the study period, but showing different behaviour in the sub-periods 1985−1993 and 1993−2001 due to variations in the contributing factors both in space and time. After the removal of the atmospheric forcing and steric contribution from sea level records, the resulting trends vary between 1.9 to 4.5 mm/yr in Antalya and −1.2 to −11.6 mm/yr in Menteş depending on the period considered. Vertical land movement estimated from GPS data seems to explain the high positive residual trend in Antalya during the whole period. On the other hand, the source of the highly negative sea level trend of about −14 mm/yr in Menteş during 1985−1993 could not be resolved with the available datasets. Interannual variability of wind and atmospheric pressure appear to dominate the sea level at both tide gauges during the study period. Atmospheric and steric contributions together account for ~50% of the total sea level variance at interannual time scales. Mass induced sea level variations which were not considered in this study may help to close the sea level trend budgets as well as to better explain the interannual sea level variance.

Keywords: coastal sea level trend, interannual sea level variation, atmospheric contribution, steric effect, GPS, vertical land movement

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1. INTRODUCTION

Understanding the mechanisms of sea level change is one of the major concerns of geosciences in the age of climate change, with consequences implied for coastal ecosystems and human societies. As emphasized in the Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC), sea level rise is not uniform for the whole globe (*Solomon et al., 2007*). Strong dependence on locality creates a demand for better estimates of regional sea level variations as well as a better understanding of the physical factors causing them.

Historical tide gauge records provide sufficient information to detect sea level change during the last century, provided that true sea level variation can be differentiated from Vertical Land Movement (VLM) inherently present in the same record. While it is possible to make VLM correction based on Glacial Isostatic Adjustment (GIA) models, these models do not fully explain the VLM component on a global basis (*Teferle et al., 2006*; *Wöppelman et al., 2007*). Therefore, independent geodetic techniques such as Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), absolute gravity, Interferometric Synthetic Aperture Radar (InSAR) etc. are often used for direct determination of VLM to reduce or overcome the contamination of sea level signal, especially at tectonically active regions such as Anatolia. The sea level signal that is corrected for VLM contains the remaining contributions of astronomical and meteorological origin, changes in oceanic circulation, as well as elements reflecting the variations in sea water density (steric contribution) and mass. By utilizing numerical models forced by atmospheric fields, temperature/salinity climatologies and GPS data, it is now possible to separate out the atmospheric, steric and VLM contributions from the observed sea level.

The Mediterranean Sea, a semi-enclosed deep sea subdivided into number of sub-basins each with their own characteristics, underwent a series of important changes in sea level over the past few decades. The 1990s are of particular importance for the Eastern Mediterranean basin, because of the occurrence of the Eastern Mediterranean Transient (EMT) between 1987–1995 (*Roether et al., 1996*) accompanied with significant circulation changes (*Malanotte-Rizzoli et al., 1999*) and steric height reduction around the 1990 (*Tsimplis and Rixen, 2002*), followed by fast sea level rise in 1993–1999 (*Cazenave et al., 2001*; *Fenoglio-Marc, 2002*), and abrupt reduction of sea level rise rates as well as negative trends in parts of the basin after mid-1999 (*Vigo et al., 2005*). Several complementary studies have been carried out to investigate the possible causes of sea level trends in the region. Atmospheric pressure changes between 1960 and early 1990s (*Tsimplis and Josey, 2001*), as well as temperature reduction and salinity changes linked to the North Atlantic Oscillation (NAO) have been claimed (*Tsimplis and Rixen, 2002*) as factors contributing to the sea level decrease prior to early 1990s. Fast sea level rise during the 1993–1999 period has been linked to changes in observed sea surface temperature (*Cazenave et al., 2001*). It was suggested by *Vigo et al. (2005)* that the sea level drop in the Mediterranean Sea after mid-1999 might be related to a return to the pre-EMT conditions. Recently *Tsimplis et al. (2005)*, *Marcos and Tsimplis (2008)*, *Tsimplis et al. (2008)* have separated the atmospheric and steric contributions from coastal sea level records in the Mediterranean, leaving significant residual trends. *Criado-Aldeanueva et al.*

(2008) suggested a basin averaged mass-induced sea level rise of 1 mm/yr for the Mediterranean Sea during 1992–2005, also demonstrating the dependence of mass-induced sea level trends on location. Recently, *Calafat et al. (2010)* found a mass-induced sea level rise of 0.8 ± 0.1 mm/yr for the 1948–2000 period.

However, only the ongoing GIA contribution to land motion has been considered in these studies, neglecting other possible sources. Since the GIA correction for the Mediterranean is less than ~ 0.5 mm/yr, only a minor part of the residual trend could be attributed to local land motion, leaving the rest of the residual unexplained. With these issues in mind, the aim of the present work is to interpret trends and interannual variability based on long term (1985–2001) sea level records obtained from two longest Turkish tide gauges: Menteş on the Aegean coast and Antalya on the Eastern Mediterranean coast of Turkey, complemented by the results from a barotropic model, as well as temperature/salinity and GPS data. A more accurate VLM correction is found from the GPS data, rather than relying on the GIA model. In addition, we provide the first estimates of low frequency sea level variations in the study region, with possible contribution to climate change studies in the Eastern Mediterranean.

2. DATA SOURCES

2.1. Tide Gauge Data

Monthly average sea level data from Antalya and Menteş tide gauges (Fig. 1) of the Turkish National Sea Level Monitoring System, operated by General Command of Mapping are used in this study. The first systems installed in early 1985 based on mechanical float gauges in stilling wells were replaced with acoustic gauges later in 1999. Since their first installations, routine leveling between the contact points of the gauges and benchmarks have been performed to ensure datum stability. Precise leveling measurements were also carried out between primary benchmarks of the initial and the replaced gauges, allowing correction of datum bias. Delayed mode quality checks of hourly sea level data were performed following the guidelines of the Global Sea Level Observing System (*http://www.gloss-sealevel.org/*) and the European Sea Level Service (*http://www.eseas.org/*). Daily and monthly means were calculated after filtering the hourly values. Monthly means are formed for those records covering at least half of the month. Data gaps shorter than 3 months are filled by linear interpolation in time.

2.2. The 2-D Barotropic Model

We use the output of a barotropic version of the HAMburg Shelf Circulation Model (HAMSOM) (*Alvarez-Fanjul et al., 1997*) to quantify the meteorological contribution to sea level trends. The data have been produced in the framework of the Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe (HIPOCAS) project (*Guedes Soares et al., 2002*) and obtained from Puertos del Estado database (*www.puertos.es*). The atmospheric pressure and wind fields produced by a dynamical downscaling of the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) reanalysis for the period 1958–2001 (*García-Sotillo et al., 2005*) were used to force a barotropic version of the HAMSOM model over the domain 30°N to 47°N and 12°W to 35°E covering the Mediterranean Sea

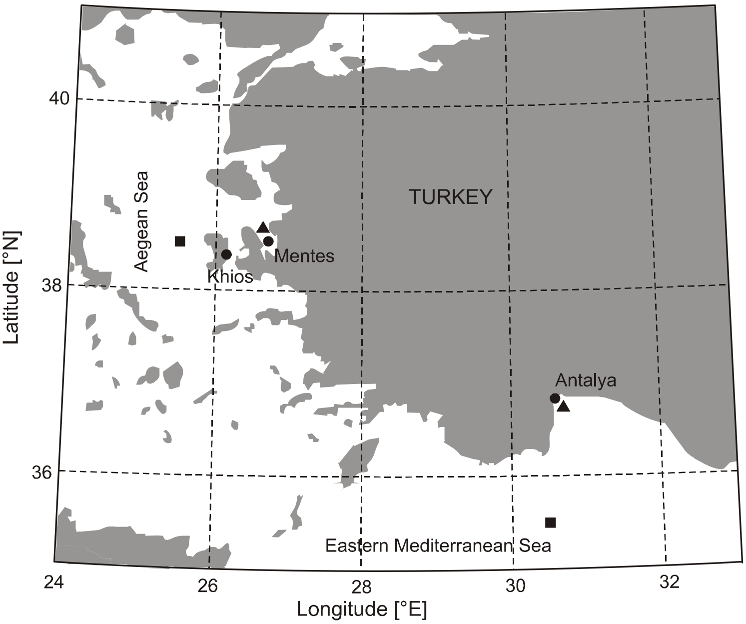

Fig. 1. Location of tide gauge stations (circles) and corresponding HIPOCAS (triangles) and steric (squares) points in the region.

and part of the Eastern Atlantic, with a spatial resolution of 1/4° × 1/6°. For each tide gauge station, monthly model values from the closest point of the HIPOCAS grid (Fig. 1) are used to correct sea level observations for atmospheric contribution.

2.3. Hydrographic Data

For the estimation of steric contribution to sea level, we use the gridded monthly subsurface temperature (T) and salinity (S) data of *Ishii and Kimoto (2009)* (version 6.7 objectively analyzed and gridded at 1° × 1° in the horizontal and at 16 levels in the upper 700 m in the vertical). The analysis has been based on data from the World Ocean Database/Atlas 2005, temperature/salinity in the tropical pacific provided by IRD (L'Institut de Recherché pour le Development, France), and sea surface temperature from the Centennial in situ Observation Based Estimates (COBE). ARGO profiling buoy data (*http://www.argo.ucsd.edu*; *http://argo.jcommops.org*) have also been used in the final several years. In version 6.7, the XBT and MBT depth bias correction has been applied (*Ishii and Kimoto, 2009*). The dataset (number ds285.3 at *http://dss.ucar.edu*) is obtained from the Research Data Archive maintained by the Computational and Information Systems Laboratory at the National Center for Atmospheric Research. The steric component has been computed as the vertical integration from surface to the bottom of the specific volume anomaly (*Tsimplis et al., 2009*). Nearest grid points to the tide gauges depicted in Figure 1 are used to account for steric sea level variations following *Marcos and Tsimplis (2007)* and *Tsimplis et al. (2005).* As a result of the limitation in depth range of the available T and S data, steric variations are computed for the top 700 m at Antalya, and for 600 m at Menteş. Detrended and atmospherically corrected tide gauge sea levels correlate equally well with the steric sea level at the nearest grid points. Correlation coefficients are 0.47 at Antalya and 0.44 at Menteş, both significant at 95% confidence level.

2.4. GPS Data

General Command of Mapping performs episodic GPS (EGPS) campaigns at 2−3 year intervals at Turkish tide gauges in order to place sea level records in a well-defined global reference system as well as to precisely monitor the VLM at tide gauges. Since 1992, 14 and 11 GPS campaigns respectively have been conducted at Antalya and Menteş, each covering 1−8 independent occupations with observation session lengths of about 5−7 hours. In addition, we have taken the advantage of continuous GPS (CGPS) stations established at Antalya in December 2003 and at Menteş in August 2003 within less than 300 m distance to tide gauge stations. Although these stations now provide sufficient record lengths to reliably determine VLM rates minimizing seasonal influences on estimated velocity (*Blewitt and Lavallée, 2002*), their time spans do not coincide with the 1985−2001 study period. Therefore, we prefer to use EGPS data coinciding with the second half of the same period to estimate VLM rates at tide gauge locations. CGPS time series spanning more than 5 years are used to assess VLM rates inferred from EGPS over the common the time period 2003−2009.

The dual-frequency GPS phase and pseudo-range data of episodic and CGPS sites used in the study are processed by using GAMIT/GLOBK (v.10.3) software (*Herring et al., 2006a,b*). All corrections except atmospheric pressure loading are applied in accordance with International GNSS Service (IGS) and International Earth Rotation and Reference Systems Service (IERS) conventions. IGS precise ephemeris in sp3 format (*Dow et al., 2009*) and Bulletin A earth rotation parameters published by IERS are utilized in the process. We use absolute elevation-dependent antenna phase center corrections for satellites and receivers and apply solid Earth and polar tide corrections following the 2003 IERS conventions (*McCarthy and Petit, 2004*) and FES2004 model for ocean tide loading corrections. Tropospheric parameters are estimated for 2 hour intervals including horizontal tropospheric gradients with the use of Global Mapping Functions of *Boehm et al. (2006)*. Since in situ meteorological data are not available at the sites, we use the Global Pressure and Temperature model developed by *Boehm et al. (2007)* for a priori pressure and temperature estimates.

We include 14 IGS sites surrounding Turkey in the process where a series of loosely constrained daily GPS network solutions are obtained for episodic GPS and CGPS sites. Loosely constrained daily GPS solutions and SOPAC (Scripps Orbit and Permanent Array Center) loosely constrained solutions (hfiles) which include all IGS stations coordinates in the world, orbit parameters and variance-covariance matrix are directly combined. Combined solutions are then transformed into coordinate time series by using 3-D seven-parameter Helmert transformation (three translations, three rotations and one scale parameter) and stations whose positions and velocities are defined in ITRF-2005. Global reference frame is defined with selected 59 IGS stations, those used by *Altamimi et al. (2002)* in the realization of ITRF-2000. Because of the relatively lower accuracy of the vertical coordinates with respect to horizontal, the weights of the vertical coordinates of the IGS core sites used for datum realization are reduced by a factor of 100 in the transformation. Finally, coordinate time series are obtained and examined for outliers and jumps.

There is a large gap in Menteş CGPS time series between 2008 and 2010 due to instrument malfunction. Antalya CGPS time series shows a large deviation during the 2006.5–2007.5 period. We investigated the reason of this deviation by using the precise leveling measurements carried out between the CGPS pillar and the tide gauge leveling benchmarks in the region. We found that CGPS pillar has moved downward in the order of 4 cm with respect to the leveling benchmarks. The period of this deviation in the CGPS time series coincides with the port enlargement project carried out near the Antalya CGPS pillar. We consider that huge rocks and other heavy construction materials piled in the vicinity of the CGPS site during the port project may have caused the local instability of the CGPS pillar. As we detected local effects to be responsible for the change, we removed this period of large deviations from the CGPS time series.

3. DATA ANALYSIS AND RESULTS

3.1. Methodology

The observed, meteorologically induced and steric sea level trends are determined by least squares linear regression of time series covering the common period of the three datasets (1985–2001). Prior to trend computation, we remove the mean seasonal cycle from each dataset. The mean seasonal cycle is estimated by calculating the mean monthly value for each month on the basis of full years only, in order to avoid biases being introduced. The mean value of each month is then removed from all corresponding months in all years. Residual time series are produced by subtracting the atmospheric and steric contributions from the tide gauge measurements. In estimating 95% confidence intervals of the computed sea level trends, noise components in each dataset are assumed to be statistically independent. Interannual meteorological and steric effects on sea level are evaluated by multiple linear regression analysis applied to de-trended and de-seasoned data.

Vertical velocities from EGPS and CGPS data are estimated using CATS (Create and Analyze Time Series) software developed by *Williams (2008)*, based on the assumption that a pure white noise model yields over-optimistic estimation of the parameter uncertainties. Daily estimates of GPS coordinates demonstrate time-correlated (colored) noise and it is therefore incorrect to assume that the observations are independent when estimating parameters from them (*Zhang et al., 1997*; *Mao et al., 1999*; *Williams, 2003*; *Williams et al., 2004*). The CATS program uses Maximum Likelihood Estimation to fit a multi-parameter model to CGPS time series, while simultaneously analyzing the data to assess the type and magnitude of the noise contained in the series. For determination of the VLM rates at tide gauge CGPS stations and their associated uncertainties, a mathematical model including the velocity and annual and semiannual seasonal components is used while only a linear model is applied to EGPS time series, without making a priori assumptions on the noise characteristics.

Table 1. Sea level trends in mm/yr for the whole data period 1985–2001, and its sub-periods 1985–1993 and 1993–2001. Observed, atmospheric, total steric, thermosteric, halosteric and residual (observation minus atmospheric and total steric) contributions to sea level trend. All uncertainties are given at the 95% confidence level.

Tide Gauge	Period	Observed	Atmos.	Steric			Residual
				Total	*T* Only	*S* Only	
Antalya	1985–2001	7.9 ± 0.8	0.6 ± 0.4	2.5 ± 0.4	1.9 ± 0.3	0.6 ± 0.3	4.5 ± 0.7
	1985–1993	−3.9 ± 2.7	−2.4 ± 1.2	−3.5 ± 1.2	−0.8 ± 0.6	−2.7 ± 1.1	1.9 ± 2.1
	1993–2001	12.3 ± 1.7	0.9 ± 0.8	8.5 ± 0.8	7.4 ± 0.8	1.1 ± 0.2	3.1 ± 1.6
Menteş	1985–2001	5.5 ± 1.0	0.9 ± 0.5	6.4 ± 0.7	1.9 ± 0.3	4.6 ± 0.6	−3.3 ± 1.0
	1985–1993	−14.1 ± 3.4	−3.1 ± 1.6	−3.5 ± 2.9	−1.0 ± 0.8	−2.6 ± 2.7	−11.6 ± 4.1
	1993–2001	10.8 ± 1.9	1.4 ± 1.1	10.5 ± 0.7	9.8 ± 0.6	0.7 ± 0.3	−1.2 ± 1.8

3.2. Sea Level Trends and Variability

Sea level trends based on tide gauge measurements and their estimated atmospheric and steric components are compared in Table 1. Observed sea level trends for the period 1985–2001 vary between 7.9 ± 0.8 mm/yr in Antalya and 5.5 ± 1.0 mm/yr in Menteş (Figs. 2a and 3a). Over this period, positive sea level trends of about 0.6 ± 0.4 mm/yr in Antalya and 0.9 ± 0.5 mm/yr in Menteş can be attributed to changes in wind and atmospheric pressure (Figs. 2b and 3b), based on the HIPOCAS product. On the other hand, the steric contribution to the sea level trend appears to be greater, being 2.5 ± 0.4 mm/yr in Antalya and 6.4 ± 0.7 mm/yr in Menteş (Figs. 2c and 3c). While the thermosteric contributions are equal at both tide gauges (Figs. 2d and 3d), salinity induced steric sea level trend at Menteş is three times stronger than that of Antalya during the whole data period 1985–2001 (Figs. 2e and 3e). The residuals obtained after removing the atmospheric and steric effects from the observations yield a positive trend of 4.5 ± 0.7 mm/yr in Antalya and a negative trend of −3.3 ± 1.0 mm/yr in Menteş, respectively (Figs. 2f and 3f).

Two distinct periods, 1985–1993 and 1993–2001, apparent in the sea level time series of both tide gauges are studied to better understand the largely different residual trends at these two stations during the 1985–2001 period. During the first period between 1985 and early 1993, both tide gauges show a clear drop in all components of sea level (Table 1). In this period, at Antalya, negative trends of −3.9 ± 2.7 mm/yr, −2.4 ± 1.2 mm/yr and −3.5 ± 1.2 mm/yr respectively are found in the observed, atmospheric and steric sea level components. The halosteric component is the main contributor to the total steric variation in Antalya during this period. Increased salinity and cooling in the region during the EMT event (*Roether et al., 1996*; *Tsimplis and Rixen, 2002*) and direct atmospheric forcing dominating the Mediterranean Sea level before 1993 (*Tsimplis et al., 2005*) are considered to be the responsible for the observed sea level drop at Antalya in this period. At Menteş, however we found a highly negative trend of −14.1 ± 3.4 mm/yr for the 1985–1993 period although the atmospheric and steric sea level trends are similar to those found in Antalya (Table 1). We make a comparison between Menteş and the neighboring RLR Greek

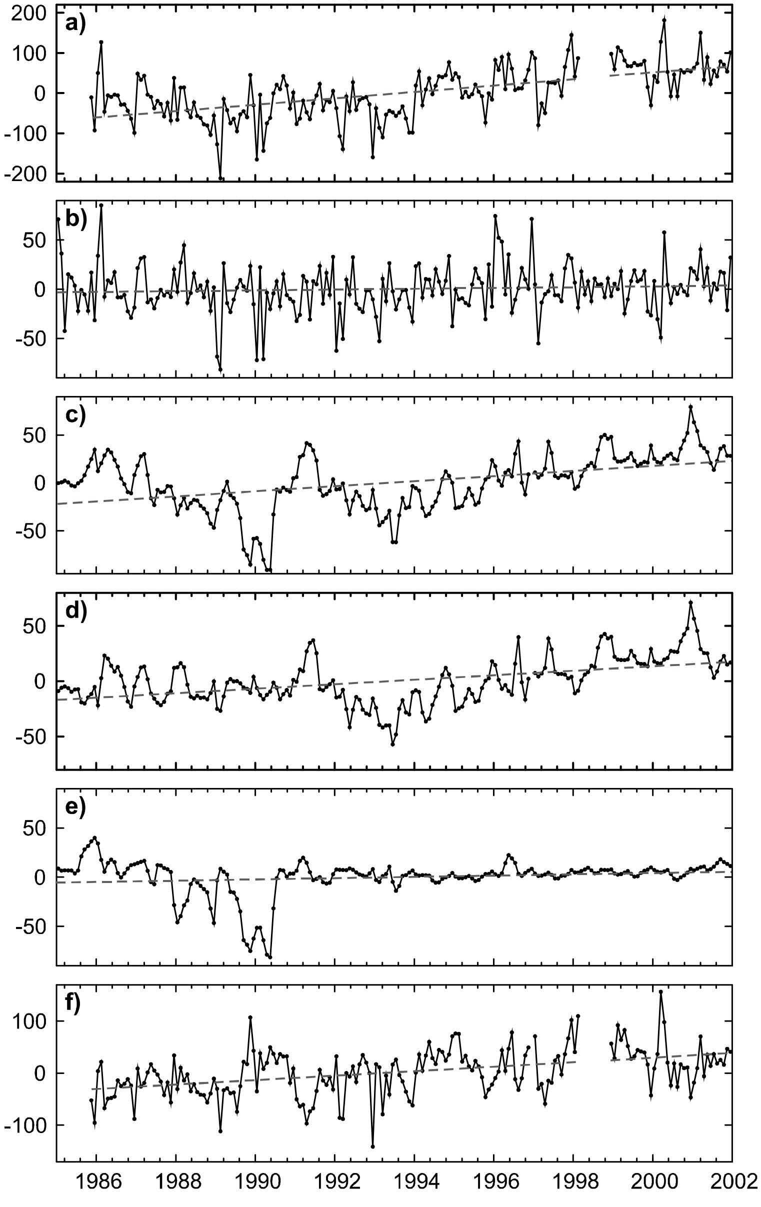

Fig. 2. Sea level trends (dashed lines) in Antalya for the period 1985−2001. **a)** Observed; **b)** atmospherically-induced; **c)** total steric; **d)** thermosteric; **e)** halosteric sea level changes. **f)** Residual (observation minus atmospheric and total steric contribution) sea level. Data are in millimeters.

station Khios (www.psmsl.org), located at an island which is only 50 km away from the Menteş tide gauge. Fig. 4 compares Menteş and Khios tide gauge monthly sea level observations between 1985 and 1993. Menteş sea level observations correlate well with the Khios sea level (~ 0.80 significant at the 95% level). Moreover, the de-seasoned Khios

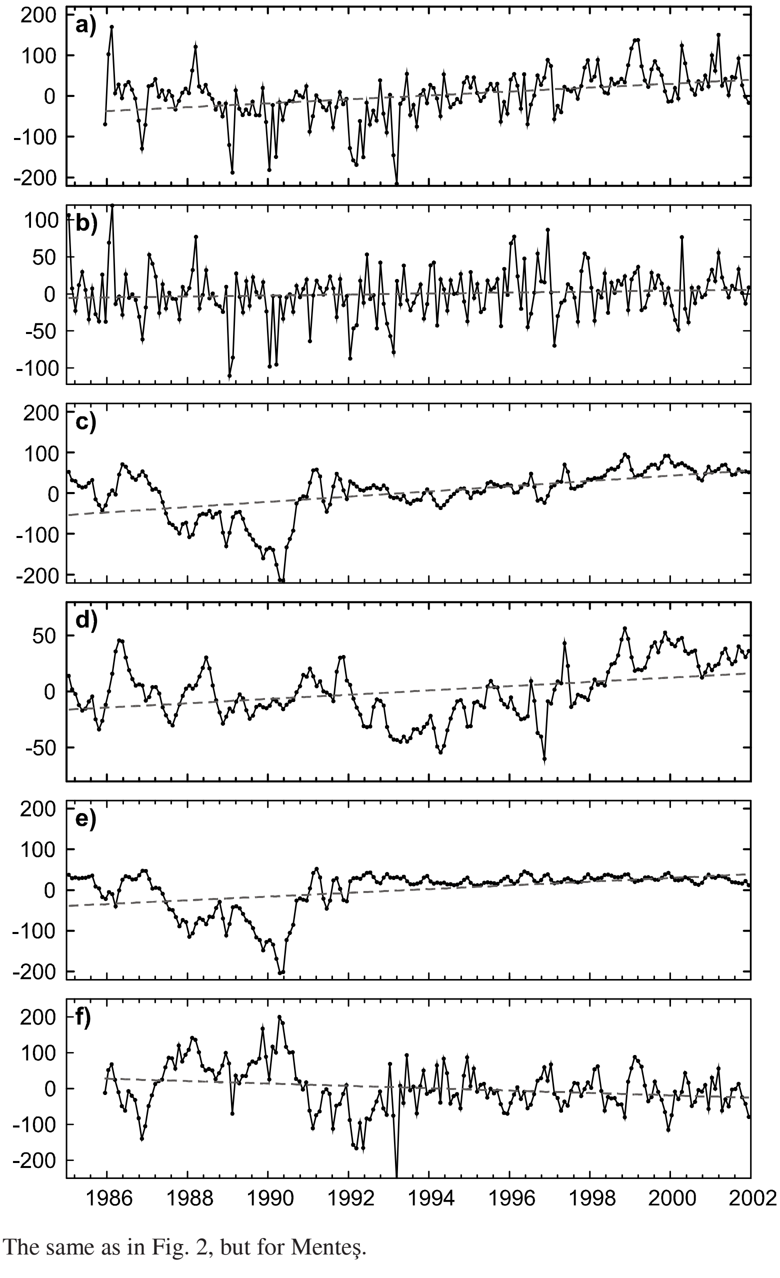

Fig. 3. The same as in Fig. 2, but for Menteş.

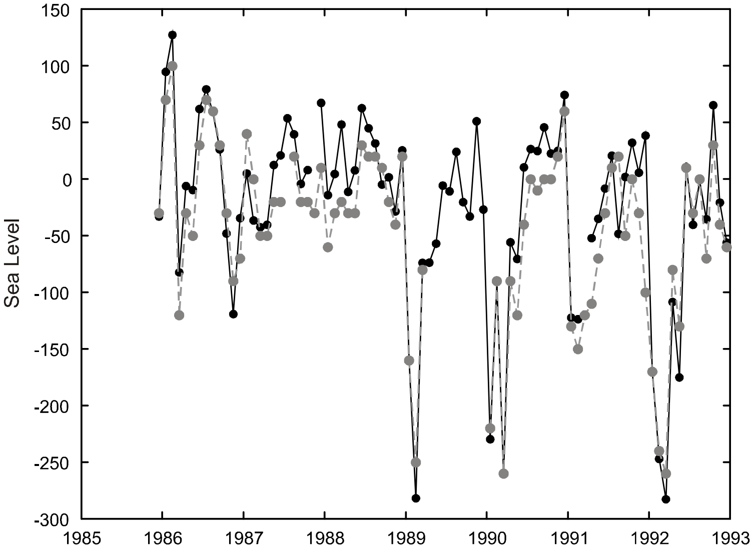

Fig. 4. Observed sea level in Menteş (black line) and in Khios (dashed gray line) for the period 1985−1993. Units are in millimeters.

monthly sea level time series over the 1985−1993 period yields −14.1 ± 3.0 mm/yr negative trend same as Menteş. Although part of the observed trend in Menteş during 1985−1993 can be attributed to the atmospheric and steric effects, the main source of the remaining high residual trend could possibly be related to the physical loss of water mass transferred from the Aegean Sea to the Eastern Mediterranean during the EMT event.

The second period of interest, 1993−2001, shows a fast sea level rise consistent with the results of *Cazenave et al. (2001)*, *Fenoglio-Marc (2002)*, *Vigo et al. (2005)* and *Criado-Aldeanueva et al. (2008)*. The major contribution to the observed trends during this period is mainly due to temperature changes, although salinity and atmospherically induced changes can not be ignored. The steric component in both tide gauges account for roughly 80% of the total observed trends. This is larger than the 55% found by *Criado-Aldeanueva et al. (2008)* during a longer period (1992−2005), who also observed a reversal in the thermosteric sea level trend in 2001. The atmospheric effects accounting for ~ 10% of the total trends during this period are in agreement with *Gomis et al. (2008)*. These results support both the global (*Holgate and Woodworth, 2004*; *Holgate, 2007*) and the regional estimates (*Cazenave et al., 2001*; *Fenoglio-Marc, 2002*) of sea level rise, linked to upper ocean temperature increase observed during the 1990s in the Eastern Mediterranean (*Tsimplis and Rixen, 2002*; *Tsimplis et al., 2009*). The sum of the sea level trends estimated for two different periods gives the total trend at Antalya but not at Menteş due to the high negative trend observed there during the first period 1985−1993.

The VLM rates estimated from EGPS and CGPS time series for both tide gauges are given in Table 2. The analysis of EGPS data at Antalya for 1994−2009 period suggests a VLM rate of −3.2 ± 0.5 mm/yr (Fig. 5a). In the 2003−2009 period, when both EGPS and

Table 2. Vertical land movement rates in mm/yr at tide gauge GPS benchmarks and continuous GPS sites for the period 1992−2009. All uncertainties are given at the 95% confidence level.

Tide Gauge	Period	EGPS	CGPS
Antalya	1994−2009	−3.2 ± 0.5	---
	2003−2009	−0.8 ± 1.8	−0.9 ± 0.8
Menteş	1992−2009	−1.3 ± 0.5	---
	2003−2009	−3.2 ± 2.7	−1.1 ± 0.6

CGPS data are available (Fig. 5b), VLM rates estimated from CGPS and EGPS data are found be consistent with each other, both showing insignificant VLM rates (Table 2). Moreover, the VLM rate estimated from EGPS data in Antalya is in good agreement with the VLM result of *Fenoglio-Marc et al. (2004)* inferred from altimetry and tide gauge differences (−3.0 ± 1.6 mm/yr). Thus, almost ~ 70% of the residual trend in Antalya is explained in terms of VLM over the period studied leaving a residual 1−1.5 mm/yr rising trend which can be attributed to the approximately 1 mm/yr mass induced sea level rise suggested by *Criado-Aldeanueva et al. (2008)* and *Calafat et al. (2010)*. A VLM rate of −1.3 ± 0.5 mm/yr is found in Menteş based on the analysis of EGPS data for the 1992−2009 period (Fig. 6), suggesting a land subsidence rate consistent with the ICE-5G (VM4) GIA model of *Peltier (2004)*. As a result, VLM as well as steric and atmospheric factors do not account for the residual sea level trend in Menteş. If the model sea levels around Menteş are correct, then there must be some other local forcings in that area which were not considered in this study.

Factors affecting the interannual sea level variability in the region are compared in Table 3, where the variance, regression statistics of considered variables, as well as the residual variances are presented. Wind and atmospheric pressure changes dominate the interannual variability of sea level at both tide gauges over the three periods studied (1985−2001, 1985−1993, and 1993−2001). Observed sea level is better correlated ($r > 0.65$) with the atmospherically induced component, accounting for ~ 45% of the variance, while it is less correlated with the steric height component ($r < 0.30$), accounting for less than 10% of the variance at both tide gauges during the 1985−2001 period. These results do not change much when a linear combination of the atmospheric and steric contributions is considered. Atmospheric and steric corrections account for more than half of the observed variability (Fig. 7). There is still ~ 50% of the variability that remains unexplained, which may be attributed to unresolved factors (such as sea water mass variations) by observations and model results used in this paper.

4. CONCLUSION

Trends and interannual variability based on 1985−2001 sea level measurements at two tide gauge stations on the Aegean and Eastern Mediterranean coasts of Turkey have been analyzed to determine the possible forcing mechanisms; in particular, the levels of contributions by atmospheric, steric and land motion.

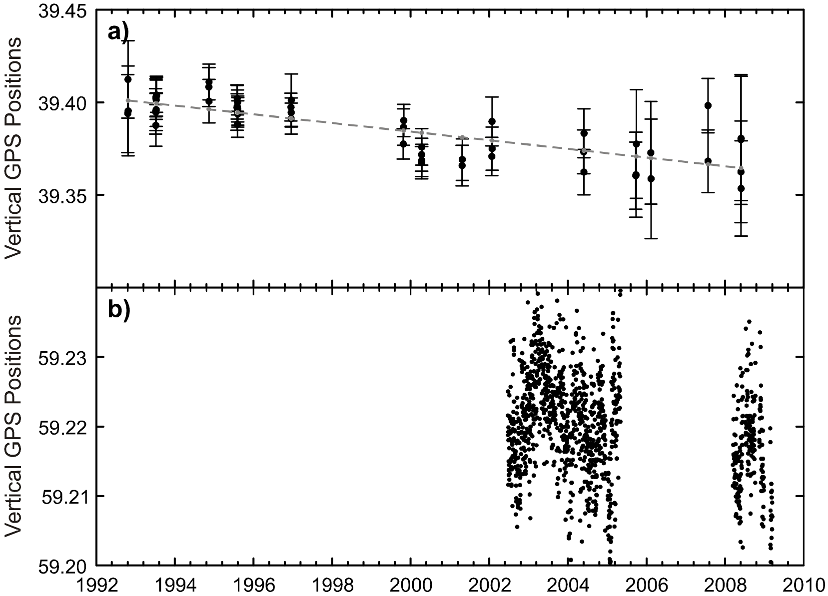

Fig. 5. Vertical GPS positions at Antalya tide gauge. **a)** EGPS time series, **b)** CGPS time series. Units are in meters.

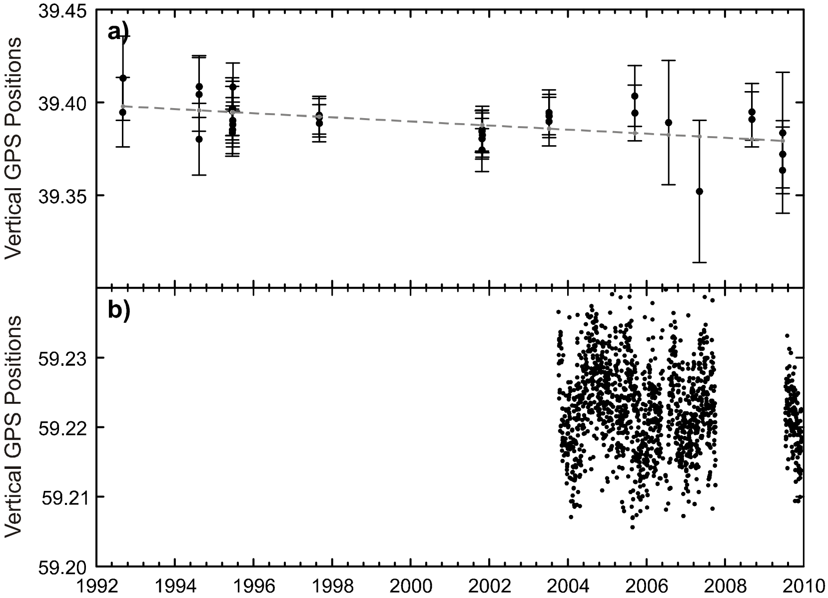

Fig. 6. The same as in Fig. 5, but for Menteş.

Table 3. Interannual total variance of sea level (cm^2), correlation coefficients (r) and relative contribution (%) of atmospheric and steric components to the variance, and residual variance (cm^2) of sea level monthly mean time series of 1985–2001.

Tide Gauge	Observed Sea Level Variance [cm^2]	Sea Level						Residual Sea Level Variance [cm^2]
		Atmospheric-Induced		Steric-Induced		Atmospheric + Steric-Induced		
		r	Variance [%]	r	Variance [%]	r	Variance [%]	
Antalya	28.04	0.69	47	0.26	6	0.62	51	13.62
Menteş	41.34	0.67	44	0.14	2	0.48	45	22.66

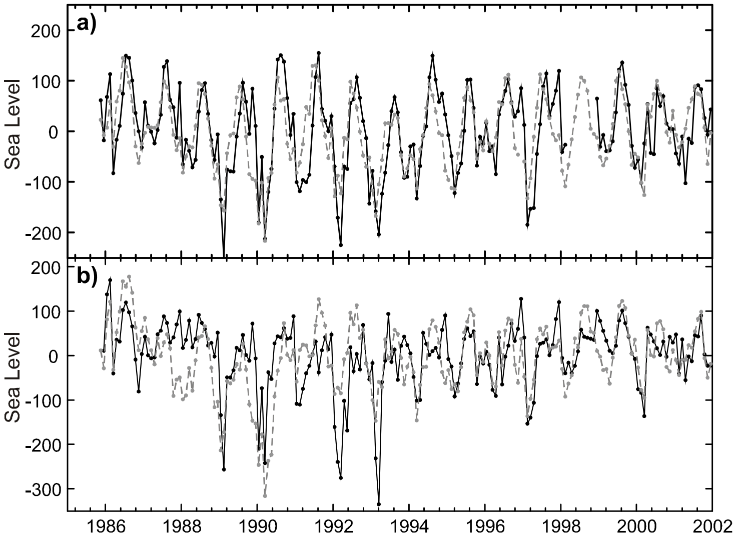

Fig. 7. Observed (black line) and linear combination of atmospherically induced and steric sea level (dashed grey line). **a)** Antalya, **b)** Menteş. Units are in millimeters.

During the period 1985–2001 the sea level trends in Antalya and Menteş are found to be 7.9 ± 0.8 mm/yr and 5.5 ± 1.0 mm/yr respectively. The atmospheric contribution only accounts for 0.6–0.9 mm/yr of trend, while the steric contribution is greater, accounting for 2.5 ± 0.4 mm/yr and 6.4 ± 0.7 mm/yr respectively in Antalya and Menteş. Almost half of the interannual sea level variance is due to the combined atmospheric and steric effects. A significant local land subsidence is detected in Antalya with a rate of −3.2 ± 0.5 mm/yr based on EGPS data, and a trend of smaller magnitude −1.3 ± 0.5 mm/yr is recorded in Menteş. After removing the GPS estimated VLM rates, and the steric and atmospheric sea level trends, there remain unexplained trends of 1.3 mm/yr and −4.5 mm/yr respectively in Antalya and Menteş. The remaining trend in Antalya is in agreement with *Calafat et al. (2010)* and could be attributed to mass induced sea level variations not considered in this study.

Two distinct periods, 1985−1993 and 1993–2001, apparent in the sea level time series of both tide gauges are studied to better understand the largely different residual trends at these two stations. In the 1985−1993 period, the observed sea level in Menteş decreases at a rate of −14 mm/yr, about 3.5 times faster than Antalya. The same downward trend is also found at Khios tide gauge located 50 km away from Menteş, On the other hand, positive sea level trends up to 12 mm/yr are found in both tide gauges for the 1993−2001 period mainly attributed to steric effect accounting for 80% of the sea level trends. The results indicate that the primary source of the discrepancy between the residual sea level trends of Antalya and Menteş over the 1985−2001 period is the highly negative trend observed at Menteş during the 1985−1993 period, the source of which could not be resolved with the available data sets.

We conclude that the mass induced sea level variations not considered in this study may help to better close the sea level trend budgets as well as to better explain the interannual sea level variance.

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