SEA LEVEL TRENDS ALONG THE WESTERN COASTS OF ANATOLIA FROM TIDE GAUGE, SATELLITE ALTIMETRY, GPS AND LEVELLING DATA

Hasan YILDIZ, Mehmet SİMAV, Erdinç SEZEN, Ayhan CİNGOZ, and Ali KILIÇOĞLU
hasan.yildiz@hgk.mil.tr, General Command of Mapping, Geodesy Department, 06100 Dikimevi, Ankara/TURKEY

European Geosciences Union General Assembly 2008,Vienna, Austria, 13 – 18 April 2008

1. INTRODUCTION

Recently released IPCC's Fourth Assessment Report (AR4) estimated that sea level will rise 18 to 59 cm (with 90 per cent confidence limits) over the period from 1980-2000 to 2090-2100 (IPCC, 2007). Rahmstorf (2006) developed a simple statistical model that related 20th century surface temperature change to 20th century sea-level change. Using this relationship and projected surface temperature increases, estimated 21st century sea level rise might exceed the IPCC projections and be as large as 1.4 m.

Therefore, studies concerning the determination of the rate of sea level changes at global, regional, and local scales as well as the physical factors that contribute to the observed variability of sea levels have increased greatly than ever before, since they may have strong impacts on coastal ecosystems and human societies.

Historical tide gauge measurements from all over the world are the primary source of information to investigate the changes in sea level that have occurred over the last century. However, sea level estimates from individual tide gauges are a combination of any true sea level variations and any vertical land movements (VLM). Although, it is possible to make this correction based on glacial isostatic adjustment (GIA) models which do not explain all of the VLM occurring at all of the tide-gauges in the world (Teferle et al.,2006), it is neccessary to determine the VLM at each tide gauge to obtain climate related component of sea level changes by using independent geodetic techniques (GPS, continuous GPS (CGPS), VLBI, absolute gravity, InSAR). Satellite altimetry providing absolute measurement of sea level variations is also used for estimates of VLM when combined with tide gauge records (Marc et al., 2004; Garcia et al., 2007).

In this study: first we investigate sea level trends at the Eastern Mediterranean, Agean and the Sea of Marmara Coasts of Anatolia derived from five coastal tide gauges which span at least 20 years of data and satellite altimetry observations. Data sets of pressure, air/sea water temperature data recorded at the nearest meteorological stations to the tide gauges are used to determine the possible link between the mean sea level trends with the local meteorological variations. Second we estimated the VLM at tide gauges by using episodic GPS, Continuous GPS and precise levelling data and compared results with the ICE-5G (VM2) GIA model (Peltier, 2004).

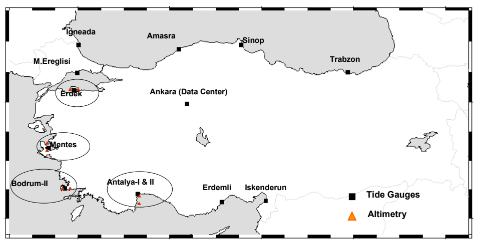
2. DATA USED

❖ **Tide Gauge Data :** Monthly sea level data of Antalya-I (1935-1977), Antalya-II (1985-2005), Bodrum-II (1985-2005), Menteş (1985-2005), Erdek (1984-2005) tide gauges operated by General Command of Mapping under the frame of Turkish National Sea Level Monitoring System (TUDES).

❖ **Satellite Altimetry Sea Level Anomaly Data :** Gridded merged multimission data known as DUACS have been used to obtain the SLA nearest to the tide gauges. The DUACS dataset are produced by the CLS Space Oceanography Division and AVISO, the French Space Agency.

❖ **Meteorological Data :** Monthly mean air pressure, air and sea water temperature data obtained from meteorology stations of Turkish State Meteorological Service (TSMS) located nearest to the tide gauges. Since the air pressure time series of Antalya-I from TSMS station do not go as far back in time as the sea level data and it is in poor quality before 1959, monthly mean sea level pressure data predicted from the monthly mean air pressures on a 5 x 10 (lat x lon) degree grid provided by UK Met Office and UEA CRU for 1935-1977 period was used instead.

❖ **Geodetic Data :** Precise leveling and episodic GPS campaigns performed at four of the tide gauges (Antalya-II, Bodrum-II, Menteş, Erdek) since 1992 at 1-2 years intervals and at least three years long CGPS time series at three of the tide gauges (Antalya-II, Menteş, Erdek)



Turkish National Sea Level Monitoring System (TUDES)

3. SEASONAL, INTERANNUAL AND INTERDECADAL PERIODIC VARIATIONS IN TIDE GAUGE'S SEA LEVEL TIME SERIES

The method proposed by Tsimplis and Spencer (1997) is adopted to determine the amplitudes and the phases of the seasonal sea level cycles. Sea level anomalies are calculated for each month on the basis of complete years only.

Strong annual signals are found at Antalya-I and Antalya-II tide gauges with estimated amplitudes of 7.8±1.2 cm and 8.9±0.6 cm respectively while at Bodrum-II, Menteş and Erdek annual signals have amplitudes less than 5.5 cm. The semiannual cycles have amplitudes less than 3 cm in the whole regions.

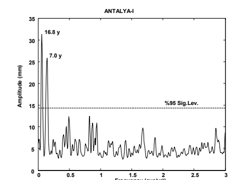
No noticeable phase differences are observed between tide gauges and the mean seasonal cycles reach their maximum in late summer (August).

Interannual and interdecadal sea level variations are determined by using spectral analysis. Before spectral analysis, the seasonal cycles estimated by harmonic analysis of the average monthly sea level anomalies and linear trends estimated by simple linear regression are removed from the monthly mean sea level data.

MC-CLEAN V2.0 software developed by (Heslop and Dekkers, 2002) is used to obtain amplitude/frequency spectrum of monthly sea level time series.

As an example, MC-CLEAN frequency spectrums of Antalya-I tide gauge obtained from the input time series after bootstrapping the signal to 50% of its original length and performing a simulation consisting of 1000 iterations is shown below.

The periods (yr) and mean amplitudes (mm) of main spectral components significant at the 95% level are given in the Table.



Period	Antalya-I	Antalya-II	Bodrum-II	Menteş	Erdek
16.8	31				
13.4		22		27	
12.5					28
7.0	26				
4.5			37		
4.0		17			
2.7					21
1.7					27

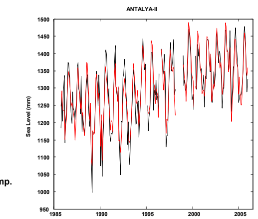
4. SEA LEVEL & TEMPERATURE TRENDS

REGRESSION MODEL

$$\underbrace{X(t)}_{\text{Mon. Sea Lev.}}=\underbrace{a_0}_{\text{Intercept}}+\underbrace{\sum_{i=1}^{n}a_1t_i}_{\text{Trend}}+\underbrace{b_1\delta P(t)}_{\text{Air Pres.}}+\underbrace{b_2\delta T(t)}_{\text{Air Temp.}}+\underbrace{\sum_{j=1}^{m}c_j\cos(\omega_jt-\varphi_j)}_{\text{Periodical Variations}}+\underbrace{v(t)}_{\text{Error}}$$

$$\delta P(t)=P(t)-\left(d_1+e_1t+\sum_{i=1}^{2}f_i\cos(\omega_it+\varphi_i)\right)$$ Air Pressure

$$\delta T(t)=T(t)-\left(d_2+e_2t+\sum_{i=1}^{2}f_i\cos(\omega_it+\varphi_i)\right)$$ Air/Sea Water Temp.



Tide gauge	Data Period	SL Trends From TG Data (mm/yr)	Altimetry Trends (mm/yr)		Air Temperature Trends ($^0C/yr$)	Sea Water Temperature Trends ($^0C/yr$)
			1 (First Nearest)	2 (Second Nearest)		
Antalya I-II	1935 2005	0.20 ± 0.19	-	-	-0.01 ± 0.01	0.01 ± 0.01
	1935 1959	1.19 ± 0.97	-	-	0.01 ± 0.06	0.09 ± 0.08
	1960 1992	-3.77 ± 0.52	-	-	-0.05 ± 0.04	-0.05 ± 0.03
	1993 1999	23.92 ± 6.77	18.04 ± 4.01	20.16 ± 4.19	0.40 ± 0.48	0.42 ± 0.31
	1993 2002	14.56 ± 2.87	9.93 ± 2.08	11.50 ± 2.16	0.29 ± 0.26	0.23 ± 0.17
	2000 2005	8.21 ± 6.07	7.47 ± 4.75	6.69 ± 4.83	0.28 ± 0.63	0.38 ± 0.43
Bodrum-II	1993 1999	-28.66 ± 8.35	17.48 ± 4.43	17.25 ± 4.46	0.18 ± 0.44	0.15 ± 0.23
	1993 2002	-1.92 ± 3.36	10.24 ± 2.30	10.15 ± 2.31	0.18 ± 0.24	0.21 ± 0.12
	2000 2005	13.26 ± 4.91	5.35 ± 5.24	5.83 ± 5.20	0.24 ± 0.59	0.37 ± 0.30
Menteş	1993 1999	18.95 ± 5.39	20.56 ± 4.21	20.47 ± 4.19	0.21 ± 0.49	0.40 ± 0.40
	1993 2002	11.96 ± 2.69	12.49 ± 2.19	12.47 ± 2.19	0.21 ± 0.27	0.25 ± 0.22
	2000 2005	9.54 ± 5.51	2.69 ± 5.13	2.76 ± 5.19	0.19 ± 0.66	0.37 ± 0.57
Erdek	1993 1999	31.24 ± 4.69	23.07 ± 4.08	22.73 ± 4.01	0.22 ± 0.48	-
	1993 2002	14.30 ± 2.94	14.86 ± 2.37	14.45 ± 2.29	0.27 ± 0.26	-
	2000 2005	0.32 ± 7.27	-5.04 ± 5.16	-4.33 ± 4.93	0.06 ± 0.65	-

5. VERTICAL LAND MOVEMENTS (VLM) AT TIDE GAUGES

❖ GPS data used in this study are processed by using GAMIT/GLOBK (V10.21) software (King and Bock, 2003). IGS precise ephemeris and Bulletin B values as earth rotation parameters published by IERS are used in the process. Processing with 13 IGS stations around Turkey, a series of loosely constrained daily GPS network solutions are obtained for episodic GPS and CGPS sites. Loosely constrained daily GPS solutions, SOPAC coordinate time series, including 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 similarity transformation and stations whose coordinates are defined in ITRF-2000.

❖ Episodic GPS and CGPS height time series analysis are carried out by CATS software which uses Maksimum Likelihood Estimation (MLE) method (Williams, 2005).

❖ For time series analysis of TG-GPS a linear model, while for the TG-CGPS time series a mathematical model including velocity + all statistically significant periodic signals is used.

Vertical velocities estimated at Tide Gauge-GPS (TG-GPS) and TG-CGPS benchmarks by MLE methods and spectral indexes from MLE.

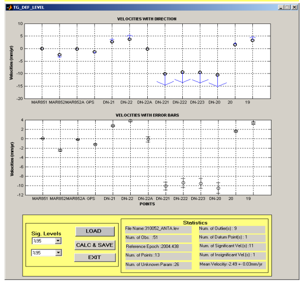
TG Name	TG-GPS Point	VLM from TG-GPS (mm/yr)	Spectral Index	TG-CGPS Sites	VLM from TG-CGPS (mm/yr)	Spectral Index	VLM from ICE-5G (VM2) GIA MODEL (mm/yr)
BODRUM	BODR	0.69 ±1.48 (Not Significant)	-1.86				0.10
ERDEK	ERDK	-0.50 ± 1.61 (Not Significant)	-1.02				0.28
	ERDE	-7.51 ± 6.34 (Not Significant)	-2.96	ERDT	0.14 ± 0.83	-0.55	
ANTALYA	ANTG	-3.78 ± 0.93 (Significant)	-1.18	ANTA	-0.15 ± 0.90	-0.34	0.23
MENTEŞ	MENT	-0.63 ± 0.50 (Not Significant)	-0.65	MNTS	-2.56 ± 0.78	-0.30	0.22

Only at Menteş (MNTS) TG-CGPS station a statisticaly significant (at 95% confidence level) vertical velocity is found which has a rate of -2.56 ± 0.78 mm/yr. Significant differences between the VLM estimated from GPS, CGPS and precise leveling data and predicted ones from ICE-5G (VM2) GIA model are found.

MODEL USED FOR LEVELLING DATA

$$l_{ij}(t)=-h_i(t)+h_j(t)-v_i(t-t_o)+v_j(t-t_o)$$

❖ Precise leveling measurements between primary TG benchmark and local leveling network points including episodic GPS and CGPS points are analyzed by using a deformation analysis software (TG_DEF_LEVEL) developed by Yıldız and Simav (2005).



6. CONCLUSIONS

❖ Rising trends relatively higher than global estimates can be seen at four of the tide gauges. Linear trends and their associated errors in mean sea levels of Antalya-I tide gauge's 1935-1977 period, Antalya-II, Bodrum-II ve Menteş tide gauges' 1985-2005 period and Erdek tide gauge's 1984-2005 period are found to be 0.7±0.2 mm/yr, 7.9±0.5 mm/yr, 2.6±0.7 mm/yr, 4.8±0.5 mm/yr ve 7.3±0.6 mm/yr by using above given regression model.

❖Estimated sea level trends at tide gauges are consistent with the ones obtained from satellite altimetry.

❖Only at Menteş (MNTS) TG-CGPS station a statisticaly significant (at 95% confidence level) vertical velocity is found which has a rate of -2.56 ± 0.78 mm/yr. Significant differences between the VLM estimated from GPS, CGPS and precise leveling data and predicted ones from ICE-5G (VM2) GIA model are found. It is planned to use satellite altimetry in combination with tide gauge to determine VLM at tide gauges.

❖ The rising sea level trends at the tide gauges are most probably caused by interannual temperature changes and may also be explained by enhanced coastal sea level rise during the 1990s suggested by Holgate and Woodworth (2004).

7. REFERENCES

Garcia, D., I. Vigo,B. F. Chao,M. C. Martinez, 2007, Vertical Crustal Motion along the Mediterranean and Black Sea Coast Derived from Ocean Altimetry and Tide Gauge Data. Pure and Applied Geophysics, 164, 4, 851-863.
Heslop, D., Dekkers, M.J., 2002, Spectral analysis of unevenly spaced climatic time series using CLEAN: signal recovery and derivation of significance levels using a Monte Carlo simulation, Physics of the Earth and Planetary Interiors, 130, 103–116.
Holgate, S.J., Woodworth, P.L., 2004. Evidence for enhanced coastal sea level rise during the 1990s. Geophysical Research Letters, 31, LO7305, doi:10.1029/2004GL019626.
IPCC (2007), Climate Change 2007 : The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
King, R.W., Bock, Y., 2003, Documentation for the GAMIT analysis software release V.10.1, Massachusetts Institute of Technology, Cambridge.
Marc, L.F., Dietz, C., Groten, E., 2004, Vertical land motion in the Mediterranean sea from altimetry and tide gauge stations. Marine Geodesy, 27, p. 1–19.
Peltier, W.R. ,2004, Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) Model and GRACE, Ann. Rev. Earth and Planet. Sci., 32, 111-149.
Rahmstorf, S., 2006, A semi-emprical approach to projecting future sea-level rise, Sciencexpress, 10.1126, Science.1135456.
Teferle, F.N., Bingley, R.M., Williams, S.D.P., Baker, T.F., Dodson, A.H., 2006, Using continuous GPS and absolute gravity to separate vertical land movements and changes in sea-level at tide-gauges in the UK, Philosophical Transaction of The Royal Society, 364, 917–930, doi:10.1098/rsta.2006.1746.
Tsimplis, M. N., and N. E. Spencer (1997), Collection and analysis of monthly mean sea level data in the Mediterranean and the Black Sea, J. Coastal Res., 13, 534–544.
Williams, S.D.P., 2005. Create and Analyse Time Series: CATS software V3.0 Beta.
Yıldız, H., Simav,M., 2005. TG-LEV-ANA V1.0 User Manuel, Developed by Geodesy Department of General Command of Mapping, Ankara, TURKEY, during the leadership of Task 2.7 of Work Package 2 in ESEAS-RI Project. December, 2005 (not pubilshed).