MEAN SEA LEVEL CHANGES AND VERTICAL CRUSTAL MOVEMENTS AT TURKISH TIDE GAUGES FOR THE PERIOD OF 1984-2001

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ABSTRACT

Turkish monthly mean sea level data for the period of 1984-2001 and periodic precise leveling and episodic GPS measurements are analyzed in order to determine relative and absolute sea level changes and the vertical crustal movements at Turkish tide gauges. The results indicate that the relative sea level changes are 7.93±0.98 mm/yr at Antalya-II, 4.59±1.59 mm/yr at Bodrum-II, 6.19±1.01 mm/yr at Menteş and 9.09±1.00 mm/yr at Erdek. The high sea level trends are found to be caused by the land subsidence that are mostly verified by the periodic geodetic measurements. When the relative sea level trends are corrected by the land subsidence rates, absolute sea level changes approximate to the global sea level rise estimates at Antalya-II and Menteş while a higher sea level rise at Bodrum and a sea level drop at Erdek are detected. It is suggested that the GPS campaigns should be reprocessed with new strategies and Turkish tide gauges be collocated with CGPS to detect the vertical crustal movements with an accuracy of a few millimeters.

1. INTRODUCTION

General Command of Mapping (GCM) that is responsible for foundation of the basic geodetic control networks in Turkey, established the first tide gauge station at Antalya Harbour in 1936 in order to define zero level for national vertical control network in Turkey. Right after the establishment of the second one at Karşıyaka/İzmir in 1937, they were transferred to the General Directorate of Meteorological Affairs. Subsequently, six more tide gauges had been set up and operated at different places of the country at different time intervals by this institution. Recording periods of time series from those gauges vary from 5 to 40 years. At all tide gauges having two stilling wells, sea level variations were recorded on daily or weekly charts with an analogous system by means of a float on a cable in a stilling well. In late 1970s, it was not possible to operate those gauges properly and to obtain correct values because of the increase in pollution and plunging of the wells caused by urbanization surrounding tide gauges (GCM, 1991; Gürdal, 1997; Demir and Gürdal, 2000).

During 1980s, considering the importance of the sea level variations and its outcomes GCM took over the responsibility of operating permanent tide gauges in order to remove deficiencies in sea level activities in Turkey. Afterwards, all the existing tide gauges were cancelled. Instead of them, four new tide gauges namely Antalya II (Mediterranean), Bodrum II and Menteş (Agean Sea) and Erdek (Marmara Sea) were established and activated with analogous systems in late 1984 and 1985. At these stations sea level variations had been recorded to the weekly charts and ancillary data such as atmospheric pressure, air temperature, humidity and sea temperature had also been measured once a day by an operator. Graphical sea level records and the ancillary data were sent to the data center monthly periods and hourly values were digitized manually and issued annually to the related national and international institutions.

In order to remove the difficulties in data reduction and eliminate the various kinds of errors experienced by analogous systems, it was aimed to modernize the existing tide gauges and establish a state of the art sea level monitoring network and expand it with new tide gauges where necessary. Furthermore, it was decided to re-digitize the historical sea level records with a computer-aided system to obtain more accurate time series. For all these purposes much effort have been made since 1995 and first step towards establishing a modern sea level network in Turkey (Turkish National Sea Level Monitoring Network) was accomplished by upgrading the existing tide gauges to GLOSS standards in 1999. In addition to those, three other new digital and automatic tide gauge stations were mounted at Black Sea coasts of Turkey in 2001 and 2002. Distribution of the existing tide gauges and location of the planned ones are depicted in Figure-1.

Figure-1: Distribution of the existing and planned tide gauges

Presently, all stations consist of a data collection unit with a self-calibrating acoustic ranging sensor and meteorological sensors such as atmospheric pressure, air temperature, air humidity, wind velocity and wind direction. Sampling rate is 10 seconds for the sea level and ancillary data. Sea level and meteorological parameters are collected at dataloggers as 15-minute averages. The data are transferred to data center once or twice a week using telephone lines and they were checked regularly for quality control. To check the tide gauge datum stability and to monitor the local vertical movements at or near tide gauges, local leveling networks consisting of 3 to 5 points have been measured at 1-2 year interval. Besides, within the frame of different projects, periodic GPS measurements have been carried out since 1992. First epoch of absolute gravity measurements were also fulfilled at tide gauge sites in 1996 (Wilmes and Kılıçoğlu, 1997; Wilmes et al., 1997).

It is well known that the sea level records contain information both for eustatic sea level changes and vertical crustal movements. Periodic geodetic measurements contribute to separate the vertical crustal movements from the sea level records to find the absolute sea level changes independent from the vertical motions of the land on which the tide gauges were placed (Baker, 1993; Xu, 1990; IOC,2000). If the vertical crustal motion contaminating the sea level records is very dominant compared to the eustatic sea level change even shorter sea level records (less than 20 years) can indicate the presence of vertical movements. However, tide gauge, by itself is not sufficient to detect whether the vertical crustal movements are regional or local.

Among the previous studies about mean sea level changes and vertical crustal movements at Turkish tide gauges, Emery et al. (1988) have found that Antalya-I (1936-1972) tide gauge is emerging +3.8 mm/yr and the Karşıyaka/İzmir (1937-1971) is submerging –4.6 mm/yr depending on the mean annual relative mean sea levels, obtained from Permanent Service for Mean Sea Level (PSMSL), which are in the metric form. They concluded that the results obtained from the Antalya-I tide gauge did not match exactly with the archeological observations of Flemming and Webb (1986) in southern Turkey. However, they found that the subsidence of Karşıyaka/İzmir tide gauge relative to sea level were consistent with the archeological considerations of Flemming and Webb (1986) and explained the reason of the subsidence by the widespread normal block faulting of the continental shelf of outer İzmir and Çandarlı Bays. Emery et al. (1988) also stated that the results of Aksu et al. (1987) who estimated the coastal subsidence of İzmir to be 1 m/1000 yrs over geological time consistent with the subsidence rate of Karşıyaka/İzmir tide gauge. Ayhan et al. (1994) found that the surrounding area of Antalya is in subsidence with a rate of 0.96-1.20 cm/year based on two GPS experiments in 1991 and 1994. They have also found that sea level is rising + 5.3 mm/yr from the monthly mean sea levels for the period of 1938-1977 by including the monthly atmospheric pressure and air temperature values in to the regression model.

In this study the mean sea level changes and vertical crustal movements at Turkish tide gauges operated by GCM for the period of 1984-2001 are determined. Firstly, the quality check procedures applied to Turkish hourly sea level data are summarized and then the sea level trends obtained from the analysis of monthly sea levels by using the harmonic analysis method with least squares adjustment are given. Successively, the periodic GPS and precise levelling measurements are analyzed by linear regression and geodetic-based absolute vertical motions are estimated by combination of periodic GPS and levelling data. The vertical crustal movements found from both relative sea level changes and periodic geodetic measurements are compared to provide the magnitude of the vertical crustal movements and absolute sea level changes at Turkish tide gauges. At last, the results are compared with the results of previous studies in order to discuss the reasons of vertical crustal movements.

2. RELATIVE SEA LEVEL CHANGES

The relative sea level measurements at a tide gauge are affected by a number of oceanographic, meteorological phenomena and vertical crustal movements. Determination of secular sea level changes (rise or fall) precisely is only possible if those effects are modeled properly and quality-checked long-term sea level records are available.

By the GCM, much effort has been made to re-process the historical sea level data using suitable methods as well as upgrading and expanding the existing sea level network. The data obtained by analogous system are subject to many errors coming from both the instrumental drift and the method of digitization. In order to eliminate the errors as much as possible we started to re-digitize historical graphical records with a computer-aided digitizer in 1995 and completed the re-digitization of sea level records of five tide gauges up to now.

Hourly sea level values are predicted from digitized values by linear interpolation and checked for quality by using the software of TOGA Sea Level Center (Caldwell, 1998) in order to eliminate time and datum shifts. Daily sea levels are obtained by using a 119-point low pass filter and monthly mean sea levels are then calculated by taking simple arithmetic mean of daily sea levels (Caldwell, 1998). Table-1 summarizes the re-processed data so far.

Table-1: Re- digitized and processed sea level data

Tide-gauge	Available data	Re-digitized	Processed	Remarks
Antalya-I	1936-1977	1936-1977	No	Not operational
Antalya-II	1985-2001	1985-1998	1985-2001	
Bodrum-II	1985-2001	1985-1998	1985-2001	
Menteş	1985-2001	1985-1998	1985-2001	
Erdek	1984-2001	1984-1998	1984-2001	

We determined the mean sea levels and its changes by analyzing the monthly mean sea level values from four tide gauges listed in Table-1 using the well known formula (Pugh, 1987),

$$h_i = Z_o + a\ t_i + \sum_{j=1}^{N} A_j \cos(\omega_j t_i - \theta_j)$$

where, t_i number of months from reference epoch t_o , Z_o mean sea level, a (mm/month) secular trend, A_j, ω_j, θ_i and N, amplitude, angular velocity, phase of the i^{th} harmonic constituent and total number of tidal constituents included in the model respectively. The frequencies of tidal constituents whose periods are longer than one month are selected among the tidal constituents of the program developed by Foreman and Neufeld (1991) for analysis of hourly sea level values for longer than 18.6 years. The coefficients in the model are calculated by least squares estimation (Nakiboğlu, 1996). Each coefficient is tested for significance by using Student's **t** test (Koch, 1987) at $1-\alpha = 90\%$ confidence interval. If two coefficients of a tidal constituent are both not significant, it is removed from the model. If one coefficient of a tidal constituent is significant and the other one is not significant, the tidal constituent is left in the model.

Meteorological parameters are not included in the model since they are not yet completely arranged before the analysis. In Figure-2, observed and modeled values, and relative sea level changes are given. It can be seen from the figure that the data has some gaps due to failures in the analogous systems. Relative sea level changes are found 7.93±0.98 mm/yr for Antalya-II, 9.09±1.00 for Erdek, 4.59±1.59 mm/yr for Bodrum, 6.19±1.01 mm/yr for Menteş tide gauge. Since there are many gaps in Bodrum monthly sea levels, the sea level trend at Bodrum is regarded as suspicious. The computed relative sea level changes at these four tide gauges which gives much higher results than global sea level rise estimates (1-2 mm/yr) (Douglas, 1997) indicates a clear evidence for the mean sea level rise with respect to the land level.

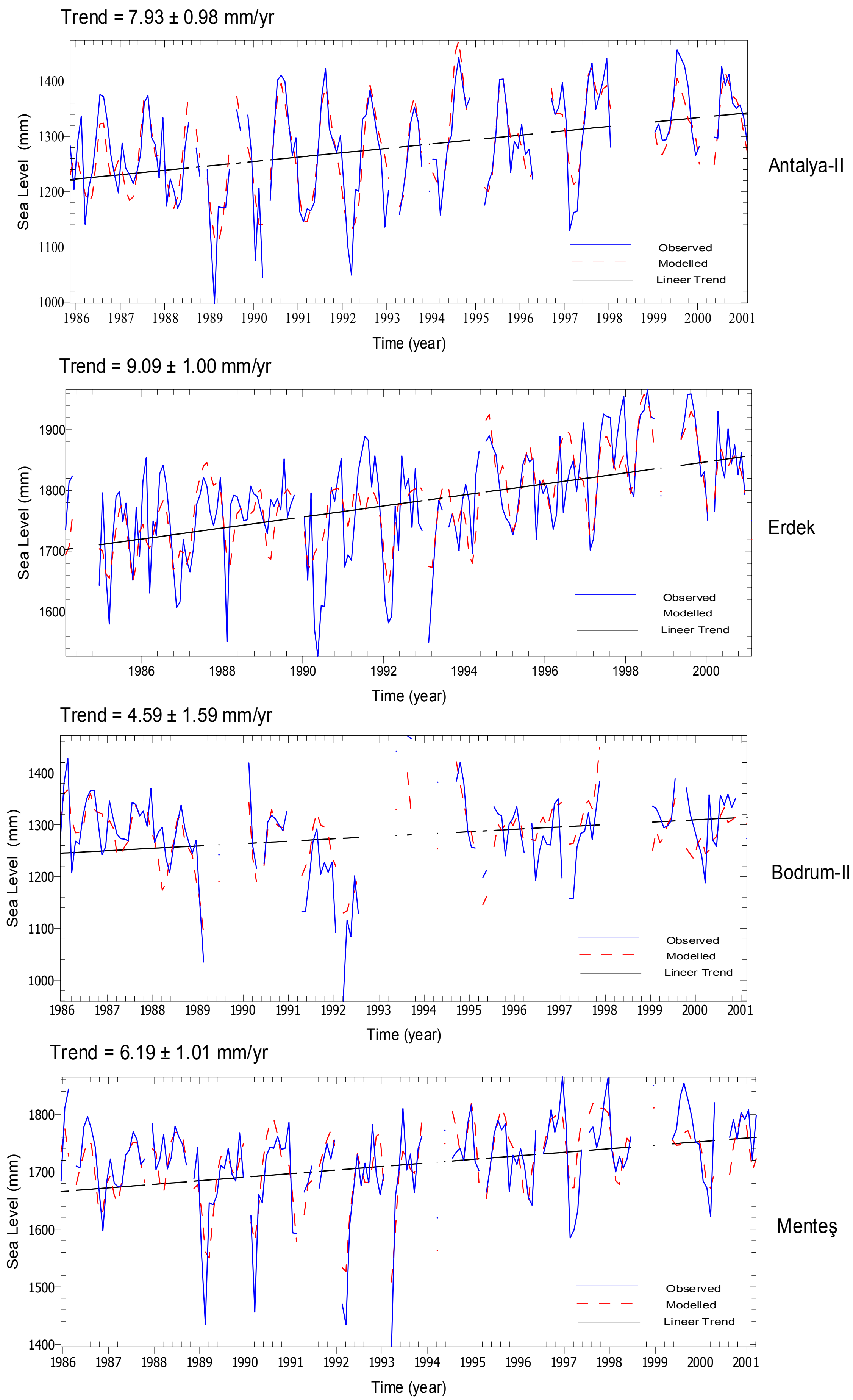

Figure-2: Observed and modeled monthly relative sea levels and relative sea level trends

3. VERTICAL CRUSTAL MOVEMENTS AND ABSOLUTE SEA LEVEL CHANGES

Turkey is situated in a tectonically very active region where major tectonic plates interact each other. GPS measurement campaigns, processed so far at four existing tide gauges, are given in Table-3. The symbol x represents the existing GPS campaign in related year.

Table-3: GPS measurement campaigns at tide gauges

Tide Gauge GPS BM /year	1992	1993	1994	1995	1996	1997	1998	2000
Antalya-II(ANTG)			x	x	x	x	x	
Bodrum-II (BODR)			x	x	x	x	x	x
Erdek (ERDK)				x		x		
Erdek (ERDE)	x		x		x			
Menteş (MENT)	x		x	x			x	

GPS campaigns conducted between 1992 and 2000 at gauges in Turkey are processed with Bernese software version 4.0 (Rothacher and Mervart, 1996) using International Geodynamics Service (IGS) products following the strategy proposed by EUREF Subcommission. Loosely constrained solution of SINEX format is combined with the GLOBK software (Herring, 1997) in ITRF96. In the combination, 1 mm constraints for both velocity and coordinates of some selected IGS sites for reference frame fixing are applied. A least squares regression analysis method is applied to the ellipsoidal heights of GPS benchmarks.

Determination of the ellipsoidal height change of Tide Gauge GPS (TG-GPS) benchmark is not sufficient alone to determine vertical change of tide gauge platform on which relative sea levels are recorded. In order to monitor the vertical motion of tide gauge platforms, it is essential to measure the relative height differences between the TG-GPS and the Tide Gauge Benchmarks (TGBM) periodically. Precise levelling measurements, processed so far at four tide gauges, are given in Table-4. The symbol x represents the levelling measurements in related year.

Table-4: Precise Levelling measurements at Turkish tide gauges

Year/ Tide Gauge	1986	1989	1990	1994	1995	1996	2000
Antalya-II	x	x	x	x	x	x	x
Erdek	x	x	x	x	x	x	x
Bodrum-II	x	x	x	x	x	x	x
Menteş	x	x	X	x	x	x	x

3.1. Antalya-II

Analysis of periodic GPS campaigns at Antalya GPS tide gauge benchmark (Figure 3 (a)) gives 3.5 ± 2.9 mm/yr absolute height change at GPS benchmark. Due to the discrepancies of the 1994 value from the trend it is removed and the rate of GPS benchmark is re-calculated from the remaining campaign solutions and is found 0.9 ± 3.2 mm/yr (Figure 3 (b)) which is statistically insignificant. In other words, the TG-GPS benchmark at Antalya is vertically stable. The TGBM is emerging relative to TG-GPS with a rate of 1.56 ± 0.12 mm/yr (Figure 4 (a)). A significant relative height change (-3.60 ± 0.32 mm/yr) is detected at TGBM with respect to the 130-20 levelling benchmark (Figure 4 (b)). This means that the tide gauge house is in relative subsidence with respect to levelling benchmark (130-20) which is approximately 2 km away from the tide gauge.

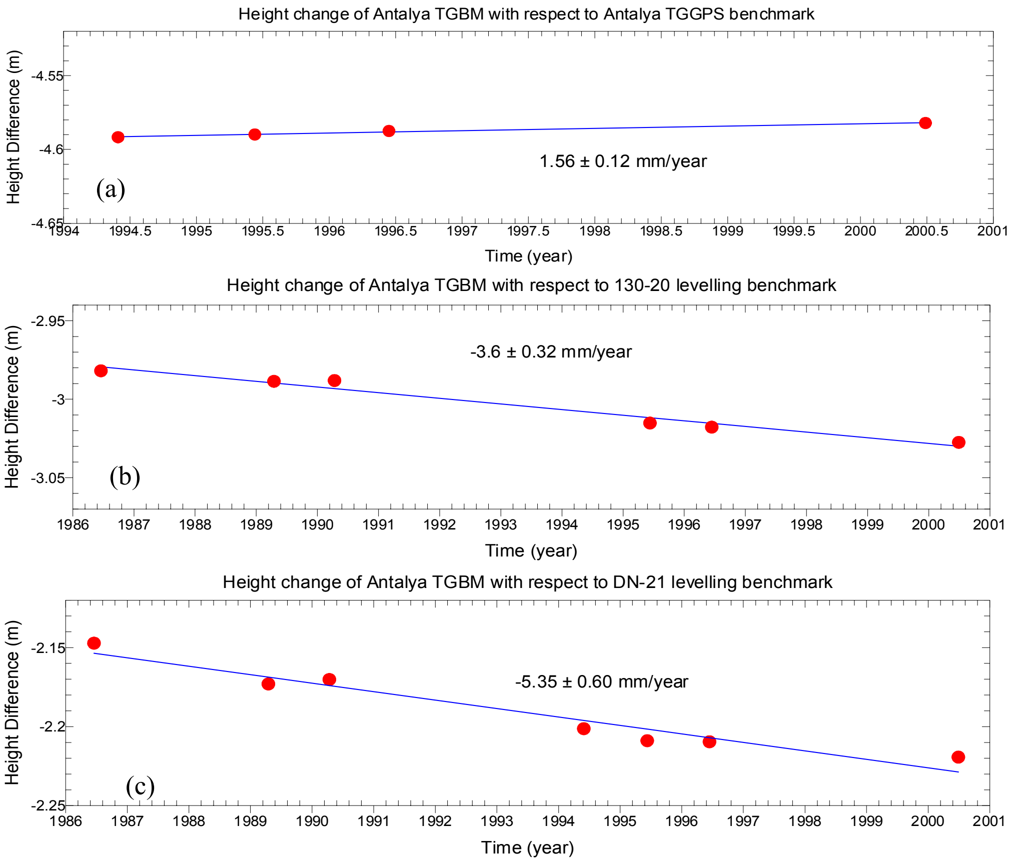

Figure-4 : Analysis of height changes of Antalya TGBM with respect to (a)Antalya TG-GPS benchmark (b) 130-20 levelling benchmark (c) DN-21 levelling benchmark.

Besides, TGBM is found to be moving downward with a rate of -5.35 ± 0.60 mm/yr with respect to the DN-21 levelling benchmark (Figure 4 (c)) which is approximately 500 m away from the tide gauge.

At Antalya tide gauge a 7.93 ± 0.98 mm/yr sea level trend (Figure-2) indicating a regular subsidence of the tide gauge house is found by harmonic analysis of sea level records of Antalya 1985-2001. Relative height changes of TGBM with respect to 130-20 and DN-21 levelling benchmarks verifies the local subsidence at the tide gauge house. When the sea level trend is corrected for local subsidence, assuming the 130-20 levelling benchmark stable, sea level rise is found 4.33 ± 1.03 mm/yr at Antalya.

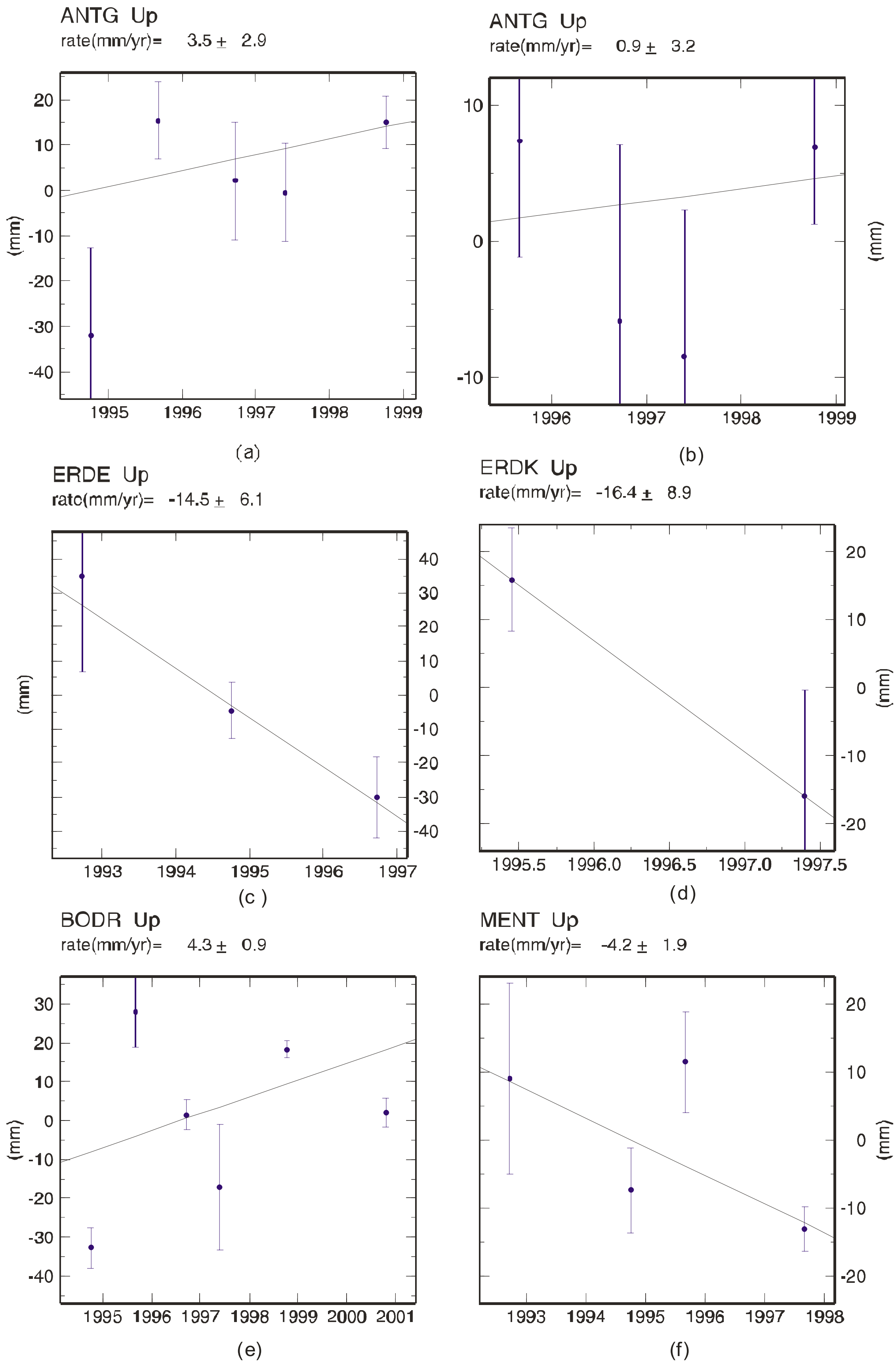

Figure-3: Absolute height changes at TG-GPS benchmarks at (a)Antalya (b)Antalya after removing the GPS campaign solution in 1994 (c) Erdek (ERDE) GPS benchmark 3.71km distant from TG (d) Erdek (ERDK) (e) Bodrum (f) Menteş tide gauges.

When the DN-21 benchmark is assumed as stable the sea level rise is found 2.58 ± 1.14 mm/yr which is more consistent with the global sea level rise estimates (1-2 mm/yr) (Douglas, 1997). The relative sea level rise and the periodic leveling measurements indicate a land subsidence at Antalya-II tide gauge. The land subsidence at Antalya-II (1985-2001) is not consistent with the land uplift (3.8 mm/yr) found by Emery et al. (1988) from 1936-1972 data, while in accordance with relative sea level rise of 5.3 mm/yr at Antalya-I (1938-1977) and the land subsidence rate of 0.96-1.20 cm/yr (Ayhan et al., 1994).

3.2. Erdek

There are two different GPS sites at Erdek tide gauge area, one is ERDE tide gauge GPS benchmark 70 m near the Erdek tide gauge station and the other one is ERDK GPS site 3.71 km away from the Erdek tide gauge in the direction to Erdek town. It is found that both GPS benchmarks are subsiding, ERDK point, near the tide gauge station, is subsiding with a rate of 16.4±8.9 mm/yr (Figure 3 (d)) higher than the rate of ERDE GPS benchmark (14.5±6.1 mm/yr) (Figure 3 (c)).

The analysis of periodic leveling measurements result in (–0.36 ± 0.08 mm/yr) relative height change of TGBM with respect to ERDK TG-GPS benchmark is (Figure 5 (a)). The height change of TGBM relative to ERDE GPS benchmark is found –1.62±0.33 mm/yr (Figure 5 (b)). It means that the tide gauge house is in relative subsidence with respect to both GPS benchmarks in addition to the absolute subsidence of GPS benchmarks.

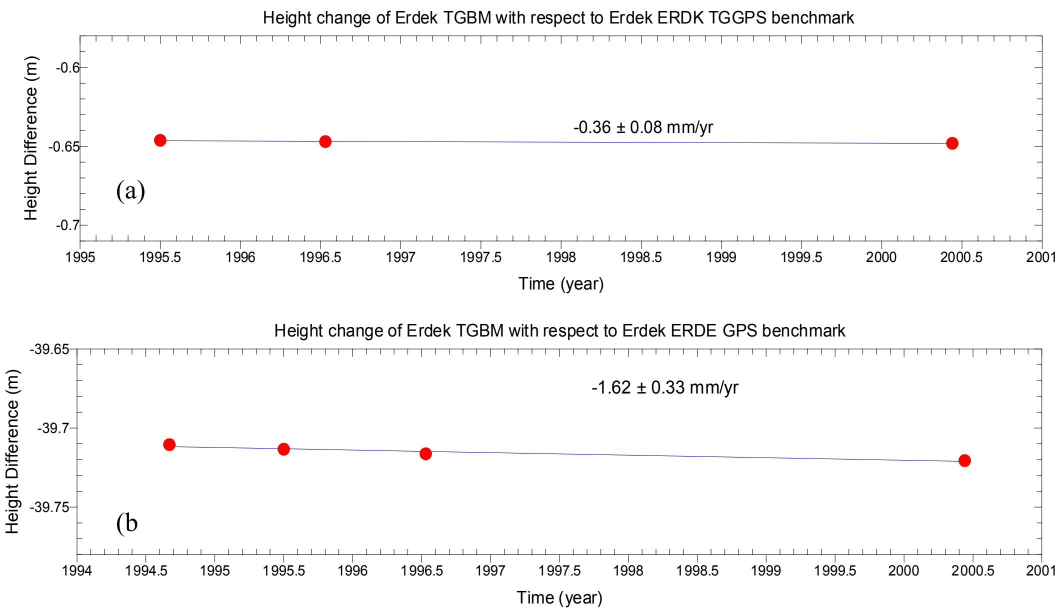

Figure-5: Analysis of height changes of Erdek TGBM with respect to (a) Erdek ERDK TG-GPS benchmark (b) Erdek ERDE GPS benchmark.

By combining the absolute height change at GPS benchmarks and the relative height change of tide gauge house with respect to GPS benchmarks, the absolute subsidence of tide gauge house is found –16.12 ± 6.11 mm/yr depending on the absolute change of ERDE GPS benchmark and -16.76 ± 8.90 mm/yr depending on the ERDK TG-GPS benchmark. As a result, the combined analysis of periodic geodetic measurements at Erdek tide gauge indicates a huge a amount of land subsidence in the area. When the relative sea level trend (9.09±1.00 mm/yr) is corrected by the land subsidence found from the combined analysis of periodic GPS measurements at ERDE

GPS benchmark and levelling measurements, eustatic sea level change at Erdek tide gauge is found –7.03 ± 6.19 mm/yr. This estimation not consistent with the global sea level rise estimates (1-2 mm/yr) should be interpreted that the vertical crustal movements are very dominant in the area. The vertical crustal movements at Erdek tide gauge and its surrounding region were investigated by Demir and Yildiz (2001) in detail. A continuous GPS station ~4 km distant to the Erdek tide gauge was installed in June,2002 in order to monitor the vertical crustal movements more precisely. Considering the huge amount of vertical crustal movements at Erdek tide gauge and its surrounding region, a 3-year joint project will be started at the beginning of 2003 on which the geodesists, geologists, geophysicists and oceanographers will study in order to determine the long term sea level changes and vertical crustal movements at Marmara Sea region. A new tide gauge is planned to be installed at Marmara Ereglisi located on the north coasts of Marmara Sea on the opposite side of Erdek tide gauge. There is already a CGPS station at Marmara Ereglisi and it is intended to install new tide gauge adjacent to that CGPS station. Also the satellite altimeter measurements is planned to be analyzed to obtain absolute sea level changes in the Marmara Sea region to control the results obtained from tide gauge data and periodic geodetic measurements.

3.3. Bodrum-II

Analysis of periodic GPS campaigns at Bodrum TG-GPS benchmark (Figure 3 (e)) gives 4.3 ± 0.9 mm/yr ellipsoidal height change at TG-GPS benchmark which points a coherent land uplift in the area. The periodic levelling measurements relative to TG-GPS benchmark (Figure 6 (a)) and the most distant levelling benchmark (DN-E7) (0.6 mm/yr) also support the uplift of the tide gauge (Figure 6 (b)).

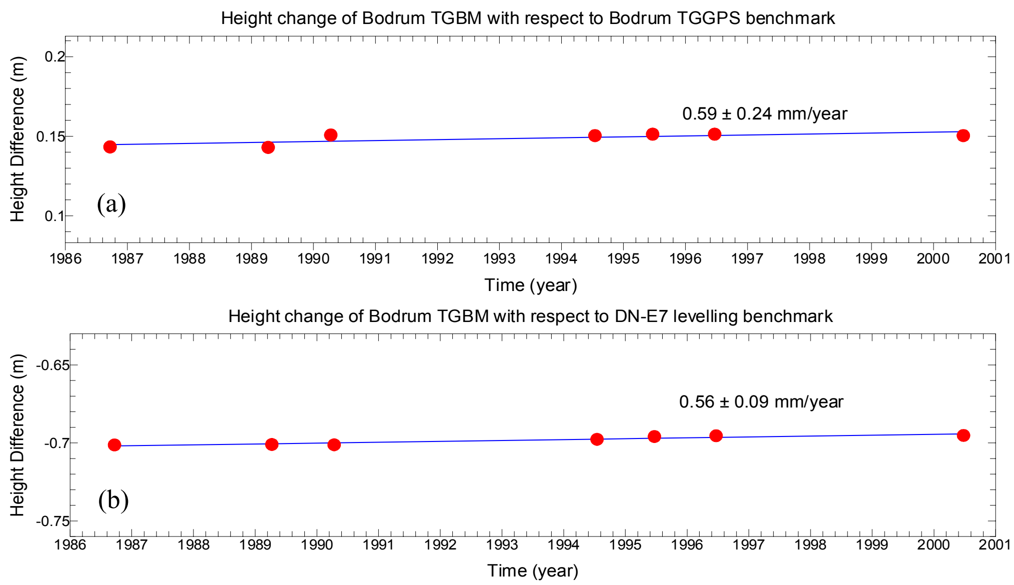

Figure-6 : Analysis of height changes of Bodrum TGBM with respect to (a) Bodrum TG-GPS benchmark (b) DN-E7 levelling benchmark.

Since the sea level trend at Bodrum (4.59 ± 1.59 mm/yr) is regarded as unreliable due to many gaps in Bodrum monthly sea level records (Figure-2), it is hesitated to make any estimation about the eustatic sea level change at Bodrum.

3.4. Menteş

Analysis of periodic GPS campaigns at Menteş GPS tide gauge benchmark (Figure3 (f)) gives –4.2 ± 1.9 mm/yr ellipsoidal height change indicating land subsidence in the area. Sea level trend at Menteş is found 6.19 ± 1.01 mm/yr (Figure-2) which is consistent with the rate of ellipsoidal height change of TG-GPS benchmark.

To investigate the local vertical crustal movements and local height change at TGBM, periodic levelling measurement results are utilized. The relative height change at TGBM mounted at the base of tide gauge house with respect to TG-GPS benchmark is –0.01 ± 0.05 mm/yr (Figure 7 (a)). The relative height change of TGBM with respect to the most distant levelling benchmark (131-DN-34) is 0.20±0.15 mm/yr (Figure 7 (b)). The analysis of periodic levelling measurements at Menteş tide gauge reveals that there is no relative vertical movement of TGBM with respect to both TG-GPS benchmark and the most distant levelling benchmark (131-DN-34).

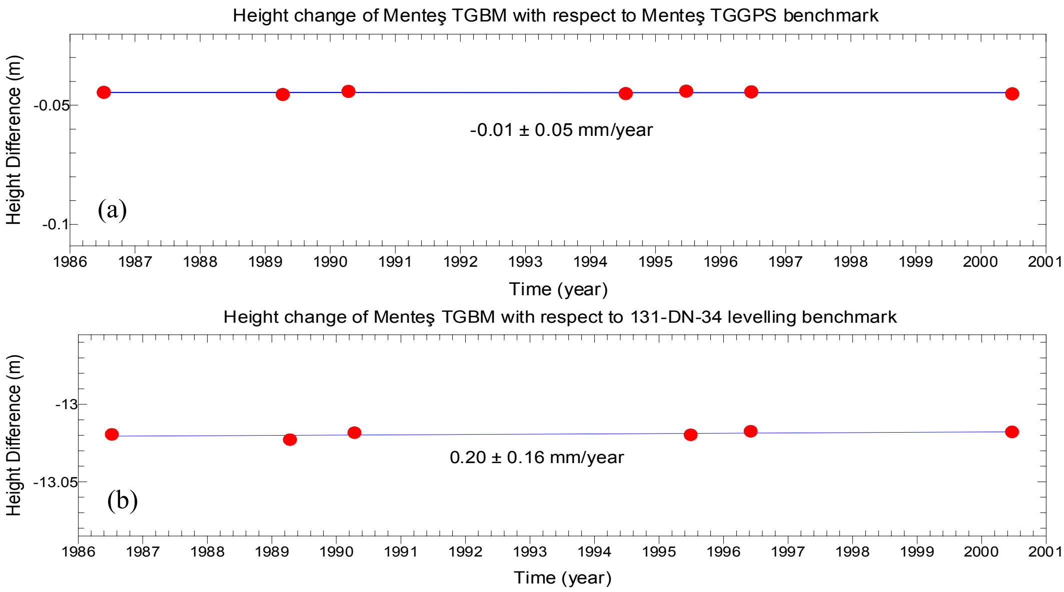

Figure-7: Analysis of height changes of Menteş TGBM with respect to (a) Menteş TGGPS benchmark (b) 131-DN-34 levelling benchmark.

When the relative sea level rise (6.19 ± 1.01 mm/yr) is corrected for the land subsidence (–4.2±1.9 mm/yr) found from periodic GPS measurements, then eustatic sea level change is estimated 1.99±2.15 mm/yr at Menteş tide gauge which is quite consistent with the global sea level rise estimates (1-2 mm/yr). Both the sea level trend at Menteş/İzmir (1985-2001) and vertical crustal movements detected by periodic geodetic measurements agrees with the land subsidence of –4.6 mm/yr.at Karşıyaka/İzmir tide gauge (1937-1971) given by Emery et al. (1988). The land subsidence at Menteş/İzmir tide gauge is also consistent with the archaeological considerations of Flemming and Webb (1986) and the coastal subsidence of İzmir (1m/1000 yrs over geological time) by Aksu et al. (1987).

Briefly, when the relative sea level trends are corrected by the land subsidence rates, absolute sea level changes approximate to the global sea level rise estimates at Antalya-II and Menteş while a higher sea level rise at Bodrum and a sea level drop at Erdek are detected. Consequently, to facilitate the interpretation, the vertical crustal movements and eustatic sea level changes calculated utilizing the periodic geodetic measurements (GPS and Levelling) and the sea level trends at Antalya-II, Bodrum-II, Erdek and Menteş tide gauges are given in Table-5.

Table-5: Rate for the vertical crustal movements, relative sea level and eustatic sea level changes at tide gauges.

Tide gauge (Monthly Sea Level Period)	Vertical Crustal Movements (mm/yr) L : Periodic Levelling GPS : Periodic GPS	Relative Sea Level Change (mm/yr)	Eustatic Sea Level Change (mm/yr)
Antalya-II (1985-2001)	-5.35 ± 0.60 (L) (with respect to DN-21)	7.93 ± 0.98	2.58 ± 1.14
Antalya-II (1985-2001)	-3.60 ± 0.32 (L) (with respect to 130-20)	7.93 ± 0.98	4.33 ± 1.03
Bodrum-II (1985-2001)	4.30 ± 0.90 (GPS)	4.59 ± 1.59	No estimation.
Erdek (1984-2001)	-16.12 ± 6.11 (GPS + L)	9.09 ± 1.00	-7.03 ± 6.19
Menteş (1985-2001)	–4.20 ± 1.90 (GPS)	6.19 ± 1.01	1.99 ± 2.15

4.CONCLUSIONS

By this study, Turkish monthly mean sea level data for the period of 1984-2001 and periodic precise leveling and episodic GPS measurements are analyzed in order to determine relative and absolute sea level changes and the vertical crustal movements at Turkish tide gauges. As a result, the relative sea level rise from 4 to 9 mm/yr at four of Turkish tide gauges and absolute sea level rise of 2-2.6 mm/yr at Antalya-II and Menteş which is consistent with the global sea level rise estimates (Douglas, 1997) and absolute sea level drop at Erdek are determined. The high amount of relative sea level changes at Turkish tide gauges indicates that Turkish tide gauges are exposed to huge amount of tectonic activity (vertical crustal movements). It is concluded that the GPS campaigns should be reprocessed with new strategies (Şanlı, 1999) in order to obtain more accurate results about the vertical crustal movements. It is hoped that the time series of Erdek CGPS time series will contribute to monitor the verical crustal movements at Erdek tide gauge and its surrounding area. A CGPS station is planned to be mounted adjacent to the Antalya-II tide gauge by the funds of ESEAS-RI project. All the other the Turkish tide gauges should be collocated with CGPS to detect the vertical crustal movements with an accuracy of a few millimeters. Furthermore, the second epoch of absolute gravity measurements should be performed in order to determine the vertical crustal movements by an alternative method.

If the relative sea level rise at Turkish coasts continues in the future, the highly populated coasts and valuable agricultural lands will be under the sea causing social and economic losses. The coastal area plans of Turkey should be revised taking into account the future relative/absolute sea levels which seems to be higher than that of today.

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