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Recent Sea-level Changes Along Israeli and Mediterranean Coasts

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Introduction

Changes in sea levels may have a dramatic impact on diverse ecological systems in coastal regions. The impact of sea-level rise can affect a significant number of people. In 1994 37% of the world's population (2.1 billion people) lived in the range of about 100 km of the shore line. In addition to the immediate hazards resulting from the flooding of low lying areas along the coast, the rise in sea-level can also cause beach erosion, salt intrusion into fresh-water aquifers, and other environmental damages. There is a growing consensus among sea-level researchers that the global sea-level rise during the past 100 years has been considerably faster than in the past two millennia (Douglas *et al*. 2000). According to reports by IPCC (2000, 2001) the principal causes for the rise of sea levels in the past 100 years have been: a) the thermal expansion of ocean waters b) the melting of glaciers (mostly continental), both generated by the greenhouse effect. Moreover, it is estimated that during the next 100 years sea-level is expected to rise by about 10 to 90 centimeters. The mean global sea-level rise in the past 100 years is estimated by various sea-level researchers to be about 5-25 cm (table 1).

This paper covers the recent trend in sea-level changes along the Israeli coast, in comparison with other parts of the Mediterranean.

Measuring sea levels

Various techniques are used for measuring sea levels for different geological and historical epochs. Figure 1 demonstrates six of the most common techniques that are currently used by sea-level researchers.

This paper deals with changes measured by tide gauges only. The data used in this paper are based on annual average of relative sea levels, measured at intervals of one hour. Tide gauge measurements are probably the most accurate sea-level records presently available. Tide gauge stations rarely existed before 1870 and spatially wide spread tide gauges records are available only for the 20th century.

During the 20th century, about 1,000 tide gauges were active around the world throughout any significant space of time (Emery and Aubrey 1991). The first tide gauges consisted of recordings on a floating cylinder and a clock mechanism. Modern gauges are digital and their records are automatically computerized. The foremost reason for the location of many tide gauges in ports and estuaries was not scientific but for navigation purposes. Sea water density in ports and estuaries is subject to great fluctuations. Land level in ports and estuaries can be affected by subsidence and compaction of sediments. Shipping traffic in and out of ports can also cause artificial waves that can create measurement noise (Pirazzoli 1998).

Pirazzoli (1998) differentiates 3 kinds of relative sea-level changes: periodic (tide dependent), random (meteorological and hydrological) and monotonic (tectonics dependent or eustatic). because one of the most significant problems in tide gauge data analysis is the removal of measurement resulting from non-eustatic factors, different time series of sea-level data are considered appropriate by sea-level researchers. A study of a long time span of sea-level changes require A full astronomical cycle of at least 19 years, in order to minimize astronomical tide effects. Some insist on a minimum record of 60 years for a proper sea-level analysis, while others settle for 10-20 years.

Trends in global sea-level changes

Many researchers believe that the average sea-level rise in the 20th century has been about 0.5-2 mm/year. Table 1 summarizes the average global sea-level rise as estimated by various researchers.

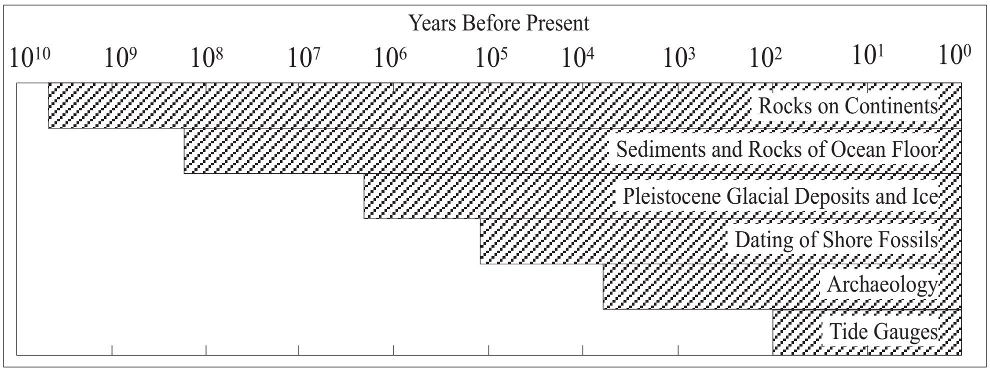

Figure 1: The different time scale and the methods used for studying sea level rise. (Emery and Aubrey 1991)

Table 1: Sea level rise in the last 100 years. (After Brochier and Ramieri 2001)

Source	Region	Date used (years)	SLR (mm/yr)
Gornitz and Lebedeff (1987)	Global	1880-1982	1.2 ± 0.3
Trupin and Waht (1990)	Global	1900-1979	1.7 ± 0.1
Douglas (1991)	Global	1880-1980	1.8 ± 0.1
Peltier and Tushingham (1991)	Global	1920-1970	2.4 ± 0.9
Shennan and Woodworth (1992)	North Occidental Europe	-	1.0 ± 0.15
Gornitz (1995b)	Eastern USA	-	1.5
Unal and Ghil (1995)	-	1807-1988	1.62 ± 0.38
Douglas (1997)	Global	-	1.8 ± 0.1

Mediterranean physical characteristics

The Mediterranean Sea is a partly enclosed basin, covering about 2.5 million km^2, extending approximately 3,800 km east-west, and 900 km north-south, with an average depth of about 1.5 km. The Mediterranean Sea is connected to the Atlantic Ocean by the Gibraltar Straits, to the Black Sea by the Dardanelle Straits, and to the Red Sea through the Suez canal. The Atlantic Ocean contributes 41,000 m^3/sec of its water to the Mediterranean, and the Black Sea contributes about 6,000 m^3/sec. of water. About 54% of the Mediterranean coasts are rocky, and 46% are sedimentary. The high evaporation rate and limited amount of sweet water pouring in to the Mediterranean Sea are the cause for its relatively high salinity (36-39 gram/liter). The Mediterranean sea-level is lower than that of the Atlantic Ocean. It is highest in the Gibraltar straits and lowest in the north Aegean Sea. The Mediterranean is characterized by a weak tide system, with a maximum range of 80 cm (Brochier and Ramieri 2001).

The Mediterranean water surface is about 0.69% of the global ocean surface, and its water volume is 0.27% of all global ocean waters. Its shorelines spread along 45,000 km, 18,000 km of which are island shorelines. Some of the greatest rivers of Europe and Africa pour into the Mediterranean, contributing about 15,000 m^3/sec of sweet water to the sea, 92% of which originate from the northern coast of the Mediterranean. Extensive damming and irrigation projects have decreased the natural flow of several rivers into the Mediterranean in the course of the past few decades. The high evaporation in the Mediterranean is not balanced by the sweet water pouring in from rivers and rain, but rather by the flow of water from the Atlantic Ocean through the Gibraltar straits. The region's climate is characterized by cold rainy winters and hot dry summers; the proximity to the sea moderates extreme daily and seasonal temperature. Precipitation decreases from north to south and from west to east and ranges between 100-1,500 mm/year (Jeftic *et al.* 1996). Owing to the relatively poor rainfall in countries surrounding the Mediterranean (in the south- east mostly), much of the rivers' sweet water is consumed by agriculture, thus reducing its natural flow to the sea (Hinrichsen 1997).

Tide gauge measurements in the Mediterranean

Tide gauge records in the Mediterranean cover only about 100 years. For further study of sea-level changes, covering longer periods of time, other sources of information, such as archeological

Table 2: Mediterranean Sea level rise in the last 100 years.(After Brochier and Ramieri 2001)

Source	**Region**	**SLR (mm/yr)**
Shennan and Woodworth (1992)	North-Western Europe	1.0 ± 0.15
Milliman (1992)	Mediterranean basin	1-2
Piervitali et al. (1997)	Central and western Meditrranean	1.5
Nichollas and Hoozemans (1996)	Genoa (1930-1992)	1.2
Zerbini et al. (1996)	Genoa (1884-1988)	1.3
Nichollas and Hoozemans (1996)	Marseilles (1885-1992)	1.2
Zerbini et al. (1996)	Marseilles (1885-1989)	1.1

relicts, ancient ports, wells, buildings and shipyards, the position of which can reveal past sea-levels, must be used (Emery and Aubrey 1991).

Brochier and Ramieri (2001) summarized several studies of sea-level changes in the Mediterranean region (table 2). Most of the cited studies estimated an annual 1-2 mm rise in sea-level.

Trends in sea-level changes along the Israeli coast

Goldsmith and Gilboa (1986) analyzed tide records from 3 gauging stations along the Mediterranean coast of Israel and from a station on the Red Sea coast in Eilat. Their analysis focused on the similarity of sea-level curves and amplitudes, confirming the reliability of both the analyzed records, and the monthly average sea-level. The curve for the latter demonstrated a marked seasonality with a range of 20 cm. In order to create a common point of reference, the gauging stations were compared with the Ashdod station, where the sea-level record was the longest. Goldsmith and Gilboa (1986) concluded that in spite of the short-term data series obtained from a limited number of years, no long-term change in average sea-level could be discerned along the Israeli Mediterranean coast through 1956-1983.

Two more recent studies analyzed sea-level changes along the Israeli Mediterranean coast. Rosen (2002) noted a sea-level rise of 10 mm/year in the Hadera gauging station during 1992-2002, a rate much higher than the average rate of 1-1.8 mm/year estimated for the past 100 years (figure 2). Another analysis of sea levels along the Israeli coast for the period 1958-2001 covered two astronomical cycles (Shirman 2001). Records from Ashkelon, Ashdod and Tel Aviv, indicated astronomical tide waves fairly parallel in time and amplitude, which made it possible to combine the records from the three stations into one data series. Ashdod and Tel Aviv tide gauges showed a 10 cm rise in sea level during 1990-2001 (Shirman 2001) (figure 2). This dramatic change of sea-level followed a 5 cm rise during 1977-1991, adding up to a 15 cm rise in the Israeli Mediterranean sea level during the past 25 years.

The Permanent Service for Mean Sea Level (PSMSL) has been collecting data from a global network of tide gauges since 1933 (more details about PSMSL activity and data sets see the PSMSL web site http://www.pol.ac.uk/PSMSL/ And Woodworth, 1991; Woodworth and Player, 2003). The organization displays sea-level data from 128 tide gauging stations that were active through the 19th century, 124 of which were still active at the beginning of the 20th century. In 1950, sea-level tide data were based on information from 748 stations, of which 581 were still active at that time. At present, the PSMSL displays data from a total of 1867 tide gauging stations, of which 1040 stations were still active in 1995. In the Mediterranean about 18 tide gauging stations were active until 1900. In 1950 records were available from 51 stations, 29 of which were still active. At present, tide gauge records are based on data collected from a total of 134 Mediterranean tide gauging stations, 58 of which were still active in 1995.

The records analyzed in this paper are Revised Local Reference (RLR) obtained from the PSMSL web site - these are corrected records linking the measured data to a known bench-mark at the tide gauge station. The PSMSL collects monthly and annual values from over 1800 tide gauging stations across the world. The data provided by these stations are known as 'Metric'

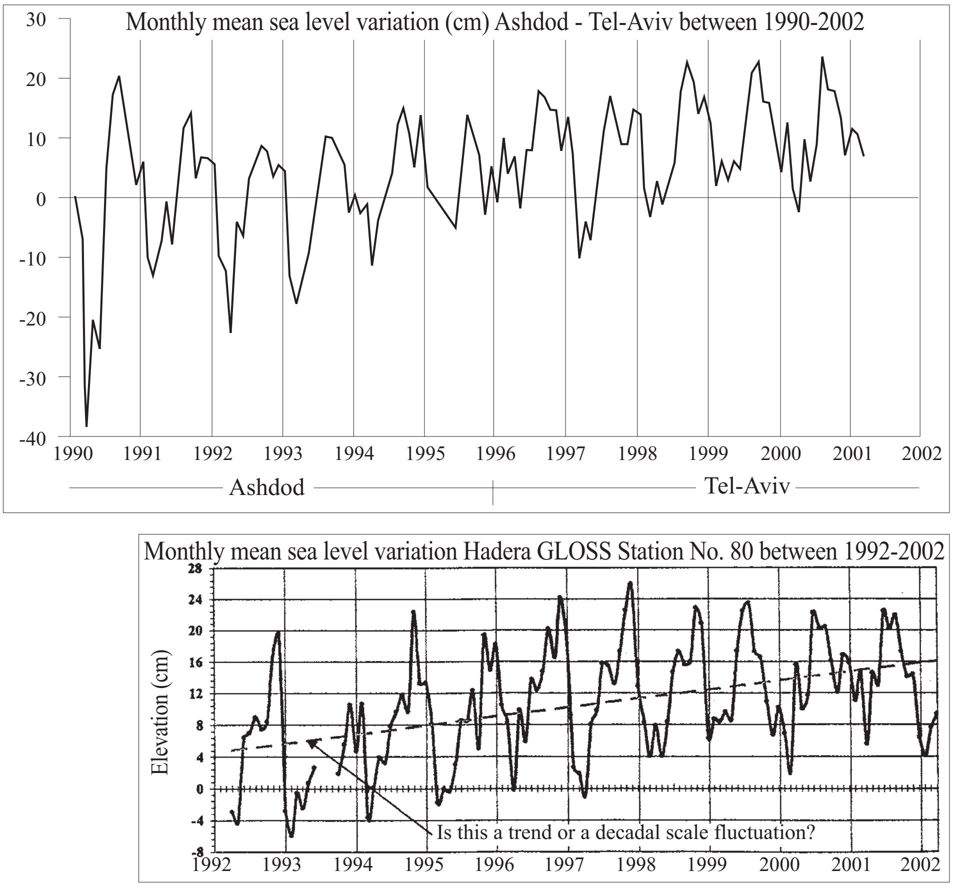

Figure 2: The sea level rise along the Israeli coast. Ashdod-Tel-Aviv after Shirman (2001), Hadera after Rosen (2002).

data. The PSMSL reduces monthly and annual means of 'metric' records to a common datum for the analysis of time series. This reduction is performed by the PSMSL making use of the tide gauge datum history and based on a common denominator of 7000 mm below average sea level (an arbitrary decision made in order to prevent negative readings of values).

In this paper the annual RLR from Mediterranean stations during 1990-2000 is analyzed. 23 tide gauging stations active during 1990-2000, were divided in to 4 sub-areas: the west basin (4 stations), the Adriatic Sea (9 stations), the Ionian Sea (4 stations) and the Aegean Sea (6 stations) (Figure 3). Data from Israeli gauging stations were matched with data from stations along the Mediterranean coast. In the southern and eastern Mediterranean there are no sufficient tide gauge data, and most of the long data series are from the north western Mediterranean.

Results

A much higher-than-global average rise in sea-level (almost 10 times the values shown in table

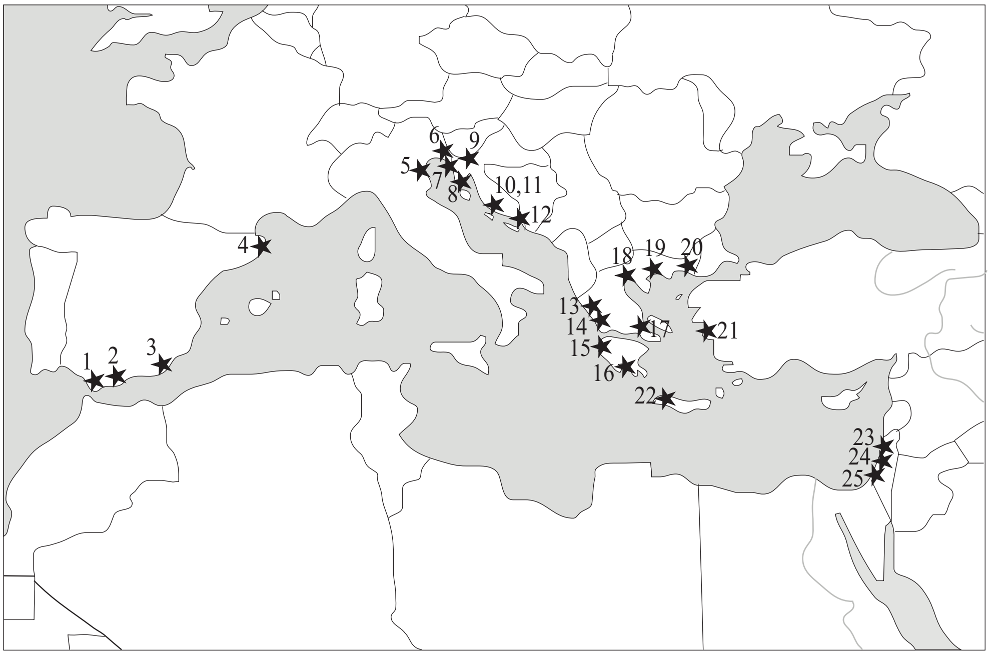

Figure 3: Location of gauging stations used in this work: 1-Algeciras; 2-Malaga; 3-Almeria; 4-L'estartit; 5-Venezia P.D Salute; 6-Trieste; 7-Luka Koper; 8-Rovinj; 9-Bakar; 10-Split Rt. Marjana; 11-Split Harbour; 12-Dubrovnik; 13-Preveza; 14-Levkas; 15-Katakolon; 16-Kalamai; 17-Khalkis North; 18-Thessaloniki; 19-Kavalla; 20-Alexandropolis; 21-Khios; 22-Soudhas; 23-Hedera; 24-Tel-aviv; 25-Ashdod.

1) was found in the western Mediterranean basin as demonstrated in figure 4a. L'estartit and Algeciras stations recorded a 6 mm/year rise during 1990-2000, while the Malaga and Almeria stations recorded a 9 mm/year rise for the same period (see the correlation equation in Figure 4a). Other tide gauging stations in the western basin like Marseille and Genova had kept an almost 100-year record of sea levels, but only partial data series for the period 1990-2000, and records of the other four stations were not always consecutive.

Figure 4b shows a higher rate of sea-level rise in the Adriatic Sea during the above decade, where all stations except Luka Koper recorded a rise of over 9 mm/year, and in some cases even as high as 14 mm/year. Figure 4c shows an average 10.6 mm/year rise in the Ionian Sea, although one of the stations recorded a much higher rate than the global average, while another station recorded a much lower-than-average rate. Figure 4d describes a less homogeneous trend in the Aegean Sea, but even here most of the stations recorded a rise in sea level higher than the global average.

The accelerated rise of the Mediterranean sea-level, as measured during the past decade, is confirmed by four gauging stations that have kept close to 100- year records (Figure 5). The sea-level changes in the four stations analyzed (Marseille: 1.25 mm/year; Genova: 1.22 mm/year;

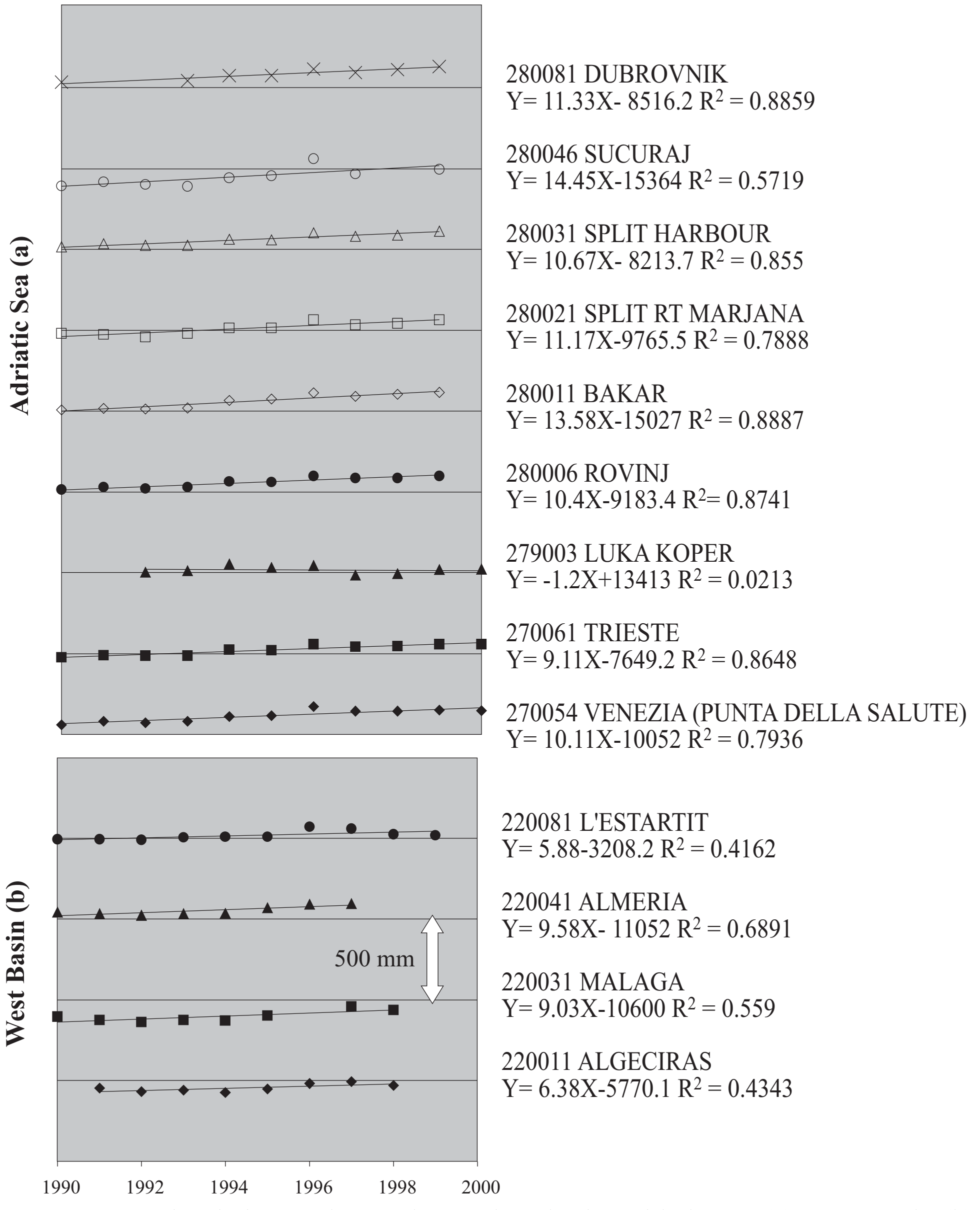

Figure 4: Sea level changes in gauging stations in the Adriatic Sea (a), West Basin (b). Correlation equations and R^2 are given for each station.

Venezia: 2.4 mm/year; and Trieste: 1.14 mm/year) concur with the global average change of about 0.5-2.0 mm/year as estimated by many sea-level researchers (Brochier and Ramieri 2001; Douglas et al. 2000; IPCC 2001), with the exception of Venezia where the sea-level rise was somewhat faster due to land subsidence. (In Figure 5 the correlation equation is given for yearly record as well as for five years running average).

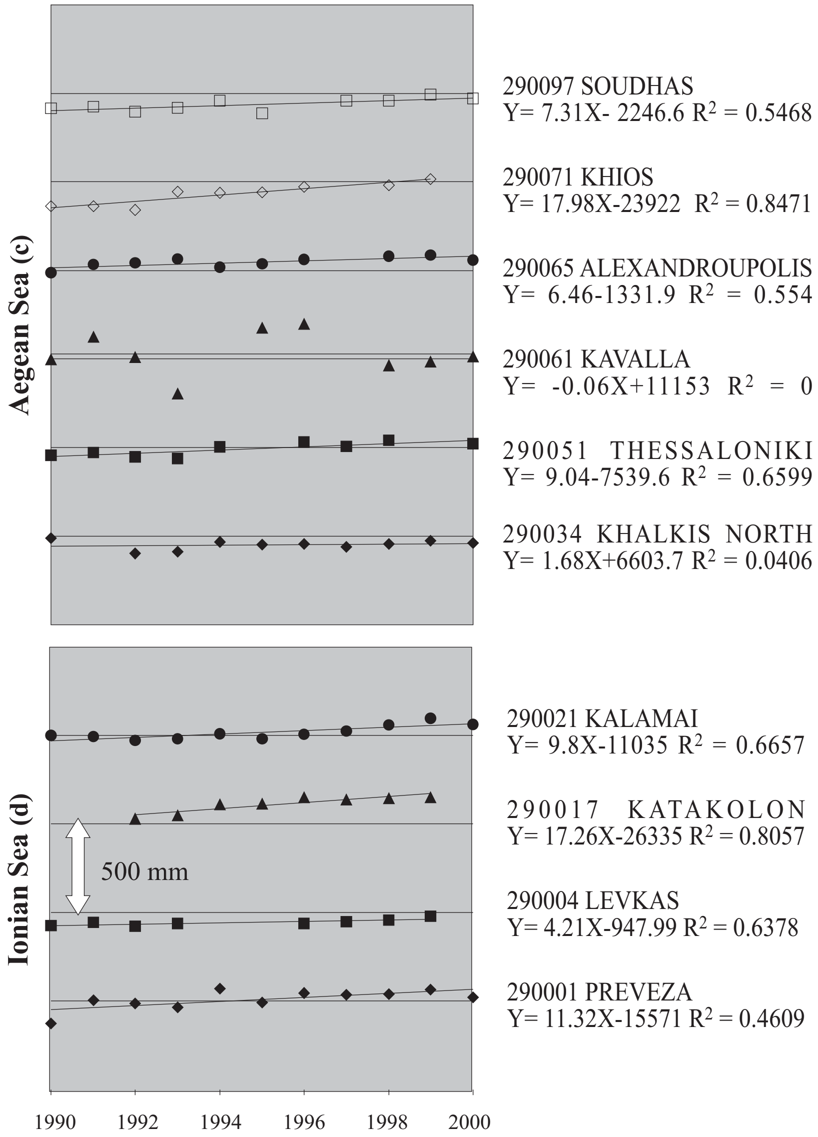

Figure 4: Sea level changes in gauging stations in the Aegean Sea (c), and Ionian Sea (d). Correlation equations and R^2 are given for each station.

A high sea level rise of 10 mm/year in a large number of stations in different regions of the Mediterranean Sea, is unique to the 1990-2000 decade. Analysis of the PSMLS data reveals a high rate of sea level change, which occurred during several decades of the 20th century, in a single station and not in most of the stations. For example: during 1896-1922, data is available for 8 stations. The highest rate was recorded in Venezia - 3.7 mm/year. During the years 1920-1950, only 4 stations were operating (Marseille, Genova, Venezia and Trieste). The highest rise for that period was recorded in Venezia 2.59 mm/year. During 1950-1970 the highest rise

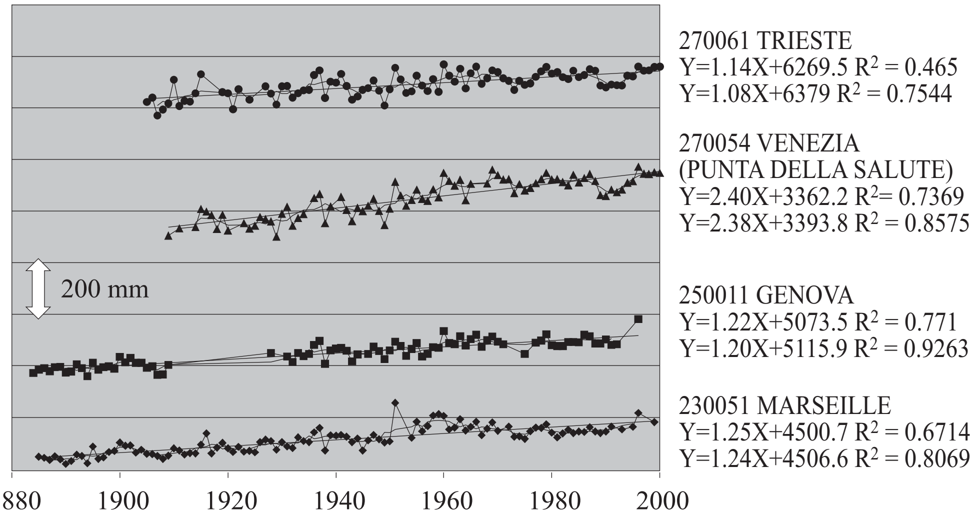

Figure 5: Sea level trends in four gauging stations that have kept sea-level records for close to 100 years (for each station the upper equation is for yearly data, the lower for five years running average).

was recorded in Venezia, 4.7 mm/year. In the 70s', high rise was recorded in the Ionian Sea, at Kalamai St., 16.5 mm/year (only six years out of the decade) and at Patrai St., 15.6 mm/year, and in the Aegean Sea, at Kavalla St., 17.5 mm/year. In the 80s', high rise was recorded in the Ionian Sea, at Patrai St., 14.5 mm/year and a very rapid decline in sea level at Posidhonia -25.4 mm/year.

The finding that five different locations along the Mediterranean coast reveal nearly the same rate of sea-level change eliminates the possibility of local tectonic activity as the cause for the results.

Conclusions

The notably high sea-level rise of about 10 mm/year, gauged in the Israeli Mediterranean coast, both in the north (Rosen 2002) and in the south (Shirman 2001), concurs with the records of other Mediterranean stations, and is by one magnitude higher than the rates measured in the past 100 years.

Assuming a 1-5% slope along the Israeli Mediterranean coast, a 0.1 meter rise in sea level would cause a retreat of the coastline of about 2-10 meters. Since the Israeli Mediterranean coastline is about 200 km long, a sea-level rise of this magnitude would result in the loss of 0.4 to 2.0 sq. km every ten years.

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