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Sea-level rise trends in the Attico–Cycladic region (Aegean Sea) during the last 5000 years

Serafim E. Poulos *, George Ghionis, Hampik Maroukian

National & Kapodistrian University of Athens, Faculty of Geology & Geoenvironment, Department of Geography-Climatology, Panepistimioupoli, Zografou 157 84, Athens, Greece

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ABSTRACT

Sea-level change during the last 18,000 years is a combination of eustatic, isostatic and tectonic contributions. In an effort to minimize the tectonic contributions, our study of sea-level changes in the Aegean Sea within historical times is focused on the aseismic Attico–Cycladic geotectonic zone. On the basis of archaeological information and radiocarbon dating of coastal sedimentological formations, a sea-level curve for the Attico–Cycladic massif has been constructed for the past 5000 years and compared with existing curves. According to this curve, the rapid increase of sea level concluded prior to 5.5 ka and was followed by a slow steady rise at a rate of 0.9 mm/a up to its present stage. The latter is attributed primarily to the process of thermal expansion and secondarily to the residual melting of the glaciers and existing ice-caps. By extrapolation of the curve, the sea level at the end of the 20th century is predicted to be about 9 cm higher than the present level; this value is much lower than the prediction of the last IPCC report (49 cm). If higher SLR rates are realised in the next few decades, then the excess 40 cm of the IPCC prediction can be attributed to human-induced global climatic change.

1. Introduction

Sea level is defined by the position of the sea surface relative to the coast, whilst sea-level change is a measure of the relative shift in position of these two surfaces (Lambeck, 1995), which coincides with the vertical and horizontal displacement of the associated coastline. Sea-level change (SLC) is the integrated outcome of eustatic (E), isostatic (I) and tectonic (T) components. Furthermore, the eustatic (E) component includes: (i) glacial eustasy (E_{gl}), due to the melt of glaciers; (ii) geoidal eustasy (E_{gd}), when sea-level fluctuations are related to changes of the geoid induced by the melting of glaciers and water accumulation in ocean basins; (iii) dynamic changes of the sea surface (E_{dy}) caused by a number of local meteorological, hydrological and oceanographic factors, including thermal expansion and (iv) rotational eustasy (E_{ro}), related to changes in the rotational state of the planet caused by glaciation and deglaciation processes (Mörner, 1996, 2000). Similarly, the isostatic component (I) is further subdivided into: (i) the hydro-isostatic component (I_{hd}) caused by the water-loading of the marine basins, that tend to subside, following the transgression; and (ii) the glacio-isostatic (I_{gl}) component resulting from the elastic deformation of the Earth's surface due to spatial and volumetric changes of the ice sheets. Crustal swelling remains significant even in non-glaciated areas, as in the case of the Mediterranean basin; this is mainly in response to the transfer of mantle material towards the formerly ice-loaded crust, which leads to crustal subsidence and to a relative sea-level rise (Lambeck, 1995). Finally, the tectonic component (T), is rather important in tectonically-active areas. Changes due to tectonic processes tend to be less predictable, of shorter time wavelength and more episodic than the glacially driven change (Lambeck and Purcell, 2005). Furthermore, a preliminary assessment of local neo-tectonic movements could be served by the criteria established by Antonioli et al. (2002), based on the local position of the 125 ka shoreline.

On the basis of the above, any sea-level change (SLC_R) relative to the adjacent coast can be expressed by the equation:

$$SLC_R = \left(E_{gl} + E_{gd} + E_{dy} + E_{ro}\right) + \left(I_{hd} + I_{gl}\right) + T. \qquad (1)$$

An estimate of sea-level change during the current interglacial period is important in the debate of the human impact on the global climate, related to the thermal expansion of the oceans and the exchange of mass between the oceans and the underground and surface water; these factors may have contributed to the recent or present sea-level rise (Church et al., 2001).

Regarding glacio-eustasy (Egl), it is accepted that at the beginning of the last transgression (18 to 21 ka BP) the sea level in the Mediterranean was 110–130 m below its present stage (Pirazzoli, 1991), which is in agreement with most of the other curves of global ocean changes (e.g. Fairbridge, 1981). Furthermore, it is also accepted that the process of glacio-eustasy has been completed approximately 6000 radiocarbon years BP (Pirazzoli, 2005). This period (from approx. 20 ka to 6 ka BP) is associated with a phase of rapid sea-level rise. However,

* Corresponding author.
E-mail address: poulos@geol.uoa.gr (S.E. Poulos).

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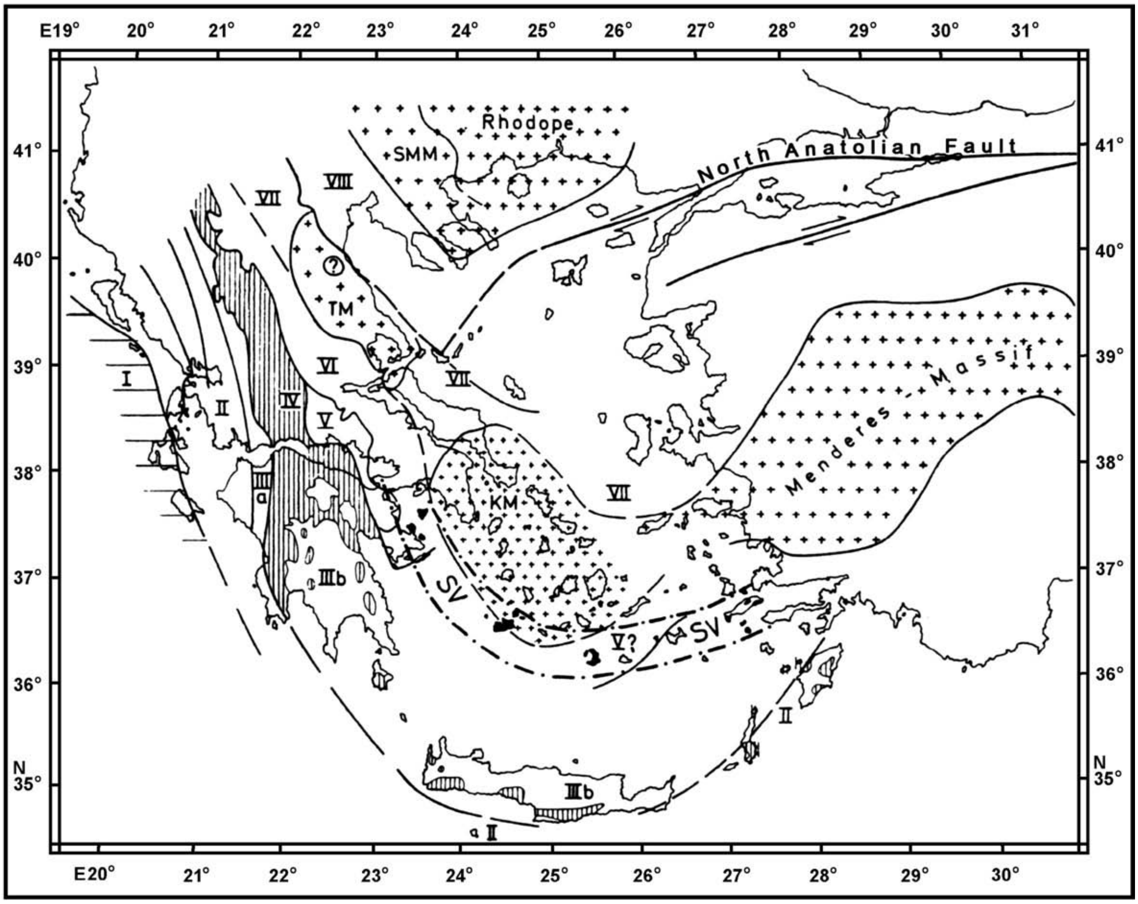

Fig. 1. Tectonic units of the Hellenides (modified from Makris, 1973). (I: Preapulian zone; II: Ionian zone; IIIa: Gavrovo zone; IIIb: Tripolitza zone; IV: Pindos zone; V: Parnass zone; VI: Subpelagonian zone; VII: Pelagonian zone; VIII: Vardar zone; SMM: Serbomacedonian massif; TM: Thessalian massif; KM: Attico–Cycladic massif; SV: South Aegean volcanic arc).

other investigators (e.g. Nakada and Lambeck, 1987; Lambeck, 1993) have stated that a small amount of additional meltwater (from a reduction in the volume of the Antarctic ice) continued to be added to the oceans until today.

Recent analyses of global sea-level change indicate an average rate of SLR of 1.8 ± 0.2 mm/a between 1950 and 2000, corrected for the isostatic signal, but with significant regional departures from the mean value, some of them being as low as 1.0 mm/a (Church et al., 2001). In agreement to the latter and for the case of the Mediterranean Sea, Lambeck et al. (2004a) have stated that, firstly, the eustatic component of sea-level rise since the Roman Period along the Tyrrhenian coast of Italy (Central Mediterranean) has been 1.25 ± 0.25 m and, secondly, that the onset of modern relative sea-level rise (0.13 ± 0.09 m) has occurred at approximately 100 ± 53 years before present (late 19th century or early 20th century). Similarly, a 20th century acceleration in global sea-level rise has been reported by Church and White (2006), whilst Cavenaze and Nerem (2004) using satellite altimetry have found a 3.1 mm/a rise of sea level between 1993 and 2003, stating that it is unclear if this is a real acceleration or due to a decadal variability.

With respect to geoidal eustasy (E_{gd}), the model of Rizos (1983) for the Mediterranean has predicted an increase in the slope of the geoid from W to E of the order of 5–10 cm/century, after taking into consideration the tectonic activity affecting the Mediterranean Basin. On a global scale, according to Mörner (2005), changes in the geoid relief are of the order of ± 30 m for a period of 20 ka and 5–10 m during the past 8000 years. The same scientist has also stated that rotational eustasy (E_{rt}) could cause decadal sea-level changes of between 0.1 and 1 m (known as super-ENSO events), whilst eustatic dynamic changes (E_{dy}) in sea-surface topography, present in the low harmonics, are of the order of 2 m. In the case of the Mediterranean, Lisitzin (1974) has estimated that the maximum dynamic variation in mean sea level due to climatic changes, referred to an unchanged quantity of sea water, may account for a sea-level difference of 0.5 m between the Aegean Sea and the Eastern Mediterranean Basin. Dynamic changes due to atmospheric forcing (Tsimplis and Josey, 2001) and changes in mean values of seawater temperature and salinity (Tsimplis and Rixen, 2002) not only have reduced the rate of sea-level rise significantly, but even changed its sign, as during the interval of 1960–1990.

The glacio-hydro-isostatic component ($I_{hd} + I_{gl}$) of the whole of the Mediterranean Basin has been calculated by Lambeck and Purcell (2005, Fig. 14), assuming that tectonic contributions are either absent or being corrected for. Analogous works have been undertaken for the French Mediterranean (Lambeck and Bard, 2000) and along the Italian coast (Lambeck et al., 2004a,b). In the case of the Aegean Sea, one of the first regions where Lambeck tested his hydro-isostatic model due to existing information (geological, archaeological) on relative sea-level changes within the middle and upper Holocene, he has found that the glacio-hydro-isostatic adjustment has reached an amplitude of 1 mm/a during the last few millennia (Lambeck, 1995). Subsequently, on the basis of this work, Lambeck (1996; Fig. 4) hindcasted the relative sea-level changes for the Aegean Sea: At 18000, 10000, 6000 and 2000 years BP, the sea level in the Aegean was 110–130 m, 44–60 m, 2–8 m and 1–1.75 m below the present-day level, respectively. Moreover, Lambeck (1995) has concluded that the rising sea level around Greece is mainly due to glacio-hydro-isostasy and not due to a long-term tectonic process. On the contrary, Pirazzoli (2005) questioned the accuracy of the results of the glacio-hydro-isostatic models, especially during the last 6000 years, supporting a nearly stable global eustasy over this period, implying that there was not any significant additional ice melting and/or a thermal expansion contribution. According to him and his colleagues, these relative sea-level changes in the Eastern Mediterranean have been attributed mainly to local tectonism (Thommeret et al., 1981; Pirazzoli et al., 1982). Moreover, Flemming (1978) investigating tectonic movements related to the geological structure of the Eastern Mediterranean and on the basis of 202 ancient harbour sites in Greece (excluding the Cycladic plateau), Turkey and Cyprus and 175 independent estimates of relative sea-level change, has stated that the overall eustatic component is <0.5 m over the last 2000–3000 years and that coastal submergence and/or emergence are due to tectonic movements of crustal blocks on a scale of 50–100 km. This neo-tectonic activity, has been also recognised by Pirazzoli (1986a) along the Hellenic Arc-Trench region (e.g. south Peloponnese, Crete, Karpathos and Rhodes islands, west and south Turkey) and even along the Israeli coast (Flemming and Webb, 1986). Pirazzoli (1986b) has identified, further, a tectonic paroxysmic phase, dated 1530 ± 40 years BP, related to a number of co-seismic events that resulted in a sudden uplift of about 10 m and/or tilting of coastal areas.

Obviously, there is a controversy between the various investigators as to whether the observed relative sea-level changes in the Aegean Sea and/or the Mediterranean basin, can be explained mainly by glacio-hydro-isostasy and/or by local neo-tectonism, assuming that the geoidal eustasy (E_{gd}), dynamic changes of sea surface (E_{dy}) and rotational eustasy (E_{ro}) played a minor role and that glacio-eustasy had concluded 6000 years BP. The glacio-hydro-isostatic model has been applied successfully in the cases of the French Mediterranean coast (Lambeck and Bard, 2000), the Italian coast (Lambeck et al., 2004a) and the central Mediterranean (Lambeck et al., 2004b), whilst relative changes of sea level have been explained by local tectonism, as in the case of the Hellenic trench (e.g. Flemming and Webb, 1986; Pirazzoli, 1986b, 2005).

On the basis of the above and in view that there is no general consensus among the scientific community regarding a unique sea-level curve for Greece, and to some extent for the eastern Mediterranean Sea, the scope of the present contribution is to present a curve of relative sea-level rise in the central Aegean Sea region from the Prehistoric period to present, using geomorphological, sedimentological and archaeological information for coastal sites. In order to minimize the tectonic contribution to sea-level change, our investigation is focused on the Attico–Cycladic geotectonic zone in the Central Aegean, which is one of the most aseismic and tectonically stable areas of Greece (see Section 3). Additionally, the proposed 'new' curve is compared with other sea-level curves for the Aegean region

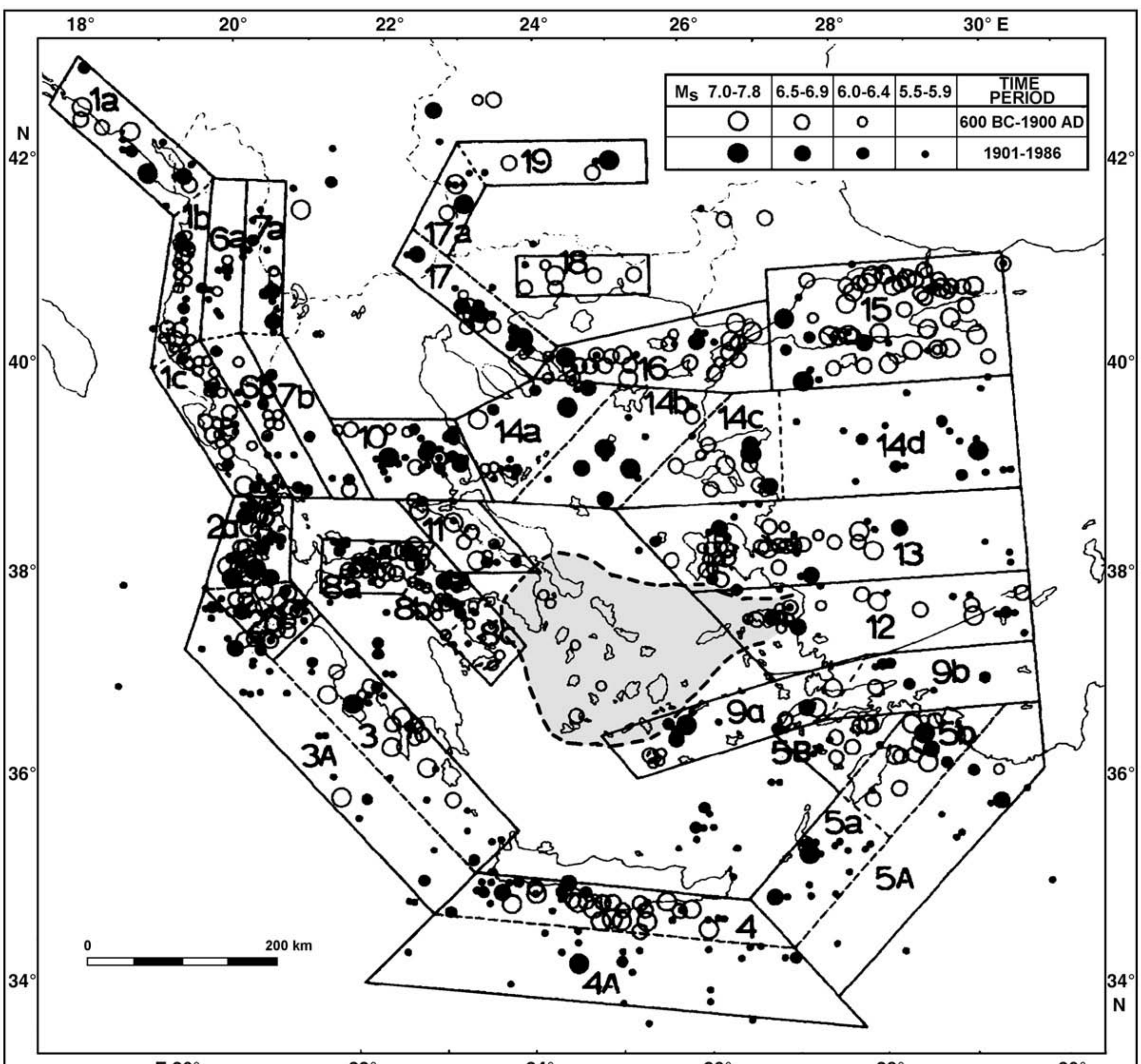

Fig. 2. The seismic zones (1,2,…,19) and seismic sources (1a,1b,…,19) of shallow earthquakes in the Aegean Sea and surrounding areas from 600 BC to 1986 AD (modified from Papazachos, 1990). The dashed line indicates the boundaries of the aseismic Attico–Cycladic massif (shaded area).

Table 1
Evidence of sea level rise in the region of Attico–Cycladic massif (central Aegean Sea, based upon published information (for locations see Fig. 3).

Site	Sea level stand (m)	Date	Time in years B.P. (2000 AD)	Description and type of evidence
Aegina Island	−2.0	100 BC	2100	Roman aqueduct[a]
Peiraeus Harbour	−1.5 ± 1.0	450 ± 50 BC	2450 ± 50	Ancient walls [a]
Zea (Attica)	−2.5 ± 0.5	500 BC	2500	Ancient quarry[a]
Phaliro (Attica)	−3.25 ± 0.25	480 BC	2480	Ancient port [a]
Kea Island	−3.4	500 BC	2500	Ruins of ancient port[b]
Dilessi (Attica)	−1.5	350 ± 50 BC	2350 ± 50	Ancient spa [c]
Magoula (Euboea Island)	−1.5	490 BC	2490	Cemetery[c]
Eretria (Euboea Island)	−1.5	550 ± 50 BC	2550 ± 50	Harbour[c]
Saliagos (Antipa-ros Island)	−5.5	5500 BC	5500	Archaeological ruins[d]
Delos Island	−2.0 ± 0.5	50 BC	2050	Submerged ancient quay[a]
Delos, Rhenia & Mykonos Islands	−3.6 ± 0.5	2000 BC	4000	^{14}C (AMS) dating on 20 samples taken from beachrocks [e]
	−2.5 ± 0.5	400 BC	2400	
	−1.0 ± 0.5	1000 AD	1000	
Marathon (Attica)	−3.55 ± 0.05	1800 BC	3800±80	^{14}C dating of borehole sedimentological samples[f]
Naxos Island	−2.8 ± 0.25	1100 BC	3100	Submerged ancient coastal road[g]

Key: (a)- Negris (1904); (b)- Mourtzas and Marinos (1994); (c)- Kambouroglou et al. (1988); (d)- Morrison (1968); (e)- Fouache et al. (2005); (f)- Baeteman (1985); (g)- Maroukian (unpublished data).

and is used to assess the predicted future sea-level trend (IPCC, 2001) in comparison to that of the Attico–Cycladic massif.

2. Geotectonic setting

The geotectonic structure of the Greek region (Fig. 1) is associated with the submergence of the African mega-plate (moving northwards) under the Eurasian mega-plate along the Hellenic Trench (Dewey et al., 1973). This deformation involves three other microplates; the Adriatic (continental) plate that is moving eastwards along the Cefallinia Transformation Fault (CFT), the Aegean plate that is subdivided further to the North and South Aegean micro-plates by the western extension of the North Anatolian Fault (NAF), and the Anatolian plate that moves westwards. The combined effect of these compressing forces is the drifting of the Greek territory towards the southwest (McKenzie 1972, 1978; Papazachos et al., 1989). This highly active geoenvironment produces 'rough' terrestrial and subaqueous topography, intense seismicity and several volcanic eruptions along the Hellenic volcanic arc. In contrast, the Aegean micro-plate was already stabilized by the middle Miocene, after the main African-Eurasian plate collision, as suggested by the presence of shoshonitic lavas at its periphery (Fytikas et al., 1976).

In the central part of the Aegean Sea, and specifically in the region consisting of the Attico–Cycladic massif, clockwise block rotations and continental extension in the Cyclades region may have taken place mostly during the Late Miocene (Avigad et al., 1998). Furthermore, this part of the Aegean Sea has been recognized as an aseismic plateau by McKenzie (1972), Morelli et al. (1975) and more recently by Papazachos (1990), as it is characterised by the relative absence of earthquakes (see Fig. 2) and, therefore, by limited neo-tectonic activity; the latter is expected to be related mostly to the periphery of the Aegean microplate. Additionally, present-day landscape features of the Cycladic islands of Tinos, Mykonos and Serifos, such as preserved planation surfaces, have formed in the Late Miocene or Pliocene in association to post-plutonic unroofing in the Cyclades plateau and have not tilted significantly since then (Hejl et al., 2002), implying limited tectonic activity in this region since the early Pleistocene.

Moreover, areas close to the periphery of the Attico–Cycladic massif show minimum or no uplift during the last few thousand years. Baeteman (1985) investigating the Holocene stratigraphic and sedimentological evolution of the coastal plain of Marathon (at the northwestern end of the Attico–Cycladic massif) has not reported any neotectonic movements. In a recent work, based partly on Baeteman's (1985) data, Pavlopoulos et al. (2006) suggested a slow rate of tectonic uplift from 5500 to 1300 BP and a slowing rate of sea-level rise from Classical times onward. However, during an extensive field study along the coastal zone of Marathon, as well as the adjacent coasts to the north and to the south, we have not found any evidence of recent tectonic uplift. Similarly, a limited tectonic effect with displacements less than 1 m over the last two millennia has been reported by Flemming (1978) for the Aegean coast of Asia Minor, from Kusandasi to Bodrum (Menderes massif), close to the southeastern end of the Cyclades plateau.

Finally, the North Aegean Trough, the northern boundary of the Aegean microplate, which is interpreted as the westward extension of the North Anatolian Fault (Dewey and Şengör, 1979), is characterised by extensional strike-slip tectonics (Mascle and Martin, 1990).

3. Data collection and analysis

There is a lot of information concerning relative sea-level change in the Aegean Sea (e.g. Flemming, 1978; Mourtzas and Marinos, 1994; Pirazzoli, 2005) based upon archaeological data and morphological coastal features from the Aegean coast of mainland Greece and Asia Minor, along the Hellenic trench (i.e. Crete, Rhodes) and only a few from the Attico–Cycladic massif.

Aiming to quantify the sea-level changes of the Aegean Sea due to eustatic and hydro-isostatic components, data collection for this study was focused on the Attico–Cycladic massif, where the tectonic contribution is minimal. Furthermore, the study of sea-level changes was restricted to the last 6000 years, for which an adequate number of accurately dated sea-level indicators exist. The collected sea-level indicator data, presented in Table 1, consist of archaeological evidence (e.g. submerged moles, piers, cemeteries), coastal formations (e.g. beachrock) and radiocarbon-dated sedimentary units (e.g. buried shallow (coastal) marine deposits). For the data derived from radiocarbon dating, the calibrated ages reported by the corresponding authors are used. All dates in Table 1 are expressed both as chronologies and as years before present (BP) to facilitate the analysis and discussion. Year 2000 AD is used as year 0 BP throughout the paper. The precision of sea-level and age estimates varies depending on the type of indicator used. Archaeological indicators, such as harbours, moles and coastal roads, are usually very precisely dated, but their estimated original elevation may be relatively uncertain. On the other hand, sedimentological and morphological indicators, such as beachrocks and sea-notches, provide very precise estimates of relative sea-level changes, but their dating may be problematic. Whenever the precision was provided or could be assessed from the description of the sea-level indicators and the dating procedures, it was included in the analysis together with the corresponding estimated sea-level and age values. A trend analysis of the data has been performed, and a prediction of sea level for the year 2100 AD has been obtained by extrapolation of the computed trend line. The proposed sea-level curve for the Attico–Cycladic massif has been compared to the sea-level curves of Kambouroglou et al. (1988), Lambeck (1996) and Vouvalidis et al. (2005) for the Aegean region and the global curve by Van Andel (1989, 1990).

Recent trends of modern sea-level changes in the Aegean Sea have also been incorporated in the present analysis on the basis of mean monthly sea-level values (1974–1991) from the tidal gauge of Syros Island, which is located in the centre of the Cycladic plateau. Thirty-two years (1974–2005) of tidal data were available for Syros; of these, 17 years of continuous tidal gauge operation (1974-1991) were used for the analysis of current sea-level trends and were compared to the latest sea-level projections for the year 2100, as given by the IPCC (2001).

4. Results and Discussion

The published sea-level curves and the estimates of sea-level changes on a global scale (Van Andel, 1989, 1990; Lambeck and Chappell, 2001; Peltier, 2002) and for the Mediterranean sea (Pirazzoli, 1991; Lambeck, 1995) show that from the onset of glacial melting, shortly after the last glacial maximum (LGM), until its termination approximately 7000 years BP, the sea level has risen rapidly (up to 15 mm/a), although at variable rates.

The data we present, from the aseismic and tectonically stable Attico–Cycladic massif (Fig. 3), show that the sea level in the Central Aegean has been rising at a steady rate, at least for the last 5000–5500 years. In the Central Aegean, 5000 years ago sea level was 4.5–5 m below its present level and it continued to rise at a steady rate of approximately 0.9 mm/a up to present. The majority of our data denote that between 2000 and 2500 years BP the sea level was 1.5 to 2.5 m below its present stage; a similar pattern of sea-level rise in the Aegean Sea has been also reported by Negris (1903, 1904), on the basis of archaeological data. Assuming minimal tectonic activity (a reasonable assumption for the Attico–Cycladic massif), this trend of 0.9 mm/a shows that the last transgression, associated with the current interglacial period, has not finished yet. The continuing sea-level rise can most likely be attributed to the residual melting of the glaciers and ice-caps and to the process of thermal expansion of the upper ocean layers; the latter could account for 0.6 m per degree Celsius of increase in the average sea temperature (Duxbury and Duxbury, 1996). Evidence of such sea-level rise comes from the general picture of retreating shorelines along the European (including the Mediterranean) coast (EUROSION, 2004).

In Fig. 4, we present five sea-level curves: (1) the curve for the Central Aegean Sea based on data from the Attico–Cycladic massif; (2) the curve of Vouvalidis et al. (2005) for the North Aegean Sea, for a rather stable margin (Thermaikos Gulf) that lies to the North of the eastern extension of the Anatolian Fault; (3) the curve published by Kambouroglou et al. (1988) based upon archaeological information from the South and North Evoikos Gulf; (4) the eustatic curve for the

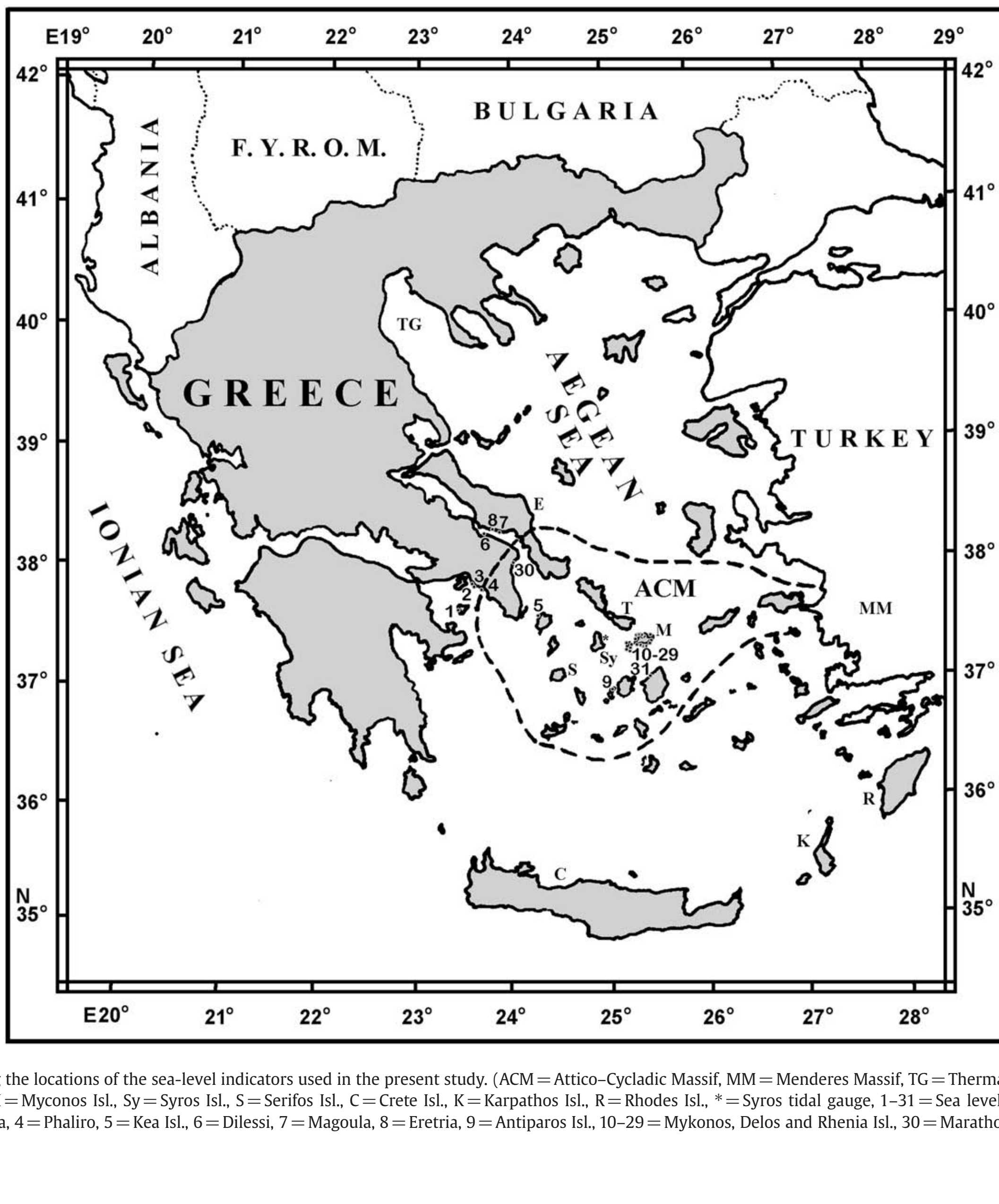

Fig. 3. Map showing the locations of the sea-level indicators used in the present study. (ACM = Attico–Cycladic Massif, MM = Menderes Massif, TG = Thermaikos Gulf, E = Euboea Isl., T = Tinos Isl., M = Myconos Isl., Sy = Syros Isl., S = Serifos Isl., C = Crete Isl., K = Karpathos Isl., R = Rhodes Isl., * = Syros tidal gauge, 1–31 = Sea level data: 1 = Aegina Isl., 2 = Peiraeus, 3 = Zea, 4 = Phaliro, 5 = Kea Isl., 6 = Dilessi, 7 = Magoula, 8 = Eretria, 9 = Antiparos Isl., 10–29 = Mykonos, Delos and Rhenia Isl., 30 = Marathon, 31 = Naxos Isl.)

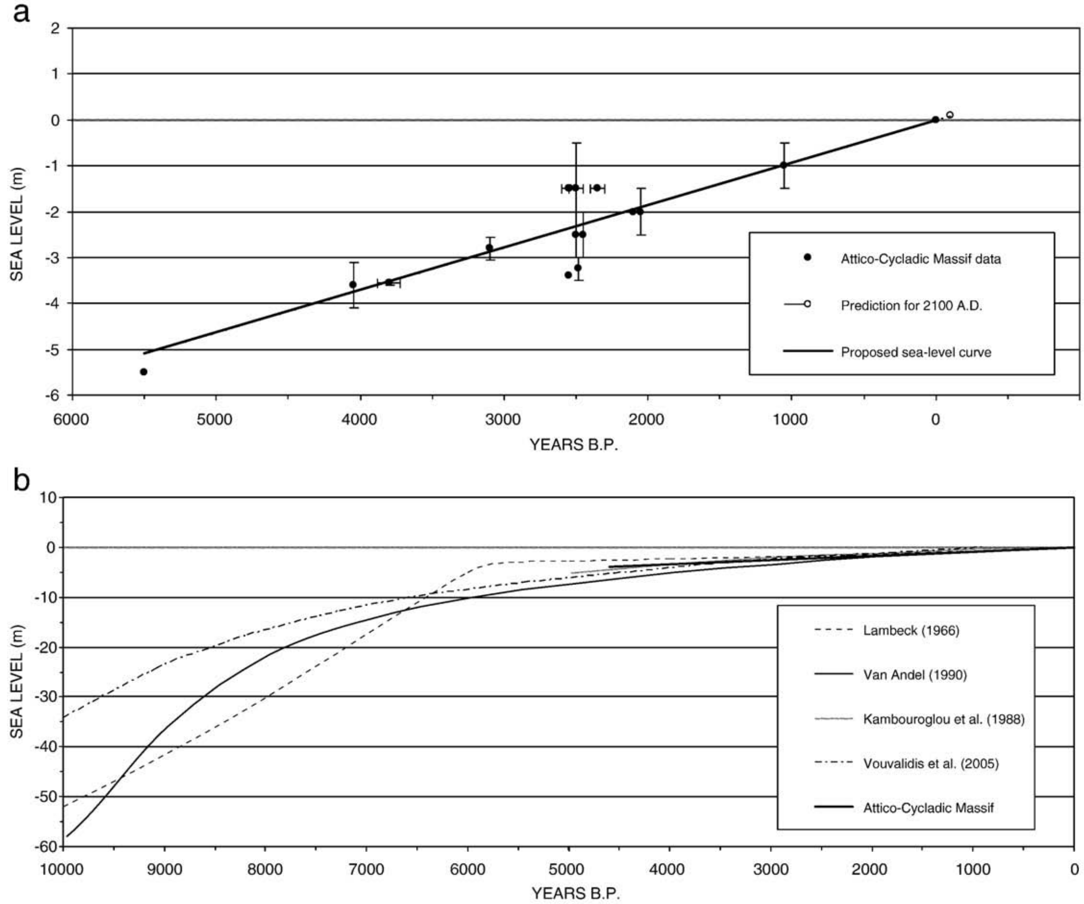

Fig. 4. a) The proposed sea level curve for the Attico-Cycladic Massif region for the last 5,500 years and b) Sea level curves for the Aegean sea and global eustatic sea level curve for the last 10,000 years.

central Aegean sea (Cycladic plateau) on the basis of Lambeck's (1996) glacio-isostatic model for the Aegean Sea; and (5) the curve of global eustatic sea-level rise by Van Andel (1990).

All curves presented in Fig. 4 are in very good agreement for the last 2000 years, whilst prior to 4000 BP the curve for Thermaikos Gulf (Vouvalidis et al., 2005) and Van Andel's (1990) global eustatic curve indicate a lower sea level (about 2 m); on the contrary, Lambeck's (1996) model estimates the position of sea surface to be approximately 1 m higher. None of the above curves indicate that sea level has ever been higher over the past 5000 to 6000 years than it is today, as has been stated earlier by Kelletat (1975). On the other hand, none of the aforementioned curves (including that of the Attico–Cycladic massif) show any sea-level change during the periods of the Little Climatic Optimum (700–1300 AD) and the subsequent Little Ice Age (1550–1850 AD) (Grove, 1988). The precision of the available data does not permit the detection of possible sea-level fluctuations during these short periods of time. Nevertheless, Mörner (1973) has reported eustatic changes of about 12 cm in the last 300 years. In the case of the Aegean Sea, although accurate estimates cannot be made due to the lack of any reliable data, the short duration of the historical time-periods, and the geomorphological complexity of the region (i.e. connection to the Atlantic Ocean but also freshwater inputs from the Balkans and the Black Sea), the expected sea-level changes are not expected to deviate much from the overall trend.

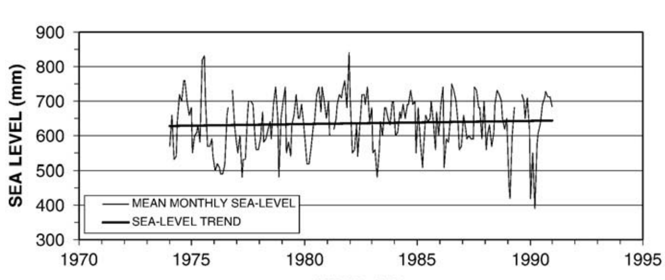

Fig. 5. Mean monthly sea level fluctuation recorded by the tidal gauge at Syros Island from 1974 to 1991, showing a positive SLR trend of 0.86 mm/a.

Recent trends (since the 19th century) of sea-level rise have been investigated worldwide using tidal data. Our analysis of the mean monthly sea-level values (1974–1991) from the tidal gauge of Syros Island, in the centre of the Cycladic plateau, shows a positive sea-level trend of 0.86 mm/a (Fig. 5). Similarly, a positive tendency of sea-level rise during the last centuries has been deduced from the records of 16 out of 23 tidal gauge stations in the eastern and central Mediterranean Sea and for time-spans between 1880 and 1980 AD (Pirazzoli, 1997; Table 5.1); in 14 stations the rates of sea-level change varied between +0.3 mm/a (Sete station (43°31′N, 03°07′E), 1888-1958), and +2.5 mm/a (Venice station (45°26′N, 12°20′E), 1872–1983). A more recent study, based on data for the whole of the Mediterranean Sea, has given a relative sea-level rise less than 2.2 mm/a (Tsimplis and Spencer, 1997; Tsimplis, 2005), while a global appraisal provided by Church et al. (2001) is 1–2 mm/a.

All data from the Attico–Cycladic massif area indicate a constant regional rate of sea-level rise during the last 5000 years. Moreover, the tidal gauge data from Syros support that this rate persists at least up to

1990. Since no acceleration of sea-level rise is detectable from the aforementioned data, a 9 cm sea-level rise by 2100 AD was predicted by a simple extrapolation of the Attico–Cycladic curve, provided that the current trend will not change. This value represents a slower sea-level rise than the one proposed by the IPCC (2001), which predicted an average global sea-level rise of 49 cm until 2100 AD, corresponding to a SLR rate of about 5 mm/a, as a result of an increase of air temperature by 2–3 °C.

Taking into account the steady rate of sea-level rise and assuming minimal vertical displacements due to tectonism, as is the case in the "stable" Attico–Cycladic massif, and/or isostatic adjustments (hydro-isostatic adjustment concluded 3–4 ka ago (according to Lambeck, 1995; Fig. 6)), it can be argued that the sea-level rise during historical times is due to eustasy which, in turn, could be caused primarily by the thermal expansion of the oceans and secondarily by the residual ice-melting ($SLC_R = E_{gl} + E_{dy}$).

The steady rate of sea-level rise (approximately 0.9 mm/a) in the Central Aegean region for the last 5000 years is much smaller than the SLR rate proposed by the IPCC (2001) for the next century; if the excess 3–4 mm/a are realised in the coming decades, they could be attributed to global warming induced by human activities (e.g. greenhouse effect). Otherwise, the IPCC (2001) predictions for the year 2100 AD seem to overestimate the sea-level rise, at least in the case of the Central Aegean region.

5. Conclusions

The main phase of rapid sea-level rise in the Central Aegean region ended prior to 5500 BP with the sea level being 4–5 m below its present stand. Subsequently, the sea level continued to rise slowly at a rate of 0.9 mm/a towards its present level, but without ever exceeding it. Due to the tectonic stability of the Attico–Cycladic Massif (central Aegean Sea), the rise of sea level within historical times is attributed to eustatic factors, with thermal expansion being the dominant one, followed by residual melting of glaciers and ice-caps. Hence, the current transgressional phase during the last interglacial period has not reached its optimum yet. No signs of accelerated sea-level rise in recent years are detectable from the available data for the Central Aegean region. The estimate of sea-level rise in the Aegean Sea for 2100 AD, on the basis of the Attico–Cycladic curve and presuming that the present trend will persist, is approximately 9 cm, which is significantly lower than the 49 cm, predicted by the IPCC (2001). Thus, any excess of the natural increment (i.e. 9 cm) during the coming decades would be attributed to the Global Climatic Change induced by human activities.

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References

Antonioli, F., Cremona, G., Immordino, F., Pugliesi, C., Romagnoli, C., Silenzi, S., Valpreda, E., Verrubbi, V., 2002. New data on the Holocene sea-level rise in NW Sicily (Central Mediterranean Sea). Global and Planetary Change 34, 121–140.
Avigad, D., Baer, G., Heimann, A., 1998. Block rotations and continental extension in the central Aegean Sea: paleomagnetic and structural evidence from Tinos and Mykonos (Cyclades, Greece). Earth and Planetary Science Letters 157, 23–40.
Baeteman, C., 1985. Late Holocene geology of the Marathon Plain (Greece). Journal of Coastal Research 1, 173–185.
Cavenaze, A., Nerem, R.S., 2004. Present-day sea-level change: observations and causes. Reviews Geophysics, 42 (3), 1–20.
Church, J.A., White, N.J., 2006. A 20th century acceleration in global sea-level rise. Geophysical Research Letters 33, L01602. doi:10.1029/2005GL024826.
Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D., Woodworth, P.L., 2001. Changes in sea level. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Climate Change 2001: Impacts, Adaptations and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. 602 pp.
Dewey, J.F., Şengör, A.M.C., 1979. Aegean and surrounding regions: complex multiplate and continuum tectonics in a convergent zone. Geological Society of America, Bulletin 90, 84–92.
Dewey, J.F., Pittman, W.C., Ryan, W.B.F., Bonnin, J., 1973. Plate tectonics and evolution of the Alpine system. Bulletin of the Geological Society of America 84, 3137–3180.
Duxbury, A.B., Duxbury, A.C., 1996. Fundamentals of Oceanography, (2nd edition). Wm. C. Brown Publishers, London. 308 pp.
EUROSION, 2004. Living with coastal erosion in Europe: Sediment and Space for Sustainability, Part II – Maps and statistics. Directorate General Environment, European Commission (B4-3301/2001/329175/MAR/B3.
Fairbridge, R.W., 1981. Holocene sea-level oscillations. In: Königsson, L.K., Paabo, K. (Eds.), Florilegium Florinis Dedicatum, Striae 14, Uppsala, pp. 131–141.
Flemming, N.C., 1978. Holocene eustatic changes and coastal tectonics in the northeast Mediterranean: implications for models of crustal consumption. Philosophical Transactions of the Royal Society of London A 289, 405–458.
Flemming, N.C., Webb, C.O., 1986. Tectonic and eustatic coastal changes during the last 10000 years derived from archaeological data. Zeitschrift für Geomorphologie 62, 1–29.
Fouache, E., Desruelles, St., Pavlopoulos, K., Dalongeville, R., Coquinot, Y., Peulvast, J.-P., Potdevin, J.L., 2005. Using beachrocks as sea level indicators in the insular group of Mykonos, Delos and Rhenia (Cyclades, Greece). Zeitschrift für Geomorphologie N.F. 137, 37–43.
Fytikas, M., Giuliani, O., Innocenti, F., Marinelli, G., Mazzuoli, R., 1976. Geochronological data on recent magmatism of the Aegean Sea. Tectonophysics 31, T29–T34.
Grove, J.M., 1988. The little Ice Age. Methuen, London. 498 p.
Hejl, E., Riedl, H., Weingartner, H., 2002. Post-plutonic unroofing and morphogenesis of the Attic–Cycladic complex (Aegean, Greece). Tectonophysics 349, 37–56.
IPCC, 2001. Climate change 2001: impacts, adaptations and vulnerability. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. 602 pp.
Kambouroglou, E., Maroukian, H., Sampson, A., 1988. Coastal evolution and archaeology north and south of Khalkis (Euboea) in the last 5000 years. In: Raban, A. (Ed.), Archaeology of Coastal Changes, vol. 404. BAR International Series, Oxford, pp. 71–79.
Kelletat, D., 1975. Eine eustatische Kurve für das jüngere Holozän, konstruiert nach Zeugnissen früherer Meeresspiegelstände im östlichen Mittelmeergebiet. N.Jahrb. Geol.Paläont., Monatsch. 6, 360–374.
Lambeck, K., 1993. Glacial rebound of the British Isles-II. A high resolution, high precision model. Geophysical Journal International 115, 960–990.
Lambeck, K., 1995. Late-Pleistocene and Holocene sea-level change in Greece and south-western Turkey: a separation of eustatic, isostatic and tectonic contributions. Geophysical Journal International 122, 1022–1044.
Lambeck, K., 1996. Sea-level changes and shoreline evolution in Aegean Greece since Upper Paleolithic time. Antiquity 70, 588–611.
Lambeck, K., Bard, E., 2000. Sea-level change along the Mediterranean coast since the time of the Last Glacial Maximum. Earth and Planetary Science Letters, 175 (3-4), 202–222.
Lambeck, K., Chappell, J., 2001. Sea level change through the last glacial cycle. Science 292, 679–686.
Lambeck, K., Purcell, A., 2005. Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas. Quaternary Science Reviews 24, 1969–1988.
Lambeck, K., Anzidei, M., Antonioli, F., Benini, A., Esposito, A., 2004a. Sea level in Roman time in the Central Mediterranean and implications for recent change. Earth and Planetary Science Letters 224, 463–575.
Lambeck, K., Antonioli, F., Purcell, F., Silenzi, S., 2004b. Sea-level change along the Italian coast for the past 10,000 yr. Quaternary Science Reviews 23, 1567–1598.
Lisitzin, E., 1974. Sea-level changes. Elsevier Oceanography Series 8. Elsevier, Amsterdam, p. 286.
Makris, J., 1973. Some geophysical aspects on the evolution of the Hellenides. Bulletin Geological Society of Greece X (1), 99–108.
Mascle, J., Martin, L., 1990. Shallow structure and recent evolution of the Aegean Sea: a synthesis based on continuous reflection profiles. Marine Geology 94, 271–299.
McKenzie, D., 1972. Active tectonics of the Mediterranean region. Geophysical Journal Royal Astronomical Society of London 30, 109–185.
McKenzie, D., 1978. Active tectonics of the Alpine Himalayan belt: the Aegean Sea and surrounding regions (tectonics of the Aegean region). Geophysical Journal Royal Astronomical Society of London 55, 217–254.
Morelli, C., Pisani, M., Gantar, C., 1975. Geophysical studies in the Aegean Sea and in the Eastern Mediterranean. Bolletino Geofisical Teoritica & Applicata 18, 127–167.
Mörner, N.-A., 1973. Eustatic changes in last 300 years. Palaeogeography, Palaeoclimatology and Palaeoecology 13, 1–14.
Mörner, N.-A., 1996. Rapid changes in coastal sea level. Journal of Coastal Research 12, 797–800.
Mörner, N.-A., 2000. Sea level changes and coastal dynamics in the Indian Ocean, Integrated Coastal Zone Management, Launch Issue, pp. 17-20.
Mörner, N.-A., 2005. Sea level changes and crustal movements with special aspects on the eastern Mediterranean. Zeitschrift für Geomorphologie N.F. 137, 91–102.
Morrison, I.A., 1968. Appendix I. Relative sea-level change in the Saliagos area since Neolithic times. In: Evans, J.D., Renfrew, C. (Eds.), Excavations at Saliagos near Antiparos, vol. 29-8. Thames and Hudson, London, p. 227.
Mourtzas, N.D., Marinos, P.G., 1994. Upper Holocene sea-level changes: Paleogeographic evolution and its impact on coastal archaeological sites and monuments. Environmental Geology 23, 1–13.

Nakada, M., Lambeck, K., 1987. Glacial rebound and relative sea-level variations: a new appraisal. Geophysical Journal of the Royal Astronomical Society 90, 171–224.
Negris, P., 1903. Régression et transgression de la mer depuis l'époque glaciaire jusqu'à nos jours. Revue universelle des Mines 3, 249-281 (in French).
Negris, P., 1904. Vestiges antiques submergés. Athenische Mitteilungen 29, 340–363 (in French).
Papazachos, B.C., 1990. Seismisity of the Aegean and surrounding area. Tectonophysics 178, 287–308.
Papazachos, B.C., Makropoulos, K., Latoussakis, J., Theodulidis, N., 1989. Elaboration of a map of seismic hazard in Greece. 2nd Report for the Program of Organization of Antiseismic Design and Protection, Athens, Greece. 24pp. (in Greek).
Pavlopoulos, K., Karkanas, P., Triantafyllou, M., Karyballis, E., Tsourou, T., Palyvos, N., 2006. Paleoenvironmental evolution of the coastal plain of Marathon, Greece, during the Late Holocene: depositional environment, climate, and sea level changes. Journal of Coastal Research 22, 424–438.
Peltier, W.R., 2002. On eustatic sea level history, Last Glacial Maximum to Holocene. Quaternary Science Reviews 21, 377–396.
Pirazzoli, P.A., 1986a. Sea-level changes and crustal movements in the Hellenic Arc (Greece). The contribution of archaeological and historical data. Proceedings of the First International Symposium "Cities on the Sea – Past and Present", Haifa, Israel, pp. 157–184.
Pirazzoli, P.A., 1986b. The early Byzantine Tectonic Paroxysm. Zeitschrift für Geomorfologie 62, 31–49.
Pirazzoli, P.A., 1991. World atlas of Holocene Sea-level changes. Elsevier Oceanography Series 58, Amsterdam. 300 pp.
Pirazzoli, P.A., 1997. Sea-level changes in the Mediterranean. In: Tooley, M.J., Shennan, I., (Eds.), Sea-level Changes, Institute of British Geographers, Special Publications Series, Page Bros (Norwich) Ltd, pp. 152-181.
Pirazzoli, P.A., 2005. A review of possible eustatic, isostatic and tectonic contributions in eight late-Holocene relative sea-level histories from the Mediterranean area. Quaternary Science Reviews 24, 1989–2001.
Pirazzoli, P.A., Thommeret, J., Thommeret, Y., Laborel, J., Montaggioni, L.F., 1982. Crustal block movements from Holocene shorelines: Crete and Antikythira (Greece). Tectonophysics 86, 27–43.
Rizos, C., 1983. Plate tectonics in the Mediterranean area and implications for the long term stability of the geoid. Proceedings of the 2nd International Symposium. Geoid in Europe and Mediterranean area (Rome, 1982), Firenze, Istitut Geography Milan. Italy, pp. 303–331.
Thommeret, J., Thommeret, Y., Laborel, J., Montaggioni, L.F., Pirazzoli, P.A., 1981. Late Holocene shoreline changes and seismo-tectonic displacements in western Crete (Greece). Zeitschrift für Geomorphologie 40, 127–149.
Tsimplis, M.N., 2005. Global sea level rise: a useful sea level predictor in the Mediterranean sea? Zeitschrift für Geomorphologie N.F. 137, 103–110.
Tsimplis, M.N., Spencer, N.E., 1997. Collection and analysis of monthly mean sea level data in the Mediterranean and the Black Seas. Journal of Coastal Research 13, 534–544.
Tsimplis, M.N., Josey, S.A., 2001. Forcing of the Mediterranean Sea by atmospheric oscillations over the North Atlantic. Geophysical Research Letters 28, 803–806.
Tsimplis, M.N., Rixen, M., 2002. Sea level in the Mediterranean Sea: the contribution of temperature and salinity changes. Geophysical Research Letters 29, 2136–2140.
Van Andel, T.H., 1989. Late Quaternary sea-level changes and archaeology. Antiquity 63, 733–745.
Van Andel, T.H., 1990. Addendum to "Late Quaternary sea-level changes and archaeology". Antiquity 64, 151–152.
Vouvalidis, K.G., Syrides, G.E., Albanakis, K.S., 2005. Holocene morphology of the Thessaloniki Bay: Impact of sea level rise. Zeitschrift für Geomorphologie N.F. 137, 147–158.