Biodata of **Michal Lichter, Dov Zviely, Micha Klein,** and **Dorit Sivan**, authors of ***"Sea-Level Changes in the Mediterranean: Past, Present and Future – A Review"***

Dr. Michal Lichter is currently a Postdoctoral Researcher in the Coasts at Risk and Sea-Level Rise (CRSLR) Research Group of the Future Ocean Excellence Cluster, based at the Institute of Geography, Christian Albrechts University, Kiel, Germany. She obtained her Ph.D. in Geography and Environmental Studies from the University of Haifa, Israel, in 2009. Dr. Michal Lichter's primary research interests are Coastal geomorphology, Geomorphological mapping, spatial analysis and GIS, shoreline changes, landform processes and environmental change, climate change, and sea-level rise.

E-mail: **mlichter@gmail.com**

Dr. Dov Zviely is Researcher in the Leon Recanati Institute for Maritime Studies (RIMS), in the University of Haifa, Israel. His scientific areas are: (1) Coastal geomorphology and sedimentology; (2) continental shelf morphodynamics; (3) Quaternary coastal paleo-geography and geo-archeology; (4) Charts, maps, hydrography, and maritime history of the eastern Mediterranean Sea.

E-mail: **zviely@netvision.net.il**

Michal Lichter

Dov Zviely

A. Israel et al. (eds.), *Seaweeds and their Role in Globally Changing Environments*,
Cellular Origin, Life in Extreme Habitats and Astrobiology 15, 3–17
DOI 10.1007/978-90-481-8569-6_1, © Springer Science+Business Media B.V. 2010

Professor Micha Klein is currently Professor Assistant in the Department of Geography and Environmental Studies, in the University of Haifa, Israel. He obtained his Ph.D. in geomorphology at the school of geography, University of Leeds, UK. His scientific areas are: (a) Geomorphology with special interest in drainage basin dynamics and in coastal geomorphology and (b) Geomorphology of Israel.

E-mail: **mklein@geo.haifa.ac.il**

Dr. Dorit Sivan, Ph.D. in Geology, The Hebrew University of Jerusalem, the Faculty of Science, Institute of Earth Sciences, Department of Geology. At present, she is a Senior Lecturer and Head of the Department of Maritime Civilizations, University of Haifa, and a researcher in the Leon Recanati Institute for Maritime Studies (RIMS).

Her research interests are mainly:

(a) Reconstruction of the coastal environment, mainly during the Holocene, and its connection to human settlement.
(b) Indications for past sea levels over the last 20,000, and mainly the last 10,000 years, during which there was intensive occupation along the Israeli coast. These two subjects, the paleogeography and sea-level curves, are essential for the understanding of mankind's historical processes, and complement historical and archeological research. This field of research is interdisciplinary and linked to the application of diverse research methods.

E-mail: **dsivan@research.haifa.ac.il**

Micha Klein

Dorit Sivan

SEA-LEVEL CHANGES IN THE MEDITERRANEAN: PAST, PRESENT, AND FUTURE – A REVIEW

MICHAL LICHTER[1], DOV ZVIELY[2], MICHA KLEIN[3], AND DORIT SIVAN[4]

[1]Coasts at Risk and Sea-Level Rise, Research Group, The Future Ocean Excellence Cluster, Institute of Geography, Christian Albrechts University, Kiel, 24098 Germany

[2]Leon Recanati Institute for Maritime Studies (RIMS), University of Haifa, Haifa, 31905, Israel

[3]Department of Geography and Environmental Studies, University of Haifa, Haifa, 31905, Israel

[4]Department of Maritime Civilizations, University of Haifa, Haifa, 31905, Israel

1. Introduction

The study of geological and historical sea-level changes constitutes an important aspect of climate change and global warming research. In addition to the imminent hazards resulting from the inundation of low-lying areas along coastal regions, the rise in sea level can also cause erosion of beaches, salt intrusion into freshwater aquifers, and other damage to the coastal environment. The utmost importance of current changes in sea level is attributed to its impact on diverse ecological systems in coastal regions (Klein et al., 2004).

On time-scales of millions of years, geological processes, such as changes in ocean basin geometry caused by plate tectonics, are dominant in affecting sea-level change, whereas on shorter time-scales of years and decades, oceanographic and climatic factors are more dominant (Lambeck and Purcell, 2005).

On time-scales of centuries and millennia, sea-level change is affected mainly by eustatic (all types of water volume variations), glacio-hydro-isostatic, and tectonic factors. Eustatic changes are global and are defined as ice volume equivalent. Isostatic sea-level changes are regional, and result from changes of ice mass balance over the crust and water and sediment over the continental shelf and ocean floor. Vertical tectonic movements are local and are caused by geological uplift or subsidence. Glacio-hydro-isostatic change has a predictable pattern, whereas tectonics is less predictable (Lambeck et al., 2004). The best way for differentiating the global, regional, and tectonic processes in long-term records is by comparing observations and glacio-hydro-isostatic models that predict the combined global and regional components (e.g., Lambeck and Purcell, 2005, and references therein). Discrepancies between the observed and the model-predicted changes are attributed to local movements, whether induced by tectonic movements, sediment compaction, or other reasons.

For short-term records of decadal scale, distinguishing between the "eustatic" component and regional–local crustal movements can be conducted only with present-day measurements. This involves simultaneous measurements of relative sea-level changes by tide-gauge and land vertical movement by GPS or other geodetic techniques. Daily and seasonal changes are caused mainly by astronomical tides and other atmospheric and oceanic forcing mechanisms.

"Eustatic" sea-level changes do not actually exist because sea-level changes are spatially heterogeneous, at least over decadal time scales (Mitrovica et al., 2001). Isostatic and local factors affecting land levels may cause relative sea-level changes that vary from place to place throughout the world (Pirazzoli, 1996).

Over the past century, sea level rose by 1–2 mm/year, with nonlinear changes ("accelerations") in different places (Woodworth and Player, 2003; Church and White, 2006; Jevrejeva et al., 2006; Woodworth, 2008), inundating flat coastal areas, and disrupting natural freshwater environments as well as human habitat in many coastal and inland communities.

2. Mediterranean Sea-Level Change Since the Middle Pleistocene

"Global" sea-level curves indicate that during the last 600,000 years (ka), the sea reached a maximum elevation of 5–10 m above present sea level (asl) (Fig. 1) at least three times and dropped to more than 100 m below present sea level (bsl) at least five times (Waelbroeck et al., 2002; Schellmann and Radtke, 2004; Rabineau et al., 2006;

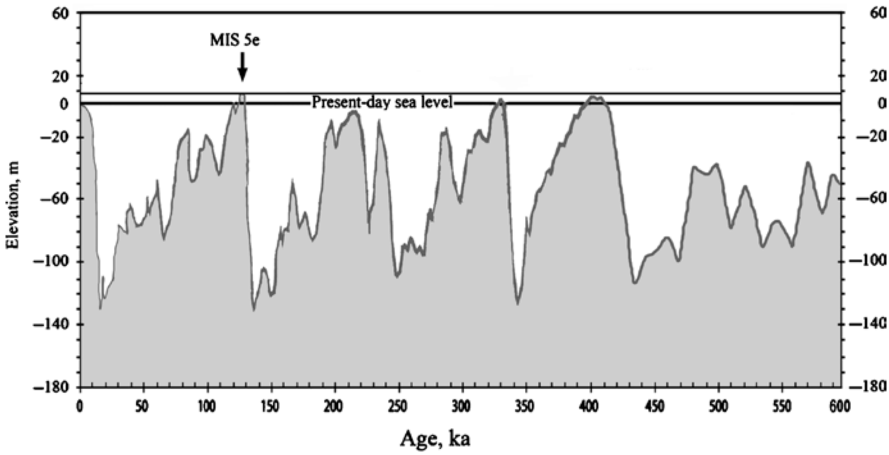

Figure 1. Global sea-level changes in the last 600 ka. (Modified after Waelbroeck et al., 2002; Rabineau et al., 2006; and Siddall et al., 2006.)

Siddall et al., 2006). The cyclic transition between glacial and interglacial cycles was about 100 ka (Shackleton, 2000), and the mean time between one glacial trough and the succeeding interglacial peak was about 20 ka.

Sea level during Marine isotope stage (MIS) 7.1, dated to between 202 and 190 ka, remained 18–9 m bsl (Bard et al., 2002), based on precise Uranium–Thorium (U-Th) dating of stalagmites from a currently submerged cave in Italy.

Sea level rose above its present level only at the peak of the last interglacial, some 125 ka ago (MIS 5e). In the Mediterranean, dating of the MIS 5e terraces is not certain, and at present there are indications of different levels, as summarized in Mauz and Antonioli (2009) and Stewart and Morhange (2009). The present elevations of the different sea-level indicators range between +175 and −125 m only in Italy because of tectonic reasons (Ferranti et al., 2006), or because of hydro-glacial adjustment of the crust (Antonioli et al., 2006). Studies in regions of the Mediterranean that are relatively tectonically stable, such as the coast of Israel (Sivan et al., 1999; Galili et al., 2007), western Sicily, and southern Sardinia, indicate that the Last Interglacial sea reached approximately 6 ± 3 m asl (Lambeck et al., 2004; Ferranti et al., 2006).

"Global" sea level later dropped to about 120 ± 5 m bsl, reaching its lowest levels during the Last Glacial Maximum (LGM), about 18 ka ago. In the Mediterranean, the longest record is found in Cosquer Cave, southern France, where Paleolithic wall paintings of horses dated to about 22 ka ago have been partially eroded by the recent rising sea water level (Lambeck and Bard, 2000 and references therein; Morhange et al., 2001).

Numerical models (Lambeck and Bard, 2000; Lambeck and Purcell, 2005) predicting sea-level changes during the last 18 ka allow estimation of the vertical movements by comparing the observations to the predictions summarized for all the Mediterranean by Stewart and Morhange (2009).

Since then, "global" sea level has been rising as a result of deglaciation and global warming (Fairbanks, 1989; Bard et al., 1990, 1996; Pirazzolli, 1991; Fleming et al., 1998; Rohling et al., 1998; Lambeck and Bard, 2000; Lambeck et al., 2002, 2004). At around 12.5 ka ago, "global" sea level rose rapidly to 70 m bsl. It continued to rise and reached 40 m bsl at the beginning of the Holocene. Levels lower than 20 bsl at the beginning of the Holocene have been observed in Israel, based on the submerged Pre-Pottery Neolithic site of Atlit Yam, situated at present 10–12 m bsl, with the bottom of one of the water wells at present 15.5 m bsl (Galili et al., 1988, 2005). Sea level continued to rise rapidly until the Mid-Holocene, when the rate slowed considerably (Lambeck and Bard, 2000; Bard et al., 1996; Lambeck et al., 2004; Poulos et al., 2009). Based on biological, sedimentological, and archeological indicators, sea-level studies around the Mediterranean indicate ±1 m bsl about 4 ka ago (Morhange et al. (2001) in the west Mediterranean, Lambeck et al. (2004) in Italy, Marriner et al. (2005) in Lebanon, and Sneh and Klein (1984), Galili et al. (1988, 2005), Nir (1997), Sivan et al. (2001, 2004), Galili and Sharvit (1998, 2000), and Porat et al. (2008) all from Israel, east Mediterranean). From about 4,000 until 2,000 years ago, there is ample archeological and biological (mainly biostructural) evidence available for sea-level reconstructions from all around the Mediterranean with better vertical accuracy of up to ±10 cm. During the Early Roman period, 2,000 years ago, sea level in the Mediterranean was 10–15 cm bsl. In Israel, Sivan et al. (2004) examined 64 coastal water wells in ancient Caesarea, and concluded that sea level was close to the present level during the Roman period. This conclusion agrees with the results found in Italy (Anzidei et al., 2008). For the Crusader period (eleventh to thirteenth centuries AD), lower levels of about 30 ± 15 cm bsl were estimated, based on the coastal water wells of Caesarea (Sivan et al., 2004; Sivan et al., 2008). These low levels are confirmed (with even lower estimated levels) by ongoing data from a few sites along the coast of Israel, based mainly on archeological evidence (Sivan et al., 2008).

3. "Global" Sea-Level Observations During the Twentieth Century

There is a consensus among sea-level researchers that the "global" sea-level rise in the past 100 years has been considerably faster than in the previous two millennia (Douglas, 2001).

"Global" sea-level rise during the twentieth century (Table 1) is estimated by most researchers to be 1–2 mm/year (Peltier, 2001; Miller and Douglas, 2004; Church and White, 2006). Church and White (2006) calculated a significant acceleration of sea-level rise of 0.013 ± 0.006 mm/year during the twentieth century.

The employment of tide-gauging facilities began in the second half of the nineteenth century, markedly improving the accuracy of sea-level measurement. Tide-gauge stations were rare prior to 1870, while spatially widespread tide-gauge records are available only for the twentieth century. Tide-gauge measurements are considered the most accurate sea-level records available for the twentieth century (Miller and Douglas, 2004), but they suffer from problems of spatial and temporal discontinuity that make calculating "global" mean trends a difficult task. Since the 1990s, sea-level measurements have also been obtained by satellite altimetry, which are often used as complementary data for tide-gauge data (Cabanes et al., 2001; Church et al., 2004). At present, more information about sea-level change

Table 1. Estimates of the "global" mean sea-level contributions from 1961 to 2003 and 1993 to 2003, compared with the observed rate of rise. (Modified after Bindoff et al., 2007.)

Source	1961 to 2003	1993 to 2003
Thermal expansion	0.42 ± 0.12	1.60 ± 0.50
Glaciers and ice caps	0.50 ± 0.18	0.77 ± 0.22
Greenland ice sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic ice sheet	0.14 ± 0.41	0.21 ± 0.35
Sum	1.10 ± 0.50	2.80 ± 0.70
Observed	1.80 ± 0.50	3.10 ± 0.70
Difference (observed-sum)	0.70 ± 0.70	0.30 ± 1.00

is available than ever before: historical data sets from tide-gauges; new understanding of postglacial rebound; precise geodetic techniques for the estimation of vertical crustal motion, and finally, more a decade of satellite altimetry, providing more precise records of recent changes in mean sea level (Cazenave and Nerem, 2004). New altimeter measurements from the TOPEX/Poseidon and Jason-1 satellites since the beginning of the 1990s have revealed a much faster rise in sea level during 1993–2003 than the average twentieth century rate. Cazenave and Nerem (2004) calculated a 2.8 ± 0.4 mm/year rise for this period (3.1 mm/year if the effects of postglacial rebound are removed).

As mentioned earlier, sea-level changes are not uniform around the Globe, e.g., Church et al. (2004) recognized a maximum sea-level rise in the eastern Pacific off-equatorial area, and minima along the equator, in the western Pacific, and in the eastern Indian Ocean.

Table 1 summarizes the contributions of thermal expansion, glaciers and ice caps, and the two ice sheets to "global" sea-level rise since 1961, according to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). It is, however, noted in the report that the total "global" sea-level change budget has not yet been satisfactorily closed.

From 1961 to 2003, thermal expansion accounted for only 23 ± 9% of the observed rate of sea-level rise (Bindoff et al., 2007). Since 1993, the contribution of thermal expansion of the oceans to the total rise of sea levels has been about 57%. The contribution of glaciers and ice caps decreased to about 28%, and losses from the polar ice sheets contributed the remainder (IPCC, 2007).

4. Mediterranean Sea Levels During the Twentieth Century

Tsimplis et al. (2008) examined sea-level trends and interannual variability in the Mediterranean (Genova and Trieste) during the years 1960–2000. Although the observed values did not show a rise in sea level, when removing the atmospheric and the steric contributions, the residual trends revealed a significant rise of 0.7–1.8 mm/year. This rise was not uniform, as two different trends were distinguished. Between 1960 and 1975, there was no significant change in sea level, but from 1975 to 2000, sea level rose at a rate of 1.1–1.8 mm/year. They attributed part of the residual trend to local land movements (0.3 mm/year), and its major part to a global signal, probably mass addition, after 1975.

Klein and Lichter (2009) compared observed Mediterranean rates with the "global" rate, and found the sea-level rise in the Mediterranean over the twentieth century to be in agreement with the mean "global" sea-level rise during the twentieth century (1.1–2.4 mm/year). They also found that this trend has not been consistent throughout the century (Table 2; Fig. 2). Three distinctly different sea-level trends were recognized. The first lasted from the end of the nineteenth century to 1960, when relative sea level in the Mediterranean rose by rates slightly higher than the overall "global" trend (1.3–2.8 mm/year). In the second, from 1961 to 1989,

Table 2. Twentieth century sea-level trends in the Mediterranean. Linear trends from the four tide-gauging stations with the longest record in the Mediterranean. The trends are presented for the full record and for the three different trends during the twentieth century: until 1960, from 1961 to 1989, and from 1990 to 2000 (not enough data).

PSMSL station No.	PSMSL station name	Start of record	Sea-level change until 1960 (mm/year)	Sea-level change 1961–1989 (mm/year)	Sea-level change 1990–2000 (mm/year)	Sea-level change full record (mm/year)
230051	Marseille (FR)	1885	1.72	−0.78	–	1.24
250011	Genova (FR)	1884	1.28	−0.03	–	1.22
270054	Venice (Ponte della Salute) (IT)	1909	2.77	0.44	10.11	2.40
270061	Trieste (IT)	1905	1.35	0.37	9.11	1.14

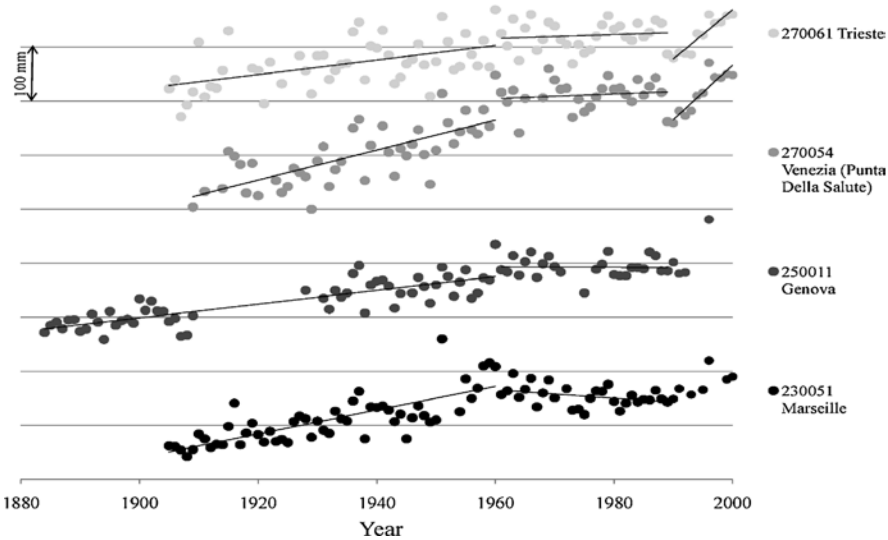

Figure 2. Linear sea-level trends from the beginning of the measurement until 1960, from 1961 to 1989, and from 1990 to 2000 in Marseilles (230051), Genoa (250011), Venice (270054), and Trieste (270061).

the observed measurements did not indicate significant changes in Mediterranean sea level. Since the beginning of the 1990s, a third, short-term trend of extremely rapid sea-level rise has been measured (4–17 mm/year). Table 2 presents sea-level trends of four Revised Local Reference (RLR) tide-gauging records in the Mediterranean, with a record of close to 100 years, available in the Permanent Service for Mean Sea Level (PSMSL) database. The stations are Marseille, Genova, Venice (with higher rates of relative sea-level rise due to subsidence in the first half of the century) and Trieste. Sea-level trends are shown for the period from the beginning of the measurement to 1960, from 1961 to 1989, from 1990 to 2000 (only Venice and Trieste had sufficient data), and for the entire record.

Klein and Lichter (2009) also found that the stability in sea level during 1961 and 1989 was the result of a rise in surface atmospheric pressure from 1961 to 1989, and that eustatic sea level has in fact been rising, but had been depressed by the rising air pressure. From 1990 onward, most gauging stations have showed an extremely high sea-level rise, 5–10 times the average twentieth century rise, and notably higher than the "global" average measured by TOPEX/Poseidon for the same years. This is in agreement with sea-level rates found in the eastern Mediterranean by Rosen (2002), who calculated a sea-level rise of 10 mm/year at the Hadera gauging station between 1992 and 2002, and Shirman (2004) who showed a 10 cm rise in sea level from 1990 to 2001 at the Ashdod and Tel Aviv tide-gauges.

New tide-gauge measurements (for location, see Fig. 3), presented in Table 3, show a slight decrease in the rate of Mediterranean sea-level rise in the first few years of the twenty-first century. The rates of sea-level rise were calculated from 27 Mediterranean PSMSL RLR tide-gauge records between 1990 and 2000, and between 1990 and 2006 (the full data sets currently available on the PSMSL website). In most stations, there has been a decrease in the rate of sea-level rise between 1990 and 2006 when compared with the trend between 1990 and 2000, but the rates remain considerably higher than the "global" and Mediterranean twentieth century rates. It is important to note that the periods considered here are short, and the

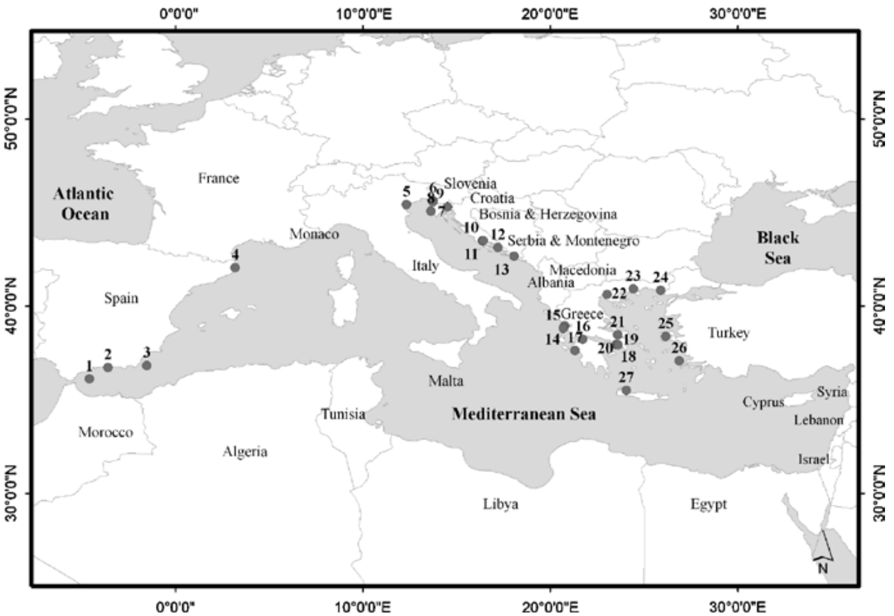

Figure 3. Location map of the tide-gauging stations presented in Table 3.

Table 3. Mediterranean sea-level trends from 1990s and onward. Linear trends are presented for 1990–2000, and where data were available trends extending to the mid-2000s were calculated.

	PSMSL station No.	PSMSL station name	Sea-level change during period 1990–2000 (mm/year)	No. of years	Sea-level change during period 1990–2006 (mm/year)	No. of years
1	220011	Algeciras (ES)	3.32	10		
2	220031	Malaga (ES)	8.62	10		
3	220041	Almeria (ES)	9.58	8		
4	220081	L'Estartit (ES)	4.50	11		
5	270054	Venezia – Ponte della Salute (IT)	10.11	11		
6	270061	Trieste (IT)	9.11	11	4.99	17
7	279003	Luka Koper (SL)	−1.20	9		
8	280006	Rovinj (HR)	10.05	11	6.24	15
9	280011	Bakar (HR)	13.52	11	8.98	15
10	280021	Split Rt Marjana (HR)	9.90	11	7.33	15
11	280031	Split Harbor (HR)	9.45	11	7.96	15
12	280046	Sucuraj (HR)	11.02	10	7.40	14
13	280081	Dubrovnik (HR)	9.51	9	7.35	13
14	290001	Preveza (GR)	11.32	11	4.92	14
15	290004	Levkas (GR)	4.21	8	2.96	12
16	290014	Patrai (GR)	14.92	8	12.88	14
17	290017	Katakolon (GR)	17.26	8	6.21	12
18	290030	North Salaminos (GR)	4.88	8		
19	290031	Piraeus (GR)	−16.15	8		
20	290033	Khalkis South (GR)	7.54	8		
21	290034	Khalkis North (GR)	1.68	10	5.71	15
22	290051	Thessaloniki (GR)	9.04	9		
23	290061	Kavalla (GR)	−0.06	9	1.70	13
24	290065	Alexandroupolis (GR)	6.46	10	5.31	15
25	290071	Khios (GR)	17.98	9	5.17	12
26	290091	Leros (GR)	−0.08	8	−1.84	11
27	290097	Soudhas (GR)	7.36	10		

trend they indicate might be merely an expression of a rising phase of an oscillating pattern. However, during no other short period in the twentieth century have tide-gauge records in the Mediterranean shown such an extreme trend.

5. Future Sea-Level Predictions

The AR4 of the IPCC (2007) predicted "global" sea-level rise of 0.18–0.59 m in 2090 and 2099, relative to 1990 and 1999 (about 2–6 mm/year) using several different future scenarios. These predictions, however, do not include uncertainties resulting from climate–carbon cycle feedbacks, or the full effects of changes in ice sheet flow. These factors are currently unknown, and therefore the upper values of these predictions are not considered upper bounds for sea-level rise.

The predictions take into consideration a contribution to sea-level rise due to increased ice flow from Greenland and Antarctica at the rates observed from 1993 to 2003. A linear increase in ice flow from the ice sheets with global average temperature change would increase the upper range of sea-level rise for these future scenarios by only 0.1–0.2 m (IPCC, 2007).

The IPCC AR4 predicts thermal expansion that contributes more than half of the average sea-level rise estimated for the twenty-first century, and land ice that loses mass increasingly rapidly. An important uncertainty relates to the question of whether discharge of ice from ice sheets will continue to increase as a consequence of accelerated ice flow, as has been observed in recent years. This would add to the sea-level rise, but quantitative predictions cannot be made with a high degree of confidence, owing to the limited understanding of the relevant processes (Bindoff et al., 2007).

The ranges of sea-level rise predictions of the AR4 are lower than those projected in the Third Assessment Report (TAR) of the IPCC (2001), because of improved information about some of the uncertainties of some contributions.

Recent attempts to predict future "global" sea-level rise confirm the ranges predicted by the IPCC reports, while others predict higher rates. Church and White (2006) estimate that if the twentieth century acceleration in sea-level rise (0.013 ± 0.006 mm/year) remains constant during the twenty-first century, sea-level would rise by 0.28–0.34 m from 1990 to 2100, a rise consistent with the middle range of the TAR and AR4 predictions.

However, Rahmstorf et al. (2007) compared sea-level predictions of the TAR with sea-level observations from the 1990s and 2000s, and found that the observations followed the upper limit of the predictions, including land-ice uncertainties. They calculated the rate of rise in the past 20 years to be 25% faster than in any other 20-year period in the last 115 years. Although they are aware of the short time interval, they conclude that these predictions may have underestimated sea-level change. Rahmstorf (2007) applied a semi-empirical methodology to project future sea-level rise by using the relations between "global" sea-level rise and global mean surface temperature. He suggests that the rate of sea-level rise is roughly proportional to the magnitude of warming above the temperatures of the pre-industrial age. This relation produced a constant of 3.4 mm/year/°C. Applying this to future IPCC scenarios, a sea-level rise of 0.5–1.4 m above the 1990 level is projected for 2100. Hence, he concludes that if the linear relations between sea-level rise and temperature that existed in the twentieth century persist through the twenty-first century, a rise of over 1 m for strong warming scenarios is not unlikely.

6. Summary

The past 600,000 years are characterized by glacial and interglacial cycles. During the glacial maxima, sea level dropped more than 100 m below its present level. Sea level in interglacial periods exceeded the present sea level by a few meters three times during that time.

During the LGM, about 18 ka ago, "global" sea level dropped by about 120 m below its present level. Since then, the transition of the global climate into an interglacial period was followed by a rapid sea-level rise until around 6,000 years ago, when there was a decrease in the rate of sea-level rise, and a relative stabilization at about the present level about 4,000 years ago.

In the Mediterranean, there are radiometric ages derived from different sea-level indicators that go back to the MIS 7.1, dated to between 202 and 190 ka ago. The last time that sea level rose above its present level was some 125 ka ago during the MIS 5e. There are ample well-dated indications for sea level during MIS 5e, located at present at different elevations due to vertical movements. There are biological, sedimentological, and mainly archeological data from the LGM, about 18 ka ago from all around the Mediterranean; the oldest being from Cosquer Cave, southern France, dated to about 22 ka ago. Sea level stabilized at almost the present level around 4,000 years ago with vertical accuracy of ±1 m. Later, 2,000 years ago, the rate of accuracy from different indicators (both biological and archeological) reaches ±10–15 cm, and fluctuations of tens of cm are recorded.

"Global" twentieth century sea-level rise is agreed by researchers to be considerably faster than in the previous two millennia. Most researchers estimate a "global" twentieth century rate of 1.0–2.5 mm/year. During the 1990s, the mean rate of "global" sea-level rise was significantly higher than the twentieth century mean rate (1.3–2.8 mm/year). Mediterranean twentieth century sea-level rise was close to the "global" rise, with the exception of the 1990s, when sea level in the Mediterranean rose at rates higher even than the unusually high "global" ones (up to three and four times the "global" 1990s rate). The rate of sea-level rise since the beginning of the 1990s has decreased in the first half of the current decade; however, it is still considerably higher than the twentieth century mean rate.

Future predictions of sea-level rise over the twenty-first century range from moderate amounts of less than 20 cm to much higher values of over 1 m. The uncertainties are attributed to the future contribution of Greenland and the Antarctic ice sheets, and uncertainties resulting from climate–carbon cycle feedback, as well as from other unpredicted proxies.

7. References

Antonioli, F., Kershaw, S., Renda, P., Rust, D., Belluomini, G., Cerasoli, M., Radtke, U. and Silenzi, S. (2006) Elevation of the last interglacial highstand in Sicily (Italy): a benchmark of coastal tectonics. Quatern. Int. **145–146**: 3–18.

Anzidei, M., Lambeck, K., Antonioli, F., Sivan, D., Stocchi, P., Spada, G., Gasperini, G., Soussi, M., Benini, M., Serpelloni, E., Baldi, P., Pondrelli, S. and Vannucci, G. (2008) *Sea Level Changes and Vertical Land Movements in the Mediterranean from Historical and Geophysical Data and Modelling. Observations and Causes of Sea-Level Changes on Millennial to Decadal Timescales*. The Geological Society, London.

Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G. and Rougerie, F. (1996) Deglacial sea-level record from Tahiti corals and the timing of global melt water discharge. Nature **382**: 241–244.

Bard, E., Hamelin, B., Fairbanks, R.G. and Zindler, A. (1990) Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. Nature **345**: 405–409.

Bard, E., Antonioli, F. and Silenzi, S. (2002) Sea level during the penultimate interglacial period based on submerged stalagmite from Argentarola Cave (Italy). Earth Planet. Sci. Lett. **196**: 135–146.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley L.D. and Unnikrishnan, A. (2007) In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) *Observations: Oceanic Climate Change and Sea Level. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cabanes, C., Cazenave, A. and Le Provost, C. (2001) Sea-level rise during past 40 years determined from satellite and in situ observations. Science **294**: 840–842.

Cazenave, A. and Nerem, R.S. (2004) Present-day sea level change: observations and causes. Rev. Geophys. **42**: RG3001.

Church, J.A., White, N.J., Coleman, R., Lambeck, K. and Mitrovica, J.X. (2004) Estimates of the regional distribution of sea level rise over the 1950–2000 period. J. Climate **17**: 2609–2625.

Church, J.A. and White, N.J. (2006) A 20th century acceleration in global sea-level rise. Geophys. Res. Lett. **33**: L01602. doi: 10.1029/2005GL024826.

Douglas, B.C. (2001) An introduction to sea-level, In: B.C. Douglas, M.F. Kearney and S.P. Leatherman (eds.) *Sea-Level Rise History and Consequences*. Academic Press, USA, pp. 1–11.

Fairbanks, R.G. (1989) A 17,000-year Glacio-Eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature **342**: 637–642.

Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., Monaco, C., Orrú, P., Pappalardo, M., Radtke, U., Renda, P., Romanoa, P., Sanso, P. and Verrubbi, V. (2006) Markers of the last interglacial sea-level high stand along the coast of Italy: tectonic implications. Quatern. Int. **145–146**: 30–54.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K. and Chappell, J. (1998) Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. Earth Planet. Sci. Lett. **163**(1–4): 327–342.

Galili, E. and Sharvit, J. (1998) Ancient coastal installations and the tectonic stability of the Israeli coast in historical times, In: I.S. Stewart and C. Vita-Finzi (eds.) *Coastal Tectonics*. Geological Society, London, Special Publications, 146, pp. 147–163.

Galili, E. and Sharvit, J. (2000) The use of archeological features as indicators for coastal displacement in the Israeli coastal region, In: *The Mediterranean: Culture, Environment and Society*. University of Haifa, Faculty of Humanities, Faculty of Social Sciences and Mathematics.

Galili, E., Weinstein-Evron, M. and Ronen, A. (1988) Holocene sea-level changes based on submerged archaeological sites off the northern Carmel coast in Israel. Quatern. Res. **29**: 36–42.

Galili, E., Zviely, D. and Weinstein-Evron, M. (2005) Holocene sea-level changes and landscape evolution in the northern Carmel coast (Israel). Méditerranée **104**(1/2): 79–86.

Galili, E., Zviely, D., Ronen, A. and Mienis, H.K. (2007) Beach deposits of MIS 5e high sea stand as indicators for tectonic stability of the Carmel coastal plain, Israel. Quatern. Sci. Rev. **26**: 2544–2557.

IPCC (2001) In: J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (eds.) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

IPCC (2007) In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Jevrejeva, S., Grinsted, A., Moore, J.C. and Holgate, S. (2006) Nonlinear trends and multiyear cycles in sea level records. J. Geophys. Res. **111**: C09012, doi:10.1029/2005JC003229.

Klein, M. and Lichter, M. (2009) Statistical analysis of recent Mediterranean Sea-level data. Geomorphology **107**(1–2): 3–9.

Klein, M., Lichter, M. and Zviely, D. (2004) Recent sea-level changes along Israeli and Mediterranean coast, In: J.O. Maos, M. Inbar and D. Shmueli (eds.) *Contemporary Israeli Geography, Special Issue of Horizons in Geography,* 60–61, pp. 247–254.

Lambeck, K. and Bard, E. (2000) Sea-level change along the French Mediterranean coast for the past 30,000 years. Earth Planet. Sci. Lett. **175**: 203–222.

Lambeck, K., Antonioli, F., Purcell, A. and Silenzi, S. (2004) Sea-level change along the Italian coast for the past 10,000 yr. Quatern. Sci. Rev. **23**: 1567–1598.

Lambeck, K. and Purcell, A. (2005) Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas. Quatern. Sci. Rev. **24**: 1969–1988.

Lambeck, K., Yokoyama, Y. and Purcell, T. (2002) Into and out of the Last Glacial Maximum: sea-level change during oxygen isotope stages 3 and 2. Quatern. Sci. Rev. **21**: 343–360.

Marriner, N., Morhange, C., Boudagher-Fadel, M., Bourcier, M. and Carbonel, P. (2005) Geoarchaeology of Tyre's ancient northern harbour, Phoenicia. J. Archaeologi. Sci. **32**(9): 1302–1327.

Mauz, B. and Antonioli, F. (2009) Comment on "Sea level and climate changes during OIS 5e in the Western Mediterranean" by T. Bardají, J.L. Goy, J.L., C. Zazo, C. Hillaire-Marcel, C.J. Dabrio, A. Cabero, B. Ghaleb, P.G. Silva, J. Lario. Geomorphology **104**: 22–37.

Miller, L. and Douglas, B.C. (2004) Mass and volume contributions to twentieth-century global sea level rise. Nature **428**: 406–409. doi: 10.1038/nature02309.

Mitrovica, J.X., Tamisiea, M.E., Davis, J.L. and Milne, G.A. (2001) Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. Nature **409**: 1026–1029.

Morhange, C., Laborel, J. and Hesnard, A. (2001) Changes of relative sea level during the past 5000 years in the ancient harbor of Marseilles, Southern France. Palaeogeogr. Palaeoclimatol. Palaeoecol. **166**: 319–329.

Nir, Y. (1997) Middle and late Holocene sea-levels along the Israel Mediterranean coast – evidence from ancient water wells. J. Quatern. Sci. **12**(2): 143–151.

Peltier, W. (2001) Global glacial isostatic adjustment and modern instrumental records of relative sea level history, In: B.C. Douglas, M.F. Kearney and S.P. Leatherman (eds.) *Sea-Level Rise History and Consequences*. Academic Press, USA, pp. 65–95.

Pirazzolli, P.A. (1991) *World Atlas of Holocene Sea-Level Changes*. Elsevier Oceanography Series 58. Elsevier, Amsterdam.

Pirazzoli, P.A. (1996) *Sea-Level Changes – The Last 20,000 Years*. Wiley, Chichester, England.

Poulos, S.E., Ghionis, G. and Maroukian, H. (2009) Sea-level rise trends in the Attico-Cycladic region (Aegean Sea) during the last 5000 years. Geomorphology **107**(1–2): 10–17. doi: 10.1016/j.geomorph.2007.05.02.

Porat, N., Sivan, D. and Zviely, D. (2008) Late Holocene embayment and sedimentological infill processes in Haifa Bay, SE Mediterranean. Israel J. Earth Sci. **57**: 21–31.

Rabineau, M., Bemé, S., Olivet, J.L., Aslanian, D., Guillocheau, F. and Joseph, P. (2006) Paleo sea levels reconsidered from direct observation of paleoshoreline position during Glacial Maxima (for the last 500,000 yr). Earth Planet. Sci. Lett. **252**: 119–137.

Rahmstorf, S. (2007) A semi-empirical approach to projecting future sea-level rise. Science **315**(5810): 368–370.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F. and Parker, D.E. (2007) Recent climate observations compared to projections. Science **316**(5825): 709.

Rohling, E.J., Fenton, M., Jorissen, F.J., Bertrand, P., Ganssen, G. and Caulet, J.P. (1998) Magnitude of sea-level lowstands of the past 500,000 years. Nature **394**: 162–165.

Rosen, D.S. (2002) Long term remedial measures of sedimentological impact due to coastal developments on the south eastern Mediterranean coast. Littoral 2002 22–26 September, Porto, Portugal.

Schellmann, G. and Radtke, U. (2004) A revised morpho- and chronostratigraphy of the late and middle Pleistocene coral reef terraces on Southern Barbados (West Indies). Earth-Sci. Rev. **64**: 157–187.

Shackleton, N.J. (2000) The 100,000-year ice-age cycle found to lag temperature, carbon dioxide, and orbital eccentricity. Science **289**: 1897–1902.

Shirman, B. (2004) East Mediterranean sea level changes over the period 1958–2001. Israel J. Earth Sci. **53**: 1–12.

Siddall, M., Chappell, J. and Potter, E.K. (2006) Eustatic sea level during past interglacials, In: F. Sirocko, F. Litt, T. Claussen and M.-F. Sanchez-Goni (eds.) *The Climate of Past Interglacials*. Elsevier, Amsterdam, pp. 75–92.

Sivan, D., Gvirtzman, G. and Sass, E. (1999) Quaternary stratigraphy and paleogeography of the Galilee Coastal Plain, Israel. Quatern. Res. **51**: 280–294.

Sivan, D., Lambeck, K., Toueg, R., Raban, A., Porath, Y. and Shirman, B. (2004) Ancient coastal wells of Caesarea Maritima, Israel, an indicator for relative sea level changes during the last 2000 years. Earth Planet. Sci. Lett. **222**(1): 315–330.

Sivan, D., Wdowinski, S., Lambeck, K., Galili, E. and Raban, A. (2001) Holocene sea-level changes along the Mediterranean coast of Israel, based on archaeological observations and numerical model. Palaeogeogr. Palaeoclimatol. Palaeoecol. **167**: 101–117.

Sivan, D., Schattner, U., Lambeck, K., Shirman, B. and Stern, E. (2008) Lower sea-levels during the Crusader period (11th to 13th centuries AD) as witnessed in Israel: do they indicate a global eustatic component? *Observations and Causes of Sea-Level Changes on Millennial to Decadal Timescales*, The William Smith Meeting of the Geological Society, London.

Sneh, Y. and Klein, M. (1984) Holocene sea-level changes at the coast of Dor, southeast Mediterranean. Science **226**: 831–832.

Stewart, I. and Morhange, C. (2009) Coastal geomorphology and sea-level change, In: J.C. Woodward (ed.) *The Physical Geography of the Mediterranean Basin*. OUP, Cpt. 13, pp. 385–414.

Tsimplis, M., Marcos, M., Somot, S. and Barnier, B. (2008) Sea level forcing in the Mediterranean Sea between 1960 and 2000. Global Planet. Change **63**(4): 325–332. doi: 10.1016/j.gloplacha.2008.07.004.

Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E. and Labracherie, M. (2002) Sea-level and deep water temperature changes derived from benthonic foraminifera isotopic records. Quatern. Sci. Rev. **21**: 295–305.

Woodworth, P.L. and Player, R. (2003) The permanent service for mean sea-level: an update to the 21st century. J. Coastal Res. **19**(2): 287–295.

Woodworth, P.L. (2008) Changes in sea level on multi-decadal and century timescales as observed from global tide-gauges data set. *Observations and Causes of Sea-Level Changes on Millennial to Decadal Timescales*, The William Smith Meeting of the Geological Society, London.