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Multi-decadal sea level trends and land movements in the Mediterranean Sea with estimates of factors perturbing tide gauge data and cumulative uncertainties

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ABSTRACT

Sea level trends in the Mediterranean Sea and their forcing parameters are explored. Multi-decadal trends from available tide gauge records are estimated together with the contribution of the oceanic (steric and mass variations) and atmospheric (pressure and wind) changes as well as land movements (including GIA). Each forcing factor is considered as an independent process creating its own signal on a tide gauge, and subject to uncertainties of measurement, deduction or interpretation of proxy data for that factor. The paper is focused on the uncertainty of the estimate of each forcing factor, including the estimate of the eustatic part affecting the Mediterranean Sea, obtained by subtracting GIA and land movements obtained from geomorphological and archaeological data at the tide gauge stations.

1. Introduction

Coastal sea level is an important environmental parameter. Its variations affect the coastal ecosystems, the inhabitants and the infrastructure of coastal areas. In addition coastal sea level can be used diagnostically as an indicator of processes related to climate change. Even within the context of global climate change when impacts come to be determined, it is the local sea level variability that is important. Therefore, practically, sea level must be considered locally. This in turn requires a good understanding of the various processes involved. If an observed measurement and trend of local relative sea level change is attributed to the wrong causes, then expensive mistakes may follow. Disentangling the various processes contributing to relative sea level change at a location is a very challenging task, involving scientific examination of numerous independent forcing factors, each producing signals which can only be separated on the basis of temporal and spatial frequencies and scales, and approximate data from proxy indicators of past levels. Sea level measurements are always a relative to a frame or point of reference. In the past, relative sea level has been used to denote the locally observed changes in sea level which includes oceanic as well as land movements. The distinction of relative sea level implies the existence of an absolute sea level value which simply does not exist. The relative sea level term has served in some context in that it ensured that researchers are aware that land movements move the local point of reference and thus some corrections have to be made if the sea level value by reference to another point, whether this is the centre of the earth or some surface dynamically determined, is to be used. In this paper we call this parameter sea level and its changes sea level changes. It is our view that this is in fact the crucial parameter that needs to be known for coastal planning purposes. Every other derivative of it is a corrected (relative to something) sea level which can be used to identify forcing factors and test theoretical models of the forcing but does not necessarily describe the coastal risks completely.

One way of categorising the various forcing parameters is by distinguishing into eustatic, glacio-hydro isostatic (GIA) and local vertical earth movement factors. In this framework eustatic factors are considered global and time-only-dependent, while the other two are considered as spatially variable as well as time dependent. While it is easy to describe these in general it is more difficult to separate them and this results into confusing terminology. For example Lambeck et al. (2004a) define the local vertical earth movement factors as "tectonic factors". This a simplification adopted in that paper probably for the purpose of separating the two categories of forcing and capable of leading to confusion. In general the word tectonic contains only movements related to structural deformation of the crust of the earth and, in our context, their vertical component.

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GIA has a vertical magnitude of the order of a few mm/yr metres maximum in the Mediterranean, and varies slowly and smoothly from region to region. Local vertical earth movements include sediment load isostasy, sediment compaction, co-seismic earthquake movements, aseismic vertical creep, fault displacements, large-scale tectonic crustal movements associated with plate boundaries and plate movements, and anthropogenic motions, for example land subsidence due to ground water extraction.

An alternative way of categorising the various factors contributing to the observed measurement of local relative sea level change is by separating the oceanic, atmospheric and land forcing parameters. In such a framework oceanic mass addition, changes in the water mass characteristics, changes in the baroclinic oceanic circulation would count as oceanic. Atmospheric pressure and wind changes and their resulting changes in the barotropic part of oceanic circulation would count as atmospheric circulation. Finally land movements due to crustal deformation and redistribution of loadings locally or globally would account for land forcing. Land movements can significantly affect the relative sea level signal along the coasts (Emery and Aubrey, 1991; Pirazzoli, 1987; Ferranti et al., 2006; Antonioli et al., 2006, 2009; Shaw et al., 2008) due to different processes acting at local (earthquakes, volcanism, soil compaction, etc.) or at regional scale (plate tectonics, isostasy). The categorisation involves several interlinked and interdependent parameters, as well as a number of forcing factors which are causally independent, even if their signals in a tide gauge record are difficult to separate.

Whichever way of conceptually understanding sea level changes is chosen, tide gauges distributed along the coasts measure the sum of all these movements by reference to an arbitrary local zero usually linked to a benchmark on land. These direct measurements are relatively simple and have been performed in some ports for more than a century (Woodworth and Player, 2003). Where benchmark information is available the tide gauge provides accurate information on the sea level change in relation to land at the particular location, assuming that the benchmark is stable relative to a fixed geoid. Instrumental errors, unrecorded changes or updates in the vertical referencing system and changes in the configuration of the proximity of the instrument, like dredging, also affect the quality of the tide gauge records and should be taken into account when sea level trends are estimated. About 160 tide gauges worldwide are collocated with GPS stations that measure rates of vertical land motion by space geodesy and fix the position of the instrument with respect to the International Terrestrial Reference Frame (Wöppelmann et al., 2007).

The observed sea level variations from tide gauges include periodic and non-periodic signals of varying strength (amplitude) and duration. Where such signals are less in period than the length of the record they can be identified and removed to leave the multi-decadal trend. But where these signals, whether periodic or aperiodic, are longer than the observational record then they cannot be removed directly and must be estimated or inferred by use of other methods or proxy data. Both locally and globally sea level has been changing at time scales with much longer periods than the observations from tide gauges have been measuring. In addition, its variations have been of two orders of magnitude larger than those observed over the past century in most parts of the world. These changes have affected the coastal environment and have left various traces that can be exploited to determine sea level changes at such longer scales. Thus the impact of sea level changes on the coastal geomorphology or coastal biology can, in particular environments, provide useful proxies in determining relative sea level changes. For example marine notches are frequently found in limestone lithologies. These are (carved) dissolved or etched into the rock within 2–5 centuries depending upon the erosion–dissolution characteristics of the coastal rock. The position of these notches in relation to present sea level, especially in areas like the Mediterranean where the tidal signal is small, can provide information on the long term relative sea level change in that location, provided of course that sea level remains steady relative to the land for such lengths of time. For example tidal notches of MIS 5.5 (last Interglacial, 125 ka BP), often mark the stable limestone coasts of the Mediterranean Sea (Ferranti et al., 2006 and references therein). These are elevated by 6–8 m above present sea level. In this context the term stable denotes that relative to land the water remained stable long enough to produce the notch. It cannot mean absence of vertical land movements but only that the same of such movements and oceanic changes in mass and volume were cancelled out for that period. Thus, when Ferranti et al. (2006) consider these stable and with absence of vertical earth movements this means that the forcing parameters cancel out—not they are all zero. On a shorter timescale, solution notches on limestone cliffs show rapid tectonic uplift of western Crete in the last few thousand years.

Remains from human coastal establishments can also be used as indicators of sea level change. Thus coastal archaeological remains aged between ~10 ka and ~1 ka cal BP, located along the coast of the Mediterranean basin, are often used as sea level markers (Flemming, 1969; Flemming et al., 1978; Flemming and Webb, 1986; Caputo and Pieri, 1976; Antonioli et al., 2007; Auriemma and Solinas, 2009).

The above mentioned methodologies provide estimates of long term changes in relative sea level. However they do not reveal whether such changes have taken place in a paced manner or whether slow and fast change periods have occurred, or even reversals of direction. In addition they say little about the contribution of the various forcings that caused these changes over such long periods.

Knowledge of particular mechanisms can also be used to infer long term sea level changes. For Glacial Isostatic Adjustment (GIA) several model estimates exist. GIA is a major driving mechanism of observed sea level changes along the coasts caused by the ongoing viscoelastic response of the solid earth following the removal of the great ice loads following deglaciation and redistribution of the mass as water on the ocean basins. This causes significant land movements in those parts of the world where ice sheets existed, for example in the Scandinavian countries where rates of land rise of several mm/yr have been measured for more than a century. The GIA is generally modelled on the basis of geophysical models which are in turn validated partly against the observed sea level measurements from tide gauges, but largely through observational data in areas where the sum of other tectonic or other vertical land movements are considered small. The previous statement itself demonstrates the problem: We fit the GIA model on the assumption that the sites used have small vertical land movements due to other forcing parameters. But this is a basic assumption which needs to be true over very long periods of time and we do not have means of confirming it other than some confidence from analyses of residual sea levels (after the GIA is removed) which have spatially consistent patterns that can be explained by other forcing factors. The ice history and the viscoelastic structure of the earth are important assumptions included in these models. Away from the areas where ice sheets existed smaller signals, in general less than 1 mm/yr, are expected. The various GIA models are in general agreement in areas away from the past location of ice sheets. However this is without considering significant perturbations of the two basic assumptions referred to above. The comparison of archaeological data with GIA estimates in the Mediterranean is an example of the ambiguity in the interpretation of GIA modelling. Even relatively small sea level trends caused by GIA, for example, 0.5 mm/yr would lead over 2000 years to a sea level rise of 1 m. While there are archaeological sites in the Mediterranean Sea that are submerged to such depths, there are other sites where sea level has retreated or has remained steady. Of course one can argue that the departure from the GIA model predictions is due to local land movements which differ between sites but this cannot be confirmed or rejected because, even if present day movements can be measured, for example through differential GPS, to suggest that present day changes reflect changes over thousands of years would be another major assumption.

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Local earth subsidence either natural (e.g. sedimentary loading of a delta) or anthropogenic, for example extraction of ground water coastal reservoirs, and fast aperiodic changes up or down caused by seismic or volcanic activity can also significantly affect local sea level measurements. See for example works on the Bay of Naples, Aeolian Islands, and Crete (Stiors, Flemming, Pirazzoli, and others). Changes in regional and local sea level are also caused by long term changes in meteorological forcing, variations in the density structure, mass addition and changes in oceanic circulation. Probably most information available relates to the effects of direct atmospheric forcing, in essence atmospheric pressure and wind changes. Estimates of steric variations are also available, albeit these are derived on the basis of unsystematic observations hardly adequate to resolve the Mediterranean basin. Very little is known on the long term changes of the circulation of the Mediterranean Sea. Thus another assumption is that such changes have not significantly changed sea level over decades or centuries.

Each tide gauge record integrates the signals from all the above forcing factors and may also be affected by reference point movements and instrumental problems. The use of geological and sedimentary proxies is usually restricted to longer signals generally believed to be associated with mass addition or removal from ice sheets and the crust's response to such movements. Proxy data based on cores through sedimentary or alluvial coastal plains or deltas will always tend to be biased downwards. All the sediment-linked processes, compacting, de-watering, slumping, isostatic loading etc., cause depression of the land surface and within the sediment column. Thus comparison between tide gauge data from a range of substrates with proxy data from cores will always tend to show the proxy data plotting below the tide gauge data. However, there are particular environments, like saltmarshes, vermetid reef, submerged or uplifted speleothems, where recent sea level can be recovered on the basis of sediments (Milne et al., 2009). Biological encrustations, trottoir, coral terraces, vermetid terraces etc., boring sponges, etc., tend to be on sites associated with bedrock, and not unconsolidated sediments. It is then an issue of using the estimates of long term sea level change from proxies in order to understand the instrumental records and, in addition, to identify recent changes in them.

The Mediterranean Sea, a semi-enclosed basin, is a part of the world where sea level changes have played an important role in the past. Sea level derived from the longest tide gauges indicates a rate of relative sea level rise for the 20th century of 1.1–1.3 mm/yr (Tsimplis and Baker, 2000; Marcos and Tsimplis, 2008), and 1.02 ± 0.21 mm/yr for the Tyrrhenian coast of Italy (Lambeck et al., 2004b). For the period 1960 to 1990 an increase in the average atmospheric pressure over the basin caused negative sea level trends (Tsimplis and Baker, 2000; Tsimplis and Josey, 2001). In the Mediterranean fast regional sea level rise was observed since the late 1990s (Cazenave et al., 2001; Fenoglio-Marc, 2001). Despite the above general statements which are derived, as customarily done in sea level research, on the basis of the longest tide gauges available and in spite of the well known bias in their spatial distribution (Tsimplis and Spencer, 1997) there are several other tide gauges in the Mediterranean Sea providing a wealth of information regarding local sea level variability.

In this work, which aims to improve the report of Marcos and Tsimplis (2008), we estimate the multi-decadal trends from the available tide gauge records in the Mediterranean Sea coasts and attempt to assess the contribution of the oceanic, atmospheric and land movements to the observed changes measured by tide gauges.

So far as possible in this paper we will consider each forcing factor as an independent process creating its own signal on a tide gauge, and subject to uncertainties of measurement, deduction, or interpretation of proxy data for that factor. Cumulatively those signals which are not caused by the long term eustatic trend of global sea level will be analysed to estimate their contribution of error or uncertainty to the estimate of the multi-decadal eustatic trend.

This logic enables both local policy makers and researchers to aggregate selected factors so as to arrive at the estimate of local relative sea level change and future trends relevant to particular problems or decisions.

Our focus in this paper is the related uncertainty of the estimate of each forcing factor, including the estimate of the eustatic part affecting the Mediterranean Sea, obtained by subtracting GIA and land movement at the tide gauge stations. The paper is structured as follows. The next section describes the sea level observations from tide gauges, which are our primary measurements. The following section discusses land movements estimated from geomorphological changes. The GIA estimates are discussed then. Finally the steric contribution and the residual trends are discussed. In the concluding section we set out the parameter the methodology, results and uncertainties are discussed.

2. Sea level observations

Mean monthly sea level values from tide gauges with benchmark datum history (Revised Local Reference—RLR) from the Permanent Service for Mean Sea Level (PSMSL) database (Woodworth and Player, 2003) have been used (Table 1). The PSMSL dataset includes also tide gauge records for which benchmark history is not available.

Non-RLR stations are those tide gauges with sea level records which are not vertically referenced during the entire period of operation of the instrument (Table 1). They may present problems such as datum shifts and spurious trends. In order to make these records usable in the context of sea level trends they have been compared against a control station: Marseille in the western basin and Trieste in the eastern basin. Both the non-RLR and the control station are corrected for GIA movements prior to comparison. The series of monthly differences has been built for the common periods and the linear trend and standard deviations are computed for the time series of the differences. Each case is then examined in detail. The methodology assumes that the GIA rates are correct and improves the consistency of the records. This, as explained earlier, is a basic assumption that cannot be proven. However, as the criteria for rejecting data at one or another station are based on differences in the mean monthly values the GIA correction is not biasing the quality control.

Some of the time series are discarded after a visual examination. The reasons can be: large percentage of data gaps, changing trends respect to the control stations and/or multiple datum shifts. The remaining non-RLR records have been corrected in two ways: whenever the trend of the differences with the control station is constant, it has been removed (12 stations) and when there are datum shifts these have been corrected as the difference for each period between the record and the control station (2 stations).

Errors have been estimated for the first group of 12 stations (only corrected for trends) as the standard error of the linear trend of the differences between each non-RLR station and the control station.

All tide gauge stations with records longer than 7 years which are used in this paper are mapped in Fig. 1. Their number, PSMSL code, location and name are listed in Table 1.

3. Sea level changes from proxies

We use changes in sea level estimated through the use of geological, geomorphological and biological shoreline indicators, as well as by maritime archaeological structures to infer changes in the local mean sea level (Lambeck and Chappell, 2001) over periods longer than tide gauge records. The vertical elevation of indicators with respect to present sea level is corrected for the tidal and the atmospheric pressure changes in sea level at the time of the measurement. The corrected sea level value is then subtracted from the elevation to obtain the change in sea level between the present time and the past. Dating techniques employed, and these vary between the various indicators, provide an estimate of the period elapsed since the time the demarcation by a

Table 1
Tide gauge stations used in this study. Numbering in column 1 is the same as in Fig. 1. Columns 2 and 3 are the reference codes and names of stations in PSMSL data base. Columns 4 and 5 are latitude and longitude of each site. Follow linear trends of observations, atmospheric and steric components for the same period covered by the records, GIA trends and trends derived from land movements only where available.

	PSMSL ref	Name	Lat	Lon	Obs trend	Error	Atm	Steric	GIA	Error GIA	Land mov.	Error land M.
1	190141	ST. JEAN DE LUZ	43 24 N	01 41 W	2.272	0.383	−0.048	0.001	0.090	0.27	–	–
2	200001	PASAJES	43 19 N	01 55 W	4.670	6.723	−0.032	−0.001	0.089	0.27	–	–
3	200006	BILBAO	43 20 N	03 02 W	3.249	2.745	0.085	0.000	0.142	0.27	–	–
4	200011	SANTANDER I	43 28 N	03 48 W	1.907	0.269	−0.045	0.001	0.153	0.26	–	–
5	200012	SANTANDER II	43 28 N	03 46 W	−3.269	1.912	−0.206	−0.000	0.152	0.26	–	–
6	200013	SANTANDER III	43 28 N	03 47 W	3.347	2.824	0.101	−0.000	0.152	0.26	–	–
7	200022	GIJON II	43 34 N	05 42 W	1.486	5.412	−0.058	−0.006	0.242	0.25	–	–
8	200030	LACORUNA I	43 22 N	08 24 W	1.539	0.270	−0.029	0.001	0.361	0.26	–	–
9	200031	LACORUNA II	43 22 N	08 24 W	0.488	0.312	−0.032	0.001	0.361	0.26	–	–
10	200032	LACORUNA III	43 22 N	08 23 W	1.243	2.869	0.178	0.002	0.360	0.26	–	–
11	200036	VILLAGARCIA	42 36 N	8 46 W	5.958	9.079	−0.252	−0.007	0.301	0.30	–	–
12	200041	VIGO	42 14 N	08 44 W	2.035	0.306	−0.020	0.001	0.262	0.31	–	–
13	200042	VIGO II	42 15 N	8 44 W	−1.459	8.882	−0.217	−0.009	0.263	0.31	–	–
14	210011	VIANA	41 41 N	08 50 W	7.889	4.155	0.355	0.003	0.223	0.33	–	–
15	210013	AVEIRO	40 39 N	08 45 W	−0.897	0.759	−0.001	0.002	0.153	0.34	–	–
16	210021	CASCAIS	38 41 N	09 25 W	0.376	0.267	−0.042	0.000	0.180	0.22	–	–
17	210023	LISBON	38 42 N	09 08 W	0.670	1.102	0.027	0.001	0.180	0.22	–	–
18	210026	SETROIA	38 30 N	08 54 W	0.979	0.608	0.008	0.002	0.136	0.23	–	–
19	210028	SINES	37 57 N	08 53 W	1.844	1.052	0.020	0.001	0.140	0.19	–	–
20	210031	LAGOS	37 06 N	08 40 W	1.191	0.311	−0.030	0.000	0.133	0.15	–	–
21	220002	CADIZ II	36 32 N	06 19 W	−0.550	1.424	0.045	−0.001	−0.023	0.17	–	–
22	220003	CADIZ III	36 32 N	06 17 W	4.048	0.303	−0.030	0.001	−0.025	0.17	–	–
23	220005	HUELVA	37 8 N	6 50 W	−4.202	6.625	−0.276	−0.001	0.003	0.19	–	–
24	220008	BONANZA	36 48 N	6 20 W	10.529	2.269	0.031	0.005	−0.022	0.18	–	–
25	220011	ALGECIRAS	36 07 N	05 26 W	0.052	0.227	−0.036	−0.172	−0.066	0.16	0.00	0.03
26	220021	TARIFA	36 00 N	05 36 W	−1.210	0.234	−0.036	−0.136	−0.061	0.16	0.00	0.03
27	220031	MALAGA	36 43 N	04 25 W	4.044	0.297	−0.035	−0.128	−0.079	0.19	0.00	0.03
28	220032	MALAGA II	36 43 N	4 25 W	4.812	2.435	0.038	0.464	−0.079	0.19	0.00	0.03
29	220041	ALMERIA	36 50 N	02 29 W	0.285	0.772	0.034	0.022	−0.060	0.16	0.00	0.03
30	220046	CARTAGENA	37 36 N	00 58 W	−0.903	1.835	−0.022	−1.190	0.024	0.13	–	–
31	220052	ALICANTE II	38 20 N	00 29 W	−0.098	0.309	−0.042	−0.024	0.074	0.12	0.40	0.08
32	220056	VALENCIA	39 28 N	0 20 W	7.392	3.704	0.072	−0.075	0.095	0.14	–	–
33	220061	BARCELONA	41 21 N	2 10 E	4.448	2.927	0.083	−0.210	0.238	0.20	–	–
34	220081	L'ESTARTIT	42 03 N	03 12 E	5.623	1.910	0.116	0.125	0.260	0.22	–	–
35	230001	BANYULS	42 29 N	03 07 E	–	–	–	–	0.224	0.17	–	–
36	230021	SETE	43 24 N	03 42 E	−2.906	6.230	−0.331	−0.554	0.171	0.15	–	–
37	230031	PORT BOUC	43 24 N	04 59 E	–	–	–	–	0.212	0.18	–	–
38	230041	MARTIGUES	43 24 N	05 03 E	–	–	–	–	0.237	0.20	–	–
39	230051	MARSEILLE	43 18 N	05 21 E	−0.111	0.232	−0.056	0.003	0.232	0.19	0.00	0.07
40	230081	NICE	43 42 N	07 16 E	3.238	0.653	−0.016	0.242	0.226	0.20	–	–
41	233021	MONACO	43 44 N	7 25 E	–	–	–	–	0.225	0.20	–	–
42	240001	LAMADDALENA	41 14 N	09 22 E	–	–	–	–	0.408	0.31	0.00	0.07
43	240011	CAGLIARI	39 12 N	09 10 E	–	–	–	–	0.416	0.29	0.00	0.07
44	250001	PORTOMAURIZIO	43 52 N	08 01 E	–	–	–	–	0.218	0.20	–	–
45	250011	GENOVA	44 24 N	08 54 E	0.517	0.281	−0.069	−0.063	0.173	0.18	0.00	0.03
46	250021	LIVORNO	43 32 N	10 18 E	–	–	–	–	0.249	0.23	0.00	0.03
47	250031	CIVITAVECCHIA	42 03 N	11 49 E	–	–	–	–	0.353	0.27	0.00	0.09
48	250035	MISENO	40 47 N	14 05 E	−0.209	4.690	−0.088	−0.028	0.408	0.27	–	–
49	250036	P. S. SOFER	40 50 N	14 07 E	–	–	–	–	0.405	0.27	–	–
50	250037	P. MOLO CALIGOLIANO	40 49 N	14 07 E	–	–	–	–	0.406	0.27	–	–
51	250038	NISIDA	40 48 N	14 10 E	–	–	–	–	0.406	0.27	–	–
52	250041	NAPOLI(ARSENALE)	40 52 N	14 16 E	–	–	–	–	0.402	0.27	−1.50	0.12
53	250051	NAPOLI(MANDRACCIO)	40 52 N	14 16 E	–	–	–	–	0.402	0.27	–	–
54	250052	NAPLES	40 50 N	14 15 E	−0.274	4.470	0.009	−0.058	0.404	0.27	–	–
55	250053	NAPOLI M. C.	40 50 N	14 16 E	2.479	4.100	−0.009	−0.015	0.404	0.27	–	–
56	250054	TORRE GRECO	40 47 N	14 22 E	–	–	–	–	0.405	0.27	–	–
57	250055	CASTELLAMMARE	40 41 N	14 28 E	–	–	–	–	0.410	0.27	–	–
58	250061	R. CALABRIA	38 06 N	15 39 E	−8.610	2.717	−0.124	0.489	0.522	0.30	1.60	0.31
59	260001	MESSINA	38 12 N	15 34 E	–	–	–	–	0.518	0.30	1.40	0.31
60	260011	PALERMO	38 08 N	13 20 E	–	–	–	–	0.485	0.29	0.00	0.03
61	260021	M. DELVALLO	37 40 N	12 34 E	–	–	–	–	0.455	0.28	0.00	0.03
62	260028	CAPO PASSERO	36 40 N	15 18 E	9.547	1.906	−0.080	0.023	0.538	0.32	0.00	0.03
63	260031	CATANIA	37 30 N	15 08 E	−2.606	1.642	−0.109	−0.014	0.529	0.30	2.00	0.30
64	265001	VALLETTA	35 54 N	14 31 E	3.191	1.848	0.026	−0.251	0.488	0.31	0.00	0.08
65	270006	TARANTO	40 26 N	17 16 E	–	–	–	–	0.389	0.23	0.10	0.01
66	270014	BRINDISI	40 38 N	17 56 E	0.469	0.990	−0.145	−0.023	0.366	0.21	0.00	0.08
67	270031	VENEZIA(S. LIDO)	45 21 N	12 23 E	–	–	–	–	0.127	0.19	−1.10	0.31
68	270041	VENEZIA(ARSENALE)	45 25 N	12 21 E	–	–	–	–	0.122	0.19	−1.10	0.31
69	270051	VENEZIA(S.STEF)	45 25 N	12 20 E	–	–	–	–	0.122	0.19	−1.10	0.31
70	270054	VENEZIA(PDS)	45 26 N	12 20 E	0.804	0.288	−0.076	−0.006	0.121	0.19	−1.10	0.31
71	270061	TRIESTE	45 39 N	13 45 E	0.775	0.262	−0.069	−0.011	0.116	0.19	0.00	0.08
72	270071	POLA	44 52 N	13 51 E	–	–	–	–	0.173	0.21	–	–
73	279002	KOPER	45 34 N	13 45 E	0.138	0.461	−0.119	0.018	0.122	0.20	−0.52	0.08

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Table 1 (*continued*)

	PSMSL ref	Name	Lat	Lon	Obs trend	Error	Atm	Steric	GIA	Error GIA	Land mov.	Error land M.
74	279003	LUKAKOPER	45 34 N	13 45 E	0.152	2.910	0.027	−0.011	0.122	0.20	−0.52	0.08
75	280006	ROVINJ	45 05 N	13 38 E	0.448	0.267	−0.072	−0.016	0.156	0.20	−0.52	0.08
76	280011	BAKAR	45 18 N	14 32 E	0.633	0.279	−0.065	−0.024	0.145	0.20	−0.52	0.08
77	280013	ZADAR	44 07 N	15 14 E	4.225	4.267	−0.091	−0.223	0.227	0.21	−0.52	0.08
78	280014	GAZENICA	44 05 N	15 16 E	−0.509	3.974	−0.127	0.018	0.229	0.21	−0.52	0.08
79	280021	SPLIT MARJANA	43 30 N	16 23 E	0.286	0.269	−0.075	−0.065	0.250	0.20	–	–
80	280031	SPLIT H	43 30 N	16 26 E	0.102	0.260	−0.075	−0.065	0.249	0.20	–	–
81	280040	VIS-CESKAVILA	43 04 N	16 12 E	−3.349	2.144	−0.149	−0.356	0.276	0.21	−0.52	0.08
82	280046	SUCURAJ	43 08 N	17 12 E	5.752	1.382	0.045	0.005	0.257	0.19	–	–
83	280081	DUBROVNIK	42 40 N	18 04 E	0.618	0.250	−0.070	−0.095	0.267	0.17	–	–
84	281011	BAR	42 05 N	19 05 E	1.292	0.495	−0.116	−0.014	0.269	0.16	–	–
85	290001	PREVEZA	38 57 N	20 46 E	−1.012	0.467	−0.048	−0.084	0.393	0.19	0.00	0.33
86	290004	LEVKAS	38 50 N	20 42 E	3.585	0.426	−0.048	−0.106	0.402	0.20	0.00	0.34
87	290011	POSIDHONIA	37 57 N	22 57 E	−11.753	0.742	0.001	−0.076	0.430	0.19	1.60	0.03
88	290014	PATRAI	38 14 N	21 44 E	16.959	0.435	−0.044	−0.016	0.420	0.20	–	–
89	290017	KATAKOLON	37 38 N	21 19 E	1.776	0.402	−0.044	−0.115	0.467	0.23	0.30	0.11
90	290021	KALAMAI	37 01 N	22 08 E	4.641	0.446	−0.041	−0.111	0.485	0.23	–	–
91	290030	N. SALAMINOS	37 57 N	23 30 E	2.555	1.224	−0.004	−0.068	0.429	0.19	–	–
92	290031	PIRAIEVS	37 56 N	23 37 E	−6.099	0.536	−0.045	−0.133	0.430	0.19	−0.15	0.41
93	290033	KHALKIS S.	38 28 N	23 36 E	−2.343	0.693	−0.022	−0.024	0.398	0.17	−0.15	0.31
94	290034	KHALKIS N.	38 28 N	23 36 E	−1.503	0.374	−0.050	−0.027	0.398	0.17	−0.15	0.31
95	290037	SKOPELOS	39 07 N	23 44 E	3.653	22.119	0.010	−1.048	0.358	0.17	–	–
96	290051	THESSALONIKI	40 37 N	23 02 E	3.267	0.413	−0.050	−0.098	0.273	0.22	–	–
97	290061	KAVALLA	40 55 N	24 25 E	−8.585	0.769	−0.049	−0.027	0.269	0.22	–	–
98	290065	ALEXANDROUPOLIS	40 51 N	25 53 E	1.139	0.396	−0.051	−0.010	0.286	0.20	–	–
99	290071	KHIOS	38 23 N	26 09 E	4.381	0.345	−0.044	−0.077	0.377	0.15	–	–
100	290081	SIROS	37 26 N	24 55 E	5.102	0.745	−0.047	−0.083	0.449	0.21	−0.45	0.31
101	290091	LEROS	37 05 N	26 53 E	1.848	0.366	−0.040	−0.058	0.425	0.19	–	–
102	290097	SOUDHAS	35 30 N	24 03 E	−0.871	0.413	−0.042	−0.048	0.496	0.26	–	–
103	290101	IRAKLION	35 20 N	25 08 E	–	–	–	–	0.495	0.27	0.00	0.32
104	290110	RODHOS	36 26 N	28 14 E	0.103	0.405	−0.038	−0.014	0.415	0.19	–	–
105	310040	KARSIYAKA	38 24 N	27 10 E	–	–	–	–	0.341	0.17	–	–
106	310041	KARSIYAKA/IZMIR	38 24 N	27 10 E	14.664	0.480	−0.047	0.018	0.341	0.17	–	–
107	310042	MENTES/IZMIR	38 26 N	26 43 E	9.788	3.967	−0.098	0.072	0.356	0.16	–	–
108	310051	ANTALYA	36 53 N	30 42 E	−11.961	113.000	−0.130	−0.344	0.279	0.15	–	–
109	310052	ANTALYA II	36 50 N	30 37 E	7.056	1.552	0.047	0.106	0.286	0.14	–	–
110	310061	ISKENDERUN	36 37 N	36 07 E	8.455	133.000	−0.103	−0.118	0.070	0.19	–	–
111	320011	HAIFA	32 49 N	35 00 E	−1.692	1.080	−0.115	−0.097	0.097	0.06	0.00	0.08
112	320016	HADERA	32 28 N	34 53 E	12.531	2.346	0.124	0.646	0.083	0.05	0.00	0.08
113	320021	JAFFA	32 03 N	34 45 E	−1.831	1.890	−0.064	−0.085	0.063	0.04	0.00	0.08
114	320031	ASHDOD	31 50 N	34 39 E	−2.148	0.860	−0.113	−0.026	0.054	0.04	0.00	0.08
115	330001	PORT SAID	31 15 N	32 18 E	–	–	–	–	0.112	0.06	–	–
116	340001	CEUTA	35 54 N	05 19 W	0.460	0.210	−0.037	−0.180	−0.072	0.16	–	–
117	330071	ALEXANDRIA	31 13 N	29 55 E	−0.555	0.290	−0.093	−0.001	0.154	0.07	−3.50	0.31

particular indicator was created. The division of the vertical change in the indicator divided by the time elapsed provides a mean estimate of the rate of sea level change for the period covered. This methodology has repeatedly been applied in the Mediterranean (for examples see: Lambeck et al., 2004b; Ferranti et al., 2006; Antonioli et al., 2007). Trends for locations close to tide gauges estimated from tectonic movements are listed in Table 1 where available.

The basic assumption is that past local vertical movement was at a steady rate over hundreds to thousands of years, and that it is continuing now at the same steady rate. Movements which are tectonic in the strict

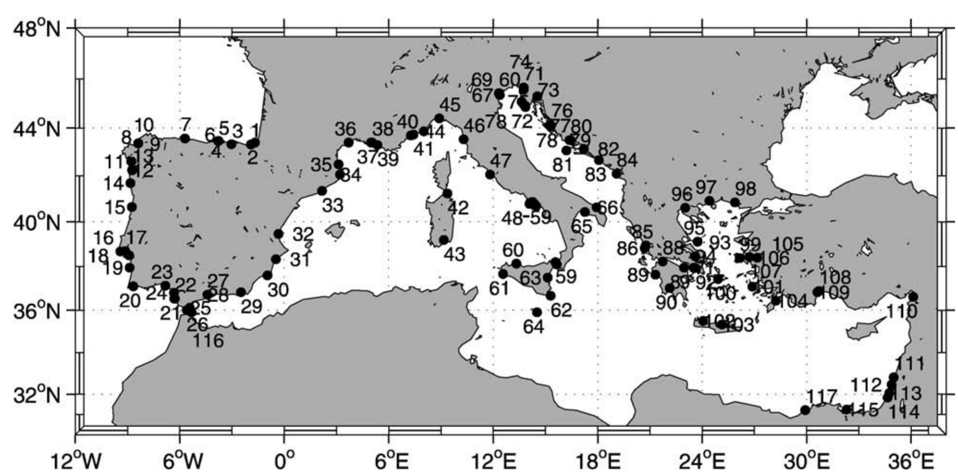

Fig. 1. Tide gauge records longer than 7 years available. Numbers correspond to those in Table 1.

sense of seismic forces are either co-seismic and discontinuous, or aseismic and may be continuous and steady. They can also reverse for short periods, due to stick-slip phenomenon in the faults, where strain builds up, and is then released. Even sedimentary compaction processes can include slump faulting, which is discontinuous, so that the rate averaged over hundreds of years is not necessarily the same over 1–20 years. This is a serious factor which in locations may be the cause of errors.

3.1. Uncertainties in estimates of sea level changes based on proxy data

Errors in this methodology are introduced by three kinds of uncertainty. The *first kind* is related to uncertainties which depend on the accuracy of the dating of the demarcation and on errors in the vertical measurement of the demarcation, including the atmospheric and tidal corrections. In most parts of the Mediterranean Sea the error in the estimation of the tidal signal is rather small (<10 cm) and storm surge effects can be estimated within 10 cm in most places and for most of the time.

The timing errors depend on the type of marker used. Corals (coespitosa) and speleothems, can be dated by U\Th method until about 600 ka BP. Fossils of marine shells by ERS or Amino acid, but these methods have larger timing errors. ^{14}C analyses can be used for dating biological indicators which lived during the Holocene (last 10 ka cal BP), that is, fossil shells, marsh, carbon or any other markers that assumed carbon from the atmosphere. Probably the best indicators are tidal organisms as *Vermetid reef* or *Ctamalid*. Because the tidal range in the Mediterranean Sea is small in most parts of it such organisms provide a vertically constrained demarcation. Archaeological markers can be dated using relics of ceramic or on the basis of architectural features. Amongst these, fishtanks as well as docks used by ancient civilisations are considered as providing the most precise information on the location of sea level (Lambeck et al., 2004b; Auriemma and Solinas, 2009).

The *second type of uncertainty* arises from the use of multiple indicators in the same area. It has been found that in some regions the elevation of demarcations of indicators can differ significantly between nearby sites. This may be caused by small scale spatial changes in land motions. In such cases it is clear that sea level change based on the various indicators may not be representative of the area.

Alternatively the differences may be caused by differential effects on the biological indicators caused by the same forcing that caused the sea level change. For example changes in the environmental conditions due to changes in the local or global climate. It may also be caused by changes in the biological characteristics of the indicators used. Note that where there is only one estimate of sea level change one cannot tell whether such estimate is indeed representative over a larger area without additional estimates from nearby sites or on different indicators made available. Thus, where there is only one estimate the formal uncertainty disappears although it is well known that the real uncertainty is in fact increased.

The *third type* of uncertainty arises from the assumptions that land movements have large spatial scales and that they are more or less uniform in time. However, large differences in estimates from sites at small distance indicate that there are areas where the first assumption breaks down, while the well documented changes in sea level following earthquakes and associated land movements indicate that the second assumption is not always fulfilled either. Faulting, earthquakes, tilting blocks, subduction, volcanism, swelling and collapsing magma domes, subsiding deltas, grabens, and stick-slip phenomena resulting in reversals are all common in the Mediterranean on horizontal scales of a few kilometers to a few tens of kilometers. In addition they are not uniform in time. Thus when land movements in the Mediterranean Sea are considered in detail they are not spatially consistent at regional scales nor are they temporally uniform in time scales of a few decades or more. There are indeed some areas where, after analysis of the data, one finds series of geographically adjacent indicators suggesting slow rates (<0.2 mm/yr) of vertical change relative to each other, These areas are either being displaced relative to present sea level while preserving horizontality over many tens of km, or are stable relative to sea level to within the limits of error of the study.

As an example of this third type of uncertainty submersions of roman period archaeological sites (~2 ka BP) can be referred to. These are in the Mediterranean submerged typically by 1 to 1.5 m in relation to present sea level. However in particular areas, for example in Crete and Rhodes, vertical differences of up to 7 m have been found within a few tens of kilometers, (Flemming and Webb, 1986; Pirazzoli, 1987). This third type of uncertainty, although the physical causes can usually be identified can be very large and is difficult to formulate into a quantitative estimate.

For example, a 7-m difference in 2000 years results in 3.5 mm/yr difference in mean sea level rate. Thus in such cases either the sea level estimates from some sites must be considered as of local character and not included in the analysis or very large errors have to be admitted as accompanying the estimates.

Obtaining a typical error for sea level change estimates from the various indicators is not an easy task and involves making assessments about the magnitude of each of the three types of uncertainty discussed above. In relation to the first type of uncertainty typical errors in mean vertical values have been estimated at ± 20 cm (Lambeck et al., 2004a; Antonioli et al., 2007; Auriemma and Solinas, 2009) and for locations are considered to be in the range of ± 10 cm but up to ± 60 cm. There are no systematic studies discussing the use of different indicators and giving estimates on the second source of uncertainty, nor for the magnitude of the third uncertainty which is spatially variable. We assume a collective error of 100 cm incorporating all three sources of errors to be a conservative estimate for most locations. This would reflect into an uncertainty of 0.5 mm/yr for an indicator referring to sea level about 2000 years ago assuming no errors in dating. If we further assume a 100 year error in dating and a 10 m elevation over the 2000 years the relevant error bar is about 0.6 mm/yr. Generally for an elevation z with error δz and a dating T with dating error δT the error in the rate $\delta\alpha$ of sea level rise α is:

$$\delta a = \sqrt{\left(\frac{\delta z}{T}\right)^2 + \left(\frac{z\delta t}{T^2}\right)^2}$$

Thus use of older indicators with the same dating error results in reduced error bars but the errors actually depend on the time and the elevations in questions, that is the signals in relation to the uncertainty.

4. Estimation of the Glacio-Isostatic Adjustment (GIA)

The effects of GIA are evaluated using SELEN, a model available to the community (Spada and Stocchi, 2007). SELEN is based on the classical Sea Level Equation (SLE) theory of Farrell and Clark (1976) (see Spada and Stocchi, 2006 for a detailed account). Farrell and Clark (1976) assume a radially stratified Earth with linear Maxwell viscoelastic rheology, they neglect the horizontal migration of the shorelines and do not account for rotational feedbacks. The same restrictions are true for SELEN. SELEN can be used to estimate the main geophysical variables associated with GIA including the rates of sea level variations and vertical movements currently expected at the tide gauges. Here, SELEN is employed to provide the estimated GIA signal and its uncertainties associated with competing assumptions regarding mantle rheology and ice sheets chronologies (Stocchi and Spada, 2009).

In its basic form, the SLE is a simple relationship that provides sea level change (S) in terms of the variations of the offset between the geoid and the solid surface of the Earth, i.e., S = N − U, where N is the geoid height variation and U is vertical displacement of sea bottom.

Since N and U are both functions of the spatio-temporal distribution of ice thickness variations and sea level variation itself, the SLE is an integral equation. Imposing mass conservation and assuming that the geoid constantly coincides with the free surface of the oceans, the SLE takes the form:

$$S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o I - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} \overline{G_s \otimes_i I} - \frac{\rho_w}{\gamma} \overline{G_s \otimes_o S}$$

where ρ_i and ρ_w are ice and water density respectively, γ is surface gravity, G_s is the viscoelastic sea level Green function ($G_s = 0$ for a rigid, non-self-gravitating Earth), I is the ice sheet thickness variation, $\otimes$i and $\otimes$o are spatio-temporal convolutions over the ice sheets and the oceans, respectively, m_i is ice mass variation, A_o is the (constant) area of the oceans. The last two terms of the equation are averaged over the surface of the oceans (Farrell and Clark, 1976).

We solve the SLE using the same pseudo-spectral, recursive method introduced by Mitrovica and Peltier (1991), but adopting an original spatial grid that allows for a straightforward harmonic analysis on the sphere (Tegmark, 1996). Since the SLE is an integral equation, we employ a standard recursive approach that as a first guess uses the eustatic (spatially uniform) solution:

$$S = -\frac{m_i}{\rho_w A_o}$$

In all computations, the maximum harmonic degree is lmax = 128. This represents an optimal compromise between accuracy and efficiency in computation (Stocchi and Spada, 2009). The present day rate of sea level change at a tide gauge is retrieved by discretizing the time-derivative

$$\xi^{GIA} = \frac{dS}{dt}\left(\theta, \lambda, t_p\right)$$

where S is the solution of the SLE, θ and λ are colatitude and longitude of the tide gauge site, respectively, and t_p denotes present time.

4.1. Uncertainty in the model assumptions

The GIA model estimates involve a number of uncertainties concerning geometrical and physical properties, whose role has not yet been completely explored. A basic assumption relates to the ice-history. Here the basic model of late-Pleistocene ice sheets is ICE-5G

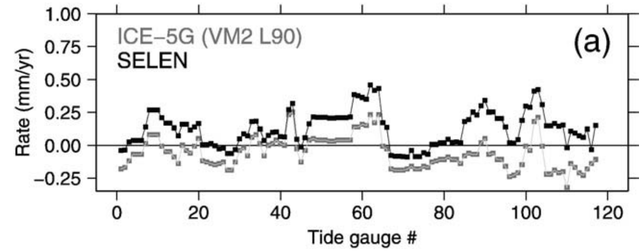

Fig. 2. Comparison between by Peltier (2004) (gray symbols, model ICE–5G (VM2 L90)), and the output of SELEN (black), for all the tide gauges considered in this study. Similarities and differences between model implementations of the SLE are detailed in Table 2.

(Peltier, 2004). This model is constrained by Holocene relative sea level observations and modern geodetic data from formerly glaciated areas (Peltier, 2004). Thus, the ICE-5G model is based at least partly on the same observations that we attempt to interpret albeit global rather than local (Mediterranean) observations are utilized and sea level information in the areas where ice sheets have been in existence are arguably significantly more important than the far field observations. Thus part of the uncertainty in the GIA estimates rises from the uncertainties in the ice sheet distribution and its history. We do not have an estimate of this uncertainty nor are we aware of any such uncertainty being published, partly because updating the ice sheet history is often performed through trial and error and is not approached in a rigorous statistical way.

A second part of uncertainty arises from the fact that we use a model based on the Farrell and Clark (1976) equation rather than on a more up to date approximations. We compare sea level predictions based on ICE-5G (VM2 L90) available from (http://www.atmosp.physics.utoronto.ca/peltier/data.php) with the output of SELEN in order to evaluate how different assumptions in GIA modeling may affect the RSL predictions at the Mediterranean tide gauges (a tentative list of modeling differences is shown in Table 2). A four-layer mantle viscosity profile that closely follows the multi-layered VM2 profile of Peltier (2004), and the same value of the lithospheric thickness of 90 km has been used for this comparison. Fig. 2 shows the results obtained from the ICE-5G implementation through SELEN for the sites of Fig. 1 (black squares) while the estimates from the global model of Peltier (2004) are shown by gray symbols. SELEN based predictions tend to be positive (i.e. they indicate a sea level rise) at all the tide gauge sites while those based on the VM2 L90 model show negative trends. The predictions from the two models are approximately shifted by 0.20 mm/yr. While

Table 2
A comparison between model approaches of Spada and Stocchi (2007) and Peltier (2004).

	Spada and Stocchi (2007)	Peltier (2004)
Model name	SELEN	ICE-5G (VM2 L90)
General theory	Follows Farrell and Clark (1976)	Extends Farrell and Clark (1976)
Viscoelastic theory	Normal modes	Normal modes
Harmonic analysis	To degree lmax = 128. Degree 1 not included	Presumably to degree lmax = 512, with degree 1 included
Mantle layering	4 layers, incompressible, with PREM-averaged density and shear moduli	finely layered PREM, compressible
Viscosity profile	Maxwell rheology, 4-layers viscosity profile that approximate the VM2 model of Peltier (2004)	Maxwell rheology, multi-layered viscosity
Lithosphere	Elastic, incompressible, thickness of 90 km	Elastic, presumably compressible, thickness of 90
Core	Inviscid, homogeneous	Presumably PREM-layered. Outer core inviscid, inner core solid
Spatial grid	Pixelization of Tegmark (1996), grid spacing of about 70 km. Ice elements of ICE-5G are converted into equal-volume disk elements to speed up computation	Ice sheets are decomposed on a Gaussian grid, with a spacing of about 0.7
Time discretization	Stepwise, with increments of 1 kyrs	Piecewise linear, increments of variable length
Ice history	Assumes equilibrium before the LGM (21 kyrs B), and a (discretized) ICE-5G history onwards. Ice volumes consistent with the "implicit ice" formulation of Peltier (2004)	Includes a loading phase before the LGM (21 kyrs B)
Shorelines	Kept fixed to present day shapes	Variable horizontally, iteratively adapted to sea level variations and Earth topography
Earth rotation	Not modelled	Rotational feedback included.

we could not identify which assumption exactly is the cause of the difference among those listed in Table 2, it can be said that the differences in the model assumptions summarized in Table 2 results in the discrepancy of 0.2 mm/yr. The positive trends predicted by SELEN are consistent, however, with the general late Holocene sea level rise effectively suggested by various field observations (Pirazzoli, 1991, 1996).

A third part of uncertainty in the modelled based GIA rates of sea level change relates on the selected model parameters concerning the response of the earth to the changes in the mass loading. We do not perform here a full exploration of the mantle viscosity values because this would also demand adjustments of the melting history of the global ice distribution in order to fit the global Holocene and contemporary observational constraints. We argue that perturbing the Earth viscosity profile will be sufficient to simultaneously determine model error bars to predicted sea level rise values ξ at tide gauges and sensitivity to the rheological parameters. Previous experience shows that once a global deglaciation model is chosen, the main uncertainties are related to mantle viscosity and lithospheric thickness (see for example Stocchi and Spada, 2009). Thus if the effective rate of GIA induced sea level change at tide gauge i is written as

$$R_i^{GIA} = \xi_i \pm \Delta\xi_i$$

where $\overline{\Delta\xi_i}$ represents the uncertainty associated with a perturbation of the reference model. Then an upper bound for $\overline{\Delta\xi_i}$ is:

$$\Delta\xi_i = \sum_{k=1}^{p} \left| \frac{\partial\xi_i}{\partial p_k} \right|_{pko} \Delta p_k$$

where p_k are uncorrelated model parameters and p_{k0} $(k=1,..., P)$ denote reference values of these parameters. Central differences are used to approximate the partial derivatives in the equation above. Following Stocchi and Spada (2009) we estimate $\overline{\Delta\xi_i}$ for three parameters (p = 3) namely lithospheric thickness h, and the mantle viscosities above and below the 670 km depth seismic discontinuity (h_u and h_l, respectively). To provide an upper bound for $\overline{\Delta\xi_i}$, we assumed an uncertainty of 20 km for the lithospheric thickness h, and uncertainties of 1×10^{21} Pa s and 1×10^{20} Pa s for the mantle viscosities h_u and h_l, respectively. The results of this analysis are shown in Fig. 3. The obtained GIA rates are between −0.1 and 0.5 mm/yr. Negative rates are only estimated for tide gauges located in southern Spain. The average uncertainty for the tide gauges introduced by the variations in these three parameters shown is ±0.3 mm/yr. It appears that the uncertainty related to the lower mantle viscosity (Fig. 3b) is the larger contributor, in excess of 0.2 mm/yr, while the uncertainty related to the depth of the lithosphere (Fig. 3d) is the smallest contributor. The sensitivity to viscosity beneath the 670 km depth discontinuity is a consequence of the relatively large spatial scale that characterized the load associated with melt water, which largely exceeds 1000 km.

Thus according to our estimate in Fig. 3, an upper bound to uncertainty in the estimates of GIA is ±0.3 mm/yr within SELEN. Of course, this estimate is strongly dependent upon the assumed uncertainty on the rheological parameters. For example, if lower mantle viscosity would be assumed to be perfectly constrained from late Holocene RSL observation, the upper bound above would be reduced by a factor of ~2. We consider that an additional error of ±0.2 mm/yr, that is, the difference between VM2L90 and SELEN estimates must be added to reflect uncertainty between models. Thus an upper bound to the error for GIA is around ±0.5 mm/yr. Furthermore an additional error reflecting the uncertainty of the ice sheet history must be added. We do not have an estimate for this nor even a feeling of how large this can be even without considering this particular error the GIA estimates are not, within the error bars, different from zero.

For sites from 110 to 117 in (Fig. 3a) (i.e., along the Mediterranean coasts of the Middle East, see Fig. 1) we simultaneously observe relatively small GIA signals (close to 0.1 mm/yr) and a reduced sensitivity to the

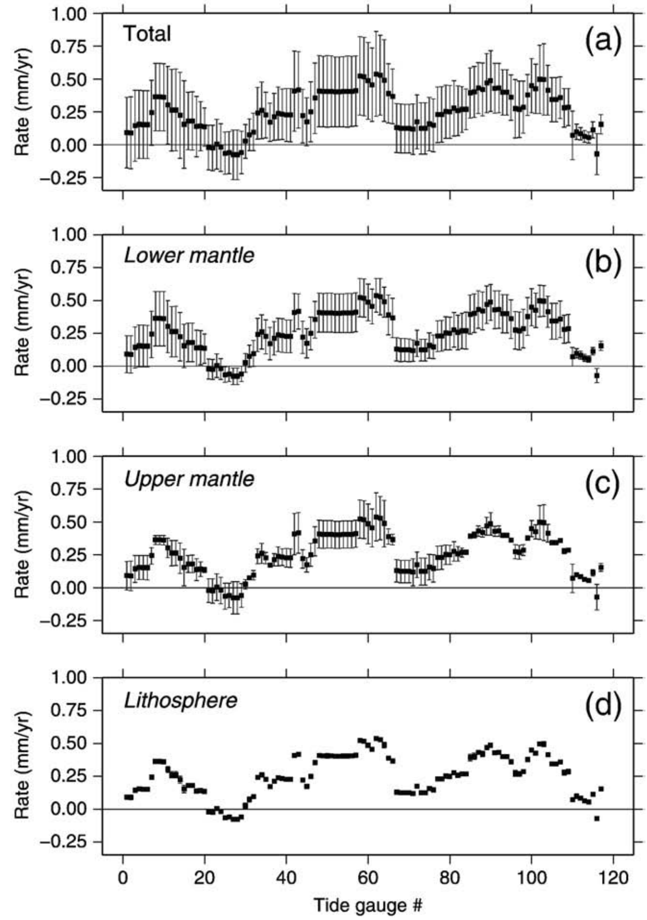

Fig. 3. Rates of sea level change _i computed by SELEN using the same settings of Fig. 1 (squares). In frame (a) error bars show GIA model uncertainties evaluated according to the perturbative approach described in the body of the manuscript. In (b), (c), and (d), error bars are decomposed in contributions from lower mantle viscosity, upper mantle viscosity, and lithospheric thickness, respectively.

variations imposed to the model parameters (no other region across the Mediterranean apparently shows this peculiarity). This observation strengthens the suggestion by Spada and Stocchi (2007), that, provided that tectonic deformations can be neglected, this region can be an ideal environment for monitoring the effects of global eustatic sea level rise. However it should be noted that the Nile delta effects and the existence of major faults on the Levant coast cast doubt on whether the Spada and Stocchi (2007) suggestion can materialise. The Mediterranean coast of Israel is surprisingly stable (Flemming et al., 1978; Sivan and Galili, 1999; Sivan et al., 2001) but there is particularly active faulting round the Haifa–Qishon graben, and again at Caesarea. Fig. 3 indicates that the GIA contribution varies between −0.1 mm/yr and 0.5 mm/yr between the various tide gauges but the error bars suggest that they can be as high as 0.75 mm/yr or as small as −0.25 mm/yr. This range suggest that over the past 2000 years sea level may have gone up by up to 1.5 m or down by 0.5 m at the various tide gauges used here.

5. Steric sea level changes

The steric sea level is computed as:

$$h(p1,p2) = \frac{1}{g}\int_{p^1}^{p^2} \frac{1}{\rho}\,dp.$$

That is the distance between the two surfaces of constant pressure $p1$ and $p2$, where ρ is the density and g the gravity. The density is computed from the gridded temperature and salinity in-situ data using the formulas of state for sea water (Gill, 1982). We use gridded values of steric sea level from 1945 to 2002. The climatology used for the Mediterranean is MEDAR (Rixen et al., 2005) while for the Atlantic we use Ishii climatology (Ishii and Kimoto, 2009). To separate the thermosteric from the halosteric effect we repeat the calculations by respectively keeping the salinity or the temperature constant to their first value.

Although the calculation of the steric trends is very simple there are several uncertainties involved. One problem arises from the changes in technology. Temperature and salinity measurements were once obtained on the basis of thermometers and water sampling with the depth determined by use of the effects of pressure on temperature using an unprotected and a protected thermometer. Expendable bathythermographs have routinely been used to measure the temperature but the determination of depth depended in them on the fall rate and the timing. Changes in the shape of the instruments have led to changes in the fall rates which in some cases were not accounted for, thus biasing the measurements (Wijffels et al., 2010). The development and the wide use of the CTD significantly improved the consistency of results obtained. However, controls on the drift of the sensors even within a cruise, could introduce significant biases. The use of the above mentioned measuring techniques was accompanied by varying practices between nations which, fortunately, over time, became internationally more uniform. The derived climatologies include most measurements, apart from those picked up by quality checks, usually errors corresponding to measurements undertaken closely in time and space as well as wild points. Thus the effected changes in technology are mixed with natural signals.

The second problem relates to the spatial and temporal sampling of oceanic parameters. Oceanic measurements have been collected opportunistically in time and space up to very recent years when systematic observations within monitoring or scientific programmes have been established. The geographical bias in some cases excluded particular areas of the Mediterranean basin, for example the Gulf of Sirte where political disputes made the access of oceanographic ships problematic. In addition to the geographical bias the density of measurements is significantly higher in the upper waters because, on one hand, these are of more interest for marine biologists and chemists and also because measurements of deeper waters are more time-consuming, thus more expensive and require more expensive infrastructure.

As a result, a question on how should one calculate the steric contribution to sea level changes becomes more complicated. Should equation 1 be applied to the whole water column? Does it apply to specific locations, for example close to tide gauges or is it a basin wide or even global parameter to estimate? As it is clear that water mass characteristics are linked with oceanic circulation the question of separating the steric effects from those of circulation changes also becomes important. It has become accepted practice to use steric sea level changes for the upper 400 to 700 m. However, this should not be taken as a confirmation that deeper layers are not important. On the contrary, in the Mediterranean, where dense and intermediate water formation is very important, the contribution of deeper layers may be proven to be important.

The physical separation of the Mediterranean Sea to sub-basins provides a convenient arrangement for the consideration of steric effects. Thus in this study we estimate the steric trends at the Western Mediterranean, the Eastern Mediterranean, the Adriatic Sea and an area of the Eastern Atlantic. Each area has several grid points. Thus one can calculate a steric trend for each of these points. We report the trend for the averaged steric sea level over the whole basin and as an error bar of this we provide the standard deviation of the trend values at each basin. This error is partly due to real spatial variability but also reflects the differences in sampling density. We present these results for steric, thermosteric and halosteric trends in Table 3 for various reference levels and for the period 1945–2002. The steric trends are negative at the three Mediterranean basins. The strongest negative trends are found in the Adriatic where the trend is dominated by what happens in the top 100 m, where a statistically significant trend of -0.34 ± 0.21 mm/yr is found. The trends increase with depth down to 450 m. No contribution is made to the trend at deeper levels. However, the spatial variability of the trends increases more than the trend for the layers between 225 and 500 m resulting that the overall trend becomes non significant. The cause of the trend is reduction of the upper water temperature which account for -0.24 ± 0.14 mm/yr for the upper 100 m. The thermosteric trend for the whole water column is around -0.37 ± 0.38 mm/yr again indicating significant spatial variability. The halosteric trends are around -0.1 mm/yr but are at all levels statistically insignificant.

Table 3
Linear trends of steric, thermosteric and halosteric sea level for each sub-basin for the period 1945–2002 as computed by MEDAR climatology.

	MED	EMED	WMED	ADR	ATL
Steric					
100 m	-0.13 ± 0.35	-0.19 ± 0.40	-0.04 ± 0.23	-0.34 ± 0.21	0.16 ± 0.01
225 m	-0.24 ± 0.41	-0.30 ± 0.48	-0.15 ± 0.24	-0.41 ± 0.32	0.30 ± 0.02
450 m	-0.33 ± 0.42	-0.41 ± 0.49	-0.23 ± 0.25	-0.50 ± 0.49	0.41 ± 0.03
550 m	-0.35 ± 0.42	-0.43 ± 0.49	-0.25 ± 0.25	-0.51 ± 0.51	0.43 ± 0.04
700 m	-0.37 ± 0.42	-0.45 ± 0.49	-0.28 ± 0.26	-0.52 ± 0.54	0.45 ± 0.04
900 m	-0.38 ± 0.42	-0.45 ± 0.49	-0.30 ± 0.26	-0.53 ± 0.56	
2250 m	-0.42 ± 0.41	-0.46 ± 0.47	-0.38 ± 0.28	-0.53 ± 0.56	
Thermosteric					
100 m	-0.04 ± 0.22	-0.11 ± 0.25	0.06 ± 0.12	-0.24 ± 0.14	0.09 ± 0.02
225 m	-0.07 ± 0.25	-0.16 ± 0.28	0.08 ± 0.12	-0.28 ± 0.21	0.17 ± 0.03
450 m	-0.08 ± 0.31	-0.22 ± 0.31	0.15 ± 0.14	-0.36 ± 0.35	0.23 ± 0.03
550 m	-0.07 ± 0.32	-0.22 ± 0.32	0.19 ± 0.15	-0.37 ± 0.38	0.24 ± 0.03
700 m	-0.04 ± 0.35	-0.21 ± 0.32	0.36 ± 0.17	-0.37 ± 0.39	0.25 ± 0.05
900 m	-0.01 ± 0.37	-0.19 ± 0.32	0.33 ± 0.19	-0.38 ± 0.38	
2250 m	0.15 ± 0.45	-0.06 ± 0.37	0.55 ± 0.32	-0.38 ± 0.39	
Halosteric					
100 m	-0.08 ± 0.15	-0.07 ± 0.16	-0.11 ± 0.14	-0.08 ± 0.08	0.04 ± 0.01
225 m	-0.15 ± 0.19	-0.11 ± 0.19	-0.23 ± 0.17	-0.10 ± 0.11	0.05 ± 0.02
450 m	-0.22 ± 0.24	-0.15 ± 0.23	-0.37 ± 0.21	-0.12 ± 0.15	0.02 ± 0.04
550 m	-0.25 ± 0.26	-0.17 ± 0.24	-0.43 ± 0.23	-0.13 ± 0.16	0.02 ± 0.05
700 m	-0.31 ± 0.31	-0.21 ± 0.28	-0.53 ± 0.26	-0.14 ± 0.19	0.03 ± 0.06
900 m	-0.36 ± 0.35	-0.23 ± 0.30	-0.62 ± 0.29	-0.15 ± 0.21	
2250 m	-0.58 ± 0.49	-0.40 ± 0.37	-0.96 ± 0.48	-0.15 ± 0.21	

For the Eastern Mediterranean Sea, the trends are negative with significant uncertainty. The basin average is -0.46 ± 0.47 mm/yr that is, not statistically significant and the contribution of cooling and salinification appears to be of equal significance except for the deep layers. Smaller trends are found in the western Mediterranean. These are not significant at the upper layers (down to 450 m). They become significant when deeper layers are considered and in particular when the layers deeper than 900 m are taken into account. Then the estimated trend becomes -0.38 ± 0.28 mm/yr. This is caused by a strong halosteric trend partly compensated by warming trend. In the eastern sector of the Atlantic the steric trends are positive, with values of 0.41 ± 0.03 mm/yr in the upper 450 m and no contribution from the deeper layers. Steric trends are mostly caused by warming, while halosteric trends are not statistically significant in this region.

Using the basin average for the steric signal is probably the best representative of changes in overall expansion in that basin. However the steric signal is not expected to be uniform everywhere, as local changes, probably coupled with circulation, may also be present. Thus, an alternative way of obtaining an estimate for steric sea level change is by looking at the available climatological data close to the tide gauge. This approach produces different steric sea level rates for the various tide gauges. For the period 1945–2002 we obtain a range of -0.9 mm/yr to 0 mm/yr for the Eastern Mediterranean, -0.7 mm/yr to 0 mm/yr for the western Mediterranean, -0.6 mm/yr to 0 mm/yr for the Adriatic Sea and around 0.3 mm/yr to 0.5 mm/yr for the Atlantic. Thus if the steric contribution to Mediterranean regional sea level change is negative for several decades, it may partially cancel out or exceed the GIA factor over the same time span. While it can be argued that the steric trend is not likely to stay in one direction for very long periods of time this is again a basic assumption that has not been proven. In fact mass addition of water to the oceans is likely to affect salinity and at the same time is likely to be coupled with warming of, at least, the areas where the ice sheets or the glaciers are located. Thus the steric effect is part of a series of forcing factors all interlinked with the earth's climate. Of course the GIA changes last for longer than the salinity or temperature changes do but these are all likely to be coupled for several hundred if not thousand years,

A second question is the variability of the estimated steric sea level trends with time. It is well established (see for example Marcos and Tsimplis, 2008) that the decadal variability of sea level trends in the Mediterranean is coherent within the basin and significant. It is also known that the empirical estimation of trend errors in sea level is usually larger than the error derived from statistical fits of the trend (Tsimplis and Spencer, 1997). However it is not clear how much of this is due to the steric component and how much is due to the atmospheric or other components. Here we attempt to answer this question by doing repeat calculations of the trends. To achieve this we calculate the trends for segments of each steric sea level record. For a given length of segment we calculate all the possible trends and their standard deviation. Thus we obtain empirically a mean error associated with the length of each segment which is defined as the standard deviation of the obtained trends for a particular length. The following ranges are based on the total trend value down to the bottom from MEDAR and to 700 m from Ishii in the Atlantic sector.

For the western Mediterranean we obtain on the basis of 5 year segments a range of values between −6 mm/yr and 10 mm/yr which is reduced to −3 and 3 mm/yr when 10 years are considered and −2 and 0.5 mm/yr when 20 years are considered. The range for the whole period is ± 0.25 mm/yr.

In the eastern Mediterranean the 5-year segments have trends ranging between −10 and 8 mm/yr, while the 10 years vary between −5 and 6 mm/yr and the 20 years segments range between −0.15 and 1 mm/yr. In the Adriatic the 5 years trends vary between −6 and 6 mm/yr, the 10 years between −1.5 and 4 mm/yr and the 20 years between −1 and 0.5 mm/yr. Finally in the Atlantic the 5 years segments have periods ranging between −2 and 2 mm/yr, the 10 year segments between −1 and 1 mm/yr and the 20 year segments between −0.5 and 1 mm/yr.

We also calculated decadal trends for successive decades but the increasing error bars at shorter time segments made any changes not statistically different.

Notably, when the same calculation of steric trend values is done in locations near tide gauges the range of values found for the worst cases ranges between −10 mm/yr and +10 mm/yr for 5 year segments reducing to −5 mm/yr to 0 mm/yr or 0 to 4 mm/yr for 10 yr segments and to −4 mm/yr to 0 mm/yr for 20 year segments. However, most of the stations examined had ranges of +5 mm/yr to −4 mm/yr for 5 year segments, −2 to 1.5 mm/yr for 10 year segments and −1 mm/yr to +0.5 mm/y for 20 year segments.

In conclusion we can say that for 20 years of data ± 1.0 mm/yr is the best one can expect from near station values and about ± 0.5 mm/yr from basin averages. Note though that in some areas near station values vary significantly more.

There is very little information on the development of steric changes in the Mediterranean over the past couple of thousand years. We assume that the changes we observe do not persist over thousands of years. Thus we only use them in order to correct the observed recent trends.

6. Atmospheric forcing

The role of direct atmospheric forcing during the past decades in the Mediterranean Sea is well established (Tsimplis and Josey, 2001; Tsimplis et al., 2005; Gomis et al., 2006; Marcos and Tsimplis, 2007, 2008). The meteorological contribution to sea level has been quantified using the output of a barotropic oceanographic model. In the framework of the HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe) project (Guedes Soares et al., 2002), atmospheric pressure and wind fields were produced by a dynamical downscaling of the reanalysis of NCEP/NCAR for the period 1958−2001 (García-Sotillo et al., 2005). These fields were used to force a barotropic version of the HAMSOM (Hamburg Shelf Circulation Model) model covering the Mediterranean Sea and the Eastern Atlantic coast, with a spatial resolution of $1/4° \times 1/6°$ (Ratsimandresy et al., 2008). The comparison between the HIPOCAS sea level hourly output and the tidal residuals at coastal sites is very good with correlations between 0.8 and 0.9 (Marcos et al., 2005). Atmospherically-induced sea level trends derived from HIPOCAS data set have already been computed in previous works (Tsimplis et al., 2005; Gomis et al., 2008; Marcos and Tsimplis, 2008). The comparison of HIPOCAS with another 2D barotropic model in the region did not reveal any artificial drift of the model (Pascual et al., 2008).

The mean basin trend for the whole Mediterranean was, for the whole period 1958–2001, −0.63 ± 0.09 mm/yr. Maximum negative trends were obtained for the Adriatic Sea were the sub-basin value was −0.74 ± 0.02 mm/yr. The Eastern Mediterranean shows smaller values (−0.66 ± 0.04 mm/yr) than the western Mediterranean basin (−0.55 ± 0.10 mm/yr). However, the spread of the values is higher in the western basin. The trend for the eastern Atlantic sector is −0.38 ± 0.04 mm/yr thus smaller in magnitude than the average for the Mediterranean. The atmospheric forcing for all basins has resulted in significant negative trends which are very consistent across the Mediterranean Sea. The trends for individual stations range between −0.18 to −0.78 mm/yr but the error bars are consistently between ± 0.11 and ± 0.20 mm/yr.

When the records are split into segments, the trend values become more variable. Following the same methodology as for steric sea level we find that in the Adriatic the range of trends for 5 year segments is between −6.6 mm/yr and 0.7 mm/yr with the spread of values ranging between ± 0.2 and ± 1.3 mm/yr depending on the period. When 10 year segments are used the range becomes 1.3 mm/yr and −2.1 mm/yr and the spread of values between ± 0.10 and ± 0.17. When 20 years are used the range reduces to −0.35 mm/yr and −0.99 mm/yr with the range of values in the basin having a standard deviation (std) of 0.04 mm/yr. For the western and eastern Mediterranean the corresponding values for 5 year segments are −4.6 mm/yr to 1.9 mm/yr with spread (std) between 0.37 and 1.3 mm/yr; for 10 yr segments the range of trend values is −1.74 mm/yr to 0.74 mm/yr with std ranging between 0.13 and 0.56 mm/yr; and for 20 yr segments the values are between −0.19 and −1.0 mm/yr with range of values of around 0.08 mm/yr. In the Atlantic sector the 5−years segments have periods ranging between −5 and 0.9 mm/yr with std between 0.5 and 1.4 mm/yr. The range is reduced to −1.65 and 0.96 for 10 years period with std up to 0.4 mm/yr and further reduced to −1.16 and 0.13 mm/yr with std of 0.15 mm/yr.

Thus the contribution of atmospheric forcing is highly variable in time although not so variable in space. Errors depend on the length of the record and vary with the period of observation. Sea level records of 5 years may include signals due to atmospheric variability that induce trends of around ± 3 mm/yr. Observations of 10 years may include errors due to atmospheric variability of ± 1.5 mm/yr while observations of 20 years the influence of atmospheric forcing is expected to be around ± 0.5 mm/yr. These are of course empirical estimates for the Mediterranean Sea and the east Atlantic.

The high spatial coherency found is not necessarily a reflection of the true situation as these are model results based on downscaled reanalysis data rather than actual values. Thus we expect that the spatial variability will be somehow larger than that stated above.

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It must be noted that another numerical calculation of the atmospheric forcing based on the MOG2D model (Carrère and Lyard, 2003) when compared with the HIPOCAS analysis indicates for particular locations in the Mediterranean discrepancies in the trends of up to 0.8 mm/yr with uncertainties between 0.4 and 0.7 mm/yr over the common period of comparison 1993–2001. These differences are spatially variable (Pascual et al., 2008) and arise partly from the different atmospheric forcing and partly from the model configuration. The period of intercomparison is 8 years and the difference between the models is half of what we see as the expected range of values over the 10 year period, which is ± 1.5 mm/yr.

Thus we suggest that the model uncertainty could introduce, for the 20 year trends, an additional error of around 0.5 mm/yr which brings the total error due to atmospheric forcing to ± 1 mm/yr.

7. Discussion

Linear trends of observations, atmospheric and steric components, GIA and tectonic effects at tide gauge sites where available are all listed in Table 2. Only those stations with simultaneous atmospheric and steric data available have been used to compute trends. Linear trends of the atmospheric and steric components correspond to the same period of operation of tide gauges. Uncertainties are provided for observed trends as the standard error and for GIA component following the methodology explained above in Section 3. Uncertainties in the vertical land movements have also been quoted. Stations are numbered as in Fig. 1.

Sea level observations from tide gauges include an error for the trend expressing the spread of the sea level values around the linear trend line fitted. This error is generally small, about ± 0.3 mm/yr. However the sea level measurements over short periods are affected by interdecadal variability. Tsimplis and Spencer (1997) have shown for the Mediterranean that records longer than 40 years introduce errors of less than 0.5 mm/yr. A 20 year long record introduces errors of around 1 mm/yr when compared with the longer term record. Of course this uncertainty related with the decadal variability is caused by the steric and atmospheric forcing activity as well as by fast changes in land movement. The errors associated with each of the factors discussed above are summarized in Table 4 below. It is evident that all of them are significant in relation to the observed sea level rise in the region over the past century which is around 1.2 mm/yr.

We now proceed in comparing tide gauge based rates of sea level change corrected for steric and atmospheric and GIA effects with trends obtained from sea level proxies over the Mediterranean Sea.

The comparison is restricted only to tide gauges with records longer than 20 years, which introduces uncertainties of around 1 mm/yr in the steric and atmospheric components according to Table 4. To these uncertainties an error of 0.7 mm/yr related to the length of the record is added.

In Fig. 4(a) we have plotted observed linear trends versus inferred land movements from proxies where available. The different regions of the Mediterranean Sea are plotted in different colours. In most cases the earth motion signal is very small when compared with the observed trends. As a result we cannot claim any correlation between the two. We further plot observed trends corrected for the steric, atmospheric and GIA effects versus land movements from proxies, together with their uncertainties. Results are plotted in Fig. 4(b). Flemming and Woodworth (1988) argue that the lack of correlation can be indicative of the inability of short term periods to provide information on the long term trends.

Table 4
Errors associated with the various parameters used. Steric and atmospheric errors are stated for records longer than 20 years.

	Associated errors
GIA	± 0.5 mm/yr
Steric	± 1.0 mm/yr
Atmospheric	± 1.0 mm/yr
Sea level (proxies)	± 0.6 mm/yr
Sea level (TG) standard error	± 0.3 mm/yr
Sea level (TG) error related to the length of the record	± 0.7 mm/yr

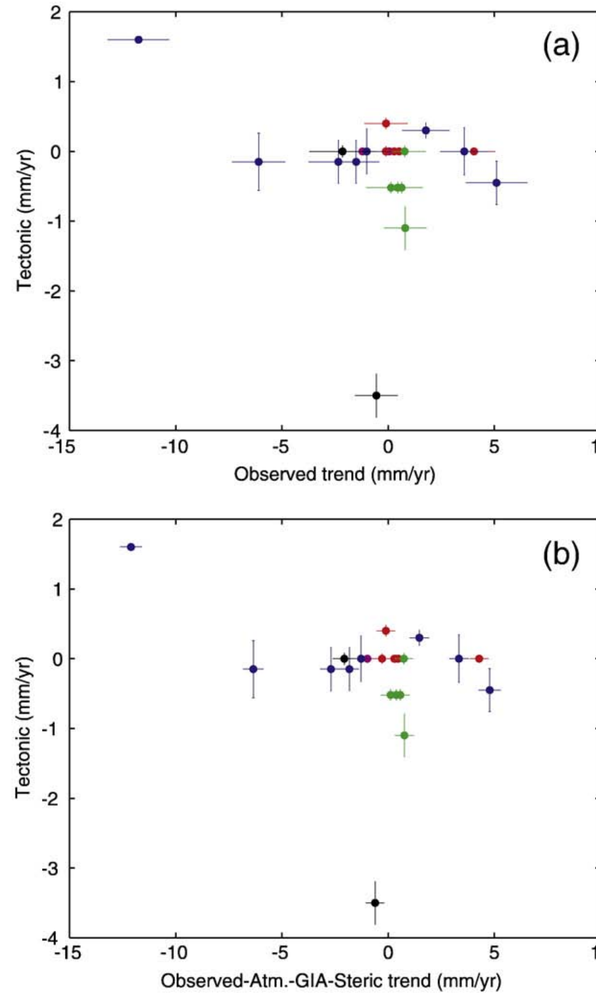

Fig. 4. a) Observed from tide gauges versus land movements linear trends for selected stations. b) As in a) but observed trends are corrected for atmospheric, steric and GIA effects. Colours identify different regions: red is western Mediterranean, pink is Gibraltar, green is Adriatic, blue is Aegean and black is eastern Mediterranean. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

However the disagreement between the trends of vertical land movements at millennium scales with the observed trends can have an alternative explanation. Lambeck et al. (2004b) found for the central Mediterranean a local sea level increase of 1.35 m ± 0.07 m on the basis of roman archaeological remnants dated 2000 years before present. They applied glacio-hydro isostatic adjustments which reduced the increase to 0.13 ± 0.09 m. This corresponds to an increase equivalent to what the Mediterranean has experienced over the past 100 years. Thus they conclude that the sea level rise observed has happened over the past 100 years. This would of course imply that a trend calculated over the longer period will be much smaller than the one based on observational data. Such conclusion is not, of course, inconsistent with Flemming and Woodworth (1988).

It is worth mentioning that earlier researchers using the same values estimated sea level rise in that area to be on average about 0.6 m less than Lambeck et al. (2004b) suggest (Leoni and Dai Pra, 1997; Pirazzoli, 1976 see also Auriemma and Solinas, 2009). This in our view demonstrates the range of uncertainty which is inherent in

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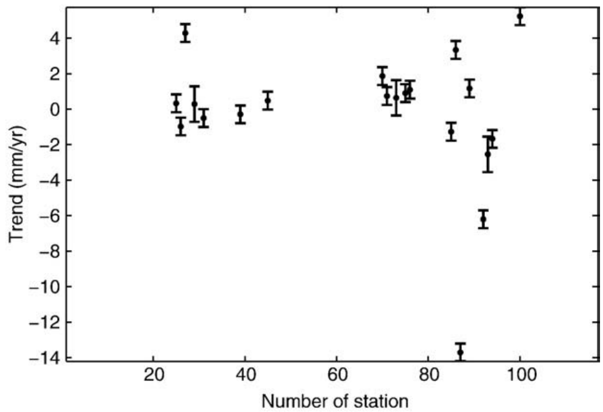

Fig. 5. Linear sea level trends at tide gauge sites corrected for atmospheric, steric and GIA effects as well as land movements. Only those tide gauges where all forcing factors are available are plotted. Greek tide gauges are excluded from the graph.

estimating sea level change from archaeological remains, but also suggests that the value of Lambeck et al. (2004b) is probably an upper limit. Some archaeological data have poor time resolution, because buildings were functioning for many decades, if not centuries. Interpreting a building or technical structure requires a full understanding of how the structure worked, and what risks of damage or down-time they were prepared to accept. If a site has a complex of structures, houses, church foundations, mosaics, tombs, roads, slipways, etc., one can find an optimum palaeo-sea level which seems to fit above and below all the different indicators in a logical way. The differences in the interpretation studies based on archaeological remnants assume stability in the water mass characteristics of the world ocean and particularly on those of the location. However moderate changes of temperature and salinity can lead to changes of 0.6 m. For example, a water column of 3 km with average T of 15 °C and average salinity of 37.8 psu would require either an average increase of 0.85 °C or an increase in salinity of 0.27 psu to show an increase of 0.6 m in sea level. As the Mediterranean has distinct water mass characteristics significantly different from the nearby Atlantic such changes cannot be ruled out. Thus although it must be made clear that there is no proof for such changes over the 2000 years the range of variability suggested is not excessive.

Antonioli et al. (2007) on the basis of tidal notch data and archaeological sites have found in Sardinia that local vertical earth movement factors are stable (in their terminology the area is "tectonically stable"). In addition, they have found that sea level changes in Sardinia are consistent with the isostatic model of Lambeck et al. (2006). In particular, they find an increase of sea level by up to 2.0 ± 0.23 m in Sardinia and up to 2.1 ± 0.6 m in the North Adriatic over the past 2 k years. In the Adriatic a tectonic signal of 0.75 mm/yr over the past 2 k is claimed. The agreement with the isostatic model would then suggest that the role of steric changes is much reduced. However it has to be recognized that the fact that the model fits with the data cannot exclude contributions of steric nature. In addition we note that intense spatial variability around the big deltas, lagoons, and active seismic/tectonics of the east coast of the Adriatic suggest that it is the particular selection of sites that leads to one number for the Adriatic.

If Lambeck et al. (2004b) are correct then there is no discrepancy between the trends from land movements and the tide gauge records. The overall sea level change consists of a relatively quiet period of eustatic change lasting for around 1.8 k years and ending about 200 years ago. It is then arguable that for what they call "tectonically stable" areas there is no need to apply land movement corrections other than those caused by the GIA. In such a case the spread in the values in the figure above is due to observational errors or local steric or other effects not well resolved by the presently available observations. As it has been discussed above the fact that a number of factors cancel each other out over 2000 years cannot lead to a conclusion that they have been cancelling each other out over shorter or longer periods.

On the alternative, if we consider the long term trends in Table 1 as representative of land movements lasting over several centuries and covering also the last century then we can correct them by these long term values. This has been done in Fig. 5 where the corrected trends are very close to zero apart from the Greek stations in the Eastern Mediterranean. Excluding the Greek stations the mean value for the observed values corrected for atmospheric and steric effects is −0.21 mm/yr. When the GIA corrections are included then this reduces to −0.34 mm/yr. However when the land movements are also included the mean value becomes 0.41 mm/yr. Within the uncertainties stated in Table 4 this indicates that the various components of sea level change calculated from various time scales and methodologies are consistent with each other. Thus, putting it in a negative way, we cannot distinguish between the Lambeck et al. (2004b) suggestion and a suggestion that uniform land movements have been taking place over the last 2000 years by the present analysis due to the errors involved in the estimates of the various components.

Flemming and Woodworth (1988) compared sea level trends from tide gauges in Greece calculated for the period 1969–1983 with archaeological data from nearby sites. They estimated relative trends by reference to Katakolon (station 89 in Fig. 1). Subtracting the values of a reference station in essence removes the common variability in the region over the period covered. Thus atmospheric and oceanic contributions as well as GIA effects, which have larger spatial scales, are to a large extent removed. This can also be confirmed by looking at the close resemblance the atmospheric, steric and GIA trends have for the stations shown in Table 5. The relevant data used by Flemming and Woodworth (1988) are shown in Table 5 too, where we have added some further information and updated trends for the tide gauges used.

Flemming and Woodworth offset the trends by assuming a subsidence values for Katakolon of −3.5 mm/yr as this maximised the correlation between the tide gauge based relative trends and the archaeological values of land movements. In Fig. 6 the data from Flemming and Woodworth (1988) (Fig. 7 in that paper) paper together with the updated trends from the tide gauges have been re-plotted.

Table 5
Relative trends from Flemming and Woodworth (1988) and associated archaeological trends from the same paper. Updated trends come from Table 1.

	Relative trend Flemming and Woodworth (mm/yr)	Updated trend (mm/yr)	Updated relative trend (mm/yr)	Closest archaeological site	Archaeological trend (mm/yr)
Posidhonia	−3.4	−11.8	−13.6	Lechaeum	−0.35
Kalamai	5.7	4.6	2.8	Akovitika	−0.71
Piraievs	−0.4	−6.9	−8.7	Phaleron	−0.5
Halkis N.	−2.4	−1.5	−3.3	Anthedon	−0.13
Khios	4.2	4.4	−2.6	Cesme	−2.0
Rhodos	−5.9	0.1	−1.7	Rhodos	0.35
Soudha	−5.5	−0.9	−2.7	Marathi	0.68
Katakolo	0.0	1.8	0	Katakolon-Pheia	−0.5

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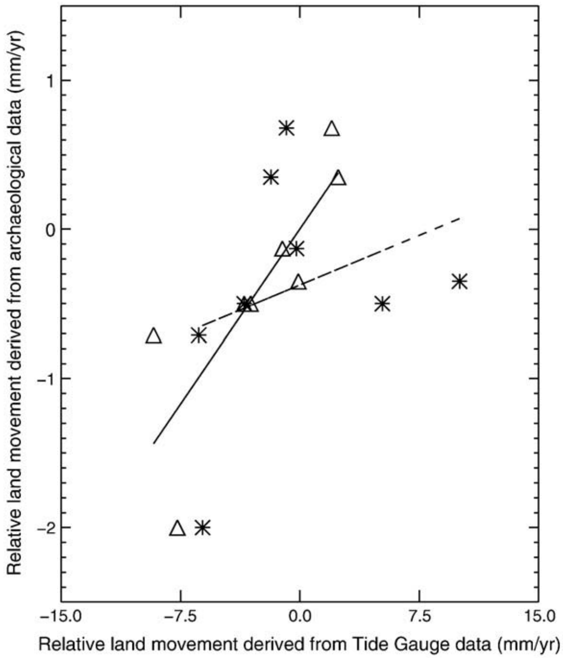

Fig. 6. Sea level trends from tide gauges relative to Katakolon and corrected by a 3.5-mm/yr subsidence value for the reference station as in Flemming and Woodworth (1988) shown as triangles. The linear trend corresponding to these data is shown as the continuous line. The correlation is 0.84. The stars show the same values for updated trends on the basis of Table 1. The linear trend is shown with the dashed line and the correlation is 0.2, that is the correlation is insignificant.

The correlation found by Flemming and Woodworth (1988) is not identifiable in the updated figures. This could be due to the mixed quality of the Greek tide gauge data commented upon by Marcos and Tsimplis (2008). Thus we conclude that the vertical movements recorded by the tide gauges do not correlate well with the trends observed from archaeological data.

Vött (2007) has produced sea level change curves for seven coastal areas at the north-western part of Greece. The range of relative sea level changes identified varies between 3.5 and 13 m over the past 8 k years. He assumes linear changes between the last measurement obtained and the present, so Vott's study cannot confirm or reject the suggestion by Lambeck et al. (2004b). However, a number of points can be made. First, the rate of sea level rise in the coastal plain called Elis is in the range 0.5 to 0.7 mm/yr over the last 2.2 k years, a rate lower than that suggested by Flemming and Woodworth (1988) for Katakolon which is in the covered area. Also the relative sea level changes by reference to one of the areas indicate for more areas smaller sea level changes over the past 2000 years which in the range of $\pm$0.8 m, in general indicating an error bar for sea level rates of change of around 0.4 mm/yr. This value reflects the potential error when using data obtained from one site to compare with a tide gauge located at a different site.

Dorale et al. (2010) suggest that the island of Mallorca has not experienced any sea level rise over the past 2800 years. They consider that the 60 cm of sea level rise predicted by GIA models is in effect erroneous for the location and hint that the nearby line of zero GIA may in fact be more relevant. The most dramatic suggestion is that sea level in this area has not changed significantly over the last 3000 years. This is certainly a contradiction of Lambeck et al. (2004b) as well as the direct estimates of Marcos and Tsimplis (2008) for an average basin sea level rise of about 1.2 mm/yr. Of course, if the trend is only present for 200 years, as suggested by Lambeck et al. (2004b), will only cause around 24 cm of sea level rise probably within the error bars of Dorale et al. (2010). In such a case there is no conflict with our results apart from the point that we consider the GIA corrections reliable. If Dorale et al. (2010) are correct and the Mediterranean sea level has remained unaltered over the past 2800 years then errors as large as 60 cm may be relevant to the interpretation of archaeological data. Due to the short periods of observations such errors do not significantly affect the sea level estimates near the tide gauges. However the conclusions of Dorale et al. (2010) are probably more relevant to sea level at Mallorca and not the whole of the Mediterranean.

In conclusion, it is fair to say that the rates of sea level change by tide gauge observations and through archaeological data differ and are not correlated in the areas studied.

This holds also for areas where previously it was suggested that such a relationship may exist (Flemming and Woodworth, 1988).

The causes of this lack of correlation are the multiple local and regional processes which perturb the rates of earth movements on different time and space scales. In fact we conclude that one should not expect such a correlation not even with respect to the direction of change of sea level change when comparing indicators of different types or at different timescales and lateral space scales.

8. Conclusions

The errors in sea level trend estimates from tide gauges depend primarily on the length of the record. However, extracting from these trends the contribution of the various contributing processes whether decadal and interdecadal atmospheric and steric changes or the much longer land movements, involves uncertainty, which in the Mediterranean Sea is of the same order of magnitude as the observed sea level trend.

Thus, accuracy of knowledge of the various contributing factors to the tide gauge based estimates of sea level rise is in general larger than either the GIA estimates or the estimates from geomorphological and archaeological data. This necessarily means that identifying the causation of present sea level rise and resolving any residual vertical land movements remains an uncertain process.

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