INTERANNUAL SEA LEVEL VARIABILITY IN THE MEDITERRANEAN SEA AND ITS RELATION TO LOCAL METEOROLOGICAL FACTORS

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Abstract

The response of the sea level in the Mediterranean to local meteorological forcing for time scales larger than the seasonal is examined. Multiple regression has indicated that the average sea level response to local air pressure is ~-0.8 cm/mb (15% of variability), and decreases toward the Eastern Mediterranean with no significant frequency dependence. The response to local wind stress is responsible for no more than 2% of the sea level variance and for most stations maximum response is in a cross shore direction. The annual cycle has amplitude ~5 cm (25% of variance) and peaks in October. According to these findings, almost 60% of variance cannot be explained by local meteorology.

Key-words: air-sea interactions, wind, time series

Introduction

The interpretation of sea level changes and variability is a complex task involving consideration of many factors. Sea level records comprise both mean sea level variability and adjacent land vertical movements. The former is a superposition of many different forcing factors operating at different time scales. For scales larger than the annual, the interpretation becomes rather difficult since the forcing is not always direct but a result of numerous positive and negative feedbacks between the atmosphere and the ocean. This variability (interannual and interdecadal) can be significant in certain parts of the world ocean hiding secular sea level changes. Due to the almost closed nature of the Mediterranean basin, climatic changes are expected to leave stronger footprints on the sea level records. Previous work in the Aegean, Ionian and Adriatic Seas [1, 2, 3] have shown that in fact this is the case in Eastern Mediterranean where sea level changes at interannual time scales can easily exceed 15 cm. In this work, we examine the effect of local meteorological factors on sea level variability, for scales ranging from seasonal to interannual and for the entire Mediterranean. Where possible, the interpretation is both qualitative and quantitative.

Data and methods

For sea level data, the PSMSL database for the Mediterranean was employed. In addition, for the Aegean and Ionian Seas, the PSMSL time series were updated with recent data obtained from the Hellenic Navy Hydrographic Service. Only the Revised Local Reference (RLR) records were analyzed since these time series have the monthly means reduced to a common datum making use of the tide gauge benchmark datum history and thus are suitable for time series analysis. A total of 76 RLR time series were analyzed, some of them going back to 1880 and some as recent as 1991. Unfortunately, with the exception of the Port Said record, the series came from the northern coasts of the Mediterranean Sea and only for comparison purposes some metric series from Israel and Africa were also examined. Records from the Black Sea and from the adjacent Atlantic Ocean were also incorporated in the analysis in order to address the spatial extend of the observed variability.

For atmospheric parameters, the COADS global marine database was employed. This database has been collected primarily from ships of opportunity and has an overlap with the temporal range of the sea level records. The data are summarized for each month of each year of the analysis period, in 2°x2° in latitude and longitude boxes. The following parameters which are included in this database were used: Sea level pressure (P), eastward and northward components of wind (u,v), scalar wind (w), eastward and northward components of wind stress (<uw>, <vw>,brackets denote monthly mean). Prior to processing, the time series were checked for spurious spikes. For multiple regression analysis, common overlap blocks between sea level and meteorological forcing were composed. For other analyses where filtering was needed in order to remove the seasonal cycle, gaps were filled prior to filtering based on seasonal means and then a 23 point low-pass triangular filter was applied. For the COADS data set one further step had to be taken. Kaufeld [4] has shown that the algorithm used to convert Beaufort scale to wind speed underestimates wind strength by a factor of about 1.4 depending on the wind speed. This introduces an artificial trend in the data because after 1960 anemometers started coming into use. Parameters having wind as an integral component were corrected in a way similar to Garrett *et al.* [5]. All the examined stations, their locations and the number of overlap PSMSL-COADS monthly data are tabulated in Table 1.

The response to local atmospheric forcing was studied by means of multiple regression in the time domain, using a model similar to that described by Thompson [6]. More specifically, the model used is:

$$h(t) = a_1P(t) + a_x\tau_x(t) + a_y\tau_y(t) + a_{12}\cos(\omega_{12}t+\theta_{12}) + a_6\cos(\omega_6 t + \theta_6)$$

where t denotes time (monthly values), h sea level, P air pressure, τ_x eastward wind stress component, and τ_y northward wind stress component. The frequency ω_{12} is that of the annual cycle and ω_6 of the semi-annual. The coefficients a and θ are to be determined by the regression analysis. The sine and cosine terms have been introduced in order to account for seasonal variability other than that present in the pressure and wind stress time series (*i.e.* steric). It should be noted here, that if the assumption of a sinusoidal response of the sea level to the wind stress is assumed, then the coefficients a_x and a_y can be replaced by $a_w=(a_x^2+a_y^2)^{1/2}$, and $\theta_w=\tan^{-1}(a_y/a_x)$. Then a_w represents amplitude of the response, and θ_w the direction of maximum response.

Results

The regression results are tabulated in Table 2 and can be summarized as follows: The response a_p of sea level to air pressure was found to be responsible for about 13% of the variance. For most of the stations was not exactly isostatic, *i.e.* -1.0 cm per mbar. It ranges from 0.0 to -1.8 cm/mb with a mean of -0.8 and a standard deviation of 0.4. Although the distribution of the response parameters is normal, there exists a correlation with longitude significant at $p<.05$. As we move eastward, a_p becomes for most of the stations smaller (less negative). Moreover no correlation was found between latitude and a_p and number of data points of each time series.

The local wind stress was responsible for about 2.5% of the total sea-level variance. Most of stations had a cross-shore maximum response to sea-level. As was the case with pressure, also the response to wind stress was significantly correlated to the longitude, and has a tendency to become weaker towards Eastern Mediterranean.

For the time series that were long enough, multiple regression was also performed in the frequency domain. However we found no significant variation of the response to pressure and wind as a function of the forcing frequency. Also it should be noted that the small amount of variance accounted for by the inverse barometer effect is not unique to the Mediterranean. Similar results have been reported for stations on the west coast of North America [7]. For the seasonal cycle, the average amplitude of the annual signal was about 5 cm and had a phase of ~295 degrees, which corresponds to maximum amplitude during late October. The amplitude exhibited substantial spatial variability resulting mainly from the long term circulation patterns; similar behavior has been observed from TOPEX/POSEIDON altimetry [8]. The semi-annual component of the seasonal cycle had an average amplitude of 2 cm and phase of ~250 degrees (early September). The variance explained by the seasonal cycle was almost 16% of the total (14% annual, 2% semi-annual). The a_{12} amplitude was correlated with longitude, while a_6 was correlated with latitude. In addition, the semi-annual phase was anti-correlated with longitude and correlated with latitude.

Although the variability of the sea-level records increases towards the eastern Mediterranean, the explained variance is higher in West Mediterranean, indicating that the former is more vulnerable to variability originating from other factors such as interannual steric fluctuations and possible vertical land movements (*e.g.* [9]). Concluding, only 31% of the variance was explained by the multiple regression procedure, and 69% of the total variance, most of it at interannual time scales.

Finally, linear trends were calculated for the longer SL records prior and after regression (on residual time series). For these records there exist enough meteorological data in order to avoid aliasing. No significant changes were noted, indicating lack of linear trends present in the meteorological forcing data.

Conclusions

In brief, from this study the following can be concluded: The average sea level response to local air pressure is ~-0.8 cm/mb (15% of variability), and decreases toward the Eastern Mediterranean. There is no significant frequency dependence. The response to local wind stress is responsible for no more than 2% of the sea level variance. For most stations maximum response is in a cross shore direction. The annual cycle has amplitude ~5 cm (25% of variance) and peaks in October. According to these findings, almost 60% of variance cannot be explained by local meteorology. Linear trends were not significantly modified by the exclusion of local meteorology. Most of the interannual variability in atmospheric and oceanic parameters is in phase in both subbasins.

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Table 1 : Larger sea level records analyzed, their location, overlap number of PSMSL and COADS data.

STATION	LONG	LAT	OVRL MONTHS
SANTANDER I	-3.80	43.47	236
LA CORUNA I	-8.40	43.47	505
LA CORUNA II	-8.40	43.47	311
VIGO	-8.73	43.47	461
LEIXOES	-8.70	41.18	359
AVEIRO	-8.75	40.65	137
CASCAIS	-9.42	38.68	844
LISBON	-9.19	38.70	164
SETROIA	-8.90	38.50	120
SINES	-8.88	37.95	107
LAGOS	-8.67	37.10	800
GIBRALTAR	-5.35	36.12	272
TARIFA	-5.60	36.00	189
MALAGA	-4.42	36.72	180
CARTAGENA	-0.97	37.60	111
ALICANTE I	-0.48	38.33	302
ALICANTE II	-0.48	38.33	328
MARSEILLE	5.35	43.30	847
NICE	7.27	43.70	154
MONACO	7.42	43.73	111
LA MADDALENA	9.37	41.23	112
CAGLIARI	9.17	39.20	201
PORTO MAURIZIO	8.02	43.87	175
GENOVA	8.90	44.40	557
CIVITAVECHIA	11.82	42.05	168
NAPOLI ARSEN	14.27	40.87	151
NAPOLI MANDR	14.27	40.87	157
PALERMO	13.33	38.13	112
CAPO PESSERO	15.30	36.67	139
CATANIA	15.13	37.50	144
TRIESTE	13.75	45.65	427
ROVINJ	13.63	45.08	310
BAKAR	14.53	45.30	320
SPLIT MARJANA	16.77	43.50	355
SPLIT HARBOUR	16.87	43.50	365
DUBROVNIC	18.07	42.67	354
KOPPER	13.73	45.55	267
BAR	19.08	42.08	307
PREVEZA	20.77	38.95	163
LEFKAS	20.70	38.83	189
POSIDONIA	22.95	37.95	145
PATRA	21.73	38.23	189
KATAKOLON	21.32	37.63	237
KALAMATA	22.13	37.02	208
PIRAEUS	23.62	37.93	196
XALKIS N	23.60	38.47	103
KAVALA	24.42	40.92	106
ALEXANDROUPOLIS	25.88	40.85	111
CHIOS	26.15	38.38	165
LEROS	26.88	37.08	176
SOUDA	24.05	35.50	235
IRAKLION	25.13	35.33	186
RHODES	28.23	36.43	172
SIROS	24.92	37.43	217
PORT SAID	32.30	31.25	227
TUAPSE	39.07	44.10	119
CEUTA	-5.32	39.50	230

Table 2 : Results of multiple regression in the time domain. Parameters displayed are: response to SLP, response to wind stress (amplitude and angle), annual and semiannual cycles, std. deviation before and after regression, variance explained

RLR STATION	a_1	a_w	θ_w	a_{12}	θ_{12}	a_6	θ_6	σi	σf	s_x
cm/mb	cm/(m/s)	(°)	cm	(°)	cm	(°)	cm	cm	%	
SANTANDER I	-0.54	.010	159	4.5	134	1.5	104	7.5	5.8	39
LA CORUNA I	-1.05	.043	85	3.4	136	1.3	116	10.8	9.0	31
LA CORUNA II	-1.24	.050	95	3.4	139	1.1	127	7.5	3.3	81
VIGO	-1.17	.057	111	3.5	159	1.6	128	9.1	6.5	50
LEIXOES	-1.14	.070	94	2.3	123	1.2	118	9.4	7.4	39
AVEIRO	-1.34	.059	83	4.2	160	1.5	146	8.3	4.2	75
CASCAIS	-0.68	.054	86	3.2	97	1.6	67	7.2	5.8	36
LISBON	-1.08	.056	101	2.7	126	0.6	127	5.7	3.7	57
SETROIA	-1.07	.084	139	2.7	122	0.7	74	6.6	4.6	52
SINES	-1.45	.075	133	4.2	131	1.2	121	5.8	2.2	86
LAGOS	-0.88	.067	118	4.4	94	1.2	90	7.7	6.1	36
GIBRALTAR	-1.16	.085	134	4.7	125	0.9	157	5.9	4.0	53
TARIFA	-0.65	.228	85	3.1	101	1.5	80	11.8	11.2	10
MALAGA	-1.09	.132	120	4.9	107	0.8	148	7.2	5.5	42
CARTAGENA	-1.42	.039	131	6.6	113	1.1	134	6.0	2.6	81
ALICANTE I	-0.90	.036	105	6.6	105	1.5	85	7.3	4.8	58
ALICANTE II	-0.69	.024	145	6.0	99	1.2	96	6.3	3.9	63
MARSEILLE	-0.77	.029	96	4.9	139	2.1	99	7.8	6.3	35
NICE	-0.99	.062	111	5.1	104	1.8	115	6.9	4.9	48
MONACO	-1.11	.080	123	4.3	130	1.9	137	6.3	4.5	48
LA MADDALENA	-0.28	.053	60	5.6	83	1.0	53	6.5	4.4	55
CAGLIARI	-0.46	.041	70	7.0	81	2.0	90	7.1	4.4	63
PORTO MAURIZIO	-0.44	.062	82	4.1	114	1.8	118	5.7	4.3	44
GENOVA	-0.50	.011	66	4.2	110	1.5	107	6.7	5.4	34
CIVITAVECHIA	-0.54	.037	98	3.5	130	2.3	94	5.8	4.2	46
NAPOLI ARSEN	-0.48	.035	161	3.6	130	2.0	92	5.5	4.5	34
NAPOLI MANDR	-0.57	.037	172	3.9	127	2.5	101	5.7	4.4	42
PALERMO	-0.17	.023	30	3.5	118	1.3	92	5.2	4.5	25
CAPO PESSERO	-1.35	.044	70	7.8	121	1.8	125	9.2	6.9	45
CATANIA	-1.29	.059	76	5.5	119	0.9	172	6.6	4.5	55
TRIESTE	-0.65	.023	32	4.3	121	3.2	117	8.2	6.6	36
ROVINJ	-0.78	.016	143	5.2	126	2.7	108	7.9	5.9	45
BAKAR	-0.66	.017	16	4.2	151	2.7	109	8.4	6.9	32
SPLIT MARJANA	-0.71	.023	49	4.1	151	2.4	113	7.1	5.5	40
SPLIT HARBOUR	-0.75	.026	54	4.6	152	2.5	110	7.3	5.5	43
VIS-CESKA	-0.77	.042	11	4.4	136	2.6	123	6.5	4.6	50
SUCURAJ	-1.00	.032	154	4.1	135	2.3	97	6.8	3.6	72
UBLI	-1.06	.059	22	4.6	133	1.3	105	7.1	3.9	69
DUBROVNIC	-0.76	.018	50	4.8	148	2.3	108	7.0	5.2	44
KOPPER -	0.90	.020	147	4.4	120	2.5	108	8.1	6.1	43
BAR	-0.99	.041	59	5.5	149	2.5	99	7.2	5.2	47
PREVEZA	-0.73	.033	80	3.3	142	1.5	24	5.7	4.9	24
LEFKAS	-0.68	.052	42	6.3	162	1.9	91	8.8	7.6	26
POSIDONIA	-1.12	.025	80	4.0	118	0.4	46	6.0	4.9	33
PATRA	-0.21	.054	144	3.8	140	0.2	82	15.9	15.4	7
KATAKOLON	-1.12	.029	70	6.9	141	0.8	18	6.6	5.0	44
KALAMATA	-0.71	.021	45	6.5	120	1.2	48	7.4	6.0	36
PIRAEUS	-1.51	.020	18	7.1	118	1.0	18	7.0	4.4	61
XALKIS N	-0.16	.026	77	3.6	155	1.6	25	64.0	5.8	17
KAVALA	-0.27	.044	30	4.4	123	1.7	180	12.1	11.4	11
ALEXANDROUPOLIS	-0.48	.013	105	1.0	85	1.6	175	6.5	5.8	21
CHIOS	-0.51	.022	146	3.0	139	1.9	4	6.6	5.9	19
LEROS	-0.73	.033	80	3.3	142	1.5	24	5.7	5.0	24
SOUDA	-1.10	.052	32	6.2	110	1.2	68	7.4	5.5	44
IRAKLION	-0.93	.018	31	6.1	111	0.4	161	9.5	8.4	22
RHODES	-0.27	.014	148	1.8	82	1.0	52	6.2	5.7	12
SIROS	-1.76	.017	90	6.3	113	0.8	32	8.3	5.9	49
PORT SAID	-0.36	.083	64	8.9	85	0.9	27	8.9	6.0	54
TUAPSE	-0.01	.022	113	7.9	143	2.6	18	9.8	7.4	43
CEUTA	-0.77	.066	87	3.9	119	1.4	87	5.6	44.0	38