MODELING THE RESPONSE OF THE MEDITERRANEAN SEA LEVEL TO GLOBAL AND REGIONAL CLIMATIC PHENOMENA

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SUMMARY

Fluctuations of the sea level pose an issue of emerging importance, especially after scientific research revealed a clear rising trend. Since the early 80's, a new technique, satellite altimetry, resulted in an abundance of sea surface height measurements and these data are crucial to both oceanographic and geodetic applications. This work presents the results of a correlation study of the Sea Level Anomaly (SLA) with global and regional climatic phenomena that influence the ocean state as well. For this reason, three correlation indexes have been examined. The first one is the well-known Southern Oscillation Index (SOI) corresponding to the ocean response to El Niño/La Niña-Southern Oscillation (ENSO) events. The next index is the North Atlantic Oscillation (NAO) index, which corresponds to the fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high. The last index is the Mediterranean Oscillation Index (MOI), which refers to the fluctuations in the difference of atmospheric pressure at sea level between Algiers and Cairo. The raw data used were SLA values from Jason-1 and Jason-2 satellite altimetry missions for a period of thirteen years (2002-2014) within the entire Mediterranean Basin. Regional multiple regression

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and correlation analyses between sea level anomalies and these indexes were carried out in order to detect and model correlations between the Mediterranean sea level and the aforementioned global and regional climatic phenomena.

Key words: Sea level, altimetry, regression analysis, PCA, Mediterranean Sea.

1. INTRODUCTION

The study of sea level rise and sea level variations is a topic of major importance for geodetic, oceanographic, environmental and other applications. In these applications, the modeling of the steric and non-steric part of the variations is a critical task as these variations are influenced by many factors. For example, some of the factors that affect the temporal and long-term variations of the sea level, are changes in sea temperature, salinity, total water volume and mass (EPA, 2011).
Satellite altimetry has changed the traditional measurement of sea level with tide-gauge stations located in coastal areas around the globe and resulted in the availability of sea surface height measurements with global coverage, homogeneous accuracy and resolution (Chelton et al., 2001; Garcia et al., 2007; Vergos et al., 2012). Since the early 80's repeated satellite altimetry data span nowadays over a period of about 35 years and the record of observations for the sea level offer new opportunities for the estimation of sea level variations and its proper modeling with global and regional climatic phenomena. A crucial point in studying the variations of the sea surface is the correlation of Sea Level Anomaly (SLA) with global and regional climatic phenomena that influence the ocean state as well, usually represented in oscillation indexes. This is also the main objective of this study.
Three oscillation indexes were selected to be examined. The first one is the well-known Southern Oscillation Index (SOI) corresponding to the ocean response to El Niño/La Niña-Southern Oscillation (ENSO) events (http://www.bom.gov.au). The next index investigated is the North Atlantic Oscillation (NAO) index, which corresponds to the fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high (Perry, 2000). The last index investigated is the Mediterranean Oscillation Index (MOI), which refers to the fluctuations in the difference of atmospheric pressure at sea level between Algiers and Cairo (Corte-Real et al., 1998). These three indexes were used in regression and correlation analyses along with satellite altimetry derived SLA data. The raw SLA data were obtained from Jason-1 and Jason-2 satellite altimetry

missions for a period of thirteen years (2002-2014) within the entire Mediterranean Basin.

2. AREA UNDER STUDY, AVAILABLE DATA AND PRE-PROCESSING

The area under study spans the entire Mediterranean Sea bounded between $30^o \leq \varphi \leq 50^o$ and $-10^o \leq \lambda \leq 40^o$. The data employed in the present work are those of the Jason-1 and Jason-2 satellite missions. For Jason-1, data during the period from 15/1/2002 (cycle 1) to 07/12/2008 (cycle 255) have been used resulting in a total number of 670703 observations while for Jason-2, data from 4/7/2008 (cycle 0) to 31/12/2014 (cycle 239), have been used with a total number of 882197 observations (see Figure 1 for the Jason ground track pattern over the area under study). Each Jason cycle consists of 254 passes with almost 20% of those having available observations in the Mediterranean Sea within the satellite's period of ~10 days. The mesh of values is not as dense as those from other satellites (e.g., ENVISAT and CRYOSAT2) and its cross track spacing at the equator is approximately 300 km. The data used have been downloaded from the Radar Altimeter Database System (RADS) operated by the Delft Institute for Earth-Oriented Space research (DEOS) (RADS 2015). RADS presents a collection of almost all past and current satellite altimetry and is DEOS' effort in establishing a harmonized, validated and cross-calibrated sea level data base from satellite altimeter data.

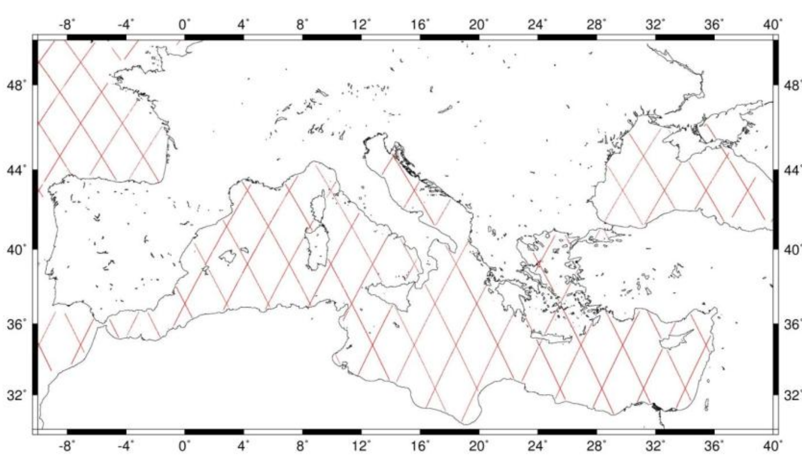

Figure 1: Jason data distribution over the Mediterranean Sea

The altimetric data are available in the form of SLAs referenced to a "mean-sea-surface" that depends on user selection within the RADS system. Therefore, it was decided to refer the data to the EGM2008 geoid (Pavlis et al., 2012). It should be noted that a zero-tide (ZT) geoid model was adopted in order to be in-line with the tide-conventions used in altimetric data processing. As far as the selection of the geophysical corrections and models used, those were a) ECMWF for the dry tropospheric correction, b) MWR(NN) for the wet tropospheric correction, c) the smoothed dual-frequency model for the ionospheric correction, d) tidal effects due to Solid Earth, Ocean, Load and Pole from the Solid Earth tide, GOT ocean tide and GOT load tide (the latest models for each satellite) and pole tide models respectively, and e) the CLS Sea State Bias (SSB) model for the SSB effect (Naeije et al., 2008) and the references herein should be advised for more details on the models used. All geophysical corrections mentioned previously have been applied to the Jason-1 and the Jason-2 raw observations, in order to construct corrected geophysical data records, i.e., corrected SLAs referenced to the EGM2008 ZT geoid (AVISO, 2015, and 2016).

Table 1: Statistics of JASON data Unit: [m].

	nr. values	**min**	**max**	**mean**	**std**
Jason-1	670073	-1.817	0.880	0.009	±0.150
Jason-2	882197	-0.783	1.169	0.041	±0.153

Tables 1 summarizes the statistics of the JASON 1/2 SLAs values for both satellites where the maximum and minimum values shown are clearly due to blunders in the available SLA data. These blunders are all located close to the coastline. Both datasets have small mean values and an agreement in the standard deviation is noticed

3. OSCILATION INDEXES

In order to investigate any possible correlation between SLA and global or regional climatic phenomena that influence the ocean state three indexes have been examined. SOI corresponds to the ocean response to El Niño/La Niña-Southern Oscillation (ENSO) events and gives an indication of the development and intensity of El Niño or La Niña events in the Pacific Ocean. It is calculated using the pressure differences between Tahiti and Darwin. Negative values of the SOI often indicate El Niño episodes, i.e., warmer waters in the eastern Tropics, while positive values of the SOI are typical of a La Niña episode, i.e., cooler waters in the eastern Tropics (Allan et al., 1991; Können, 1998; Ropelewski et al., 1987). The next index investigated is NAO. It controls winter climate variability in the North Atlantic from central North America to Europe. Positive values of NAO result in warm and wet winters in Europe, dry winters in Mediterranean and in cold and dry winters in northern Canada and Greenland, while negative values of the NAO bring moist air into the Mediterranean and cold air to northern Europe (Tsimplis amd Josey, 2001; Osborn, 2006 and 2011; Wakelin et al., 2003; Woolf et al., 2003). The last index investigated is the Mediterranean Oscillation Index (MOI), which refers to the fluctuations in the difference of atmospheric pressure at sea level between Algieres and Cairo. It is an indicator of climate variability in the Mediterranean, since positive values of MOI are related to dry weather throughout the Mediterranean, except from the south-eastern part. On the contrary, negative values of MOI are related to cyclogenesis in west Mediterranean and abnormally wet weather, except from the south-eastern part (Palutikof, 2003; Tsimplis and Shaw, 2006; Supic et al., 2004; Sušelj and Bergant, 2006; Vergos and Natsiopoulos, 2012). For this study all data for oscilation indexes have been accessed from the Climate Research Unit of the University of East Anglia (http://www.cru.uea.ac.uk/). Tables 2-4 below summarizes the values of each index for the period of study.

4. REGRESSION AND CORRELATION ANALYSIS

A regional multiple regression analysis between SLA variance values (*Co*) of Jason-1 and Jason-2 and SOI, MOI and NAO indexes is carried out to model the response of the Mediterranean to these global and regional climatic phenomena. Assuming that the observations are given in discrete points in the area,the computation of the covariance function is carried out by numerical integration (Tcherning and Rapp, 1974). If each observation y_i represent a small area A_i and y_j represents an area A_j then the empirical covariance is given by the following equation:

$$C(\psi) = \frac{\sum A_i A_j y_i y_j}{\sum A_i A_j}, \qquad (1)$$

with $\psi_{k-1} < \psi_{ij} < \psi_k$ where ψ is the spherical distance. If the area is subdivided into small cells holding one observation each and A_i and A_j are assumed to be equal then Eq. (1) reduces to

Table 2: MOI values for period under study

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2003	-0.20	-0.12	0.42	-0.30	0.40	0.35	0.75	0.61	0.32	-0.63	-0.56	-0.15
2004	0.21	-0.25	-0.23	-0.38	-0.12	0.33	0.68	0.39	0.40	-0.45	-0.05	-0.66
2005	0.84	-0.22	-0.32	-0.28	0.00	0.32	0.50	0.65	0.30	-0.12	-0.56	-0.08
2006	-0.26	-0.30	-0.33	-0.22	-0.14	0.19	0.72	0.47	0.08	-0.05	0.09	0.10
2007	0.14	0.14	-0.09	-0.29	0.24	0.27	0.82	0.38	0.31	-0.27	-0.41	0.23
2008	0.33	0.13	-0.19	-0.29	-0.63	0.41	0.65	0.62	0.10	-0.34	-0.58	-0.52
2009	-0.98	-0.36	-0.49	-0.22	0.00	0.27	0.71	0.38	0.13	0.12	-0.18	-0.99
2010	-0.91	-1.18	-0.30	-0.16	-0.08	0.12	0.60	0.68	0.14	-0.51	-1.04	-0.73
2011	-0.18	0.29	-0.60	-0.10	0.07	0.44	0.41	0.48	0.48	0.06	-0.70	0.27
2012	0.54	0.25	0.23	-0.81	0.15	0.36	0.86	0.61	0.12	-0.50	-0.73	0.18
2013	-0.18	-0.59	-1.18	-0.50	-0.06	0.57	0.73	0.60	0.21	-0.20	-0.11	0.31
2014	-0.79	-0.45	0.02	-0.27	-0.05	0.13	0.30	0.39	-0.07	-0.12	-1.26	0.07

Table 3: SOI values for period under study

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2003	-0.30	-0.90	-0.91	-0.48	-0.85	-1.75	0.26	-0.35	-0.18	-0.26	-0.32	0.92
2004	-1.31	0.77	-0.11	-1.91	1.22	-1.91	-0.72	-0.90	-0.31	-0.42	-1.05	-0.94
2005	0.20	-2.99	-0.26	-1.22	-1.46	0.11	0.06	-0.97	0.34	1.12	-0.42	0.01
2006	1.29	-0.26	1.93	1.17	-0.96	-0.98	-0.90	-1.75	-0.60	-1.52	0.05	-0.39
2007	-0.83	-0.38	-0.30	-0.35	-0.30	0.14	-0.44	0.01	0.12	0.44	0.82	1.49
2008	1.54	2.05	1.04	0.56	-0.25	0.34	0.20	0.64	1.26	1.52	1.64	1.43
2009	0.85	1.37	-0.21	1.06	-0.86	-0.45	0.18	-0.59	0.35	-1.66	-0.67	-0.95
2010	-1.13	-1.59	-1.40	1.88	0.85	0.24	1.95	1.77	2.44	1.80	1.62	2.90
2011	2.01	2.12	2.09	3.02	0.46	-0.04	1.11	0.07	0.96	0.91	1.41	2.45
2012	0.90	0.22	0.20	-0.65	-0.38	-1.51	-0.15	-0.74	0.22	0.17	0.33	-0.77
2013	-0.10	-0.47	1.06	0.01	0.90	1.45	0.76	-0.23	0.41	-0.34	0.75	-0.05
2014	1.24	-0.28	-1.64	0.98	0.69	-0.37	-0.26	-1.42	-0.78	-0.92	-1.08	-0.72

Table 4: NAO values for period under study

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2003	0.15	1.34	1.08	-1.74	1.17	-0.86	0.09	-0.99	0.35	-3.68	0.31	-0.85
2004	0.2	-1.23	1.07	1.08	-0.67	-0.38	-0.3	-0.76	2.51	-2.18	-0.55	1.27
2005	1.82	-2.25	-1.29	0.71	-0.13	-1	-0.08	0.94	0.5	-0.45	-1.01	-0.81
2006	-0.1	-1.24	-1.12	0.57	-0.22	-0.41	0.83	-2.47	-1.02	-1.97	1.7	3.08
2007	1.77	0.42	2.03	-0.1	0.62	-3.34	-1.05	-3.41	-1.18	-0.02	-1.67	1.42
2008	1.87	1.81	0.37	-2.02	-3.26	-2.05	-1.38	-0.21	-2.07	0.01	-1.3	-0.58
2009	0.61	-1.43	0.15	1.74	1.52	-3.05	-0.92	1.07	-0.63	-2	1.68	-3.72
2010	-2.38	-3.25	-0.8	-1.03	-1.66	-2.4	0.06	-2.01	-2.38	-2.41	-3.34	-4.62
2011	-1.38	2.79	-0.44	2.39	1.08	-1.58	-3.39	-0.18	2.97	1.45	0.74	3.2
2012	2.05	1.28	1.78	-2.36	-0.83	-2.58	-1.31	-0.44	-1.44	-3.21	-1.11	0.6
2013	1.08	-0.26	-3.75	0.03	1.23	1.4	2.52	2.16	-0.57	-0.36	0.04	3.54
2014	0.71	2.32	1.64	0.84	-0.08	-1.98	0.91	1.14	-2.1	0.31	-2.17	1.89

$$C_k = \frac{\sum y_i y_j}{N_k}, \tag{2}$$

where N_k is the number of products $y_i\, y_j$ in the k^{th} interval (Knudsen 1988). From Eq. (2), C_o may be computed by the following formula

$$C_0 = \frac{\sum y_i y_i}{N}. \tag{3}$$

Regarding the oscillation index values, these were normalized using the minimum and maximum values of NAO, in order to obtain values coherent to each other. More specifically, all indexes values were first normalized to [0,1] as follows:

$$x' = \frac{X - X_{min}}{X_{max} - X_{min}}, \tag{4}$$

and then rescaled to [-1,1] by applying the following formula:

$$x' = x' * 2 - 1. \tag{5}$$

The monthly values for C_o and the normalised monthly value of each index were then used in order to estimate the three regression coefficients. The computed values of each coefficient are provided in Table 5. The b_1 coefficient corresponds to MOI, b_2 to SOI and b_3 to NAO.
During all years, MOI should be the most proper measure of climatic forcing contribution to sea level variations in the Mediterranean. The large values of the MOI coefficient (b_1) indicate a strong correlation with the SLA. The SOI coefficient values are smaller than the ones of MOI, while during the years that the ENSO events are strong (2011, 2013) b_2 is larger than b_1. Given that El Niño and La Niña may not be representative for the Mediterranean Sea, due to their distance and the characteristics of the latter as a closed sea area, NAO should be more appropriate to indicate any correlation between atmospheric forcing and SLA variations. The absolute values of the NAO coefficient (b_3) are close to 1 signaling that atmospheric conditions in the North Atlantic are not the dominant contributing factor for the Mediterranean Sea, while the large value of 2010 can be attributed to the small value of SOI. This is in-line with the findings of previous researchers (see, e.g., Tsimplis and Shaw, 2008), and signals that atmospheric forcing is not the contributing factor to the steric sea level variations in the Mediterranean.

Table 5: Regression coefficients for JASON satellites:

Satellite	Year	b_1	b_2	b_3
JASON1	2002	6.198	-3.055	1.128
	2003	6.839	0.365	0.285
	2004	8.564	1.182	1.586
	2005	11.102	-1.335	-1.708
	2006	9.144	2.031	0.298
	2007	5.808	1.844	0.952
	2008	2.882	2.508	-1.371
JASON2	2009	5.234	3.032	0.209
	2010	6.143	0.666	3.407
	2011	2.464	3.362	-0.692
	2012	5.436	2.224	-0.958
	2013	-5.598	7.767	2.347
	2014	6.741	1.622	0.918

A correlation analysis was also carried out to model any seasonal correlation between SLA and these indexes. Four periods with a duration of 3 years each (2002-2004, 2005-2007, 2008-2010, 2011-2013) have been checked. The correlation ($\rho_{X,Y}$) between two variables (X, Y) is estimated by:

$$\rho_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y}, \quad (6)$$

where cov is the covariance function and σ_X, σ_X are the standard deviations of X and Y, respectively. The covariance functions is defined as

$$cov(X, Y) = E[(X - \mu_X)(Y - \mu_Y)], \quad (7)$$

where μ_X is the mean of X and E is the expectation. Then Eq. (6) becomes:

$$\rho_{X,Y} = \frac{E[(X-\mu_X)-(Y-\mu_Y)]}{\sigma_X \sigma_Y}. \quad (8)$$

In this study X is the average of seasons for each year of the period under study, μ_X the average of all seasons and σ_X, σ_X the corresponding standard deviations.

Figure 2 depicts the correlation between seasons and indexes for a period of three years. The results presented in Figure 2 are similar to those found in the regression analysis, i.e., the correlation is similar to the values of the computed regression coefficients (see Table 5). Although a seasonal effect is not obvious, due to the fact that periods of three years are tested, it can be noticed that MOI and NAO are strongly correlated with SLA during the winter months of each year. This is in line with the fact that NAO and MOI are well correlated and follow each other, especially during winter. On the other hand, the seasonal correlation between SOI and SLA depends on the strength of ENSO events and it is presented with a lag of 4-8 months.

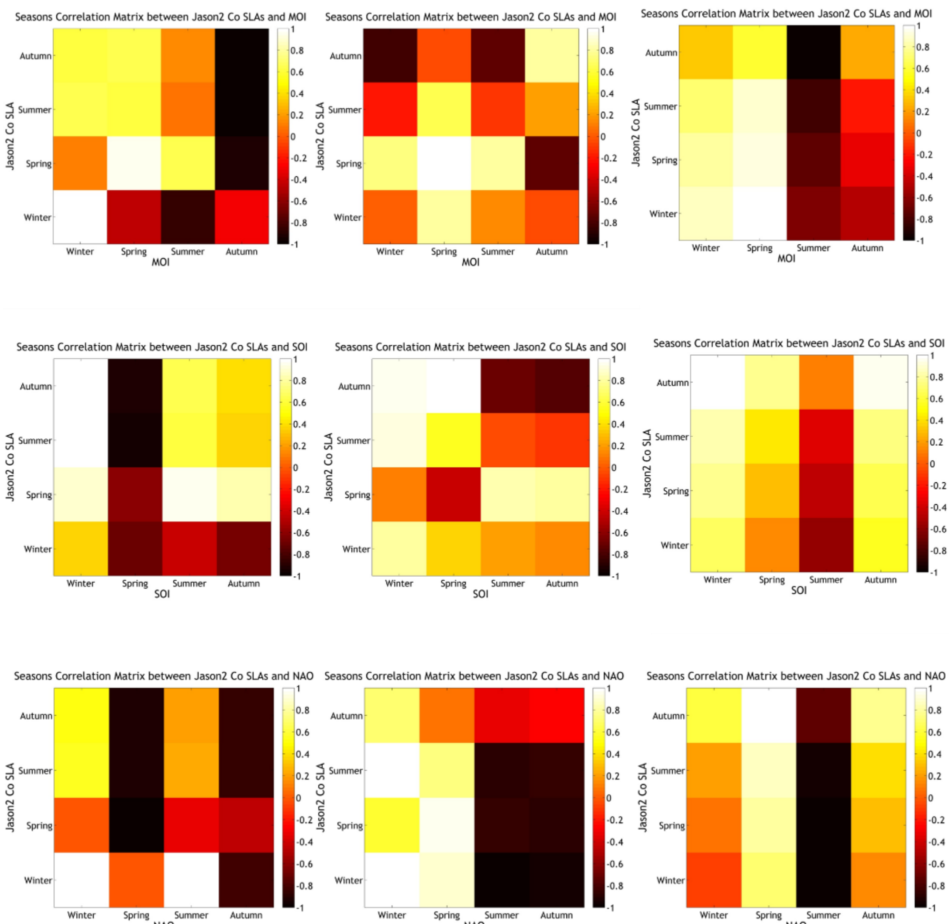

Figure 2: Correlation between Seasons and MOI (top), SOI (center) and NAO (bottom) for periods (2002-2004, 2005-2007, 2011-2013).

CONCLUSIONS

In this paper, an analytical outline of the use of satellite altimetry for modeling the correlation between global and regional climatic phenomena, was presented. Jason-1 and Jason-2 satellite altimetry derived sea level anomalies for a period of thirteen consecutive years (2002-2014) and for the entire Mediterranean basin were used for conducting regional multiple regression and correlation analyses with the SOI, MOI and NAO indexes. These analyses aimed in detecting and modeling correlations between the Mediterranean sea level and global and regional climatic phenomena. From the regional multiple regression analysis, it was concluded that the response of the Mediterranean Sea is more predominant with the MOI. During years with strong ENSO events the regression coefficient for the SOI index has the largest values. From the correlation analysis carried out, it was found that some correlation between ENSO events and SLA variations can be seen while NAO is strongly correlated with MOI and SLA for winter months. The weak response of the SLA in the Mediterranean Sea level during Summer implies that atmospheric forcing is not a contributing factor to the steric sea level variations in the Mediterranean during that period.

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