Contribution of climate forcing to sea level variations in the Mediterranean Sea

D.A Natsiopoulos G.S. Vergos and I.N. Tziavos

Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Univ. Box 440, 54 124, Greece

Introduction and Problems

Fluctuations in the level of the sea pose an issue of emerging importance, since latest scientific research shows a clear trend in the rise of the sea level. A crucial point to studying the variations of the sea surface is the correlations of Sea Level Anomaly (SLA) with global and regional climatic phenomena that influence the ocean state as well.

This work presents correlations of the Sea Level Anomaly (SLA) with global and regional climatic phenomena. The developed covariance functions are used in order to investigate any possible correlations with climate change indices over the Mediterranean Sea.

Three such indexes have been investigated. 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 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. 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.

Data used and corrections

The raw data used are SLA values from ENVISAT satellite for 9 years (2002-2010) and from CRYOSAT2 satellite for a period of six years (2010-2015) within the entire Mediterranean Basin ($30° \leq \phi \leq 50°$ and $-10° \leq \lambda \leq 40°$).

The data have been downloaded from RADS server (DEOS Radar Altimetry Data System) in the form of SLAs relative to EGM2008, after applying all the necessary geophysical and instrumental corrections.

ENVISAT satellite consists of 1003 passes within the satellite's period of 35 days. For each year 10-11 cycles and ~110000 observations per year are available with a cross track spacing of 75 km at the equator. CRYOSAT2 satellite has a 369 day orbit with a cross track spacing of 7.5 km at the equator and ~142000 observations per year within the Mediterranean (Fig.1).

The last step in the analysis of the SLAs is to investigate for any possible correlations with global and regional climatic phenomena that influence the ocean state as well. Three such indexes have been investigated, SOI, MOI and NAO.

For the present study, NAO, SOI and MOI data have been acquired from the Climate Research Unit of the University of East Anglia (http://www.cru.uea.ac.uk/)

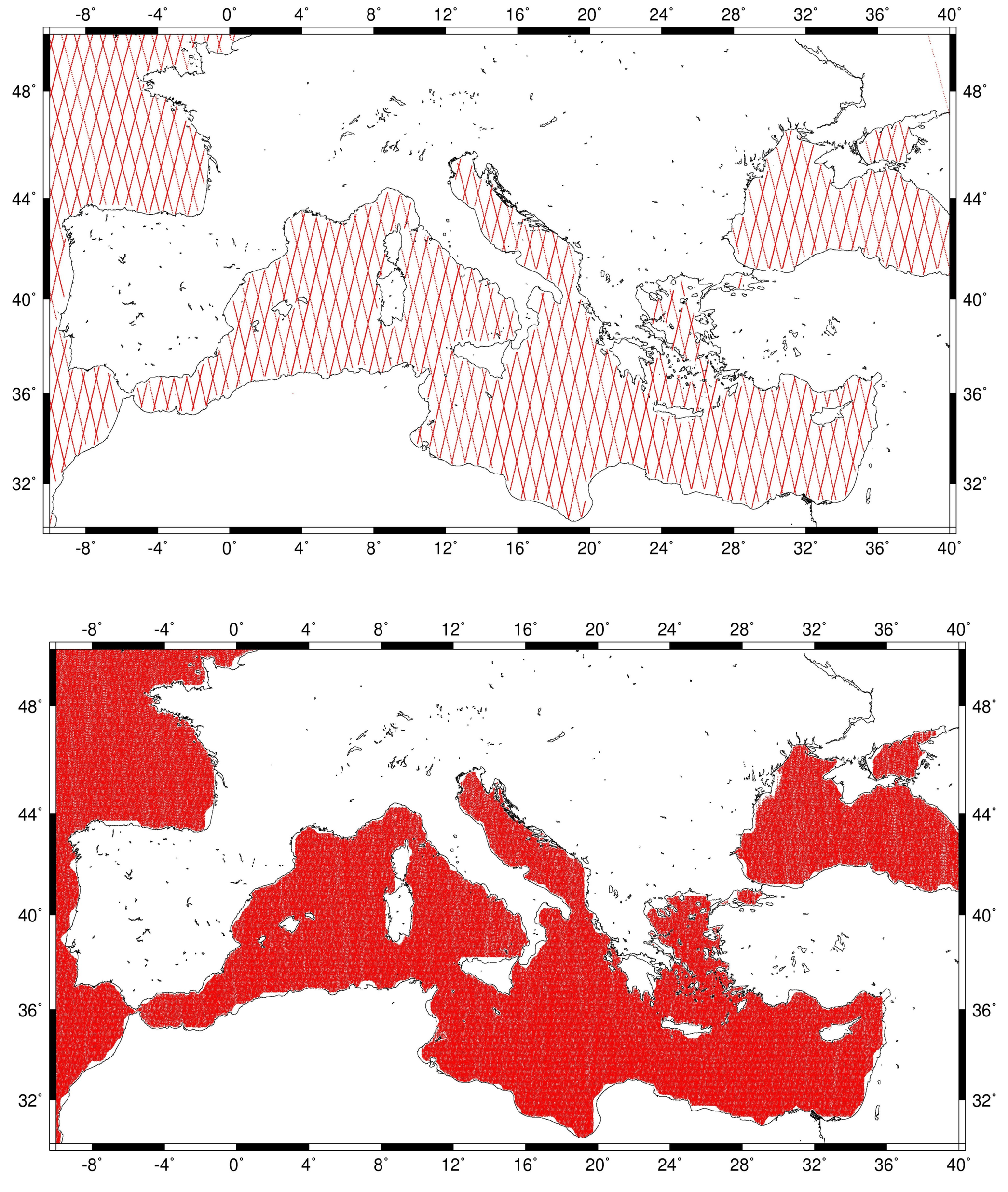

Figure 1: ENVISAT (top) and CRYOSAT2 (bottom) data distribution

SLA Variations in the Mediterranean Sea

Table below summarizes the statistics of the annual ENVISAT & CRYOSAT2 SLAs after the application of all geophysical corrections. The maximum and minimum values shown are clearly due to blunders in the available SLA data and they are located in all cases close to the coastline. Both fields have small mean values and a variation of the order of ~2-3cm can be seen in the std.

Statistics of annual ENVISAT SLAs (m)

Year	min	max	mean	std
2002	-0.519	1.291	0.121	±0.148
2003	-0.769	1.007	0.053	±0.157
2004	-0.766	1.132	0.086	±0.176
2005	-0.939	1.304	0.074	±0.167
2006	-1.381	0.971	0.086	±0.164
2007	-2.723	0.936	0.076	±0.152
2008	-0.709	0.926	0.072	±0.158
2009	-0.681	0.700	0.083	±0.129
2010	-0.529	1.104	0.080	±0.153

Statistics of annual CRYOSAT2

Year	min	max	mean	std
2010	-0.918	0.935	0.117	±0.145
2011	-1.601	1.009	0.044	±0.149
2012	-1.033	0.845	0.047	±0.137
2013	-1.258	1.184	0.071	±0.149
2014	-1.126	1.622	0.066	±0.145
2015	-0.985	1.054	0.061	±0.153

Table1: ENVISAT (top) and CRYOSAT2 (bottom) SLA statistics (m).

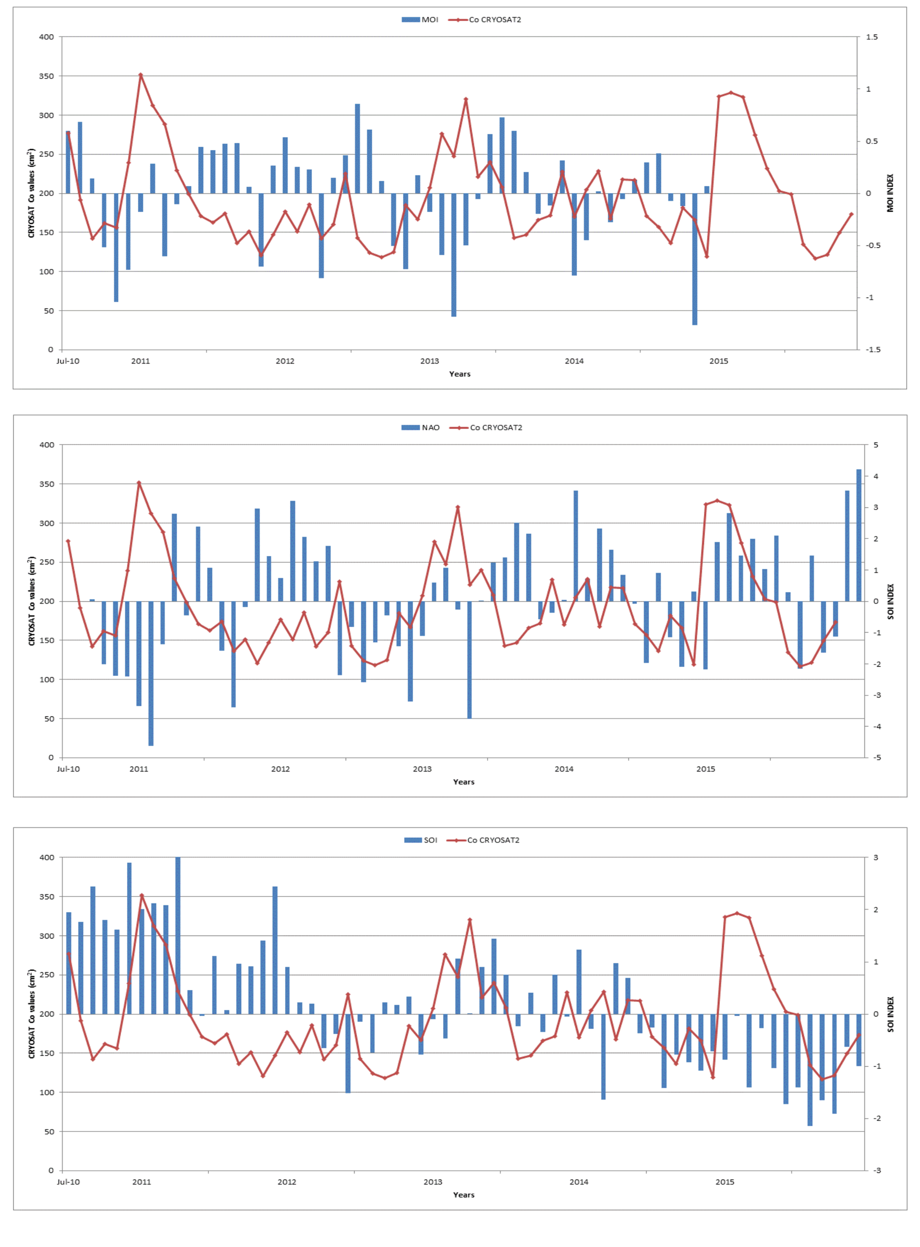

Figure 3: CRYOSAT2 SLA variances from the monthly empirical covariance functions fluctuations and correlation with NAO (top), MOI (middle) and SOI (bottom).

Objectives

This work presents correlations of the Sea Level Anomaly (SLA) with global and regional climatic phenomena that influence the ocean state as well. The possible correlation is investigated in both monthly and annual scales, while a regional multiple regression and a principle component analysis (PCA) between the SLAs and oscillation indexes is carried out.

Multiple regression and PCA have been used as tools in order to deduce possible correlations between the Mediterranean sea level variations and the aforementioned oscillation indexes, under the assumption that SLA variations are driven by steric forcing.

Finally, evidence of the sea level cyclo-stationarity in the Mediterranean Sea is deduced from the analysis of empirically derived covariance functions at monthly intervals from the available SLA data.

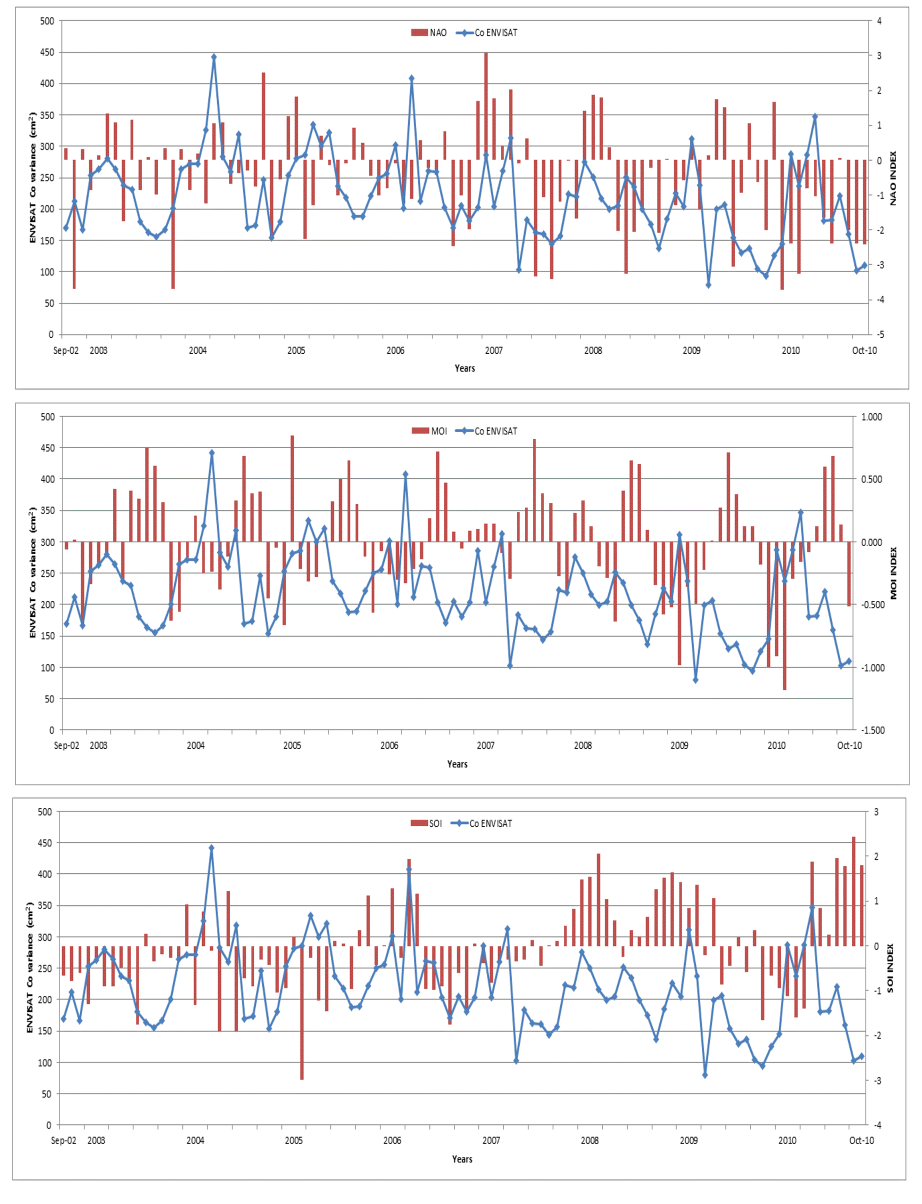

Figure 2: ENVISAT SLA variances from the monthly empirical covariance functions fluctuations and correlation with NAO (top), MOI (middle) and SOI (bottom).

From Fig. 2 and Fig. 3 it can be concluded that some correlation between ENSO events and SLA variations in the Mediterranean can be seen, even though with a phase offset of 3-6 months. The large negative values at the beginning of 2004 and 2005 are related to the highs in Mediterranean SLAs which appear in Spring of 2004 and of 2005. The El Niño appearance in Summer of 2006 and in Autumn-Winter of 2009 has a more rapid signature in the Mediterranean SLA data, since it results in significant increase in the SLA in Winter 2006, and in Spring of 2010 i.e., a time period of 4-6 months. The same behavior is evidenced for the La Niña events too, as it can be seen for the moderate occurrences in late 2007-early 2008 and for the strong event of late 2010 and early 2011. These result in significant depressions in the SLA variances, which reach their smallest values in Summer 2008 and in Spring 2011, i.e., with a time lag of ~3-5 months.

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, the NAO index should be more appropriate to indicate any correlation between atmospheric forcing and SLA variations. It is now evident that a stronger correlation can be seen, since the negative NAO values are related to more immediate increases in the Mediterranean sea level Autumn (2002, 2004, 2006, 2007, 2010, 2012, 2014), while positive ones to low sea levels. Noticing are the positive NAO values at the beginning of 2007, 2008, 2011, 2012, 2014 which are immediately depicted as depressions in the Mediterranean SLA with a time lag of less one-two months. The same behavior is found for most winter months, i.e., a good correlation, while for summer months the response of the Mediterranean sea level to variations in NAO is not so well depicted (2002, 2004, 2006-2010,2012, 2014).

MOI should be the most proper measure of atmospheric forcing contribution to sea level variations in the Mediterranean. From Fig.2 and Fig.3 it becomes clear that positive phases in MOI are related to depressions in the SLA due to dryer conditions, as can be seen in Spring and Summer of every year .during this period of ten years. The same behavior can be seen for the negative MOI values, which result in increased sea levels as for example in early 2002, 2004-2007, 2010-2011 and 2013. In most cases trends in the SLA are directly correlated with MOI while NAO and MOI are also well correlated and follow each other, especially for the winter months. The anti-correlation between NAO and MOI and their disagreement in Spring and Summer signals that atmospheric conditions in the North Atlantic are not the dominant contributing factor for the Mediterranean Sea.

Regional multiple regression analysis

A regional multiple regression analysis between SLA Co values of ENVISAT and CRYOSAT2 satellites and SOI, MOI and NAO indexes is carried out to model the response of the Mediterranean to these global and regional climatic phenomena.

3 regression coefficients

$$C_O = b_1 \times MOI + b_2 \times SOI + b_3 \times NAO$$

A linear regression with three regression coefficients between the Co values and tree indexes has been used. The values of the indexes have been normalized, using the minmax values of NAO, in order to take values to be coherent to each other. Moreover, period from 2003 to 2014 have been selected because Co values are available for all months while for 2015 there are not MOI data.

Year	b_1	b_2	b_3
2003	9.074	1.969	-0.192
2004	10.685	1.524	2.392
2005	13.906	-1.022	-3.062
2006	13.313	4.457	-0.608
2007	7.232	3.947	1.382
2008	2.920	4.039	-1.498
2009	4.270	3.999	-0.112

Year	b_1	b_2	b_3
2011	3.324	3.505	-0.721
2012	6.009	2.699	-1.172
2013	-4.936	7.314	2.226
2014	7.533	1.583	0.705

Table2: ENVISAT (top) and CRYOSAT2 (bottom) regression coefficients values

The correlation between SLA and the indexes depicted in Fig. 2 and Fig.3 is similar to the values of the regression coefficients. During all years, the coefficient of MOI takes the biggest values, resulting in good correlation with the SLA. The SOI coefficient values are smaller, while during the years that the ENSO events are strong (2008, 2013) b_2 is bigger than b_1. Finally, NAO coefficient b_3 generally takes small values signaling that atmospheric conditions in the North Atlantic are not the dominant contributing factor for the Mediterranean Sea while the big value of 2005 can be attributed to the small value of SOI.

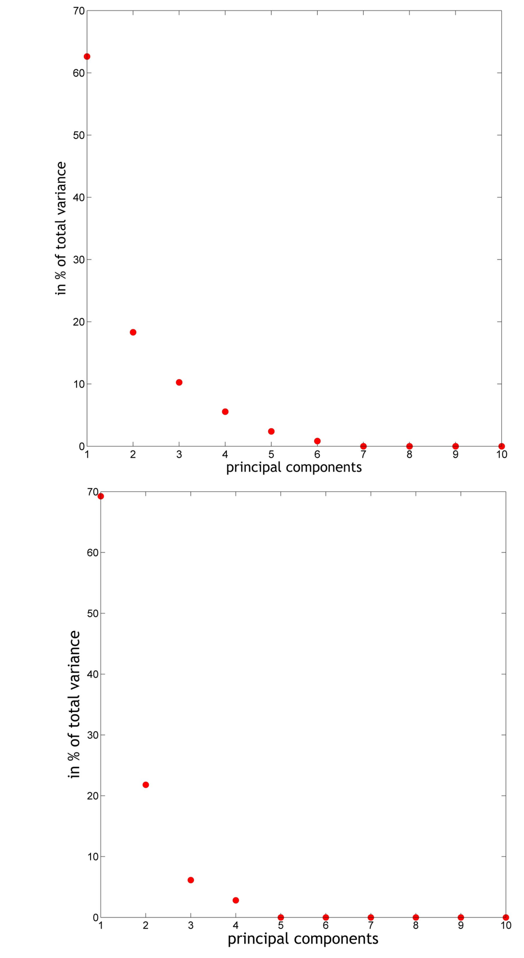

Figure 6: ENVISAT (top) and CRYOSAT2 (bottom) principal components

Correlation analysis

A correlation analysis between SLA Co values of ENVISAT and CRYOSAT2 satellites and SOI, MOI and NAO indexes is carried out to model any monthly correlation between SLA and these indexes through each year .

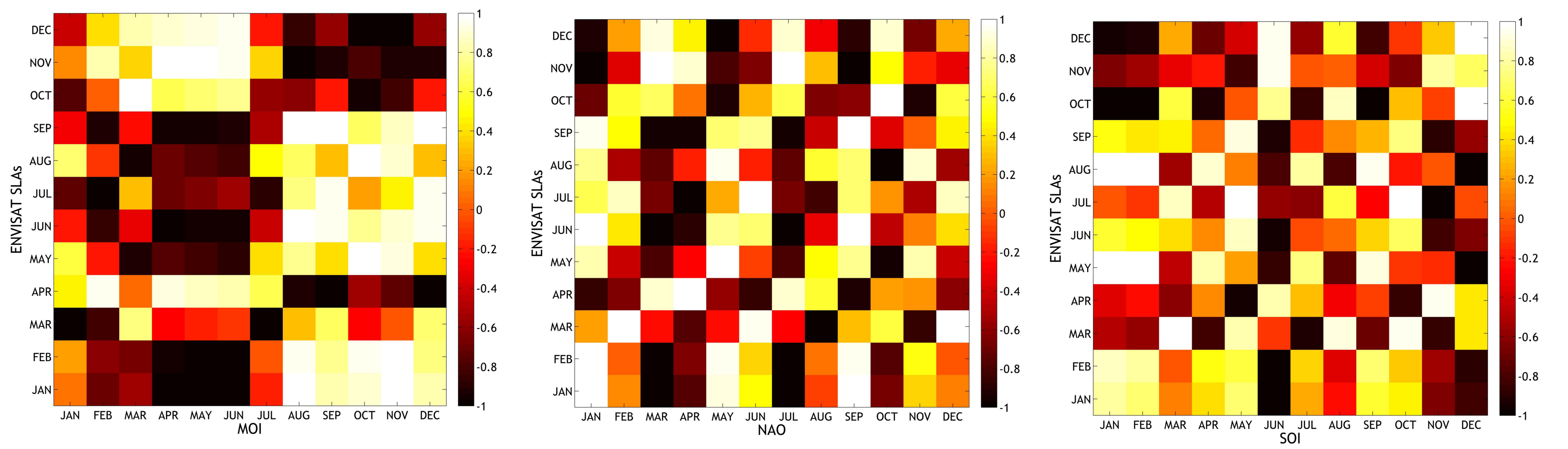

Figure 4: Correlation between ENVISAT Co and MOI (left), NAO (middle) and SOI (right) for year 2009.

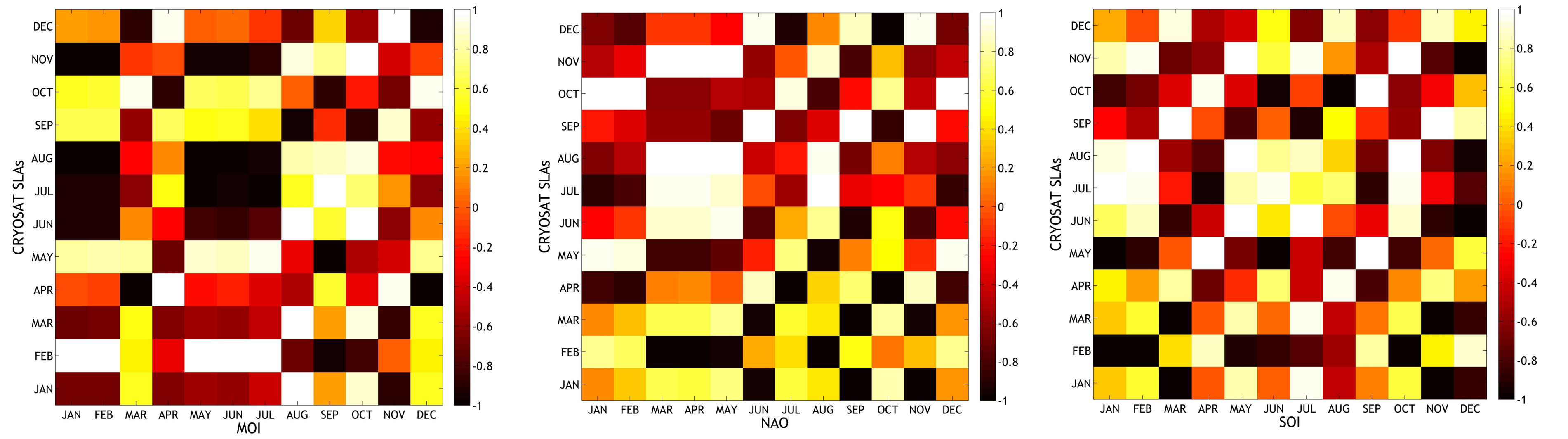

Figure 5: Correlation between CRYOSAT2 Co and MOI (left), NAO (middle) and SOI (right) for year 2014.

In Fig.4 and Fig5.correlation between Co and indexes for a one year is depicted. (ENVISAT-2009 and CRYOSAT2-2014). Although a strong effect is not obvious, due to the fact that only one year is tested, it can be noticed that MOI is stronger correlated with SLA during the Spring-Summer months of each year. Additionally, smaller correlation can be found and in early months of the year with NAO index. This is in line with the fact that NAO and MOI are well correlated and follow each other. On the other hand, the correlation between SOI and SLA depends on the strength of ENSO events and it is presented with a lag of 4-8 months .

Principal Component analysis

The last step in the analysis of the SLAs and indexes is a Principal Component analysis.. For this analysis, Co and oscillation indexes values for seven consecutive years of ENVISAT (2003 -2009) and four of CRYOSAT2 satellites have been employed.

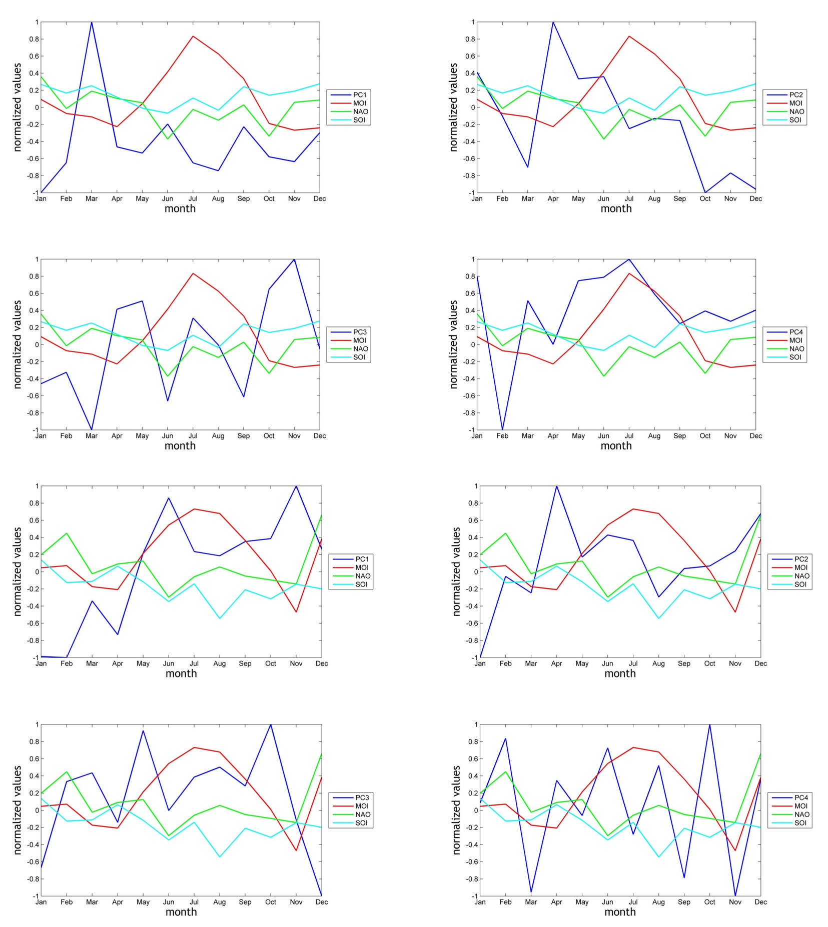

Figure 7: ENVISAT (top) and CRYOSAT2 (bottom) PCs and normalized indexes time series

From Fig.. 6 it is obvious that the first two components are clearly distinguishable in the spectrum of data matrix. They correspond to the annual and semi-annual SLA changes in the Mediterranean Sea. The third and fourth component represent seasonal and climatic signal modes.

In Fig. 7 first four principal components of ENVISAT and CRYOSAT2 SLA variances and normalized indexes time series are depicted. Although, the a strong effect is not obvious, it can be concluded that ENVISAT fourth and CRYOSAT2 third principal component is related to the MOI index which is the most proper measure of atmospheric forcing contribution to sea level variations in the Mediterranean.

Conclusions

- A regional multiple regression, a correlation analysis and a principal component analysis between sea level anomalies and the SOI, MOI and NAO indexes was carried out to model any possible correlation between the Mediterranean sea level and these global and regional climatic phenomena while the developed empirical covariance functions of SLA are also used.
- Cyclo-stationarity in the SLA can be evidenced from the empirical covariance functions for both satellites. The statistical characteristics of the SLA follow a regular pattern with the variation of the epochs.
- Through regional multiple regression analysis between sea level anomalies and the SOI, MOI and NAO, it is obvious that the response of the Mediterranean Sea is more predominant with MOI.
- A correlation analysis was carried out to model any seasonal correlation. Some correlation between ENSO events and SLA variations can be seen while NAO is well correlated with MOI and SLA for winter months.
- The small response of the SLA in the Mediterranean sea level during Summer signals that atmospheric forcing is not the contributing factor to the steric sea level variations in the Mediterranean during the summer period.
- Through Principal Component Analysis, it can be noticed that components of SLA represent seasonal and climatic signal modes. Comparing the PCs with the indexes time series it can be concluded that ENVISAT fourth and CRYOSAT2 third principal component is related to the MOI index.

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