



# Modeling the response of the Mediterranean sea level to global and regional climatic phenomena

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## Introduction & Objectives

The exploitation of altimetric data sets from past and current satellite missions is crucial to both oceanographic and geodetic applications. For oceanographic studies it allows the determination of Sea Level Anomalies (SLA), as deviations from a static mean sea level, while it is also fundamental for marine geoid and gravity determination.

This work presents correlations of the SLA with global and regional climatic phenomena that influence the ocean state as well. 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.

The developed covariance functions are used in order to investigate any possible correlations with climate change indices over the Mediterranean Sea.

## Data used and Corrections

The raw data used are SLA values from Jason-1 and Jason-2 (Fig. 1-right) satellites for a period of thirteen years (2002-2014) and from CRYOSAT-2 (Fig. 1-left) satellite for a period of 6 consecutive years 2010-2015 within the entire Mediterranean Basin ( $30^{\circ} \leq \phi \leq 50^{\circ}$  and  $-10^{\circ} \leq \lambda \leq 40^{\circ}$  ).

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.

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.

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/>)

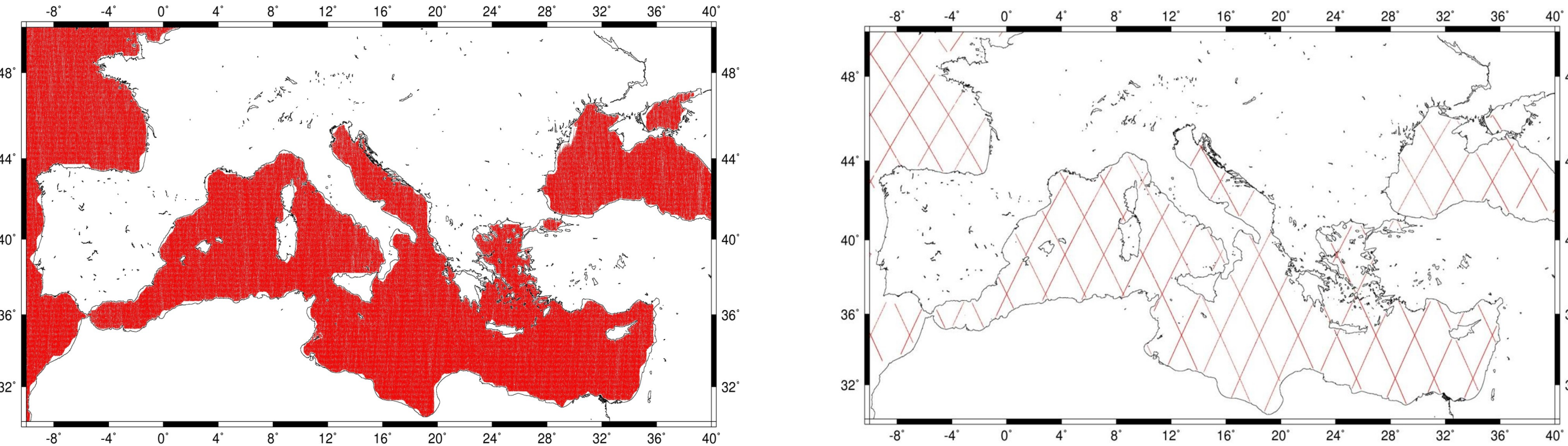


Figure 1: CRYOSAT2 (left) and JASON satellites (right) data distribution

Each Jason-1 and Jason-2 cycle consists of 254 passes with almost 15% of those having available observations in the Mediterranean Sea within the satellite's period of 10 days. For each year 36 cycles and ~92000 observations are available with a cross track spacing of 300km at the equator while CRYOSAT2 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.

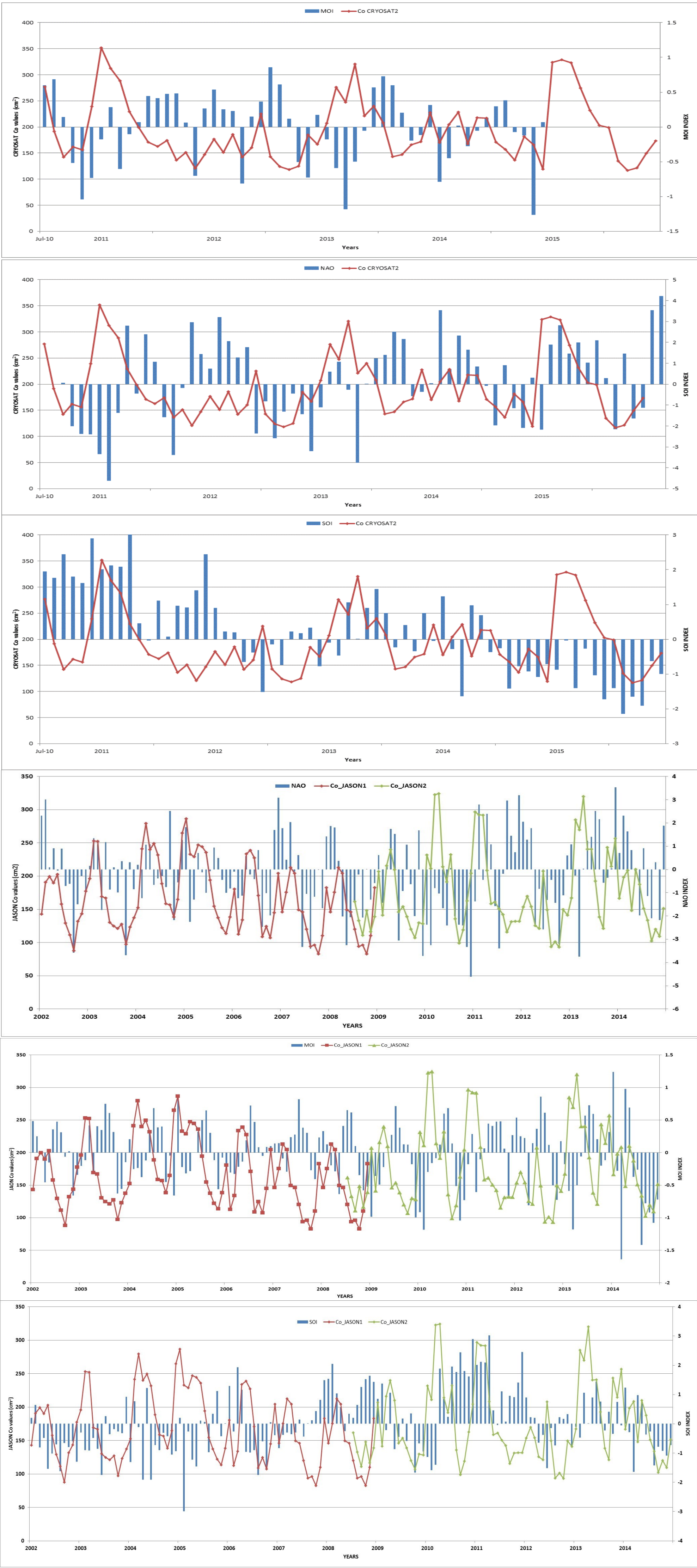


Figure 2: CRYOSAT2 SLA variances from the monthly empirical covariance functions fluctuations and correlation with MOI (top), NAO (middle) and SOI (bottom).

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.

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

The NAO index is 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.

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.

## Regional multiple regression analysis

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

3 regression coefficients

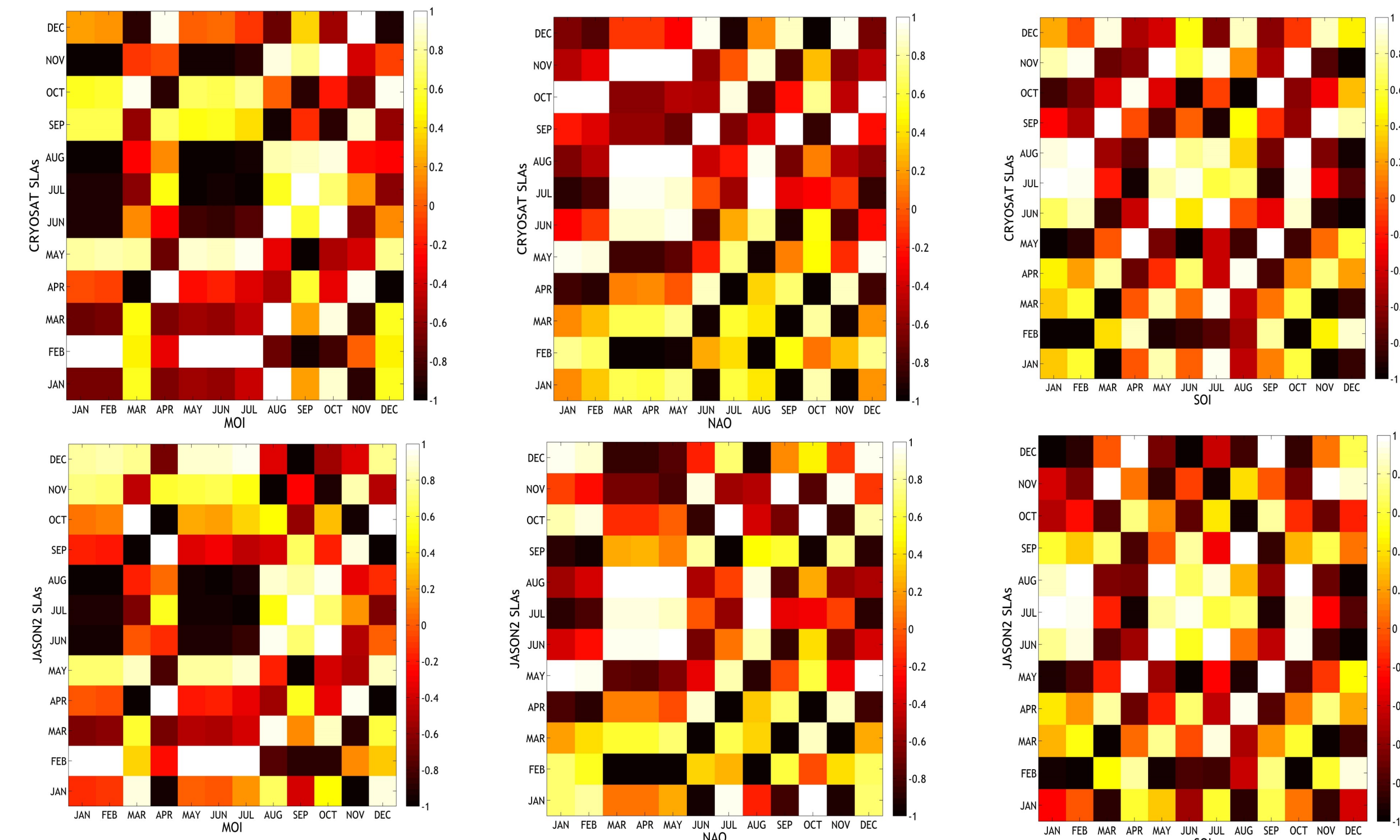
$$Co = b_1 \times MOI + b_2 \times SOI + b_3 \times NAO$$

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 2002 to 2014 have been selected because Co values are available for all months while for 2015 there are still not MOI data.

Year	$b_1$	$b_2$	$b_3$
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

Year	$b_1$	$b_2$	$b_3$
2011	3.324	3.505	-0.721
2012	6.009	2.670	-1.172
2013	-4.936	7.314	2.226
2014	7.533	1.583	0.705

Figure 4: CRYOSAT2 and JASON SLA variances from the monthly empirical covariance functions fluctuations and correlation with MOI, SOI and NAO



In Fig.4 correlation between Co and indexes for the same year is depicted (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. 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 .

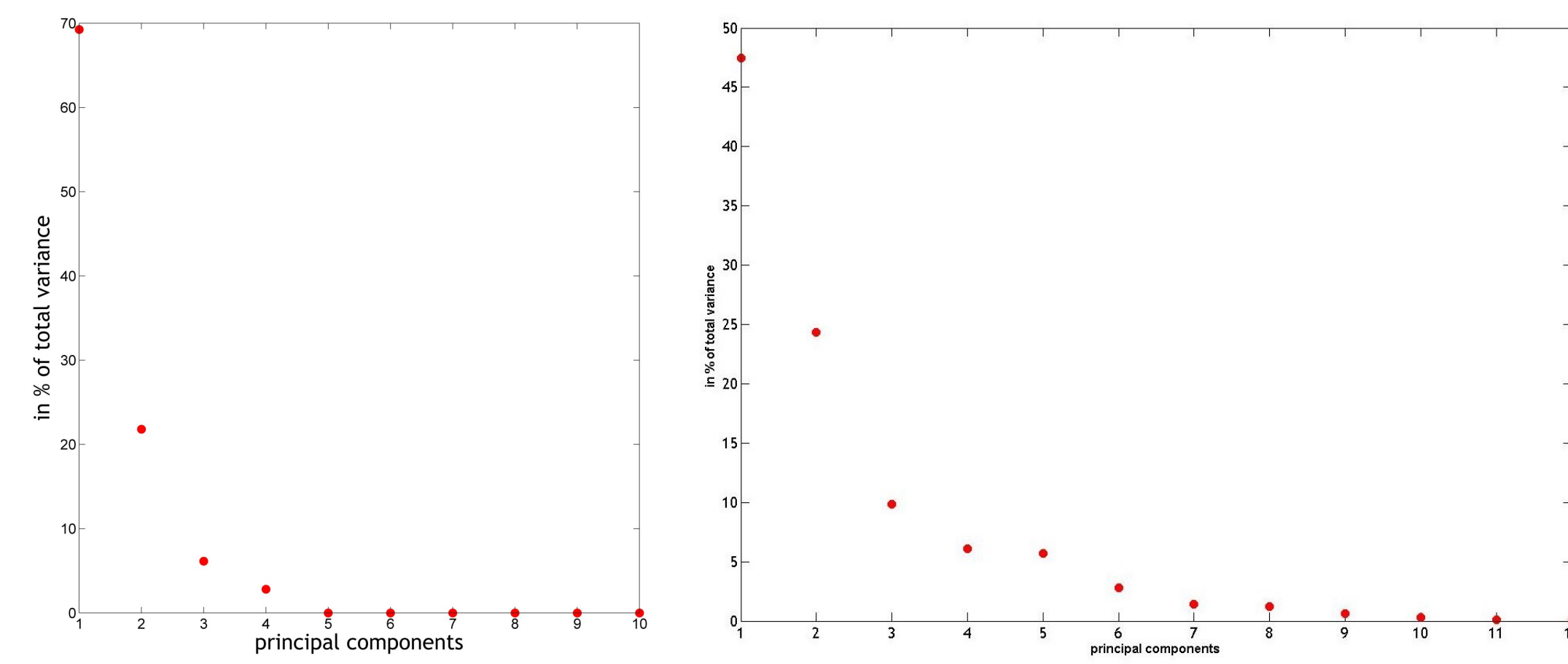


Figure 6: CRYOSAT2 right and JASON (left) principal components

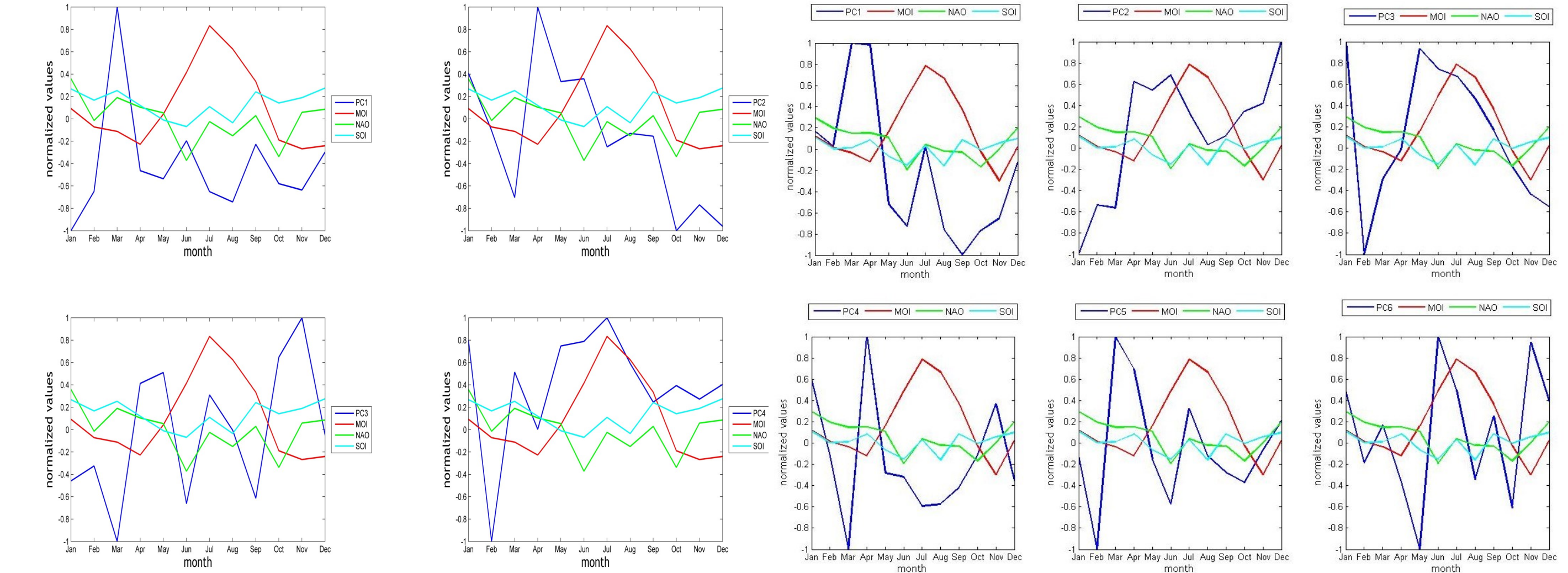


Figure 7: CRYOSAT2 (bottom) PCs and normalized indexes time series

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.

## Conclusions

- 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 the third principal component of both satellites is related to the