# LOW FREQUENCY VARIABILITY IN TWO ATMOSPHERIC MODES OF THE MEDITERRANEAN BASIN

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## RESUMEN

Dos modos atmosféricos, la Oscilación del Mediterráneo (MO) y la Oscilación del Mediterráneo Occidental (WeMO) contribuyen significativamente a la variabilidad climática anómala de la región Mediterránea. En este estudio se examinaron los índices de MO y WeMO con una resolución temporal diaria y estacional para detectar la variabilidad de baja frecuencia. Para llevar a cabo este análisis se ha utilizado el método de Descomposición en Modos Empíricos (EMD), que está indicado para el análisis de series temporales no lineales y no estacionarias, y se comprobó la significancia estadística de los modos frente al ruido rojo.
Los resultados muestran que la variabilidad multidecadal del índice MO en verano es estadísticamente significativa, y relacionada con la variabilidad del mismo tipo detectada en los índices relacionados con la temperatura superficial del mar (TSM) en el Mediterráneo. En los índices estacionales WeMO, se detectan tendencias significativamente diferentes del ruido en verano y otoño, además de una variabilidad multidecadal significativa en otoño. Estas tendencias y variabilidad multidecadal en los índices WeMO se relacionan con las de los índices del modo Dipolar de las TSM en el Mediterráneo.

**Palabras clave**: Mediterráneo, Modos Empíricos, Atmósfera, Tendencias, Variabilidad Multidecadal.

## ABSTRACT

Two atmospheric modes, the Mediterranean Oscillation (MO) and the Western Mediterranean Oscillation (WeMO) contribute to the anomalous climatic variability in the Mediterranean region. In this study MO and WeMO indices at daily and seasonal temporal resolution were examined for trends and low frequency variability. Here, the Empirical Mode Decomposition method, intended for nonlinear and non- stationary time series analysis was applied and the statistical significance of the modes was tested against red noise. A trend was detected in the daily WeMO index. In the seasonal MO indices case, the multidecadal variability was significant in summer and related to a similar variability detected in the Sea Surface Temperature (SST) Mediterranean field. In the seasonal WeMO indices, trends were found significantly different from noise in summer and autumn, while the multidecadal variability was significant in autumn. The multidecadal variability in the MO indices were related to those of the Western Mediterranean SST indices, while the (decreasing) trends and low frequency variability in the WeMO indices were associated to those of the SST Mediterranean Dipole Mode indices.

**Key words**: Mediterranean, Empirical Modes, Atmosphere, Trends, Multidecadal Variability.

## 1. INTRODUCTION

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC 2013) and several more recent studies highlighted large uncertainties concerning the trends and internal climate variability at multidecadal and centennial timescales in the Mediterranean region (Collins et al, 2013; Paeth et al., 2017).

The Mediterranean Oscillation (MO) is an atmospheric mode spanning the Mediterranean sea, presenting special teleconnection properties with the observed Italian precipitation and hydrography (Conte et al., 1989). It is monitored by the MO index, defined as the difference between the observed Sea Level Pressure (SLP) at Algiers station and those of Cairo (Conte et al., 1989; Palutikof et al., 1996). Its strength outweighs that of the North Atlantic Oscillation (NAO) index at all locations during all seasons, except for the eastern and northern Mediterranean during winter. Criado-Aldeanueva and Soto-Navarro (2014) found that the MO mode had the highest influence in the heat and freshwater fluxes on the annual mean. The upper-level MO (ULMO) relates to a stationary Rossby wave over the Mediterranean Sea (Palutikof, 2003). Different versions of the ULMO index combined with the Atlantic Multidecadal Oscillation (AMO) index (Enfield et al., 2001) presented important prediction skills for annual and monthly temperature and precipitation anomalies at 53 stations around the Mediterranean basin (Redolat et al. 2018).

The Western Mediterranean Oscillation (WeMO), was defined as a dipole composed in its positive phase by the anticyclone over the Azores and the depression over Liguria and characterized by the WeMO index, defined as the difference between the SLP standardized anomalies at San Fernando (Spain) and Padua (Italy) (Martin-Vide and Lopez-Bustins 2006). During the WeMO positive phase, the SLP gradient across the western Mediterranean favors a northern deviation of the Atlantic cyclonic disturbances and hinders their penetration into the western Mediterranean.

The negative phase is associated to the torrential rainfall in the western Mediterranean, a feature which is not well captured by the NAO (Millan et al., 2005). It also influenced the atmospheric variability in northwestern Spain (Sanchez-Lorenzo etal., 2009; Vicente-Serrano et al., 2009). Martin-Vide and Lopez-Bustins (2006) did not find significant trends in the monthly WeMO indices corresponding to the coldest (December to March) months during the period 1870-2000. Significant peaks in the WeMO spectrum corresponded to interannual and decadal frequencies.

Two relevant climatic signals were found recently in some analyses of the observed Mediterranean SST (Marullo et al., 2011; Ortiz-Bevia et al., 2012 (OB2012); Ortiz- Bevia et al., 2016 (OB2016)). One of these, the Western Mediterranean (WM) SST mode presented maximum coherent anomalies in the western and central Mediterranean SST, displaying a multidecadal component in its variability. The other the SST Mediterranean Dipole mode, (MDM) had the form of a dipole pattern between the western and eastern Mediterranean anomalous SST. Together they accounted for more than 80% of the anomalous SST field, thereby conditioning the summer air temperature anomalies in the European region.

The present study aimed at:

-Testing the existence of trends in the atmospheric indices.

-Characterizing its dominant time scales of variability.

-Determining the covariability of the atmospheric modes with the indices of the other relevant data field, the Mediterranean SST.

## 2. DATA

The MO index was obtained from the Climate Research Center Unit (CRU). It consists of daily values of the normalized SLP differences between Gibraltar northern frontier (36.1º

N, 5.3º W) and Lod Airport in Israel (32.0º N, 34.51º E), following Palutikof et al. (1995) and covers the years 1948 - 2016. A monthly version was built through averaging. For the sake of the statistical significance and to compare against the WeMO index, an extended version of the MO index, covering 1870-2005, was obtained using HadSLP2 (Allan and Ansell, 2006).

The WeMO index was obtained from the University of Barcelona Climatology Group web page. It consists of monthly values of SLP differences between San Fernando (Cadiz) (36º24' N, 6º12' W) and Padua in Italy (32.0º N, 34.5º E), according to Martin-Vide and Lopez-Bustins (2006). The location of the stations used in this case are marked in the figure 2b. It covers the years 1870-2016. Additionally, a short version (1951-2018) of this index at daily resolution was obtained from Martin-Vide and Lopez-Bustins.

The NAO index was used to characterize the atmospheric anomalous state in the North Atlantic sector. It is defined as the Gibraltar- Reykjavik normalized SLP differences (Jones et al., 1997).

The Mediterranean Sea anomalous state was represented here by the WM index and the MDM index. The indices were identified as the first and the second Principal Components (PC) of the SST field, which was obtained from an updated version of the global HadSST2 dataset (Rayner et al., 2006) at 1º x 1º resolution, covering the years 1870-2013, in the sector [7º W- 36º E, 30º N-70º N] as described in Ortiz-Bevia et al., (2016).

Given the seasonal nature of the interactions in the Mediterranean basin, seasonal versions of the indices were also built was by subtracting from three months overlapping averages their climatological mean (for instance DJF, JFM, FMA, ...).

## 3. METHOD.

Linear regression can be used for the determination of the indices trend coefficients and their confidence intervals at the 5 % significance level if the stationarity and linearity hypothesis are satisfied. Otherwise, the indices were analyzed with a method that did not assume the linearity or stationarity of the time series: Empirical Mode Decomposition (EMD) (Wu et al., 1998; Wu and Huang, 2008). The algorithm was aimed at distinguishing between the noise produced by the intrinsic atmospheric variability and that due to other (external) causes. The technique has been successfully applied to the multiscale analysis of some teleconnection indices (Franzke, 2009),including NAO.

$$S(t) = I_j(t) + R(t); \; I_j(t) = B_j(t)\sin\vartheta_j(t)$$

The Intrinsic Mode Functions (IMFs), $I_j(t)$, were obtained through a 'sifting' process (Huang et al., 1998). It consisted in the iteration of three steps: 1) Estimation of upper (lower) envelope of the time series obtained by a spline through all the maxima (minima). 2) Identification of the i-order IMF as the mean envelope obtained by averaging the envelopes (absolute) values. 3) Subtraction of the IMF from the initial time series yielding a remainder time series that must be submitted again to the sifting process in order to determine the (i+1) IMF. The process was halted when a higher order IMF could not be identified.

Significant differences of each of the IMFs from noise are tested using a big ensemble of N (N=1000) of simulations of the original time series internal variability. The variability was estimated through an AR(1) model.

$$S(t) = a\,S(t-1) + r(t)$$

where denotes the autoregression coefficient at lag 1. The synthetic time series undergo an EMD analysis, and a statistical test is applied on the variance of each of the resulting IMFs

and residuals. The upper and lower percentiles for a given α confidence level were identified by fitting a probability density function (pdf) to each IMF variance and if the observed variance lied outside the null hypothesis was rejected.
The covariability between the two seasonal atmospheric indices (MO or WeMO), between each of them and the NAO index or between each index and the most relevant SST modes were estimated by the Pearson linear correlation coefficient.

## 4. RESULTS.

The daily MO and WeMO indices were analyzed using the EMD. The statistical significance test (whose results are shown in figure 1) did not retain any low frequency variability in neither of the two indices and detected a trend only in the case of the WeMO index. The Empirical Modes found significant in the daily WeMO index analysis were de 1st and 2nd and the 5th and 6th, whose time evolution is represented in the figures 2a, 2b, 2c and 2d. The two first corresponded to high frequency variability while the last ones presented semi-annual and quasi-annual frequencies. The significant trend evolution is represented in figure 2e.
The more than a century spanning of the seasonal versions of the indices might offer better prospects at detecting quasi-decadal or multidecadal variability. Visual inspection of the MO index, pointed to the existence of this kind of variability. Moreover, the existence of a trend in the seasonal WeMO index, could be tested using linear regression analysis only in the last half of the record (1948-2015).
The test on the EMD analysis of the summer (JJA) MO index retained only a significant low frequency component, the 4th IMF, as can be appreciated in figure 1a. This component is associated to low frequency variability and its close relationship to the AMO index is highlighted by the figure 3b, where the evolution in time of this IMF and of the AMO index are depicted together, and also by the highly significant value between both time series. The correlation between the MO index and the WM SST index reached a -0.45 value at this season.

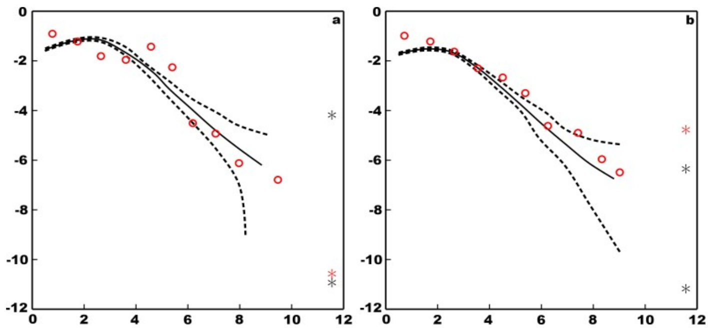


*Fig.1: a) The results of the statistical tests on the significance of the Intrinsic Mode Function of the daily MO index. The values of the variance corresponding to each IMF obtained from the Empirical Mode Decomposition of the index is depicted with red empty circles. The solid black line is the mean variance of the AR(1) ensemble and the dashed line represent the 2.5 % and 97.5 % percentiles. The axes have a natural logarithmic scale. The variance of the residual of the index is depicted with a red asterisk, while the black asterisk represents the AR(1) residuals percentile. b) As in a) but for the results of the Empirical Mode Decomposition analysis of the daily WeMO index.*

In the seasonal WeMO index, trends were found significant although barely in summer and autumn while a multidecadal variability was also barely significant in autumn.

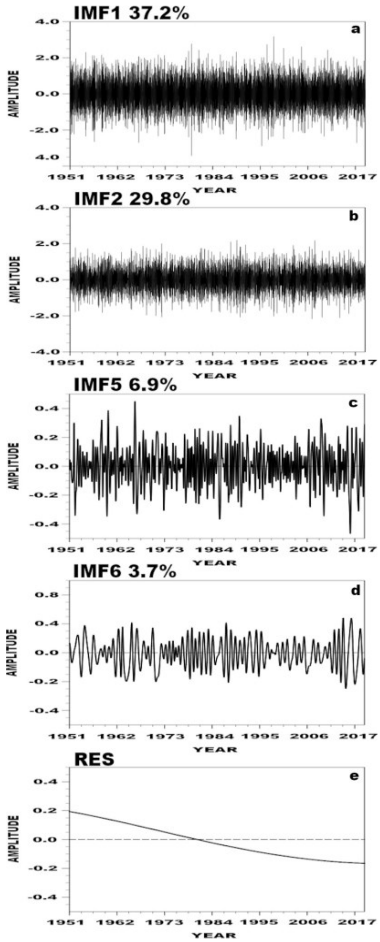


*Fig.2: The intrinsic mode functions and explained variance of the daily WeMO index EMD decomposition. In the last box, the residual curve (trend).*

Moreover, the correlation between the WEMO and the MO indices for the period 1870-2004 exceeded significance threshold only at the transition seasons. Those between the WeMO and the WM SST indices did it from spring to autumn.

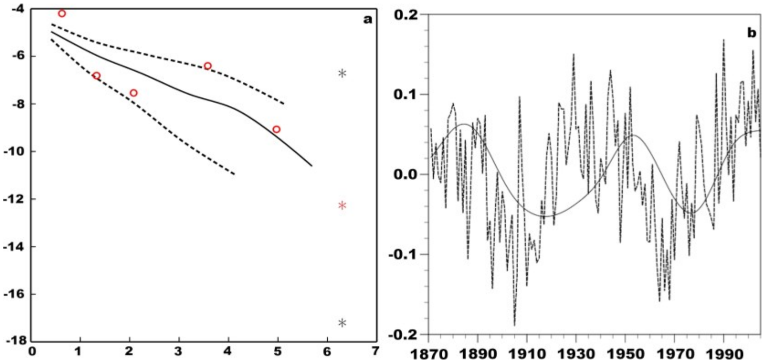


*Fig. 3: a) The results of the statistical test on the significance of the Intrinsic Mode Function of the summer MO index. Symbols, lines and axes as in Fig. 1a. b) Evolution in time of the phase inverted 4th IMF of the EMD of the summer (JJA) MO index (continuous solid line) against the summer AMO index (dashed line).*

On the contrary, the correlations between the WeMO and the SST MDM indices were significant from winter to autumn. Finally, the correlation of the NAO index with the WM SST index did not test significant at any season while those between the NAO and the SST MDM indices tested barely significant at all seasons.

## 5. DISCUSSION

The statistical method EMD, used for the detection of trends and low frequency variability, was applied here to the analysis of the indices of two atmosphericMediterranean modes.
The analysis performed on the daily indices reveals a significant trend only in the case of the WeMO index, and no other significant low frequency variability. The decreasing trend in the WeMO index can be traced back to a weakening of the Paduan low associated to an increase of the temperatures in that region.
Seasonal versions of the indices, spanning more than a century, were also analyzed using the EMD method. The 4th mode found in the analysis of the summer MO index, which was significantly different from noise, was related to the oceanic AMO index. This relationship might be conveyed through the one with the WM mode, but the variability of this last, although also multidecadal, is associated with 60-80 years' periods, while the AMO variability is associated with periods in the range of 40-60 years.
Trends and multidecadal variability also appeared in the WeMO indices at the transitions seasons, which might be more relevant, due to the importance of the precipitation processes at these seasons. However, as they are barely significant, it cannot be discarded that they might be an artifact of the seasonal filter used.

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