Examenarsbete

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In search for interannual and interdecadal relations between climate variability and continental freshwater discharge to the Mediterranean Sea

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1. Introduction

The term "teleconnection pattern" refers to a recurring and persistent, large-scale pattern of pressure and circulation anomalies that extent over vast geographical areas. The investigation on specific periodicities of the climate signals, over which multiple terrestrial phenomena can be linked with each other, is of particular interest in teleconnection research. Although patterns typically last for several weeks to several months, they can sometimes be prominent for several consecutive years, thus reflecting an important part of both the interannual and interdecadal variability of the atmospheric circulation, having also an impact on river discharge (CPC, 2014).

The objective of this study is to individuate periodical relations between long-term oscillations in river discharge in the Mediterranean basin and single teleconnection patterns (i.e. East Atlantic, North Atlantic Oscillation, Pacific Ddecadal Oscillation and Scandinavia).
However, such relations only reflect qualitative expectations in terms of increase or decrease in river discharge under specific teleconnection patterns conditions and do not allow in any case to quantify the variation of freshwater that is discharged into the Mediterranean Sea.

2. Description of the study area: the Mediterranean Basin

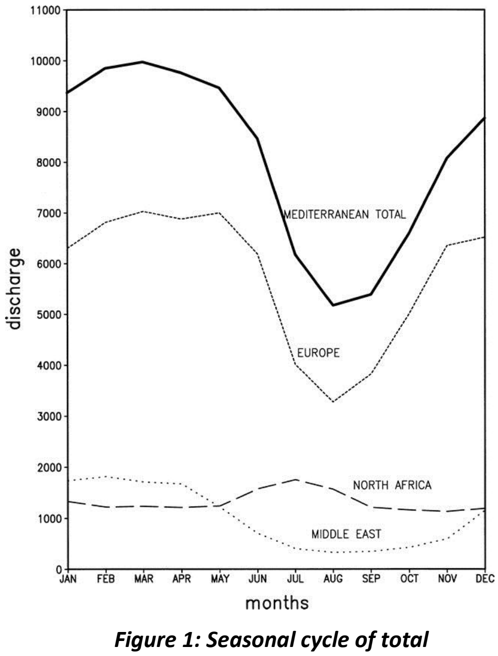

Figure 1: Seasonal cycle of total discharge into the Mediterranean Sea and its decomposition by continent of origin (Struglia et al., 2004)

The variability of Mediterranean river discharge is strongly based on the atmospheric water budget as well as on the geographical characteristics of the Mediterranean catchment. Geographically the Mediterranean catchment is extremely heterogeneous, extending from the source of the Nile River, approximately at the equator, to the source of the Rhone River around the 48°N. It consists of great valleys, such as the Nile and the Rhone valleys or the Po plain, high mountains, such as the Alps, where most of winter precipitation is in form of snow, and mountains, such as the Atlas in northeastern Africa and the Taurus in Turkey, that can capture moisture by means of orographic effects from eastward-propagating mid-latitude cyclones generated in the North Atlantic Ocean and in the eastern Mediterranean Sea (Struglia et al., 2004).

The continental river discharge into the Mediterranean Sea is mainly associated with Rhone, Po, and Nile rivers that discharge, respectively, about 1700, 1500, and 1200 m3 s−1. Secondary, but still relevant contributions, are from Ebro, Arno and rivers on the eastern Adriatic coast (e.g. Adige). Very little is contributed by North African rivers, other than the Nile (Struglia et al., 2004).

Fig. 1 also displays different contributions to the total discharge by specifying the continent of origin. European discharge appears as the main contributor, clearly determining the time curve of the whole Mediterranean seasonal cycle. This includes discharge from the Rhone, Po, and Ebro that are the three major European rivers, whose annual mean discharge is estimated around 5.7×10^3 m^3 s^{-1} (Struglia et al., 2004), around the 76% of the total annual mean discharge. The seasonal cycle has its minimum of about 3×10^3 m^3 s^{-1} in mid-late summer and its maximum from fall to spring of about 7×10^3 m^3 s^{-1} (Struglia et al., 2004).

3. Climate variability: Northern Hemisphere Teleconnection Patterns

Pressure dipoles are long distance climate phenomena (teleconnection) that are defined by anomalies of opposite polarity appearing at two distinct locations at the same time and are represented as a fixed spatial pattern associated to an index time series that evidence its evolution in terms of amplitude and phase (IPCC, 2007). Dipoles play a key role for the understanding of climate variability and are known to impact precipitation and temperature anomalies worldwide (Kawale et al., 2012).

For this study, the current known patterns that have an influence on the climate and weather in Mediterranean basin are presented

3.1. East Atlantic

The East Atlantic (EA) pattern shows the effects of its low-frequency variability over the North Atlantic area and appears as a leading mode in all months. Its structure, similar to the NAO, and consists of a north-south gradient covering the North Atlantic from east to west. EA can be considered as a "southward shifted" NAO pattern because of the displacement of the anomaly centers southeastward to the approximate nodal lines of the NAO pattern (CPC, 2014). The positive phase of the EA index leads to above-average surface temperatures in Europe and it is also associated with above-average precipitation over northern Europe and Scandinavia, and with below-average precipitation across southern Europe.

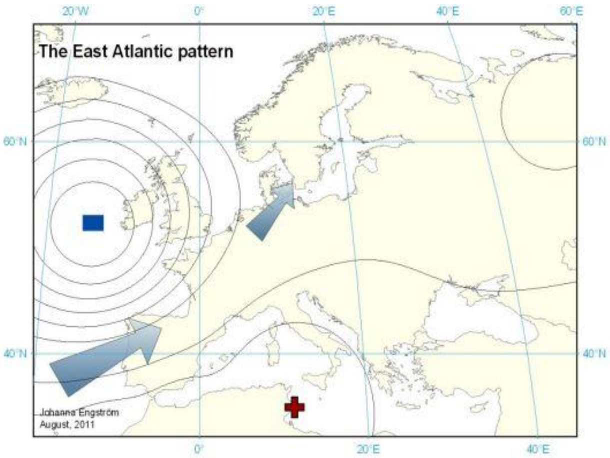

Figure 2: EA anomaly centers and atmospheric circulation directed, under the positive phase, towards northern Europe (Engström, 2011)

3.2. North Atlantic Oscillation

The North Atlantic Oscillation (NAO) teleconnection pattern is one of the most prominent teleconnection patterns, leading or significantly influencing the atmospheric circulation in nine out of twelve months and active all year around. (Barnston and Livezey, 1987).

The North Atlantic Oscillation index is expressed as the standardized difference of the surface sea-level pressure between the Azores High (subtropical region) and the Icelandic Low (subpolar region). Strong positive phases of NAO index lead to above-average temperatures over northern Europe and below-average temperatures in Greenland and oftentimes across southern Europe and the Middle East. Positive phases tend also to be associated with above-average precipitation over northern Europe and Scandinavia in winter, along with below-average precipitation over southern and central Europe. Opposite configurations related to temperature and precipitation anomalies have been observed during strong negative NAO index phases (CPC, 2014).

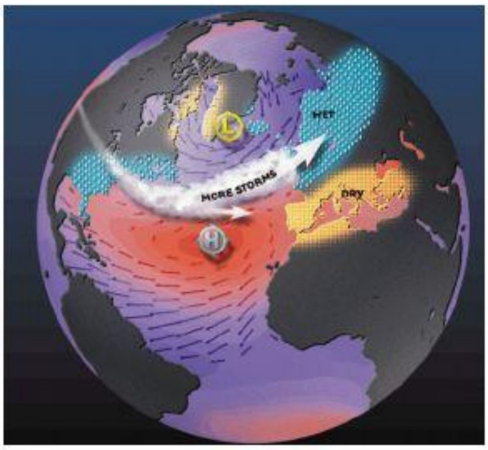

Figure 3: Positive NAO phase characterized by very low pressures in the subpolar region and very high pressures in the subtropical region (Bell, 2009)

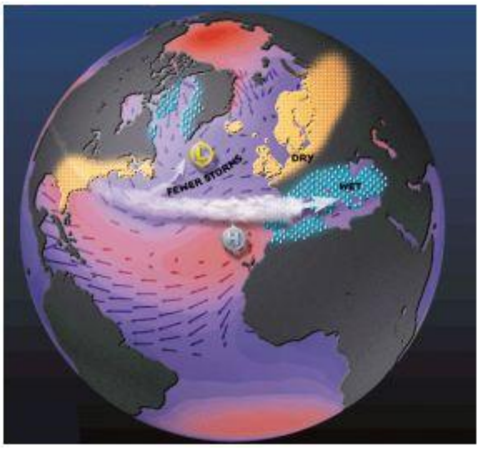

Figure 4: Negative NAO phase characterized by weak low pressures in the subpolar region and weak high pressures in the subtropical region (Bell, 2009)

3.3. Scandinavia

The Scandinavia pattern (SCAND) consists of a primary circulation center extended over Scandinavia and large portions of the Arctic Ocean north of Siberia: weaker centers having of opposite signs are located over Western Europe and western Mongolia (CPC, 2014).

Ciccarelli et al. (2008), have found that positive phases of the Scandinavian pattern, along with and the presence of blocking episodes (i.e. interruption of the normal zonal flow is interrupted by meridional flow) are correlated with an increase in precipitation and decrease in temperature especially during summer and fall periods and cold temperatures in Mediterranean basin, more specifically in north-western Italy.

3.4. Pacific Decadal Oscillation

The Pacific Decadal Oscillation is identified with low frequency variations in the leading of sea surface temperature (Zanchettin et al., 2007) and its variability shows similarities with El Niño–Southern Oscillation (ENSO) (see Figure 14), although it varies over a longer period. Indeed, the PDO can linger on the same positive or negative phase for 20-30 years, while ENSO periodicity usually lasts for 6 to 18 months. The variation of PDO can be monitored through PDO index, defined as the projections of winter mean sea surface temperature (SST) anomalies onto their first empirical orthogonal function vectors in the North Pacific area (north of 20º parallel).

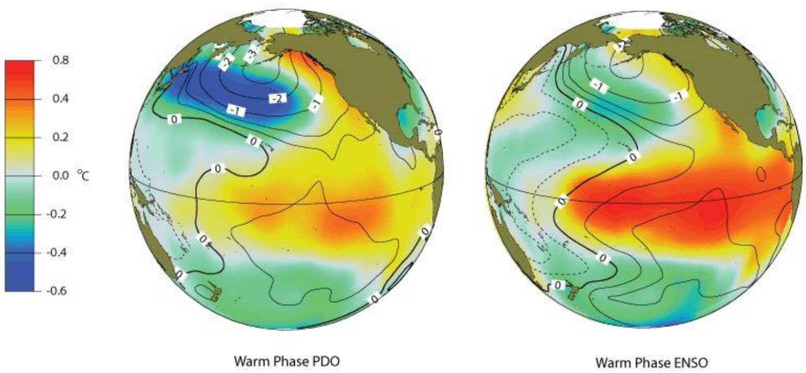

Figure 5: regional similarities in warm PDO and ENSO phases (Climate Impact Group, University of Washington, 2014)

4. Data

4.1. River discharge time series

Rivers with no regulation, or at least negligible regulation, are the only ones that can be considered to estimate the variability of natural continental discharge in the Mediterranean basin. As described in section 2., Rhone, Po and the Nile rivers Major overall contribute to continental discharge to the Mediterranean basin while secondary inputs are from Ebro, Adige (Struglia et al., 2004) and Arno rivers. However, although the contribution of river Nile discharge, estimated around 1200 m^3s^{-1} at its outlet (Struglia et al., 2004), is relevant for the hydrological balance of the Mediterranean Sea, Nile river is not object of this study because of the heavy regulation that has distorted the natural seasonal discharge of its waters over decades.

The selected Rivers are listed in Table, along with the relative name of the outlet rivers´ station where flow measurements have been performed.

River	*Outlet station*	*Time series*	*Data Source*
Adige	*Boara Pisani*	*1922-2008*	*ARPA Veneto*
Arno	*San Giovanni alla Vena*	*1960-2012*	*Autorità di Bacino Arno*
Ebro	*Tortosa*	*1952-2012*	*Confederación Hidrográfica del Ebro*
Po	*Pontelagoscuro*	*1919-2012*	*ARPA Emilia Romagna*
Rhone	*Beaucaire*	*1921-2012*	*Compagnie Nationale du Rhône*

Table 1: Selected Rivers

4.2. Teleconnection patterns time series

With the exception of PDO, whose analysis extents from 1900 to 2012, the teleconnection patterns time series of EA, NAO and SCAND cover the 1950-2012 period.

Teleconnection pattern	*Time series*	*Source*
EA	*1950-2012*	*Climate Prediction Center - NOAA*
NAO	*1950-2012*	*Climate Prediction Center - NOAA*
SCAND	*1950-2012*	*Climate Prediction Center - NOAA*
PDO	*1900-2012*	*JISAO - Washington*

Table 2: Selected teleconnection patterns

5. Methodology

Long-term river discharge and teleconnection pattern time series are studied using wavelet transform method. Wavelet transforms can be divided in 2 classes: the Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). As DWT is mainly used for noise reduction and data compression, while CWT is a common tool to extract signals from time series and to analyze localized intermittent oscillations, this study will be focusing on this last class, which is more indicated for feature extraction purposes (Grinsted et al., 2004). Then cross wavelet technique is applied to examine coherence and phase relations between pairs of time-series on interannual scale to find individuate the teleconnection pattern signal in river discharge data. Cross-wavelet analysis identifies regions where time series have common power, whereas wavelet coherence identifies regions where time series show correlated (or coherent) fluctuations (Cazelles et al., 2008; Grinsted et al., 2004). All the analyses were carried out using a MatLab software package written by Torrence and Compo (available at “http://atoc.colorado.edu/research/wavelets/'').

Continuous wavelet analyses were performed for the available time period of each river discharge and teleconnection pattern time series. The cone of influence, indicated with a lighter shade outside, highlights the area of the graph where the power spectrum might be distorted since the wavelet is not completely localized in time (Lidén et al., 2012).
Wavelet power spectra, ranging from 1/8 to 4 values (respectively indicated in blue and orange), have been examined for all the selected rivers, whose discharge data are standardized by daily means and standard deviations observed in the relative monitoring period. A similar process has been used for the analysis of teleconnection patterns: here the standardization was done by monthly means registered during the monitoring periods.

For a correct interpretation of wavelet-based statistical results of non-stationary events, significance tests cannot be omitted. The statistical significance level of the wavelet power is estimated by using Monte Carlo method. The generation of a large ensemble of data set pairs constitutes the basis for the calculation of the wavelet coherence. The Monte Carlo estimation of significance level requires around 1000 surrogate data set pairs (Grinsted et al., 2004). By performing Monte Carlo method it is possible to compute the 95% confidence interval, highlighted with black solid contours (see Figure 17).

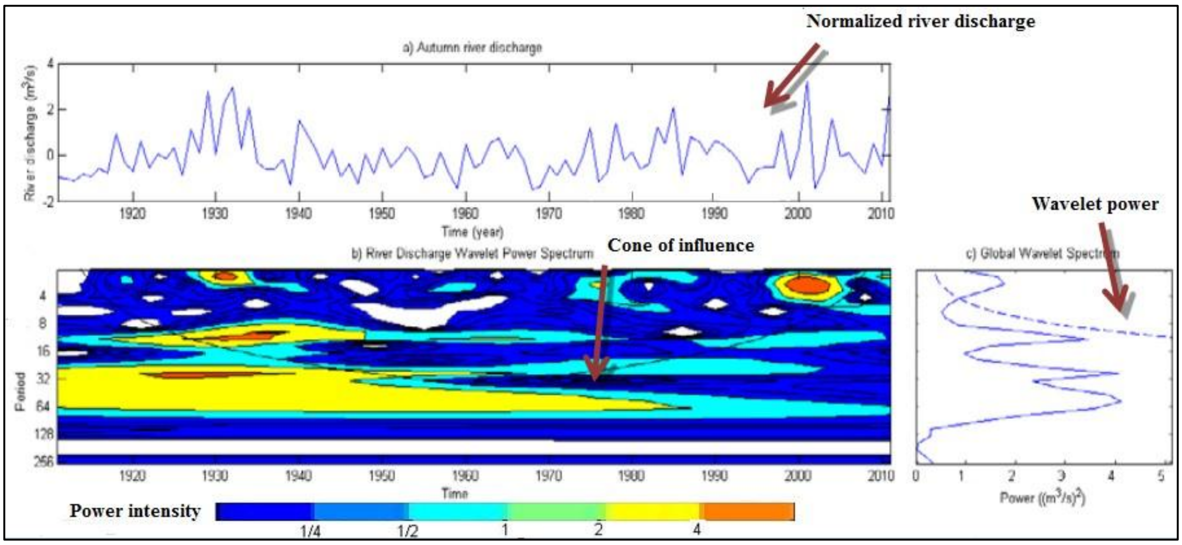

Figure 6: River discharge wavelet analysis (Lidén et at., 2012)

5.2. Cross wavelet analysis

From two CWTs we construct the Cross Wavelet Transform (XWT) which is a powerful method for showing eventual relations between two time series, as it exposes their common power and relative phase in time-frequency space. The cross wavelet transform (XWT), on the basis of two time series (x and y), is defined as $W^{XY}=W^{X}W^{Y*}$, where * denotes complex conjugation and the cross-wavelet power, $|W^{XY}|$, indicates areas having high common power between time series x and y (Grinsted et al., 2004). Obviously, cross wavelet analysis can be performed only if two time series are extended over the same time period.

Although it is difficult to calculate the confidence interval of the mean angle reliably (especially because the phase angles are not independent), the arrows in the graph show where the two wavelet transforms are in phase or anti-phase, pointing respectively to the right or to the left (see Figure 18).
The cone of influence highlights the area of the graph having major statistical significance because of the data availability over a certain time period. The black contours highlight statistically significant wavelet power at the 5% level of a red noise process.
Although it is difficult to calculate the confidence interval of the mean angle reliably (especially because the phase angles are not independent), the arrows in the graph show where the two wavelet transforms are in phase or anti-phase, pointing respectively to the right or to the left (see Figure 18).

The cone of influence, as described in section 5.1., highlights the area of the graph having major statistical significance because of the data availability over a certain time period. The black contours highlight statistically significant wavelet power at the 5% level of a red noise process.

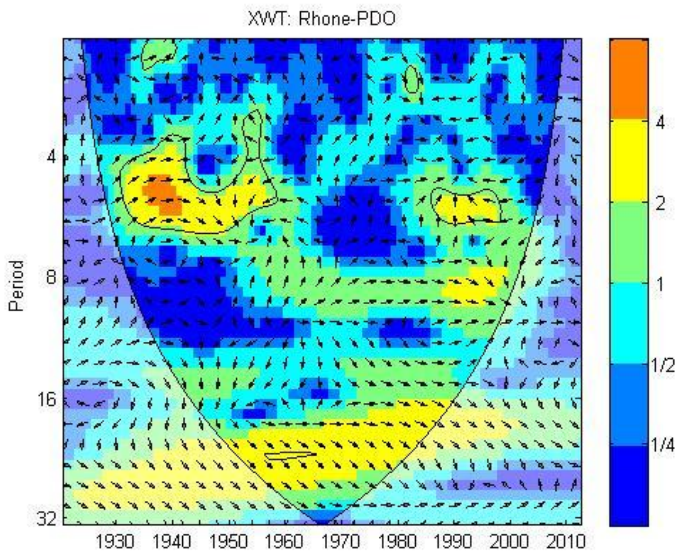

Figure 7: Rhone river discharge and PDO index cross-wavelet analysis. It is possible to note the COI, the black solid contours highlighting 5% significance level and the power intensity scale

6. Results

In this section, the relations between the outlined river discharge time series and large-scale atmospheric circulation patterns are investigated by means of cross wavelet analyses. Wavelet analysis of each river discharge time series has been cross-checked with wavelet analyses of the four selected teleconnection pattern time series, searching for climate variability influence on river discharge in the Mediterranean basin and significant results are hereby presented.

6.2. Cross Wavelet Analysis

6.2.1. Adige

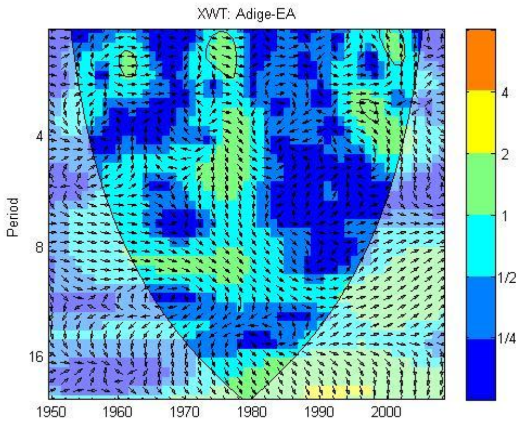

Figure 8: Adige and EA cross wavelet analysis

Figure 28 shows XWT results by using the standardized Adige river discharge and EA teleconnection pattern time series. Power 1 values are obtained in the ≈2, 4-6 and ≈8 year periods while higher power values can be foreseen outside the cone of influence. The 5% significance level is found in correspondence of the ≈2 year period, around 1963, 1975 and 2000 and in correspondence of the ≈4 year period around 1997. In three of the four listed cases, the events are in phase, as shown by the right-pointing arrows.

6.2.2. Arno

The Cross Wavelet Transform (XWT) of the standardized Arno river discharge and Scandinavia teleconnection pattern time series shows high power in ≈2 and ≈8 year periods. This information is also validated by the 5% significance level respectively around 1990 and the period 1980-1990 (see Figure 34). In both year periods, the pointing-right arrows show that the two events are in phase, i.e. under positive phases of Scandinavia pattern there is also an increase in Arno river discharge.

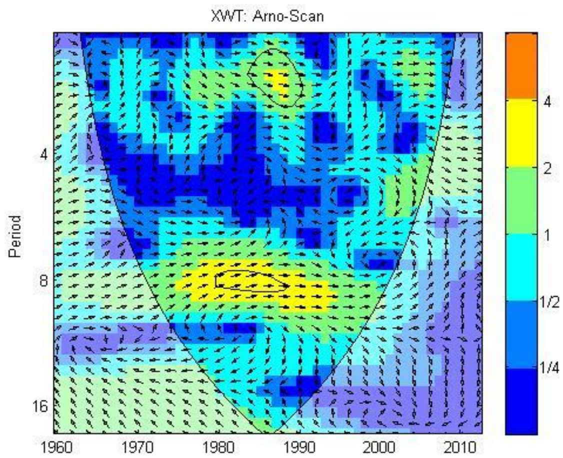

Figure 9: Arno and Scandinavia cross wavelet analysis

6.2.3. Ebro

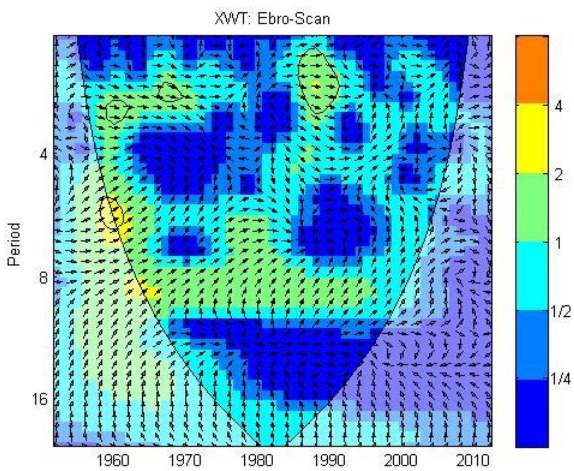

Figure 10: Ebro and Scandinavia pattern cross wavelet analysis

The ≈2 year period of Ebro river discharge and Scandinavia XWT exhibits power 1 values. This information is also accompanied by the individuation of the 5% significance level that is shown in the early and late 1960s as well as in the late 1980s. The ≈6 and ≈8 year periods show even higher power values and the 5% significance level is obtained around 1960. In these periods, the study highlights that Adige river discharge and Scandinavia index are in phase.

6.2.4. Po

The XWT of the standardized Po river discharge and PDO index time series shows high power in the ≈6, ≈8 and ≈20 year periods. The 5% significance level is spotty observed in correspondence of the ≈2 year period around 1940, 1960 and 1980, where wavelet analysis shows power 1. The same significance level is found, the 5% significance level is found in correspondence of the ≈6 year band around 1940, the ≈8 year band between 1990 and 2000 (partly outside the COI) and the ≈20 year period between 1950 and 1970. Most of the results highlighted by high wavelet power and 5% significance show with the right-pointing arrows the in-phase behavior of the analyzed time series.

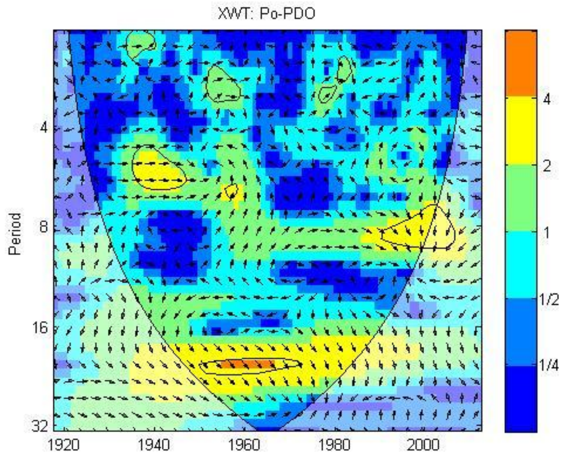

Figure 11: Po and PDO index cross wavelet analysis

6.2.5. Rhone

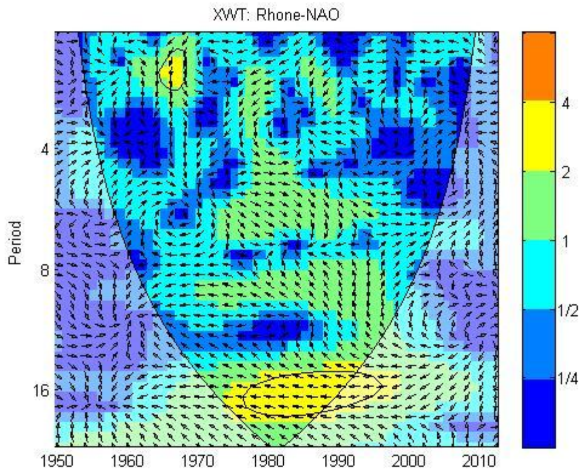

Figure 12: Rhone and NAO pattern cross wavelet analysis

The ≈2 and ≈16 year periods of Rhone river discharge and North Atlantic Oscillation XWT exhibit high power values. This information is also accompanied by the individuation of the 5% significance level that is registered, respectively, around 1965 and in the period between late 1970s and late 1990s. Power 1 signal is found in the 2-6 and ≈8 year bands. The results concerning phase angle in the ≈2 year band do not show a clear behavior of the two time series while in the ≈16 year period the anti-phase behavior of Rhone river discharge and NAO is highlighted by high power values, 5% significance level and left-pointing arrows.

7. Discussion

This study confirms that wavelet analysis is a useful tool to expand a time series into a time frequency space. The Morlet wavelet maintains a good balance between frequency and time information: for this reason, it can be considered a good choice when using wavelets for feature extraction purposes. By using two CWTs, it is possible to proceed with the XWT that shows its results for the time period covered by the two selected time series. Then, the XWT highlights regions having common power and reveals information about the phase relationship of the analyzed time series (Grinsted et al., 2004).

The EA shows a behavior that disassociate with the description given in section 3.1.. Indeed, although relevant studies have associated the positive phases of the EA with above-average precipitation over northern Europe and Scandinavia and with below-average precipitation across southern Europe, the obtained results do not confirm this type of observation. The XWT of EA and Adige, Po and Rhone river discharge highlight the in-phase behavior of the analyzed time series. However, it is important to underline how the highest cross wavelet power values are found, for all rivers, in correspondence of the same time periods, in particular around the 2-4 and ≈8 year bands.

The NAO is well known to lead, under positive phases, to above-average precipitation over northern Europe and Scandinavia and to below-average precipitation over southern and central Europe. This study confirms this observation: the XWTs between NAO and the analyzed rivers show the anti-phase behavior of the time series in the ≈2 and ≈16 year periods. Moreover, the NAO-Po and NAO-Rhone XWTs show similar results, registering common power as well as the 5% significance level in correspondence of the same year bands (i.e. ≈2 and ≈16).

From the CWT of Scandinavia, it is possible to individuate the periodical recurrence of this teleconnections pattern, showing its highest intensity in the ≈2 and ≈8 year period bands. In the same year period bands, the XWTs of Scandinavia teleconnection pattern and selected river discharge time series confirm the thesis that, under positive phases, above-normal precipitations are registered across southern Europe. This result seems relevant to speculate about the periodical influence of Scandinavia teleconnections pattern on river discharge in the Mediterranean basin.

In regard to PDO, 20-30 years phase variability has been registered. Indeed, the CWT of PDO (see Figure 27) shows that high wavelet power values are found in correspondence of the 20-30 year period band. Thus, it is not relevant to speculate about PDO influence on climate variability over shorter periods although CWT of PDO shows high wavelet power and 5% significance level also in correspondence of the ≈6 year period band.

8. Conclusion

It is possible to identify three major year bands in which most of the teleconnection patterns are related to river discharge variability in the Mediterranean area. Indeed, the most significant relationships between time series are registered in correspondence of the ≈2, ≈8 and ≈20 year period bands.

The EA pattern mostly influences the northern Rivers that flow into the Mediterranean Sea (i.e. Po and Rhone). These rivers, show an increase of freshwater flux under positive phases of the EA climate pattern. The NAO impacts rivers´ discharge at different time scales. Indeed, it shows its influence on all the selected rivers both over short periods (i.e. around 2 years) and longer ones (i.e. around 20 years) as well as its anti-phase behavior in relation to river discharge variability. The SCA shows a pronounced periodical impact on river discharge variability over the ≈2 and ≈8 year period bands. The analysis carried out from the standardized index series of SCA and the discharge time series of the Mediterranean basin Rivers clearly highlights their in-phase behavior. The PDO impacts the ≈20 year discharge variability of rivers in the Mediterranean area: under its positive phases, this climate pattern seems to be related to an increase of freshwater flow into the Mediterranean Sea.

These potential relations can be useful to predict freshwater discharge variability occurring over the Mediterranean basin. In this regard, further studies are necessary to propose and obtain more robust evaluations. This can be done by broadening this contribution with:

- the analysis of additional rivers that significantly contribute to the freshwater input into the Mediterranean Sea and whose flow is not heavily conditioned by regulatory frameworks;

- the analysis additional climate patterns whose impact is estimated to be relevant within the Mediterranean basin;
- the estimation of the impact of coupling and/or interference between two or more teleconnection patterns;
- the adoption of further statistical methods and as data driven analyses.

9. References

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