Wavelet Analysis: A Links Between the North Atlantic Oscillation and Winter Drought in the Mediterranean Watersheds of the Western Rif (North Morocco)

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Abstract

Morocco in general and the Mediterranean watersheds of the Western Rif in particular, occasionally have been affected by the negative impacts of drought, as demonstrated by the drought of 1944-1945, 1980-1984, 1994-95, 1998-2000, 2004-2005, 2011-12 and 2015-2016. This study aims (1) to identify and characterize the dry winters (DJFM) recorded in the Mediterranean watersheds of the Western Rif, and (2) to analyse the variability of precipitation in this region over the last few decades in relation to the North Atlantic Oscillation (NAO). The results of this study show that the years 1980-81, 1994-95, 1999-2000 and 2011-12 recorded the most severe winter drought. In addition, the wavelet coherence values between the NAO index and the SPI winter index (DJFM) for the period (1978-79/2014-15) show a very close relationship between the two variables for all time scales (ranging from 2 to 13 years), especially since the early 1990s. The phase angle shows a negative correlation between the drought index (SPI) and the NAO index.

Keywords: Drought, Wavelet, SPI, Western Rif, NAO

Introduction

Drought is a recurrent regional phenomenon, characterized by a severe and temporary decrease in water availability, with significant social, economic and environmental impacts (Tsakiris et *al*., 2013). It occurs in both high and low rainfall areas (Wilhite, 1993).

Due to its location on the margins of the trajectories of mid-latitude disturbances, Morocco's climate has long been marked by the occurrence of drought. The drought of 1980-1984, 1994-95, 1998-2000, 2004-2005 and

2015-2016 are so many examples of the degree to which the Moroccan economy is dependent on climate variability. The Mediterranean watersheds of the Western Rif that are the subject of this study are not exempt from what is happening at the national level. Indeed, the region occasionally experiences dry years, the latest of which is 2015-16. This drought caused, among other things, the establishment of water supply rationing in the fall of 2016.

The NAO can be defined as a large-scale meridian oscillation of air masses between two regions, one low-pressure area near Iceland and the other high pressure area over the Azores (Hurrell, 1995; Hurrell and Deser, 2015). Several studies have shown that the North Atlantic Oscillation (NAO) is responsible for the interannual variability of atmospheric circulation at mid- and high latitudes in the North Atlantic (van Loon and Rogers, 1978; Wallace and Gutzler, 1981; Barnston and Livezey, 1987; Kushnir and Wallace, 1989, Hurrell, 1995). To study the different variations of this oscillation, a NAO index has been developed since 1932 by Walker and Bliss. This index is calculated on the basis of the normalized pressure difference between two stations located near the Iceland-Azores action zones (Jones et *al.*, 1997). The stations used in the calculations are either the Lisbone - Stykkisholmur stations (Hurrell, 1995), Gibraltar - Reykjavik (Jones et *al*., 1997) or Ponta Delgada-Akureyri (Rogers, 1984).

The North Atlantic oscillation is characterized by two distinct phases with strong impacts on the climate of the North Atlantic and the contiguous continents. The phase is qualified as positive when there is synchronization between low pressure anomalies over the Icelandic region and high pressure anomalies over the subtropical Atlantic (Visbeck et *al.*, 2001). The opposite "negative" phase is marked by a subtropical high and a weaker than normal Icelandic depression (Wanner et *al.*, 2001). The transition from one phase to the other is accompanied by a multitude of changes that affect the speed and direction of westerly winds, the transport of heat and moisture between the Atlantic and neighboring continents, and the number, intensity and trajectory of weather disturbances (Rogers, 1997; Hurrell and Deser, 2015). Thus, during the positive phase, westerly winds over Europe are 8 m-s^{-1} stronger than during the negative phase, so that the wet flows associated with these winds move towards northern Europe resulting in higher than normal wet conditions from Iceland to Scandinavia, and a significant reduction in atmospheric humidity flows over southern Europe, the Mediterranean and North Africa and therefore drier conditions (Hurrell, 1995). While the negative phase is characterized by light westerly winds, less frequent and more southerly trajectories (Gordo et *al*., 2011) due to the low barometric gradient between the two action centres, resulting in wet conditions over southern Europe, the Mediterranean and North Africa, while northern Europe and Scandinavia are affected by dry conditions (Wanner et *al*., 2001).

At the scale of the Western Mediterranean, many studies have focused on the impact of NAO fluctuation on hydro-climatic variability. For example, Trigo (2011) showed that the precipitation regime in the western Mediterranean is strongly influenced by the NAO model with about 40% of winter precipitation being associated with the NAO index.

In Morocco, several studies have studied the influence of the North Atlantic oscillation (NAO) on rainfall variability. Knippertz et *al*., (2003) showed that the NAO index explains 50% of the precipitation variance in the Atlantic region and that during some months, this value reaches 60%. Also, Belaassal (1998) demonstrated that the NAO is a decisive factor in the variability of Moroccan precipitation. Lamb and Peppler (1987) and Ward et *al*., (1999) showed strong negative correlations between precipitation and the North Atlantic oscillation index (NAOI) at least for northern and western Morocco.

Although the influence of the NAO on the Moroccan climate is known, particularly for rainfall patterns, there are no studies describing the impacts of the NAO on the occurrence of droughts in the Mediterranean watersheds of the Western Rif. Thus, this work aims to identify winter dry events (DJFM) in the Mediterranean watersheds of the Western Rif during the period 1978-79 / 2014-15 on the one hand, and to study the influence of NAO phases on drought conditions in this region by using wavelet analysis techniques, on the other hand.

The document is structured as follows: Section 1 presents the study area and describes the data and methods used. The identification of dry winters and the relationships found between the NAO index and the drought index series are presented and discussed in Section 2. The conclusions of the work and perspectives for future research are presented in Section 3.

1. Study area, data and methods

The study area is located in the extreme northwest of Morocco, over an area of 3350 km² between latitudes 35º and 35.9º North, and longitudes -4.87º and -5.65º West. The climate of the region is Mediterranean. The summer is hot and very dry, and the winter is mild and rainy. The annual average rainfall for the period 1978-79 and 2014-15 is 667 mm at Sebta station, but exceeds 1000 mm on the summits (1094 mm at Bab Taza). In terms of hydrology, river flows show strong monthly and interannual variations.

The rainfall data used in this study come from 5 rainfall stations under the responsibility of the Hydraulic Basin Agency of Lokkous. A reference period 1978-79/2014-15 was defined, this period having the particularity of presenting common data for all the stations selected for the study. The winter NAO index data (December to March) used in this study were compiled by

Hurrell (1995) based on the normalized pressure difference between the Lisbone station (Portugal) and the Stykkisholmur station (Iceland).

In this work, the methodological approach adopted is based on the use of the standardized precipitation index (SPI) to identify dry events on the one hand, and wavelet analysis to assess the drought/ North Atlantic oscillation of the (NAO) relationship on the other hand.

1.1 Approach to calculating the Standardized Precipitation Index (SPI)

The approach to calculating the Standardized Precipitation Index (SPI) is extensively detailed in the literature, especially in the work of: Tsakiris et *al*, (2007) and Şen (2015). This process includes the following steps:

The first step is to find the probability density function that best describes the distribution of precipitation. According to Thom (1958), the Gamma distribution is well adapted to precipitation time series. The Gamma distribution is defined by its probability density function as follows:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}} \quad for\ x > 0$$

where $\alpha > 0$ and $\beta > 0$ are the shape and scale parameters respectively, x is the amount of precipitation and $\Gamma(\alpha)$ is the Gamma function which is defined by:

$$\Gamma(\alpha) = \int_0^{+\infty} y^{\alpha-1}\, e^{-y} dy$$

Parameters α and β of the Gamma probability density function are optimally estimated using the maximum likelihood method:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right), \ \beta = \frac{\bar{x}}{\alpha} \quad and \quad A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$$

where n is the number of observations and $\bar{x}$ is the average of the observed precipitation.

The resulting parameters are then used to find the cumulative probability of a given precipitation event by integrating the probability density function g(x):

$$G(x) = \int_0^x g(t)dt = \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})} \int_0^x t^{\hat{\alpha}-1} e^{-\frac{t}{\hat{\beta}}} dt$$

G(x) represents the cumulative probability that a quantity of precipitation has been observed over a given period.

Since the Gamma function is not defined as $x = 0$ and a rainfall series may contain zeros, the cumulative probability becomes:

$$H(x) = q + (1 - q)G(x)$$

where *H(x)* is the cumulative probability or distribution function of observed precipitation and q is the probability of not having precipitation estimated from the analyzed series.

The method described in Edwards and McKee (1997) uses the technique developed by Zelen and Severo (1965) for converting the cumulative probability into a standard normal variable Z of 0 mean and unit standard deviation.

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad for\ 0 < H(x) \leq 0{,}5$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad for\ 0{,}5 < H(x) \leq 1$$

where:

$$t = \sqrt{ln\left(\frac{1}{(H(x))^2}\right)} \qquad for\ 0 < H(x) \leq 0{,}5$$

$$t = \sqrt{ln\left(\frac{1}{(1 - H(x))^2}\right)} \quad for\ 0{,}5 < H(x) \leq 1$$

$$c_0 = 2{,}515517\ ;\ c_1 = 0{,}802853\ ;\ c_2 = 0{,}010328\ ;\ d_1 = 1{,}432788$$
$$d_2 = 0{,}189269\ ;\ d_3 = 0{,}001308$$

1.2 The wavelet transform

The wavelet transform is a useful mathematical method of decomposing a time series in time-frequency space using an analysing function called the mother wavelet (Daubechies, 1990). The continuous wavelet transform of a time series x(t) by a given mother wavelet is as follows (Partal, 2012):

$$\psi_{(\tau,s)} = s^{-\frac{1}{2}} \int_{-\infty}^{\infty} x(t)\psi^*\,(\frac{t-\tau}{s})dt$$

where: $\psi_{(\tau,s)}$ denotes the daughter wavelet, $(*)$ represents the complex conjugate of the ψ scaled and translated wavelet, $\boldsymbol{s}^{-\frac{1}{2}}$ is the normalization factor to have unit energy $\left\|\psi_{(\tau,s)}\right\| = 1$, $\boldsymbol{t}$ represents time, $\boldsymbol{\tau}$ the translation parameter and ***s*** is the dilation parameter controlling the width of the wavelet.

The major advantage of the continuous wavelet transform is its ability to determine the dominant modes of variability in a given signal and to locate them in the time-scale or time-frequency space. The effectiveness of this technique in analyzing hydro-climatic signals has been well illustrated, for example, in the work of Farge (1992), Torrence and Compo (1998), Torrence and Webster (1999), and Coulibaly and Burn (2004).

In addition to the traditional uses of the wavelet transform (the continuous or discrete wavelet transform), there are several related techniques that are very useful for quantifying the relationship between non-stationary time series in the time-scale or time-frequency domain. These are essentially:

- The wavelet coherence: mathematically, the wavelet coherence function can be described as a linear correlation between two processes/signals (Vadrevu and Choi, 2011). This correlation is localized in the time-frequency space (Grinsted et *al*., 2004).

The squared wavelet coherence between two time series x(t) and y(t) is defined as the absolute squared value of the smoothed cross-wavelet spectrum, normalized by the smoothed wavelet power spectra (Torrence and Webster, 1999).

$$R_n^2(s) = \frac{\left|S\left(s^{-1}W_n^{XY}(s)\right)\right|^2}{S(s^{-1}|W_n^X(s)|^2)S(s^{-1}|W_n^Y(s)|^2)}$$

where S is a smoothing operator that is used to balance time-frequency resolution and statistical significance (Mihanović, 2009).

- The phase difference between two time series provides information on the phase delay between time series oscillations as a function of frequency (Bloomfield et *al*., 2004). The determination of the phase difference $\phi_{x,y}(f,\tau)$ can be given by the following equation (Torrence and Compo, 1998; Grinsted, 2004):

$$\phi_{x,y}(f,\tau) = tan^{-1}\frac{\Im(\langle W_{x,y}(f,\tau)\rangle)}{\Re(\langle W_{x,y}(f,\tau)\rangle)}$$

where $\Im(\cdot)$ and $\Re(\cdot)$ are the imaginary and real parts of the cross wavelet spectrum.

The Matlab codes used in this study for wavelet analysis were implemented by Grinsted (2004) and are available via the link: https://noc.ac.uk/marine-data-products/cross-wavelet-wavelet-coherence-toolbox-matlab. Also, the codes developed by Torrence and Compo (1998) were used: http://atoc.colorado.edu/research/wavelets/

2. Results and discussion

2.1 Identification of dry events

The analysis of the results of the calculation of the winter SPI index for the various stations (Fig. 1) showed that the dry years of 1980-81, 1994-95, 1999-00 and 2011-12 affected all the stations studied. In addition, there were other more limited drought such as those in 1991-92 and 1992-93. The winter of 2011-12 was the driest during the period of this study, with an average SPI of -2 at all stations, with a minimum of -2.23 at the Chibich station. The winter of the hydrological year 1994-95 was characterized by an average SPI of -1.91, with a minimum of -2.07 at the Nakhla dam Station. During the 1998-99 winter drought, the average intensity was -1.77 compared to a minimum of -1.96 at Beni Hassan station.

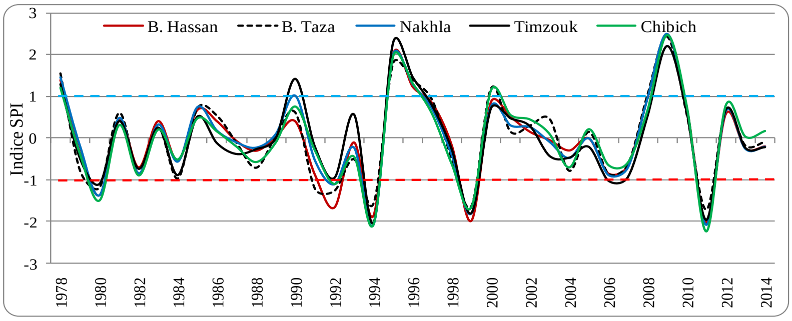


Figure 1. Fluctuation of winter SPI of the stations analysed during 1978-79 and 2014-15

The percentage for dry, normal and wet winter was obtained. Thus, it is estimated that drought conditions occurred 13.5% of the time covered by this analysis compared to 13.5% and 73% for wet and normal winter respectively. All stations have more or less similar percentages of dry winters (14% in Beni Hassan, Nakhla and Chibich, and 16% in Bab Taza), showing a homogeneity of local climatic conditions. This homogeneity is demonstrated by a correlation coefficient of 96% on average between the SPI values of all stations.

The drought recorded caused a high rainfall deficit. Indeed, during the winter of 2011-12 the deficit reached 86%, 82%, 81% and 80% for the stations of Chibich, Nakhla, B. Hassan and Timzouk respectively. As for the drought of 1994-95, it was accompanied by a decrease in rainfall equivalent to 80% on average, with only 82 mm of rainfall at Beni Hassan station compared to an average of 435 mm; and 69 mm at Nakhla dam compared to 402 mm during a normal winter.

The drought that occurred during this period had a significant impact on surface water resources, especially in the so-called critical years, such as 1994-95 and 2011-12. During the drought year 1994-95, water resources at the K. Kouriren station on the Wadi Laou River were significantly reduced by 97% compared to the average of 1978-2012, and by 95% at the Torreta station on the Wadi Martil River. For the drought year of 2011-12 decreases with proportions of 95% and 96% were observed at the K. Kouriren and Torreta station respectively.

The most severe and critical droughts recorded in the study area date back to the 1980s and 1990s, which corresponds to the period when climatic conditions were abnormally dry over the whole of southern Europe and the Mediterranean in relation to a persistent positive phase of NAO (Hurrell and van Loon, 1997).

2.2 Results of the wavelet analysis

The analysis will focus on the coherence between the drought index for the months of December to March (DJFM) and the NAO index, since the latter is more active at this time of year (Hurrell et *al*., 2003). In addition, the inter-decadal variability of NAO appears to be high from December to March and its influence on climate reaches its maximum during this period (Osborn et *al*., 1999).

The results of the continuous wavelet transform (Fig. 2) show that for the NAO the energy is high in two bands 2-4 years and 4-8 years but without any statistical significance, while for the drought index (DJFM) the power of the wavelets is high in the band 4-8 years during 1990-2003, the statistical significance of this power peak has been demonstrated against a red noise process based on the autoregressive coefficient of order 1 (AR1) with 1000 substitute data sets.

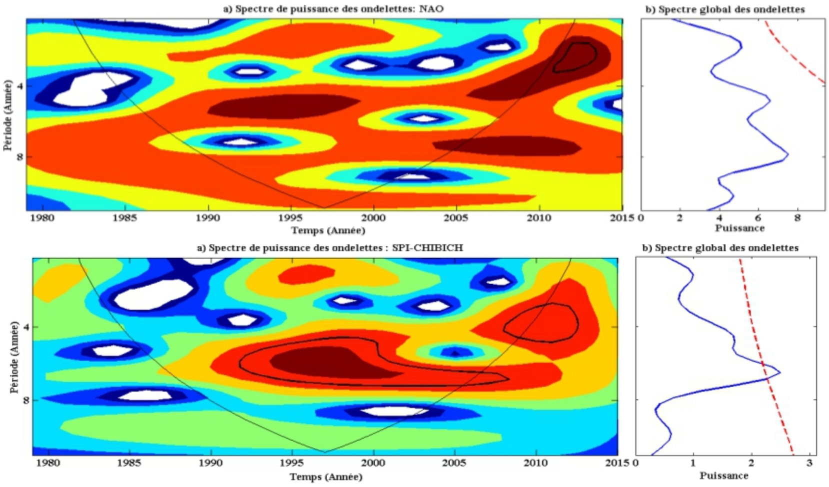


Figure 2. a) Wavelet power spectrum using the Morlet wavelet mother. The thick black contour is the 5% significance level, using a red noise spectrum. The thin "U" line represents the cone of influence where the region is not influenced by edge effects. b) The global wavelet spectrum (blue line) and the dotted line is the significance level of 5% against a red noise process.

The coherence between the winter SPI values calculated for the 5 selected stations and the North Atlantic Oscillation index (NAO) shows that the stations are subject to the influence of the so-called oscillation (Fig. 3). However, it remains variable both in time and scale. In general, several characteristic periods can be distinguished on the basis of the presence or lack thereof of significant SPI-NAO coherence. Thus, for the 2-year variability mode, all stations are characterized by the presence of a strong and significant coherence since the early 1990s, unlike the previous period when the coherence was weak and non-significant. For the 4-year scale, the SPI-NAO coherence only became statistically significant for all stations in the mid-

1990s. This study shows also the existence of a vertical band in the time-scale diagram between 2-4 years characterized by very low coherence values. On the 8-year scale, the SPI/NAO correlation appears to be very low and only becomes strong and significant after the early 2000s for all stations. Consequently, the homogeneity of the rainfall response of the stations studied to the climate forcing of the North Atlantic oscillation is quite obvious.

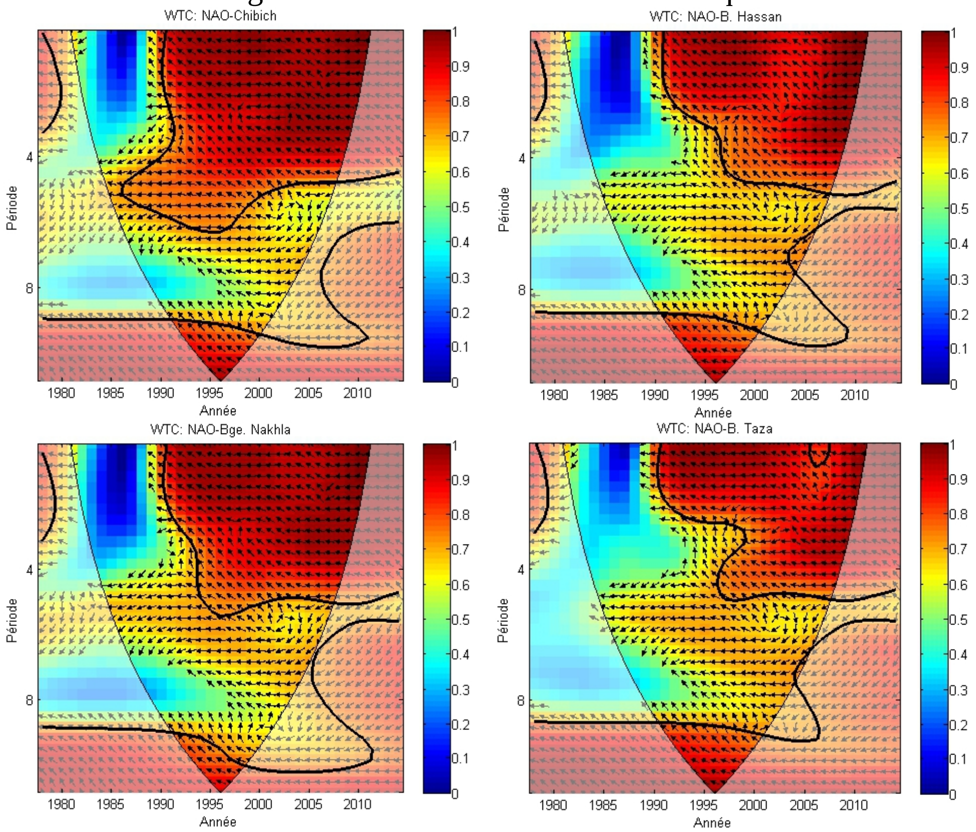
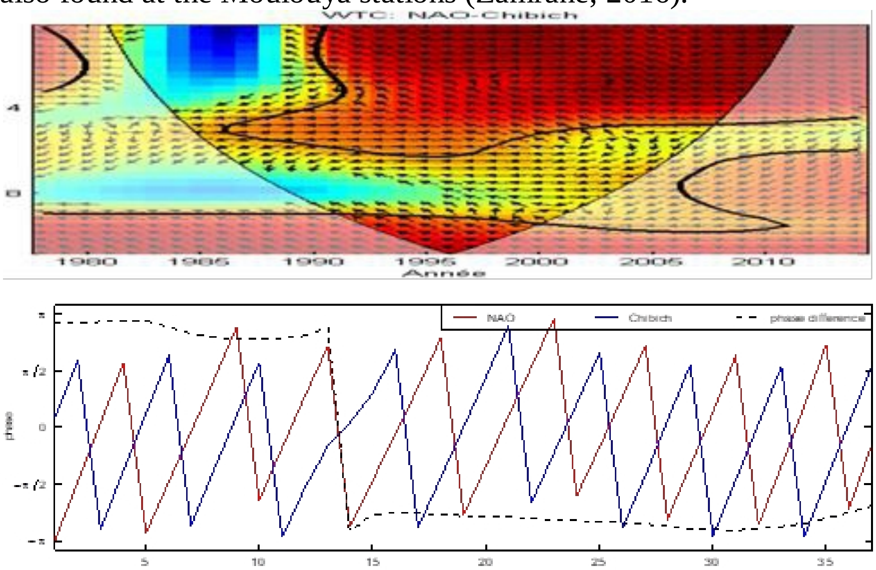


Figure 3. Wavelet coherence analyses between the NAO-SPI time series. The thick black contour indicates the level of significance α = 5% implemented by the Monte Carlo method using a red noise model (AR1). The cone of influence (thin black curve) represents the region not influenced by edge effects. The arrows indicate the relative phase relationship of the time series (right pointing: perfect correlation (in phase); left: anti-correlation (anti-phase); down: the NAO leads the SPI by 90°).

The study of the phase difference shows that the relationship between the winter SPI time series and the NAO index is in anti-phase for all stations and on almost all time scales. The arrows pointing to the left and the phase difference between [π/2, π] and [-π, -π/2] indicate a negative correlation (Fig. 4). Consequently, rainfall in the Mediterranean watersheds of the Western Rif tends to be lower (higher) when the NAO index is in its positive (negative) phase. This dichotomy is best illustrated by the winter of 1994-95 and 1995-96. Thus, during the first winter the drought index was -2.07 at the Nakhla dam station for a NAO index of 3.96, while the second winter recorded an SPI index of 1.98 at the same station against a NAO equivalent to -3.78.

Since wavelet coherence is considered as a linear correlation (similar to the determination coefficient r^2) between two processes/signals, it can be used to determine the proportion of variance explained by an explanatory variable (x) in the total variability of a dependent variable (y). Thus, using wavelet coherence, the contribution of the NAO to the variability of the SPI and therefore to rainfall variability was quantified for different variability modes (Fig. 5). The coherence at the level of the 2-year mode shows contributions ranging from 76% in Timzouk to 79% in Chibich. This contribution has been strong since 1991, exceeding 90% at all stations (95% at Bab Taza, 96% at the Nakhla dam and 97% at Chibich). This is an additional argument for the homogeneity of the NAO's influence on the stations studied. The 4-year mode shows an average NAO coherence between 64% in Beni Hassan and 75% in Chibich; it has been more important since 1995. The 2-4 and 4-8 year modes show a coherence that varies between 70% and 78% for the first fluctuation mode (2-4 year) and between 60% and 64% for the second. Smaller contributions are recorded for the 8-year mode since they rarely exceed 61%. A strong contribution can be observed for the 8-12 year mode between 72% and 83%. Finally, for all time scales combined, the NAO explains on average 67%, 69%, 70%, 70% and 72% of the total variance of drought index at Timzouk, Beni Hassan, Bab Taza, Nakhla and Chibich stations respectively. The increase in coherence values, especially after 1995, observed in this study was also found at the Moulouya stations (Zamrane, 2016).



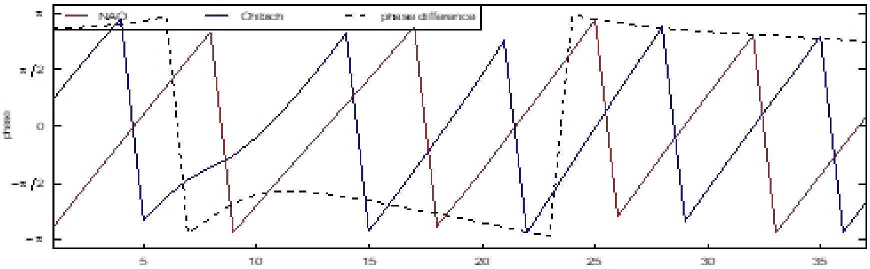


Figure 4. Wavelet coherence and phase analysis of time series. The upper panel represents the coherence of the wavelets (NAO - SPI Chibich). The middle and bottom panel represent the phase analysis between the two series (in blue and red). The white/green rectangles represent a few periods of time when the relationship (NAO - SPI Chibich) is in anti-phase. The dotted black line indicates the phase difference within an interval of [-π, π].

According to the results of the study, the climatic factor (NAO) explains on average 70% of the total variance of the fluctuations of the winter SPI index. The percentage variance not explained by the NAO is probably due to other factors, the most important of which would be the effects of the site (orography, exposure) and the influence of the West Mediterranean Oscillation (WeMO). The latter plays a major role in the fluctuations in rainfall across the Western Mediterranean. Thus, in Morocco, the influence of WeMO on hydrological variability in the Tensift, Sebou and Moulouya watersheds has been well demonstrated by Zamrane (2016). For the Moulouya watershed, the author estimated that the WeMO/Rainfall coherence values vary between 51% and 69% in Berkane and between 58% and 74% in Guercif, while in the Sebou watershed they vary between 66% and 86% in Ait Khabbach and between 64% and 68% in Bab Ouender, depending on the mode of variability.

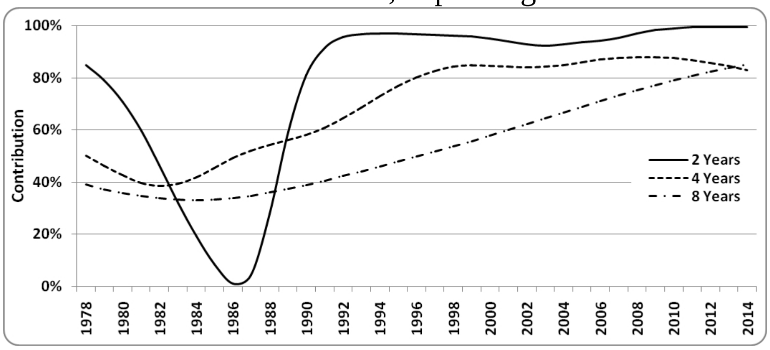


Figure 5. Percentage of the NAO contribution to the total variability of winter SPIs at the Nakhla Dam Station for the 2-year, 4-year and 8-year variability modes.

Conclusion and perspectives

During this work, it was possible to identify and characterize the drought observed in terms of intensity and associated rainfall and hydrometric deficit. Thus, the most critical winter droughts recorded in the Mediterranean watersheds of the Western Rif during the period 1978-79 / 2014-15 are those of the years 1980-81, 1994-95, 1999-2000 and 2011-12. For example, the last one was accompanied by an average rainfall deficit of 81% with a maximum of 86% at the Chibich station. The droughts recorded had a negative impact on water resources, especially in 1994-95 when they fell by 97% at K. Kouriren station.

The results obtained show that the climatic factor (NAO) explains on average 70% of the total variance of the fluctuations of the winter SPI index, which means that the role of this atmospheric circulation mode is crucial to the occurrence of dry events in the study area. As well, the results indicate that the stations studied have reacted in a similar way to the climate forcing produced by the North Atlantic oscillation and the resulting atmospheric circulation models, especially since the early 1990s. Thus, the coherence at the level of the 2-year mode between the NAO and the winter SPI has exceeded 90% since 1991 at all stations (95% at Bab Taza, 96% at the Nakhla dam and 97% at Chibich).

The droughts identified coincided with a positive phase and high NAO index, suggesting that any blocking of the NAO in a positive phase will lead to frequent drought with all the negative impacts that may occur in this region of the Moroccan Mediterranean.

This study suggests the need to further investigate the occurrence of drought in relation to other climate indexes such as the Western Mediterranean Oscillation (WeMO), to provide essential information on the atmospheric factors that combine with the NAO to promote the onset and repetitiveness of dry events. Thus, a partial and multiple wavelet coherence study between drought index, the NAO and the WeMO, would be the basis for future research.

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