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Multiscale analysis of climatic teleconnections and rainfall variability in Northern Algeria

(An advanced assessment of water resources in the face of climate change)

تحليل متعدد المقاييس للترابطات المناخية عن بعد وتقلبات تساقط الأمطار في شمال الجزائر

(تشخيص متقدم للموارد في مواجهة التغير المناخي)

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Abstract

Northern Algeria is a hotspot of vulnerability to climate change, where the anthropogenic acceleration of aridity directly threatens water security. The non-linear, non-stationary and highly intermittent nature of rainfall limits the effectiveness of conventional statistics in planning water resource management. This review compares the contributions of four families of advanced signal processing algorithms applied to monthly and daily rainfall time series, in order to analyse their multi-scale variability and teleconnections. Spectral and multifractal analyses confirm the scale invariance of rainfall and reveal significant spatio-temporal heterogeneity. Hurst analysis and the continentality effect highlight contrasting patterns: coastal regions exhibit long-term memory, leading to a clustering of extreme events (the Joseph effect), whilst inland areas display anti-persistent and patchy behaviour. In the long term, empirical mode decomposition (EMD) reveals a strong and systematic downward trend in precipitation over the last 60 years. Finally, cross-correlation analysis and TDIC patterns demonstrate the predominance

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and robustness of the Mediterranean Oscillation (MO) in high-frequency local variability compared with the NAO, whilst remote indices (ENSO, AMO, PDO) dictate decadal modulations. These in-depth mathematical analyses go beyond the theoretical framework to provide essential decision-making tools for water security. They pave the way for a transition from reactive management to predictive governance: seasonal optimisation of dams by anticipating teleconnections, redesigning hydraulic structures to cope with multifractal flash floods, and strategic storage planning during persistent cycles.

Keywords: Multi-scale analysis, rainfall, climate change, water security, Northern Algeria.

ملخص

تعتبر منطقة شمال الجزائر، بؤرة ساخنة لسرعة التأثر بالمناخ، حيث يهدد التسارع البشري المنشأ لظاهرة الجفاف الامن المائي بشكل مباشر. وتحد الطبيعة غير الخطية، وغير المستقرة، والشديدة المتقطعة لهطول الامطار من فاعلية الإحصاءات التقليدية في تخطيط إدارة الموارد البشرية. وقد قارنت هذه الدراسة المرجعية بين اسهامات أربع مجموعات من خوارزميات معالجة الإشارات المتقدمة، المطبقة على السلاسل الزمنية الشهرية واليومية لهطول الامطار، وذلك بغرض تحليل تقلباتها متعددة المقاييس وروابطها المناخية عن بعد. وتؤكد التحليلات الطيفية والمتعددة الكسيرات ثبات مقاييس هطول الامطار، كما تكشف عن تباين مكاني وزماني ملحوظ. ويسلط تحليل 'هيرست' وتأثيرات القارية الضوء على أنماط متباينة، حيث تظهر المناطق الساحلية ذاكرة طويلة المدى تؤدي الى تكتل الظواهر المتطرفة (تأثير جوزيف) في حين تبدي المناطق الجزرية سلوكا غير مستمر ومتناثرا. وعلى المدى الطويل، يكشف تفكيك الأنماط التجريبية عن اتجاه نزولي قوي ومنهجي في معدلات التساقط على مدار الستين عاما الماضية. وأخيرا، يوضح تحليل الارتباط المتبادل وانماط معامل الارتباط هيمنة وقوة التذبذب الديناميكي المعتمد على الزمن المتوسطي في التقلبات المحلية عالية التردد مقارنة بتذبذب شمال الأطلسي، بينما تفرض المؤشرات النائية، تعديلات عقدية. وتتجاوز هذه التحليلات الرياضية المعمقة الإطار النظري لتوفير أدوات أساسية لصنع القرار من اجل تحقيق الامن المائي. كما انها مهدت الطريق للانتقال من الإدارة القائمة على رد الفعل الى الحوكمة الاستباقية، المتمثلة في الاستخدام الأمثل الموسمي للسدود عبر التنبؤ بالروابط المناخية عن بعد، وإعادة تصميم المنشآت الهيدروليكية لمواجهة الفيضانات الخاطفة متعددة الكسيرات، والتخطيط الاستراتيجي للتخزين خلال الدورات الجافة المستمرة.

الكلمات المفتاحية: تحليل متعدد المقاييس، تساقط الأمطار، تغير المناخ، الأمن المائي، شمال الجزائر.

I. Introduction

For several years now, extreme hydro-climatological and meteorological events, such as floods and torrential rain, hurricanes and prolonged droughts, have been becoming increasingly frequent across the globe. The cause: climate change. Whilst these disruptions are mainly attributed to human-induced factors, a fundamental question remains for our region: to what extent is the convergence of natural cycles and current climate disturbances affecting the resilience of our water systems?

However, despite extensive research, climate variability and rainfall dynamics in particular remains a complex subject.

For around 5,000 years, the entire region of North Africa, the Sahara and the Sahel has been undergoing a process of gradual desertification and persistent aridity. Although initially a natural process, it is now being drastically accelerated and exacerbated by human pressures. This major human influence is now reshaping hydrological cycles, making our ecosystems particularly vulnerable.

In order to unpick the intrinsic cycles of these fluctuations, we propose an approach based on a multi-scale analysis of rainfall time series at monthly and daily intervals. This study aims to analyse the periodicity, trends and short-, medium- and long-term oscillations in the rainfall data.

Next, we will analyse indicators of large-scale oceanic and atmospheric oscillations. The aim is to highlight the influence of teleconnection patterns on rainfall dynamics in northern Algeria.

II. Overview of the study area

2.1. Study area

The study area extends across northern Algeria, covering an area of approximately 200,000 km² (Fig. 01). This area is geographically bounded to the north by the Mediterranean coastline and to the south by the natural barrier formed by the Saharan Atlas and the Aurès mountains. Owing to its strategic location, this region constitutes the country's water reservoir. It is, in fact, the region with the highest rainfall, home to the bulk of the country's water resources, with more than 80 dams in operation.



Fig. 01: - Location of the study area corresponding to Northern Algeria.

2.2. Datas

The data are drawn from the databases of the National Water Resources Agency and the National Meteorological Office, via a network of stations reflecting the full range of climatic conditions in northern Algeria (the coast, the Tell region and the High Plateaus).

We also looked at atmospheric and oceanic oscillation indices. Teleconnection patterns have a decisive influence on regional precipitation dynamics. Our analysis focused on:

- **Global indices**: the North Atlantic Oscillation (NAO), the El Niño–Southern Oscillation (ENSO), the Arctic Oscillation (AO), the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO).
- **Regional circulation patterns**: the Mediterranean Oscillation (MO) and the Western Mediterranean Oscillation (WeMO), which have a direct impact on the frequency and intensity of rainfall events in North Africa.

These time series (NAO, ENSO and WeMO) are compiled and updated by the Climatic Research Unit (CRU) at the University of East Anglia in the United Kingdom.

Much of this data is also centralised and disseminated by the NOAA (*National Oceanic and Atmospheric Administration*).

III. The Methodology

Our approach combines a univariate analysis of climate signals with a cross-correlation analysis, in order to reveal the dynamic relationships

between precipitation and oscillations. The relevance of this approach lies in the synergy of four complementary families of algorithms: the Hilbert-Huang Transform (HHT), the Wavelet Transform, the Stockwell Transform and the Time-Dependent Intrinsic Correlation (TDIC).

This framework is underpinned by supplementary statistical tools that refine the diagnostic analysis. These tools will be briefly discussed at the start of the preliminary analyses. The preliminary results are based on long-term dependence (R/S), spectral analysis, fractal analysis and multifractal analysis.

3.1. The Hilbert-Huang Transform (HHT): The HHT was used to extract background trends. The method was proposed by Huang et al. (1998, 2003) to efficiently extract information in both the time and frequency domains directly from the data. It is adaptive, efficient and free from prior assumptions. It combines Empirical Mode Decomposition (EMD) with Hilbert Spectral Analysis. The Hilbert transform, denoted $H\{x\}(t)$ or $y\hat{}(t)$, of a function of the real variable x(t) is a linear transformation that extends a real signal to the complex domain, such that it satisfies the Cauchy–Riemann equations. By definition:

$$\mathcal{H}\{x\}(t) = \hat{y}(t) = (h * x)(t) = vp\left\{\int_{-\infty}^{\infty}(\tau)h(t-\tau)d\tau\right\} = \frac{1}{\pi}vp\left\{\int_{-\infty}^{\infty}\frac{x(\tau)}{t-\tau}\,d\tau\right\} \qquad (01)$$

where

$$h(t) = \frac{1}{\pi t} \qquad (02)$$

and

$$vp\left\{\int_{-\infty}^{\infty}x(\tau)h(t-\tau)d\tau\right\} = \lim_{\epsilon\to 0}\left\{\int_{-\infty}^{t-\epsilon}x(\tau)h\left(t-\tau\right)d\tau + \int_{t-\epsilon}^{+\infty}x(\tau)h(t-\tau)d\tau\right\} \qquad (03)$$

and where is the abbreviation for Cauchy principal value. The Hilbert transform was used to calculate instantaneous frequencies and amplitudes and to describe the signal in more local terms.

The main idea behind empirical modal decomposition is to regard the signal as a superposition of several oscillations, each with its own characteristic scale. The decomposition is carried out iteratively, assuming at each step that the signal is the sum of a slow component the 'residual'

and a fast component the 'IMF'. The iteration continues by decomposing the resulting residual once more; ultimately, a time series x(t) which is the sum of a finite number of IMFs and a residual r(t) .

$$x(t) = \sum_{j=1}^{N} IMF_j(t) + r(t), \qquad (N \in \mathbb{N}^*), \qquad (04)$$

where is the oscillation, is the residual of the decomposition and is the number of IMFs (or modes).

3.2. The Wavelet Transform: The Morlet continuous wavelet transform was chosen for the time-scale coherence analysis (Hsiang, 2010). The continuous wavelet transform of a signal x(t) produces a local wavelet spectrum w_x (a,τ), defined by the following equation:

$$w_x(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t)\varphi\left(\frac{t-\tau}{a}\right)dt \qquad (05)$$

Where φ (t) represents the wavelet function, which acts as a convolution kernel and may be real or complex; the parameter a represents the scale factor and controls the expansion or contraction of the function φ (t); the parameter τ is interpreted as a time-shift or frequency-shift factor for the function (t).

3.3. The Stockwell Transform: This method is renowned for its cyclic accuracy. It uses a variable, adaptive window length and employs the Fourier kernel to provide phase information referenced to the origin of time (Lokhande, 2017). The S transform defined by Stockwell for a time-varying signal is:

$$S_x(\tau,f) = \int_{-\infty}^{+\infty} x(t)w(t-\tau,f)e^{-2\pi ift}dt \qquad (06)$$

Where the window function $w(\tau - t, f)$ is chosen as:

$$w(t,f) = \frac{1}{\sigma(f)\sqrt{2\pi}} e^{\frac{-t}{2\sigma f^2}} \qquad (07)$$

and $\sigma(f)$ is a function of frequency as follows:

$$\sigma(f) = \frac{1}{|f|} \tag{08}$$

Consequently, transformation S becomes :

$$S_x(\tau, f) = \frac{|f|}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} x(t) e^{\frac{-(t-\tau)^2 f^2}{2}} e^{-i2\pi f t} dt \tag{09}$$

The 1D function of the time variable τ and the fixed frequency *f_1* defined by *S_x=(τ,f_1)* is called the channel. The 1D function of the frequency variable *f* and the fixed time *τ_1* defined by *S_x=(τ_1,f)* is called the local spectrum (Yanwei, 2011; Yun et al., 2013; Lokhande, 2017).

3.4. Time-Dependent Intrinsic Correlation (TDIC): This method is strongly recommended for characterising non-stationary local interactions (Chen et al., 2010; Huang and Schmitt, 2010; Yang et al., 2020). Time-dependent intrinsic correlation analysis is used to determine the relationship between climate oscillation indices and rainfall at different timescales. This time-dependent intrinsic correlation is defined as follows:

$$R_{ij}(t_k^n) = Corr(C_{1,i}(t_w^n) C_{2,j}(t_w^n)) \tag{10}$$

In the time domain, the cross-correlation function of two signals (t) and $y(t)$ is determined to assess a possible correlation. Pearson's linear correlation coefficient is the most commonly used cross-correlation function and is defined as follows:

$$y_{xy} = \frac{cov((t), y(t))}{\sigma(x(t))\sigma(y(t))} \tag{11}$$

where $cov(t)$ is the covariance of two signals;

$d\sigma(t)$ is the standard deviation of the signal;

y_{xy} : can vary from −1 to +1 (where a value of 0 indicates no correlation between the two signals; a value of −1 indicates a perfect negative correlation; and a value of +1 indicates a perfect positive correlation).

IV. Results and Discussion

4.1. Preliminary analyses

For long-term dependence (R/S), it is common in hydrological studies to observe different behaviours depending on the station or timescale. In Northern Algeria, two distinct behaviours have been observed. In coastal regions, the Hurst coefficient (H) is generally slightly greater than 0.5; in such cases, the system exhibits long-term memory. Events tend to cluster together. A period of rain is slightly more likely to be followed by further rainy days (Fig. 02). However, in inland regions and on the high plateaus, H is less than 0.5; there, the system is unstable, indicating that the distribution of rainfall over time is not uniform. Rainfall therefore forms a Gaussian noise with a slight anti-persistence phenomenon.

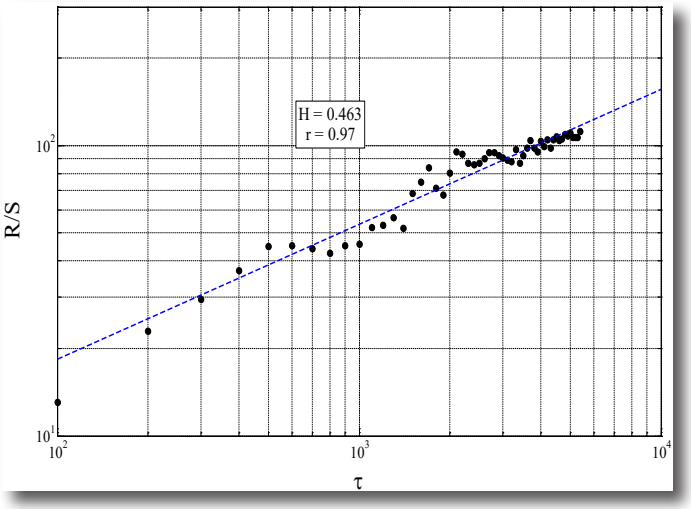


Fig. 02: Example of an *R/S* analysis of the daily rainfall series for station 013304 in the Wilaya of Tiaret, showing a slight anti-persistence phenomenon.

We used various techniques to estimate the Spectral Power Density (SPD) in order to isolate the dominant frequency components (Djoudi, 2016). For station 60390 at Dar El Beida (Fig. 03), the scale invariance range is characterised by a spectral exponent of less than 1, highlighting the conservative nature of the rainfall time series (Taouti, 2012).

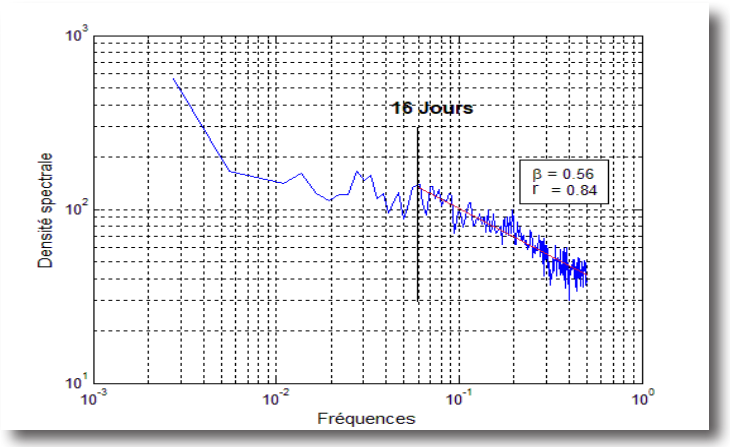


Fig. 03: - Average spectrum of the daily rainfall series 60390 for Dar El Beida, with a spectrum exponent of 0.56, which is a conservative estimate.

For the fractal analysis, we calculated the fractal dimension using the box-counting algorithm for the Mandelbrot relation. The map (Fig. 04) highlights a continentality effect, whereby the fractal dimension decreases with aridity, revealing an increasingly patchy and intermittent rainfall pattern further inland.

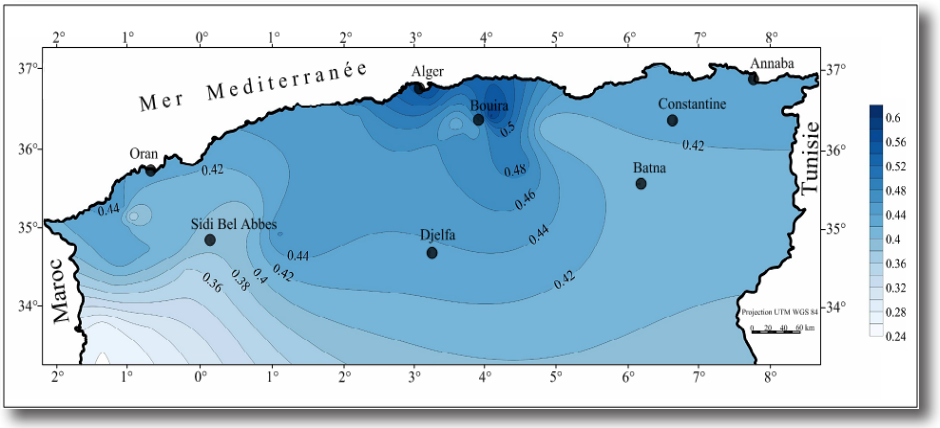


Fig. 04: - Map of the fractal dimension of Northern Algeria.

Furthermore, multifractal analysis using trace moments as a function of the scale ratio λ reveals multifractal behaviour across a range of scales from 1 to 32 days for stations located on the Oran Plateau and the highlands (Taouti, 2012). For stations located on the coast, the behaviour of trace moments as a function of the scale ratio λ reveals multifractal behaviour over a range of scales from 1 to 16 days. These results suggest power-law behaviour. The property of scale invariance, previously detected

by spectral analysis, is confirmed by examining moments of different orders. The multifractal behaviour is only evident for scales ranging from approximately 1 day to 1 month for the rainfall time series.

Analysis of the variation in the generalised Hurst exponent reveals the intrinsic multifractal characteristics of the rainfall regime in the study area. The multifractal spectra take the form of a parabolic curve (Fig. 05), indicating a heterogeneous structure composed of regions characterised by different Hölder exponents(α), which further confirms the multifractal structure of the analysed rainfall series (Taouti and Chettih, 2026).

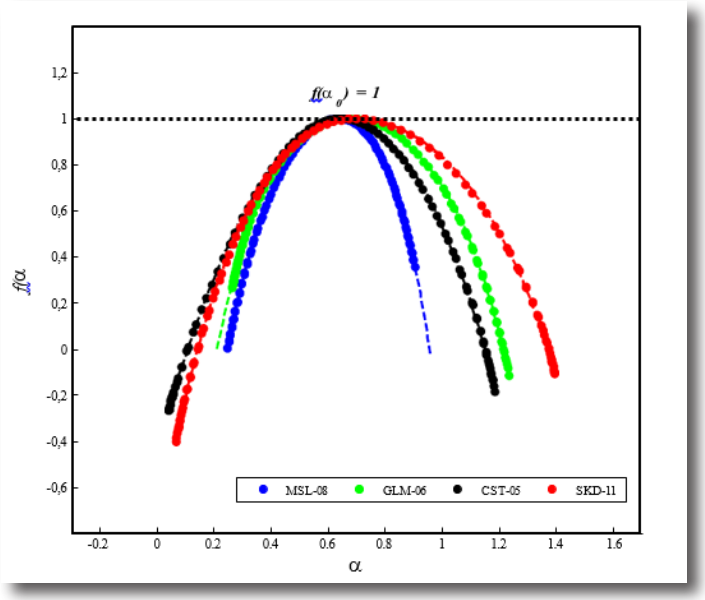


Fig. 05: - Multifractal spectra of daily rainfall at four stations in northern Algeria.

4.2. Hilbert-Huang analysis

When applied to rainfall data from the Dar El Beida station for illustrative purposes, the IMFs show that there are significant fluctuations, particularly on a small scale. However, the residuals indicate that rainfall is on a downward trend (Fig. 06).

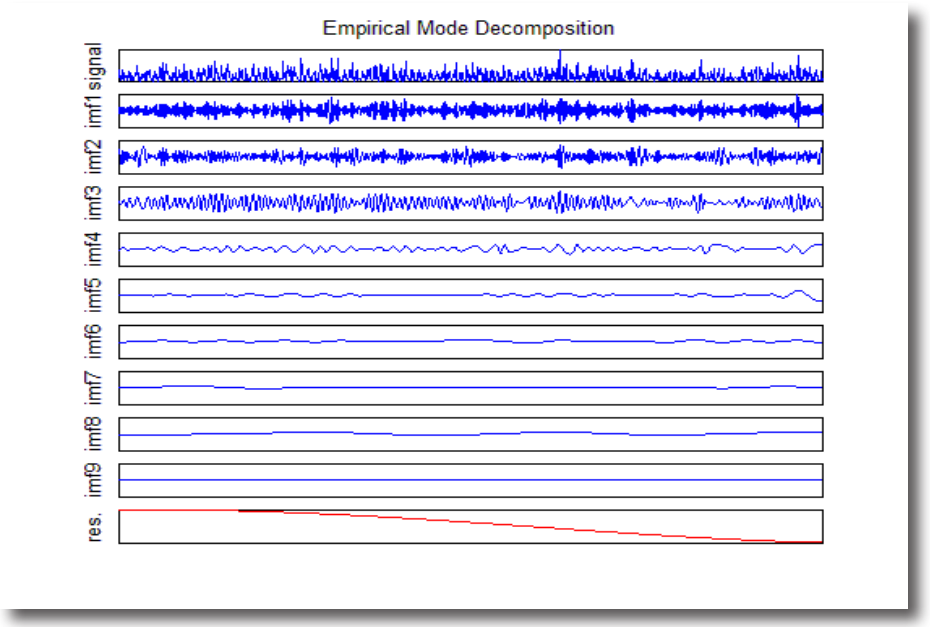


Fig. 06: - EMD decomposition of monthly rainfall at the Dar El Beida station: the original signal (Rainfall), the 9 IMFs, and the residual (from top to bottom).

The Hilbert-Huang spectrum (Fig. 07) shows that the most characteristic and highest frequencies are those corresponding to the annual cycle. Other, less pronounced frequencies corresponding to cycles of 6 months, 4 months and 3 months are also visible. These same findings also apply to the other monthly rainfall series for coastal and inland regions.

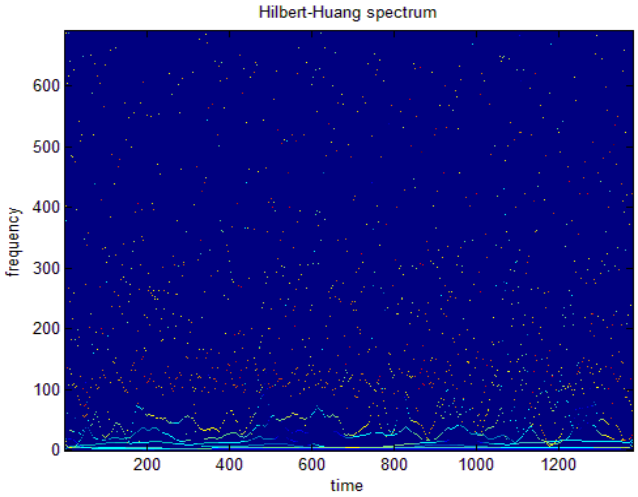


Fig. 07: - Hilbert-Huang spectrum of monthly rainfall at the Dar El Beida station.

As a guide, for the monthly rainfall series from the stations at Dar El Beida, Annaba, Oran and Aïn Oussera, a cross-scale analysis (Fig. 08) reveals an increase in scalar coherence between teleconnections and monthly rainfall variability, suggesting a predominant influence of synoptic forcings at aggregated scales (Djoudi, 2016; Chettih and Djoudi, 2020).

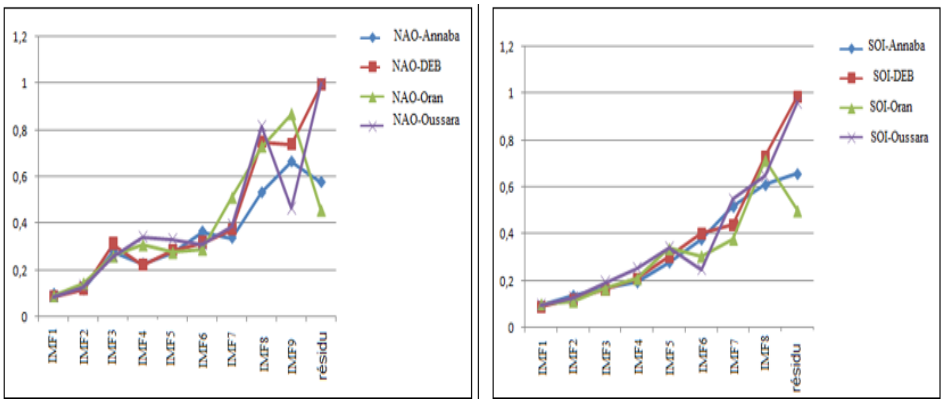


Fig. 08: - Average IMF-to-IMF coherence between the NAO and SOI indices and rainfall in Annaba, Dar El Beida, Oran and Ain Oussera.

4.3. Wavelet Analysis

The wavelet analysis of daily rainfall (Fig. 09) primarily revealed the existence of long-term non-stationary structures (Mandelbrot and Wallis, 1969): the annual component and multi-annual processes similar to the 'Joseph' effect (Benmebarek, 2024).

The wavelet spectrum of the Regional Mediterranean Oscillation (MO) reveals a six-month seasonal component and an annual component, as is the case with rainfall (Fig. 10).

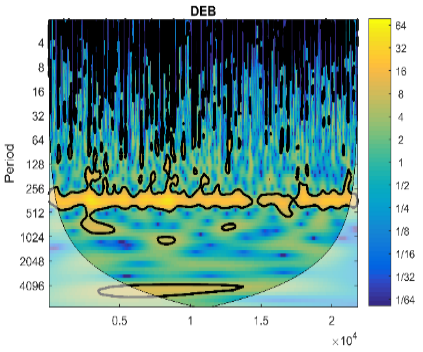


Fig. 09: - Morlet wavelet spectra of the daily rainfall series at Dar El Beida.

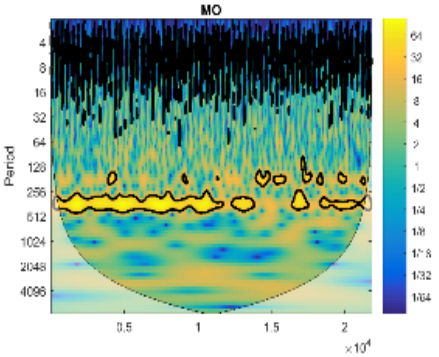


Fig. 10: - Morlet wavelet spectra of the Mediterranean Oscillation Index.

Cross-wavelet analysis reveals a differentiated scalar structure of climatic influence: indices of high-frequency and regional variability (NAO, MO, WeMO) show significant coherence with short-term interannual variability modes, whilst distal forcings (ENSO) dictate the low-frequency modulations of the rainfall regime.

4.4. Stockwell's analysis

The Stockwell transform combines the frequency resolution of classical Fourier analysis with the temporal localisation of wavelets. However, it tends to be 'too' noisy when applied to non-stationary and noisy signals such as ENSO or NAO. For rainfall, the S-spectrogram (Fig. 11) highlights mainly the annual component, which is clearly visible in the global spectrum that yields the Fourier spectrum.

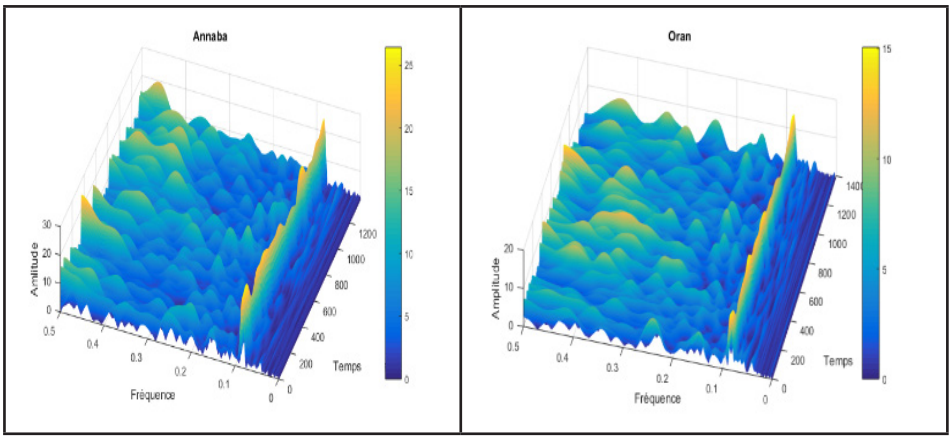


Fig. 11: - Stockwell spectrogram of monthly rainfall in Annaba and Oran.

The spectra reveal the seasonal component at 6 months but drift at high frequencies. The sensitivity of the S-Transform to local fluctuations tends to generate high-resolution artefacts that obscure the information-bearing structures. This phenomenon of spectral noise complicates the isolation of deterministic components buried within the variance of processes such as ENSO, the PDO or the NAO.

Similarly, for daily rainfall, the spectra show only the annual component and sometimes the seasonal component, before diverging completely. Cross-analysis between the MO and rainfall at the Dar El Beida station reveals primarily the annual frequency. The amplitude and coherence functions for the annual component show good phase coherence between the MO and rainfall.

4.5. Time-Dependent Intrinsic Correlation (TDIC)

The TDIC plots (Fig. 12) reveal a significantly more consistent correlation pattern for the MO–Rainfall pair on a daily basis than for the AO or the NAO. An area of negative correlation (shades ranging from light green to aqua) persists across all scales.

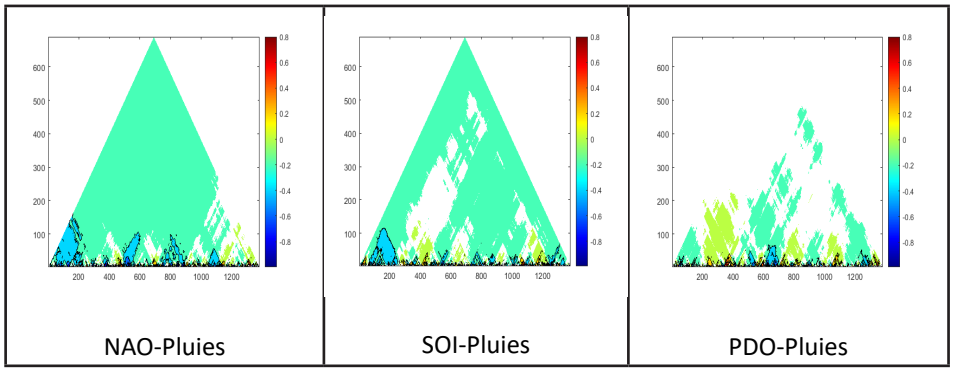


Fig. 12: - Cross-correlations between climate oscillation indices and rainfall in Dar El Beida using the TDIC method.

Conversely, for the AO and the NAO, this signal is more diffuse, which confirms the robustness of the correlation between the regional oscillation and precipitation. The monthly charts for ENSO, the AMO, the NAO and the PDO show robust and synchronous correlation patterns across several scales.

V. Conclusion

By highlighting the impact of the convergence of natural cycles and anthropogenic disturbances on northern Algeria, this study demonstrates the need to rethink our water management paradigms in the face of accelerating aridity. The multi-scale analysis and the use of empirical mode decomposition (EMD) confirm a marked downward trend in precipitation. This underlying downward trend must now be incorporated into future spatial planning master plans.

Faced with this trend towards water scarcity, the response can no longer be linear. On the one hand, the high multifractal variability of rainfall and the ubiquity of flash floods necessitate a fundamental review of the design models for hydraulic structures, so that they can cope with increasingly extreme intermittency. On the other hand, the continentality effect observed in southern regions characterised by sporadic rainfall

requires the deployment of highly responsive rainwater collection systems capable of capturing very brief but highly intense events.

Finally, the resilience of our water systems will depend on our ability to anticipate events. The correlation identified between large-scale oscillation indices and local rainfall patterns paves the way for predictive and seasonal reservoir management, particularly during periods of frequency synchronisation. Furthermore, the identification of a clustered pattern of events (the Joseph effect) presents a strategic opportunity to plan periods of artificial and intensive groundwater recharge, whilst the instability of southern regimes will need to be offset by more flexible surface storage facilities. In short, the region's water security will depend on this transition from reactive management to predictive and highly adaptive governance.

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