The climatic evolution of the Inaouen River Basin in Morocco: Rainfall variability and its connection to the North Atlantic Oscillation

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Abstract: The Inaouene basin is considered among the basins most subject to rainfall variability, marked by sometimes exceptional dry periods (as low as 252.2 mm) and rainy periods (up to 1129 mm), as recorded at the Taza station, due to the variability of atmospheric factors that control atmospheric circulation, in particular the North Atlantic Oscillation.This study therefore aims to know the impact of this oscillation on the variability of rainfall by calculating the standardized precipitation index and the correlation coefficient. The study revealed that the dominance of the positive phase of the North Atlantic Oscillation since the end of the seventies had a major role in the absence of moist air masses towards Morocco, which caused the stability of climatic conditions of drought in the study area, with the presence of some extreme rainfall events, in which the evidence of the North Atlantic Oscillation is weak.
Keywords: Inaouene basin, Rainfall variability, standardized precipitation index, North Atlantic Oscillation.

1. Introduction

The North Atlantic Oscillation (NAO) was adopted as a factor structuring the general atmospheric circulation, at the beginning of the eighties of the last century, thanks to certain studies which relied on quantitative methods, in particular that of [1], thanks to which the first steps of what was called dimensional correlation (Teleconnection) were taken, because this constituted an important development in climate research, and thus everyone became aware that the general dynamics air is subject to global structural links.

Thanks to the growing attention paid by climatologists to these teleconnections, tangible results have been obtained in terms of understanding the mechanisms controlling general air circulation or identifying the factors of climate variability [2]. The North Atlantic Oscillation represents a redistribution of atmospheric mass between the Arctic/subarctic

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regions and the subtropical regions of the Atlantic and links the intensity of the Icelandic Low to the strength and extension of the Azores High.

We distinguish two phases: a positive phase when the two centers of action strengthen (deepening of the Icelandic depression, swelling and intensification of the Azores Anticyclone) and a negative phase when, on the contrary, the two weaken simultaneously or reverse each other. It is one of the most important atmospheric fluctuations that dominates the mid and Mediterranean latitudes, in which Morocco is located. In the negative phase, the atmospheric situation allows humid air masses and a series of oceanic disturbances to be directed towards Morocco.

Thus, several studies have worked on explaining the variability of precipitation in Morocco by linking it to the North Atlantic oscillation atmospheric regime, which was known during the study period (1970-71 to 2021-22), that is to say a regime of stabilization of positive phases in southern Europe and North Africa [3-4]. More recent studies on extreme climatic phenomena in Morocco [5-6] also indicate a close relationship with the North Atlantic Oscillation. Thus, the main objective of this contribution is to study over a longer and more recent period, the effect of this fluctuation on the variability of precipitation in the north of Morocco and more particularly in the Inaouène watershed. The latter experiences major problems related to water management because climate variability tends to limit its availability [3]. To deal with this situation, the water resources management policy and the construction of these hydro-agricultural works for this hydrographic basin require a good knowledge of rainfall variability.

2. Study area

The work presented in this article concerns the watershed of Oued Inaouène, a main tributary of Oued Sebou in the north of Morocco located between 33°.84' N and 34°.58' N (Fig.1). It covers an area of 3601 km^2 upstream of it. Geomorphologically, the north of the watershed is a region of marl and clay hills of the pre-Rif; and to the south it is a region of stepped limestone plateaus (the causses to the west) and the folded chains of the Middle Atlas (to the east). The altitudes in this watershed are between 230 m at the El kouchet station and 1981 m at the summit of Tazekka.

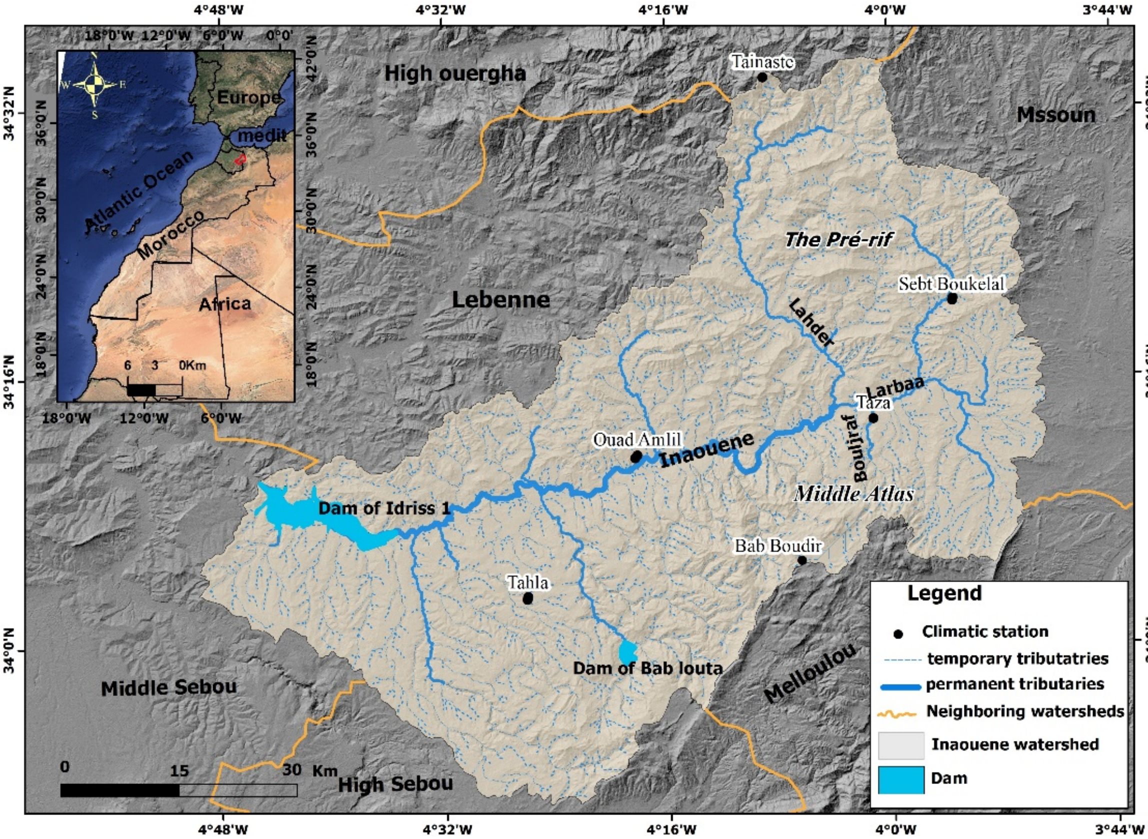

Fig. 1: Geographical location of the Inaouène watershed

The Inaouène watershed is part of a semi-arid Mediterranean climate characterized by a wet winter and a hot, dry summer, a climate controlled by atmospheric circulation (subtropical jet stream at altitude) and anticyclonic weather types (Azores anticylone at the surface) depending on the variability of the North Atlantic Oscillation (NAO) [3].

3. Materials and methods

3.1 Data Description

The monthly precipitation data used in the study were obtained from the Sebou Bassin Agency. They concern six stations in total located in Figure 1: El Kouchet (230 m), Oued Amil (235 m) and Taza (458 m) located along the Inaouène wadi from downstream to upstream; Tainaste (1200 m) on the right bank and Bad Boudir (1568 m) and Tahla (560m) on the left bank. The analysis period spans 52 years, from September 1970 to August 2022.

Table 1: Geographical locations of stations.

	Latitude (N°)	Longitude (O°)	Elevation (m)
Taza	34°13'	4°20'	458
Oued Almlil	34°12'	4°13'	235
Bab Boudir	34°06'	4°12'	1568
Tainast	34°55'	4°13'	1200
El Kouchet	34°13'	4°29'	230
Tahla	34°04'	4°24'	560

The North Atlantic Oscillation index values were downloaded for the same period from the following site: http://www.cru.uea.ac.uk/cru/data/nao.htm. The research cited above guided us in the choice of data to be used in this present study. These are the winter season precipitation and the NAO indices which are calculated over the five months from November to March.

3.2. Methodology Adopted

Two approaches were applied to study the relationship between rainfall variability in the Inaouène watershed and the North Atlantic Oscillation:

- The Standardized Precipitation Index (SPI), developed by [7], is a widely used meteorological index for detecting, assessing, and characterizing the intensity and frequency of droughts across various time scales. This index is based on precipitation data from a specific location and quantifies precipitation deficits, as well as their impacts on critical factors such as reservoir storage, groundwater levels, soil moisture, streamflow, and snow cover [8]. The SPI calculates cumulative precipitation over defined periods, known as accumulation intervals, to refine the cumulative probability distribution of the time series. Total precipitations are typically fitted to a gamma distribution using the maximum likelihood method, although other distributions may also be suitable. To enable the comparison of SPI values across different time periods, the quantiles of the gamma distribution are transformed into standard normal variables (Equation 1). As a result, negative SPI values indicate precipitation below the median, while positive values signify precipitation above the median.

$g(X)=1/\beta\alpha\Gamma(\alpha)\ X\alpha-1e-X/\beta$ (1)

In this study we use standardized precipitation index to measure the rainfall impact of the two oscillation phases, the standardized precipitation index (SPI) was calculated. It is expressed mathematically by the following equation (2):

$IPS = (Pi - Pm)/\sigma.$ (2)

Where:

Pi: total precipitation per year (in mm);
Pm: average precipitation for the winter season (November, December, January, February, March.) In mm;
σ: standard deviation of the rainfall series.

- Karl Pearson’s Correlation Coefficient, often simply referred to as Pearson's *r*, is a measure of the linear correlation between two variables X*X* and Y*Y*. It provides a value between -1 and 1, where:

1 indicates a perfect positive linear relationship,
-1 indicates a perfect negative linear relationship,
0 indicates no linear relationship.

The formula for Pearson's correlation coefficient is:

$$r = \frac{cov(X,Y)}{(\sigma X \sigma Y)}$$

Formula Breakdown:
r : Pearson's correlation coefficient.
cov(X,Y): Covariance of variables X and Y, indicating how they vary together.
σX: Standard deviation of variable X.
σY: Standard deviation of variable Y.

the objective of using Karl Pearson's correlation coefficient: To examine the statistical relationship between the standardized precipitation index and the North Atlantic Oscillation indices, the correlation coefficient was calculated.

4. Results and discussions

4.1 The spatial variability of rainfall in the Inaouène watershed (1970-2022)

The Inaouène watershed is characterized by significant spatial variability in rainfall. Between 1970 and 2022, the annual rainfall totals ranged from 492 mm at El Kouchet, the most downstream station, to 1089 mm at Bab Boudir, the highest station (1568 m) located upstream on the left bank. The seasonal rainfall totals (November to March) for these same stations ranged from 311 mm to 746 mm, respectively (Table 1).

Table 1. Average annual and seasonal (November to March) rainfall totals in six locations within the Inaouène watershed (1970-2022 period).

Periods	Taza	Oued Amlil	Bab Boudir	Tainast	El Kouchet	Tahla
annual Average (mm)	586	505	1089	676	492	605
seasonal Average (November to March) (mm)	416	343	746	450	311	393

4.2 Temporal variability of annual rainfall in the Inaouène watershed (1970-2022)

The analysis of precipitation patterns from 1970/71 to 2021/22 reveals that there is no consistent long-term trend of increase or decrease across the monitored stations. Instead, rainfall shows strong year-to-year fluctuations, with alternating periods of deficit and surplus, reflecting a climate marked by structural instability (Fig.2). Droughts have recurred at different times, particularly during the 1980s, mid-1990s, and more intensely since 2014, when annual precipitation often fell below long-term averages. The severity of these deficits varies depending on local topography and location.

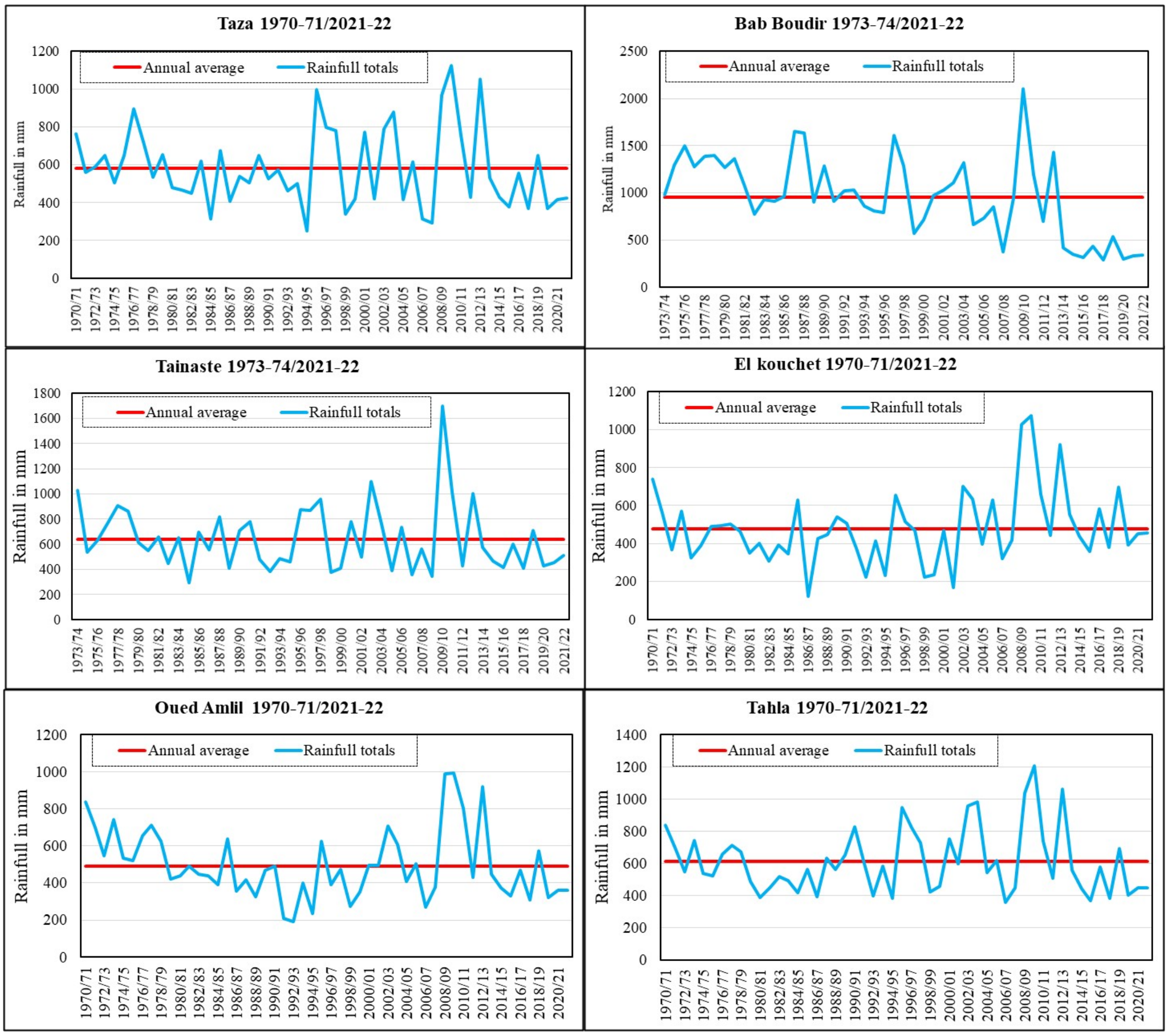

Fig. 2. Temporal variability of annual rainfall in the Inaouène watershed (1970–2022).

At Taza station, particularly low rainfall was recorded in 1984/85 (around 314 mm) and 1994/95 (approximately 252 mm), compared to the annual average of roughly 580 mm, with deficits continuing in recent years. Bab Boudir station, with a higher mean annual rainfall of about 953 mm, also experienced relative shortfalls in 1982/83 (around 770 mm) and 1998/99 (roughly 565 mm), along with a prolonged dry period after 2014. Tainast station saw significant droughts in 1984/85 (around 294 mm) and 1992/93 (about 387 mm). El Kouchet and Oued Amlil stations were particularly vulnerable, recording extremely low values in some years—for example, 123 mm at El Kouchet in 1986/87 and 223 mm at Oued Amlil in 1992/93—with deficits continuing in recent years. Tahla station showed a similar pattern during 1991/92 and 1992/93.

On the other hand, there were years of unusually high rainfall. Exceptional surpluses occurred in 1995/96 and 2002/03, reaching peaks in 2008/09, 2009/10, and 2012/13, with some stations in mountainous areas receiving more than double their annual averages. Taza station, for example, recorded 996 mm in 1995/96 and peaked at 1124 mm in 2009/10. Bab Boudir saw extraordinary totals exceeding 1600 mm in the late 1980s, peaking at about 2104 mm in 2009/10. Tainast station had intense rainfall in 2002/03 (around 1098 mm), reaching 1698 mm in 2009/10. Even the typically low-precipitation stations of El Kouchet t and Oued Amlil experienced notable surpluses in 2008/09 and 2009/10, demonstrating the extreme variability of rainfall.

Since the early 2000s, these observations suggest that interannual variability has intensified, with extremely dry years occurring alongside sharply wet years, showing no sign of long-term climatic stability. This pattern points to the influence of large-scale climatic drivers, such as the North Atlantic Oscillation (NAO), which help explain the irregularity and extremes in annual precipitation.

4.3. The impact of the NAO on precipitation in the Inaouène watershed

With negative values, the correlation coefficients (Table 2) indicate an inverse statistical relationship between the standardized precipitation index and the North Atlantic Oscillation indicators. This relationship is statistically significant at the $\alpha = 0.05$ level. The values of this coefficient range between -0.39 and -0.50, which explains that the correlation between the variables is at best 25%.

Table 2. Correlation coefficient between the standardized precipitation index (November to March) and the North Atlantic Oscillation indices (1970-2022 period).

Climate stations	Taza	Oued Almlil	Bab Boudir	Tainast	El Kouchet	Tahla
Correlation coefficient (r)	-0.46	-0.50	-0.39	-0.46	-0.40	- 0,33
Statistical significance (p)	0,009	0,001	0,038	0,026	0,003	0,001

High values of oscillation indicators correspond to low standardized precipitation indices, indicating that the North Atlantic Oscillation system in its positive phase causes a reduction in precipitation in the Inaouène watershed. For example, the winter season of 1989-90 was marked by climatic drought (-0.17 at Tainast and -0.14 at Taza) with an NAO index that reached +1.23 (Fig. 3). In contrast, the maximum value of the NAO index during the winter season of 2010-11 in its negative phase (-2.34) corresponds to positive precipitation indices (approximately 0.5 for Taza and 1.2 for Tainast). Similarly, the highest precipitation indices (3 at Taza and almost 4 at Tainast) recorded in the preceding year correspond to a negative NAO index (-0.5).

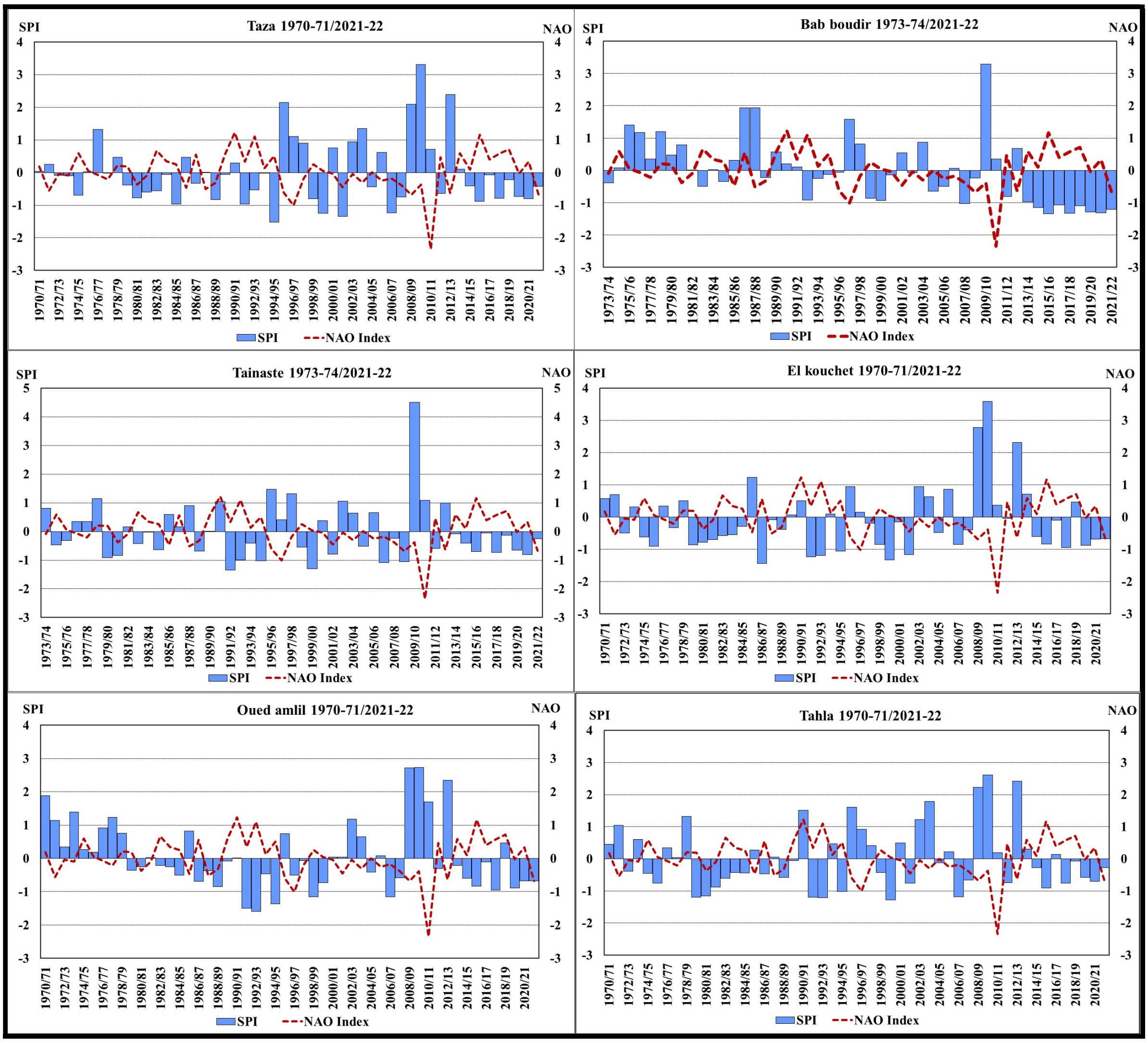

Fig. 3. Phase opposition between the standardized precipitation index (SPI) and the North Atlantic Oscillation index (NAO) over the period 1970-2022 at two weather stations located in the Inaouène watershed.

To understand the rainfall impact of atmospheric circulation at Morocco's latitudes, atmospheric pressure field maps from the Climate Reanalyzer are illustrated for these two seasons in opposite phases of the NAO (Fig. 4). Thus, during the winter of 1989-90 and 2015-16 (left map), the expansion of the Azores High is observed, with a maximum average pressure around 1023 hPa in the first year and 1030 hPa in the second year, blocking the deeply entrenched Icelandic Low (991 hPa) at northern latitudes and preventing Atlantic disturbances from approaching Moroccan latitudes. In contrast, during the winter of 2009-10 and 2012-13 (right map), the contrast in atmospheric pressure between the two centers of action is reduced (average maximum pressure of 1017 hPa and 1020 hPa for the Azores High and 1008 hPa to 1010 hPa for the Icelandic Low), and, more importantly, the more southerly position of the system allows the Icelandic Low to direct moist air masses toward Moroccan latitudes.

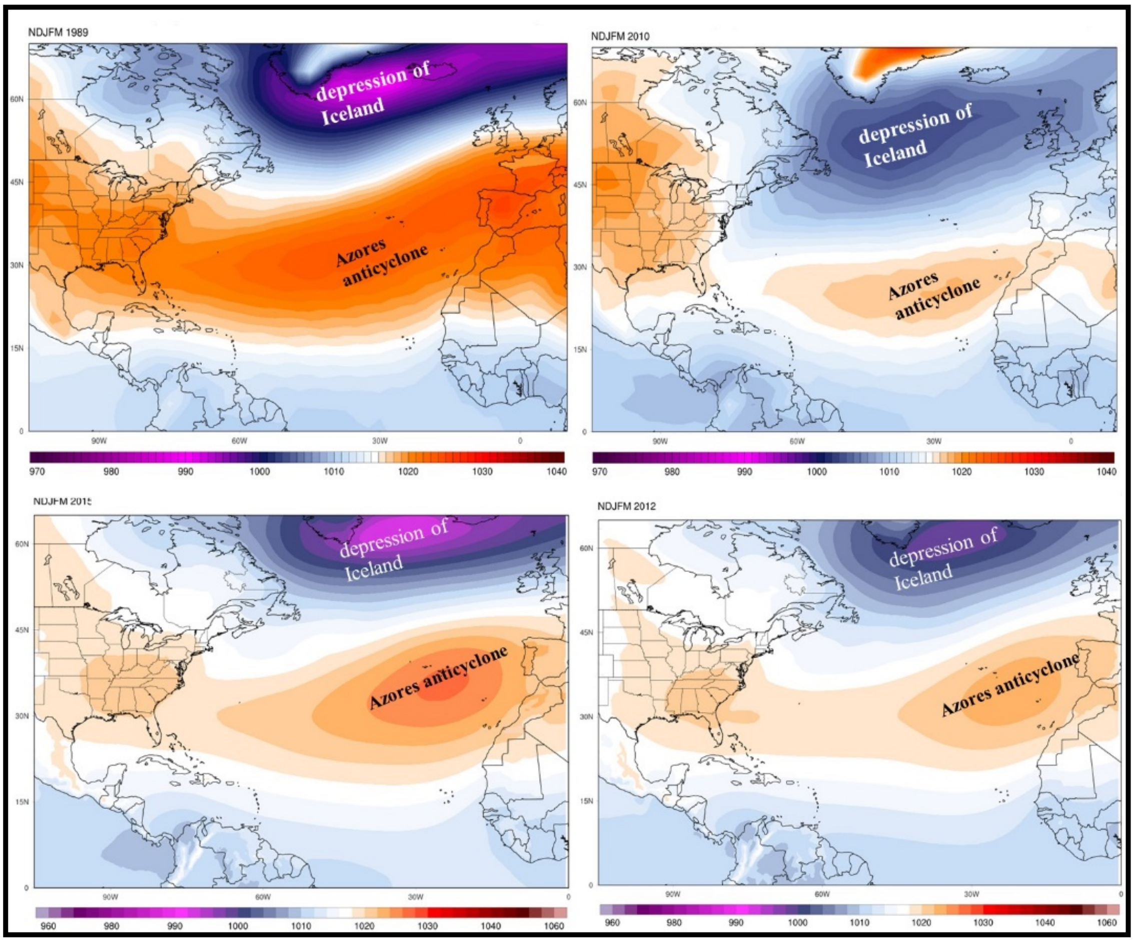

Fig. 4: Average atmospheric pressure fields (in hPa) over the North Atlantic during the months of November, December, January, February, and March of the winter of 1989-90 and 2015-16 illustrating the positive phase of the NAO (left map) and the winter of 2010-11 and 2012-13 illustrating the negative phase of the NAO (right map). (Source : https://climatereanalyzer.org).

It is therefore clear that the North Atlantic Oscillation system plays a fundamental role in the distribution of precipitation in the Inaouène watershed. In general, it is observed that the wet periods from 1970-71 to 1978-79 and from 2007-08 to 2013-14 correspond to a negative NAO index, whether weak (as in 2009-2010) or strong (as in 2010-2011), which favored the circulation of moist air masses in more southerly positions, allowing disturbances to penetrate into Morocco [9].

5. Conclusion

By studying the relationship between precipitation variability and the North Atlantic Oscillation, it was found that the latter significantly contributes to precipitation variability in the Inaouène watershed, both in terms of climatic drought and exceptional rainfall events. This is demonstrated by the correlation coefficient between the standardized precipitation index (November to March) and the North Atlantic Oscillation indices (1970-2022 period). Similarly, a phase opposition between the SPI and the North Atlantic Oscillation (NAO) is noteworthy. The calculation of the standardized precipitation index revealed a normal and/or surplus phase spanning the period 1970-71 to 1978-79. After this period and during 1979-80 to 2021-22, an alternation between dry years (29 years), sometimes closely spaced, and wet years (14 years) is observed. This situation affects water resource availability in the Inaouène watershed and the yields of agriculture, which remains predominantly rain-fed. On the other hand, it can lead to extreme hydrological events that pose risks to populations increasingly exposed to flooding, particularly in the city of Taza and Oued Amlil [10].

The inclusion of large-scale climate indices like NAO index in regional water resource planning and early warning systems is essential to cope with precipitation variations in the Inaouène watershed. Climate monitoring and quality of data could be improved Besides the development of adaptive agricultural practices, as well as better management of watersheds, reponses to dry spells or extreme rainfall events can be minimized. Vulnerability areas must be well protected by flood prevention and urban drainage facilities. It is recommended that future studies adopting climatic indices would integrate them with hydrological models as well as at a high-resolution scale for improved prediction and mitigation of climate-related risks.

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