

SECULAR EVOLUTION OF PRECIPITATION IN THE NORTH AFRICAN STEPPE

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Abstract. North Africa is one of the most disadvantaged regions in the world in terms of water resources. In the context of global warming, any water deficit could significantly impact the water balance, particularly in arid areas. Analysis of long-term rainfall patterns, especially in steppe and semi-arid regions, is crucial to anticipate potential effects on water resources and local ecosystems. Previous studies have highlighted a decreasing rainfall gradient across North African countries but were limited by spatial and temporal constraints. This study examines rainfall trends across all North African countries, utilizing 27 gridded statistical series, distributed as follows: 4 in Morocco, 10 in Algeria, and 13 in Tunisia, from the CRU (Climatic Research Unit) at a resolution of $0.5^\circ \times 0.5^\circ$ ($50 \text{ km} \times 50 \text{ km}$) from the year 1901 to the year 2022. The data are aggregated by wilayas (local governorates) or departments for a precise analysis of climatic trends. This work is structured around three main hypotheses: (1) Has rainfall in North Africa shown a declining trend? (2) Does a longitudinal drying gradient exist? (3) Can any period be identified during which a break in rainfall homogeneity occurred? The results reveal regional variations. Stations located in Eastern Algeria and Tunisia do not show a long-term decrease in rainfall, while those in Western Algeria and Eastern Morocco indicate a general downward trend. A decreasing gradient from east to west is observed, as well as breaks in homogeneity at certain stations. These results are essential for developing region-specific adaptation strategies to ensure sustainable water resource management in the face of climate change.

Keywords: *rainfall, North Africa, trend, statistical tests, drying*

Introduction

In the context of global warming, especially in North Africa, the study of rainfall evolution is of particular importance. According to recent predictions by the IPCC (Intergovernmental Panel on Climate Change), “It is highly likely that the Mediterranean region will experience a rise in temperatures accompanied by a significant decrease in rainfall, thereby worsening the climate and increasing the imbalance in the water budget, which will impact agriculture and natural ecosystems” (Pörtner et al., 2022).

This is why the study of long-term rainfall trends is crucial for understanding and predicting the impacts of climate change in regions as vulnerable as the arid to semi-arid steppe areas of North Africa. However, to our knowledge, no synoptic long-term analysis has been conducted at the scale of the Maghreb.

Admittedly, such studies do exist, but they are often relatively confined to specific regions, which limits the generalization of conclusions (Meddi and Meddi, 2009). They involve only a limited number of meteorological stations, thereby reducing the

robustness of the results (Kadi, 1993; Hirche et al., 2007). Additionally, they are often discontinuous and cover specific periods, which can skew the conclusions (Djellouli and Djebaili, 1984). Long-term variations are often underutilized due to the difficulty in accessing data covering extended periods (Hallouz et al., 2019).

Numerous studies have been conducted on climate change in the Maghreb steppes, often in relation to natural resources, particularly pastoral ones. The results are generally consistent, while also revealing regional and temporal nuances.

In Algeria, the work of Daget and Djellouli (1992) provides valuable insight into climate trends, notably highlighting the relative stability of rainfall in the southern Algiers steppes during the century leading up to 1990. Despite this, the observations of Hirche et al. (2007), Meddi and Meddi (2009), and Meddi et al. (2009) underscore a trend toward increasing aridity in the Western region of Algeria. However, the majority of authors observe a trend toward climatic aridification in certain areas, manifested by negative slopes and regression lines, although these are not always statistically significant (Hirche et al., 2011; Elouissi et al., 2016, 2017; Bellala et al., 2018).

In Morocco, climate studies reveal drying trends, though these trends can significantly vary depending on the regions and periods considered. Indeed, according to Kessabi et al. (2022), a significant decrease in precipitation has been observed in the Sebou River basin as well as in the Fès-Meknès region over a period of nearly 60 years (1961-2018). This trend has major consequences for water resource management and the agricultural sector in this region.

The study carried out by Bouchaib and Nahli (2020) in the Tafilalet region reveals a decline in rainfall between 1976 and 2016, followed by a subsequent increase, indicating significant rainfall variability.

These observations align with those reported by Nouaceur et al. (2014), who identified a return of wet years across the Maghreb after 2008.

Bouizrou et al. (2022), along with Aissam et al. (2023), clearly illustrate how certain regions, particularly coastal and mountainous areas of Morocco, can experience increases in rainfall, whereas the eastern zone, contiguous with the Algerian steppes, remains arid. This demonstrates the vital importance of analyzing climate trends at regional and local scales, as even relatively close areas can exhibit markedly different trends.

In Tunisia, Driouech et al. (2013) report the absence of a clear drying trend at the scale of the Maghreb. Meanwhile, Chargui et al. (2018) highlight local variations within the Merguellil drainage basin observed between 1961 and 2011, with some areas displaying an increasing trend in precipitation, while others exhibited no notable trend. This shows that climatic variations can be influenced by local factors such as topography, altitude, and microclimatic conditions, as evidenced by discrepancies between observation stations.

The work of Farhat et al. (2019), analysing rainfall trends in Mahdia between 1960 and 2017, found no evidence of a drying trend, which contrasts with certain other regions of the Maghreb that have shown signs of increasing aridity.

The observations of Mathlouti and Lebdi (2021) highlight a specific and noteworthy climatic dynamic in the Ghezala dam region. They indicate a trend of seasonal drying, particularly during the month of March, while showing no significant annual trend toward aridification. This dynamic emphasizes the importance of analyzing climatic trends on a seasonal scale to uncover specific variations that might be obscured at an annual scale.

Derouiche et al. (2022) pointed out relatively severe drought periods in Northern Tunisia, particularly between 2015 and 2023, indicating a trend toward increasingly dry climatic conditions. Meanwhile, Chargui et al. (2022) revealed a statistically insignificant increase in annual precipitation.

Ben Othman and Abida (2022), in a study of the Merguellil drainage basin, identified recurring drought periods between 1983 and 2018.

The observations of Latrech et al. (2023) provide an interesting perspective. Their study shows that there is no drying trend in the Cap-Bon region between 1982 and 2020, which contrasts with trends observed in other regions of Tunisia that are experiencing increasingly dry conditions.

Overall, it emerges that certain major patterns in the trends of annual rainfall evolution can be observed in the Maghreb, particularly in Tunisia. Climatic variations clearly demonstrate that results may vary depending on regions, time periods, and data sources. This underlines the importance of conducting analyses at various temporal and geographical (local, regional, and global) scales to develop more effective adaptation and resource management strategies.

The objective of this work is to address three key hypotheses:

The initial question is as follows: Has rainfall in North Africa shown a declining trend?

The second objective is to examine the existence of a longitudinal drying gradient.

The third: Can any period be identified during which a break in rainfall homogeneity occurred?

Materials and methods

Overview of the study area

Algeria, with an area of 2,381,741 km², stands out as the tenth largest country in the world, the largest in Africa, the Arab World, and the Mediterranean basin. Law No. 19-12 of December 11, 2019, published in the Official Journal of the People's Democratic Republic of Algeria, regarding territorial organization, divides the country into 58 wilayas (equivalent to governorates in Tunisia and to regions in Morocco), 44 delegated wilayas, and 1541 communes. It is traversed by two mountain ranges: the northernmost, the Tell Atlas, and the southernmost, the Saharan Atlas, which create a natural boundary between the more humid Mediterranean regions and the vast expanses of arid steppe. The northern part of the country is bordered by the Mediterranean Sea, with a coastline stretching over 1200 km. Ten steppe wilayas are covered by this study (*Fig. 1*).

Morocco, with an area of 446,550 km², presents a remarkable geographical mosaic. Bordered to the north by the Mediterranean Sea and to the west by the Atlantic Ocean, the country has a coastline extending to 3500 km. It is divided into several regions, of which we will consider only four (*Fig. 1*):

- Souss-Massa, located in the southwest, is dominated by arid and semi-arid plains influenced by the Atlantic Ocean.
- Drâa-Tafilalet, located to the east of Souss-Massa, is known for its arid climate and its oases, with low annual precipitation.
- Guelmim-Oued Noun, located to the south of Souss-Massa, has semi-arid characteristics with varied landscapes ranging from coastal plains to mountains.
- Oriental, located in the far east, is mostly arid with low rainfall and harsh climatic conditions.

Tunisia, with an area of 163,610 km² and a coastline of 1566 km, is composed of 20 governorates, which are characterized by diverse conditions. However, this study focuses only on 13 governorates located in predominantly arid to semi-arid areas (Fig. 1).

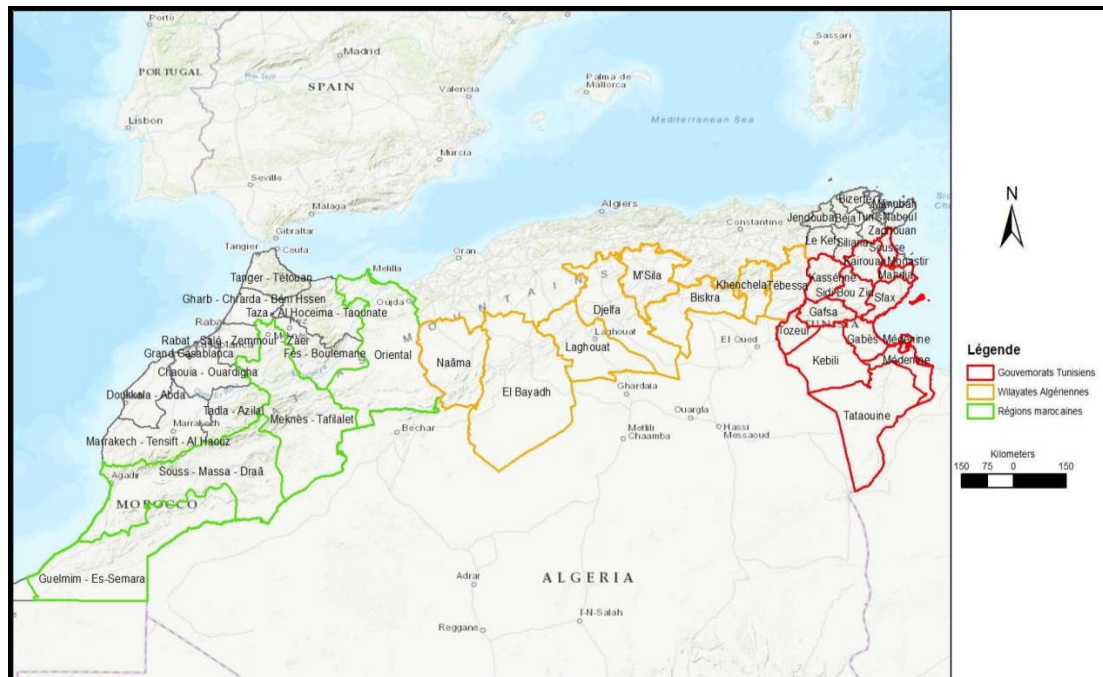


Figure 1. Geographic location of the study area

Data sources

The data used in this study were obtained from the World Bank website, which relies on records from the CRU (Climatic Research Unit) at the University of East Anglia. These datasets are globally recognized and employed by prestigious institutions such as the IPCC (Intergovernmental Panel on Climate Change), attesting to their high quality and relevance for studying both natural and anthropogenic climate changes (<https://crudata.uea.ac.uk/cru/data/hrg/>).

These records cover an extended period from 1901 to 2022, offering uninterrupted perspective on long-term climatic trends. This continuity and consistency in the data enable the identification of variations and potential breaks in climatic trends. They also facilitate an understanding of climate dynamics, which is essential for forecasting future impacts and developing adaptation strategies in the arid and semi-arid regions of North Africa.

The CRU provides gridded daily datasets derived from observations, as well as quality-controlled temperature and precipitation data and derived information such as long-term historical and monthly climatologies. The gridded datasets have a spatial resolution of $0.5^\circ \times 0.5^\circ$ (approximately 50 km \times 50 km), enabling detailed and precise analysis of climatic variations at different geographical scales. These datasets have been supplemented with point data from the NMO (National Meteorological Office) stations, which, although covering a limited period, help identify recent variations and trends that

may not be apparent in longer data series. Historical records play a crucial role in providing a solid foundation for understanding past and present climatic contexts.

Climatic data, whether observational or historical, come from thousands of meteorological stations worldwide that continuously collect data, including temperatures (mean, minimum, and maximum) and precipitation. However, in our case, we focused solely on precipitation data. For each variable, the data are grouped at the national and subnational levels to provide an accurate overview. In our study, we utilized data representing the largest administrative units, referred to as wilayas in Algeria, regions in Morocco, and governorates in Tunisia. As part of this study, we have selected a total of 27 weather stations, distributed as follows: 4 in Morocco, 10 in Algeria, and 13 in Tunisia.

Methodology

Temporal trends

To identify a monotonic trend (either increasing or decreasing) in a time series, the non-parametric Mann-Kendall trend test (1945) was applied. Prior to conducting the test, autocorrelation between variables was verified to ensure the validity of results. A trend is considered significant at a *p-value* of 0.05. To complement the Kendall test, Sen's slopes were calculated to determine the direction of the trend. Additionally, the slopes of regression lines derived using the least squares method were used as supplementary indicators. The analyses were performed using the XLSTAT® software on Windows operating system.

Temporal variation of precipitation

To analyze the relationship between precipitation (considered as the dependent variable) and years (independent variable), a least squares linear regression was used. This analysis was complemented by the computation of the coefficient of determination (r^2), which was considered significant if the error risk (*p-value*) was less than 5%.

The normal distribution of both variables was verified using Lilliefors' test for homogeneity of variances.

Time series homogeneity

To verify the homogeneity (absence of significant differences) between pairs of time series, the non-parametric Mann-Whitney U-test (Mann and Whitney, 1947; Dagnelie, 1970) was applied. If the error probability (*p-value*), corrected by the Monte Carlo method, is less than 5%, the series are considered heterogeneous. This analysis was performed using XLSTAT® software on the Windows operating system.

Breaks in homogeneity in the time series

As a complement to the Mann-Whitney test, the statistical tests of Pettitt (1979), Alexandersson (1986), and Buishand (1982, 1984) were applied to identify breaks in the homogeneity of the time series between different regions.

The Pettitt test (1979), as referenced by Demaree (1990), Sutherland et al. (1991), and Vannitsem and Demaree (1991), considers a sequence of independent random variables X_1, X_2, \dots, X_N . This sequence is assumed to contain a break point at time t for

the X_t values for which two distributions $F_1(X)$ and $F_2(X)$, are defined. The null hypothesis assumes no break in their homogeneity, while the alternative hypothesis suggests the presence of a break. No specific conditions are required for the functional forms of F_1 and F_2 , other than continuity.

The Buishand statistic is derived from an original formulation provided by Gardner (1969). Specifically, the Gardner statistic is used for a two-tailed test of a mean shift at an unknown time. The test takes into account the probability P_k , which represents *a priori* the break in homogeneity between two series occurring immediately after the k -th observation.

The Alexandersson statistic, also known as the SNHT method (Standard Normal Homogeneity Test), is based on identifying the location of the change point between two time series by creating a series of weighted means. The statistic $Q_p = \max_{i=1 \dots n-1} \{ |Q_i| \}$ is considered significant if it exceeds its critical value (Alexandersson, 1986), and its index corresponds to the position of the shift (p). A correlation coefficient between the base series and the neighboring series j is calculated and denoted by p_j . The null hypothesis is rejected, validating a change in the mean of the series. These analyses were performed using the XLSTAT® software on the Windows operating system. Rainfall totals and variations by data source.

Results

Total precipitation and its variations by data source

Case of Algeria

Statistical data indicate that the average annual precipitation values from stations in northwestern and central Algeria show quite contrasting means, generally higher in the center than in the region bordering Morocco (*Tables 1a, b*). This may be due to specific geographical and climatic factors influencing the distribution of precipitation.

In the western steppes, the El-Bayadh station records an average precipitation of 177.59 mm, which is lower than that of Naâma. Although the northern part of this wilaya is mountainous and more densely populated, the extension towards the south, in the pre-desert regions, influences the overall average precipitation.

The coefficients of variation (CV) of the CRU data, at around 20%, indicate significant but relatively stable variability across the different regions. This contrasts with the coefficients of variation from the point-based meteorological stations of the National Meteorological Office, which reach approximately 30%. This clearly highlights that while aggregated data are suitable for studying water balance on a large scale, they are less appropriate for analyzing climatic variability at the local and station levels.

Table 1a. Means and variability of rainfall at the station and regional scales in the Western and Central Algerian steppes. The period covering the years 1901 to 2022

Data type		El-Bayadh	Naâma	Biskra	Djelfa	M'sila	Sidi Bel Abbès
Gridded CRU	M	177.59	281.39	173.47	310.23	413.56	373.68
	SD	38.26	69.05	38.46	61.65	85.00	79.33
	CV	21.54	18.37	22.17	19.87	20.55	21.22

M = Mean; SD = Standard deviation; CV = Coefficient of variation

Table 1b. Means and variability of rainfall at the station and regional scale in the Eastern Algerian steppes. The period covering the years 1901 to 2022

Data type		Souk Ahras	Oum El Bouaghi	Bordj Bou Arreridj	Khenchela
Gridded CRU	M	753.59	494.52	306.55	455.80
	SD	139.35	95.01	57.36	109.29
	CV	18.49	19.21	18.71	23.97

M = Mean; SD = Standard deviation; CV = Coefficient of variation

The precipitation averages estimated by the CRU show generally higher values, with the exception of Khenchela, which exhibits trends similar to those of El-Bayadh. It shows the existence of a latitudinal gradient between the western and eastern stations, from west to east.

Case of Morocco

Annual precipitation varies significantly between regions, from the semi-arid climate in Souss-Massa and Drâa-Tafilalet to the pre-Saharan climate in Guelmim-Oued Noun, and the semi-arid climate in the oriental region.

The coefficients of variation, ranging from 20% to 30%, illustrate the variability in annual precipitation. This is slightly underestimated due to data aggregation. Aggregated data may smooth out certain local variations, but a detailed analysis reveals the crucial specifics for each region (Table 2).

Table 2. Statistics of the regions of Morocco. The period covering the years 1901 to 2022

Region	Guelmim-Oued Noun	Souss-Massa	Drâa-Tafilalet	Oriental
M	113.08	211.04	240.29	356.89
SD	30.37	57.23	49.49	79.68
CV	26.85	27.12	20.60	22.33

M = Mean; SD = Standard deviation; CV = Coefficient of variation

Case of Tunisia

The different Tunisian stations reveal significant climatic variations, ranging from the Saharan (less than 100 mm of rain per year) in Tataouine and Tozeur, to the arid *sensu lato*, including the lower arid or pre-Saharan (100-200 mm of rain per year) in Gabes, Kébili, and Medenine. The moderate arid (200-300 mm of rain per year) in Sidi Bouzid, Gafsa, and Mahdia. The upper arid (300-400 mm of rain per year) in Kairouan, Monastir, and Sousse, while Kasserine, exceeding 400 mm per year, places this region in the semi-arid zone (Table 3).

The coefficients of variation (CV) are around 30% in the Saharan and pre-Saharan areas, and about 20% in the higher arid and semi-arid zones. These statistics, derived from the gridded data, show less variability than the point-based climate station data. This is due to the aggregation of the data, which tends to smooth out the extreme variations observed locally (Table 3).

Table 3. Statistics of the Governorates of Tunisia. The period covering the years 1901 to 2022

Governorate	Gabes	Gafsa	Kairouan	Kasserine	Kebili	Mahdia	Monastir	Medenine	Sfax	Sidi Bouzid	Sousse	Tataouine	Tozeur
M	176.26	197.96	399.89	449.41	100.07	278.52	312.15	166.03	244.95	294.70	358.74	93.09	94.76
SD	52.74	53.66	85.65	98.26	30.31	67.76	69.26	50.07	64.70	75.04	74.76	29.63	26.77
CV	29.92	27.10	21.42	21.86	30.29	24.33	22.19	30.16	26.41	25.46	20.84	31.83	28.25

M = Mean; SD = Standard deviation; CV = Coefficient of variation

Trend test

In Algeria

Stations in Western and Central Algeria

The analysis of precipitation trends in the Oran region reveals significant differences from one area to another. The stations of Naâma and Saïda exhibit a negative Sen's slope, indicating a drying trend and rejection of the null hypothesis (H₀). However, although the null hypothesis is not rejected at the El-Bayadh station, the p-value approaches the critical threshold of 0.05, suggesting an alarming trend toward aridification, reflecting increasingly arid climatic conditions (Table 4). These trends toward aridification underscore the likelihood of a challenging water future for the Oran region.

The established graphs (Fig. 2) visually confirm the trend toward aridification in Western Algeria.

The El-Bayadh station, although not exhibiting a statistically significant trend toward aridification, is very close to the statistical rejection threshold (0.006) with a negative Sen's slope. This suggests a slight trend toward reduced precipitation, even if it is not strictly meaningful in statistical terms (Table 4). This p-value could be considered as "nearly significant" or "marginally non-significant," even though it is not a new statistical category, but rather to highlight that the result is close to the commonly used threshold and that caution should be taken when interpreting the absence of significance. This nuance is particularly important in climate trend studies, where emerging patterns may require monitoring and further investigation, even if statistical evidence does not yet meet strict significance thresholds.

Table 4. Centennial precipitation trends in selected stations of Western and Central Algeria. The period covering the years 1901 to 2022

	El-Bayadh	Naâma	Saïda	Biskra	Djelfa	M'sila
Kendall's Tau	-0.115	-0.192	-0.201	-0.061	-0.084	-0.111
S	-836.00	-1392.00	-1460.00	-443.00	-612.00	-808.00
Var (S)	199246.667	199246.66	199246.66	199245.66	199246.66	199246.66
P-value (two-tailed)	0.061	0.002	0.001	0.322	0.171	0.071
Alpha	0.05	0.05	0.05	0.05	0.05	0.05
H ₀	Accepted	Rejected	Rejected	Accepted	Accepted	Accepted
Sen's slope	-0.212	-0.633	-0.874	-0.109	-0.241	-0.412
Confidence Interval S	]-0.316, -0.112[	]-0.812, -0.480 [	]-1.071, 0.649[	]-0.198, -0.024[	]-0.386, -0.084[	]-0.596, 0.229[
Least squares slope	0.261	-0.722	-0.902	-0.073	-0.211	-0.365

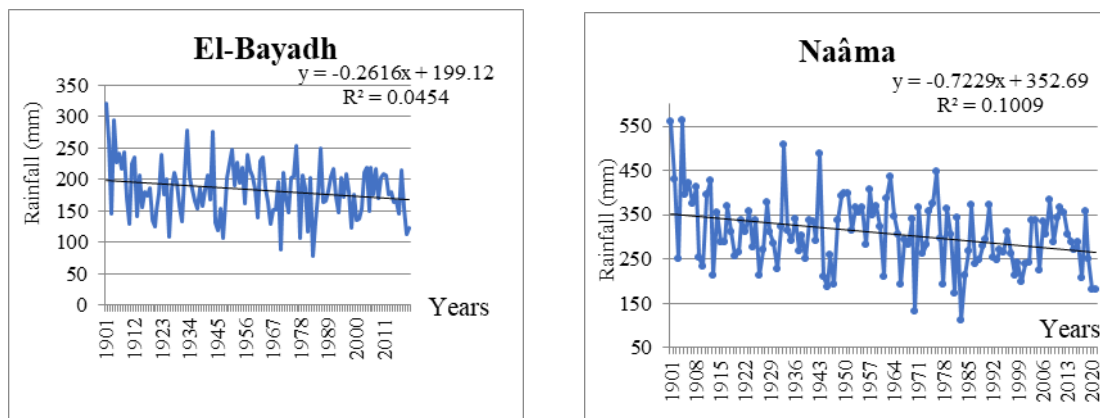


Figure 2. Evolution of rainfall at some stations in Western Algeria

Furthermore, a distinct dry period emerges between the early 1980s and the early 2000s.

However, statistical analyses clearly show that the central region of Algeria does not yet exhibit a statistically significant trend towards aridification, but the p-values are close to the rejection thresholds, indicating a possibility that the trend might become significant if conditions change. The negative Sen slopes suggest a slight downward trend in precipitation, although it is not yet conclusive (Fig. 3). Nonetheless, in the event of a prolonged future drought, the region could shift toward a significant drying trend.

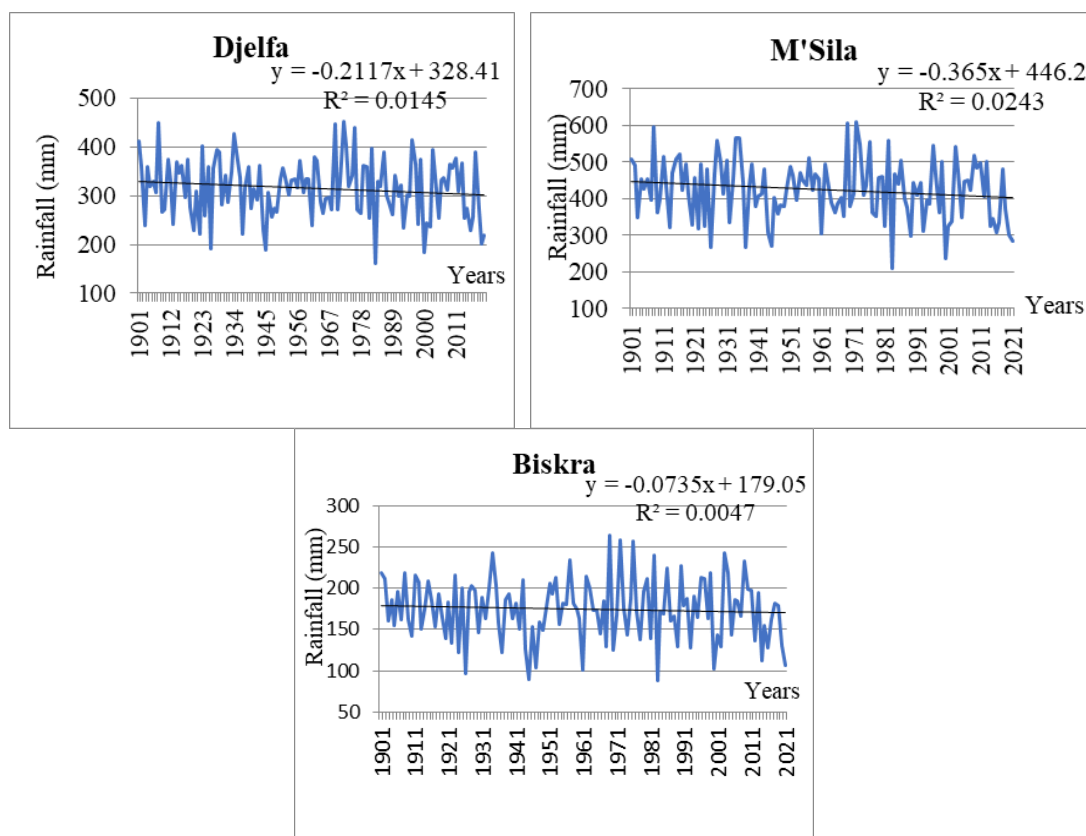


Figure 3. Evolution of precipitation in some wilayas of Central Algeria

Stations of Eastern Algeria

Over the century, no wilaya in Eastern Algeria shows a significant drying trend, regardless of their geographical or bioclimatic position.

The p-values around 0.8 support the null hypothesis, indicating no statistically significant drying trend over the century (Table 5). However, the negative Sen slopes suggest a general decrease in precipitation, although this is not statistically confirmed. The last three years of drought further reinforce this downward trend, though it remains statistically unverified (Table 5).

Table 5. Centennial trends in precipitation for several stations in Eastern Algeria. The period covering the years 1901 to 2022

	Khenchela	Tebessa
Kendall's Tau	-0.014	0.017
S	-103.000	122.000
Var (S)	199245.667	199246.667
P-value (two-tailed)	0.819	0.786
Alpha	0.05	0.05
H ₀	Accepted	Accepted
Sen's slope	-0.041	-0.454
Sen's slope CI	]-0.171, 0.093[	]-0.674, -0.272[
Least squares regression slope	0.013	0.095

Figure 4 shows the evolution of precipitation in eastern Algeria.

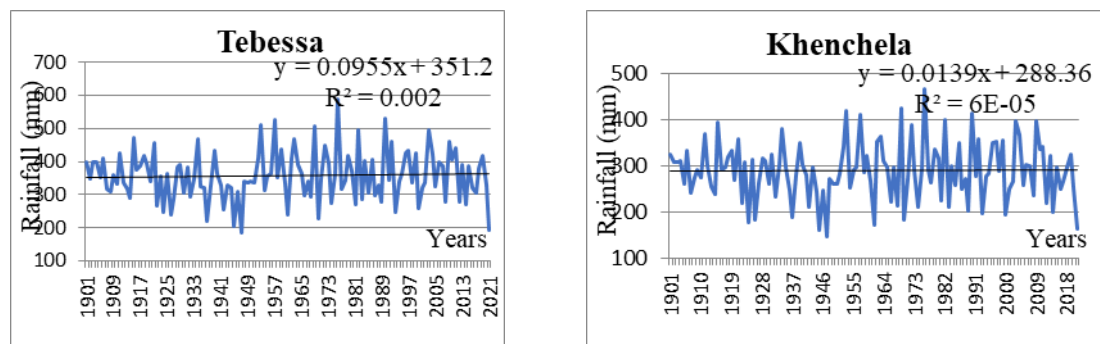


Figure 4. Evolution of precipitation in some stations of Eastern Algeria

In Morocco

It is observable that the results vary depending on the regions. For Guelmim-Oued Noun and the Oriental, the null hypothesis is rejected with very low p-values (< 0.001), indicating a significant drying trend in these regions. However, for Souss-Massa and Drâa-Tafilalet, no significant drying trend was observed in these regions, indicating a relative stability of precipitation (Table 6). These results are generally consistent with most studies on climate in Morocco, although there may be discrepancies depending on the regions and observation periods. This underlines how relatively close areas can have very different climatic dynamics, emphasizing the importance of a detailed regional analysis.

Table 6. Century-long trends in precipitation in some regions of Morocco. The period covering the years 1901 to 2022

	Guelmim-Oued Noun	Souss- Massa	Drâa-Tafilalet	Oriental
Kendall's Tau	-0.132	-0.074	-0.094	-0.260
S	-977.000	-548.000	-697.000	-1921.000
Var (S)	204205.667	204206.667	204207.667	204207.667
P-value (two-tailed)	0.031	0.226	0.124	< 0.0001
alpha	0.05	0.05	0.05	0.05
H ₀	Rejected	Accepted	Accepted	Rejected
Sen's slope	-0.156	-0.191	-0.225	-0.892
Sen's slope CI	] -0.290, -0.016[	] -0.480, 0.113[	] -0.495, 0.065[	] -1.234, -0.504[
Least squares regression slope	-0.0808	-0.1357	-0.1905	-0.9283

In Tunisia

Statistical tests for stations in arid Tunisia, unlike those in Morocco and Western Algeria, indicate that the null hypotheses are accepted, showing no significant drying trend. The p-values are far from the significance threshold, further supporting this result. Moreover, the Sen's slopes obtained are positive, reinforcing this observation. This suggests that, contrary to some regions in Morocco and Algeria, arid Tunisia does not exhibit significant signs of drying over the study period (*Tables 7a, b*).

Table 7a. Century-scale rainfall trends in selected governorates of Tunisia. The period covering the years 1901 to 2022

	Gabès	Gafsa	Kairouan	Kasserine	Mahdia	Sousse
Kendall's Tau	0.025	0.061	0.025	0.019	0.065	0.053
S	186.000	447.000	187.000	139.000	481.000	391.000
Var (S)	204206.667	204205.667	204207.667	204207.667	204207.667	204207.667
P-value (two-tailed)	0.682	0.324	0.681	0.760	0.288	0.388
alpha	0.05	0.05	0.05	0.05	0.05	0.05
H ₀	Accepted	Accepted	Accepted	Accepted	Accepted	Accepted
Sen's slope	0.058	0.136	0.097	0.073	0.207	0.180
Interval	] -0.186, -0.314[	] -0.144, -0.401[	] -0.346, -0.556[	] -0.428, -0.546[	] -0.150, -0.545[	] -0.206, -0.582[

Table 7b. Century-scale rainfall trends in selected governorates of Tunisia. The period covering the years 1901 to 2022

	Monastir	Medenine	Sfax	Tataouine	Tozeur	Kebili
Kendall's Tau	0.069	-0.037	0.053	-0.042	0.033	0.020
S	509.000	-270.000	391.000	-308.000	242.000	146.000
Var (S)	204207.667	204206.667	204207.667	204204.667	204204.667	204206.667
P-value (two-tailed)	0.261	0.552	0.388	0.497	0.594	0.748
alpha	0.05	0.05	0.05	0.05	0.05	0.05
H ₀	Accepted	Accepted	Accepted	Accepted	Accepted	Accepted
Sen's slope	0.201	-0.081	0.144	-0.043	0.031	0.021
Interval	] -0.158 - 0.562[	] -0.312 -0.184[	] -0.177 - 0.475[	] -0.180 - 0.089[	] -0.103 - 0.164[	] -0.132 -0.186[

Homogeneity tests

In Algeria

In Algeria, the results indicate that the null hypotheses are accepted, meaning there is no generalized trend of climatic shifts across the country, suggesting some level of climatic stability on a national scale. However, certain stations exhibit significant climatic breakpoints, notably those in the Southern Oran region. These breakpoints correspond to key transitional periods, such as 1976, which marked a climatic shift between dry and wet periods (*Table 8*).

Table 8. Results of homogeneity break tests in Algeria. The period covering the years 1901 to 2022

Country	Wilayas	Pettitt test			Buishand test			SNHT test		
		Year	P-value	H0	Year	P-value	H0	Year	P-value	H0
Algeria	Biskra	2011	0.582	Fail to reject H0	2011	0.743	Fail to reject H0	2013	0.283	Fail to reject H0
	Bordj Bou Arreridj	1976	0.596	Fail to reject H0	1976	0.193	Fail to reject H0	2013	0.093	Fail to reject H0
	Djelfa	1982	0.825	Fail to reject H0	1982	0.419	Fail to reject H0	2013	0.177	Fail to reject H0
	El-Bayadh	1964	0.290	Fail to reject H0	1964	0.078	Fail to reject H0	1908	0.002	Reject H0
	Naâma	1976	0.008	Reject H0	1964	0.001	Reject H0	1908	0.001	Reject H0
	Bechar	1923	0.160	Fail to reject H0	1923	0.020	Reject H0	1908	0.0001	Reject H0
	Saida	1976	< 0.0001	Reject H0	1976	< 0.0001	Reject H0	1976	< 0.0001	Reject H0
	Sidi Bel Abbas	1976	< 0.0001	Reject H0	1976	0.000	Reject H0	1976	0.000	Reject H0
	Laghouat	1908	0.451	Fail to reject H0	1908	0.656	Fail to reject H0	1902	0.082	Fail to reject H0
	M'sila	1936	0.682	Fail to reject H0	1976	0.263	Fail to reject H0	2013	0.073	Fail to reject H0
	Oum-El-Bouaghi	1921	0.216	Fail to reject H0	2011	0.892	Fail to reject H0	2020	0.438	Fail to reject H0
	Tebessa	1951	0.888	Fail to reject H0	1951	0.253	Fail to reject H0	2020	0.390	Fail to reject H0
	Khenchela	1951	0.160	Fail to reject H0	1951	0.639	Fail to reject H0	2020	0.518	Fail to reject H0

In Tunisia

The Tunisian stations also showed that the null hypothesis is accepted everywhere, indicating the absence of a significant trend towards aridification, reflecting a certain climatic stability. However, the stations of Gafsa and Mahdia, in which significant trends were detected, highlight important local variations. This finding is understandable considering the lack of a significant trend towards aridification detected by the statistical tests, with the exception of the two previously mentioned stations (*Table 9*). However, the years indicated generally fall within the period 1947-1956 for most stations, except for the pre-Saharan stations like Tataouine and Medenine, which have more recent dates (1998 and 1986, respectively), suggesting different climatic dynamics and perhaps region-specific influences.

Table 9. Results of homogeneity break tests in Tunisia. The period covering the years 1901 to 2022

Country	Governorates	Pettitt test			Buishand test			SNHT test		
		Year	P-value	H0	Year	P-value	H0	Year	P-value	H0
Tunisia	Gabes	1952	0.656	Accepted	1952	0.128	Accepted	2020	0.081	Accepted
	Gafsa	1956	0.197		1952	0.047	Rejected	2020	0.116	Accepted
	Kairouan	1947	0.574		1947	0.252	Accepted	2020	0.042	Rejected
	Kasserine	1951	0.905		1951	0.308	Accepted	2020	0.066	Accepted
	Mahdia	1947	0.126		1947	0.037	Rejected	2020	0.092	Accepted
	Monastir	1947	0.176		1947	0.252	Accepted	1947	0.170	Rejected
	Medenine	1986	0.616		1997	0.670	Accepted	2020	0.058	Accepted
	Sfax	1947	0.198		1997	0.062	Accepted	2020	0.086	Accepted
	Sidi Bouzid	1947	0.267		1947	0.069	Accepted	2020	0.110	Accepted
	Sousse	1947	0.433		1947	0.139	Accepted	2020	0.090	Accepted
	Tataouine	1998	0.579		1997	0.713	Accepted	2019	0.079	Accepted
	Tozeur	1961	0.585		1952	0.188	Accepted	2020	0.128	Accepted
	Kebili	1952	0.797		1952	0.180	Accepted	2020	0.085	Accepted

In Morocco

In Morocco, the results of the homogeneity tests show that the null hypotheses (H0) are accepted, indicating an absence of significant breaks in most stations, thus suggesting a certain climatic stability. However, trend tests indicate an overall tendency toward drying, with subtle but significant changes that warrant particular attention. The years 1972, 1976, 1980, and 1997, identified as periods close to breaks, are particularly interesting as they mark significant transition periods (*Table 10*). These results highlight the importance of monitoring and analyzing transition periods to better understand long-term climate dynamics.

Table 10. Results of homogeneity break tests in Morocco. The period covering the years 1901 to 2022

Country	Regions	Pettitt test			Buishand test			SNHT test		
		Year	P-value	H0	Year	P-value	H0	Year	P-value	H0
Morocco	Sous- Massa	1980	0.989	Accepted	1972	0.697	Accepted	2012	0.280	Accepted
	Drâa- Tafilalet	1977	0.477		1977	0.165		2012	0.353	
	Guelmim- Oued Noun	1920	0.277		1972	0.630		2012	0.373	
	Oriental	1976	< 0.0001		1976	< 0.0001	Rejected	1980	0.0001	Rejected

Evolution of rainfall in recent period

To better understand the evolution of rainfall in recent years, we segmented climate data into 30-year periods: 1901-1931, 1932-1961, 1962-1991, and 1992-2021, in accordance with the recommendations of the World Meteorological Organization (WMO).

In Algeria, the results highlight a general downward trend in rainfall, particularly pronounced during the last period (1992-2021). This decrease is clearly noticeable in the western regions, such as Naâma and Sidi Bel Abbès, and to a lesser extent in central areas like M'sila, influenced by a pre-Saharan climate (see *Appendix 1*).

In Tunisia, the recent period (1992-2021) is also identified as the driest. However, this trend varies regionally. It remains relatively mild in the northern coastal areas, such as Sousse and Monastir, but becomes significantly more pronounced in steppe regions like Gafsa, Sfax, and Kasserine. In the south, the trend is more heterogeneous and depends on the meteorological stations. For example, regions with a desert climate, such as Tataouine and Tozeur, generally show a decrease in rainfall, consistent with global drought trends. However, local variations are sometimes observed, particularly in Médenine, where certain periods of increased rainfall occur, though these events remain rare (see *Appendix 2*).

In Morocco, a generalized decrease in rainfall is observed across all regions, with a particularly marked decline in the eastern areas (see *Appendix 3*).

Discussion

The analysis of rainfall trends reveals a gradient of drying across the Maghreb, from the eastern to the western regions, with Morocco and Northwestern Algeria being the most affected, confirming the vulnerability of these regions to global warming.

The analysis of rainfall trends in Algeria is particularly interesting, as the country is located at the crossroads between Tunisia and Morocco, offering a unique position to observe diverse climatic trends. The main Algerian provinces reveal that most of the central and eastern territories show no signs of drying, in contrast to the western regions of Algeria, which display different trends, often pointing towards drying (Meddi and Hubert, 2003; Hirche et al. 2007; Taïbi et al., 2017; Belala et al. 2018; Benzater et al., 2019; Taïbi et al., 2019; Achour et al., 2020).

However, studies such as those by Bessaklia et al. (2018) show an increase in the intensity of precipitation, indicating stronger and more concentrated rainfall periods. Meanwhile, Beldjazia and Alatou (2016) emphasized the variability of precipitation, highlighting the importance of understanding local climate fluctuations.

Furthermore, the figure highlights three notably dry periods in the latter half of the century: the early 1980s, the decade of the 2000s, and the period from 2018. Indeed, the initial dry spell in the 1980s coincided with the increasing rate of degradation in steppe pastures, a process significantly amplified by the subsequent dry period in the 2000s. This latter period intensified arid conditions and had substantial consequences for the local ecosystem (Meddi and Hubert, 2003; Hourizi et al., 2017; Belala et al., 2018; Oukil et al., 2020). Although a wetter phase followed the 2000s, precipitation amounts have not recovered to the levels observed before the 1980s. Finally, the relatively dry years from 2019 to 2021 have underscored the increasing climatic variability in the region.

In Morocco, the overall trend is towards a decrease in rainfall, especially in the eastern region, a natural extension of the Algerian steppe, but there are some differences between the regions and authors.

Stour and Aggoumi (2009) show the general increase in drought in Morocco. The Eastern region is particularly marked by this trend, suggesting increasingly arid climatic conditions.

Sebbar et al. (2011) highlight aridification in Morocco starting from 1970. This aridification indicates a shift towards more frequent and intense drought periods.

Ait Brahim et al. (2017) report a significant decline in precipitation in the eastern region of Morocco, reaching a deficit of 30 to 40 mm between the periods 1971-1980 and 1998-2007.

Ait Ouhamchich et al. (2018) provide an interesting perspective by highlighting that, despite some trends towards drying observed in other studies, the climatic indices analyzed through ombrothermic diagrams do not show any significant changes in the bioclimates of certain regions of Morocco, particularly in Béni Mellal, Khénifra, and Drâa-Tafilalet. This indicates a relative stability of the bioclimatic conditions in the studied regions.

Driouche et al. (2020), over a period spanning from 1960 to 2013, show that the drying trend varies across Morocco's geographical regions. However, the Eastern part, which extends the Algerian steppes, exhibits a clear drying trend, confirming observations from other studies on this vulnerable area.

The analysis performed by Khomsi et al. (2015) in the Tensift and Bouregreg regions, covering the period from 1983 to 2005, did not identify a clear drying trend, which contrasts with the findings of Driouech (2010) and Singla et al. (2010) but this period is shorter and other studies analyzed the Bouregreg basin over an extended period from 1977 to 2023 and their studies reveal a significant drying trend, differing from some studies that did not report such a pronounced pattern. This analysis highlights a critical situation in the Bouregreg basin.

The work of Sheffield and Wood (2007) enhances the understanding of climatic trends in Morocco, particularly in the northern regions, showing significant drying trends in annual precipitation. These findings align with those reported by other researchers, such as Hirche et al. (2007), Hirche (2010), Driouech et al. (2013), and Belala et al. (2018), who identified a similar gradient despite limitations stemming from the sparse distribution and temporal coverage of meteorological stations.

According to Nguyen Quang Thi et al. (2023), a notable drought was observed in Morocco during the past decade. However, the Mann-Kendall test shows no significant trend over the 1981–2010 period, despite the recent drought. This finding indicates that drying trends may emerge over shorter timescales or localized areas but are not always generalizable over longer periods. These observations emphasize the need to combine short- and long-term analyses to gain a comprehensive understanding of climatic trends.

The topographical complexity of Morocco, characterized by numerous mountain ranges and long coastlines, creates marked regional climatic variations. Indeed, the trend towards drying does not appear in regions such as Souss-Massa and Drâa-Tafilalet, unlike Guelmim-Oued Noun and the Oriental, which experience more arid conditions, clearly illustrating this climatic diversity. The neighboring Algerian steppes, influencing the climatic conditions of the Oriental, add another layer to this complexity. This underscores the importance of considering the specific geographical and topographical characteristics of each region to understand local climatic dynamics.

In Tunisia, there is no global trend towards rainfall diminution. The regional study by Driouech et al. (2013) also confirms this climatic stability in contrast to the pronounced drying trend observed in Morocco. The work of Abd El-Hameed et al. (2023) further validates the idea of climatic stability in Tunisia. By analyzing monthly rainfall data from 16 stations across Tunisia over a 62-year period (1958–2020), they found similar results, indicating no significant drying trend for the majority of stations. These findings align with earlier observations of climatic stability in Tunisia.

The study by Dorsaf and Tarhouni (2020) reveals a downward trend in precipitation over a 38-year period (1975–2013) in Southeastern Tunisia, contrasting with the stable trends observed in other regions of the country. These findings highlight the complexity of climate studies and the importance of accounting for regional specificities. A broad-scale approach could overlook significant local trends, as exemplified by Southeastern Tunisia.

Finally, the Western Maghreb, including Eastern Morocco and Western Algeria, is particularly vulnerable due to arid conditions and chronic water deficits. This conclusion reinforces the urgency of implementing region-specific measures and strategies to address this aridification and protect these areas. However, the southern Algerian region shows early signs of aridification, which is concerning, especially with p-values close to threshold values and negative Sen slopes. It is also interesting to underline that Southern Tunisia shows a downward trend (Dorsaf and Tarhouni, 2020), suggesting that homogeneous study periods would likely reveal a decrease. This suggests that, even though aridification is not yet statistically significant, trends should be closely monitored. For now, only Eastern Algeria and Northern Tunisia appear to be relatively unaffected, although diminution can be visualized on the graphs, statistically significant trends are not detected.

The analysis of rainfall averages over several periods clearly shows that the end of the XXth century and the beginning of the XXIth century were marked by significant drought periods, highlighting the importance of monitoring these trends to anticipate and mitigate their impacts. The trend towards reduced rainfall at the start of this century is concerning and calls for proactive measures to mitigate its potential impacts.

The fact that current statistics do not show a significant trend for the steppe regions of Central and Eastern Algeria and Tunisia is reassuring in the short term. However, it is concerning that, in the coming years, if dry sequences persist, future statistical studies could confirm a trend towards decreasing rainfall. Furthermore, even in the eastern regions, partial studies have shown signs of aridification, through a decrease in seasonal rainfall, particularly in spring, and an increase in the number of dry days, highlighting the urgency of this situation.

It is crucial to continue monitoring climate trends and to prepare adaptation strategies in order to mitigate potential impacts. Current data and analyses will serve as a solid foundation for future measures to manage and preserve water resources.

Conclusion

The analysis of rainfall trends in the main administrative subdivisions of the Maghreb reveals that, overall, the Western Maghreb, particularly the Eastern Morocco and Western Algeria regions, which partly encompass the steppe areas, show a clear and concerning trend towards drought, with a progressive aridification, especially in the spring.

These areas, already burdened by chronic water deficits, have seen their vulnerability exacerbated, especially in the last 30 years, during which a downward trend was often observed. However, the relative stability observed in the northeast of Algeria and Tunisia is reassuring, in contrast to the Western Maghreb.

This difference highlights the variability of climatic dynamics within the same geographic region. Generally, the graphs show negative slopes, although statistically insignificant. This aligns with previous studies and highlights the vulnerability of the Western Maghreb, which is already marked by a water deficit and progressive aridification, particularly in the spring. The increase in the number of dry days, successive dry years, and extreme weather events is alarming indicators.

The future of the Western Maghreb looks challenging, and it is essential to promote the implementation of mitigation measures such as the construction of dams, seawater desalination, and wastewater treatment, which remain crucial to addressing these challenges. These initiatives, along with proactive and sustainable water resource management, are essential to ensure the resilience of local communities and ecosystems in the face of the impacts of climate change.

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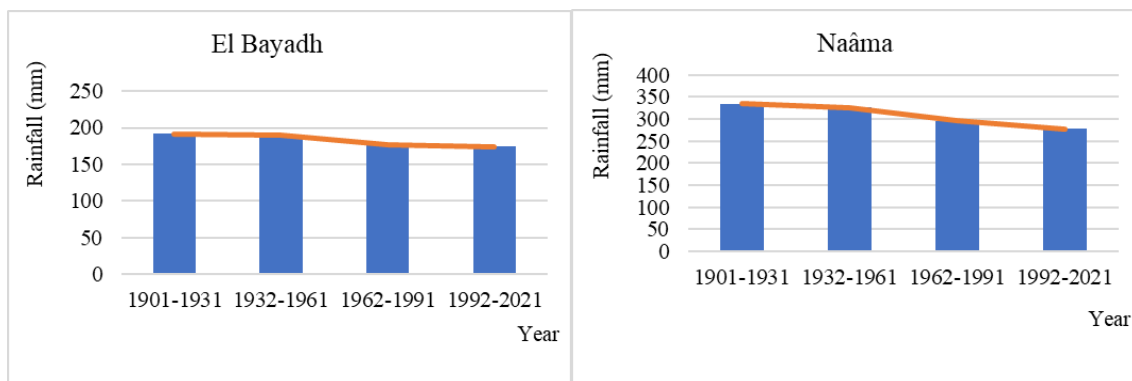
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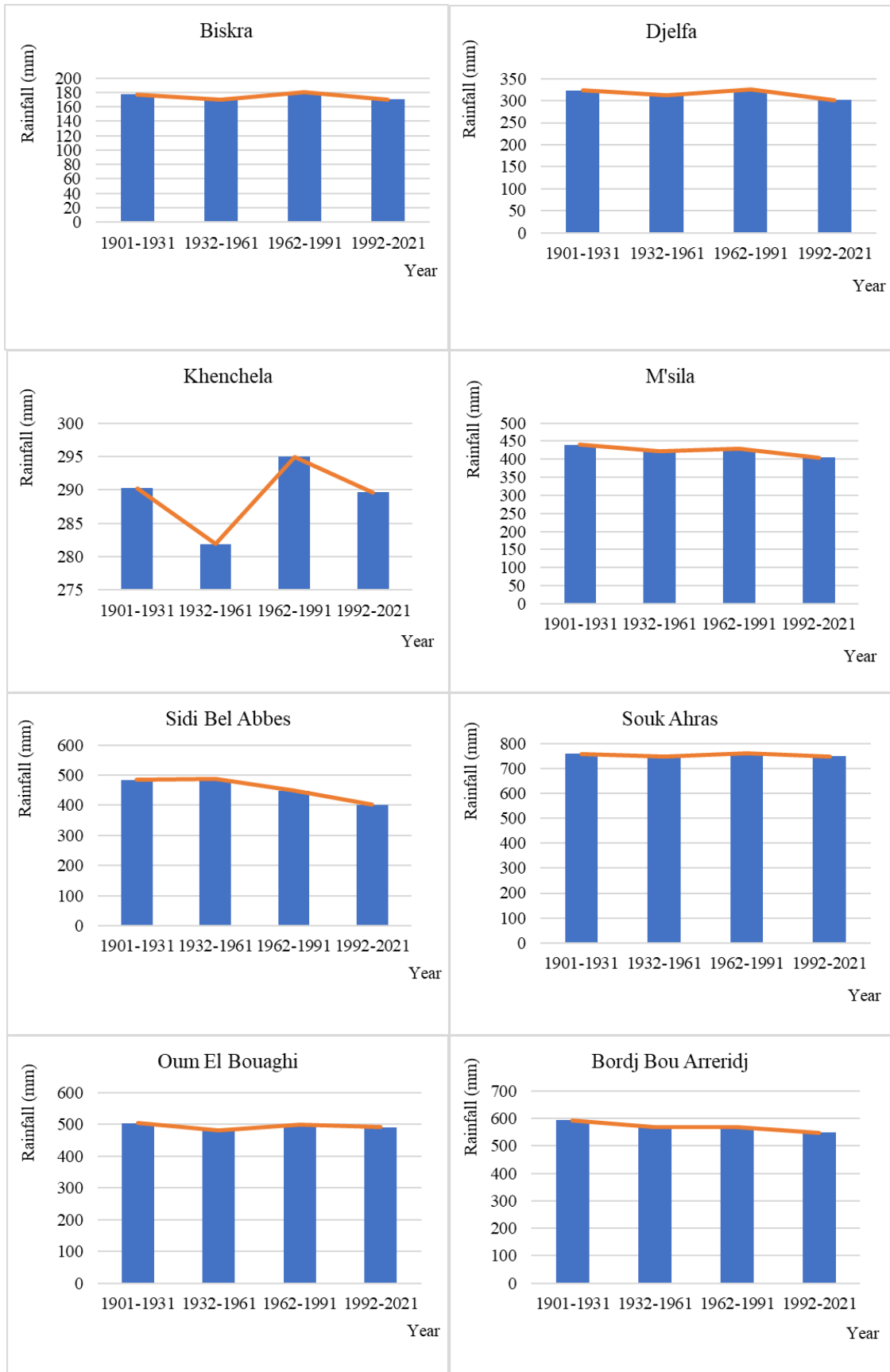
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APPENDIX

Appendix 1

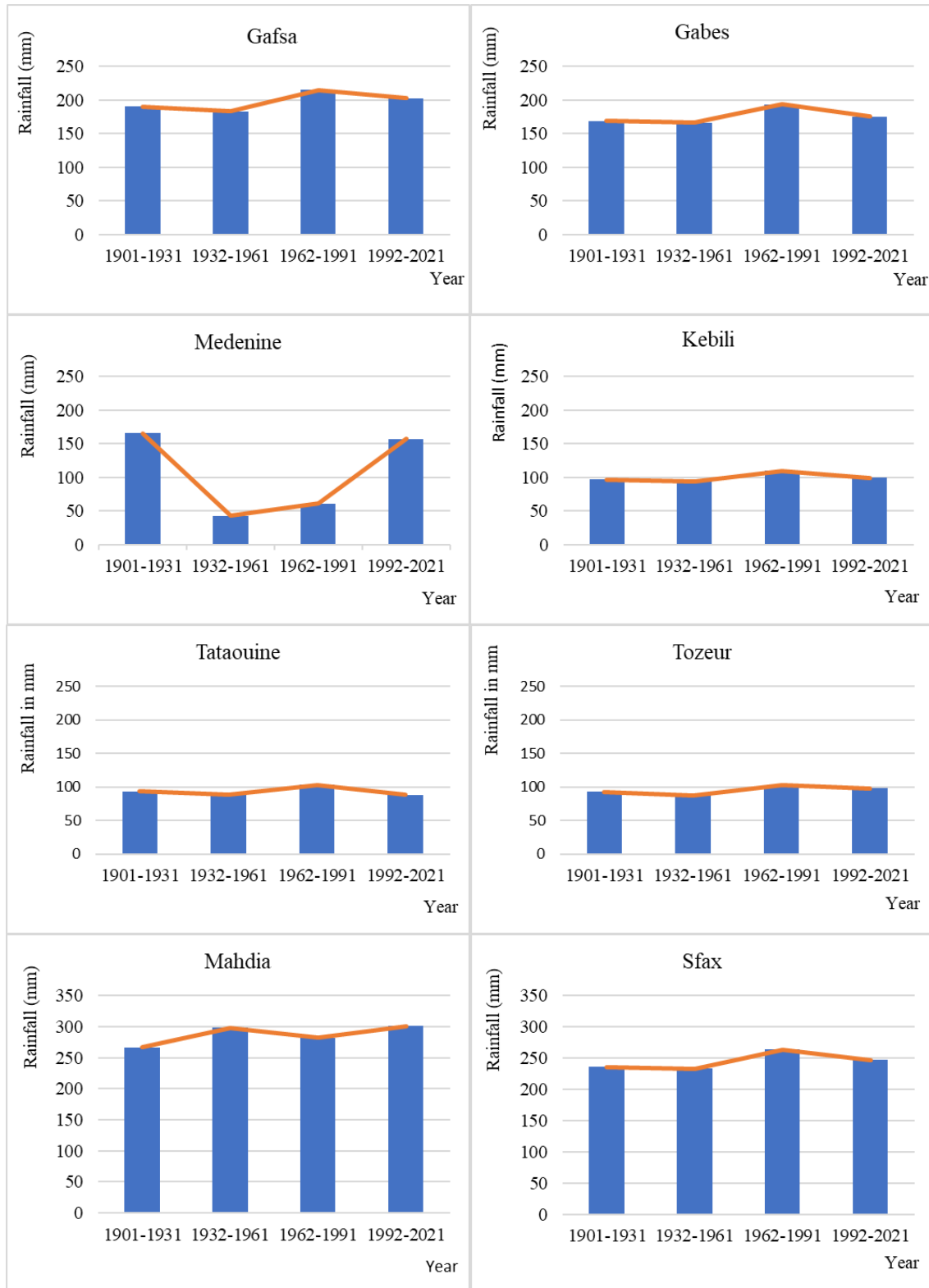
Algerian recent period

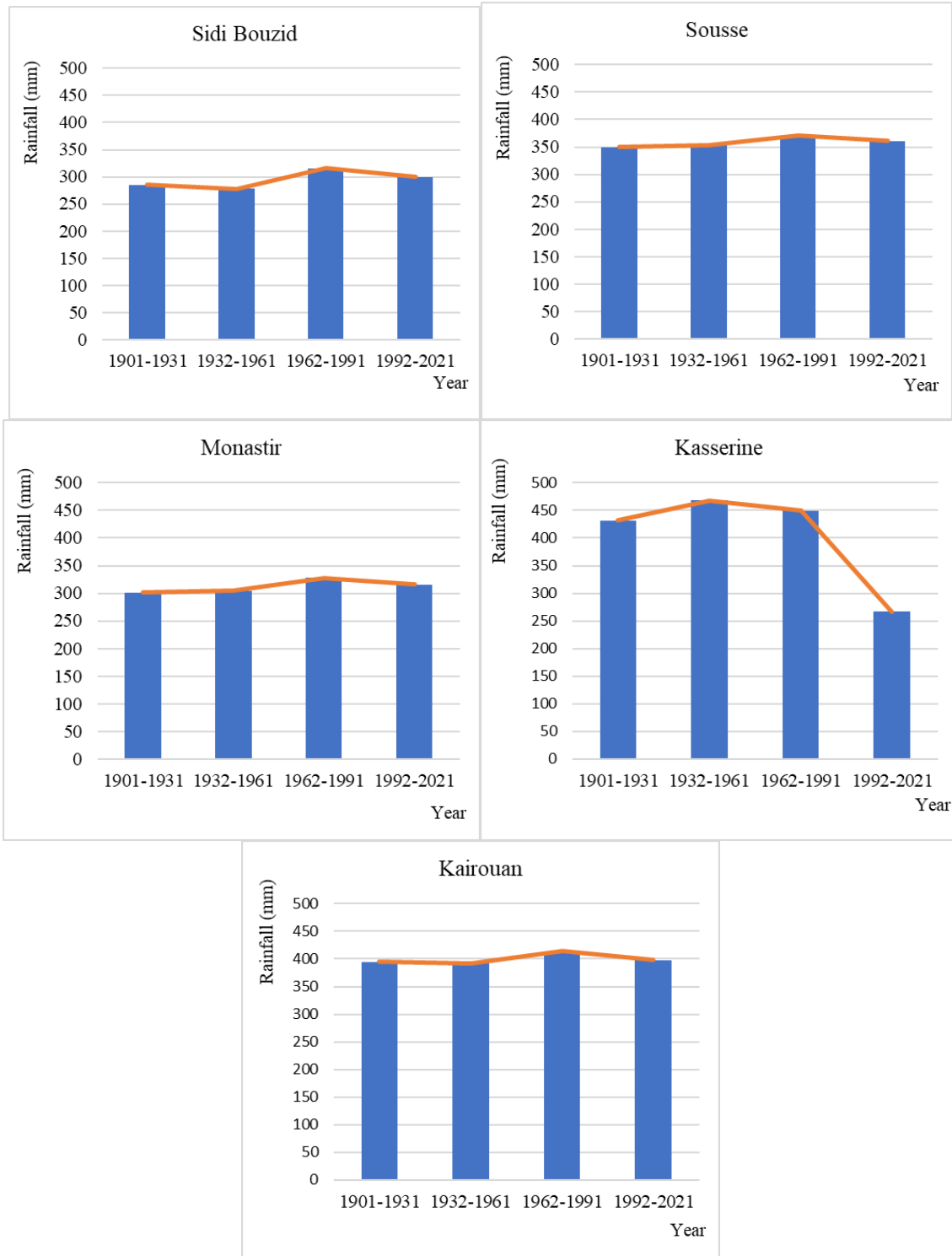




Appendix 2

Tunisian recent period





Appendix 3

Moroccan recent period

