Temporal trends in extreme temperature and precipitation events in an arid area: case of Chichaoua Mejjate region (Morocco)

Abdessamad Hadri, Mohamed El Mehdi Saidi, Tarik Saouabe and Abdelhafid El Alaoui El Fels

ABSTRACT

Extreme climate events often have a significant and direct impact on social, economic, and environmental systems. This study is an attempt to characterize the current trends and future projections of extreme climatic indices in an arid region of Morocco on both an annual and a seasonal scale using 12 precipitation and temperature-based indices. The Mann–Kendall test was used to assess the trends, and the inverse distance weighted interpolation method was employed to analyze the spatial distribution of extreme precipitation indices. The results showed that the most extreme climate indices are spatially distributed with a clear gradient from the mountainous area toward the plains. Furthermore, the analysis indicates nonsignificant downward trends in the number of days with a rainfall amount greater than 10 or 20 mm. However, a significant negative trend in the consecutive dry days was observed at the Iloujdane and Sidi Bouathmane stations. The temperature indices have recorded statistically significant upward trends at all the stations. Finally, based on the RCP4.5 and RCP8.5 scenarios, future climate change simulations show, respectively, annual precipitation decreases of 23 and 34% and temperature increases of 1.9 and 2.8 °C, which could imply substantial losses of cereal yield in the rainfed agriculture.

Key words | arid region, extreme precipitation, extreme temperature, future projection, Morocco, trend

Abdessamad Hadri (corresponding author)
Mohamed El Mehdi Saidi
Tarik Saouabe
Abdelhafid El Alaoui El Fels
Georesources, Geoenvironment and Civil Engineering Laboratory,
Cadi Ayyad University,
Marrakesh,
Morocco
E-mail: *hadri.abdessamad@gmail.com*

HIGHLIGHTS

- Use of 12 indices to analyze trends of temperature and precipitation.
- Annual and seasonal trends are performed with statistical significance.
- Use of five Regional Circulation Models (RCMs) for the future projections and evaluation of RCM simulations.
- Analyze the spatial distribution of the extreme precipitation indices and potential associated impacts of future climatic projections.

INTRODUCTION

Around the world, extreme weather events have been increasing in recent years, including heavy rains, heat waves, snowstorms, floods, and droughts (Katz & Brown 1992; Yan *et al.* 2002; Frei *et al.* 2015; Ummenhofer & Meehl 2017). New trends in these extreme events could accompany global climate change. It is important to understand these trends because of their significant impacts on the socio-economic and natural environment (Chuntian & Chau 2002; Chau 2019; Piya *et al.* 2019). While changes in average

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rainfall and temperature are informative on different aspects, they do not answer questions about changes in extreme events such as droughts, heavy rainfall, or heat and cold waves. And it is often changed in extremes that have the greatest and most direct impact on social, economic, and ecological systems (Easterling *et al.* 2000; Wigley 2009; Lobell *et al.* 2011).

Africa is the continent most vulnerable to climate change and global warming in the 21st century (Intergovernmental Panel on Climate Change (IPCC) 2007). The Mediterranean part of Africa is no exception and is already under water stress (Douglas *et al.* 2008; Sullivan & Huntingford 2009). Rainfall is projected to decrease along with the rise in average temperature, which may reach or even exceed 2–4 °C by the end of the current century (Giorgi & Bi 2005; Paeth *et al.* 2009; IPCC 2018).

Morocco, due to its atmospheric and oceanic characteristics and geographical position, is particularly exposed to the risks associated with climate change. Its sensitivity and vulnerability to climatic hazards are not to be neglected (Schilling *et al.* 2012). Previous studies of future climate projections identify Morocco as one of the countries most likely to be harmed by climate change (Battisti & Naylor 2009). Currently, Morocco is going through the longest drought in its modern history, characterized by a global decrease in precipitation and a clear upward trend in temperature (Driouech *et al.* 2010; Schilling *et al.* 2012; Khomsi *et al.* 2013; Zkhiri *et al.* 2018). Studies suggest that the temperature will continue increasing in the future; but in terms of the precipitation trend, the studies are inconclusive. Some suggest that precipitation will decrease in the future (Born *et al.* 2008; Driouech *et al.* 2009; Ait Brahim *et al.* 2016), while some others have projected a slight increase. Driouech *et al.* (2010) predict a decrease in total precipitation for several stations in Morocco for the period of 2021–2050. Similarly, Tramblay *et al.* (2012) showed a decrease in extreme precipitation, especially for the 2070–2099 projection period in the Atlantic coastal areas. Filahi *et al.* (2017) analyzed the RCP4.5 and RCP8.5 emission scenarios for two time horizons, 2036–2065 and 2066–2095. They concluded that the minimum temperature will increase more than the maximum temperature in most regions of Morocco and that there is a clear decrease in total precipitation in the various simulations. A similar prediction can be made for western central Morocco, where the study area is located. Recent projections in some areas in Morocco predict a future decline in precipitation, which will negatively impact water resources and exacerbate the drought (Filahi *et al.* 2017; Hertig & Tramblay 2017; Marchane *et al.* 2017). Furthermore, several analyses of drought and future projections of temperature and precipitation (Khomsi *et al.* 2016; Bouras *et al.* 2019; Meliho *et al.* 2019) predict a systematic increase in maximum and minimum temperature, ranging from 1 to 6 °C.

While many studies have investigated climatic changes in western central Morocco, most of them have focused on changes in the mean values of climatic variables (Khomsi *et al.* 2016; Fniguire *et al.* 2017; Bouras *et al.* 2019; Meliho *et al.* 2019). Changes in extreme temperature and extreme rainfall have rarely been investigated. In addition, most of these studies do not address the behavior of spatiotemporal extremes on a local scale, focusing on the regional level. The main objective of the present work is to fill this gap by looking at trends in extreme temperature and precipitation and analyzing the spatial and temporal variation of these extremes in a local watershed of the Chichaoua-Mejjate region. It is worth noting that recent papers have recommended doing analysis of hydroclimatic variables on the local scale rather than on a large or regional scale since trends and their impacts could vary from one area to another (Sharma & Shakya 2006; Barua *et al.* 2012).

In the Marrakesh region, and particularly in the Chichaoua-Mejjate, the socio-economic impacts of climate change would be closely related to the quality and quantity of available water. The main effect will be the loss of agricultural income through reduced crop yields, which would trigger the displacement of populations. In fact, climate extremes such as recurring droughts, erosive rain, rainfall variability, and flooding are already beginning to have harmful socio-economic effects on the local population (especially the farmers) through the drop in the water table level, the drop in the flow rates of the surface sources used for irrigation, and recurring flood damage. The lack of knowledge and control of such extreme events patterns constitutes a barrier to the proper design of adaptation strategies to extreme events and, thus, makes populations less resilient to the harmful impacts of these phenomena. Therefore, policy-makers and local water users need exact information on annual and seasonal patterns in extreme climate events.

With this in mind, the aim of this study is to analyze trends in extreme climatic indices to inform climate policy and adaptation to climate change. We do this by assessing (i) the past spatiotemporal trends of extreme precipitation and temperature indices using observation datasets from the Chichaoua-Mejjate region (annual and seasonal trends of the indices have been done together with their statistical significance) and (ii) the future effects of climate change on these indices using a set of different RCM simulations performed by the regional climate model initiative Med-CORDEX (Ruti *et al.* 2016).

This is the first study to provide an assessment of past and projected future changes in extreme precipitation and temperature in an agricultural region of west-central Morocco. We use several innovative tools and models to assess multiple timescale behavior of extreme events for both historical and future periods, integrating 12 climatic indices in an annual and seasonal timescale. The spatial distribution of these extreme precipitation indices is interpreted using the inverse distance weighted (IDW) interpolation method, and the nonparametric Mann–Kendall trend test is used to examine the nonlinear trend in each extreme climate index at each station for each season. Assessing the trends in extreme precipitation and temperature indices is essential for monitoring climate abnormalities and mapping spatial variability of extreme climatic events with large spatial coverage (Goodess 2003; Zhang & Yang 2004; Zhang *et al.* 2008). Then, given the importance of using regional models at smaller spatial scales, five RCMs derived from a regional downscaling initiative are used to examine future patterns of extreme indices according to the representative concentration pathway RCP4.5 and RCP8.5 scenarios. Finally, we present a simple case study illustrating the potential influence of weather pattern changes on agriculture, based on the historical impact of the rainfall on crop yield and cultivated areas.

METHODS

Study area

The study area covers 5,193 km^2. It is located about 40 km west of Marrakech. It consists of three separate topographic areas: High Atlas Mountains, a piedmont area, and a plains area (Figure 1). The main watercourses are Oued Chichaoua and Oued Assif El Mal. Both of them start at the Western High Atlas and are often dry, as their flow depends on rainfall from rainy periods. The study area has a semi-arid continental climate. It rains mostly from autumn to spring and the precipitation is very irregular. Drought is quite frequent, in particular in the plains, where temperature and evaporation rates are high.

The Chichaoua-Mejjate region is the least studied part of the Haouz plain in terms of the impact of climate change on water resources. Understanding the variability, trends, and characteristics of climate indices in this region is crucial for ensuring water availability and designing appropriate adaptation strategies for the agriculture sector. This region has an important contribution to the economic development of the Marrakech region. Although it is arid, its economy is mainly based on agriculture. Water demand is high and will be even higher in the future in a situation of climate change and demographic evolution.

Data sources

The rainfall monitoring network of the study area consists of four observation posts belonging to the synoptic network of the ABHT (Tensift Hydraulic Basin Agency). The data analyzed in this study comes from this agency. The monitoring of daily rainfall was launched in 1971, 1989, 1989, and 1970, respectively, at the main stations of Chichaoua, Iloujdane, Sidi Bouathmane, and Abadla. However, the temperature is only monitored at the Abadla station (Table 1). Precipitation data were recorded daily at the four stations, and temperature data were recorded daily at the Abadla station.

Figure 2 shows the seasonal variability of precipitation and temperature in the study area. At the Abdala station, the average monthly temperatures, calculated over the period 1982–2017, vary between 13 and 29 °C. The hottest months are usually July and August (28.7 °C on average, but their maxima can reach 45–46 °C). The coldest month is January (the average is 12.8 °C, but the daily minima can fall below 1 °C). We note that the extreme temperatures recorded vary significantly. They can drop below 0 °C in winter and exceed 45 °C in summer. For rainfall, the annual average is 182 mm and there are two clearly

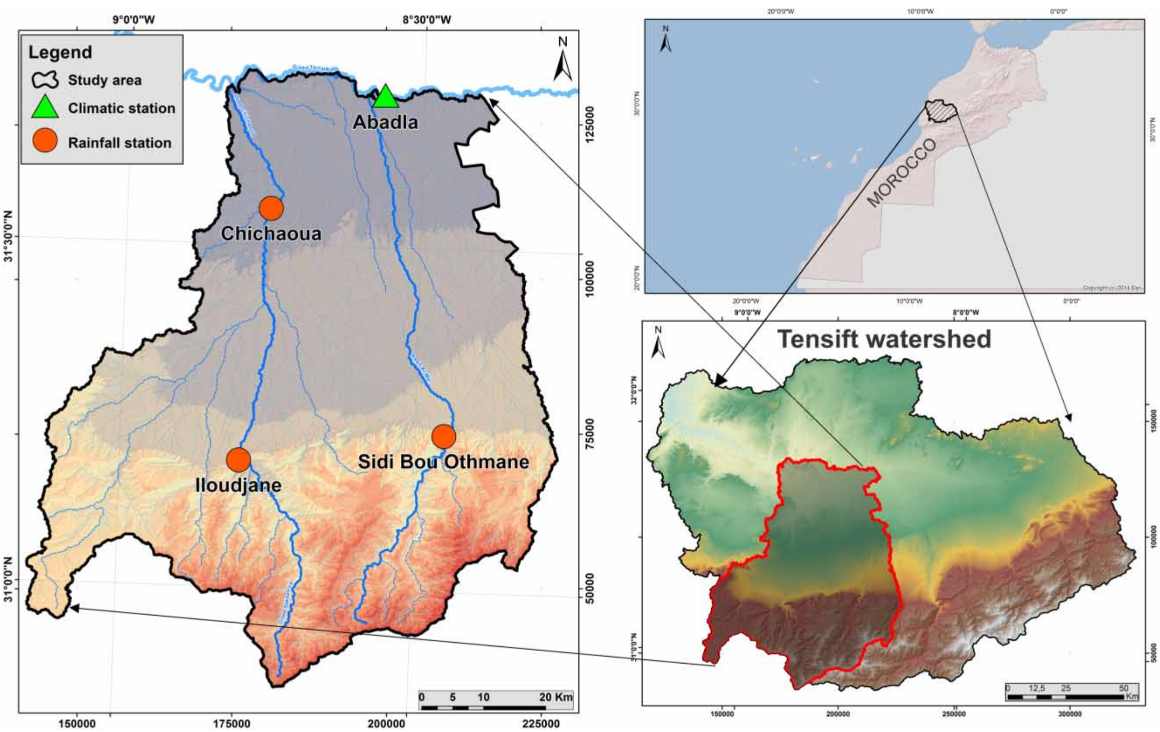

Figure 1 | Study area.

Table 1 | Characteristics of rainfall stations

Station	*X* (km)	*Y* (km)	*Z* (m)	Periods of records	Precipitation (mm/year)	Temperature (°C/year)
Chichaoua	181.525	111.200	340	1971–2017	180	–
Iloudjane	176.245	70.525	757	1989–2017	315	–
Sidi Bouathmane	209.400	74.300	820	1989–2017	355	–
Abadla	199.842	129.853	250	1970–2017	173	–
				1982–2017	–	20.6

differentiated characteristic periods (Figure 2): (i) from November to April, a wet season during which almost all of the rainy episodes occur, constituting 81% of the annual rainfall, with peaks in November and March and (ii) from May to October, a dry season, which accounts for only 19% of the annual rainfall.

Data quality control

Generally, data quality control has already been carried out by the Hydraulic Basin Agency, which provided the data. Nevertheless, we have carried out the following additional quality control steps on the data used in our study:

- Automatically changing to a missing value a recorded daily precipitation value of less than zero;
- Automatically changing to a missing value both the daily maximum and daily minimum temperature if the recorded daily maximum temperature is below the daily minimum temperature; and
- Identifying outliers in daily precipitation and daily maximum and minimum temperature. Data is statistically considered an outlier if it is outside this range:

$$[Q1 - 1.5 \times (Q3 - Q1),\ Q3 + 1.5 \times (Q3 - Q1)]$$

where $Q1$ is the first quartile of the temperature or precipitation series and $Q3$ is the third quartile. Checking which

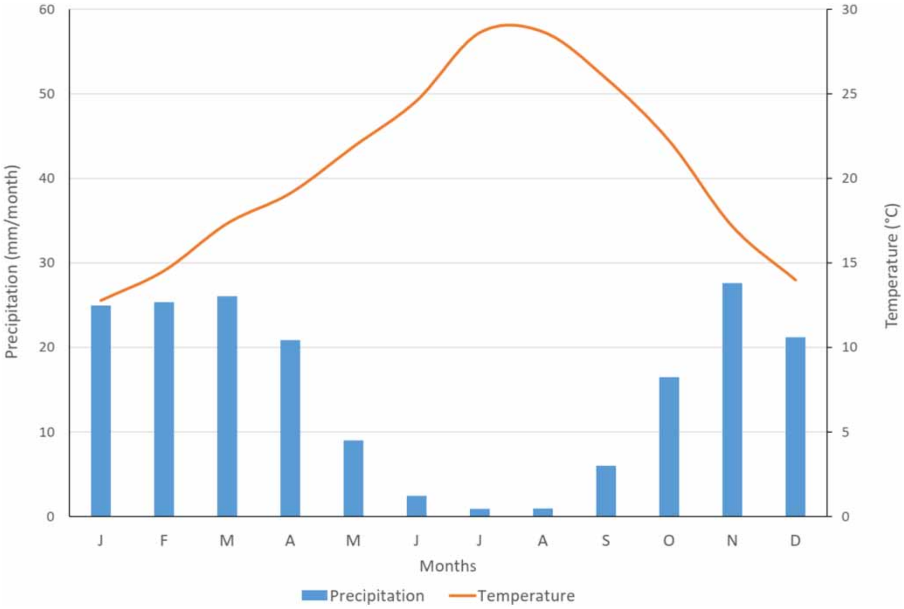

Figure 2 | Mean inter-annual monthly precipitation and temperature for the study area.

values belong in this interval was done using a computer spreadsheet program. No data were found outside of these thresholds.

The data were tested for homogeneity in order to detect artificial variations within the meteorological series and to avoid biased results. (The only known factor that may have affected the homogeneity of the time series data is the change in the collection of these data after 2010 that took place when the Hydraulic Basin Agency subcontracted the measurement to a private entity in 2010.) Several statistical tests have been used for a similar purpose at the Upper Indus Basin in Pakistan (Hasson *et al.* 2015; Latif *et al.* 2020). We assessed data homogeneity using two methods:

- The quantile matching (QM) method using the RHtest package in R, developed at the Climate Research Branch of the Meteorological Service of Canada and available from the ETCCDMI website. This program is based on a two-phase regression model with a linear trend for the entire base series (Wang 2008). The work of Wang (2008) explains this model in more detail.
- The classical double-mass curve technique. This method consists of plotting the cumulative time on the abscissa and the cumulative rainfall value on the ordinate. These methods showed the absence of heterogeneity in the rainfall and temperature series.

Climate model outputs from Med-CORDEX

For the future projections, five simulations of regional circulation models (RCMs) were used. RCMs are suitable for the dynamic modeling of the climate on a regional scale (Giorgi 2006; Laprise 2008; Rummukainen 2010). The advantage over general circulation models is that they operate over a limited area. This increases the spatial resolution. In addition, RCMs are specifically designed to suit the needs of scientists working in economically developing countries. Huntingford & Gash (2005) highlighted the importance of RCMs in involving scientists from developing countries in climate research. These simulations are derived from the Med-CORDEX (Mediterranean Coordinated Regional Climate Downscaling Experiment) initiative (Ruti *et al.* 2016), which has provided simulations at different resolutions, taking into account the specificity of the Mediterranean climate. The Med-CORDEX project has considered several combinations of global and regional circulation patterns to assess uncertainties in future projections (Table 2).

Med-CORDEX belongs to a new generation of regional climate model simulations devoted to the Mediterranean

Table 2 | Description of the different simulations of the different Climate Regional Climate Models used in this study

Simulation	Period covered	Model	RCM	Forced by	Resolution
HIST (Historical runs)	1951–2005	CNRM	ALADIN	GCM:CNRM	50 km
		ICTP	RegCM4	GCM: HAD	
		CMCC	CCLM	GCM: CMCC	
		GUF	CCLM	GCM: MPI-ESM	
		IPSL	LMDZ	GCM: IPSL	
EVAL (Evaluation runs)	1979–2012	CNRM	ALADIN	ERA-Interim reanalysis	
		ICTP	RegCM4		
		CMCC	CCLM		
		GUF	CCLM		
		IPSL	LMDZ		
Scenario RCP 4.5	2006–2100	CNRM	ALADIN	GCM:CNRM	
		ICTP	RegCM4	GCM: HAD	
		CMCC	CCLM	GCM: CMCC	
		GUF	CCLM	GCM: MPI-ESM	
		IPSL	LMDZ	GCM: IPSL	
Scenario RCP 8.5	2006–2100	CNRM	ALADIN	GCM:CNRM	
		ICTP	RegCM4	GCM: HAD	
		CMCC	CCLM	GCM: CMCC	
		GUF	CCLM	GCM: MPI-ESM	
		IPSL	LMDZ	GCM: IPSL	

ERA, European Reanalysis; GUF, Goethe University Frankfurt; IPSL, Institut Pierre Simon Laplace; CNRM, Centre National de Recherches Météorologiques; ICTP, International Centre for Theoretical Physics; CMCC, Centro Euro-Mediterraneo sui Cambiamenti Climatici.

area. It performs recent dynamic downscaling simulations and provides a high-resolution regional climate model (50 km). The advantages of Med-CORDEX are that (i) it covers the entire north of Morocco, including our study area, and (ii) it is commonly used in the Haouz region and has been evaluated by many authors in that context (Tramblay *et al.* 2013; Marchane *et al.* 2017; Zkhiri *et al.* 2018).

Five simulations are provided by the Med-CORDEX project. They result from different GCM/RCM combinations aiming to assess the uncertainty of future projections.

RCP4.5 and RCP8.5 are the two future climate simulations considered in the Med-CORDEX project. They represent two out of four greenhouse gas concentration trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014. These two RCP scenarios represent a possible range of additional radiative forcing values in the year 2100 equal to +4.5 and +8.5 $W\,m^{-2}$, respectively, with respect to the pre-industrial climate. RCP4.5 and RCP8.5, widely used for future climate forcing, are the most representative projections and represent, respectively, the optimistic and pessimistic scenarios with respect to the greenhouse gases concentration. RCP 4.5 explores a pathway for the stabilization of radiative forcing by 2100, while RCP8.5 corresponds to the pathway with the highest greenhouse gas emissions.

Four simulations are available for each model. They were performed in the same area at a 50-km resolution. In total, 20 simulations were performed. The data from the grid point corresponding to the Chichaoua-Mejjate zone have been extracted.

Extreme precipitation and temperature indices

Several indices of climatic extremes have been defined through a number of workshops and studies at the international level (Karl *et al.* 1999; Folland *et al.* 2001; Manton *et al.* 2001). Currently, several definitions of several series of climatic indices are found in the literature, some of which are more recommended by the international scientific community. These include ClimDex's series of 27 climatic indices (http://cccma.seos.uvic.ca/ETCCDMI/software.shtml) that were developed at different stages (Frich *et al.* 2002; Zang & Yang 2004). The evolution of some of these indices has been studied in the context of Morocco by

Driouech (2006) and Khomsi *et al.* (2015). Another series of 57 climatic indices was defined by the European project SRATDEX (Goodess 2003), conducted from February 2002 to July 2005 and coordinated by the University of East Anglia (http://www.cru.uea.ac.uk/projects/Stardex).

Table 3 gives a summary of the indices calculated in this study, using international definitions, including those used by the Expert Team in Climate Change Detection Indices (ETCCDI) – Climatology Commission (CCl) of WMO7 (Frich *et al.* 2002; Driouech 2006).

Out of the 27 indices, the 12 that are recommended by the World Meteorological Organization (WMO) were chosen to represent different aspects of the change in extreme climate. These indices have a direct impact on regional water resources and ecological systems. They allowed us to characterize the temporal variation of climatic extremes and were not limited to the average state of the climate. Six precipitation-based indices were used to assess the amount and intensity (pav and pq90) and duration (pn10 mm, pn20 mm, CDD, and CWD) of extreme precipitation events. Six temperature-based indices were used to analyze the frequency (Tav, Tnav, and Txav) and magnitude (TX90p, TX10p, and WSDI) of both hot and cold extremes. These indices are adapted to the region and sufficient to assess the frequency and the intensity of climatic extremes and to consider the regional spatial differences.

Table 3 | Calculated precipitations end temperature indices

Indices	Definitions	Units
pav	Mean climatological precipitation	mm/year
pq90	Heavy rainfall threshold: 90th percentile of rain day amounts	mm/day
pn10 mm	Number of days with precipitation ≥ 10 mm	days
pn20 mm	Number of days with precipitation ≥ 20 mm	days
CDD	Longest dry period: maximum number of consecutive dry days (Pday < 1 mm)	days
CWD	Longest wet period: maximum number of consecutive wet days (Pday ≥ 1 mm)	days
Tav	Mean Tmean	°C
Tnav	Mean Tmin	°C
Txav	Mean Tmax	°C
TX90p	Warm days: percentage of days when TX > 90th percentile	days
TX10p	Cool days: percentage of days when TX < 10th percentile	days
WSDI	Warm spell duration indicator: annual count of days with at least six consecutive days when TX > 90th percentile	days

Trend analysis

To examine the nonlinear trend in each extreme climate index of each station for each season, we employed the non-parametric Mann–Kendall trend test (Mann 1945; Kendall 1975), and we did the analysis at the 95% confidence level. At this significance level, a negative trend is significant when its *p*-value is ≤0.05, and a positive trend is significant when its *p*-value is ≥0.05. This test, which has been widely used to analyze trends in hydrometeorological time series (Yue & Pilon 2004), has proved to be suitable for non-normally distributed data. It can also be used to detect trends in the time series and their significance (Yue & Wang 2002; Tramblay *et al.* 2013) and to identify monotonic trends (upward and downward trends) in the time series data.

The Mann–Kendall test statistic is calculated according to the following equation:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(X_j - X_k) \tag{1}$$

with

$$\operatorname{sgn} = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases} \tag{2}$$

where n is the total number of years in a time series and X_j and X_k represent, respectively, the annual values of years j and k. The significance test Z, which designates an upward or downward trend, is described as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sigma} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sigma} & \text{if } S < 0 \end{cases} \tag{3}$$

$$\sigma^2 = \frac{\left\{ n(n-1)(2n+5) - \sum_{j=1}^{p} t_j(t_j-1)(2t_j+5) \right\}}{18} \tag{4}$$

where p is the number of tied groups and t_j is the number of data values in the jth group.

The presence of a statistically significant trend is evaluated using the Z-value. A positive Z-value indicates an upward trend, and a negative value indicates a downward trend. If $|Z| > Z_{1-\alpha/2}$, the null hypothesis (H_0) is rejected and a statistically significant trend is said to exist in the climatic time series.

The existence of a serial correlation will affect the results of the Mann–Kendall trend analysis. For this purpose, we have used the lag-I autocorrelation test at 0.05 level of significance to check the independence and randomness in the time series. The lag-I coefficients were not statistically significant for any of the time series of temperature and precipitation used in this study. We assume, therefore, the absence of serial correlation in these series. It should be noted that the majority of the previous studies in the Haouz region also assumed that sample data are serially independent. The autocorrelation coefficient r_k of a time series for lag-k is calculated as follows:

$$r_k = \frac{\sum_{k=1}^{n-k} (x_t - \bar{x}_t)(x_{t-k} - x_{t+k})}{\sqrt{\sum_{k=1}^{n-k} (x_t - \bar{x}_t)^2 (x_{t+k} - \bar{x}_{t+k})^2}} \quad (5)$$

where r_k is the lag-k serial correlation coefficient, k is the time lag, n is the number of observations in the time series, x_t is the observation at time t, and $\bar{x}$ is the mean of series.

The annual and seasonal (Winter: December, January, and February; Spring: March, April, and May; Summer: June, July, August, and Autumn: September, October, and November) trend analysis of extreme precipitation and temperature indices were performed.

Spatial distribution analysis of extreme precipitation indices

To interpret the spatial distribution of the extreme precipitation indicators, the IDW interpolation method is used (Shepard 1968). Several spatialization methods make it possible to predict the attribute value of a variable at positions where no sample is available. This depends on the spatial distance between this position and other positions where samples have been collected. But the IDW interpolator has the advantage of taking into account more observations to achieve the predictions. It supposes that each input point has a local influence that diminishes with distance. It is a moving average interpolator that is usually applied to highly variable data and that is likely to improve the accuracy of predictions.

RESULTS

Spatial distribution of extreme precipitation indices

Some extreme precipitation indices decrease from south to north: pq90 (heavy rainfall threshold), pav (mean climatological precipitation), pn10 mm (number of days with precipitation ≥10 mm), and pn20 mm (number of days with precipitation ≥20 mm) (Figure 3). pq90 ranged from 13 to 22.1 mm/day, with the highest value in the piedmont area and the lowest value in the plains area. Between 1972 and 2017, the mean daily maximum precipitation exceeded 80 mm/day at the Sidi Bouathmane station; however, pq90 in Chichaoua-Mejjate never exceeded 31 mm/day. Therefore, pq90 is not a suitable threshold to detect heavy rainfall events, especially in the south of this region. pn10 mm ranged from 12.8 days in the southeast to 4.9 days in the north, which was consistent with the spatial patterns of annual precipitation (Figure 3). pn20 mm ranged from 1.36 to 4.7 days, decreasing from south to north. For more than half of the studied area, the recorded values did not exceed 3.5 days.

On the other hand, spatial patterns of CDD (longest dry period: maximum number of consecutive dry days (Pday <1 mm)) increased from the southeast to the north in the Chichaoua-Mejjate zone. It increased from 83.7 days at the Sidi Bouathmane station to 131.4 days at the Chichaoua station. More than 80% of the area has experienced periods of more than 100 consecutive dry days, which implies that the Chichaoua-Mejjate plain is at risk of severe drought events. CWD (longest wet period: maximum number of consecutive wet days (Pday ≥ 1 mm)) ranged from 3.5 to 4.5 days for the whole region (Figure 3).

Trend analyses of extreme precipitations indices

Table 4 shows a mixed pattern of upward and downward trends on the temporal changes of the precipitation-based

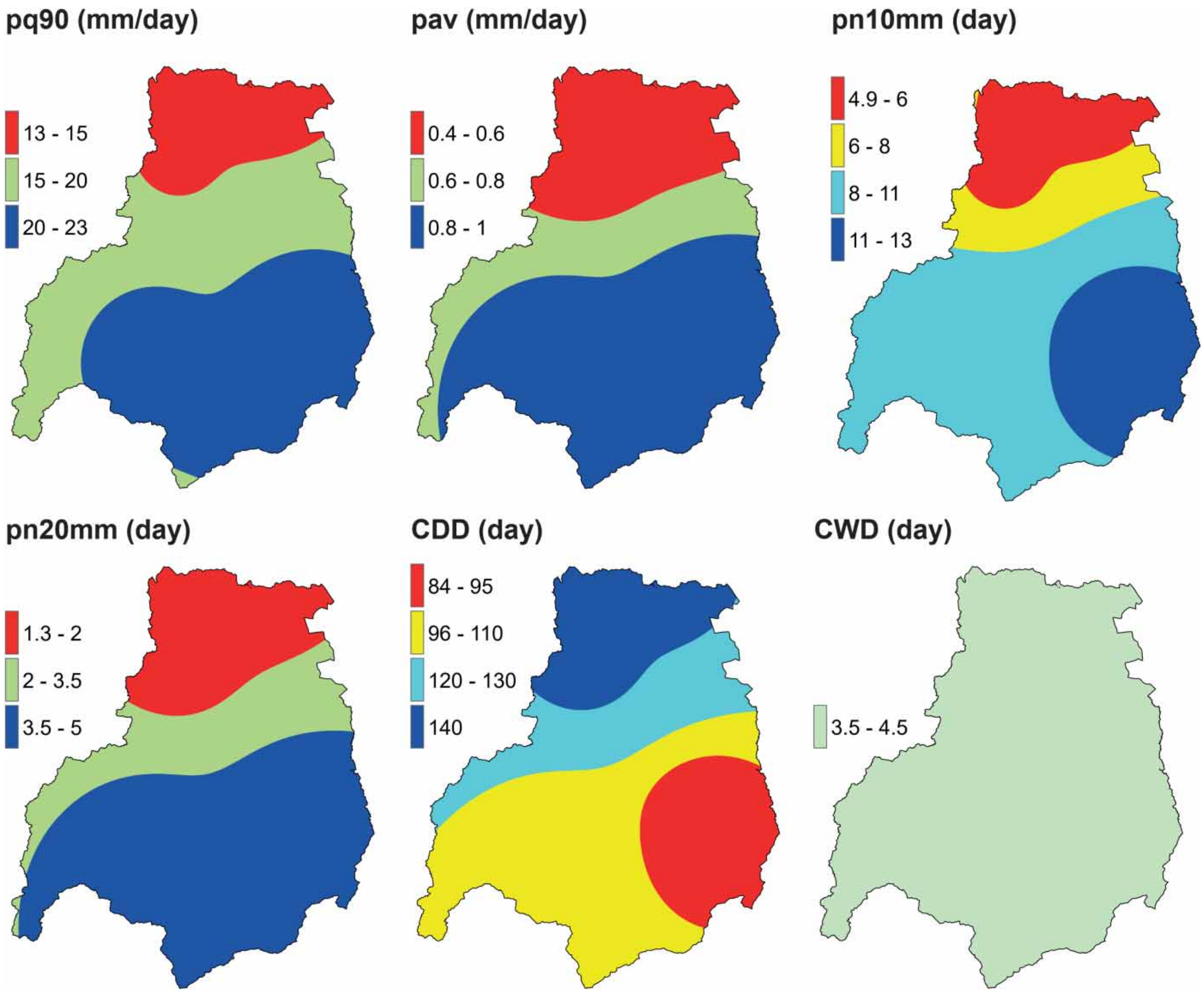

Figure 3 | Spatial distribution of extreme climate indicators in the study area.

indices. However, in most cases, the trends are not significant.

In winter, the pq90 (heavy rainfall threshold) displays a downward trend at all four stations. This trend is more important in Iloujdane, where the pq90 has decreased by −0.43 mm/day/year. However, no trend is statistically significant. For the other seasons (autumn, spring, and summer), the pq90 show an upward trend at all four stations. We concluded that a kind of transfer of the heavy rainfall threshold takes place from winter to the other seasons, especially to summer. The annual mean value of pq90 at three of the stations was 13 mm/day (Abadla), 14.53 mm/day (Chichaoua), 21.87 mm/day (Iloujdane), and 22.11 mm/day (Sidi Bouathmane).

With pn10 mm, although a downward trend is detected at three of the stations (Chichaoua, Iloujdane, and Sidi Bouathmane), no trend is statistically significant. The most important annual mean change magnitudes for the downward trends were observed at the Iloujdane station (−0.2 day/year). The winter is the season most affected by the decrease in pn10 mm (Figure 4). For pn20 mm, although a downward trend is detected at the Iloujdane and Sidi Bouathmane stations, no trend is statistically significant. The most important annual mean change magnitudes for the downward trends were observed at the Sidi Bouathmane station (−0.03 day/year). At the Chichaoua station, change tends toward zero.

For the CDD (longest dry period), the Iloujdane and Sidi Bouathmane stations (which represent the rainiest zone of

Table 4 | Trend rate and test of significance results for precipitations indices

Station	Indices	Trend rate	*p*-value	Significance
Chichaoua	pav	−0.5 mm/year	0.51	NS
	pq90	−0.04 mm/year	0.75	NS
	pn10 mm	−0.03 day/year	0.41	NS
	CDD	0.63 day/year	0.26	NS
	CWD	−0.014 day/year	0.27	NS
Iloujdane	pav	−2.64 mm/year	0.36	NS
	pq90	−0.19 mm/year	0.59	NS
	pn10 mm	−0.22 day/year	0.06	NS
	CDD	−2.48 day/year	0.009	S
	CWD	−0.09 day/year	0.83	NS
Sidi Bouathmane	pav	1.85 mm/year	0.48	NS
	pq90	−0.08 mm/year	0.43	NS
	pn10 mm	−0.016 day/year	0.87	NS
	CDD	−1.85 day/year	0.02	S
	CWD	0.009 day/year	0.77	NS
Abadla	pav	0.35 mm/year	0.75	NS
	pq90	−0.76 mm/year	0.13	NS
	pn10 mm	0.04 day/year	0.36	NS
	CDD	−1 day/year	0.15	NS
	CWD	0.006 day/year	0.81	NS

S, significant; NS, not significant.

the study area) had downward trends. The annual mean values of CDD at these stations are 101 and 84 days, respectively, and the mean change magnitudes were −2.5 and −1.8 days/year. It should be noted that, unlike others, the downward trend in CDD at these stations is statistically significant according to the Mann–Kendall test. For Chichaoua, the CDD had an upward trend, the mean change magnitude at this station was 0.63 days/year (Figure 5). For the CWD (longest wet period), the Chichaoua and Iloujdane stations had downward trends. The annual mean values of CWD at these stations are 3.7 and 4 days, respectively, and the mean change magnitudes were −0.014 and −0.09 days/year. At the Sidi Bouathmane station, a slight upward trend was detected (0.007 days/year). No trend is statistically significant (Figure 5).

Trend analyses of extreme temperature indices

The temperature has been recorded only at the Abadla station. The Mann–Kendall analysis revealed that the air temperature in Chichaoua-Mejjatz increased over the 1982–2017 period. This is consistent with the results of the 2018 IPCC report, which states that human activities are estimated to have caused a global warming of approximately 0.8–1.2 °C above pre-industrial levels. Global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate (IPCC 2018).

Figure 6 and Table 5 display the temporal evolution for the temperature indices. The analysis of these indices leads to the following observations:

- All the indices had increasing trends.
- The three extreme temperature indices (Tav, Tnav, and Txav) had statistically significant trends.
- The Mann–Kendall analysis revealed that the air temperature in the study area has increased over the past 35 years.
- The increasing rate of the average annual temperature is around 0.03 °C/year (for comparison, the overall rate in Morocco is 0.02–0.06 °C/year (Ait Brahim *et al.* 2016) and the rate in the world is 0.013 °C/year (IPCC 2007).
- Tnav exhibited the strongest annual upward trend (0.07 °C/year), followed by Txav (0.05 °C/year) and Tav (0.03 °C/year).
- In terms of the seasons, the upward trend was the strongest for the Tav and Txav in spring and for Tnav in winter.
- The most important upward trend is recorded for Tnav in winter (0.09 °C/year).

Assessment of RCM simulations over the reference period

The precipitation and temperature outputs of the RCM simulations were compared with the observed temperature and precipitation in order to assess the quality of the RCM simulations for the historical period 1979–2005. The RCM grid size is equal to 2,500 km^2. In order to compare the RCM simulations and observations at the same scale, we used data from the Chichaoua station as observed data for this comparison.

The shape of the monthly observed temperature is reproduced by the RCM simulations very well, but with a slight underestimation of 0.1–1.2 °C. Both simulations driven by ERA-Interim (European Centre for Medium-Range Weather Forecasts (ECMWF) ReAnalysis), as well as different GCMs, are able to reproduce the seasonal cycle of temperature. Those driven by ERA-Interim (EVAL) generate a much

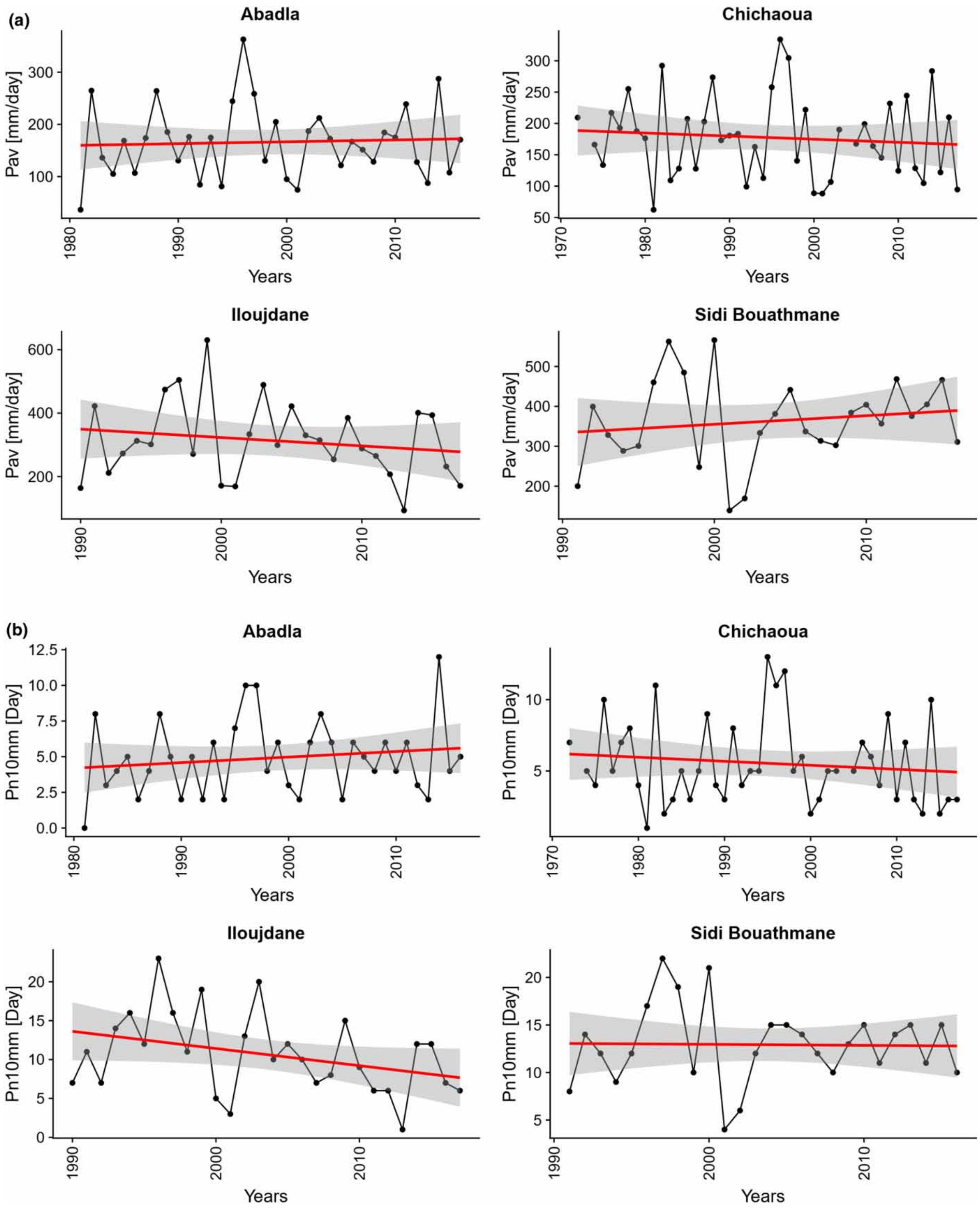

Figure 4 | The trends of pav and pn10 mm in the four stations.

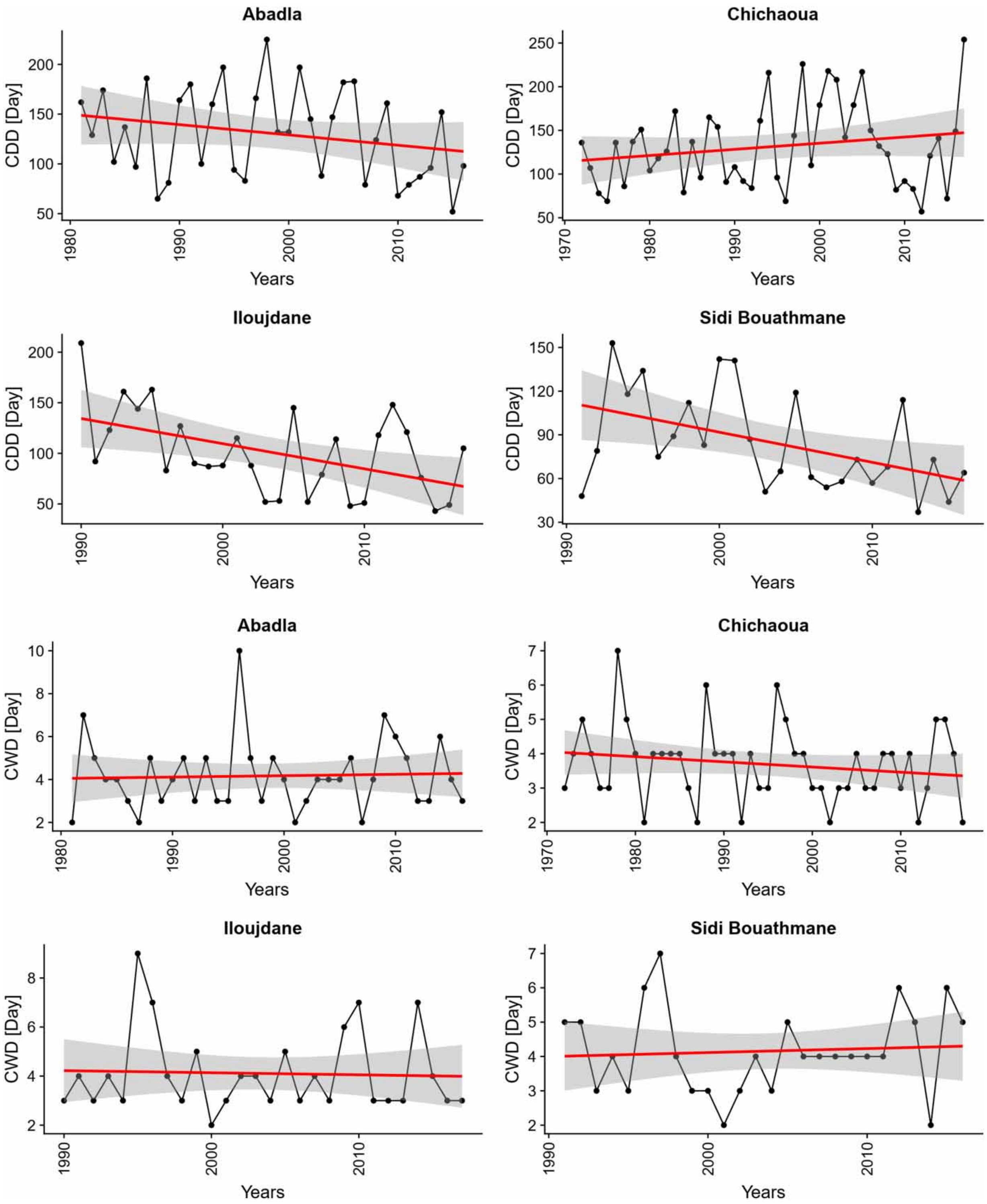

Figure 5 | The trends of CDD and CWD in the four stations.

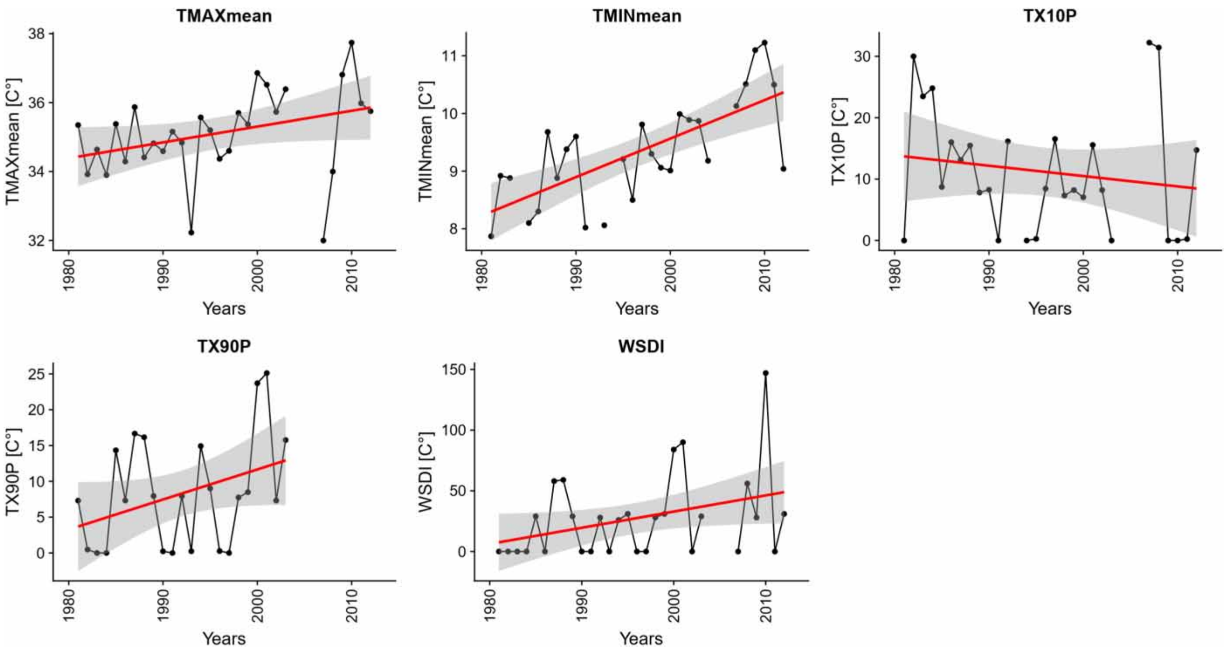

Figure 6 | The trends of temperature indices in the Abdala station.

Table 5 | Trend rate and test of significance results for temperature indices in Abadla

Station	**Indices**	**Trend rate**	***p*-value**	**Significance**
Abadla	Tav	0.03 °C/year	0.000	S
	Txav	0.05 °C/year	0.045	S
	Tnav	0.07 °C/year	0.000	S
	TX90p	0.46 day/year	0.027	S
	TX10p	−0.19 day/year	0.37	NS
	WSDI	1.33 day/year	0.055	NS

better reproduction of the seasonal cycle of observations, with $R^2 = 0.94$ (Figure 7).

In terms of precipitations, Figure 8 compares the observed precipitation with that simulated by the RCMs for the period of 1979–2005. For all RCMs, precipitation is underestimated in winter and spring and overestimated in summer. These RCMs are based on a forcing protocol that may have limits and uncertainties. The results of these

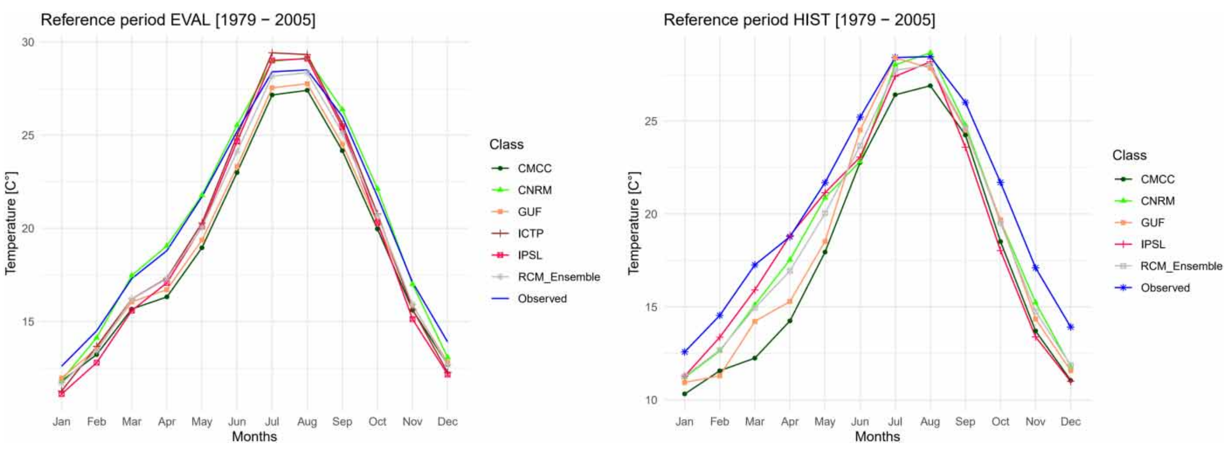

Figure 7 | Seasonal cycle of observed and RCM of temperature (1979–2005).

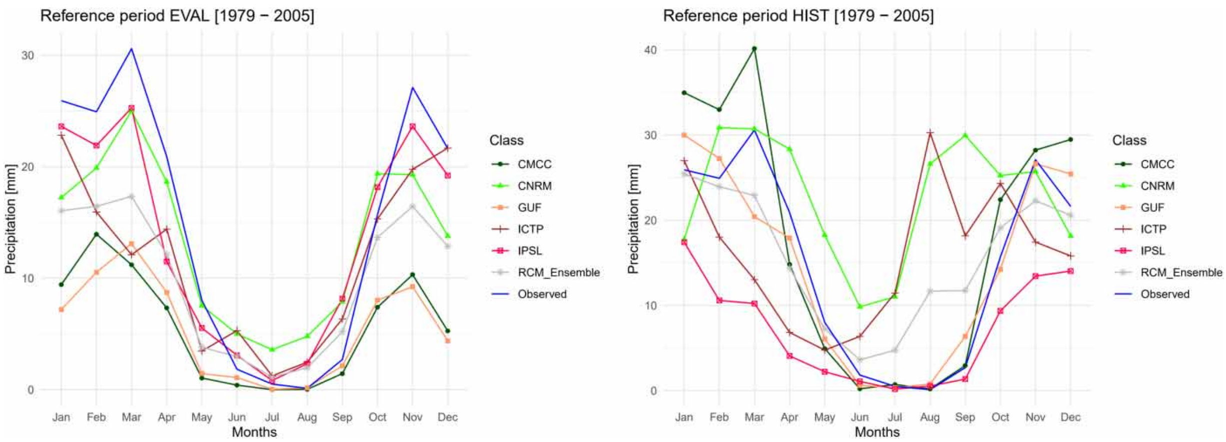

Figure 8 | Seasonal cycle of observed and RCM of precipitation (1979–2005).

models are strongly dependent on the initial conditions (i.e. the data injected into each mesh of the model). We may, therefore, have an overestimation or underestimation compared to the observed data. The seasonal cycle was reproduced much better for the evaluation period (EVAL), $R^2 = 0.94$, than over the historical period (HIST), $R^2 = 0.80$. The Institut Pierre Simon Laplace (IPSL) model for the evaluation period is the model that agrees most closely with observations.

Projected monthly changes in temperature and precipitation

In order to show the projected changes in temperature and precipitation in the medium term, the projection period 2039–2065 was chosen. The regional climate model (RCM), which is better suited to generating finer scale projections of local climatologies (Xu et al. 2007; Zhang et al. 2008), was used to analyze future responses to climate change for a period of time centered on 2050 (2039–2065). The 2050 horizon is generally chosen by researchers and water planners since it represents a medium term in the middle of the 21st century.

The relative change was evaluated between the historical period of 1979–2005 and the projection period of 2039–2065 from the multi-model ensemble mean with the radiative concentration pathways scenarios RCP4.5 and RCP8.5. The evaluation shows that all climate simulations predict a decrease in precipitation. A decrease of −23 and −34% of total precipitation is projected for RCP4.5 and RCP8.5, respectively. This decrease is most pronounced in winter and spring (Figure 9 and Table 6).

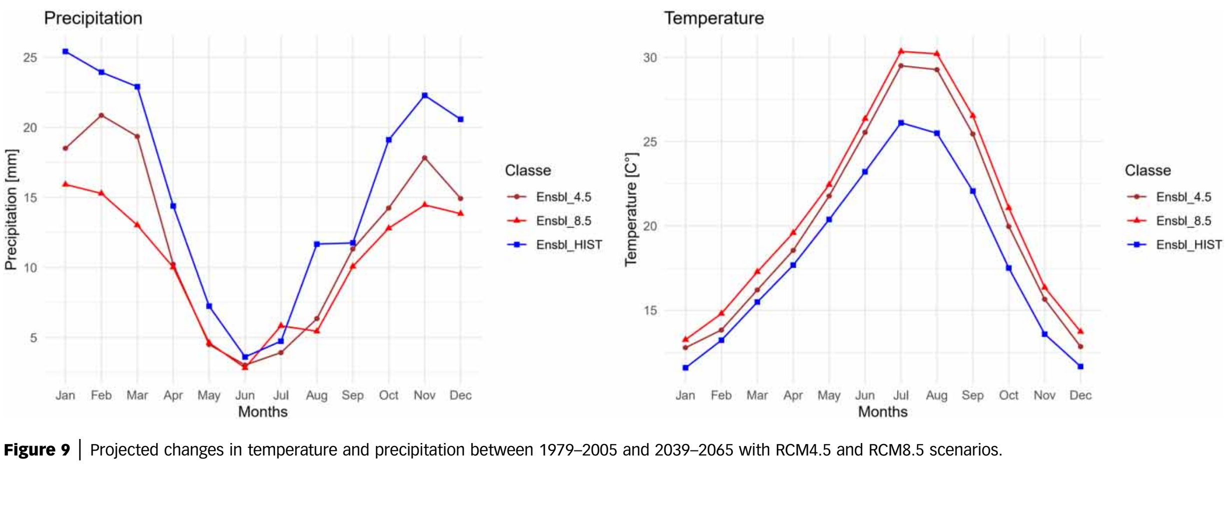

Figure 9 | Projected changes in temperature and precipitation between 1979–2005 and 2039–2065 with RCM4.5 and RCM8.5 scenarios.

Table 6 | Temperature and precipitation change signal between 1979–2005 and 2039–2065

		CMCC	CNRM	GUF	ICTP	IPSL
Precipitation (%)	RCP4.5	−17	−16	−17	−40	−31
	RCP8.5	−30	−15	−50	−49	−37
Temperature (°C)	RCP4.5	+2.3	+1.5	+1.6	–	+1.3
	RCP8.5	+3.3	+2.1	+2.6	–	+2.3

The precipitation change signal (%) between 1979–2005 and 2039–2065 oscillates between −16% (RCM CNRM) and −40% (RCM ICTP) for RCP4.5 and between −15% (RCM CNRM) and −50% (RCM GUF) for RCP8.5 (Table 6).

Regarding temperature, the change signal between 1979–2005 and 2039–2065 shows an increase of 1.9 and 2.8 °C for RCP4.5 and RCP8.5, respectively. This increase is more accentuated in the summer (Figure 9 and Table 6).

Future change in climatic indices

We assessed future changes in the Chichaoua-Mejjate region based on the climatic indices representing the average and extreme rainfall and temperature. Future changes in each of the indices (and therefore the different aspects of the climate) were evaluated over the period of 2039–2065 by comparing the index calculated for this period to that calculated for the period of 1979–2005.

Future changes for some rainfall indices are shown in Table 7. Under the RCM 4.5 and RCM 8.5 scenarios, the average rainfall would decline for all regional models. This decrease varies between −16 and −40% for RCM4.5 and between −15 and −50% for RCM8.5.

According to the scenarios, the amplitude of the events of heavy precipitation (pq90) would decrease from −10 to −49%. The number of days with a cumulative rainfall exceeding the threshold of 10 mm (pn10 mm) would drop from −6 to −62%. The number of successive days of drought would increase under RCP4.5 and RCM 8.5. However, no notable changes were predicted for the CNRM and ICTP models. For the rest of the models, the maximum drought period (CDD) would extend from 13 to 40 days and from 29 to 50 days, respectively, for RCM 4.5 and RCM 8.5. Along with this increase in successive days of drought, the

Table 7 | Climatic indices change signal between 1979–2005 and 2039–2065

	The change signal					
Index	**Period**	**CMCC**	**CNRM**	**GUF**	**ICTP**	**IPSL**
pav (mm/day)	Hist – 4.5	– 17%	– 16%	– 17%	– 40%	– 30%
	Hist – 8.5	– 31%	– 15%	– 50%	– 49%	– 39%
CDD (day)	Hist – 4.5	13.4	3.68	21.52	0.78	39.49
	Hist – 8.5	29.74	1.94	47.29	1.82	50.71
CWD (day)	Hist – 4.5	– 0.9	– 0.5	– 0.5	– 1.2	– 0.6
	Hist – 8.5	– 1.3	0.1	– 1.0	– 1.1	– 1.1
PRCPTOT (mm)	Hist – 4.5	– 16%	– 17%	– 16%	– 42%	– 32%
	Hist – 8.5	– 30%	– 15%	– 50%	– 51%	– 39%
pn10 mm (days)	Hist – 4.5	– 16%	– 14%	– 15%	– 49%	– 47%
	Hist – 8.5	– 28%	– 6%	– 55%	– 62%	– 60%
pq90 (mm)	Hist – 4.5	– 10%	– 24%	– 21%	– 38%	– 32%
	Hist – 8.5	– 27%	– 18%	– 49%	– 49%	– 17%
WSDI (days)	Hist – 4.5	– 0.19	– 0.34	– 0.26	0.24	2.52
	Hist – 8.5	0.33	0.85	– 0.3	1.87	2.6
Tav (°C)	Hist – 4.5	2.33	1.48	1.62	1.12	1.29
	Hist – 8.5	3.31	2.04	2.59	3.48	2.29
Txav (°C)	Hist – 4.5	2.51	1.57	1.77	0.63	2.26
	Hist – 8.5	3.62	2.06	2.87	3.97	3.14
Tnav (°C)	Hist – 4.5	2.16	1.39	1.47	1.61	0.32
	Hist – 8.5	3.01	2.03	2.32	2.99	1.43

models project a decrease in consecutive wet days, which ranges from −0.5 to −1.3 days.

Future changes in temperature are shown in Table 7. These changes are generally homogeneous for different climate scenarios. The average temperature (Tav) would increase from 1.1 to 2.3 °C for RCM4.5 and from 2 to 3.5 °C for RCM8.5. The average maximum temperature (Txav) would increase significantly and reach 4 °C for the ICTP model under the climate scenario RCM8.5. The number of heat wave days would also increase by 0.5 and 1 day, respectively, for RCP4.5 and RCP8.5.

Potential associated impacts of future climatic projections

In this part, we present a case study of the possible impacts of extreme events on rainfed agriculture, where cereals occupy 99% of the cultivated area. The areas cultivated with cereals show a strong inter-annual variability in productivity according to the pluviometry. The rainfed agriculture is the most sensitive to climate change-related hazards. Indeed, precipitations inter-annual variability and rising trends of temperature affect crop productions. The effect in the case of rainfed agriculture is more apparent and easier to study than in irrigated agriculture where the intervention of anthropogenic factors can deviate or distort interpretations. Moreover, access to data on irrigated crops is quite difficult.

To illustrate this variability in the productivity, we took the areas cultivated in cereals in the Chichaoua-Mejjate between 2010–2011 and 2014–2015. Figure 10 shows that in the rainy year (2014–2015), 129,070 ha are sown in cereals compared to only 45,000 ha in the dry year (2010–2011). The yields are also strongly affected by the rainfall of the year; in a rainy year, they reach 6.6, 7.4, and 5.3 quintals/ha for durum wheat, soft wheat, and barley, respectively, while in the dry year, they are almost zero (0.30, 0.03, and 0.26 quintals/ha, respectively, for durum wheat, soft wheat, and barley).

For the period 2039–2065, if we consider the pessimistic scenario of a 34% reduction in rainfall, the average rainfall will roughly correspond to the rainfall recorded in 2011–2012. Cereal yield during this year has dropped considerably. Therefore, according to the climate projections, the case of the year 2001–2012 will represent the normal case of precipitation in the future. These changes will have considerable impacts on food production and security, and especially on the farmer's socio-economic situation. Agriculture is the main component of economic activity in the study area. It provides permanent employment to 32,066 individuals as a wage and family labor force and contributes up to 40% of the province's GDP.

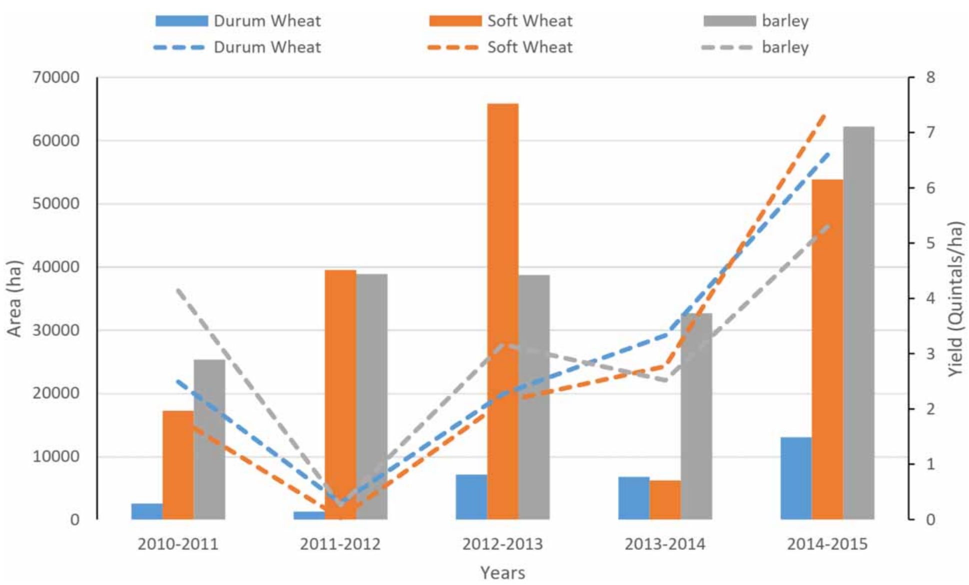

Figure 10 | Areas and yields of cereals in the rainfed zone.

DISCUSSION

The analysis of temporal trends in temperature and precipitation indices in the Chichaoua-Mejjate region for the period 1971–2017 shows a mixed pattern of upward and downward trends in the precipitation-based indices. However, in most cases, the trends are not significant, although, for temperature-based indices, all stations have significant increasing trends, especially in the minimum temperature.

Based on the above-mentioned results, the temporal features of the amount of precipitation indices (pav and pq90) at annual and seasonal scales reveal several aspects of the characteristics of extreme dry events. Several duration indices (pn10 mm, pn20 mm, CDD, and CWD) were performed to represent the durations of extreme wet and dry events. The changing trends of these indices demonstrate that the duration of extreme wet events tended to decrease between 1971 and 2017, particularly in the winter. Furthermore, stations in the piedmont zone, where the main annual precipitation reaches 355 mm/year, are more affected by this downward trend than stations located in the plain area, where it does not exceed 173 mm/year.

The mean percentages of dry days each year at all four stations (Chichaoua, Abadla, Iloujdane, and Sidi Bouathmane) were 35, 34, 27, and 23%, respectively. The percentages of annual dry days show a decreasing trend which is statistically significant at the 0.05 significance level at the Sidi Bouathmane and Iloujdane stations. The upward trend of the CDD recorded at the Chichaoua station shows that the dry sequences are getting longer on the plain. This is consistent with the results found by Driouech (2006) at the Marrakech station, which is located 70 km east of the Chichaoua station. The results obtained by this author showed that the Marrakech station recorded a 14-day CDD increase in 40 years and that the CDD trends in this zone are all nonsignificant according to the Mann–Kendall test. The same study exhibited as well that the trends for CDD are positives (+4 to +6 days per decade) at the majority of stations in Morocco (10 stations out of 14 studied); however, none of these trends is statistically significant. This relatively high positive trend of CDD at the Chichaoua station is probably due to an earlier end of the rainy season or to a later start of it. Indeed, the disruption of the rainy season and the extension of the maximum period of winter drought have been identified at most stations in Morocco by other authors (Driouech 2006). The rainy season is now starting rather late and stopping too early (April), whereas it was extending until May. This is mainly due to the long dry sequences observed around the year 2000 and that of 2017, the most severe ever observed.

The increase in average temperature is affected by the minimum more than the maximum temperature as seen in the results of this study. The increasing rate of average annual temperature is around 0.03 °C/year (0.02–0.06 °C/year in Morocco (Ait Brahim *et al.* 2016) and 0.013 °C/year in the world (IPCC 2007)). Previous studies are in line with these results and have shown that at the Marrakech station (70 km east of the Chichaoua station), the trend of global warming is significant and is 0.3 °C per decade. The strong upward trends of autumn and spring are causing annual warming of the climate (Driouech 2006; Driouech *et al.* 2010). This is consistent with our results showing that among seasons, the increasing trend was the strongest in spring for the Tav and Txav and in winter for Tnav.

Climate change is likely to produce these changing trends of precipitation and temperature extremes as is the case with other regions of the world (Allan & Soden 2008). Amplifications of precipitation and temperature extremes associated with a decrease of precipitation totals and rising temperature are revealed by many authors in Morocco (Gao *et al.* 2006; Giorgi & Lionello 2008; Driouech *et al.* 2010; Khomsi *et al.* 2013). These studies indicate that the temperature in the region as well as in the country is increasing as a result of global climate change. Moreover, rainfall is more influenced by the cyclonic activity and by disruption of the ocean-atmosphere system (Lotsch *et al.* 2005). In addition, several studies supported dependencies between precipitation extremes and NAO (North Atlantic Oscillation) in Morocco (Tramblay *et al.* 2012; Zemrane *et al.* 2016).

For the future projections, no study considered climate model simulations to provide future scenarios for the Chichaoua-Mejjate region. The results exhibit some uncertainties related to the choice of climate models and scenarios, as noted by many other authors (Dobler *et al.* 2012; Majone *et al.* 2012). The relative differences between

1979–2005 and 2039–2065 periods showed a global decreasing trend for intensity and duration indices of extreme precipitation projected by most of the models with both RCP4.5 and RCP8.5 scenarios. This is supported by Driouech *et al.* (2010), whose study confirms a decrease in precipitation from events exceeding high percentiles in the same region in future climate simulations. A significant decline in the average rainfall intensity and in the amplitude of the events of heavy precipitation, which is accompanied by a significant decrease of the number of days with a cumulative rainfall exceeding the threshold of 10 mm, is projected in the region. In parallel, the consecutive dry days will increase significantly, especially in the plains area, which can have a very dangerous effect on agricultural activity in the region.

The projections of temperature trend analyses indicate that the climate in the Chichaoua-Mejjate region will become warmer and will experience an important increase of both the minimum and maximum temperatures. The mean temperature change signal between 1979–2005 and 2039–2065 will range from 1.12 to 2.33 °C and from 2.04 to 3.31 °C under RCP4.5 and RCP8.5, respectively, which will imply that the Chichaoua-Mejjate plain area, which contains an area of irrigated perimeters that exceeds 20,000 ha, will face serious challenges in meeting the water needs of crops, which will increase significantly as a result of raised evapotranspiration impacted by temperature increases.

The adverse changes in the weather patterns as expected from the climatic trend analysis presented in this study will lead to a reduction in (i) surface water runoff and (ii) groundwater recharge by direct infiltration of rainfall. The main user of water in the Chichaoua-Mejjate is the agriculture sector which will experience new complexities due to the decrease of precipitations and the increase in water demand (evapotranspiration) accompanying the rising temperature.

The period of crop growth would be affected by projected changes of precipitation and temperature in the region. These changes will have, as well, an unavoidable impact on the crop cycles (especially for market gardening which is widely practiced in the region and represents 46% of the irrigated area in the Chichaoua-Mejjate region), on the water availability at the appropriate time, on the growing period, on dry spells in the beginning, middle, and end of the cycle of annual crops, on the efficiency at the plot and on the appearance of new crop diseases.

On the other hand, changes in precipitation and temperature extremes patterns could lead to an increased probability of occurrence of events fostering both floods and droughts (Gao *et al.* 2006). These phenomena could cause different troubles for various socio-economic sectors and trigger new challenges for water resource management, especially in a region where the vulnerability of the populations to extreme hydrological events is high (Douglas *et al.* 2008; Di Baldassarre *et al.* 2010).

CONCLUSIONS

This study provides an assessment of past and projected changes in extreme precipitation and temperature in the west-central region of Morocco using extreme climate indices and RCM data.

Most extreme climate indices were spatially distributed with a clear gradient from the mountainous area toward the plains. The analysis showed overall decreasing trends in the heavy rainfall threshold, in the number of days with rainfall greater than 10 or 20 mm and in the consecutive wet days. At the seasonal scale, the indices showed sometimes a downward trend in winter, and sometimes a slight upward trend in autumn, spring, and summer. These trends were observed most prominently at the Iloujdane station. Few precipitation-based indices had significant trends. However, the temperature indices have recorded statistically significant upward trends at all the stations. These trends originate from global climate change, which is particularly prominent in the Mediterranean region, designated as a 'hot spot' by the IPCC experts.

For climate simulations, the validation of the past simulations was essential for analyzing climate change projections for the future. The observed monthly temperature was successfully reproduced with the regional circulation model (RCM) and both the GCM simulation and ERA-Interim have well reproduced the seasonal temperature cycle. However, monthly rainfall amounts are underestimated in winter and spring and slightly overestimated in summer for all RCM models. Projected changes in annual precipitation from the historical period (1979–2005) to the projection period (2039–2065) showed decreases of 23 and 34%, respectively, under the RCP4.5 and RCP8.5 scenarios. These decreases are prominent in winter and spring. In addition, temperature increases of 1.9 and 2.8 °C are predicted for those scenarios, particularly pronounced in summer. Such future scenarios could have serious direct effects in future water availability for rainfed agriculture and resultant cereal yield, which will hamper agricultural sustainability and have significant impacts on food production and security, and especially on farmers' socio-economic situation in the Chichaoua-Mejjate region.

The assessment of the spatiotemporal features of past and future precipitation and temperature extremes, established in this study, provides valuable information for climate-induced drought control and water resources management, which are important for anticipating climate change, developing climate policy, identifying adaptation measures and maximizing the resilience of communities. In addition, it is crucial to better understand the potential relationships between extreme precipitation events and crop production. Further studies need to be conducted in this field to guide policy-making, planning, and management of the agricultural sector to help the region adapt.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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