Recent observed country-wide climate trends in Morocco

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Abstract

In this study, we evaluate trends in precipitation and temperature and their related extreme indices in Morocco based on a set of National Climate Monitoring Products defined the by the commission for climatology of the WMO. We use daily precipitation, maximum and minimum temperature data from 30 meteorological stations distributed throughout the country and covering the period from 1960 to 2016. Statistically significant increasing trends in warm temperature events and a tendency towards decreasing cold extremes at both daytime and night are depicted across the country consistent with the generalized observed global warming. We found that the daily temperature in Morocco has risen with higher rates than the global scale. The depicted trend of 0.33°C per decade corresponds to a warming of approximately 1.1°C for the period 1984–2016. The annual mean precipitation and the standardized drought index show less spatially consistent tendencies despite the predominance of negative trends. Considering the effect of the warming in the analysis of drought evolution using the Standardized Precipitation-Evapotranspiration Index, we detected statistically significant trends towards dryer conditions in different regions of the northern half of the country. Analysis of the relationship between precipitation in Morocco and the large-scale atmospheric circulation in the Atlantic area confirmed the effects of the North Atlantic Oscillation, especially for the winter season (with low influence at the annual scale). Moreover, we found that the NAO exerts significant influence on winter extreme temperatures during night time. However, such correlations alone may not explain the depicted significant generalized warming trends and the drying evolution.

KEYWORDS

climate change, extremes, Morocco, North Africa, observed trends

1 | INTRODUCTION

Studies conducted at global, regional and national scale have highlighted Morocco as one of the most vulnerable territories to climate change in the Mediterranean and North Africa (e.g., Diffenbaugh and Giorgi, 2012; Schilling et al., 2020). Geographically, Morocco is located in the Northwest of the African continent, extending from

21°N to 37°N and bordering the Mediterranean Sea in the north and the Atlantic Ocean in the West.

Moroccan climate is influenced by the Atlantic Ocean, the Mediterranean Sea and the Sahara (Knippertz et al., 2003; Driouech et al., 2009; Tramblay et al., 2012) leading to sub-humid to semi-arid climate in the north and to arid to desert climate in the south. The mid-latitude storm tracks exert a strong influence on precipitation especially in the most humid region (Bolle, 2002; Driouech et al., 2009). The North Atlantic large-scale circulation (extratropical circulation modes) can lead to normal, dry or humid conditions during wintertime depending on the type of weather regime (Driouech et al., 2010a). In particular, the weather regime reminiscent to the positive (negative) phase of the north Atlantic oscillation (NAO) is generally associated with dry (wet) conditions. Very humid conditions in the north-eastern part of the country can be generated by blocking in the Mediterranean pressure systems (e.g., El Hoceima November 2003). Tropical storms moving up into the Atlantic coast have repeatedly resulted in extreme precipitation events (e.g., Tantan August 2003, Casablanca November 2010) in agreement with results of previous studies highlighting tropical-extra-tropical interactions in the region (Knippertz and Martin, 2005; Xoplaki et al., 2012).

Analyses of trends in precipitation and temperature in Morocco using observed and reanalysis data, have indicated trends towards warmer and dryer conditions (e.g., Tramblay et al., 2013; Driouech et al., 2013; Donat et al., 2014; Filahi et al., 2015; Alexander, 2016; Sippel et al., 2017). Driouech et al. (2013) depicted a tendency towards warming and drying conditions in many regions based on observations from 17 meteorological stations covering the period of 1961–2008. Positive trends in mean temperature and warm extremes and decreasing trends in cold events have been identified by Donat et al. (2014) using data from 10 meteorological stations. Tramblay et al. (2013) and Filahi et al. (2015) highlighted decreasing trends in precipitation especially in the interior of the country and at stations with long-term time series (i.e., about four decades). Although the above studies have pointed to trends towards more persistent drought (Driouech et al., 2013; Tramblay et al., 2013), changes in extreme precipitation events were less consistent (Tramblay et al., 2012; Donat et al., 2014; Filahi et al., 2015; Khomsi et al., 2016).

In terms of future changes, most of the climate model projections agree on future changes in the Moroccan climate, consistent with the whole Mediterranean region, including an increase in the mean and high temperatures and a decrease in the total annual precipitation amounts (e.g., IPCC, 2013; Driouech and El Rhaz, 2017; Fischer

and Knutti, 2015; IPCC, 2018; Polade et al., 2017; Dosio and Panitz, 2016; Knutti et al., 2015). These projections are issued from models with different resolutions (ranging from few hundreds of km to about 12 km) and under different emission scenarios (from low to high). Projected changes in future precipitation indicate a decrease that could intensify with the global warming (Knutti et al., 2015). A recent study by Driouech and El Rhaz (2017), projected warmer and drier conditions that could intensify with the greenhouse gas emissions. Future changes in extremes are also consistent with the projected evolutions. Indeed, many studies suggest a tendency towards increasing droughts and a decrease in high precipitation events (Giorgi et al., 2014; Dosio et al., 2015; Molinié et al., 2016; Platon et al., 2016; Betts et al., 2018).

Impacts of projected changes in Moroccan climate are far from positive and the higher the future emissions the more likely the effects would be harmful. Most of the studies evaluating climate change impacts in Morocco have focused on water resources and/or agriculture due to their high climate dependency and to their social and economic implications on the development of the country. For example, water resources (surface water and groundwater) are projected to decrease (Driouech et al., 2010b; Schewe et al., 2014; Wanders and Wada, 2015; Tramblay et al., 2016; Marchane et al., 2017; Betts et al., 2018; Döll et al., 2018) which will negatively impact crop yields (Niang et al., 2014; Brouziyne et al., 2018). Negative climate effects have already been witnessed in the past. For instance, the dry conditions that occurred during 1982–1983 and 1994–1995, two of the most general droughts that affected the country, led to a drop of water reserves impacting not only irrigated agriculture but also drinking water supplies and electricity production (e.g., Benassi, 2008; Verner et al., 2018). Ground water resources and water reservoirs benefit greatly from wet periods, however intense rainfall periods often lead to devastating floods. The floods of 29 and November 30, 2010 (223 mm in 2 days) caused considerable damage to infrastructure and loss of life in Casablanca. Other flood events in different parts of the country resulted in disruptions, life loss and damage to the infrastructure (e.g., Settat flood, December 23–24, 2001, the Ourika valley flood on the August 17, 1995 [Saidi et al., 2003], and a recent flood in late summer and beginning autumn of 2019 in southern Morocco).

Assessing climate trends at the national scale provides useful information for high level decision making and contributes to raising awareness and understanding of the effects of climate variability and change. Moreover, such assessment is relevant for developing adaptation and resilience strategies to climate change. Most of the

few studies on observed climate trends in Morocco cited above have been conducted either at individual stations, catchment level, or in specific regions. However, there has not yet been a study at the national scale.

A set of "National Climate Monitoring Products" (NCMPs) (World Meteorological Organization, 2017a) have been recently defined by the World Meteorological Organization's (WMO) Commission of Climatology through its Expert Team on National Climate Monitoring Products (ET-NCMP). The objectives of NCMPs were to (a) provide consistent and comparable information on the state of climate, (b) summarize climatic conditions at a national scale, (c) show how current conditions compare with those in the past and (d) facilitate climate monitoring and detection of trends and change in the climate patterns. Therefore, this article evaluates trends in rainfall, temperature and related extreme indices at the national scale of Morocco using NCMPs (detailed in Section 2) and the Standardized Precipitation-Evapotranspiration Index (SPEI) derived from 30 meteorological stations covering all the main climate zones of the country.

In addition to assessing trends at the country scale, as a first application of the NCMPs in Morocco, we also conducted trend analysis at the regional and station levels. Lastly, we examined the relationship between Moroccan precipitation and the NAO to assess the usefulness and constraints of NCMPs. NAO is one of the main climate patterns affecting the Mediterranean region as reported by several studies (i.e., Hurrell, 1995; Seager et al., 2019).

The structure of this article is as follows: Section 2 presents the data pre-processing and the calculation of climate indices. Section 3 presents the results and discussion which include analysis of Moroccan climate based on NCMPs, trend analysis for each index and the relationship between NCMPs and NAO. We conclude the study in Section 4.

2 | DATA AND METHODS

2.1 | Data

We use daily precipitation, maximum and minimum temperature data over the period 1960–2016 collected from a set of 30 meteorological stations distributed across Morocco. The data is provided by the Moroccan National Meteorological Service (La Direction de la Météorologie Nationale, referred to as DMN). Out of all the data records available, the percentage of missing precipitation data does not exceed 0.7% of the total number of precipitation days at each station except at one a station (Kasbat-Tadla, #2 in Table 1) where 2% of the daily

records is missing. The missing data of maximum and minimum temperature series do not exceed 3 and 2%, respectively. Those days with missing data were omitted from the analysis.

The geographic distribution of the stations covers most of the country and its main climate regions despite the inhomogeneous spatial coverage between regions (Figure 1). Climate regions as defined by Knippertz et al. (2003) and Born et al. (2008) were used. The north-western quarter region (Atlantic region, hereafter Region I) corresponds to the wettest part of the country and its climate is predominantly influenced by the north Atlantic circulation (Knippertz et al., 2003). The Mediterranean region (Region II) encompasses the north-eastern part of the country and is mostly influenced by the Mediterranean, and Region III (south of the Atlas) corresponds to the south east of the country. Additionally, we have added the southern region (Region IV) that was not part of the previous climatic regionalization. This climate region is mostly influenced by the Saharan heat low.

The NAO index is downloaded from NOAA National Centers for Environmental Information (https://www.ncdc.noaa.gov/teleconnections/nao/; NAO; NCEI, 2019).

2.2 | Data quality control and homogeneity check

The data quality is routinely controlled by the DMN to identify suspicious or unreasonable values before being publicly available. We have performed additional quality control of the data using the RClimdex software package (Zhang and Yang, 2004). RClimdex can automatically detect unreasonable values for example daily precipitation amounts less than zero, daily maximum temperature less than daily minimum temperature. The software can also detect outlier values outside an interval defined as the mean plus or minus n times standard deviation of the value for the day, that is, [mean $-$ n*std, mean $+$ n*std]. For this task, the factor n was set to 5 for temperature parameters to get reasonable number of flagged data (3 and 4 have been tested as well). A default Rclimdex range defined by n + 2 standard deviation is used for precipitation data. We have also checked for the large values such as precipitation exceeding 200 or temperatures with absolute values over 50°C.

Overall, the Rclimdex quality control analysis did not show any unreasonable values of precipitation or temperatures. The very few-flagged precipitation data corresponded to daily records that are genuinely recorded in exceptional humid situations explaining the relatively high precipitation amounts detected. Several daily

**TABLE 1** Periods covered by each of the time series of the 30 stations used after homogeneity tests

Station #	Station name	Precipitation	Maximum temperature	Minimum temperature	Climate region
1	Agadir	1960–2016	1960–2016	1960–2016	Region I
2	Béni Mellal	1970–2016	1970–2016	1970–2016	Region I
3	Bouarfa	1981–2016	1981–2016	1981–2016	Region III
4	Casablanca	1960–2016	1960–2016	1971–2016	Region I
5	Dakhla	1980–2016	1980–2004	1980–2016	Region IV
6	El Hoceima	1964–2016	—	—	Region I
7	El Jadida	1981–2016	1981–2016	1981–2016	Region I
8	Er-Rachidia	1973–2016	1973–2016	1973–2016	Region III
9	Essaouira	1960–2016	1960–2016	1960–2016	Region I
10	Fès	1961–2016	1961–2016	1961–2016	Region I
11	Ifrane	1960–2016	1960–2016	1960–2016	Region I
12	Kasba-Tadla	1983–2016	1983–2016	1983–2016	Region I
13	Kenitra	1960–2016	1960–2016	1964–2016	Region I
14	Khouribga	1984–2016	1984–2016	1984–2016	Region I
15	Laayoun	1976–2016	1976–2016	1976–2016	Region IV
16	Larache	1962–2016	1962–2016	1962–2016	Region I
17	Marrakech	1961–2016	1961–2016	1961–2016	Region I
18	Meknès	1960–2016	1960–2016	1960–2016	Region I
19	Midelt	1960–2016	1960–2016	1960–2016	Region I
20	Nouasser	1970–2016	1970–2016	1970–2016	Region I
21	Ouarzazate	1960–2016	1960–2016	1960–2016	Region III
22	Oujda	1960–2016	1960–2016	1960–2016	Region II
23	Rabat	1961–2016	1974–2016	1961–2016	Region I
24	Safi	1960–2016	1960–2016	1960–2016	Region I
25	Sidi Ifni	1975–2016	1975–2016	1975–2016	Region IV
26	Sidi Slimane	1980–2016	1980–2016	1980–2016	Region I
27	Tanger	1960–2016	1960–2016	1960–2016	Region I
28	Tan-Tan	1975–2016	1978–2016	1978–2016	Region IV
29	Taza	1960–2016	1960–2016	1967–2016	Region I
30	Tétouan	1963–2016	1963–2016	1968–2016	Region I

Note: Climate region corresponding to each station are indicated in Column 5 based on Knippertz *et al.* (2003) classification.

maximum temperature values have also been flagged by Rclimdex especially during the summer season. However, these values corresponded to short heat wave periods in coastal stations known for higher temperature values caused by synoptic situations with hot easterly or southerly winds followed by a relatively rapid decrease caused by sea breezes. The flagged minimum temperature data corresponded to keying errors (mostly related to point position in the record values). In total, 18 values (all temperature time series included) were corrected based on comparison with station's archives and expert judgement and knowledge of the local weather and the climate conditions.

In addition to the quality control, we also conducted homogeneity check of the data. Climatic time series may exhibit spurious jumps and/or gradual shifts due to non-climatic factors such as station relocation, changes in the environment surrounding the station, changes in instrumentation or observing practices resulting in inhomogeneous data that affect the long-term trends (Alexandersson, 1986; Vincent *et al.*, 2005; Wijngaard *et al.*, 2003; Alexander, 2016). Therefore, homogeneity tests are applied to detect possible non-climatic artefacts in data and ensure accurate estimates for climate trends. Several homogeneity testing methods have been described in the literature (e.g., Peterson *et al.*, 2008;

FIGURE 1 Geographical distribution of stations used in this study and their record lengths. Circles indicate the location and the name of the station with fill colours showing climate regions they belong to. The colours of the squares at each station indicate the record length (after homogeneity tests) of the precipitation, maximum and minimum temperature time series, respectively from left to right. White boxes indicate the series that are truncated after homogeneity check and have less than 30 years (i.e., Dakhla truncated at 2004 and T_{max} and T_{min} are not considered for AlHoceima station)
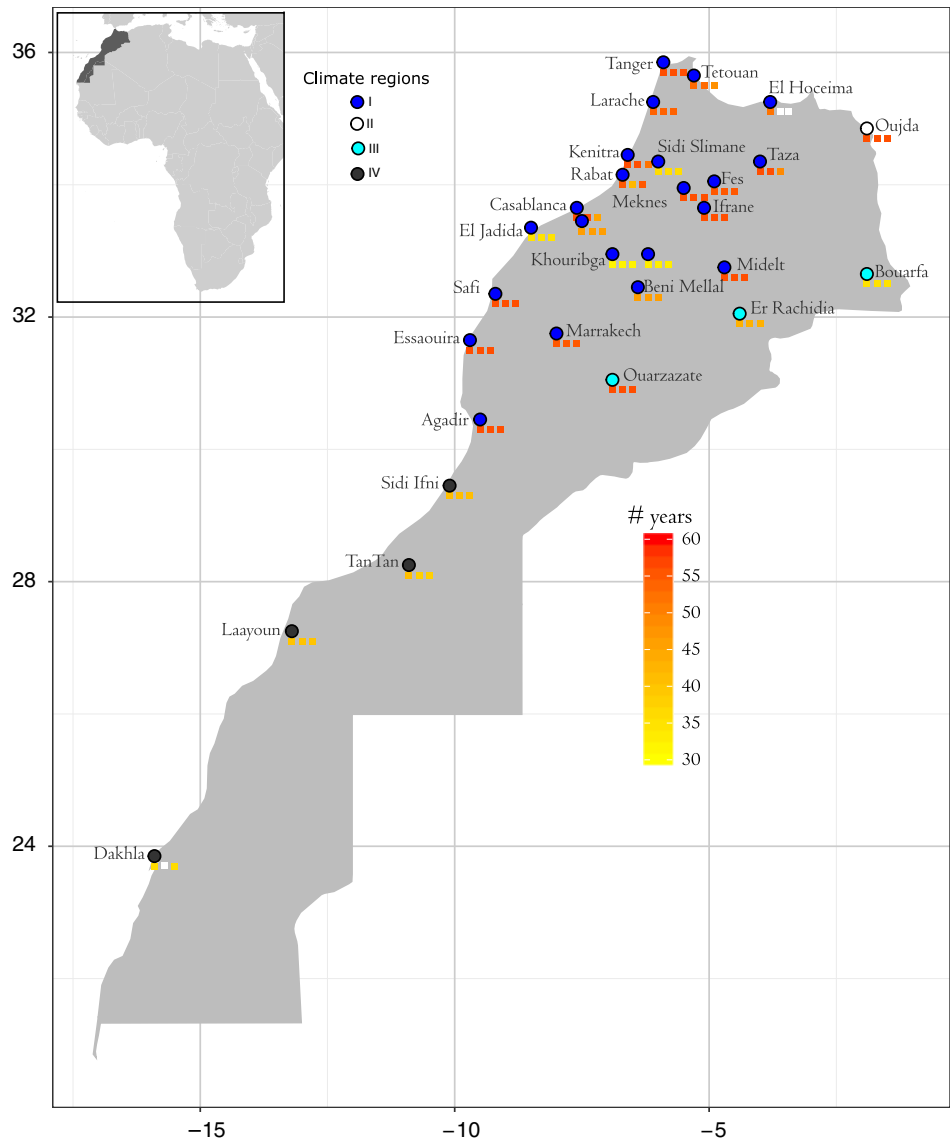
Aguilar *et al.*, 2003; Beaulieu *et al.*, 2007, 2008; Venema *et al.*, 2012); however, given the complexity of the homogenization process, there is no single most appropriate method. It is particularly problematic if no nearby homogeneous reference station is available or when focusing on the daily time scale of the data.

In this study, we have used two different software packages encompassing two different homogenization processes: (a) ACMANT software; Adapted Caussinus-Mestre Algorithm for homogenizing Networks of Temperatures series (Domonkos, 2014; Domonkos and Coll, 2017) and (b) RHtest (Wang and Feng, 2009) using RH-TestV3 program. RHTest is used with a penalized maximal F-test (e.g., Wang, 2008) to identify potential change points in the time series, based on two-phase regression models for the detection of shifts in individual station time series. ACMANT is based on a bivariate detection of changes that includes a penalty term

(Caussinus and Mestre, 2004). The level of confidence at which the tests are conducted to identify change points (potential breaks) have been set to the default values (0.05 for RHtest and 0.01 for ACMANT). Note that due to the generally large distances between the stations, we have not used testing methods that make use of reference stations. Only the potential changes identified by the two tests were retained for verification against available metadata or known climate conditions. Breaks occurring at relatively close dates for the two methods were also inspected. Using both tests, none of the stations showed potential breaks in precipitation series except the station of Fes (#10) but the dates of the jumps are different (i.e., in 1966 and 2002 using ACMANT, 2008/08 and 2011/11 after RHtest) and the available metadata do not support the existence of a non-climatic source for the jumps. Temperature data exhibits more potential breaks and many of them have not been documented especially

around strong El Niño years or during the 1970s; a period that was particularly humid and sometimes cold in many regions across the country. Time series with potential breaks and no available metadata for a given station have been discarded or reduced to their homogeneous recent part, except the most southern station Dakhla, where the

TABLE 2 List of the NCMPs used in this study and their corresponding definitions (Rows 2–5)

Index	Index name	Definition	Unit
NCMP1	Mean temperature anomaly	The mean temperature anomaly for each year (or month in case of monthly scale) averaged across the country (or region) for the national (or regional) scale.	°C
NCMP2	Rainfall anomaly	Annual (or monthly in case of monthly scale) total precipitation anomaly (normalized), calculated as a simple difference from the base-period average, expressed as a percentage of the base-period average. The values are averaged across the country (or region) for the national (or regional) scale.	%
NCMP 3	Standardized precipitation index (SPI)	It is a percentile-based measure of the standardized rainfall anomaly for each year (or month in case of monthly scale) averaged across the country (or region) for the national (or regional) scale.	No unit
NCMP 4	Warm days index (percentage of days)	It is a measure of the percentage of days in year (or month in case of monthly scale) that exceeded the ninetieth percentile of the base-period distribution for maximum temperatures for the day averaged across the country (or region) for the national (or regional) scale.	%
NCMP 5	Cold nights index (percentage of days)	It is a measure of the percentage of days in each year (or month in case of monthly scale) that fall below the tenth percentile of the base-period distribution of minimum temperatures for the day averaged across the country (or region) for the national (or regional) scale.	%
CDays	Cold days index (percentage of days)	It is a measure of the percentage of days in each year (or month in case of monthly scale) that fall below the tenth percentile of the base-period distribution of maximum temperatures for the day averaged across the country (or region) for the national (or regional) scale.	%
WNights	Warm nights index (percentage of days)	It is a measure of the percentage of days in year (or month in case of monthly scale) that exceeded the ninetieth percentile of the base-period distribution for minimum temperatures for the day averaged across the country (or region) for the national (or regional) scale.	%
SPEI	Standardized precipitation-evapotranspiration index (SPEI)	It is a percentile-based measure calculated using the difference between precipitation and reference evapotranspiration. For each year (or month in case of monthly scale), the SPEI values are averaged across the country (or region) for the national (or regional) scale.	No unit

Note: We also included cold days, warm nights and the SPEI index to the analysis (rows 6–8). Anomalies and the thresholds (90th percentiles) are calculated over the base period 1981–2010 as recommended by the WMO Guideline for NCMPs (World Meteorological Organization, 2017a).

maximum temperature time series has been cut to their longest period (1980–2004). This allows conserving valuable information in a region with very few observed data. The retained stations (Figure 1) and the corresponding time series are shown in Table 1.

2.3 | Definition of climate indices

Precipitations data, maximum and minimum temperatures are used to calculate climate indices (i.e., NCMPs) following the guidelines of the WMO on generating a defined set of Standard NCMPs (World Meteorological Organization, 2017a). We use the NCMPs R package to generate the indices. The package has been developed to help countries producing NCMPs consistently and regularly (ET-NCMP, 2018).

For the purpose of this study, we used the first five NCMPs (Table 2) which include: the mean temperature anomaly (NCMP1), the total rainfall anomaly (NCMP2), the percentage of warm days ((NCMP4) and cold nights (NCMP5) and the drought index SPI (standardized precipitation index, NCMP3). The percentage of cold days (Cdays) and warm nights (Wnights) are also included in the analysis in order to give a more comprehensive picture on the changes in extreme temperature events. We have not used the sixth NCMP since it is more appropriate for the monitoring than for trend analysis.

To take into account the effect of the warming on drought conditions, we have added the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010, 2015; Paulo et al., 2012) to the list of indices examined in this work. Several studies have shown that temperature rise affects the severity of droughts and the role of warming-induced drought stress has been highlighted in different studies on drought impacts (Martínez-Villalta et al., 2008; Barriopedro et al., 2011; Linares and Camarero, 2011). This multi-scalar drought index considers the effect of potential evapotranspiration (PET). It uses the monthly difference between precipitation and PET, which provides a simple measure of the water surplus or deficit for the analysed month (Vicente-Serrano et al., 2010). A log-logistic probability distribution function is used to fit the data series of accumulated values (depending on the time scale) of these monthly differences as explained by Vicente-Serrano et al. (2010) and Vicente-Serrano and Beguería (2016).

To calculate SPEI it is required to estimate the reference evapotranspiration (ET0). Initially, the SPEI was proposed by Vicente-Serrano et al. (2010) to be calculated using ET0 based on Thornthwaite (1948) approach, which requires only monthly-mean temperature data. Vicente-Serrano et al. (2012) suggested to include more reliable PET estimates based on the Hargreaves (Hg) or Penman–Monteith Equations (PM), in order to reflect better the role played by PET on drought severity and make the SPEI more suitable to identify drought-related impacts across systems. PM equation requires extensive data (solar radiation, temperature, wind speed and relative humidity), and long-term records of these variables are not available for many stations. Thus, the Hargreaves equation (Hargreaves and Samani, 1985) is used in this study. The calculation of SPEI was performed using the R package SPEI version 1.7 (Beguería et al. (2014)). To the best of our knowledge, the SPEI has never been used for drought trends analysis in Morocco using observed station data.

All the indices considered in this study are calculated at the monthly and annual scales (see Table 2 for each index and its definition). The annual values are used for the trend analysis whereas the monthly indices of NCMPs are used to compute the seasonal values for analysis of the association of climate indices to the NAO.

2.4 | Interpolating, averaging and trend calculation

After computing the indices at each station, we have interpolated these to obtain a regular grid covering the country (region) to define national (regional) scale values. The interpolation is undertaken using ordinary Kriging (Cressie, 1993) one of the most commonly used techniques. The method accounts for the uneven distribution of stations and provides a reasonable estimate of what the index would be at an intermediate location (World Meteorological Organization, 2017a). For each index, an empirical variogram is created and fit by a functional variogram model that minimizes the mean squared error. Three types of models; exponential, spherical and Gaussian, are tested in each case. The variograms of annual indices are shown in Figure S1. The variograms have been established over the base period 1981–2010, this period has also complete data for most of the stations. Based on the final variograms, the Kriging is performed with a resolution of 0.5°. We have performed the interpolation calculations using the NCMPs R package (ET-NCMP, 2018), for each of the indices both annually and monthly.

Next, we averaged each index across the country using the interpolated data to calculate the National values of the indices. We calculated an area weighted average of all the grid cells except those falling outside

the country's borders. Lastly, yearly and monthly time series of each climate index is generated to use for the trend analysis. Given differences in climate-types of sub-regions, we have also calculated averages at regional scale by averaging the grid point values falling within each of the four main Moroccan climate regions.

Finally linear trends of each index are calculated at station, region and country scale levels using the Sen's slope method (Sen, 1968) and lag-1 autocorrelation removal procedure (Zhang *et al.*, 2000) in order to produce more reliable estimates of the magnitude and the statistical significance of the trend. Most climate series (including precipitation and temperature) are, in fact, serially correlated due to the multi-year nature of natural climate variability (i.e., decadal), which may influence trends. The non-parametric Kendall's rank correlation tau (Sen, 1968) used strengthens the computation since it is robust to the effect of the outliers and to the non-normality of datasets. The statistical significance of the trends is evaluated at 5% level using the non-parametric Mann-Kendal test (Mann, 1945; Kendall, 1975).

The trends at the country and regional scales are calculated over a common period 1984–2016. The regional trends are also computed over the period covered by most of the stations of each region: 1964–2016 for Region I, 1960–2016 for Region II, and 1976–2016 for Region IV. The trends at individual stations are computed over the entire available period of each station (Table 1).

## 3 | RESULTS AND DISCUSSION

3.1 | Climatology analysis

The annual mean temperature in Morocco ranges generally from about 11.8–21°C with the lowest values registered in mountainous regions (e.g., Ifrane station) and the highest ones in the southern stations (e.g., Laayoun). Temperatures typically increase as we move from the coasts to the inland areas and from the north to the south. The annual temperature variation coefficient (i.e., the ratio of the standard deviation and the mean), ranges from 2 to 7% exhibiting a relatively low interannual variability. Precipitations occur mainly from October to March with high spatial and temporal variability. The mean annual totals range from over 700 mm in the north and in the highland regions to less than 100 mm in the south and the south-east of the country. The variation coefficient varies from approximately 30% in the northern half of the country to more than 50% in the south and can reach 90% in the extreme south, a region where mean annual precipitation does not exceed 30 mm.

Summers are generally dry, and the small precipitation amounts received are mostly of storm-origin.

Analyses of the temperature anomalies (NCMP 1) computed at the annual scale for the period 1984–2018 across the country, indicate that the top 10 warmest years in Morocco have all been recorded in the last two decades. The warmest year is recorded in 2010 with 1.26°C above the 1981–2010 average. The second warmest year is 2015 (0.79°C above average) followed by 2016 with 0.77°C above average (Figure 2). Both 2015 and 2016 were the warmest years on record globally and in many individual countries (World Meteorological Organization, 2016; World Meteorological Organization, 2017b). The second NCMP (i.e., rainfall anomaly) calculated at the annual scale and country-wide, shows that the highest national total annual precipitation amounts for the period 1984–2016 was recorded in 1996 followed by 1991 exceeding the normal by about 80 and 70%, respectively (Figure 2b). The year 1996 was also marked by above normal conditions in all stations with record breaking in precipitation at most of them. The lowest rainfall amounts were recorded in 2001, followed by 2000 then 1984. Nearly half of the annual rainfall (16 out of 33 years) was below normal conditions. Since 1984, the rainfall deficit periods range from 1 to 4 consecutive years with 1999–2002 being the longest deficit period followed by 1992–1994 period. In 1984, rainfall was well below normal with a deficit of about 40% at the national scale. In fact, this was part of a well-known dry period in the first part of eighties (1980–1986) which resulted in severe negative impacts. This dry period is clearly visible in the NCMP2 index at the regional and individual stations. For example, at the Region I (Figure S2), one of the most, affected regions in terms of agriculture and water resources. Other rainfall deficit periods are also recorded in the last decade with the most notable period recorded in 2012–2016. These periods of relatively high rainfall deficit are also depicted through the SPI (NCMP 3) with the six highest negative annual SPI values are recorded in 2001, 1992, 2000, 1984, 1994 and 2013 (Figure 2c).

The above mentioned rainfall deficit periods or years were marked by at least one strong El Niño -Southern Oscillation (ENSO) events (1991–1992, 1994–1995, 1997–1998, 2002, 2014–2016). The period 1995–1996 experienced a moderate to strong La Niña event started from July 1995 to February 1996. Some effects of ENSO on precipitation in North-West Africa have been reported in different studies (e.g., Nicholson and Kim, 1997; Ward *et al.*, 1999, Mariotti *et al.*, 2002; Knippertz *et al.*, 2003; Driouech *et al.*, 2010a; Donat *et al.*, 2014), especially in the spring following an ENSO event. However, drawing robust conclusions on the link between ENSO events and

FIGURE 2 Trends in (a) mean annual temperature (NCMP1, °C), (b) annual rainfall anomalies (NCMP2, %) and (c) standard precipitation index (NCMP3) in Morocco. The left column indicates trends (per decade) at the national scale (calculated over a common period of 1984–2016) and the right column (maps) indicates station-based trends (calculated over varying periods of each station from 1960 to 2016). The green/red and brown/blue colours indicate positive and negative trends, respectively. Statistically significant trends at 5% confidence level are represented by solid triangles. The size of the triangles is proportional to the magnitude of the trend
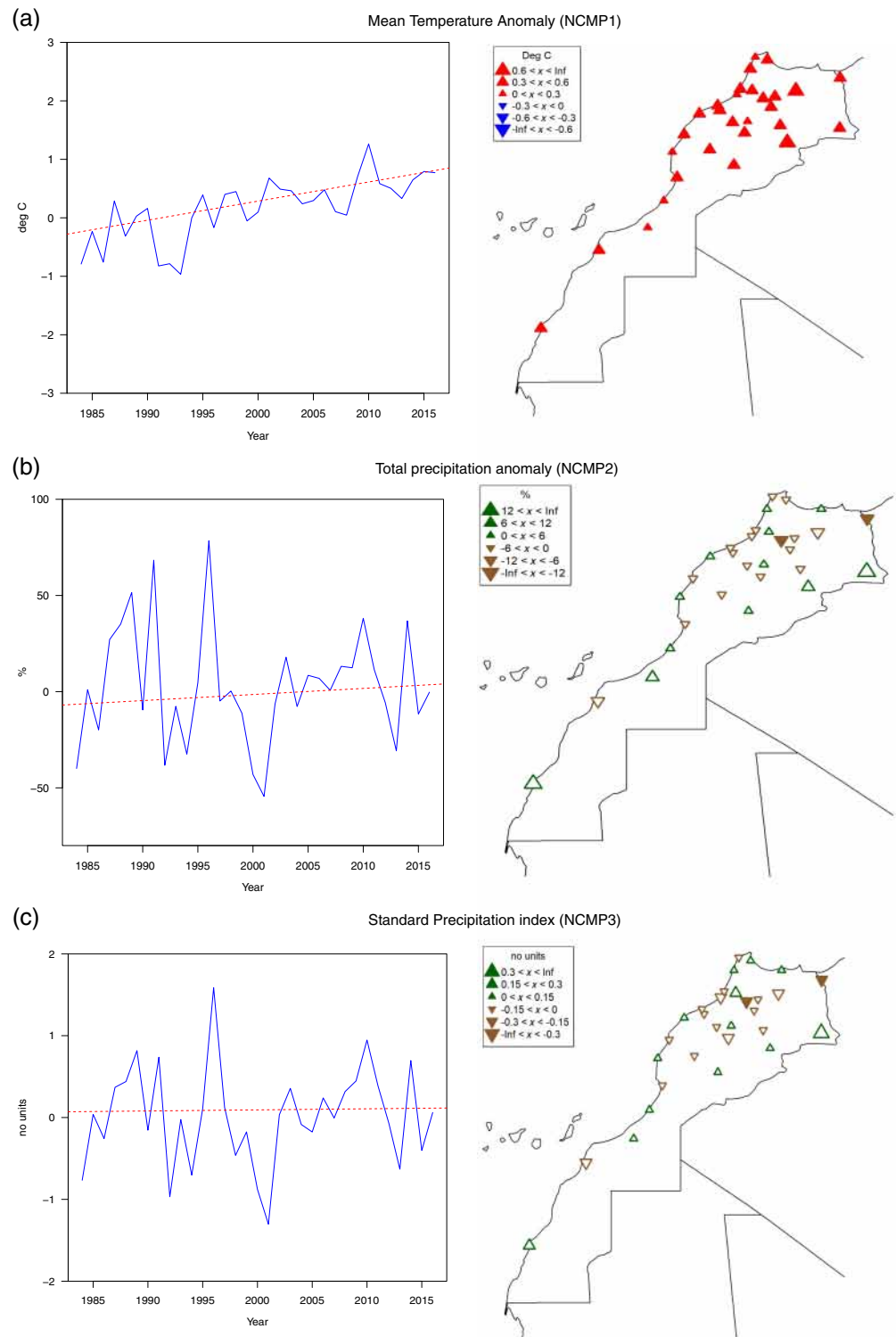
Moroccan climate requires further investigations which are beyond the scope of the present study. A special focus on droughts and ENSO in Morocco would shed more light on such an impactful climate oscillation. Precipitation patterns in Morocco are also affected by the NAO and several previous studies have highlighted this association (Ward *et al.*, 1999; Knippertz *et al.*, 2003, Trigo *et al.*, 2004; Driouech *et al.*, 2010b; López-Moreno *et al.*, 2011). The

relationship between NAO and NCMP2 is further discussed in Section 4 of this study.

3.2 | Trends in temperature based indices

Analyses of trends in temperature and extreme temperature indices (i.e., NCMP1, NCMP4, NCMP5, Cdays and Wnights) at each individual station and at the regional and the country scales, indicate an overall trend towards warming conditions in Morocco (Figures 2a and 3 with the magnitude of trends shown in Table 3). The mean temperatures have increased at the country-scale at a rate of 0.33°C/decade corresponding to a warming of approximately 1.1°C for the period 1984–2016 (Table 3). Statistically significant upward trends at the country scale are noticed in both daytime and night temperatures (Figure 3 and Table 3). The annual percentages of warm days and warm nights exhibit statistically significant positive trends with an increase of 12 and 9%, respectively over the period (1984–2016) (Table 3). Trends in low temperature extremes reveal a statistically significant decrease with a rate of about 6% in both the percentage of cold days and nights (Table 3). We found statistically

significant upward trends in the mean temperature anomalies at all the analysed stations across the country regardless of their varying record lengths (map in Figures 2a). Extreme temperature indices are also indicating warming conditions at the majority of stations (maps in Figure 3). Regionally, we found statistically significant changes in both mean temperature anomalies and high and low extreme events consistent with the warming trends detected at the country scale (Table 3). The eastern region (Region II) and south-eastern part (Region III) witnessed relatively higher rates in temperature increase (about 0.5 and 0.4°C per decade over 1984–2016, respectively). Trends calculated over the longest available period of each region show contrasted differences in the more recent period. In particular, Region I and Region IV indicate some slowdown in temperature trend in the last three decades compared to trends over 1964–2016 and 1976–2016, respectively. Similar temporal behaviour is reported in parts of the Mediterranean region in Spain for example (Gonzalez-Hidalgo et al., 2016; Vicente-Serrano et al., 2017) especially in the cold season. This has been linked to cold temperatures in the Eastern Pacific region (Kosaka and Xie, 2013). A slowdown is also witnessed by the decreasing trends of cold events in all the regions and in most of the stations. In contrast,
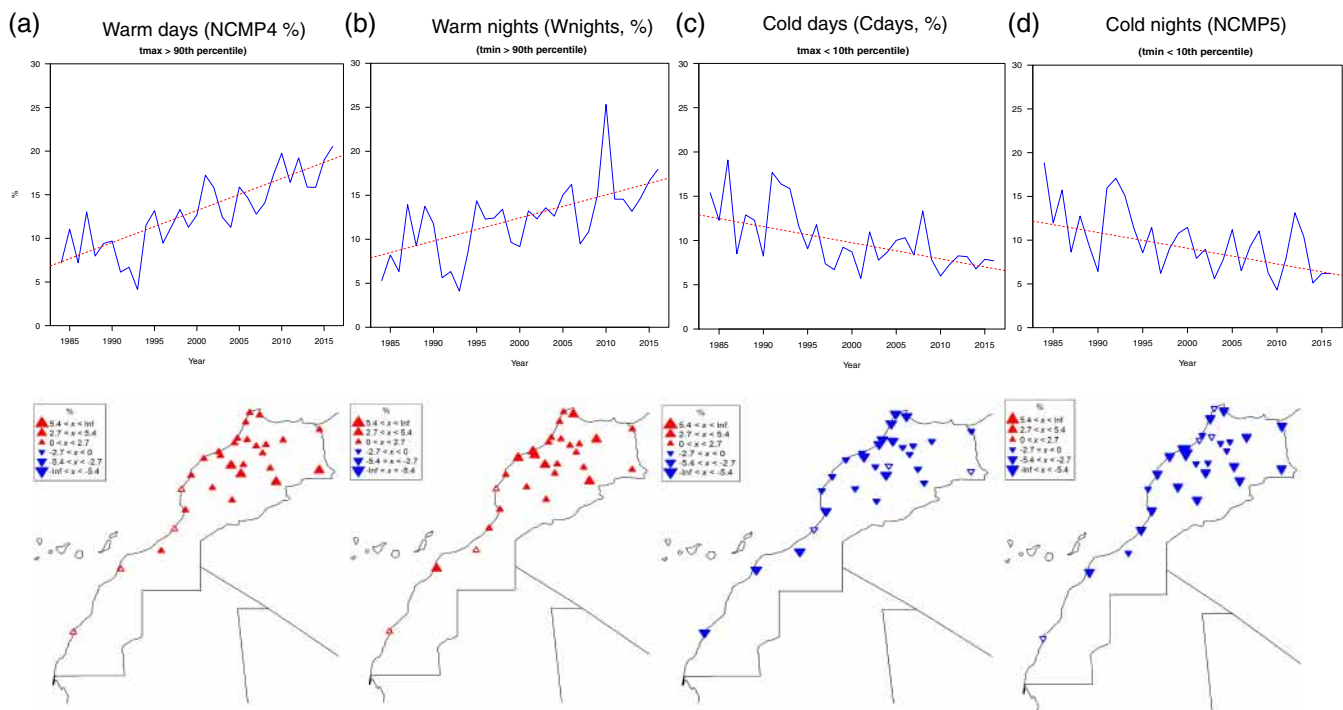

FIGURE 3 Trends in extreme temperature indices over Morocco for (a) warm days (NCMP4), (b) warm nights (Wnights), (c) cold days and (Cdays) and (d) cold night (NCMP5). The first column indicates trends at the national scale over the period 1984–2016 and the second column shows trends (per decade) at each individual station with varying record lengths from 1960 to 2016. The red and blue triangles indicate positive and negative trends, respectively. Statistically significant trends at 5% confidence level are represented by solid triangles. The size of the triangles is proportional to the magnitude of the trend

TABLE 3 Trends of the climate indices in Morocco

Indices	Spatial scale	Country scale	Region I		Region II		Region III	Region IV	
	Period	1984–2016	1984–2016	1964–2016	1984–2016	1960–2016	1984–2016	1984–2016	1976–2016
NCMP 1: mean temperature anomaly (°C decade^{-1})		**0.33**	**0.32**	**0.39**	**0.53**	**0.46**	**0.41**	**0.28**	**0.32**
NCMP 2: total precipitation anomaly (% decade^{-1})		3.16	2.89	−3.23	6.50	−5.55	0.31	−0.63	0.57
NCMP 3: standardized precipitation index (no unit)		0.01	0.06	−0.07	0.13	−0.15	0.02	0.02	0.02
NCMP 4: percentage of warm days (% decade^{-1})		**3.67**	**2.91**	**1.94**	**4.21**	**2.03**	**5.41**	**3.30**	**2.15**
NCMP 5: percentage of cold nights (% decade^{-1})		**−1.80**	**−1.87**	**−3.33**	**−2.62**	**−3.32**	**−1.47**	**−1.86**	**−3.41**
WNights: percentage of warm nights (% decade^{-1})		**2.62**	**2.67**	**2.12**	**3.73**	**2.21**	**2.48**	**2.54**	**2.44**
CDays: Percentage of cold days (% decade^{-1})		**−1.82**	**−1.90**	**−2.67**	**−2.07**	**−2.50**	**−2.47**	−1.25	**−2.90**
SPEI: standardized precipitation-evapotranspiration index (no unit)		−0.11	−0.05	**−0.18**	−0.14	**−0.28**	−0.35	−0.18	**−0.20**

Note: Trends are computed over the period 1984–2016 at the country and regional scales and over 1960–2016, 1964–2016 and 1976–2016 at regional scale depending on the region. Blue and red shades indicate positive and negative trends, respectively. Statistically significant trends at 5% confidence level are in bold. See *p* values in Table S1.

Region II shows relatively higher warming rate in the recent period reflected mainly by warm days and nights. Despite the quasi-general accelerating rate of increase in warm extremes depicted during the last 30 years, the decreasing trends of cold days and nights show higher magnitudes when considering all the available periods in each region. This narrowing of the temperature distributions have also been pointed out by Donalt *et al.* (2014) based on station temperature trends across the Arab region. Similarly, Donat and Alexander (2012) highlighted changes towards smaller variance of the temperature distributions in the northern hemisphere extra-tropics during the past 60 years.

Many studies have shown changes in extreme events of temperature consistent with the detected warming trends, specifically a decline in the number of cold days and cold wave days and an increase in the number of hot days and of heat wave days (Boris and Seneviratne, 2012; IPCC, 2012; Cohen *et al.*, 2014; Donat *et al.*, 2014; Driouech and El Rhaz, 2017). The increase in extremes including hot temperature events in the mid-latitudes (20 N–50 N), over the last decades seems to be dynamically linked to the rapid arctic amplification (consisting in enhanced Arctic warming relative to that in mid-latitudes) through three potential pathways: changes in storm tracks, the jet stream, and planetary waves and their associated energy propagation (Francis and Vavrus, 2012; Cohen *et al.*, 2014; Walsh, 2014; Francis and Skific, 2015). The increase of high temperatures events in North-west Africa is attributed at least partially to anthropogenic climate forcing (Diffenbaugh *et al.*, 2017). Our depicted mean

and extreme temperature trends are also consistent with the observed global warming reported in the IPCC reports including the recent ones (IPCC, 2018; IPCC, 2019).

In order to examine how the increase in Moroccan mean temperature compares with the global warming, we calculated the trend of the global mean temperature using the annual mean temperature anomalies from CRUTEM4 time series (Brohan et al., 2006). Based on annual trends for the period 1984–2016, the results indicate that the rate of increase in Moroccan regional temperatures is higher than the global warming with about 8% to more than 40%, especially over the northern half of the country. Region IV shows smaller rate by 5%. The country-wide trend of mean temperature exceeds the global trend by about 11%. Higher observed rates of climate change compared to the global scale have also been found in the Mediterranean region by Cramer et al. (2018). Moreover, comparison between temperatures trends in Spain and the northern hemisphere, showed 50% higher increase in this Mediterranean country (Bladé and Castro-Diez, 2010).

3.3 | Precipitation based indices

The temporal evolution of precipitation indices along with their trends and significance are shown in Figure 2 and Table 3. Both precipitation anomaly (NCMP2) and the standardized precipitation index (NCMP3) at the country scale show small positive trends that are not statistically significant over the last three decades (1984–2016; Figure 2b,c).

At the regional scale, trends in NCMP2 and NCMP3 exhibit similar patterns over the same period except for Region IV (South) where the trend of NCMP2 is negative but also not statistically significant (Table 3). Trends computed over the whole available record at each climate region, show decreasing evolution in NCMP2 and NCMP3 at regions with long data records (i.e., Region I 53 years and Region II; 57 years; Table 3 and Figure S2). At individual sites, almost 2/3 of the stations indicate downward trends in both precipitation anomaly (NCMP2) and drought index SPI (NCMP3) however trends are not statistically significant at 5% level except in stations of Meknes #18 and Oujda (map Figure 2b).

The negative trends depicted in NCMP2 and NCMP3 over the last 50–60 years when using longer records, are consistent with the large-scale decreasing precipitation tendencies found in the Mediterranean and the Maghreb since the early 1900s (Born et al., 2008; Hoerling et al., 2012). Drying trend across North Africa has also

been highlighted by a more recent study done by Seager et al. (2019) over the period 1901–2016. The authors concluded that such evolution would not have arisen from internal climate variability alone and that external forcing has made an important contribution.

3.4 | Standardized precipitation-evapotranspiration index

Analysis of the SPEI at the national scale for the period 1984–2016 exhibits a decreasing tendency (Figure 4, Table 3) in contrast to the positive trends depicted using precipitation-based indices (i.e., the annual mean precipitation and the SPI). The trends of this drought index is however not statistically significant for such period. Regional trends show similar results particularly for Region I, Region II and Region III. Negative and statistically significant trends in the SPEI are found for the longer periods (50–60 years), which was not the case for the precipitation based drought index (SPI). This shows the role of temperatures increase in drought intensification through its effect on evapotranspiration especially in the context of warming climate. This effect is also discernable when considering the recent period (1984–2016; Table 3). In fact, the SPEI takes into account the sensitivity to changes in evaporative demand, remediating to one of the main limitations of SPI (Vicente-Serrano et al., 2010, 2015).

The influence of the warming conditions can also be seen at individual stations (Figure 4, right panel) where the number of negative and statistically significant SPEI trends has increased (compared to SPI) particularly in the northern half of the country (i.e., Tangiers, Oujda, Meknes, Taza, Benimellal, Marrakech, Tan Tan). Many positive trends in SPI are found negative when using SPEI (i.e., Tetouan, Larach, Sidi Slimane, Ouarzazate, Errachidia, Bouarfa, TanTan, Dakhla), which further strengthen our findings on the observed tendency towards drying climate in Morocco. We also note the increase in the strength of negative trends and the decrease in the values of positive trends with SPEI at most of the stations compared to SPI. The above conclusions have been also examined in stations with different periods for precipitation and temperature (i.e., Casablanca, Rabat, Taza, Kenitra, Tan Tan, Tetouan, Dakhla) on a common period for SPI and SPEI. The effect of temperature increase on drought has also been confirmed at station level over the recent period (1984–2016; see Table S3).

The drying trends depicted here for the period 1960–2016, using SPEI, is in agreement with the results of other studies that assessed drought evolution at the global scale based on drought or aridity indices that
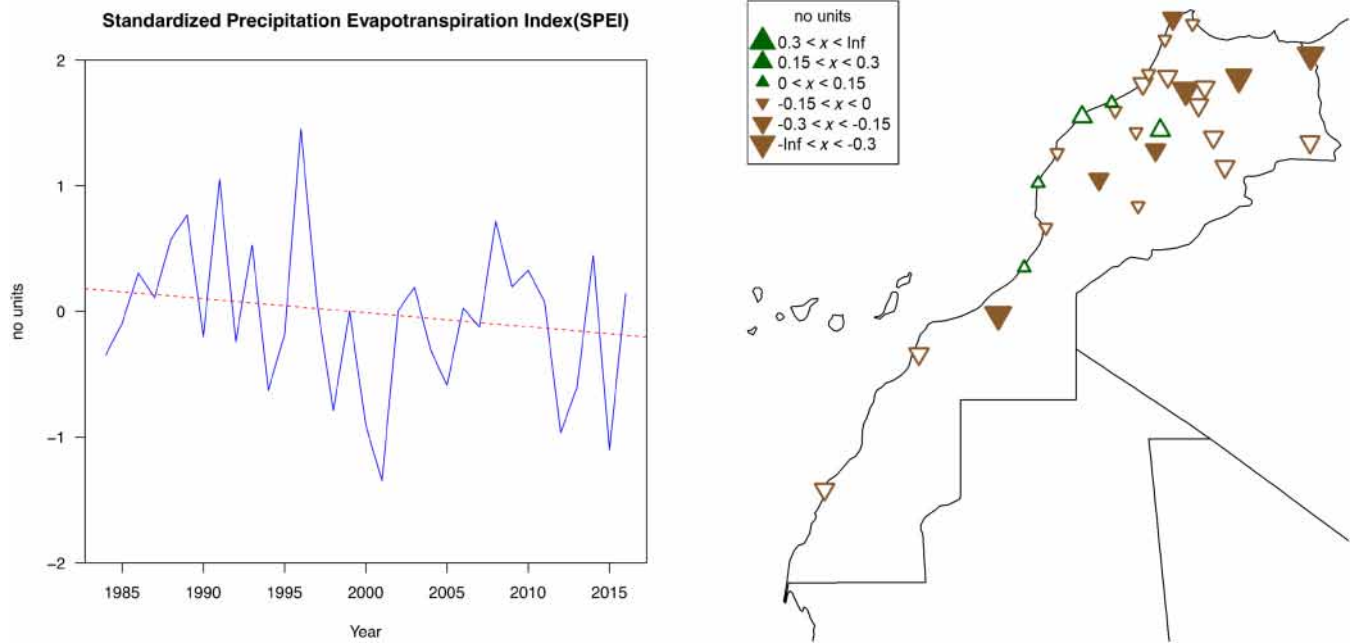
FIGURE 4 Trends in the SPEI at the country scale (left panel) and at individual stations (per decade) across Morocco (right map). The green and brown colours indicate positive and negative trends, respectively. Statistically significant trends at 5% confidence interval are represented by solid triangles. The size of the triangles is proportional to the magnitude of the trend

consider both precipitation and evapotranspiration. For example, Greve *et al.* (2014), highlighted a significant change towards drier conditions at the gridded pixels located in Moroccan highlands of the northwest of the country. Increase in drought (frequency, duration, and severity) have also been depicted over the period 1951–2010 by Spinoni *et al.* (2014).

The causes of detected change towards drier conditions in the Mediterranean region have been investigated by different studies including those summarized in the IPCC assessment reports. For instance, the IPCC Special Report on Climate Change and Land (IPCC, 2018) stated that enhanced greenhouse forcing contributed to increased drying in the Mediterranean region, including Southern Europe, Northern Africa and the Near-East. The report stated that this tendency will continue to increase under higher levels of global warming. A special focus should be devoted, in a dedicated study, to the attribution of the recent past changes in the Moroccan climate including potential connections with changes in sea surface temperature (Hoerling *et al.*, 2012) and the role of land-atmosphere feedbacks in dry extremes (Lorenz *et al.*, 2016).

3.5 | On the link between NCMPs and the NAO

The NAO is responsible for most of the climate variability in the North Atlantic, influencing the direction and the intensity of the westerlies and the location of the anticyclones (Hurrell, 1995; Wanner *et al.*, 2001). Several studies highlighted significant correlations between NAO indices and Moroccan precipitation (El Hamly *et al.*, 1997; Ward *et al.*, 1999; Knippertz *et al.*, 2003; Trigo *et al.*, 2004; Driouech *et al.*, 2010b; López-Moreno *et al.*, 2011). The few studies that investigated the influence of NAO on high temperature extremes suggesting that NAO negative periods are associated with higher maximum temperatures (e.g., Donat *et al.*, 2014). To date, none of the above studies evaluating the correlations between NAO and Moroccan climate events used country wide indices neither investigated the whole set of climate indices represented in Table 2. In this section, we evaluate the relationships of climate extremes in Morocco with large-scale internal variability in the climate system linked to NAO using the five NCMPs, Cdays, Wdays and SPEI (Table 2). We use the Hurrell NAO index based on the surface sea-level pressure difference between the Subtropical (Azores) High and the Subpolar Low (NAO; NCEI, 2019). Each of the indices was de-trended before the correlations (Spearman rank correlation) were calculated. We computed correlations between NAO index the climate indices (Table 2) at the country scale and at each region for the common period 1984–2016 (Table 4 and Table S2). We also computed correlations at individual stations over the entire available period of each station (Figure 5). The correlations over the period covered by most of the stations of each region are also calculated for NCMP2 (Table 4) to assess the dependence on the period.

Correlations at the annual scale are weak and predominantly not statistically significant for NCMP2, regardless of the targeted period (Table 4 and Figure 5), consistent with the finding of Filahi *et al.* (2015) who highlighted a weak relationship with NAO the period 1970–2012. However, analysis at the seasonal scale shows higher and significant correlations (at 5% level) especially in Region I during winter, underlying the effect of the North Atlantic circulation on the Moroccan precipitation, especially in the west of the Atlas Mountains, as demonstrated by previous studies including a recent study by Raymond *et al.* (2017). The negative correlations of NCMP2 with NAO are statistically significant in the two-third of the stations (Figure 5). The highest correlation scores range between −0.6 and −0.7 (11 stations). Similar results are exhibited by NCMP3 (SPI). The NAO effect on Moroccan precipitation extends to October–February period with a similar spatial distribution of correlations and signs as in winter (December–February; Table 4 and Figure 5). During the winter season changes in the NAO phase lead to shifts in the location of the centres of action and in the associated storm tracks (Trigo, 2006). In particular, the positions of the Azores High and extratropical depressions determine the flow direction in Morocco, and then the circulation weather types mainly in the wet season (October–April; Born *et al.*, 2010). A positive phase of NAO coincides with a strong Azores High or located in a relatively eastern position is unfavourable to the precipitation events, mainly in Region I (Knippertz *et al.*, 2003). Conversely, in the negative phase, significant negative (positive) sea level pressure anomalies are observed in the Azores high (Iceland low) and North Atlantic cyclones move southward favouring precipitation conditions. The link to NAO may explain the decadal variability signals exhibited by precipitation based indices in Region I (Figure S2; Ward *et al.*, 1999;

Knippertz *et al.*, 2003). The correlations found using NCMP2 and NCMP3 for the remaining regions (Regions II, III and IV) are also consistent with previous findings highlighting a weaker role of NAO in those regions (Born *et al.*, 2010).

As found for precipitation, most of the correlations issued from temperature-based indices are weak and statistically not significant at the annual scale (Table S2). The country-wide indices shows however more significant correlations in winter, especially for the warm nights (Table S2). Correlations are negative and statistically significant in all regions (Figure 5 and Table S2) and at nearly all the stations with the most important ranging between −0.6 and −0.7 (at 14 stations; Figure 5). This result reflects the effect of positive NAO in reducing the number of warm nights, probably through land-atmosphere energy exchange processes consisting in enhanced land radiation (longwave) emissions during night time due to reduced clouds. In fact, the anticyclonic conditions induced by positive NAO are favourable to subsidence of cold and dry air coming from boreal latitudes bringing low amount of water vapour and non-saturated air masses which leads to clear sky and absence of precipitation (Raymond *et al.*, 2017). Opposite but consistent effect of NAO is exhibited by the cold nights (NCMP5) which show positive correlations (Figure 5) although relatively weaker. The NAO seems to exert, to a lesser extent, similar influence on day temperature extremes but the correlations remain weaker and mostly not significant (Table S2). We note that the relationships tend to be stronger with warm extremes than cool extremes consistently with Donat *et al.* (2014). The correlations found here between extreme temperature events and NAO index are consistent with the accelerated increase in warm extreme events depicted in the last three decades (1984–2016) compared to the cold events decrease rate

TABLE 4 Correlations between NAO index and NCMP2 (precipitation anomaly) at the country and regional scales and the corresponding *p* values for winter DJF (first two columns), ONDJF (second two columns) and the annual period (last two columns)

	DJF		ONDJF		Year	
	Correlation	*p* value	Correlation	*p* value	Correlation	*p* value
National (1984–2016)	−0.3	.09	−0.31	.08	**−0.38**	.03
Region I (1984–2016)	**−0.58**	0	**−0.55**	0	−0.21	.23
Region I (1964–2016)	**−0.54**	0	**−0.43**	0	−0.12	.38
Region II (1984–2016)	−0.28	.12	−0.29	.1	−0.04	.81
Region II (1960–2016)	−0.07	.63	−0.09	.51	−0.24	.08
Region III (1984–2016)	−0.1	.6	−0.06	.75	−0.13	.47
Region IV (1984–2016)	−0.25	.17	−0.3	.1	−0.25	.15
Region IV (1976–2016)	−0.16	.33	−0.29	.07	−0.25	.12

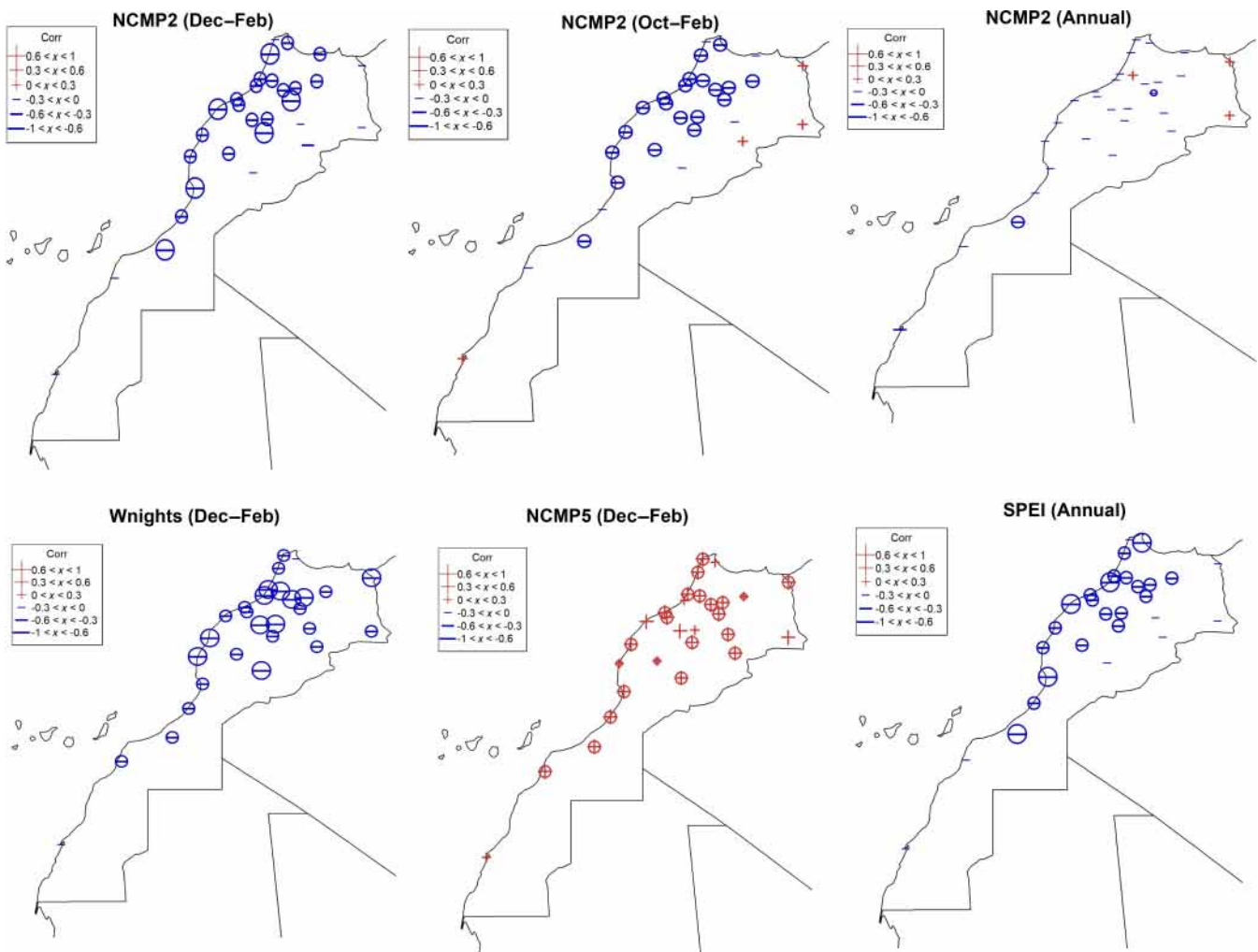*Note:* Significant correlations at 5% level are shown in bold.

FIGURE 5 Correlations between NAO index and climate indices at station level and for winter Dec–Feb (NCMP2, WNights, CNights and SPEI), Oct–Feb (NCMP2) and annually (NCMP2). Circles indicate significant correlations at 5% level. Correlations at station level are calculated over the available period of each station (see Table 1)

(Section 3.2). In fact the NAO has been dominantly positive in such a period (especially in the 1980s and 1990s) (Delworth *et al.*, 2016). Nevertheless, we should note that linking the rather complex NAO–NCMP correlations to the depicted trends here requires further investigation. This is particularly true for SPEI trend given the differential roles for temperature and precipitation. Additionally, the known decadal fluctuations of NAO (Delworth *et al.*, 2016) suggest NAO is unlikely to explain the entire SPEI trend although a contribution (either internal to the atmosphere or externally forced) is not excluded. This remains a topic for further investigation.

Overall, with the proper setting of the seasonal analysis, the NAO—rainfall correlations were recovered consistent with the literature. This analysis, undertaken using NCMPs, showed also the usefulness of calculating the NCMPs at sub-annual scale.

4 | SUMMARY AND CONCLUSION

This study examines the evolutions and trends of climate indices (including extreme indices) in Morocco based on observations of daily maximum and minimum temperature and precipitation from 30 meteorological stations over the period 1961–2016. Homogeneity checks of the quality-controlled datasets have been performed before the calculation of the climate indices. We used 8 climate indices; temperature anomaly, the number of hot and cold days and nights, precipitation anomaly and two drought indices: SPI and SPEI. Trends have been evaluated at the country scale, regional and at station levels. Our results show significant changes in temperature related indices over time suggesting a generalized tendency towards warmer conditions through both mean and extreme temperature events. Trends in the mean temperature exhibit a high warming rate exceeding the

rate recorded at the global scale, particularly in the northern half of the country. In terms of extreme temperature, results indicate evolutions towards more high extreme temperature events and less cold extremes in both night and daytime. Trends in the precipitation-based indices are predominantly not statistically significant. Besides, and consistent with the drying evolution depicted by previous studies in the Mediterranean region, we found significant changes in the drought SPEI index demonstrating the importance of considering the combined effects of changes in precipitation and temperature.

We also analysed the relationship between Moroccan climate and large-scale atmospheric circulation in the Atlantic using NAO index and each of the climate indices (NCMPs) at the country, regional and station scales. Overall, our results corroborate with the previous findings regarding the significant effect of NAO in winter (i. e., Ward *et al.*, 1999; Knippertz *et al.*, 2003; Driouech *et al.*, 2010b; Raymond *et al.*, 2017) however, when using precipitation indices at the regional scale (especially for the region in west of the Atlas Mountains), the signal was weakened when working with values at country scale. Similar correlation patters are exhibited by the SPI in winter but limited to the west of the Atlas Mountains region. Significant correlations are also found with temperature indices, especially in night time. A positive phase of NAO would increase cold extremes and decrease the warm temperatures. Though the correlations found here, NAO variability alone is unlikely to explain all the depicted generalized warming and drying trends and further investigations are required.

Overall, this study provides an updated assessment of observed trends across Morocco and demonstrates the usefulness of the NCMPs defined by the Expert team of the WMO Commission of Climatology on NCMPs to summarize climatic conditions at a national scale of Morocco although some constraints may emerge when combining sub-regions with different climate characteristics. Our incorporation of the SPEI proved useful as an index encompassing the combined effects of temperature and precipitation, which we propose to include in the list of NCMPs.

Further investigations on sources and mechanisms involved in the observed evolutions of the above climate indices would further improve our understanding of the climate evolution in Morocco and in north-west Africa. Additionally, the evaluation of sector-specific indices should provide insights on the potential effects on socio-economic sectors such as water resources, agriculture, health and tourism. Sparse weather datasets is one of the constraints of this analysis, therefore increasing and extending the weather observation network particularly in the south and the east of the country would provide valuable monitoring data.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.