Drought projection from CMIP6 Climate models over Morocco in the 21st century using the Standardized Precipitation Evapotranspiration Index (SPEI)

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Abstract. Quantifying how climate change drives drought in the 21st century is a priority to inform policy and adaptation planning in Morocco. SPEI drought index calculated from precipitation and temperature at 12 months' time-scale covering the agricultural year September-August was carried out for each of the five models over the future period 2023-2099. The average changes across Morocco were obtained by comparing between the averages of SPEI values and the drought zone percentages (Light, Moderate, Severe and Extreme). Also, by comparing drought characteristics for the different 11-year time horizons 2023-2033, 2034-2044, 2045-2055,
2056-2066, 2067-2077, 2078-2088 and at the end 2089-2099 . The study of future drought projections based on the SSP2-4.5 scenario of the CMIP6 models indicates a worsening of drought in Morocco during the second half of the century. Moderate drought is expected to predominate, with a sharp increase in the area affected by drought, even reaching 90% over six years. These results are essential for decision-makers in water resources management, highlighting the need to put in place strategies to mitigate the adverse effects of drought, including the efficient use of water resources.

1 Introduction

A commonly accepted drought definition emphasizes the meteorological factors and characterizes drought as a prolonged period with notably deficient precipitation, resulting in a significant lack of moisture, leading to a substantial hydrological imbalance (WMO, 1992). Due to advances, Models have become an important tool in the climate change process in terms of modeling and implications for the climate system. General circulation models (GCMs) can simulate and predict future climate change under various scenarios. The World Climate Research Program (WCRP) developed the Coupled Inter-Model Comparison Project, which provides data simulated using various climate models. Multi-model integration can produce more reliable predictive data [1]. In addition, the sixth experiment of the Coupled Model Intercomparison Project (CMIP6) for the IPCC Grade 6 Assessment Report is provided. A lot of effort was put into the development of CMIP6, including a larger number of fine-resolution models, more scenes and more recorded diagnostics than previous CMIP experiments.

Although these models provide crucial information for anticipating future climate developments, they remain tools subject to a certain uncertainty due to the complexity of climate systems and the limits of our current knowledge.

The objective of this study is to assess the average future change in drought and its trends until the end of the current century. As well as the projection of drought characteristics in the future using SPEI data calculated based on precipitation and temperature from the five GCMs CMIP6 models. Namely, the future duration, severity and intensity of droughts are identified for future water needs and water resources management in Morocco.

Morocco is located in the northwest of the African continent, along the Atlantic Ocean and the Mediterranean Sea. It has a wide variety of reliefs. Morocco is dominated by mountain ranges: Rif, Middle Atlas, High Atlas (3,000 to 4,000 m) and Anti-Atlas, spread out on a NE-SW axis which subdivides it into two parts: a part to the west and north of the reliefs, which is subject to the influences of North Atlantic disturbances and an eastern and part where influences from the south-east (Saharan) dominate. The average interannual rainfall decreases from north to south and from west to east [2]. Agricultural areas are concentrated in the north of the country Deserts cover the south and southeast.

Fig. 1 represents the map of annual precipitation normals over the base period 1981-2010 based on interpolated data from the General Directorate of Meteorology (DGM). We can see, the spatial variation of precipitation in Morocco, the northeast is generally more watered than the rest of the kingdom of Morocco. Annual rainfall totals exceed 600 mm per year in the mountain ranges shown by the blue color. Furthermore, the average annual rainfall decreases from west to east and from north to south. The map also shows the 20 weather stations used in this study, which cover most of the country.

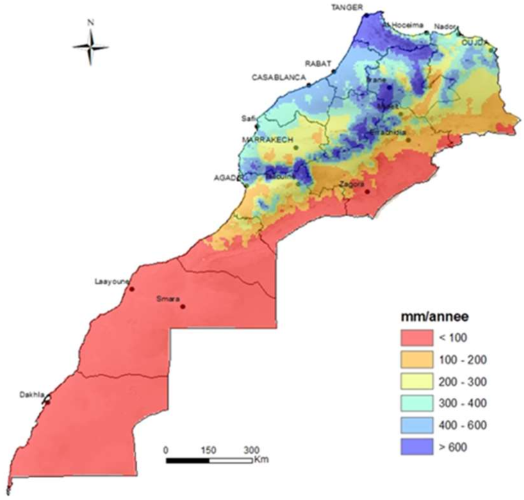

Fig. 1. Map of annual precipitation normals over the base period 1981-2010.

2 Materials and methods

2.1 Simulations of CMIP6 global climate models

Regarding the projection of the chosen indicators into the future. Climate models are the only way to adequately and realistically anticipate how the climate system is likely to be modified by human activity. Coupled atmosphere-ocean general circulation models (CGM) provide an overall representation of the climate system, which is one of the most complete in the spectrum currently available. this digital representation is modelled from a set of mathematical equations representing the physical laws (fluid mechanics, thermodynamics, etc.) which describe the planet and the interactions between its different reservoirs which modulate the climate: the atmosphere, the ocean and continental surfaces, given their computational cost and the quantity of data they generate, generally have spatial resolutions of a few hundred km [3]. CMIP6 uses an improved set of emissions scenarios based on Shared Socio-Economic Pathways SSP. The set of SSPs therefore establishes a matrix of global radiative forcing levels and socio-economic scenarios.

The list of parameters ultimately used in this study include monthly maximum and minimum temperatures as well as monthly precipitation for the periods 2023 to 2066 of the five climate models presented on Table 1:

Table 1. Description of the CMIP6 global climate models used in this study.

Model	Horizontal resolution	Institution
ACCESS-CM2	250 km	ACCESS Australia
CNRM-CM6-1-HR	50 km	CNRM, France
HadGEM3-GC31-LL	250 km	Met Office, UK
GFDL-ESM4	100 km	MIROC JAPAN
MIROC6	140 km	NOAA-GFDL USA

3 Standardized Precipitation-Evapotranspiration Index (SPEI)

The Standardized Precipitation-Evapotranspiration Index (SPEI) is considered a suitable alternative to the Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI) [4]. It integrates temperature data for the calculation of potential evapotranspiration. The SPEI index characterizes drought events in the context of increased evapotranspiration [5]. Therefore, it combines the sensitivity of PDSI to changes in evapotranspiration demand caused by air temperature fluctuations and the multi-temporal nature of SPI [6,7]. The SPEI calculate the degree of difference between precipitation and evapotranspiration that deviates from the average drought state. The calculation steps are as follows: firstly, the calculation of the potential evapotranspiration (PET) based on the temperature data at 2m using the Thornthwaite method, one of the most used methods in the calculation of the potential evapotranspiration (PET) (Thornthwaite C.W., 1948), Then we calculate the difference between the monthly cumulative precipitation and the monthly potential evapotranspiration. Besides the SPI which could be calculated with a two-parameter distribution (e.g., a gamma distribution), a three-parameter distribution is necessary to calculate the SPEI. the log-logistic distribution is better compared to the other three selected three-parameter distributions (Pearson III, log-normal and extreme value theory) [4]. Therefore, the log-logistic probability function was used to fit the SPEI.

The drought level was defined as five types [8] given in Table 2.

Table 2. Drought levels underlying SPEI values.

SPEI Values	Drought category
$0 \leq$ SPEI	No drought
$-1 \leq$ SPEI < 0	Light drought
$-1.5 \leq$ SPEI < -1	Moderate drought
$-2 \leq$ SPEI < -1.5	Severe drought
SPEI < -2	Extreme drought

4 Results and discussion

In this part, the main objective is to assess future changes in drought over the whole of Morocco using five CMIP6 models, for the SSP2-4.5 scenario as an intermediate path between pessimistic and optimistic scenarios, until 2099. An individual analysis of each model is not feasible, but rather to cover part of the uncertainties linked to the models. This makes it possible to take into account both the variability between the models and the different possible projections for each time horizon.

The analysis of drought was carried out in the study area by applying the two indicators: drought severity corresponds to the given value of the drought index, and the drought area which is defined as the ratio between the number of drought pixels (where SPEI < 0) and the total number of pixels (total area of Morocco). In addition, the intensity, duration and number of drought episodes were also calculated in the next part on projected drought characteristics. The SPEI classes are given in Table 2 seen before (light, moderate, severe and extreme). The SPEI drought index was used to forecast the 12-month drought assessment (September- August) for the years between 2023 and 2099 for the SSP2-4.5 scenario.

4.1 Projected trends of drought severity and area

Concerning the analysis of climate models, we are more interested in long-term trends. An analysis of the severity trends and the drought zone for 2023-2099 were calculated, as well as their level of significance presented in table 3.

Table 3. Severity and drought area Trends for 2023-2099 and their level of significance (p-value).

Indicator	Trend by Decade	Significance (p value)
Drought severity (SPEI values)	-0.3	4.45.10-35
Percentage of area of light drought	5.94	3.77.10-14
Percentage of area of moderate drought	4.038	1,28.10-21
Percentage of area of severe drought	2.5	2,48.10-13
Percentage of area of extreme drought	0.7	7,11.10-6

The trends calculated on the annual series of drought severity and the percentage of the drought area according to their four categories (Light, Moderate, Severe and extreme) shows an increasing trend, statistically significant for all these parameters. The significant trend in drought severity is equal to -0.3/10 years, which was calculated over the entire Moroccan territory, while the drought severity expressed by the SPEI values of agricultural years will increase. worsen by 0.3 each decade.

The series of annual percentages of drought area also show, in all cases, statistically significant increasing trends. The maximum value equal to +6%/decade of the Light drought zone and +4%/decade of the Moderate drought zone. Also, the trends calculated on the annual series of the spatial extent of Severe and extreme drought which experienced an increasing trend of +2.5%/decade and +0.7%/decade respectively.

4.2 Projected Changes in Drought Characteristics

Drought was studied using drought characteristics including Number of drought events, duration and intensity. The duration of a drought event is the period during which the value of the drought index is lower than the standard value selected for the analysis (for our case 0). While drought intensity is the fraction of drought severity to drought duration (Dingman, 2002). These characteristics were calculated over seven 11-year periods spanning the study period 2023-2099 (Table 4).

Table 4. Drought characteristics over seven 11-year periods spanning 2023-2099.

Period (11 years/132 months)	Average intensity	Average duration (months)	Maximum duration (months)	Number of events
2023-2033	-1,01	1	2	1
2034-2044	-1,29	2	3	2
2045-2055	-1,4	3	5	4
2056-2066	-1,58	3	7	6
2067-2077	-1,63	3	9	9
2078-2088	-1,79	4	12	10
2089-2099	-1,79	5	15	10

Analysis of drought characteristics based on the previous 12-month SPEI monthly series showed that all periods are expected to have drought events occurring under Moderate to Severe drought conditions. For example, moderate drought is expected to occur between 2023 and 2033, 2034 and 2044, 2045 and 2055, while severe drought events observed
between 2056 and 2066, 2067 and 2077, 2078 and 2088, and 2089 and 2099. Conditions Moderate drought events are expected to occur between 2045 and 2055, 2056 and 2066, 2067 and 2077 with the number of drought events increasing from four to nine drought events with an average duration of 3 months, as well as for the period 2078-2088 which will experience six drought episodes lasting 4 months on average with an intensity of -1.79. Likewise, the duration of drought events will be extended by one month for the period 2023-2033 and two months for 2034-2044, up to five successive months for 2089-2099 with a drought intensity of −1.79 representing a severe drought and a number of drought events of ten.

5 Conclusion

Projecting future droughts plays an important role in water resources planning and management. The future scenario SSP2-4.5 of the five climate models of CMIP6 was evaluated for future droughts based on the SPEI standardized precipitation and evapotranspiration index for Morocco. The results of the study indicate that the ongoing drought in Morocco is expected to worsen during the second half of the century, an increase in drought zones throughout the projected period 2023-2099, with a predominance of severe and extreme drought mainly in the last half of the century.

Analysis of long-term trends shows a significant increase in drought severity, with an increase of 0.3 per decade across the entire Moroccan territory. Annual drought area percentages also show increasing trends, including an increase of 6% per decade for mild drought and 4% for moderate drought. Severe and extreme droughts are increasing by 2.5% and 0.7% per decade, respectively. Analysis of drought characteristics based on monthly series of the 12-month Standard Precipitation Evapotranspiration Index (SPEI) reveals that moderate and severe drought events are expected throughout the study period, with varying durations ranging from 3 to 5 months. Drought severity reaches a level of -1.79, indicating severe drought, and the number of drought events increases over time.

In summary, the study suggests a worrying increase in drought in Morocco during the second half of the century, with significant impacts on agriculture and the environment. These results can help water resource management policymakers and government agencies focus on adapting to and mitigating the negative impacts of drought. Appropriate strategies and joint efforts with decision-makers at all levels are needed. They can respond to droughts by taking appropriate measures to efficiently utilize water resources in urban and agricultural sectors, thereby mitigating droughts.

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