Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre, 2024, n° 46, 83–96

e-ISSN : 2458-7184

Projection of Future Drought Characteristics in Morocco under CMIP6 Scenario SSP2-4.5

Projection des caractéristiques futures de la sécheresse au Maroc sous le scénario CMIP6 SSP2-4.5

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Abstract. Understanding how climate change will affect drought in Morocco throughout the 21st century is essential for effective mitigation strategies implemented by policymakers. This study uses CMIP6 models under the SSP2-4.5 scenario to project future drought trends. The Standardized Precipitation Evapotranspiration Index (SPEI) is derived from precipitation and temperature data across five CMIP6 models spanning from 2023 to 2099, using a 12-month timescale that aligns with the agricultural cycle from September to August in Morocco. Before delving into the analysis of future climate projections of our study area, it is crucial to conduct an assessment of the selected models to evaluate their accuracy in estimating the observed climate conditions. The analysis focused on assessing average SPEI changes and the spatial distribution of drought severity (Light, Moderate, Severe, and Extreme) across Morocco. The results indicate a marked worsening of drought conditions throughout the 21st century, with a particular intensification in the latter half of the century. The study shows a substantial increase in the extent of drought-affected areas, with projections suggesting that over 80% of Morocco's surface area could be affected by drought by century's end. Key drought indicators, such as frequency, severity, and duration, are all expected to increase significantly. Specifically, the Standardized Precipitation-Evapotranspiration Index (SPEI) is projected to decline from -1.01 in the early 2020s to -1.79 by the end of the century, signaling a steady rise in drought severity. Moreover, the number of drought events is expected to escalate dramatically, from 1 to 10 events per 11-year interval. These findings highlight the urgent need for proactive water management strategies to mitigate drought impacts, emphasizing efficient use of water resources.

Keywords: Drought, Climate change, Morocco, CMIP6, Scenario SSP2-4.5.

Résumé. Comprendre comment le changement climatique affectera la sécheresse au Maroc tout au long du XXIe siècle est essentiel pour mettre en œuvre des stratégies efficaces de mitigation par les décideurs politiques. Cette étude utilise les modèles CMIP6 sous le scénario SSP2-4.5 pour projeter les tendances futures de la sécheresse. L'Indice Standardisé de Précipitation-Evapotranspiration (SPEI) est dérivé des données de précipitations et de température à partir de cinq modèles CMIP6 couvrant la période de 2023 à 2099, en utilisant une échelle de temps de 12 mois qui correspond à l'année agricole de sep-tembre à août au Maroc. Avant d'approfondir l'analyse des projections climatiques futures de notre zone d'étude, il est crucial de procéder à une évaluation des modèles sélectionnés pour évaluer leur précision dans l'estimation des conditions climatiques observées. L'analyse s'est concentrée sur l'évaluation des changements moyens de SPEI et la distribution spatiale de la sévérité de la sécheresse (Légère, Modérée, Sévère et Extrême) à travers le Maroc. Les résultats indiquent une aggravation des conditions de sécheresse tout au long du 21e siècle, avec une intensification particulière dans la seconde moitié du siècle. En plus d'une augmentation substantielle de l'étendue des zones touchées par la sécheresse, les projections suggèrent que plus de 80% de la superficie du Maroc pourrait être touchée par la sécheresse d'ici la fin du siècle. Les principaux indicateurs de sécheresse, tels que la fréquence, la gravité et la durée, devraient tous augmenter de manière significative. Plus précisément, l'indice normalisé de précipitation-évapotranspiration (SPEI) devrait passer de -1,01 au début des années 2020 à -1,79 d'ici la fin du siècle, indiquant une augmentation de la gravité de la sécheresse. De plus, le nombre d'épisodes de sécheresse devrait augmenter, passant de 1 à 10 événements par intervalle de 11 ans. Ces résultats mettent en évidence la nécessité urgente de stratégies proactives de gestion de l'eau pour atténuer les impacts de la sécheresse, en mettant l'accent sur l'utilisation efficace des ressources en eau.

Mots clés : Sécheresse, Changement climatique, Maroc, CMIP6, Scénario SSP2-4.5.

ملخص. فهم تأثير التغير المناخي على الجفاف في المغرب على مدار القرن الحادي والعشرين أمر بالغ الأهمية للتكيف الفعال وصياغة السياسات المناسبة. تستخدم هذه الدراسة نماذج CMIP6 تحت السيناريو المعتدل SSP2-4.5 لتوقع اتجاهات الجفاف المستقبلية. تم استخدام مؤشر الجفاف SPEI، المستمد من بيانات الأمطار ودرجات الحرارة على مدار فترة 12 شهرًا (من شتنبر إلى أغشت) فترة السنة الفلاحية في المغرب، عبر خمس نماذج CMIP6 تمتد من عام 2023 إلى 2099. قبل التفصيل في تحليل توقعات المناخ المستقبلية المحددة لمنطقتنا، من الضروري القيام بتقييم للنماذج المختارة لقياس دقتها في قياس الظروف المناخية الملاحظة، خاصة فيما يتعلق بدرجات الحرارة والأمطار. ركز التحليل على تقييم التغيرات المتوسطة في SPEI وتوزيع الجفاف (خفيف، معتدل، شديد، وقصوي) عبر المغرب. وتشير النتائج إلى تفاقم ملحوظ في ظروف الجفاف طوال القرن الـ21، مع تفاقم خاص في النصف الأخير من القرن. كما توجد زيادة كبيرة في حجم المناطق المتأثرة بالجفاف، حيث تشير النتائج إلى أن أكثر من 80% من مساحة المغرب يمكن أن تتأثر بالجفاف بحلول نهاية القرن. ومن المتوقع أن تزداد الخصائص الرئيسية للجفاف بشكل كبير، مثل التواتر والشدة والمدة. وعلى وجه التحديد، من المتوقع أن ينخفض المؤشر الموحد لهطول الأمطار والتبخر (SPEI) من -1.01 في أوائل عام 2020 إلى -1.79 بحلول نهاية القرن، مما يشير إلى ارتفاع مهم في شدة الجفاف. وعلاوة على ذلك، من المتوقع أن يتصاعد عدد أحداث الجفاف بشكل كبير، من 1 إلى 10 أحداث كل فترة من 11 عامًا. تبرز هذه النتائج الحاجة الملحة لاستراتيجيات إدارة مياه نشطة للتخفيف من تأثيرات الجفاف، مع التركيز على استخدام فعال لموارد المياه وممارسات إدارة مستدامة للمياه.

الكلمات الرئيسية: جفاف، تغير المناخ، المغرب، CMIP6، السيناريو SSP2-4.5.

INTRODUCTION

Drought is a natural phenomenon with significant economic and ecological impacts. It poses a critical risk to agriculture, water resources, ecosystems, and human well-being, ranking among the costliest natural disasters (Dai 2011). Damages induced by drought, such as food shortages, famine, population displacement, and mortality, have affected approximately 1.1 billion people worldwide and incurred over $100 billion in costs over the past two decades (UNESCO & UN-Water 2020). Meteorologically, drought is characterized by a notable absence of precipitation. It can be defined as an exceptionally dry period marked by prolonged deficits in rainfall over an extended period, ranging from several weeks to years, leading to severe hydrological imbalances. Despite being primarily associated with reduced rainfall, drought also has a significant human dimension. This can result from reduced water supply, increased water demand, or a combination of both. Decreased water supply may be due to natural factors or human-induced changes, whereas increased water demand is exclusively driven by human activities. Therefore, the severity of water scarcity depends on both available resources and the effectiveness of water management strategies (WMO 2022). Unlike rapid-onset disasters such as earthquakes or tsunamis, drought acts insidiously, gradually intensifying its destructive effects over time. In cases of severe drought, this phenomenon can persist for years, exerting devastating impacts on agriculture, ecosystems, and water availability (OSS 2009).

Climate change is leading to increased droughts in many regions of the world. Episodes of drought are likely to become more frequent, with human-induced climate change making drought in the Northern Hemisphere "at least 20 times more likely," and continued warming would make these episodes more intense and frequent (Masson-Delmotte *et al*. 2021). Since 1950, historical data on precipitation, and drought indices derived from observations have indicated a trend of increased aridity across several regions, including Africa, southern Europe, east Asia, eastern Australia, northwest Canada, and southern Brazil (Dai & Zhao 2017, Zhao & Dai 2022). However, it is important to note that some of these regional drying patterns may be influenced by internal multidecadal climate variability (Dai 2021). Given Africa's vulnerability to climate fluctuations shaped by its latitudinal range, geographical diversity, and proximity to the ocean (Schilling 2012). Some regions are already experiencing increased drought risks. Notably, the Mediterranean region shows a clear drying trend (Cook *et al.* 2016) and Morocco has been facing drought conditions since 2019 to 2024. Monitoring the evolution of this hazard in terms of frequency and intensity is crucial, especially in the context of climate change. In this context, assessing climate trends at the national scale provides valuable information for high-level decision-making and contributes to raising awareness and understanding the effects of climate variability and change. Furthermore, this assessment is relevant for developing adaptation and resilience strategies to climate change.

General circulation models (GCMs) have emerged as indispensable tools in the study of climate change. They are capable of simulating and projecting future climate scenarios under diverse conditions. The World Climate Research Program (WCRP) has developed the Coupled Model Intercomparison Project (CMIP), which provides simulated data from various climate models. This initiative is pivotal as it facilitates the creation of multi-model ensembles, enhancing the reliability of predictive data (Li 2011). CMIP6, the latest iteration of this project utilized for the IPCC Sixth Assessment Report, represents a significant advancement. It includes a range of climate models with improved resolution, a wider array of scenarios, and more comprehensive diagnostic capabilities compared to previous experiences of CMIP (Tebaldi & Knutti 2007). Substantial efforts have been invested in the development of CMIP6 to ensure robust and detailed climate projections for global assessments. However, before proceeding to study the future changes projected by the different models for the climate at the level of the target area of the study, it is important to carry out a review of the models used in order to have a general idea of their ability to reproduce the climate observed in our area of interest, mainly in terms of temperature and precipitation. Recent studies have used CMIP6 multi-model ensembles to assess changes in drought conditions and warming at both global (Li 2020) and regional scales, including regions such as South Asia, the Mediterranean (Babaousmail *et al.* 2022, Cos 2022). and the Middle East and North Africa (MENA). While many of these studies focus on the improvements in temperature and precipitation simulations with CMIP6 compared to CMIP5, there are also studies that still primarily rely on CMIP5, particularly in Africa (Ongoma 2018, Dike 2014).

The aim of this study is to evaluate the anticipated average changes in drought severity and extent using SPEI data derived from precipitation and temperature data obtained from five CMIP6 GCM models. and its patterns until the conclusion of the present century. It also involves forecasting future drought characteristics This analysis identifies the duration, and intensity of future drought events to inform future water requirements and resource management strategies in Morocco.

MATERIALS AND METHODS

Study area

The study focuses on Morocco, encompassing its diverse climatic regions and geographical features. Situated in the northwest of the African continent, Morocco's climate varies significantly from Mediterranean in the north to arid and semi-arid in the south, influenced by proximity to the Atlantic Ocean and several mountain ranges. Annual rainfall averages decrease from north to south and from west to east. Agricultural zones are predominantly situated in the northern part of the country, while deserts dominate the south and southeast of the country.

(Fig. 1) illustrates the map of Morocco's Köppen-Geiger climate classification, highlighting the country's diverse regional climate variations, which include six climate types. In the northern coastal areas, a transition occurs between a temperate climate (Csa: Mediterranean climate with hot, dry summers and mild, wet winters) and a cooler, wetter climate (Csb: Mediterranean climate with warm, dry summers and cool, wet winters) in the mountainous regions, particularly the Atlas Mountains. These areas receive substantial annual rainfall, often exceeding 700 mm. This analysis encompasses Morocco's entire territory, considering regional climate nuances and topographical features. In contrast, in the middle and northeastern regions (Oriental) of the country, the climate shifts to become hotter and drier, transitioning from a semi-arid or steppe climate (BSh) with low precipitation and hot summers to a cold semi-arid or steppe climate (BSk). This climate type experiences low precipitation and cooler temperatures than the hot semi-arid climates (BSh), often featuring distinct seasonal temperature variations. As you move to the southern and southeastern regions, the landscape shifts dramatically, revealing areas that experience an arid

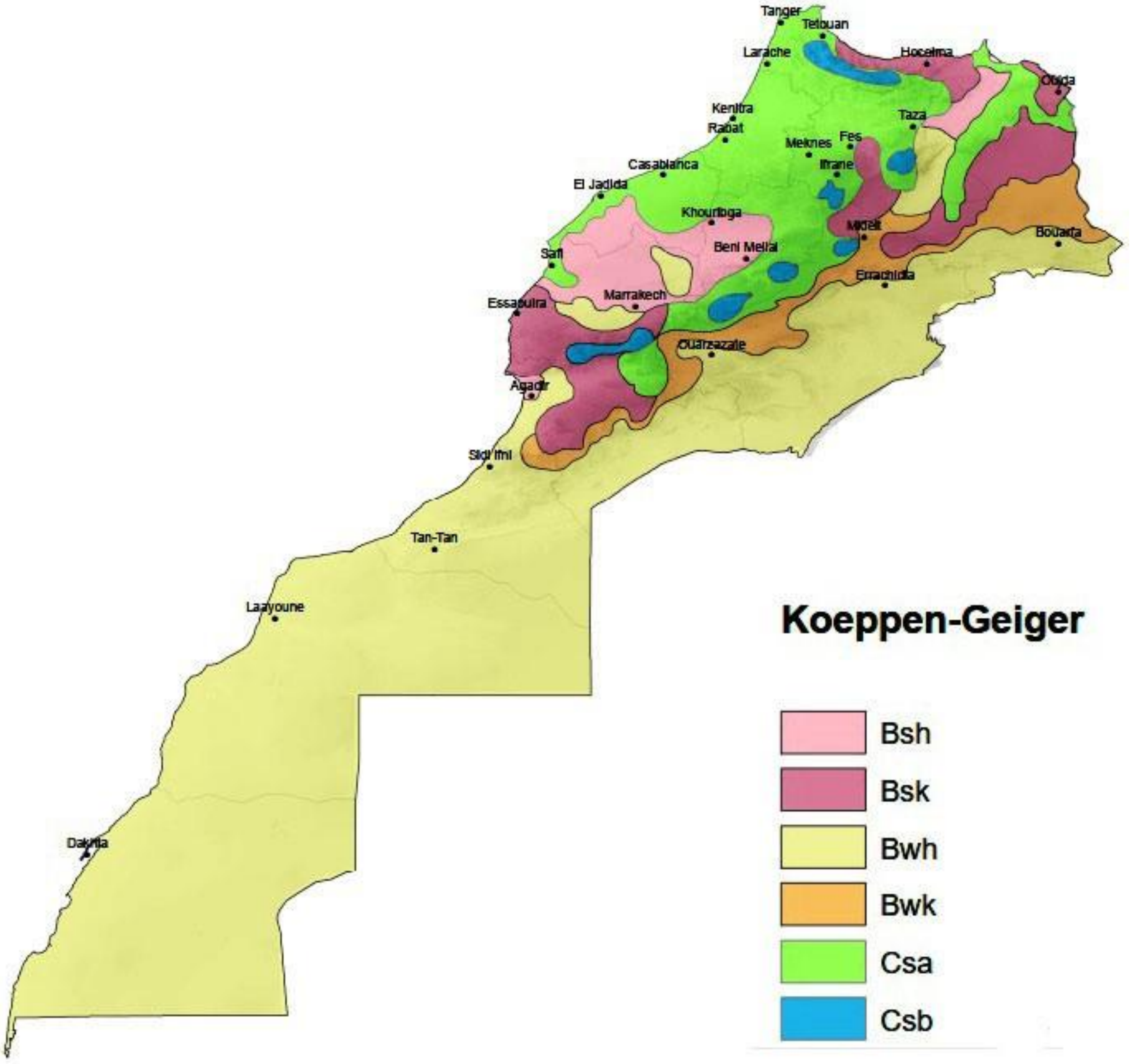

Figure 1. TheKöppen -Geiger climate classification map based on interpolated DGM ground observation data collected over the period from 1981 to 2010 (DGM, 2021).

desert climate (BWh: Hot desert climate, characterized by very low precipitation and high temperatures) marked by scorching temperatures and minimal annual rainfall. Additionally, the cold desert climate (BWk) experiences low precipitation and significant temperature variations between summer and winter, especially in the southeastern regions.

Data sources

Observed Data from the General Directorate of Meteorology (DGM)

The General Directorate of Meteorology operates a network of meteorological observation stations covering various climatic and geographical regions of Morocco. These meteorological stations (or Provincial Meteorological Centers, CPM) adhere to the current standards of the World Meteorological Organization (WMO) ensuring the reliability and accuracy of the data collected. For our analysis, we will focus on climate data from 20 specific stations, each of which maintains a data deficiency rate of less than 1% in most instances (Moutia *et al.* 2021). The selected stations include Agadir, Beni-Mellal, Casablanca, Errachidia, Essaouira, Fes, Hoceima, Ifrane, Laayoune, Larache, Marrakech, Meknes, Midelt, Ouarzazate, Oujda, Rabat, Safi, Tangier, Taza, and Tetouan. These stations are illustrated in Fig 1, providing a visual representation of their geographic distribution across the country. This network plays a crucial role in monitoring weather patterns and supporting climate research in Morocco.

Simulations of CMIP6 Global Climate Models

Global Climate Models (GCMs) are the primary tool for accurately predicting potential changes in the climate system due to human activities. A climate model is a numerical representation of the Earth's climate system incorporating on the physical, chemical, and biological properties of its components and their interactions processes. Using these models, scientists can simulate climate behavior under various conditions and make forecasts regarding future changes. Coupled atmosphere-ocean general circulation models (CGMs) provide a comprehensive representation of the climate system, which is among the most detailed currently available. These models typically operate at spatial resolutions of a few hundred kilometers (Chen *et al.* 2021). The CGMs used in CMIP6 (Coupled Model Intercomparison Project Phase 6), as described in the IPCC Sixth Assessment Report (2021-2022), generally feature increased complexity (more components) and higher spatial resolution. This allows for a more detailed representation of atmospheric, oceanic, and small-scale processes like clouds, water vapor, and aerosols. The enhanced spatial resolution contributes, among other benefits, to improved representation of temperatures and precipitation in mountainous regions compared to CMIP5 simulations.

Climate change scenarios provide future projections of anthropogenic concentrations or emissions of radiative active substances such as CO2 and CH4, which alter the composition of the atmosphere and drive climate changes. These scenarios are employed in future climate projections using coupled atmosphere-ocean general circulation models. A significant difference between CMIP5 and CMIP6 lies in the emission scenarios used to project future global climate change levels. CMIP5 used Representative Concentration Pathways (RCPs), whereas CMIP6 employs an enhanced set of emission scenarios based on Shared Socio-Economic Pathways (SSPs). SSPs complement RCPs by standardizing exploration of the socio-economic conditions underlying various emission levels. The latest Climate Change Assessment Report (AR6) uses a new set of scenarios based on Shared Socio-Economic Pathways (SSPs). The full range of SSPs recognizes that global levels of radiative forcing can be achieved through different pathways of CO2, non-CO2 greenhouse gases, aerosols, and land use. AR6 identifies four key scenarios as priorities:

- SSP1-2.6 for sustainable pathways;
- SSP2-4.5 for a middle-of-the-road trajectory;
- SSP3-7.0 for regional rivalries;
- SSP5-8.5 for intensive fossil fuel development.

The study examines daily maximum and minimum temperatures, along with daily precipitation, The data is sourced from five global climate models under the SSP2-4.5 median scenario: ACCESS-CM2, CNRM-CM6-1-HR, HadGEM3-GC31-LL, GFDL-ESM4, and MIROC6 (Tab. 1). This dataset is first used to evaluate CMIP6 performance against observed data for the baseline period of 1981–2010. Additionally, the data is employed to assess future climate projections for the period 2023–2099.

Standardized Precipitation-Evapotranspiration Index (SPEI)

The Standardized Precipitation Evapotranspiration Index (SPEI) is a drought index that incorporates both precipitation and temperature data to assess drought conditions. It measures the difference between precipitation and potential evapotranspiration (PET), which is influenced by temperature. SPEI is standardized to have a mean of 0 and a standard deviation of 1, making it comparable across different locations and time periods. It provides insights into the severity and duration of droughts, considering changes in both precipitation and temperature patterns over time (Vicente-Serrano *et al.* 2010). Unlike SPI, SPEI incorporates temperature data to calculate potential evapotranspiration, making it sensitive to changes in evapotranspiration demand due to temperature increase (Huopo & Jianqi 2015). SPEI calculation involves several steps: first, potential evapotranspiration (PET) is calculated using 2-meter temperature data, typically applying the Thornthwaite method, a widely accepted approach (Thornthwaite 1948). Subsequently, the difference between monthly cumulative precipitation and PET is determined. Among the distributions considered (Pearson III, log-normal, extreme value theory), the log-logistic distribution is favored for fitting SPEI (Vicente-Serrano *et al.* 2010).

The SPEI categorizes drought severity into five levels, as defined in (Tab.2) (Yang *et al.* 2016):

Table 1.A list of the CMIP6 models used in this study. Only one run (r1ip1f1) was used for each model.

Model	Institution	Resolution	References
ACCESS-CM2	Australian Community Climate and Earth-System Simulator	1.88 x 1.25	(Dix 2019)
CNRM-CM6-1-HR	National Centre for Meteorological Research (CNRM), France	1.41 x 1.39	(Voldoire 2019)
HadGEM3-GC31-LL	Met Office Hadley Center,UK	1.85 x 1.24	(Ridley 2018)
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory, USA	1.25 x 1.00	(Krasting 2018)
MIROC6	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, Japan	1.41 x 1.39	(Shiogama H. 2019)

Table 2. Drought levels underlying SPEI values.

SPEIValues	Droughtcategory
0 ≤SPEI	Nodrought
-1≤SPEI<0	Lightdrought
-1.5≤SPEI< -1	Moderatedrought
-2≤SPEI<-1.5	Severedrought
SPEI<-2	Extremedrought

Drought characteristics

A drought event can be defined as a period during which the SPEI index consistently reaches a value of -1.0 or less for at least one month and ends with the SPEI value rising above -1.0 (Tan *et al.* 2015). Once a drought episode has been identified, drought-related indicators, including duration and intensity, are calculated. The duration of a drought episode is the number of months from its beginning (inclusive) to its end (exclusive) (Li 2012). The intensity (severity) is the absolute value of the sum of all SPEI values during a drought event divided by its duration. A higher intensity value indicates a more severe drought (Chunping *et al.* 2015).

RESULTS

Evaluation of Five CMIP6 Global ModelsA brief evaluation of the models is conducted by comparing the averages derived from each model parameter (precipitation and mean temperature) with those calculated using observed data. When evaluating or comparing gridded data with station observations, it is common practice to compare the observational series with the nearest grid point series of the parameter in question (Ensor *et al.* 2008). The evaluation period chosen spans 30 years from 1981 to 2010, using data from the twenty study stations previously introduced. However, relying on a single method is neither necessary nor sufficient to establish confidence in the ability of climate models to accurately replicate reality (Jacob *et al.* 2007). Therefore, to assess global climate models in terms of monthly average precipitation and temperature, capturing seasonal cycles, we found it pertinent to examine their ability to reproduce the distribution of these parameters on an interannual scale as well.

Evaluation of Precipitation

1. Seasonal Cycle

The evaluation of model performance in precipitation involves a comprehensive assessment of the seasonal cycle, which is crucial for understanding how well the models replicate observed precipitation patterns throughout the year. Analyzing how precipitation varies across different months and seasons, such as winter, spring, summer, and autumn. This helps to identify whether the models accurately capture the timing and intensity of seasonal patterns of precipitation events. The figure 3 illustrates the monthly sums of precipitation from the models in comparison to those derived from observations. The graphs focus on a select few stations from the twenty available, highlighting the performance of each model. The results indicate a generally good representation of the seasonal cycle across all models, particularly in coastal cities such as Agadir, Rabat, and Tangier.

However, it is important to note that the HadGEM3-GC31-LL model, highlighted in yellow, tends to overestimate precipitation during both the rainy season and the summer months, particularly in inland regions such as Marrakech and Oujda. This overestimation can be attributed to the model's coarse resolution, which is significantly larger compared to the other models. As a result, the nearest grid point from this model to the observation stations is relatively far, leading to less accurate representation of localized precipitation patterns.

2. Interannual Variability

In the domain of climate and climate change, analyzing interannual variations of observed and simulated climatic variables is crucial to assess the model's performance in replicating real climate behavior (Almazraoui *et al.* 2020). The coefficient of variation, also known as the relative standard deviation, is a measure of relative dispersion defined as the ratio of the standard deviation to the mean. It provides insight into the relative spread of data; a higher coefficient of variation indicates greater dispersion of data around the mean. In this section, we aim to calculate coefficients of variation for annual cumulative precipitation simulated by the models and those observed during the 1981-2010 period across twenty meteorological stations (Tab. 3). This analysis allows to evaluate the models' ability to simulate year-to-year precipitation variability.

The coefficient of variation (CV) for annual cumulative precipitation across the studied stations ranges between 25% and 50%, indicating moderate variability in precipitation. However, two stations, Agadir and Laayoune, exhibit CV values exceeding 50%, suggesting a higher degree of variability in these locations. Specifically, Agadir, located on the southwestern coast, shows a CV of 57%, reflecting significant inter-annual variability in precipitation patterns, likely influenced by oceanic and atmospheric conditions. Laayoune, situated further south, records an even higher CV of 60%, supporting the hypothesis of increasing precipitation variability as one moves southward in Morocco. This variability may be driven by local climatic factors, such as the interaction between the Atlantic Ocean and Saharan air masses. In contrast, the lowest CV values are found at stations in the northeast, with Oujda recording a CV of 25% and Meknes a CV of 30%, suggesting more stable precipitation patterns in these areas compared to the southern regions.

When comparing the observed variability in annual cumulative precipitation to the outputs from the five climate models used in this study, the coefficient of variation (CV) values for the models ranges between 18% and 60%, demonstrating a larger variation than what was observed during the study period. The models tend to underestimate the coefficient of variation, particularly in regions with high variability, such as Agadir and Laayoune. This underestimation is evident in 82% of the cases, suggesting that the models fail to fully capture the inter-annual variability observed in the actual data. For example, the CNRM-CM6-1-HR model estimates a CV of 35% for Agadir, while the actual observed CV is 57%, indicating a clear underestimation of the precipitation variability. Similarly, the GFDL-ESM4 model predicts a CV of 38% for Agadir, while the true value is 57%. Likewise, the HadGEM3-GC31-LL model predicts a CV of 39% for Laayoune, whereas the observed value is 60%, highlighting the model's tendency to smooth out or underestimate regional precipitation variability. This consistent bias in the models may be attributed to their coarse spatial resolution, which is insufficient to capture the fine-scale variability typical of

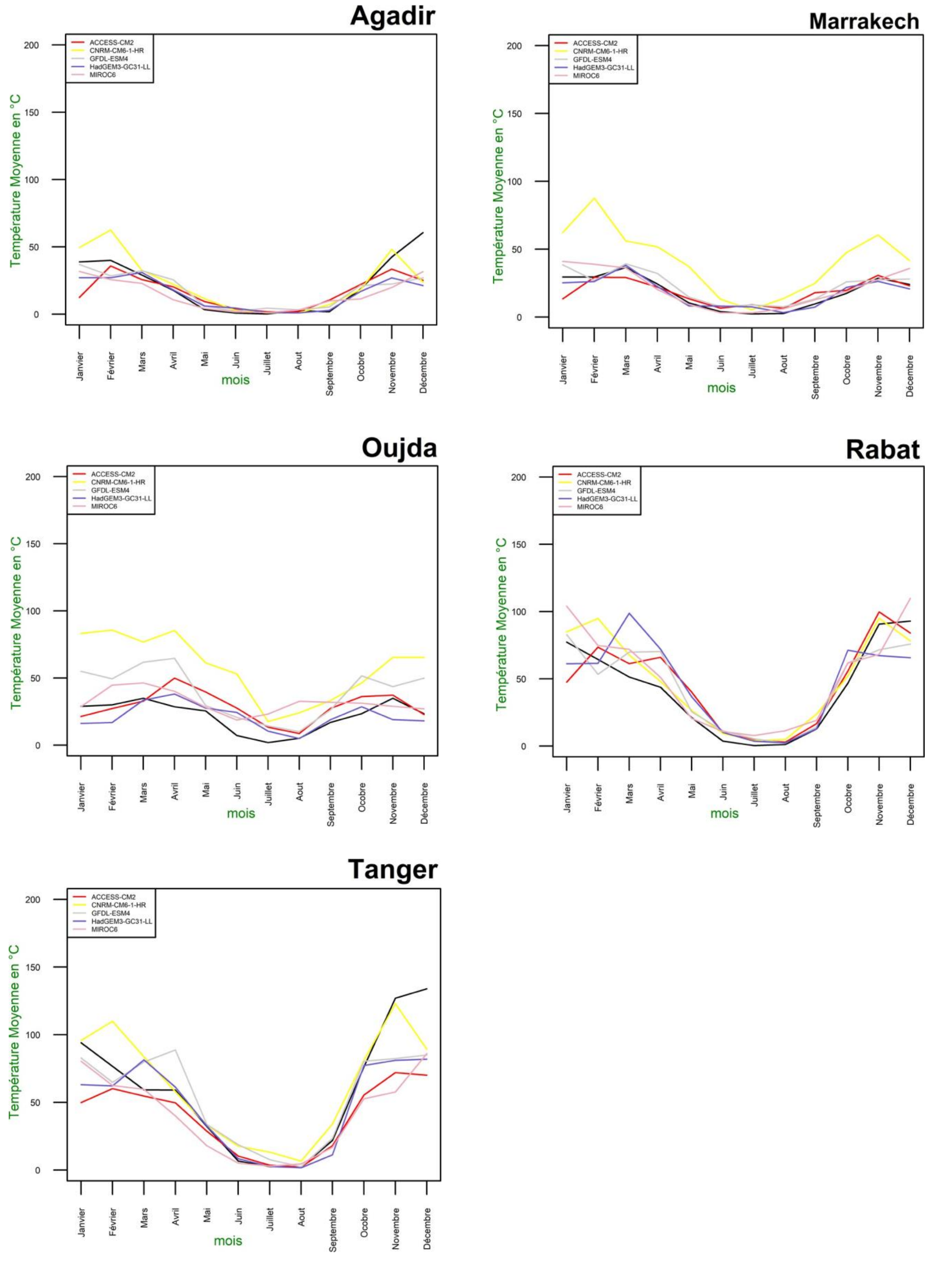

Figure2. Monthly cumulative precipitation (in mm) from different models compared with observations (black line) collected at meteorological stations in Rabat, Tangier, Marrakech, Oujda, and Agadir, for the period 1981-2010.

Table 3. Coefficients of variation (in %) of interannual precipitation from models and observations of the twenty stations for the period 1981-2010.

Station	Observations	ACCESS-CM2	CNRM-CM6-1-HR	GFDL-ESM4	HadGEM3-GC31-LL	MIROC6
Agadir	57	47	35	38	60	41
Beni-Mellal	34	41	23	28	38	24
Casablanca	42	32	18	30	42	24
Errachidia	43	44	58	45	41	25
Essaouira	49	39	31	33	49	37
Fes	35	29	18	25	33	24
Hoceima	39	27	20	30	43	21
Ifrane	36	33	18	26	29	20
Laayoune	60	48	47	58	39	38
Larache	41	28	16	29	40	27
Marrakech	39	36	30	31	50	29
Meknes	30	29	18	26	33	24
Midelt	33	33	27	31	29	19
Ouarzazate	47	51	54	44	52	25
Oujda	25	31	23	28	28	19
Rabat	39	28	17	29	36	26
Safi	45	36	23	33	50	32
Tanger	36	28	18	29	40	27
Taza	37	29	20	27	33	18
Tetouan	40	27	18	29	43	27

regions with strong local climatic influences, such as coastal areas and desert zones. These findings underscore the need for improved regional climate models with better spatial resolution in order to better represent the spatial heterogeneity and variability of precipitation patterns.

Evaluation of Mean Temperature

1. Seasonal cycle

Similar to precipitation, the evaluation of model performance in replicating temperatures across Morocco involves comparing monthly average temperatures from models with those calculated from observations. The figure 3 presents graphs for a selection of previously mentioned stations (Agadir, Marrakech, Oujda, Rabat, and Tangier) out of the twenty available. The graphs highlight that all models demonstrate a strong capacity to accurately replicate the seasonal temperature cycle, with summer months consistently being the warmest and winter months the coolest. However, it is important to note that the MIROC6 model shows a slight tendency to overestimate temperatures across all seasons, which may be attributed to its coarse resolution of 250 km. This larger grid size can lead to inaccuracies in capturing localized temperature variations. Additional data for the other stations can be found in Appendix B, providing a more comprehensive assessment of model performance in capturing temperature fluctuations across different regions of Morocco.

2. Interannual variability

In this section, our objective is to calculate the coefficients of variation for annual mean air temperatures simulated by the models and observed during the 1981-2010 period across twenty meteorological stations. This evaluation aims to assess the models' ability to simulate interannual variability for air temperatures (Tab. 4). The coefficients of variation calculated for annual mean temperatures from each model and observed data are displayed in (Tab. 3). Unlike precipitation, interannual variability is well represented by all models in the case of temperature. The bias does not exceed 2% in all cases.

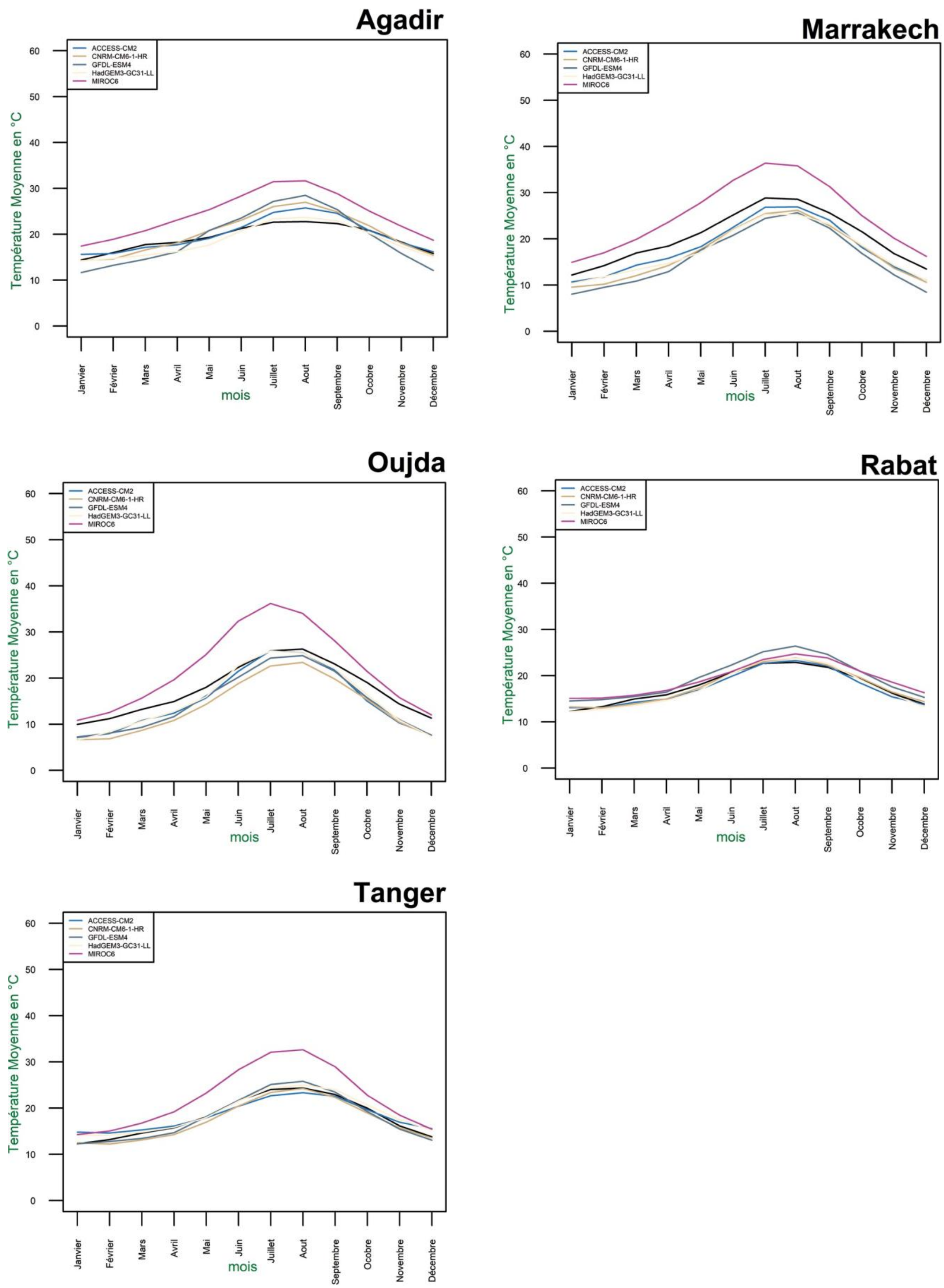

Figure 3.Monthly average temperatures (in °C) from the different models and the one calculated using observations from the Rabat, Tangier, Marrakech, Oujda, and Agadir meteorological stations (black line) for the period 1981-2010.

Table 4. Coefficients of variation (%) of interannual mean temperatures from models and observations for the period 1981-2010 across twenty meteorological stations.

Station	Observations	ACCESS-CM2	CNRM-CM6-1-HR	GFDL-ESM4	HadGEM3-GC31-LL	MIROC6
Agadir	4	3	3	8	3	3
Beni-Mellal	3	4	5	10	6	4
Casablanca	3	4	3	6	4	4
Errachidia	3	4	4	13	6	4
Essaouira	4	3	2	8	3	3
Fes	4	4	5	13	6	3
Hoceima	3	2	3	6	4	3
Ifrane	5	4	5	11	6	4
Laayoune	3	3	3	4	2	2
Larache	4	2	3	7	3	3
Marrakech	3	4	4	11	4	3
Meknes	3	4	5	11	6	3
Midelt	4	4	7	15	6	4
Ouarzazate	3	3	5	13	5	4
Oujda	4	4	5	11	6	4
Rabat	3	3	2	5	4	3
Safi	3	4	3	5	4	3
Tanger	3	2	2	7	3	3
Taza	4	4	5	10	6	4
Tetouan	2	2	2	7	4	3

The annual mean temperature is a more stable meteorological parameter compared to precipitation, with interannual variability typically ranging between 2% and 3% across most of the studied stations. However, Ifrane station stands out with a higher coefficient of variation (CV) of 5%, suggesting slightly greater fluctuations in temperature from year to year in this region. This higher variability at Ifrane could be attributed to its elevated location and the presence of mountainous climate, which often experiences more pronounced thermal fluctuations due to local topographic effects.

When comparing the performance of the five climate models used in this study, we observe that the models ACCESS-CM2 and MIROC6 closely replicate the observed interannual variability in temperature across all twenty studied stations, with CV values ranging between 2% and 5%. Both models show a relatively accurate representation of the thermal variability, with only slight deviations from the observed data. This suggests that these models can simulate the thermal dynamics in the region well, likely due to their more refined representation of regional climate processes.

Following these models, the CNRM-CM6-1-HR and HadGEM3-GC31-LL models exhibit a slightly higher degree of overestimation of variability. These models show variability estimates ranging from 2% to 6% across the stations, with some stations, such as Midelt, showing slight overestimations of around 6%. On the other hand, the GFDL-ESM4 model significantly overestimates the interannual temperature variability, with values reaching as high as 11% at Midelt station. This substantial overestimation suggests that the GFDL-ESM4 model may be too sensitive to certain climate factors, possibly over-representing the natural variability in temperature. The model's larger variability could be its lower spatial resolution that might not capture the localized effects that help stabilize temperature in certain regions.

Projection of Drought in Morocco using CMIP6 Climate Model

Individual model analysis is not feasible nor the main objective, but rather to cover some uncertainties associated with models. As previously mentioned, the focus is on analyzing future drought changes across Morocco using results from five global climate models originating from different centers and countries: ACCESS from Australia, CNRM from France, Met Office from the UK, MIROC from Japan, and NOAA-GFDL from the USA. These models are evaluated under the SSP2-4.5 scenario, chosen as a middle ground between pessimistic and optimistic scenarios, projecting future drought changes across Morocco up to the year 2099.

Drought severity and extent area Projection

1. Drought severity projection

The Figure 4 illustrates the projected severity of droughts based on Standardized Precipitation-Evapotranspiration

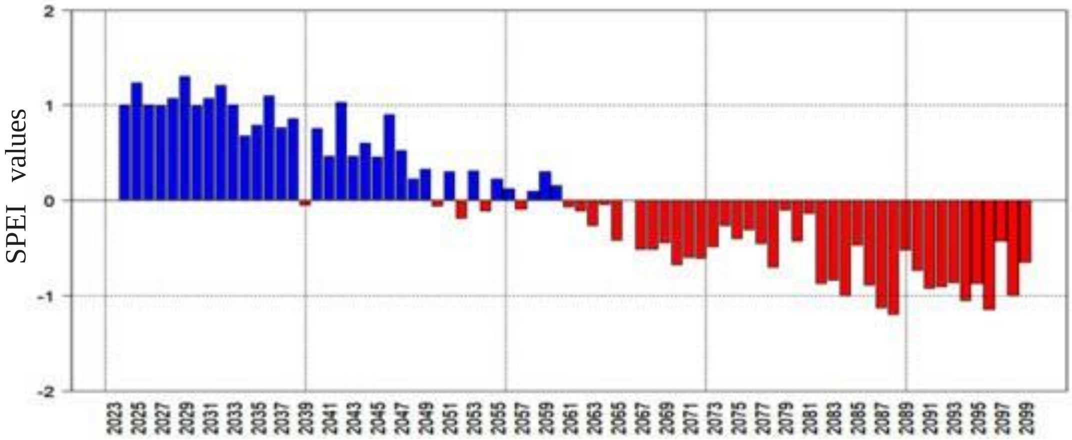

Figure 4. Annual variation of SPEI values (drought severity) averaged across Morocco for the agricultural year (September-August) between 2023 and 2099 under the SSP2-4.5 scenario (DGM, 2021).

Index (SPEI) values at the 21st century. The SPEI, which combines precipitation and temperature data to assess drought conditions, The SPEI values, which remain almost entirely negative throughout the second half of the 21st century, indicate a significant worsening of drought conditions. Starting from near-normal levels in the early 2020s, the graph highlights a gradual decline in SPEI, reflecting an intensification of drought severity. By the end of the century, the SPEI values drop substantially, signaling increasingly extreme drought conditions well beyond historical averages. Additionally, the risks of severe and extreme droughts are projected to dominate primarily during the latter phase from 2070 to 2099. Generally, the drought occurrence area is expected to exceed 50% of Morocco's surface area starting from the year 2063, surpassing 80% of the study area for 14 agricultural years and reaching 90% for six years.

2. Drought area projection

The results of the drought area over 12 months based on four drought types (light, moderate, severe, and extreme) were analyzed as presented in (Fig. 5). These categories were defined according to the standard drought intensity scales.

Throughout the projected agricultural years in Morocco, the analysis shows that mild to moderate droughts will be the most frequent drought types. Specifically, the percentage of land area affected by these types of droughts is expected to rise progressively across the projection period. The mild droughts are expected to affect a larger portion of the country initially, but their prevalence will gradually decrease as moderate droughts become more widespread. By the end of the century, a significant portion of Morocco is expected to experience moderate drought conditions during the agricultural years, with this category showing an increase in spatial extent over time. Additionally, while severe and extreme droughts remain less frequent in the projections, their occurrence rates are anticipated to gradually increase as well. These more severe drought events are projected to become more frequent concentrated over areas of Morocco. The SSP2-4.5 scenario, which represents a medium emissions pathway, suggests that climate change will likely exacerbate drought conditions in Morocco's regions due to higher temperatures and reduced precipitation during growing seasons.

The results under the SSP2-4.5 scenario indicate a clear trend of increasing drought extent over the period from 2023 to 2099. By the latter part of the century, projections indicate a noticeable shift toward more severe and extreme droughts, which will likely have significant implications for agricultural practices and water resources management across Morocco.

Drought trends projection

In the context of climate model analysis, emphasis is placed on long-term trends. An evaluation of drought severity and

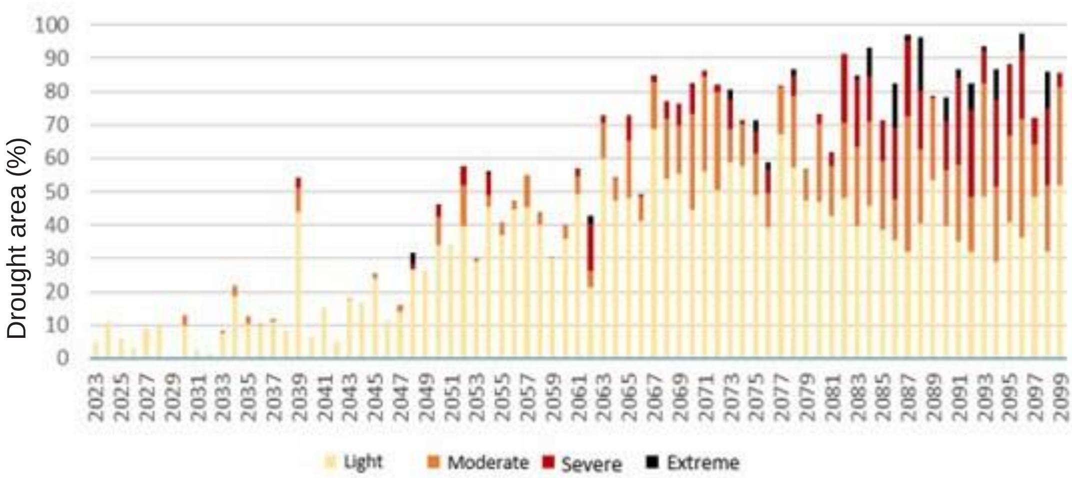

Figure 5. Interannual variability of drought area for four severity levels: Light, Moderate, Severe, and Extreme.

Table 5. Trends in drought severity and area for 2023-2099, along with their significance level in terms of p-value.

Indicator	Trend/decade (10 years)	Significance (p value)
Droughtseverity(SPEI values)	Decrease of- 0.3	$4.45.10^{-35}$
Percentage of areas of light drought	Increase of 5.94	$3.77.10^{-14}$
Percentage of Moderate Drought Area	Increase of 4.038	$1,28.10^{-21}$
Percentage of Severe Drought Area	Increase of 2.5	$2,48.10^{-13}$
Percentage of Extreme Drought Area	Increase of 0.7	$7,11.10^{-6}$

extent trends from 2023 to 2099 was undertaken, alongside their respective significance levels, detailed in (Tab. 5), and the extent of different drought categories, supported by low p-values indicating high statistical significance.

The table 5 presents Key indicators of drought trends across Morocco, based on projected changes per decade under the SSP2-4.5 scenario. These trends reflect significant trends in drought severity and affected areas over time, as quantified by the Standardized Precipitation Evapotranspiration Index (SPEI) values: The analysis reveals a notable decreasing trend in SPEI values of -0.3 per decade, indicating a consistent worsening of drought conditions across Morocco. This trend suggests that the country is likely to experience increasingly drought conditions in the future, with more frequent and intense droughts. The negative SPEI trend aligns with the broader expectation of declining precipitation and rising temperatures under the SSP2-4.5 scenario, both of which contribute to exacerbating drought conditions. Concurrent with the worsening drought severity, the analysis indicates an increase in the percentage of areas affected by various levels of drought. Specifically: Light drought areas are projected to increase by 6% per decade, moderate drought areas are expected to rise by 4% per decade, severe drought areas are projected to increase by 2.5% per decade and extreme drought areas will see a more modest increase of 0.7% per decade.

These trends suggest that while light and moderate droughts will become more widespread across Morocco, more extreme drought events, although increasing, will remain less frequent in comparison. However, the observed trends in the increase of drought severity and the expansion of drought-affected areas across all severity levels are statistically significant, as indicated by the low p-values (less than 0.05). As droughts become more frequent and intense, it will be crucial to implement adaptation strategies to mitigate the impacts on vulnerable regions and ensure sustainable water management practices.

Projection of drought characteristics

Drought analysis focused on key characteristics such as the frequency of drought events, their duration, and intensity. Duration refers to the period when the drought index remains below the predefined standard value for analysis (in this study, 0). Meanwhile, intensity measures the severity of drought relative to its duration (Moutia & Sinan 2024).

The table 6 summarizes the evolution of drought characteristics over seven consecutive 11-year periods spanning from 2023 to 2099. The intensity of drought events, measured by the drought index, shows a gradual increase from -1.01 in the first period (2023-2033) to -1.79 in the last period (2089-2099), indicating worsening drought severity over time. The duration of drought events, defined as the consecutive months where the drought index remains below the threshold (0 in this analysis), also demonstrates a consistent trend of escalation. Starting at 1 month in the earliest period, the duration increases progressively to 5 months by the end of the century. Maximum duration refers to the longest continuous period of drought within each 11-year span, and it similarly shows a notable increase from 2 months in the initial period to 15 months in the final period. This highlights the growing persistence of severe drought conditions over time. Additionally, the number of drought events per period steadily rises from 1 event in the first period to 10 events in the last period. This indicates an increasing frequency of drought occurrences throughout the study period. Overall, (Tab. 5) underscores the intensifying nature of drought in Morocco, characterized by longer durations, more frequent events, and greater severity as projected through the 21st century under the SSP2-4.5 scenario. These findings emphasize the imperative for robust strategies in water resource management and adaptation to mitigate the escalating impacts of drought in the region.

Table 6. Characteristics of drought over seven periods of 11 years spanning 2023-2099.

Period (132 months)	Intensity	Duration	Maximum duration	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

DISCUSSION

This study highlights the significant effect posed by drought in Morocco, driven by climate change, a concern that has profound implications for agriculture, water resources, ecosystems, and human well-being. The findings from the CMIP6 models under the SSP2-4.5 scenario are consistent with previous research, indicating that drought conditions are likely to worsen throughout the 21st century, both globally (Zhao & Dai 2022, Cook *et al.* 2020) and specifically in Morocco (Zellou *et al.* 2023, Babaousmail *et al.* 2022). The evidence indicates a clear trajectory toward increased drought severity and frequency, emphasizing the urgency of proactive measures to enhance resilience and adaptive capacity across vulnerable sectors.

The evaluation of model performance over the period from 1981 to 2010 reveals that the climate models demonstrate a higher degree of accuracy in simulating temperature variations compared to precipitation patterns. Specifically, when analyzing seasonal cycles, the models consistently show strong alignment with observed temperature data, accurately capturing the typical fluctuations throughout the year. In contrast, the representation of precipitation is less reliable, exhibiting more variability and deviations from actual observations. Furthermore, the evaluation of the five CMIP6 models indicates that model performance also depends on spatial resolution. Models with a lower resolution do not show better results compared to those with a relatively better resolution. The higher-resolution models are better at capturing localized climate patterns due to their closer proximity to observation stations, resulting in more accurate simulations. Our results are in line with findings from previous research (Zhu & Yang 2020), which indicates that higher-resolution models can better simulate regional climate. This highlights the need for models with improved resolution to enhance the reliability of precipitation forecasts, which are crucial for effective water resource management and agricultural planning in the context of climate change. Enhanced resolution could provide more precise data, enabling better adaptation strategies to address the challenges posed by drought. Moreover, when considering interannual variability «the changes in climate conditions from one year to the next» the models the models also perform better with temperature projections. This indicates that the models are more adept at predicting long-term temperature trends and anomalies than they are with precipitation events and patterns. These discrepancies highlight the need for further refinement in precipitation modelling to enhance its reliability.

First, the analysis reveals a clear trajectory of worsening drought conditions over the 21st century. Drought severity, as measured by the SPEI shows a steady increase in drought severity, as reflected in the Standardized Precipitation-Evapotranspiration Index (SPEI), with values projected to decline from -1.01 in the early 2020s to -1.79 by the end of the century. This worsening trend is compounded by an anticipated rise in the number of drought events, escalating from 1 to 10 events over successive 11-year intervals. These trends indicate a heightened frequency and intensity of droughts, posing severe challenges to water availability and agricultural productivity across Morocco. Furthermore, the study highlights the anticipated increase in the frequency of drought events, suggesting that Morocco may experience a significant rise in the number of drought occurrences per year. This trend could exacerbate existing vulnerabilities in regions already prone to water scarcity, particularly in the southern and southeastern parts of the country. Additionally, the geographical distribution of projected drought conditions reveals that a substantial portion of Morocco, potentially over 80% of its surface area may be affected by drought by the end of the century.

While our study contributes valuable insights into the evaluation of CMIP6 models in Morocco, one of the main weaknesses of our study is the lack of a detailed sensitivity analysis regarding the choice of models and scenarios. While we have selected a subset of models under the SSP2-4.5 scenario, future work could explore the impact of different Shared Socioeconomic Pathways (SSPs) or the inclusion of additional models from other international modeling centers to test the robustness of our findings. Furthermore, the study could benefit from a deeper analysis of the temporal evolution of model biases, particularly in the context of extreme climate events like droughts, which could provide additional insights into model performance. While this approach presents some limitations, particularly regarding the spatial resolution mismatch, it offers a unique contribution by highlighting the raw performance of these models and identifying the challenges of applying them at local scales. Future research should explore downscaling techniques, apply bias correction where appropriate, and investigate additional climate variables to provide a more comprehensive evaluation of model performance.

In terms of novelty, our work provides a fresh perspective by focusing on drought characteristics projections over the current century of CMIP6 models. The analysis of climate change in terms of drought allows for a more comprehensive understanding of the climate signal in Morocco. As mentioned earlier, while climate change and drought are global concerns, their impacts are not uniform across the world; each continent, country, and region will experience different effects, with varying rates of warming and drought severity, despite scientific advances. Climate global models, however, have inherent limitations such as an imperfect ability to translate our understanding of the climate system into precise mathematical equations which presents challenges for decision-makers who must anticipate changes in their regions, this study uses coarser resolution models with smaller data sizes, which is a choice specific to this research and not a recommendation, as ideally, higher-resolution models should be used for more reliable outputs. What makes this research unique is its focus on the projection of drought characteristics such as duration, intensity, and frequency using SPEI drought index, which adds value by providing more detailed insights for policymakers, unlike other studies that focus primarily on temperature and precipitation patterns.

As a summary, this study is one of the first evaluations of CMIP6 climate models specifically applied to Morocco for projecting drought characteristics. It offers valuable information on drought trends and can serve as a reference for the Food-Water Nexus, supporting more informed decision-making in climate change adaptation and drought management, it also points to areas for future refinement, particularly in terms of model resolution and bias correction. Further research should focus on downscaling techniques, the inclusion of additional models, and sensitivity analyses of different SSP scenarios to improve the reliability and precision of climate projections for Morocco and similar regions.

CONCLUSION

In conclusion, this study underscores the escalating threat of drought in Morocco driven by climate change under the SSP2-4.5 median scenario. The findings highlight the urgency of adopting proactive measures to increase resilience and adaptive capacity across sectors most vulnerable to drought impacts. Specifically, policy interventions are essential to enhance water resource management, boost agricultural resilience, and support ecosystems that are increasingly under stress. This outcome is critical for agricultural planning and resource management, particularly in vulnerable regions, and reinforces global assessments linking climate change to increased drought frequency and intensity. While the SSP2-4.5 scenario offers a moderate mitigation pathway, the anticipated increases in drought severity underscore the urgent need for adaptation strategies. It's important to note that the actual impacts may be even more severe, as the median scenario used in this study may not fully capture the potential realities of more pessimistic pathways, such as RCP8.5. Future research should focus on refining local-scale modeling and integrating socio-economic factors to improve the accuracy of drought impact assessments, with long-term monitoring and data collection being essential for validating model projections and informing effective adaptive strategies.

To mitigate the adverse effects of droughts and safeguard the well-being of Morocco's population, government agencies must prioritize climate adaptation policies at both national and regional levels. Immediate policy recommendations include the development of a national drought adaptation strategy, the integration of climate risk assessments into land-use planning and agricultural policies, and the implementation of water conservation and management policies that account for future water scarcity projections. Furthermore, collaboration between policymakers, scientific institutions, and local communities is critical to ensure that policies are both scientifically sound and locally relevant. For example, community-based early warning systems and local climate adaptation plans should be prioritized, particularly in vulnerable regions such as southern and southeastern Morocco.

In line with these findings, increasing the resilience of Moroccan society to climate change-induced droughts is an urgent priority. Morocco has already begun national planning and adaptation strategies, which are critical components in several national frameworks, such as the National Climate Plan (PNC) and the National Adaptation Strategy (PNA). These plans aim to protect food security, especially in the face of prolonged droughts, like the recent drought between 2019-2024. Ministries such as the Ministry of Agriculture and the Ministry of Equipment and Water have already launched key strategies, including increasing the area under drip irrigation, desalination projects, the construction of new dams, water transfers, the reuse of wastewater, groundwater recharge, and demand management. By promoting these efforts, Morocco can build a sustainable future in the face of evolving climate risks.

ACKNOWLEDGMENTS

We are grateful to "La Direction Générale de la Météorologie (DGM)" for donating the daily data for the period 1981-2010 that were essential for our research.

The authors would like to express their gratitude to the editor of the "Bulletin de l'Institut Scientifique Section Sciences de la Terre" ACHAB mohammed, to Dr Rachid HADRIA and another anonymous reviewer for their significant contribution to the improvement of the manuscript.

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Manuscrit reçu le 11/07/2024
Version révisée acceptée le 14/11/2024
Version finale reçue le 18/12/2024
Mise en ligne le 31/12/2024