J. P. Soaphys, Vol 5, N°1 (2025) C25A07
http://dx.doi.org/10.46411/jpsoaphys.2025.C25.07

Journal de physique de la SOAPHYS
http://www.soaphys.org/journal/
ISSN Print : 2630-0958

Assessment of High-Resolution Regional Climate Models for West Africa Within the Framework of CORDEX.

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INFOS SUR L'A R T I C L E

Historique de l'article:
Reçu le : xx juillet 201x
Reçu en format revisé le : xx juillet 201x
Accepté le : xx juillet 201x

Mots-Clés : CORDEX-Afrique, Afrique de l'Ouest, Modèles climatiques régionaux, Précipitations, Température de l'air, Évaporation.

Keywords : CORDEX-Africa, West Africa, Regional Climate Models, Precipitation, Air temperature, Evaporation.

ABSTRACT

This study evaluated nine regional climate models (RCMs) within the Coordinated Regional Climate Downscaling Experiment-Africa (CORDEX-Africa) to assess their performance in simulating climate patterns over West Africa (WA) from 1970 to 2005. Key climate variables, including precipitation, air temperature, and evaporation, were analyzed using statistical parameters such as correlation coefficient, mean bias (Mbias) compared to ERA5, and root mean square error (RMSE) compared to ERA5 data. The resolution of CORDEX RCMs is standardized to 0.25° × 0.25° grids. Results indicate R^2 values of 91% for the Sahel, 95% for the savannah, and 88% for the Guinea Coast for precipitation. Negative Mbias values reveal an underestimation of monthly precipitation by the RCMs compared to ERA5. RMSE values range from 84 to 151.53 for the coastal zone, 38.54 to 78.03 for the savannah, and 27.34 to 42.15 for the Sahel. Evaporation R^2 values are 93% for the Sahel, 93% for the savannah, and 86% for the Guinea Coast, with negative Mbias values except for CCLM5 simulations. RMSE varies from 23.09 to 61.41 for the coastal zone, 9.54 to 58.94 for the savannah, and 14.81 to 35.45 for the Sahel. Air temperature R^2 values are 86% for the Sahel, 93% for the savannah, and 93% for the Guinea Coast, with positive Mbias indicating that RCMs overestimate monthly air temperature. RMSE values range from 81.04 to 84.96 across West Africa. Overall, CORDEX RCMs show an underestimation of precipitation, varied estimates of evaporation, and an overestimation of temperature, while maintaining strong correlation coefficients for all variables.

RESUME

L'étude a évalué neuf modèles climatiques régionaux (RCM) de CORDEX-Afrique pour simuler les conditions climatiques en Afrique de l'Ouest de 1970 à 2005. Les variables clés telles que les précipitations, la température de l'air et l'évaporation ont été analysées à l'aide de paramètres statistiques comme le coefficient de corrélation, le biais moyen (Mbias) et l'erreur quadratique moyenne (RMSE) en comparaison avec les données ERA5. Les RCMs CORDEX, avec une résolution normalisée à des grilles de 0,25° × 0,25°, montrent des valeurs R2 élevées pour les précipitations (91% au Sahel, 95% dans la savane, 88% en zone côtière). Les Mbias négatifs indiquent une sous-estimation des précipitations mensuelles. Pour l'évaporation, les R2 sont élevés avec des Mbias négatifs, sauf pour les simulations CCLM5. Concernant la température de l'air, les RCMs présentent une surestimation, avec des Mbias positifs dans toute l'Afrique de l'Ouest. En résumé, les RCMs de CORDEX montrent une sous-estimation des précipitations, des estimations variées de l'évaporation et une surestimation de la température, tout en maintenant des coefficients de corrélation élevés pour toutes les variables.

I. INTRODUCTION

West Africa is one of the most populous regions in Africa, and its climate significantly affects the well-being of its people. Weather and climate conditions in West Africa have major impacts on agricultural potential, water resources, and human health, and they also influence other sectors of the economy, such as energy production, transportation, and tourism (Douglas et al., 2018). Most of West Africa's key economic sectors, including agriculture, power generation, and industry, are highly dependent on climate, with seasonal precipitation being a critical component (Janicot et al., 1996; Sultan et al., 2003). Given the variability of the climate and its sometimes dramatic consequences, the evolution of water resources is a significant concern for many regions worldwide. This is especially true for the African countries in the Sudano-Sahelian zone, which have experienced persistent drought for approximately thirty years (Servat et al., 1998; Ardoin

et al., 2003). Seasonal forecasting appears to be a way to address climate variability; however, numerical weather forecast information is underutilized across various economic sectors in decision-making (Morss et al., 2008; Hamadan, 2002). Numerical Weather Prediction (NWP) on the African continent remains a significant scientific challenge. The obstacles to achieving realistic forecasts are numerous, as they require accounting for the diverse weather conditions and climatic regimes across the continent. These range from mid-latitude systems at the northern and southern extremes to the climates of equatorial forests and desert areas, all of which are subject to extreme weather conditions over a wide range of temporal and spatial scales (Douglas et al., 2018). For NWP, the initialization and modeling of mesoscale convective systems (MCS) continue to be major scientific challenges.
Africa's weather systems play a crucial role in influencing the weather and climate of other regions through complex interactions on intra-seasonal timescales and even in 3-day forecasts (Douglas et al., 2018). Therefore, developing climate change (CC) projections for this region is of critical importance. Such projections help measure vulnerability and anticipate adverse consequences, enabling the implementation of effective adaptation strategies. Global Climate Models (GCMs) have often been used to simulate climate change in this region (Semyon et al., 2001). GCMs are key tools for assessing global climate projections and simulating climate responses to changes in greenhouse gas concentrations, as recognized in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Almagro et al., 2020). However, GCMs have resolutions of 100-200 km (Ngai et al., 2020), which limits their ability to capture mesoscale processes and their direct application in regional hydrological impact assessments (Giorgi, 1990; Fowler et al., 2007; Maraun et al., 2017).

Regional Climate Models (RCMs), with resolutions of approximately 12-50 km (Dong et al., 2018), offer higher resolution and better representation of regional climate characteristics (Giorgi and Gutowski, 2015). RCMs have proven advantageous for predicting regional climate information and simulating hydrological processes (Leung et al., 2004; Niu et al., 2020). Understanding the spatial distribution and intensity of extreme climate events is crucial for mitigating their negative impacts on economies and livelihoods (Nicholson, 2017). Climate change is expected to increase the frequency and intensity of such events globally (Seneviratne et al., 2012). While short-term weather forecasts have improved sub-seasonal planning, long-term projections remain essential for managing climate variability and its dramatic consequences. This is particularly relevant for African countries in the Sudano-Sahelian zone, which have experienced persistent drought for approximately thirty years (Servat et al., 1998; Ardoin et al., 2003).

II. METHODOLOGY AND DATA

II.1. Output of CORDEX-Africa Regional Climate Models

The World Climate Research Programme (WCRP) sponsors the Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi et al., 2009; Jones et al., 2011; Nikulin et al., 2018; CORDEX Website) to harmonize international efforts in downscaling General Circulation Models (GCMs) to the regional level. Initially, CORDEX produced simulations at a horizontal resolution of 0.44°×0.44°, which was later improved to 0.22°×0.22° in 2019. The organization of CORDEX is similar to the Coupled Model Intercomparison Project phase 5 (CMIP5) global model simulations.
Due to the challenges of inadequate ground observation data, climate change vulnerability, and low adaptive capacity in Africa, CORDEX prioritizes the continent, making it a key focus among other regions. The performance of CORDEX Regional Climate Models (RCMs) over West Africa has been evaluated in numerous studies (Klutse et al., 2016; Diallo et al., 2012; Sylla et al., 2013) and similar evaluations have been conducted in other parts of Africa (Ayugi et al., 2020; Maure et al., 2018). Many of these studies utilize output from the first phase of CORDEX RCMs, which used ERA-Interim reanalysis data (Dee et al., 2011; Akinsanola et al., 2017), or from the second phase, which involved dynamically downscaling CMIP5 GCMs to a resolution of 0.44°×0.44° (Taylor et al., 2012).

II.2. ERA5 DATA

ERA5 is the most recent reanalysis product from the European Centre for Medium-Range Weather Forecasts (ECMWF). It is produced by combining a numerical weather prediction model with observational data from satellites and ground observations. ERA-Interim, introduced in 2007 (Dee et al., 2011; Simmons et al., 2007), provided daily climate information until August 2019. Since then, it has been replaced by ERA5 (Hersbach et al., 2019), which offers hourly meteorological conditions back to 1979 and is expected to extend coverage back to 1950. Both versions of the ECMWF reanalysis are based on the Integrated Forecasting System (IFS) and use a four-dimensional variational analysis (4D-Var).

There are several substantial differences between the two datasets concerning the forecast model, observational input, and uncertainty estimation. ERA5 data is available at higher spatial and temporal resolutions compared to ERA-Interim. Specifically, ERA5 data is provided on a 0.25° grid with hourly intervals, while ERA-Interim data is on a 0.75° grid with 6-hour intervals. Additionally, the vertical resolution increased from 60 levels in ERA-Interim to 137 levels in ERA5 (Hersbach et al., 2019; Hennermann et al., 2020).

ERA5 incorporates a greater number of observational datasets, including satellite estimates of precipitation, which were not considered in ERA-Interim. Moreover, ERA5 provides an estimate of data uncertainty based on a 10-member ensemble run at a 63 km resolution, whereas ERA-Interim did not include uncertainty estimates. While ERA-Interim started in 1979, ERA5 is planned to cover the period from 1950 to near-real time.

II.3. METHODS OF ANALYSIS

To evaluate the performance of the CORDEX RCMs, the simulations compared to observational data from the ERA5 reanalysis using the following statistics:

The bias measures the difference between actual measured and expected physical quantities. If P_i is the forecast on date i and O_i is the observation on date i, the bias between the forecast and the observation on date i is given by the following relation:

$$BIAS_i = P_i - O_i \qquad (1)$$

The average bias over a long period of time (MB) is given by:

$$MBIAS = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \qquad 2)$$

Where N is the expected date number of the period.

The indicator called Root Mean Square Error (RMSE) is the square root of the mean squared error. It measures the average magnitude of the errors made by the forecast by synthesizing them into a single value. He is particularly sensitive to large differences.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2} \qquad (3)$$

O_i is the value of the observation of the day i.
P_i is the value of the forecast of day i.
N is the number of months in the forecast.

The calculated error gives a synthetic measure of the overall error in a single value.

The correlation coefficient R^2 is used to measure the intensity of the linear connection between two variables (Saporta., 2006). It is obtained by the ratio:

$$R^2 = \frac{cov(PR,OB)}{\sigma PR \times \sigma OB} \qquad (4)$$

Where $\sigma PR, \sigma OB$ are the standard deviations of PR and OB respectively, and $cov(PR, OB)$ are their covariances. Its value is between -1 and 1 or expressed as a percentage.

III. RÉSULTS AND DISCUSSION

III.1. Evaluation of monthly estimates of precipitation

Model simulations of monthly precipitation are evaluated with respect to the ERA5 product taken as reference.

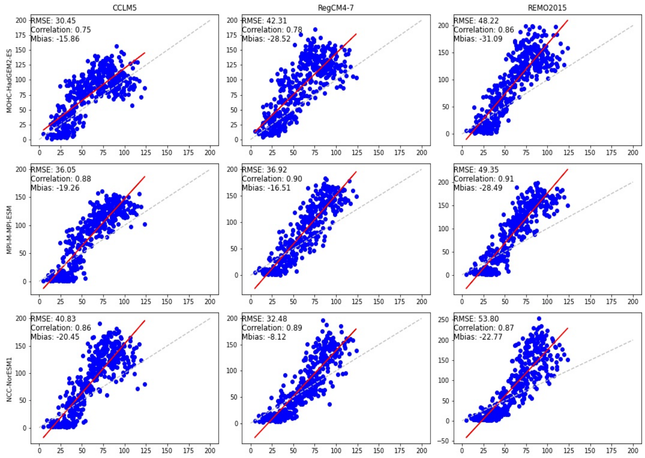

Figure 1: statistical evaluation of the precipitation over West Africa.

Figure 1 shows that the correlation coefficients reach 88% for the CCLM5 simulations, 90% for the RegCM4-7 simulations, and 91% for the REMO2015 simulations. The negative Mbias values in the scatter plots indicate an underestimation of the RCM monthly precipitation estimates compared to the ERA5 data overall. The RMSE values range from 30.45 to 40.83 for the CCLM5 simulations, from 32.48 to 42.31 for the RegCM4-7 simulations, and from 48.22 to 53.80 for the REMO2015 simulations.

Table 1: The correlation coefficient, Mbias, RMSE of the precipitation for the climatic zones of West Africa.

		Guinea zone			Savannah			Sahel		
RCM	GCM	R^2	RMSE	Mbias	R^2	RMSE	Mbias	R^2	RMSE	Mbias
CCLM5	MOHC-HadGEM2-ES	0.71	87.71	-25.8	0.9	45.36	3.07	0.89	30.86	-12.53
	MPI-M-MPI-ESM	0.88	72.79	-17.64	0.92	43.09	-5.31	0.9	37.78	-19.4
	NCC-NorESM1	0.85	99.65	-24.7	0.93	43.41	22.28	0.8	30.25	0.93
RegCM4-7	MOHC-HadGEM2-ES	0.68	151.53	-89.16	0.87	95.57	-49.36	0.78	33.9	-7.04
	MPI-M-MPI-ESM	0.81	84	-15.7	0.92	78.03	-30.48	0.84	42.15	-13.21
	NCC-NorESM1	0.73	123.14	-25.64	0.9	53.97	-0.28	0.72	34.92	9.3
REMO2015	MOHC-HadGEM2-ES	0.82	137.68	-69.28	0.94	60.62	-24.37	0.91	27.34	-9.91
	MPI-M-MPI-ESM	0.88	101.89	-41.3	0.95	56.87	-24.02	0.9	31.13	-11.44
	NCC-NorESM1	0.76	143.75	-37.45	0.94	38.54	12.56	0.83	30.39	11.77

Simple statistical methods are used to evaluate simulations of monthly precipitation, evaporation, and air temperature from CORDEX regional climate models between 1970 and 2005 against observational data from ERA5. These methods include the correlation coefficient (R^2), mean bias (Mbias), and root mean square error (RMSE). To facilitate a comparison with the monthly data results, we adjusted the resolution of the original CORDEX RCMs from 0.22° × 0.22° to a grid of 0.25° × 0.25° to standardize the grids.

We compared the precipitation from CORDEX RCMs to ERA5 data. The results show that R^2 values reach 91% in the Sahel, 95% in the savannah, and 88% for the Guinea

Coast (Table 2). The negative Mbias values in the scatter plots indicate an underestimation of the monthly precipitation estimates from the RCMs compared to the ERA5 data in the three regions (Table 2). The RMSE values range from 84 to 151.53 in the coastal zone, from 38.54 to 78.03 in the savannah, and from 27.34 to 42.15 in the Sahel zone (Table 2). These results are consistent with findings from Ilori and Balogun (2021), Akinsanola and Ogunjobi (2017) over West Africa, and Mathewos et al. (2023) in East Africa.

III.2. Evaluation of monthly evaporation

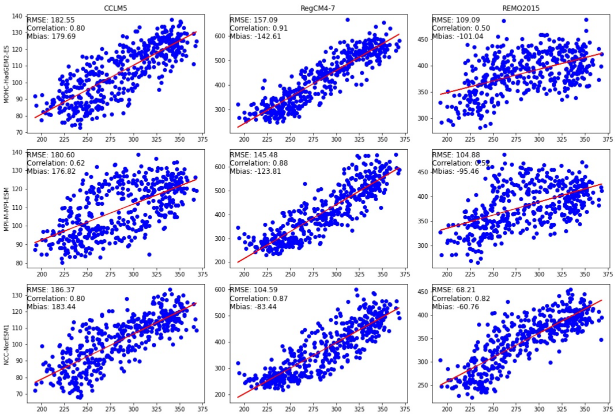

Figure 2: statistical evaluation of the evaporation over West Africa.

Figure 2 shows that the R^2 values reach 80% for the CCLM5 simulations, 91% for the RegCM4-7 simulations, and 82% for the REMO2015 simulations. The negative Mbias indicates an overall underestimation of the evaporation estimates, except for the CCLM5 simulations, which overestimate evaporation compared to the ERA5 data. The RMSE values range from 180.60 to 186.37 for the CCLM5 simulations, 104.59 to 157.09 for the RegCM4-7 simulations, and 68.21 to 104.88 for the REMO2015 simulations.

Table 2: Statistical Evaluation of the evaporation.

		Guinea zone			Savannah			Sahel		
RCM	GCM	R^2	RMSE	Mbias	R^2	RMSE	Mbias	R^2	RMSE	Mbias
CCLM5	MOHC-HadGEM2-ES	-0.1	60.75	59.72	0.82	57.57	54.81	0.93	33.62	29.47
	MPI-M-MPI-ESM	-0.32	61.71	60.41	0.76	56.67	53.71	0.91	32.15	27.65
	NCC-NorESM1	0.81	24.27	-22.38	0.91	58.94	56.59	0.89	35.45	31
RegCM4-7	MOHC-HadGEM2-ES	0.82	34.81	-33.16	0.87	39.99	-34.31	0.88	27.37	-16.05
	MPI-M-MPI-ESM	0.86	23.09	-20.33	0.9	37	-30.43	0.91	29.38	-18.53
	NCC-NorESM1	0.81	24.27	-22.38	0.87	34.89	-23.73	0.8	19.52	0.31
REMO2015	MOHC-HadGEM2-ES	0	27.64	-21.88	0.69	23.31	-16.64	0.81	15.7	-7.25
	MPI-M-MPI-ESM	0.18	24.3	-17.37	0.78	20.89	-15.37	0.82	14.81	-6.92
	NCC-NorESM1	0.58	19.02	-13.51	0.93	9.54	-2.86	0.89	15.6	11.56

Comparison of the monthly evaporation from CORDEX RCMs with ERA5 data shows that R^2 values reach 93% in the Sahel, 93% in the savannah, and 86% for the Guinea Coast (Table 3). Overall, the Mbias values are negative, with the exception of the three CCLM5 simulations. The RMSE values range from 23.09 to 61.41 in the coastal zone, 9.54 to 58.94 in the savannah zone, and 14.81 to 35.45 in the Sahel zone (Table 3). This result is consistent with the findings of El-Mahdy et al. (2021) in Egypt.

III.3. Evaluation of monthly air temperature

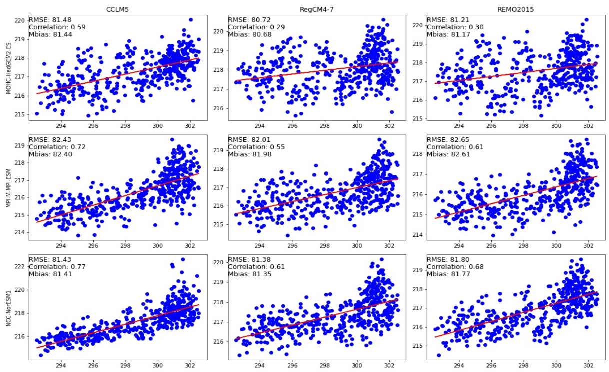

Figure 3: statistical evaluation of the air temperature over West Africa.

Figure 3 shows that the correlation coefficient values reach 82% for the CCLM5 simulations, 61% for the RegCM4-7 simulations, and 68% for the REMO2015 simulations. The positive Mbias values indicate an overall overestimation of the RCM air temperature estimates compared to the ERA5 data. The RMSE values range from 81.43 to 82.43 for the CCLM5 simulations, 80.72 to 82.01 for the RegCM4-7 simulations, and 81.21 to 82.61 for the REMO2015 simulations.

Table 3: Statistical Evaluation of the air temperature.

		Guinea zone			Savannah			Sahel		
RCM	GCM	R^2	RMSE	Mbias	R^2	RMSE	Mbias	R^2	RMSE	Mbias
CCLM5	MOHC-HadGEM2-ES	0.22	81.75	81.74	0.43	82.87	82.52	0.59	84	83.96
	MPI-M-MPI-ESM	-0.07	82.52	82.51	0.01	83.56	83.54	0.51	84.73	84.69
	NCC-NorESM1	0.33	81.29	81.28	0.29	82.46	82.44	0.64	83.76	83.72
RegCM4-7	MOHC-HadGEM2-ES	0.22	80.88	80.87	0.06	82.15	82.13	0.08	83.44	83.38
	MPI-M-MPI-ESM	-0.2	82.2	82.19	-0.14	83.38	83.36	0.29	84.59	84.54
	NCC-NorESM1	0.3	81.04	81.03	0.11	82.5	82.48	0.42	84.03	83.99
REMO2015	MOHC-HadGEM2-ES	0.23	81.36	81.36	0.23	82.63	82.61	0.19	83.92	83.87
	MPI-M-MPI-ESM	-0.07	82.58	82.57	-0.03	83.73	83.71	0.36	85	84.96
	NCC-NorESM1	0.41	81.13	81.13	0.32	82.54	82.52	0.55	84.12	84.08

We compared the air temperature of the CORDEX RCMs with that of ERA5. Compared to the monthly gauging readings, the R^2 values reach 86% in the Sahel and 93% for both the savanna and Guinea Coast zones (Table 4). The overall positive Mbias indicates an overestimation of the monthly air temperature estimates by the RCMs compared to ERA5 data in all three regions (Table 4). The RMSE values range from 81.04 to 84.96 across the climatic zones of West Africa (Table 4). This result is consistent with those of Okafor et al. (2019) over the Volta Basin, Mostafa et al. (2019) over Egypt, and Demissie et al. (2021) over southwest Ethiopia.

IV. CONCLUSION

The main aim of this study was to assess the performance of CORDEX RCMs in simulating precipitation, air temperature, and evaporation over West Africa. The results show that the R^2 values reach 91% in the Sahel, 95% in the savannah, and 88% for the Guinea Coast. The negative Mbias values in the scatter plots indicate an underestimation of monthly precipitation estimates from the RCMs compared to ERA5 data in all three regions. The RMSE values range from 84 to 151.53 in the coastal zone, 38.54 to 78.03 in the savannah, and 27.34 to 42.15 in the Sahel.

For monthly evaporation, the R^2 values are 93% in the Sahel, 93% in the savannah, and 86% for the Guinea Coast. The Mbias values are generally negative, except for three CCLM5 simulations. The RMSE values range from 23.09 to 61.41 in the coastal zone, 9.54 to 58.94 in the savannah, and 14.81 to 35.45 in the Sahel.

For air temperature, the R^2 values reach 86% in the Sahel, 93% in the savannah, and 93% for the Guinea Coast. The positive Mbias values indicate an overestimation of monthly air temperature estimates by the RCMs compared to ERA5 data in all three regions. The RMSE values range from 81.04 to 84.96 across all climatic zones of West Africa.

This study demonstrates that the CORDEX RCMs generally underestimate precipitation, underestimate evaporation (with exceptions in the CCLM5 simulations), and overestimate temperature. However, there is a strong correlation for all variables.

Acknowledgement:
This work was supported by the West Africa Science Service Center on Climate Change and Adapted Land Use (WASCAL).
Acknowledgement to the International Science Programme (ISP/IPPS) through its founded research group MAL01 for providing workspace and data for this study.

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