

Assessment of the sensitivity of the RegCM5 model to physical parameterization schemes in precipitation simulation in the Bandama watershed (Côte d'Ivoire)

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Abstract

This study evaluates how different physical parameterization schemes affect precipitation simulation in the Bandama watershed (Côte d'Ivoire) using the RegCM5 regional climate model. Thirteen configurations were developed, combining various convection schemes (MIT-Emanuel, Kain-Fritsch, Grell, Tiedtke), microphysics schemes (SUBEX, Nogherotto–Tompkins, or NoTo), and planetary boundary layer schemes (Holtslag, University of Washington – UW) for the 2001–2009 period, with boundary conditions from the ERA5 reanalysis. Simulated precipitation was compared to CHIRPS observations (2001–2009) using statistical metrics such as relative bias, RMSE, Pearson correlation, distribution scores. The results indicate that the choice of convective scheme has the most significant impact. Simulations using the Tiedtke or Emanuel schemes, especially when paired with the UW PBL, performed best, accurately reproducing the seasonal rainfall structure and minimizing systematic biases (annual relative bias generally less than 30%). In contrast, Grell or Kain-Fritsch schemes produced substantial overestimates (biases often exceeding +100%), making them unsuitable without major adjustments. The choice of boundary layer scheme is also crucial. Configurations using the UW scheme consistently exhibit lower errors and better temporal agreement than those using Holtslag. The advanced NoTo microphysics reduced some overestimations compared to SUBEX, particularly for heavy precipitation.

Keywords: West Africa; Bandama Basin; Regional climate model; Physical parameterization schemes, precipitation

1. Introduction

The Bandama watershed, located in the humid intertropical zone of West Africa, is particularly vulnerable to spatio-temporal variations in precipitation. Indeed, hydrological dynamics and water availability in this region depend heavily on the West African monsoon and associated tropical convective systems (Janicot et al. 2011; Nicholson 2013). Rainfall seasonality is pronounced, with a short dry season from December to February, an initial wet season in spring, a relative lull in July–August, and a major rainy season lasting until November. These rainfall patterns are influenced by the migration of the Intertropical Convergence Zone (ITCZ), Atlantic monsoon winds, East African waves, mesoscale convective systems, and oceanic teleconnections such as ENSO, equatorial Atlantic anomalies, and the Indian Ocean Dipole (IOD) (Fink and Reiner 2003; Lafore et al. 2017). Uncertainties in the simulation of the annual precipitation cycle and its interannual variability thus have major implications for water resource management, agriculture, and energy production in the Bandama basin (Fig. 1).

High-resolution regional climate models (RCMs) that explicitly represent convection are essential tools for modeling these precipitation patterns at the watershed scale (Giorgi et al. 2023; Torma and Giorgi 2025).

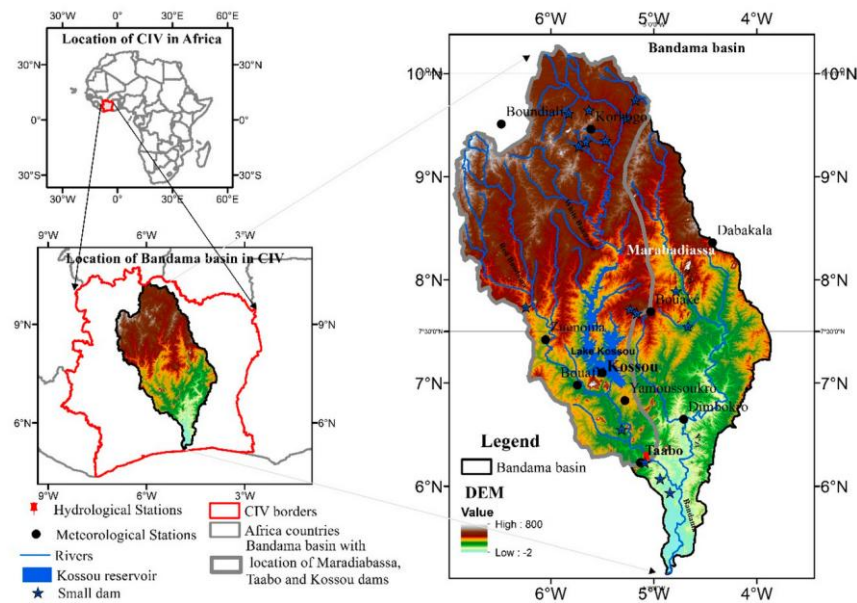


Fig. 1: Overview of the Bandama watershed (Kouame et al. 2019)

However, their performance in West Africa depends greatly on the choice of physical parameterization schemes, particularly for cumulus convection, microphysics, and the planetary boundary layer (Diallo et al. 2012; Sylla et al. 2010). Conceptual differences between these schemes often lead to contrasting model responses, especially since the West African

climate is dominated by organized convection (Koné et al. 2018; Marsham et al. 2013; Silué et al. 2024). For example, Koné et al. (2018) showed that depending on the convective scheme used, RegCM4 could exhibit either a significant dry bias or better precipitation agreement, recommending Emanuel’s scheme for this region. It is therefore crucial to determine the optimal configurations in order to reduce the uncertainties associated with the simulations.

For precipitation studies, these authors showed that the most sensitive schemes are convection, the boundary layer, and cloud microphysics. Version 5 of the RegCM model (RegCM5) (Giorgi et al. 2023) provides an appropriate framework for this study, as it incorporates several established convective schemes (MIT-Emanuel, Kain–Fritsch, Grell, and Tiedtke). It also offers resolved microphysics schemes: SUBEX (Subgrid EXplicit moisture) (Pal et al. 2000) and Nogherotto–Tompkins (NoTo) (Nogherotto et al. 2016), as well as advanced boundary layer schemes, notably Holtslag (Holtslag et al. 1990) and University of Washington (UW) (Bretherton et al. 2004). A sensitivity study is therefore essential to identify the optimal configuration that could account for high-resolution precipitation representation. We will also use the ERA5 reanalysis (Hersbach et al. 2020) for high-quality initial and boundary conditions, providing a realistic large-scale framework.

The objective of this study is to assess the impact of the choice of these physical parameterization schemes on the simulation of precipitation in the Bandama basin using RegCM5, and to identify the most relevant combinations for regional climate applications. To this end, thirteen numerical experiments were conducted, combining various convective, microphysical, and PBL schemes, and then compared with observational data (CHIRPS) (Funk et al. 2015). Here we describe the study’s design, the indicators used, and the main results regarding simulated precipitation; we then discuss the relative performance of the tested configurations in light of recent literature, before concluding with the prospects they open up.

2. Methodology

2.1. Model configuration

The simulations were performed using the RegCM5 regional climate model, developed by the International Centre for Theoretical Physics (ICTP) (Giorgi et al. 2023). This version is the most recent iteration of the RegCM family and incorporates a non-hydrostatic dynamic core derived from the MOLOCH model (Coppola et al. 2025; Giorgi et al. 2023), enabling a more explicit representation of convective processes at high resolutions.

In this study, RegCM5 is used in parameterized convection mode with a 6-hour temporal resolution and a 12-km horizontal resolution (364 x 184).

The simulation domain corresponds to the Western Africa (WAF) region as defined in the IPCC AR6 Regional Atlas (Iturbide et al. 2020). It extends approximately from 20°W to 20°E and from the equator to 20°N, including the major river basins of West Africa. The topography and spatial extent of the simulation domain are shown in Fig. 2. Vertically, the model uses 18 levels down to a pressure of 50 hPa. No additional nesting was employed.

The land surface scheme adopted is CLM4.5 (Lawrence et al. 2011; Oleson et al. 2013), widely used in regional African studies (Koné et al. 2018; Silué et al. 2024). Ocean surface currents are represented using the Zeng scheme (Zeng et al. 1998; Zeng and Beljaars 2005), while radiative transfer is simulated by the RRTM scheme (Mlawer et al. 1997), recognized for its robustness in regional models.

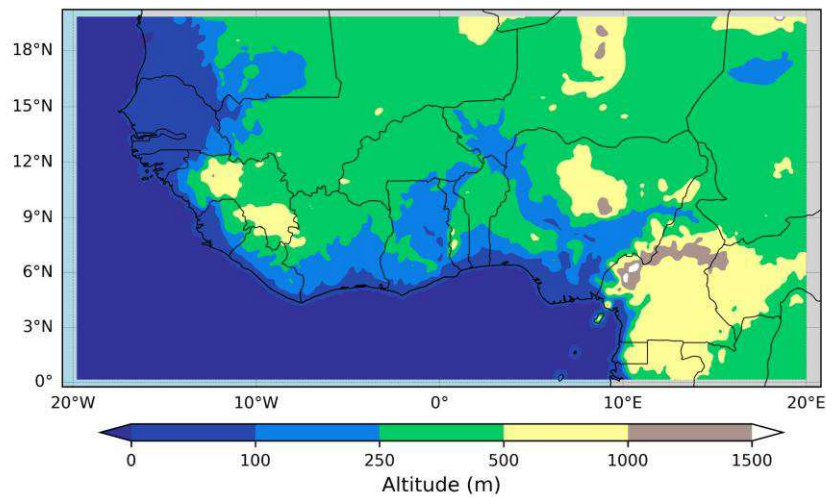


Fig. 2: Topography of the simulation domain

2.2. Forcing data and experimental setup

Initial conditions and lateral boundary conditions are derived from the ERA5 reanalysis, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al. 2020). Hourly surface fields were downloaded from the RegCM data server (http://climadods.ictp.it/Data/RegCM_Data).

For the study period 2000–2009, a one-year spin-up (for the year 2000) is applied to stabilize soil conditions and surface fluxes. The sea surface temperatures used as forcing are derived from the NOAA OI SST v2 product (Reynolds et al. 2002), updated daily.

For the evaluation of simulated precipitation, the observational reference used is CHIRPS v2.0 (hereafter, CHIRPS), a high-resolution (0.05°) satellite product combining infrared data and rain gauge measurements (Funk et al. 2015). CHIRPS precipitation aggregated over the

Bandama basin serves as the ground truth for model evaluation. To enable a consistent comparison, all simulated fields were interpolated onto the CHIRPS grid using bilinear interpolation, in accordance with recommendations for evaluating regional models (Iturbide et al. 2020).

For the experiments, the RegCM5 model offers a modular selection of physical parameterizations that we combined to isolate the impact of each process (convection, microphysics, boundary layer) on simulated precipitation. Our strategy consisted of selecting schemes commonly used in West Africa in recent literature (Koné et al. 2018; Silué et al. 2024; Sylla et al. 2010) and constructing a set of approximately 16 possible configurations. Table 1 summarizes the selected schemes and their abbreviations.

Table 1: Physical parameterization schemes considered in the study.

Scenario	Land CC	Ocean CC	Microphysics	PBL	Ocean Surface Flux	Radiation	Land Surface
S1	Tiedtke (T)	MIT	NoTo (N)	Holtslag (H) UW (U)	Zeng	RRTM	CLM4.5
S2			SUBEX (S)	Holtslag			
S3				UW			
S4			Emanuel (E)	NoTo			
S5	UW						
S6	SUBEX			Holtslag			
S7				UW			
S8	NoTo		Holtslag				
S9	Grell (G)		UW	Holtslag			
S10			SUBEX	UW			
S11				Holtslag			
S12			NoTo	Holtslag			
S13	Kain-Fritsch (K)		SUBEX	UW			
S14				Holtslag			
S15			SUBEX	UW			
S16				Holtslag			

Combining these options yields a maximum factorial design of 4 (cumulus) $\times$ 2 (microphysics) $\times$ 2 (boundary layer), resulting in 16 distinct configurations, labeled S1 through S16. Each configuration shares the same surface (CLM4.5 for land, Zeng for ocean) and radiation (RRTM) schemes, differing only in the three parameterizations tested. Table 1 presents all experimental configurations and their corresponding schemes. Among these 16 experiments, three (S2, S10, and S14) encountered simulation failures. These cases were therefore not included in the analysis, which ultimately covers 13 functional configurations.

2.3. Performance metrics and evaluation methods

To quantitatively evaluate the performance of each RegCM5 simulation, we calculated a set of statistical metrics by comparing the simulated precipitation to the CHIRPS reference

over the 2001–2009 period. These metrics allow us to analyze different aspects of the model error: mean bias, amplitude of variability, temporal correspondence of fluctuations, and similarity of statistical distribution.

All statistics are calculated using observed time series Y_t^{obs} and simulated time series Y_t^{sim} , for $t = 1, \dots, n$. To quantify the model's systematic error, the percentage bias is used. It expresses the model's tendency to overestimate or underestimate cumulative precipitation. The relative bias is given by Eq. 1:

$$Bias(\%) = \frac{\sum_{t=1}^n (Y_t^{sim} - Y_t^{obs})}{\sum_{t=1}^n Y_t^{obs}} * 100 \quad \text{Eq. 1}$$

To evaluate the error normalized by the variability of the observations, we use the RMSE–Observation Standard Deviation Ratio (RSR), the ratio of the root mean square error (RMSE) to the observed standard deviation (Moriiasi et al. 2007). This quantity is defined by Eq. 2:

$$RSR = \frac{\sqrt{\sum_{t=1}^n (Y_t^{sim} - Y_t^{obs})^2}}{\sqrt{\sum_{t=1}^n (Y_t^{sim} - \bar{Y}^{obs})^2}} \quad \text{Eq. 2}$$

The model's ability to reproduce the temporal variability of precipitation is evaluated using Pearson's linear correlation coefficient. This measures the agreement between simulated and observed anomalies. Its formulation is given by Eq. 3:

$$r = \frac{\sum_{t=1}^n (Y_t^{obs} - \bar{Y}^{obs})(Y_t^{sim} - \bar{Y}^{sim})}{\sigma_{obs}\sigma_{sim}} \quad \text{Eq. 3}$$

The evaluation also requires a comparison of the internal variability of the series. The standard deviation of precipitation is therefore calculated for the observations and for each simulation, according to Eq. 4:

$$\sigma = \sqrt{\frac{1}{n} \sum_{t=1}^n (Y_t - \bar{Y})^2} \quad \text{Eq. 4}$$

To assess the model's ability to reproduce the statistical distribution of precipitation, two additional metrics are used: the Brier Score (BS) and the Significance Score (SS). The BS corresponds to the mean squared error of the probabilities of simulated and observed precipitation intensities (Glenn 1950; Murphy 1973; Wilks 2011). It is defined by Eq. 5:

$$BS = \frac{1}{N} \sum_{i=1}^N (P_i^{sim} - P_i^{obs})^2 \quad \text{Eq. 5}$$

where P_i^{sim} and P_i^{obs} represent the simulated and observed probabilities in the interval i , for a total of N classes.

The SS measures the similarity between distributions and corresponds to the sum of the minimum common probabilities between simulations and observations (Perkins et al. 2007). It is defined by Eq. 6:

$$SS = \sum_{i=1}^N \min (P_i^{sim}, P_i^{obs}) \quad \text{Eq. 6}$$

A low BS and a high SS indicate a better representation of the simulated precipitation distribution.

Together, these indicators provide a robust basis for comparing the different physical configurations of the RegCM5 model, in order to identify those that best reproduce the seasonal structure, variability, and statistical distribution of precipitation in the Bandama basin.

3. Results

3.1 Analysis of overall errors

We first present the overall results in terms of mean errors and the simulated annual cycle. Fig. 3 illustrates the average annual cycle of precipitation simulated by each configuration, compared to observed monthly data (CHIRPS) for the Bandama watershed. The observed seasonal structure is typical of the West African monsoon, with a gradual increase in rainfall starting in March, a first peak in May–June, a relative decline in July–August (short dry season), and then a marked second peak in September–October. Most RegCM5 scenarios adequately reproduce the phases of this annual cycle: in particular, configurations S4, S5, and S6 successfully represent the transition to the wet season as well as the double seasonal peak in precipitation. However, there are notable discrepancies regarding the intensity of simulated precipitation at the peak of the monsoon: several configurations overestimate the seasonal amplitude of the annual cycle compared to observations.

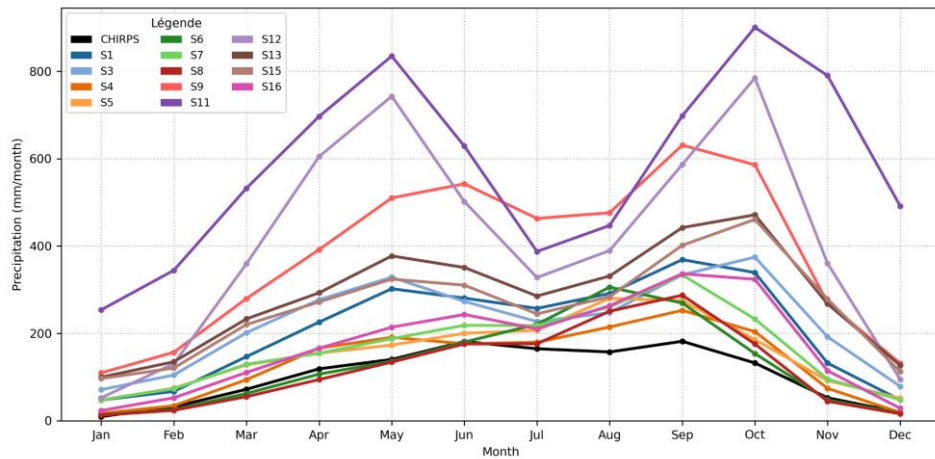


Fig. 3: Average annual cycle (Jan.–Dec.) of simulated precipitation over the Bandama watershed for different RegCM5 physical configurations, compared to CHIRPS observations (2001–2009).

Several trends emerge depending on the choice of schemes. Configurations using Tiedtke or Emanuel convection coupled with the SUBEX microphysical scheme (e.g., S4, S7, S8) generally reproduce the shape of the observed annual cycle, but with a tendency to overestimate precipitation during the wet season (May to October). In particular, the S4 (Tiedtke–SUBEX–UW) and S8 (Emanuel–SUBEX–UW) scenarios show good consistency during transition periods (the beginning and end of the rainy seasons), which is consistent with their moderate biases (less than 30% in absolute terms, according to Table 2).

Table 2: Mean bias and RSR for each scenario (annual precipitation over 2001–2009).

scenario	Bias (%)	RSR
S1	96.0	1.44
S3	111.6	1.44
S4	26.7	1.10
S5	47.0	1.26
S6	20.9	1.27
S7	56.8	1.93
S8	13.4	1.82
S9	255.3	2.33
S11	441.1	5.23
S12	281.6	4.19
S13	166.2	1.75
S15	143.3	2.50
S16	62.2	1.70

Scenarios using the NoTo microphysical scheme—typically S5 (Emanuel–NoTo–Holtslag) and S6 (Emanuel–NoTo–UW)—also successfully reproduce the intra-annual dynamics of precipitation. Nevertheless, their magnitude remains consistently higher than that observed: they tend to overestimate cumulative rainfall during monsoon peaks. This results in fairly significant positive biases (ranging from +20% to +50% according to Table 2), suggesting that

despite good temporal synchronization, these configurations generate an excess of water compared to CHIRPS.

In sharp contrast, configurations involving the Grell convection scheme (notably S9, S11, S12) show a massive overestimation of precipitation throughout the year. These scenarios produce monthly totals that are often two to three times higher than observed values. The tendency toward overestimation is particularly pronounced during seasonal maxima (May–June and September–October), when the model with Grell convection simulates torrential rains far exceeding reality. Error metrics confirm these extreme discrepancies: for example, scenario S11 exhibits a bias exceeding +440% and an RSR greater than 5 (Table 2), indicating very poor performance. Similarly, scenarios based on Kain-Fritsch convection (S13, S15) generate precipitation that is far too heavy compared to CHIRPS, with biases generally exceeding +140%. These results reflect an unrealistic representation of convective processes by the Grell and Kain-Fritsch schemes over the Bandama region, leading to the logical exclusion of these configurations from in-depth analyses.

In general, the overall metrics of bias and RSR clearly identify the best and worst configurations. Table 2 presents the bias (%) and RSR values calculated over the entire period for each scenario. It is observed that configuration S4 (Tiedtke–SUBEX–UW) offers the best compromise with a moderate bias of only +26.7% and a low RSR (~ 1.10), indicating good consistency between the simulated and observed variability. Scenario S6 (Emanuel–NoTo–UW) stands out for its low bias (+20.9%), while also maintaining a low RSR (≈ 1.27), reflecting an excellent ability to reproduce the observed annual accumulation while respecting the temporal structure of rainfall. The S5 configuration (Emanuel–NoTo–Holtzlag) exhibits a higher bias (+47%) but retains a relatively low RSR (~ 1.27), highlighting a respectable performance despite a notable overestimation. Conversely, scenarios S7, S8, and S16 achieve more intermediate error scores: their biases (approximately +13% for S8, +57% for S7, +62% for S16) remain acceptable overall, but their RSR values (> 1.7) indicate temporal variability that is less well synchronized with that of CHIRPS, especially during seasonal peaks.

In summary, this initial error analysis highlights that certain scheme combinations offer significantly better performance than others in simulating rainfall in the Bandama region. Configurations based on *Tiedtke/SUBEX* (e.g., S4) or *Emanuel/NoTo* (S5, S6), particularly when combined with the UW boundary layer scheme, are among the most consistent and reliable. Conversely, configurations involving the *Grell* convective scheme (and to a lesser

extent *Kain-Fritsch*), which generate enormous biases and very high normalized errors, must be excluded from climate applications in this region as they currently stand. These general trends will be explored in greater depth through the study of the seasonal variability and spatial distribution of simulated precipitation.

3.2. Seasonal Variability of Precipitation

The analysis above considered annual accumulation and the average cycle. We now examine in greater detail the intra-seasonal variability simulated by the different configurations, using boxplots of average precipitation by season. Fig.4 presents, for each scenario, the statistical distribution (median, dispersion, and range) of average precipitation across the four climatic seasons: DJF (December–January–February, dry season), MAM (March–April–May, early rainy season), JJA (June–July–August, peak monsoon season), and SON (September–October–November, main rainy season). These simulated distributions are compared to the CHIRPS precipitation distribution over the same periods.

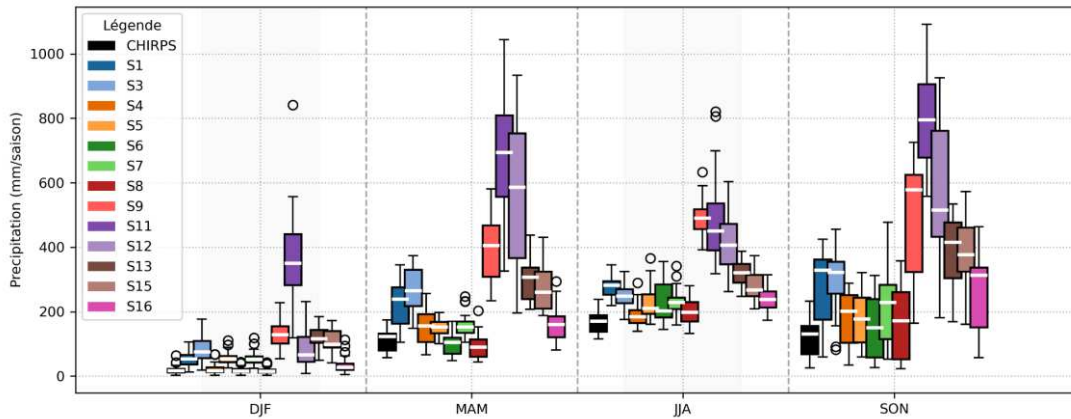


Fig. 4: Distributions (box-and-whisker plots) of seasonal precipitation (DJF; MAM; JJA; SON) simulated by the different model configurations over the Bandama basin (2001–2009).

During the dry season (December–February), observed precipitation in the Bandama region is very low (averaging 20 to 50 mm per month). Ideally, the model should therefore simulate values close to zero during this period. We observe that several scenarios manage to maintain very low rainfall in Dec–Jan–Feb, consistent with observations: this is particularly the case for S4, S5, S6, S7, S8, and S16, whose medians and dispersions of Dec–Jan–Feb rainfall remain close to zero. In contrast, certain configurations (particularly those based on Grell, e.g., S9 or S12) generate artificial convective activity during the dry season, with modeled precipitation that is significantly too high for this normally arid period. This erroneous behavior of the Grell

schemes is evident in DJF boxplots showing abnormally high values, while CHIRPS records virtually no rainfall.

In the spring (MAM), a crucial period corresponding to the gradual onset of the monsoon, we observe that scenarios S4, S5, S6, and S7 correctly reproduce the gradual increase in precipitation from March through May. Their medians are close to the CHIRPS values, and the simulated dispersion remains within the range of observed values, indicating good performance in capturing the onset of the wet season. In contrast, the wettest configurations identified previously (those with Grell, but also certain Kain-Fritsch models) greatly amplify their precipitation excesses during MAM. For example, S9 and S12 show high median accumulations as early as spring, well above the observed median, which already foreshadows the massive overestimation they will produce during the peak of the monsoon.

During JJA (June–July–August), the heart of the monsoon and a period of heavy rainfall, the trends of the various scenarios are confirmed. The S4, S5, S6, and S16 configurations exhibit behavior similar to CHIRPS, both in terms of average amplitude and interannual variability: their JJA medians are on the same order of magnitude as the observed values, and their dispersion (difference between wet and dry years) is comparable to that of the data. In contrast, S7 and S8 (Emanuel with SUBEX) show a more pronounced overestimation during JJA—their medians exceed the CHIRPS median, indicating a systematic excess, and the dispersion of S7/S8 is wider than that observed, a sign of slightly excessive simulated variability. Note, however, that even these biases remain moderate compared to the enormous errors of the Grell or Kain-Fritsch configurations, which we have ruled out: the latter would have shown JJA boxes well above the CHIRPS scale, confirming their inadequacy.

Finally, in autumn (SON), which corresponds to the second observed rainfall maximum, we observe that scenarios S4, S5, S6, S7, S8, and S16 adequately reproduce the order of magnitude of the rainfall. Their simulated SON medians are close to the observed median, and most remain within the CHIRPS interquartile range, indicating a good representation of the main monsoon peak. However, some discrepancies remain: for example, S7 and S8 retain medians slightly higher than the observations (indicating a slight overestimation at the end of the rainy season), and some of these scenarios exhibit higher interannual variability than that of CHIRPS, perhaps reflecting a tendency to simulate exceptionally rainy seasons more frequently than they actually occur.

In summary, the seasonal analysis confirms the findings of the annual analysis: the S4, S5, and S6 configurations (and to some extent S7, S8, and S16) stand out for their ability to reproduce the seasonal variability of the Bandama River's rainfall regime. They succeed in maintaining low precipitation levels during the dry season and in correctly representing both the onset and the retreat of the monsoon. The excesses they exhibit during the peak of the rainy season remain relatively contained compared to less effective scenarios. These results reinforce confidence in the Tiedtke and Emanuel convection schemes (especially when coupled with the PBL UW) for capturing the rhythm of the Ivorian monsoon. They also highlight, once again, the significant deviations caused by unsuitable convective schemes (such as Grell), which disrupt the simulation from the first spring rains and accumulate errors throughout the wet season.

3.3. Spatial evaluation of simulated precipitation

We now turn to the spatial evaluation of the precipitation produced by the different configurations. This analysis aims to verify whether the models correctly reproduce the geographic distribution of rainfall over the Bandama basin and its surroundings, in addition to the average value across the entire basin. Fig. 5 through 7 present a spatial comparison between the simulations and CHIRPS observations, focusing on the six most relevant configurations identified previously (S4, S5, S6, S7, S8, and S16). These six scenarios were selected because they offer the best overall and seasonal performance, and thus provide a representative sample of RegCM5's spatial skills and biases. Scenarios with significantly degraded performance (such as those based on Grell) are not considered here, in order to focus the analysis on potential solutions for regional modeling.

Fig. 5 shows the seasonal precipitation totals (averages over 2001–2009) simulated by each of the six selected configurations for the four seasons DJF, MAM, JJA, and SON, alongside the observed seasonal totals from CHIRPS. This allows us to visualize the spatial distribution of rainfall throughout the year and compare each scenario with the observed map. Overall, we observe that all scenarios correctly reproduce the region's major climatic gradients. These findings indicate that the model, regardless of the configuration, successfully simulates the basic monsoon regime, and the orography of the domain appears to be correctly accounted for. Nevertheless, notable differences emerge between the configurations regarding the local intensity of simulated rainfall. For example, during JJA (the active monsoon period), scenarios S4 and S6 produce seasonal totals very close to those of CHIRPS over most of the basin:

336 simulated values range between 800–1000 mm in the southern part of the basin, consistent with
337 observations. In contrast, scenarios S7 and S8 (Emanuel with SUBEX) tend to overestimate
338 accumulations in certain areas: pockets appear where totals exceed 1100 mm, whereas CHIRPS
339 does not reach such extremes. These excesses are particularly visible near coastal areas and
340 mountainous terrain, suggesting that the Emanuel+SUBEX combination tends to generate
341 convective events that are too intense locally.

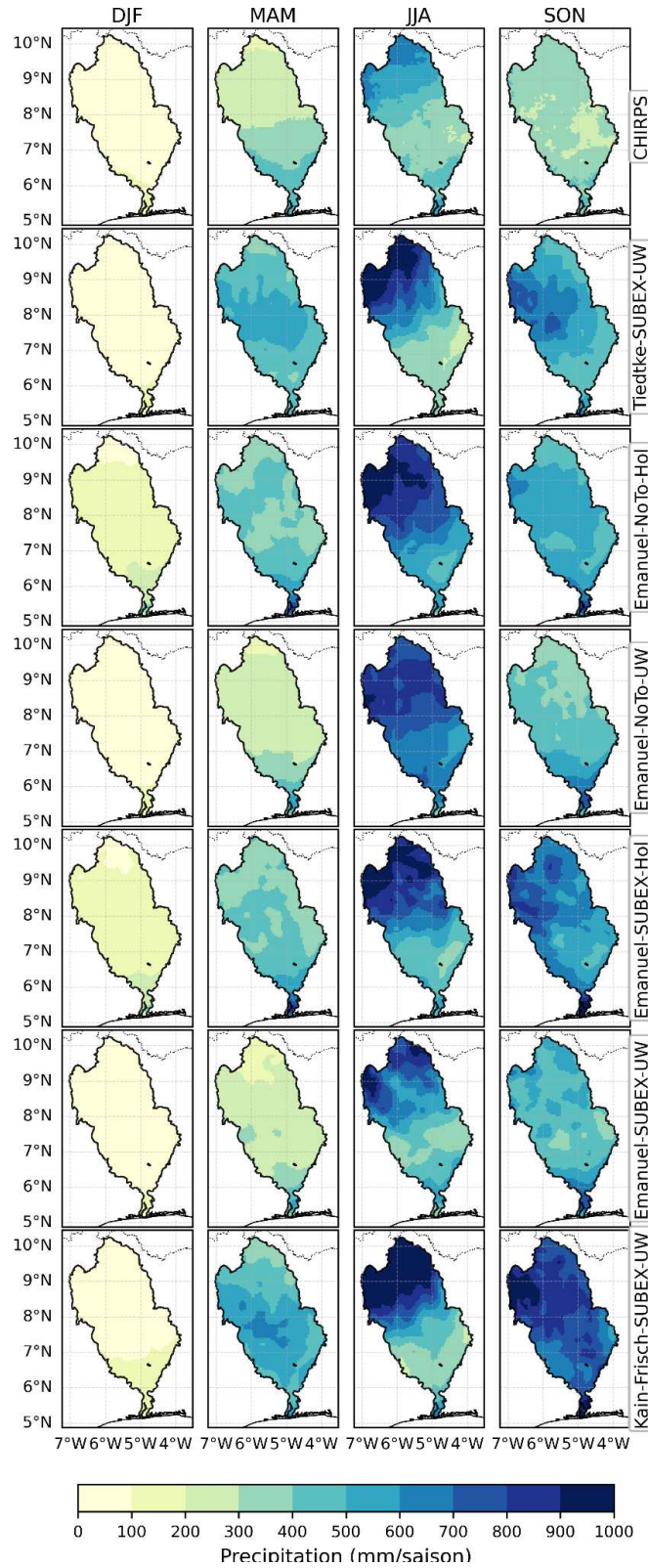


Fig. 5: Seasonal precipitation totals (DEC–FEB, MAR–MAY, JUN–AUG, SEP–NOV) simulated by the six most representative configurations (S4, S5, S6, S7, S8, S16) over the Bandama Basin (2001–2009 period).

Scenario S5 (Emanuel–NoTo–Holtslag), on the other hand, shows a spatial pattern quite similar to S6 (Emanuel–NoTo–UW), except for a slight overestimation over the center of the basin in

SON. Finally, configuration S16 (Kain-Fritsch–SUBEX–UW), although generally more biased, exhibits a spatial distribution of rainfall that is relatively consistent with what is expected, albeit with slightly exaggerated accumulations across the entire area (SON totals are seen to be slightly higher than those of CHIRPS everywhere).

Fig. 6 complements this analysis by presenting, for each configuration, a map of spatial biases (% deviation) in annual precipitation relative to CHIRPS. These bias maps numerically confirm the previous observations. Scenarios S4 and S6 show biases close to 0% over most of the Bandama basin, with a few minor local underestimates (light blue areas) offset by slight overestimates elsewhere (green-yellow areas). The average spatial bias of S4 across the entire basin is approximately +27% (Table 2), with no “hotspots” of strong local bias, making it the most homogeneous configuration. S8 exhibits a very low bias in the northern part of the basin (close to 0), but areas of more pronounced positive bias ($> +20$ to $+50\%$) are evident in the southern and western parts of the basin, reflecting the rainfall excesses mentioned during the rainy season. S7 shows a similar pattern but amplified: widespread overestimates across nearly the entire basin, often in the range of $+50\%$ to $+100\%$, indicating that this scenario makes all regions much too wet. S5 and S16 exhibit moderate spatial biases, generally ranging from 0 to $+50\%$ depending on the location, with no localized extreme errors, although S5 tends toward a slight generalized overestimation while S16 leans toward a more pronounced overestimation in the south than in the north. These maps thus highlight that high-performing convective schemes (Tiedtke, Emanuel) coupled with appropriate microphysics/PBL choices can limit the average spatial error to below 30–40%, whereas less suitable choices (Emanuel+SUBEX in S7, or Kain-Fritsch as in S16) can easily lead to regional overestimates of $+50\%$ or more compared to observations over large areas.

Fig. 7 examines the local spatial correlation between simulated and observed precipitation. For each grid point in the domain, we calculate Pearson’s r coefficient between the simulated monthly time series (2001–2009) and the corresponding CHIRPS series.

This yields correlation coefficient maps, which indicate where the model succeeds (or fails) in tracking observed temporal fluctuations. Here again, the six selected scenarios show varying performance. Configurations S4, S5, and S6 show correlation coefficients greater than 0.8 across most of the Bandama basin, indicating very good temporal synchronization at the local scale. S4 even achieves correlations of around 0.9 over large portions of the basin.

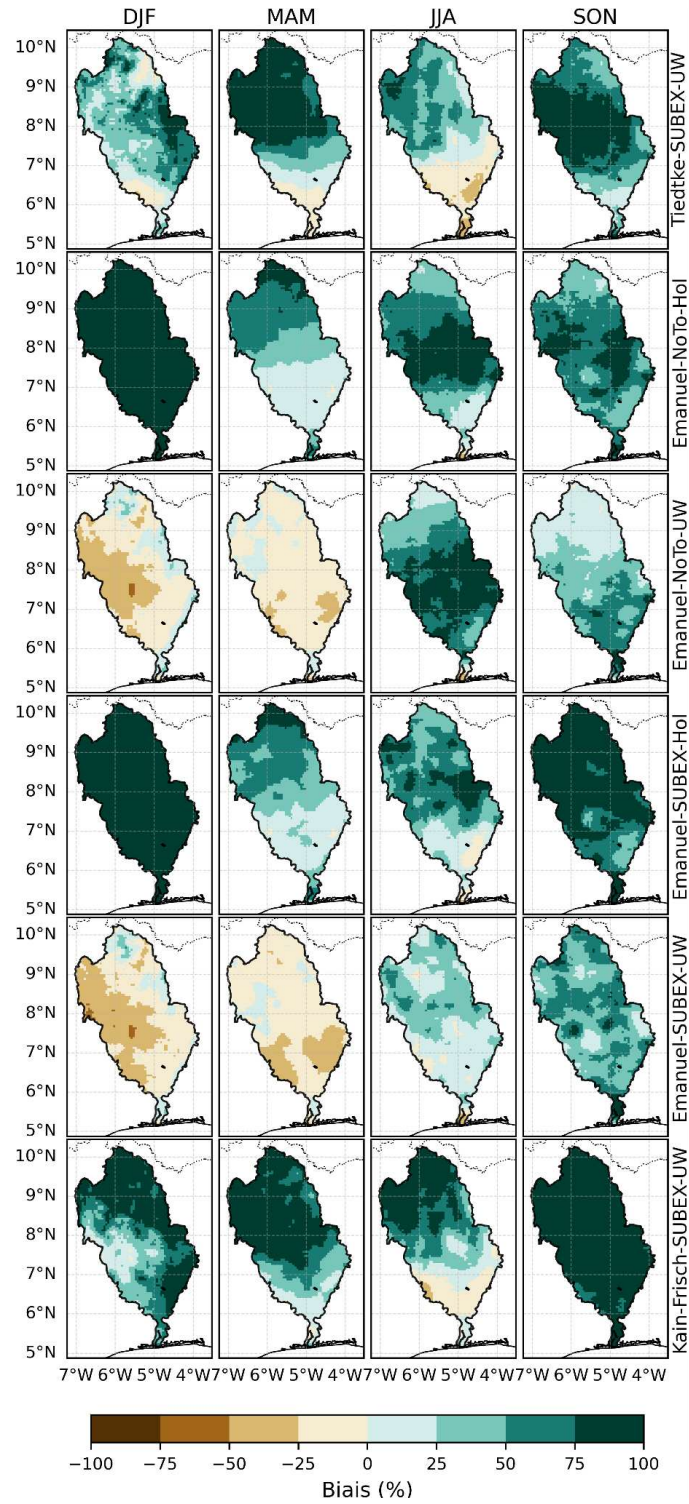


Fig. 6: Spatial bias of simulated precipitation (%) over 2001–2009 for each configuration (CHIRPS as reference).

S8 also achieves high correlations (>0.8) over the northern and central half of the basin, but a decrease in coefficients ($r \sim 0.6$ – 0.7) is observed toward the extreme southern coast, suggesting that this scenario has more difficulty precisely matching the timing of rainfall along the coastal fringe (perhaps related to its slight overestimation of coastal rainfall).

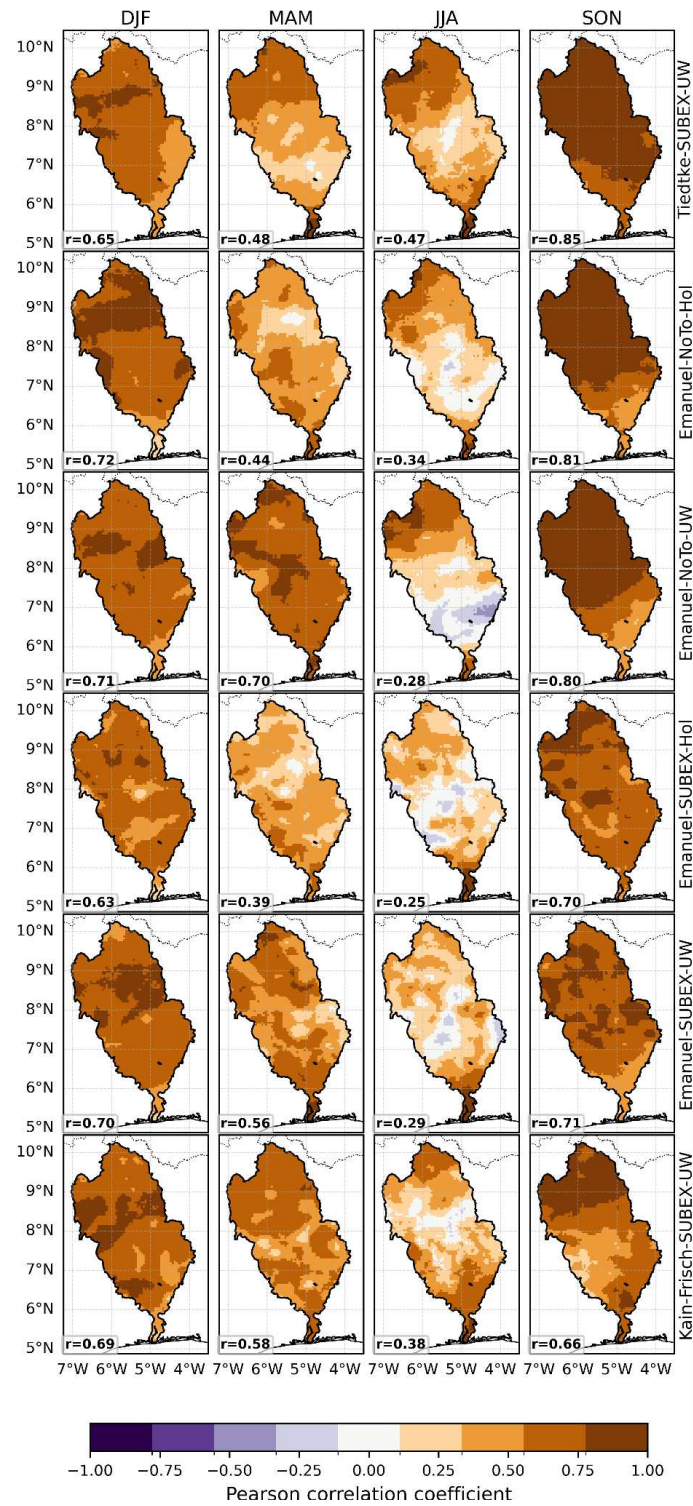


Fig. 7: Map of the correlation coefficient r (Pearson) between simulated and observed (CHIRPS) monthly precipitation for 2001–2009, calculated locally for each model grid cell.

The S7 scenario shows the weakest correlations of the set, with large areas where r falls to between 0.4 and 0.6, particularly in the southern part of the basin and in forested areas. This indicates that, in addition to overestimating precipitation amounts, S7 fails to accurately

reproduce the temporal sequence of rainfall events in these regions. As for S16, it exhibits intermediate correlations, often around 0.7, reflecting a decent performance without being excellent. In summary, the use of the UW boundary layer scheme appears beneficial here as well: the S4 and S6 runs (with UW) achieve higher spatial correlations than their counterparts S5, S7/8 using Holtslag or SUBEX with Emanuel.

Finally, Fig.8 compares the statistical distributions of simulated and observed daily precipitation across the entire Bandama basin. The probability density functions (PDFs) of daily rainfall are plotted for CHIRPS and for each scenario (averaged over 2001–2009), allowing us to assess whether the models accurately reproduce the frequency of dry days, moderate rainfall, and extreme events. In addition, Table 3 summarizes the Brier Score (BS) and Significance Score (SS) values for these six configurations, calculated separately for each of the four seasons. These quantitative scores facilitate the comparison of the shapes of the simulated versus observed distributions.

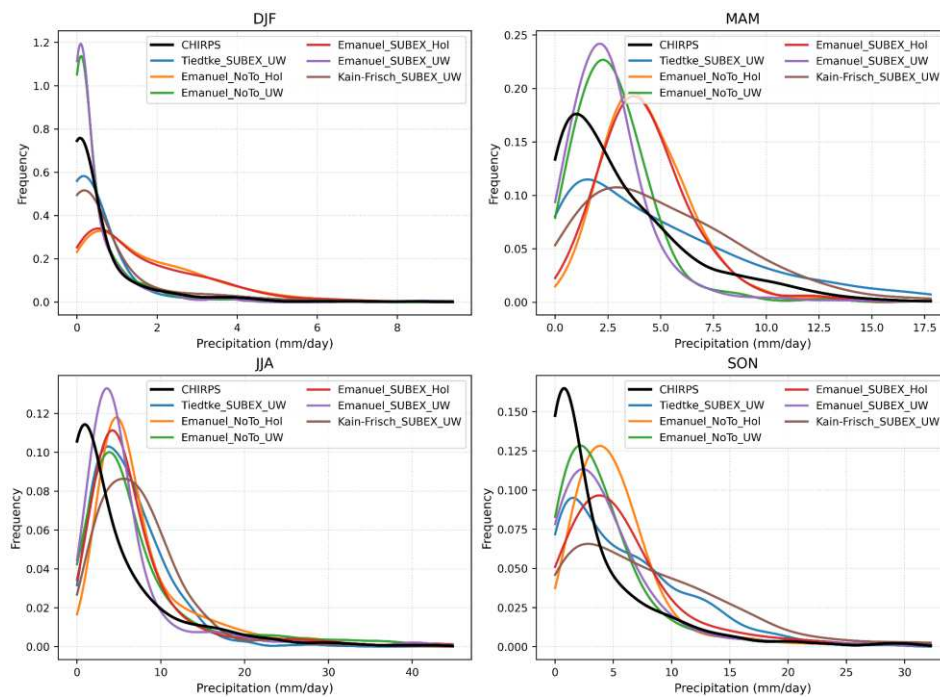


Fig.8: Probability density function (PDF) of daily precipitation over the Bandama basin simulated by different configurations, compared to the observed distribution (CHIRPS, black curve).

Examination of the PDFs reveals that configurations S4, S6, and S8 satisfactorily reproduce the distribution of daily precipitation. In particular, they correctly capture the high frequency of rainless or low-rainfall days (low intensities) while simulating a realistic occurrence of intense

events. For example, CHIRPS indicates that a small proportion (a few percent) of days exceed 50 mm of rain, and a similar order of magnitude is found in S4, S6, and S8 a sign that these scenarios do not generate torrential rains too often. Their seasonal Brier Scores are very low (in the range of 0.0001 to 0.004, see Table 3), indicating a good match between the simulated probabilities and the observed probabilities. At the same time, their Significance Scores are high: for example, S4 achieves an SS of ~ 0.56 in JJA and ~ 0.69 in SON, meaning that more than 50% of the statistical distribution of simulated rainfall coincides with the observed distribution, which is quite respectable for a model.

Table 3: Daily precipitation distribution scores for several configurations. Values are given by season (DJF, MAM, JJA, SON).

Scenario	BS				SS			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Tiedtke-SUBEX-UW	0.000061	0.000237	0.003068	0.001019	0.897282	0.785986	0.562780	0.695165
Emanuel-NoTo-Hol	0.005787	0.000971	0.003966	0.002912	0.460646	0.594924	0.503632	0.550547
Emanuel-NoTo-UW	0.000231	0.000532	0.003617	0.001175	0.854128	0.724786	0.567410	0.722749
Emanuel-SUBEX-Hol	0.005726	0.000991	0.003780	0.002519	0.479582	0.604244	0.524744	0.604253
Emanuel-SUBEX-UW	0.000134	0.000577	0.003793	0.001109	0.890278	0.708969	0.548838	0.737101
Kain-Frisch-SUBEX-UW	0.000210	0.000496	0.003157	0.001608	0.880571	0.737341	0.566586	0.611828

Scenarios S5 and S7 show slightly lower performance in terms of distribution. S5 (Emanuel–NoTo–Holtslag) tends to overestimate the frequency of moderate to heavy rain, shifting its PDF slightly toward higher intensities than that of CHIRPS. As a result, its Brier Score is higher (e.g., ~ 0.0058 in Dec–Feb, ~ 0.0039 in Jun–Aug), and its Significance Score is lower (~ 0.46 to 0.60 depending on the season, see Table 3), indicating a poorer reproduction of the shape of the rainfall histogram. S7 (Emanuel–SUBEX–Holtslag) suffers from the same issue of over-representation of heavy precipitation, with a high BS and a lower SS (~ 0.52 on average). Finally, the S16 configuration (Kain-Fritsch–SUBEX–UW) yields acceptable results for the distribution (relatively low BS ~ 0.001 – 0.003 and SS around 0.56 – 0.74 depending on the season), although slightly lower than those of S4 or S6. This suggests that despite its larger overall bias, S16 still manages to simulate the general shape of the rainfall distribution relatively accurately, particularly during the main rainy season (SON, where SS ~ 0.61).

In conclusion to this spatiotemporal assessment, the S4 (Tiedtke–SUBEX–UW) and S6 (Emanuel–NoTo–UW) configurations appear to be the most robust and consistent for simulating precipitation in the Bandama Basin. They combine a low overall bias, a good representation of the seasonal cycle, a realistic spatial distribution of accumulations, and a satisfactory reproduction of rainfall event statistics. Configurations S5, S8, and S16 follow closely in terms of performance, with some biases that are more pronounced either spatially or

in the distribution, but remain far superior to the other schemes tested. In contrast, the configurations not presented here due to their errors (notably those using Grell or Kain-Fritsch without UW) illustrate the pitfalls to avoid, having shown unacceptable spatial and temporal discrepancies (severe overestimations and poor variability). These results provide an objective basis for the optimal selection of physical parameterizations in the context of regional climate simulations over West Africa.

4. Discussion

The numerical experiments conducted have highlighted the extent to which the choice of physical parameterization schemes can influence the quality of precipitation simulations in the West African tropical climate. In the Bandama basin, our results show that cumulus convection schemes are the primary source of uncertainty in RegCM5, followed by planetary boundary layer schemes, while microphysical schemes have a secondary but non-negligible impact. This hierarchy aligns with the conclusions of other sensitivity studies conducted in the region: (Sylla et al. 2010) and (Diallo et al. 2012) had already highlighted that convective parameterization is a critical factor explaining the discrepancies between regional simulations in West Africa. More recent studies, such as (Koné et al. 2018) and (Komkoua Mbienda et al. 2021), confirm that the choice of convective scheme remains the primary determinant of regional model performance in this area, despite improvements made by the latest generations of RCMs.

A comparison of the Tiedtke, Emanuel, Grell, and Kain-Fritsch convection schemes revealed starkly contrasting behaviors. The Grell and Kain-Fritsch schemes lead to massive and unrealistic rainfall overestimates in our configuration, producing nearly continuous precipitation, even during the dry season, and highly exaggerated amounts during the monsoon. These findings are consistent with (Adeniyi 2019) and (Komkoua Mbienda et al. 2021), which show that these schemes often trigger convection too easily in West Africa due to CAPE-based convective closures that are insufficiently self-limiting. This finding is consistent with recent reviews on the limitations of convective parameterizations in the tropics (Legg 2021; Prein 2023), which highlight that parameterized convection schemes struggle to represent the mesoscale organization of African convective systems.

In contrast, the Tiedtke and Emanuel schemes provide much more satisfactory results. Tiedtke, based on a mass-flow scheme with moisture-convergence closure, appears well-suited to modulating tropical convection: it produces realistic accumulations without continuously

triggering convection. Our simulations show that Tiedtke, combined with SUBEX and the UW (S4) scheme, offers the best overall agreement with observations, which is consistent with (Adeniyi 2019) and (Koné et al., 2018). The Emanuel (MIT) scheme, based on a quasi-equilibrium closure of convective instability, also correctly reproduces the timing and distribution of rainfall, particularly when combined with NoTo and UW (S6). These results confirm recent recommendations arising from the development of RegCM5 (Coppola et al. 2025; Giorgi et al. 2023), which identify Emanuel as one of the best-performing schemes in humid tropical environments.

The role of the global boundary layer parameterization has also proven crucial. The use of the UW scheme consistently improves results compared to Holtslag, reducing biases and improving the temporal synchronization of rainfall. This result is consistent with recent work by (Silué et al. 2024), which shows that UW better reproduces vertical heat-moisture exchanges in RegCM5 over West Africa and thus limits the explosive convective responses characteristic of Holtslag. Recent literature on turbulence-convection interactions (Jia et al. 2023) also highlights the importance of non-local PBL schemes for tropical regions.

Regarding microphysics, the influence is more subtle but noticeable. In several configurations, NoTo helps limit overestimates of precipitation through a more realistic representation of ice microphysics. Our results align with the conclusions of (Keshta et al. 2025), which show that NoTo better reproduces the heavy end of rainfall distributions than SUBEX. However, NoTo's effectiveness depends on the associated convective scheme and PBL, confirming that microphysics does not compensate for an inadequate convective choice, as also shown by (Villalba-Pradas and Tapiador, 2022) and recent reviews on the limitations of classical microphysical schemes.

Our results have important implications for climate and water resources modeling in West Africa. The ability to correctly simulate the spatial distribution and seasonal sequence of rainfall determines the relevance of regional climate projections and impact studies. The marked sensitivity to convection schemes underscores the necessity of testing multiple parameterizations rather than relying on the standard settings of an RCM. Two different configurations of the same model can lead to opposing conclusions regarding future precipitation trends, as also documented in the work of (Prein 2023).

Finally, despite the improvements brought by certain schemes, residual discrepancies remain compared to observations, highlighting the limitations of parameterized convection approaches.

Recent studies (Berthou et al. 2019; Coppola et al. 2025; Marsham et al. 2013) show that switching to resolutions ≤ 4 km and explicit convection significantly improves the representation of convective systems and extreme events. In the case of Bandama, it is likely that some of the errors attributed to convective schemes result from these inherent limitations. The use of the RegCM5 non-hydrostatic core therefore paves the way for future high-resolution simulations to further refine regional modeling in Côte d'Ivoire.

5. Conclusion and Outlook

In this study, we examined in detail the impact of the choice of RegCM5 physical parameterization schemes on precipitation simulation in the Bandama watershed (2001–2009). Thirteen combinations of convective (Tiedtke, Emanuel, Grell, Kain–Fritsch), microphysical (SUBEX, NoTo), and boundary layer (Holtslag, UW) schemes were compared with CHIRPS observations.

Our results highlight that the choice of convection and boundary layer schemes is critical to the quality of the simulations. More specifically, configurations combining Tiedtke or Emanuel with the UW PBL scheme stood out for their strong performance. In particular, the Tiedtke–SUBEX–UW combination (S4) and the Emanuel–NoTo–UW combination (S6) best reproduced the Bandama rainfall regime: they exhibit moderate annual biases ($<30\%$), correctly capture the two monsoon peaks as well as the intervening dry season, and display a realistic spatial distribution. In contrast, configurations based on Grell or Kain–Fritsch produced massively overestimated precipitation (cumulative totals several times higher than observed) and a shifted temporal variability, rendering them unsuitable in their current state for climatic or hydrological applications in this basin.

These findings provide concrete recommendations for future regional modeling work in West Africa. For any study focused on climate or water resources in Côte d'Ivoire, it appears advisable to prioritize RegCM5 configurations using the Emanuel or Tiedtke convective scheme and the UW boundary layer scheme, possibly combined with the advanced NoTo microphysics. Such configurations maximize the chances of accurately reproducing observed rainfall amounts and variability, thereby improving the reliability of climate projections. This finding aligns with recent conclusions obtained in other tropical contexts using RegCM5, where these combinations have also demonstrated better representation of monsoon rains and intense events. Conversely, the use of less effective convective schemes (such as Grell) without

preliminary evaluation could lead to significant biases and misinterpretations, particularly regarding the impact of climate change in the region.

Looking ahead, several avenues for further research are possible. On the one hand, it would be useful to extend the analysis to longer time periods (e.g., several decades) and to other West African basins in order to test the spatial and temporal robustness of the optimal configurations identified. On the other hand, simulations with even finer resolution (a few kilometers), where convection would become explicit, should be explored. The non-hydrostatic core of RegCM5 makes these experiments possible; they could improve the representation of mesoscale systems and extreme rainfall, as demonstrated in recent studies on West Africa. The integration of more advanced microphysical schemes, derived from recent developments in cloud modeling, could also help refine the simulation of intense events.

Finally, from an applied perspective, the configurations optimized by this study can be utilized in coupled impact simulations (e.g., hydrological coupling of the Bandama River, flood and drought risk assessments, or regionalized simulation ensembles) to provide decision-makers with more reliable regional rainfall information. Such an approach will help improve water resource management and the anticipation of hydrometeorological risks in a context of increased climate variability.

In summary, this study helps to better understand the uncertainties associated with the choice of physical parameterizations under monsoon conditions. It provides an operational framework for selecting the most appropriate schemes in RegCM5 for West Africa and highlights the importance of local model calibration. These evaluation and optimization approaches are essential for more confidently anticipating the impacts of climate change on precipitation patterns in humid tropical environments.

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The article does not contain any studies involving human or animal participants

Author contributions

All the authors contributed to the design and implementation of the study. The supercomputer was made available by Benjamin Komenan Kouassi, Adama Diawara and Arona Diédhiou. The preparation of the materials, data collection and analysis were carried out by Mamadou Doumbia, Fidèle Yoroba, Brahim Koné and Ibrahim Touré Salifou. The research was supervised by Fidèle Yoroba, Touré Dro Tiémoko and Kouakou Kouadio. The first draft of the manuscript was written by Mamadou Doumbia, and all authors provided comments on previous versions of the manuscript. All authors have read and approved the final version of the manuscript.

Data Availability

The RegCM5 code is available from the project website: <https://github.com/graziano-giuliani/RegCM/tree/5.0.0>. The RegCM5 used to produce the results used in this paper is archived by Zenodo at <https://doi.org/10.5281/zenodo.7548172> (Giorgi et al. 2023).

The data used in this work can be found at: CHIRPS: Funk et al. (2015), ERA5: Hersbach et al. (2020).

The model is distributed with a public license and available for download from the github repository: <https://github.com/ICTP/RegCM>