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Optimizing Precipitation Parameterizations in Regional Climate Model (RegCM5): A Case Study of the Upper Blue Nile Basin (UBNB)

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Abstract.

Accurate simulation of precipitation over complex terrains such as the Upper Blue Nile Basin (UBNB) is essential for water resource management and climate impact assessments. The UBNB is characterized by complex terrain and convective precipitation systems that challenge the fine-scale climate simulation processes. This research aims to investigate the best precipitation parameterizations in the Regional Climate Model System (RegCM5) simulating different convective and large-scale schemes over the UBNB domain with 10 km resolution. The RegCM5 is driven by the fifth generation atmospheric reanalysis (ERA5) for a period of (2000-2009) using the hydrostatic dynamical core. The total precipitation simulations of the different calibration scenarios are assessed to select the most optimal RegCM5 configuration over the UBNB. Results show that the Emanuel scheme coupled with Nogherotto-Tompkins (NoTo) is the most effective parameterization to capture precipitation but reveals significant overestimation with an accepted wet bias of 66%. The model highlights challenges in reproducing the UBNB's precipitation variability with a moderate to relatively good correlation of precipitation patterns from 0.46 to 0.77. Sensitivity analysis suggests that the interplay between the model's hydrostatic configuration and vertical domain extent significantly influences precipitation outputs, where deficiency in capturing the large-scale circulations. The research recommended to focus on dynamics advancement, and exploring parameterization schemes enhancing the precipitation representation such as the Planetary Boundary Layer (PBL) in Future.

1 Introduction

The seasonal rainfall over the Upper Blue Nile Basin (UBNB) is the main determinant of the variability in the entire River Nile basin hydrology, where there is a strong correlation between the fluctuations in both basins flows (Conway and Hulme, 1993). A more reliable simulation of the UBNB climate, especially rainfall, can help in the water resources management of the riparian countries of the Nile basin. The UBNB climate variability is affected by several global phenomena and mechanisms due to the ocean-atmosphere interaction. Among these mechanisms, the El-Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are the major drivers of the tropical climate (Coppola et al., 2012; Elsanabary and Gan, 2014; Siam and Eltahir, 2017). ENSO and IOD are phenomena relevant to the teleconnection of the rainfall variability (seasonal to interannual) to the global Sea Surface Temperatures (SSTs). (Abtew et al., 2009)found that the dry/wet years of the UBNB were linked to El Niño/La Niña events. El Nino disrupts the moisture transport into the basin reducing the rainfall, while La Nina enhances it promoting convective activities and causing heavy rainfall over the UBNB (Conway, 2000). A positive/negative IOD is associated with above/below-average rainfall over the UBNB due to the warm/cool water in the Indian Ocean near Africa (Elsanabary and Yew, 2015). At seasonal timescales, the Inter-Tropical Convergence Zone (ITCZ) influences the spatiotemporal variability of the UBNB rainfall as a main rain producing system (Tariku and Gan, 2018a; Zaroug et al., 2014). The UBNB is affected by the three Ethiopian climate seasons; Short Rain Season (Spring), Long Rain Season (Summer), and Winter Dry Season (Keshta, 2020). The various atmospheric systems that control the spatiotemporal variations of these seasons were comprehensively identified by (Camberlin and Philippon, 2002; Diro et al., 2011; Fekadu, 2015; Segele and Lamb, 2005).

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The Short Rain Season starts from February until May (FMAM) and its weather pattern is derived by the interaction between the mid-latitude and tropical weather systems. While the Long Rain Season occurs from June to September (JJAS), in which the rainfall onset and distribution follow the ITCZ oscillation and the anticyclones intensity of the southern hemisphere. The Winter Dry Season, October-January (ONDJ), is dominated by the northern hemisphere subtropical anticyclones and dry cool northeasterly monsoon. The JJAS rains represent the highest proportion of the total UBNB rainfall with 70% to exceeding 75% (Mellander et al., 2013), where the average annual rainfall over the UBNB is around 1200 mm (Amin and Kotb, 2015). (Elsanabary and Gan, 2015) explored the impact of the ENSO and IOD on the UBNB FMAM and JJAS rainy seasons. They found that El Niño increases the FMAM rainfall and decreases the JJAS rainfall, while La Niña showed the opposite effect. However, during FMAM, the UBNB central part is unaffected by ENSO. The IOD has a wet effect on the FMAM and JJAS rainfall. The ITCZ migration is governed by the Earth tilting, so its effect varies with season due to the UBNB location in the northern hemisphere. During JJAS, the UBNB captures high moisture from the Atlantic Ocean, released by the Ethiopian highlands, due to the developed subtropical high pressure systems with the blew wind from southwest to northeast together that followed the ITCZ migration (Camberlin, 2009). Hence, the UBNB southwestern part is exposed to the westerly advective rains for a longer time than the northeast part. In ONDJ, the UBNB is located above the ITCZ, which migrates gradually to the southern hemisphere due to the wind blew from the north to south (Birhan et al., 2019). Therefore, the UBNB couldn't get sufficient precipitation. Moreover, the UBNB has varied topography combining lowlands and high mountains; the Ethiopian Plateau, in which the elevation ranges from 2000 to more than 3500 m a.m.s.l (Shahin, 1985) (Fig.1). This topographic altitude influences the fine-scale spatial distribution of the basin rainfall (Mohamed et al., 2005; Rientjes et al., 2013; Zeleke et al., 2013), since the mountain ranges generate local wind circulation patterns.

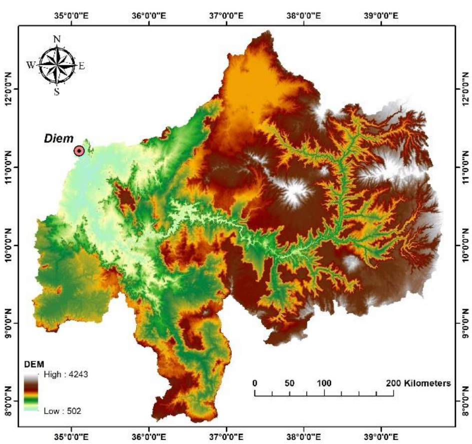

Figure 1. The topography of the UBNB (Keshta, 2020)

The Regional Climate Models (RCMs) can simulate climate over a region of interest at resolutions finer than the Global Circulations Models (GCMs) providing more accurate information. RCMs performance is usually being assessed to investigate the climate characteristics, and studying the change of climate as well as land use impacts on the climate variables. A significant challenge in improving RCM performance over the area of interest lies in selecting the most appropriate physical parameterization schemes, developed for a specific climate condition and resolution. Hence applying identical schemes produces different results not only in different regions but also in different seasons of the same region (Giorgi and Marinucci, 1996). It is demonstrated that the cumulus convection schemes (CCs) have a greater influence on the performance of RCM simulation than other schemes (Li et al., 2023) since CCs control the dynamics and the rainfall regimes variability.

In Africa, especially over Eastern Africa, the Nile basin, and Sahel region, the versions of the Regional Climate Modelling system (RegCM) and Weather Research and Forecasting (WRF) have been commonly used for different climate applications. Over Eastern Africa, the performance of ten COordinated Regional climate Downscaling Experiment (CORDEX) RCMs forced by European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) was assessed by (Endris et al., 2013) in simulating the rainfall. They found an overestimation over the Ethiopian highlands for all RCMs with relatively low spatial correlation, however the ensembles mean outperformed the individuals. (Tariku and Gan, 2018b) applied the WRF over the Nile basin showing the same rainfall overestimation over the Blue Nile basin in Ethiopian highlands and demonstrated this result as a predominance of a strong convective regime over the Indian Ocean. Despite this wet bias, they concluded that the Kain-Fritsch CC (Kain, 2004) better simulated the rainfall over the entire basin. (Abdelwares et al., 2018) recommended another CC (Betts-Miller-Janjic scheme (BMJ) (Janjić, 1994)) when developing WRF over the Eastern Nile Basin. Focusing on the UBNB, they found that the combinations that used CCs of Kain-Fritsch and Grell 3D (Grell, 1993) highly overestimated rainfall compared to those that used BMJ, which captured the rainfall annual cycle with a small wet bias during the wet season.

Most studies using the RegCM over eastern Africa also found difficulties in reproducing the rainfall patterns correctly. (Segele et al., 2009) used the RegCM3 to simulate eastern Africa reporting an overestimation of the Ethiopia precipitation when using the Grell and Emanuel (Emanuel, 1991) CCs. (Zeleke et al., 2016) evaluated the RegCM4 to simulate the precipitation of rain seasons over the UBNB using the mixed CCs of Grell/Emanuel over land/ocean. Using the initial and boundary conditions of ERA-Interim they found that the precipitation was overestimated over the southwest and central regions and underestimated over the eastern region. Over West Africa, (Koné et al., 2018) found that a dry bias dominated the RegCM4 simulation, which was more pronounced using the CC of Tiedtke (Tiedtke, 1989) and recommended the Emanuel CC when using the RegCM4 with the land surface scheme of CLM4.5 (Community Land Model version 4.5 (Oleson et al., 2013)).

These selected schemes in previous works are limited due to the coarse model resolution that misses the finer local climate features. The fifth generation atmospheric reanalysis (ERA5) data provides advancements in the spatiotemporal resolution of ~31 km with 1 hour intervals. Compared with the ERA-Interim, ERA5 improves the vertical coverage, and tropospheric processes and tropical cyclones representation enhancing the model's ability to simulate the precipitation in the deep tropics (Hoffmann et al., 2019). In this study, different physical parameterization sets are simulated with finer spatiotemporal resolution initial and boundary conditions provided by the ERA5 data to get the most optimal configuration of the last RegCM version (RegCM5 (Giorgi et al., 2023a)) over the UBNB. Finding out the best configuration over the UBNB helps in many climate applications such as studying the impacts of climate change projection, seasonal forecasting and land use change.

2 Model Description and Data

The RegCM5 is a freely available, and flexible Regional Earth System model. It is the last version of the RCMs series developed at Abdus Salam International Centre for Theoretical Physics (ICTP), which was improved in collaboration with the Institute of Atmospheric Sciences and Climate of the National Research Council (ISAC-CNR) of Italy. A new dynamical core option (the non-hydrostatic core of the weather prediction model MOLOCH) has been added to this new version (Giorgi et al., 2023a). Now there are three options; hydrostatic, non-hydrostatic, and MOLOCH non-hydrostatic, to be selected as a dynamical core option for a simulation. The RegCM5 parameterization set comprises various schemes such as the land surface, planetary boundary layer, sea surface flux, cumulus convective, microphysics, and radiation schemes. For the precipitation representation, there are five different cumulus convective schemes and three different microphysics schemes. In addition, mixed convective schemes over land and ocean can be used. More details on the model parameterization schemes can be found in (Giorgi et al., 2023b).

The model initial and boundary conditions are driven by the ERA5 hourly data with 0.25º × 0.25º resolution from the ECMWF (Hersbach et al., 2020) for the period (2000-2009). The Sea Surface Temperature (SST) is also from the ERA5 reanalysis hourly data with 0.25º × 0.25º resolution but on a single level for the period (2000-2009). For calibration, observed daily rainfall data with a spatial resolution of 20 km × 20 km is obtained for the period of (2001-2009) from the Pre-Processor 7

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(PP7). PP7 is a merge between gauge and satellite data blended in the Nile Forecasting System (NFS) database (NFC., 2009) in the Egyptian Ministry of Water Resources and Irrigation (MWRI).

3 Model Setup and Calibration

3.1 Domain

The domain for the RegCM5 simulation over the UBNB is selected to capture both local and large-scale atmospheric processes influencing the precipitation in the region. The domain is nested at 10 km resolution and extends from 5° S to 21° N latitude and 27° E to 53° E longitude, Fig. 2, involving the different topographical features and a range of climate zones such as the Ethiopian Highlands, the Western Indian Ocean, the Arabian Peninsula, and the Southern Red Sea. The model utilizes 18 vertical sigma levels and a top at 50 hpa. Table 1 involves the details of the domain extent. The selected domain is large enough to ensure more reliable simulations of the main climate characteristics, among which the moisture transport from the main sources for the region's precipitation dynamics like the East African Monsoon and the Indian Ocean (Endris et al., 2013).

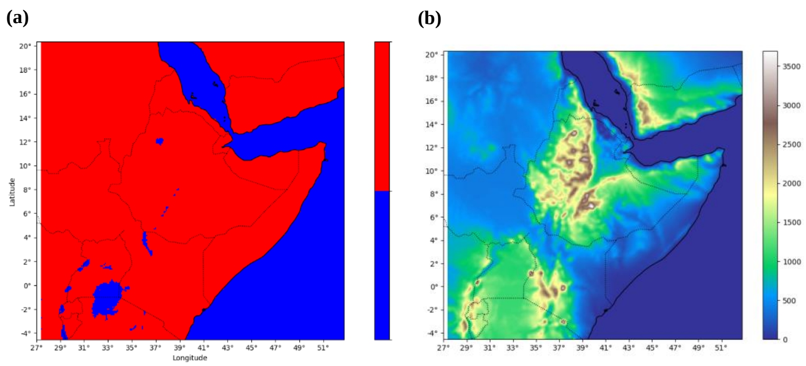

Figure 2: The extent of the UBNB Domain. [(a) Land Mask; (red for land and blue for water), and (b) Topography; (unit: m)].

Table 1. The domain extent

Longitude	27° E - 53° E
Latitude	05° S - 21° N
Nesting Ratio	1 : 3
Resolution	10 km
No. of grid cells	280 × 280
Vertical layers	18 vertical sigma levels
Top pressure	50 hPa

3.2 Physics Parametrization

The hydrostatic dynamic core (Giorgi et al., 1993) is used for the RegCM5 configuration in the different calibration scenarios. To optimize the number of trials due to the high computational cost, the selection of the parameterization schemes representing the precipitation is divided into two parts to be tested over the UBNB, where the second part has resulted from the initial evaluation of the first one as follows:

1. First, four Cumulus Convective (CC) schemes are tested; Grell (closure of Fritsch-Chappell), Emanuel, Tiedtke, and Kain-Fritsch schemes, to represent the convective precipitation over land. Over the ocean, only the Emanuel scheme is selected as mixed convection with all four CCs over land. The SUB-grid EXplicit (SUBEX) (Pal et al., 2000) is used for large-scale (resolvable, or non-convective) precipitation. The SUBEX is selected as a resolved-scale cloud physics option, which

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is usually used in the earlier RegCM versions over the UBNB or around the basin such as Ethiopia, East Africa, and west Africa (Endris et al., 2013; Koné et al., 2018; Nikulin et al., 2012; Segele et al., 2009; Zeleke et al., 2016).

2. Second, after the initial evaluation of the results, a high overestimation of the precipitation is noticed, especially in the scenario that used the Grell. As a result, the Grell is excluded, and a decision was made to enhance the choice of schemes that can also affect the precipitation simulation. Hence, another look at the schemes that represent the other precipitation component (non-convective) is required. The new microphysics scheme, Nogherotto-Tompkins (NoTo) (Nogherotto et al., 2016), treats the mixed-phase clouds removing the oversimulation of the upper level cloud characteristics of the SUBEX scheme. Over East Africa, (Gudoshava and Semazzi, 2019) revealed that the NoTo generally reduces the overestimation of CCs, however they recommended the SUBEX with the Grell (Fritsch-Chappell closure). In addition, (Kalmár et al., 2021) tested different resolved-scale cloud microphysics schemes over a mountainous region in eastern-central Europe. They found the SUBEX overestimated the high intensity tail of the observed precipitation, while the NoTo reproduced it better whatever the type of the dynamical core (hydrostatic or non-hydrostatic). Therefore, in this research, the NoTo is added as another option for large-scale precipitation.

The planetary boundary layer (PBL) scheme developed by (Holtslag et al., 1990) is used to represent the vertical interaction between the surface (land or ocean) and the atmosphere. In addition, the ocean flux scheme developed by (Zeng et al., 1998) is used and the rapid radiation transfer scheme (RRTM) is used as the radiation scheme. Finally, the CLM4.5 is used for the land surface representation. These schemes are chosen based on recommendations provided in previous studies conducted near the UBNB as the choice of SUBEX (above). It should be noted that in all convection schemes, the default parameter values are used. Table 2 summarizes the selected parameterization schemes for the different seven calibration scenarios.

Table 2. Combination of physical parameterization schemes selected for calibration

<table>
<tr><th>Scenario</th><th>Land CC</th><th>Ocean CC</th><th>Microphysics</th><th>PBL</th><th>Ocean Surface Flux</th><th>Radiation</th><th>Land Surface</th></tr>
<tr><td>S1</td><td>Grell</td><td rowspan="7">Emanuel</td><td rowspan="4">SUBEX</td><td rowspan="7">Holtslag</td><td rowspan="7">Zeng</td><td rowspan="7">RRTM</td><td rowspan="7">CLM4.5</td></tr>
<tr><td>S2</td><td>Emanuel</td></tr>
<tr><td>S3</td><td>Tiedtke</td></tr>
<tr><td>S4</td><td>Kain-Fritsch</td></tr>
<tr><td>S5</td><td>Emanuel</td><td rowspan="3">NoTo</td></tr>
<tr><td>S6</td><td>Tiedtke</td></tr>
<tr><td>S7</td><td>Kain-Fritsch</td></tr>
</table>

3.3 Calibration Methodology

Some statistical criteria are used for the performance evaluation of the different physical parametrizations of RegCM5 calibration over the UBNB. Two statistical criteria; Percent Bias (Bias%), Eq. (1), and Root Mean Squared Error to observation Standard Deviation Ratio (RSR), Eq. (2), are calculated on a monthly basis as an error indication.

$$Bias\% = \left[\frac{\sum_{t=1}^{n}\left({Y_t}^{sim} - {Y_t}^{obs}\right)*100}{\sum_{t=1}^{n}\left({Y_t}^{obs}\right)}\right], \tag{1}$$

$$RSR = \left[\frac{\sqrt{\sum_{t=1}^{n}\left({Y_t}^{sim} - {Y_t}^{obs}\right)^2}}{\sqrt{\sum_{t=1}^{n}\left({Y_t}^{obs} - \overline{Y^{obs}}\right)^2}}\right], \tag{2}$$

where n is the number of observations, ${Y_t}^{sim}$, ${Y_t}^{obs}$ are the simulated and observed precipitation at time t respectively, and $\overline{Y^{obs}}$ is the mean of the precipitation observations during the calibration period.

To check the annual cycle and spatial distribution, some criteria are estimated for the three climate seasons FMAM, JJAS, and ONDJ. The correlation coefficient in time is calculated for the three seasons to measure the strength of a linear

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association between the simulations and observation patterns for each grid point to check spatiotemporal distribution. The correlation coefficient (R^2) is given by Eq. (3).

$$R^2 = \frac{\sum_{t=1}^{n}\left(Y_t{}^{obs} - \overline{Y^{obs}}\right)\left(Y_t{}^{sim} - \overline{Y^{sim}}\right)}{\sigma^{obs}\,\sigma^{sim}}\,, \qquad (3)$$

where $\overline{Y^{sim}}$ is the mean of the simulated, and σ^{obs} and σ^{sim} are the standard deviation of the observed and the simulated precipitation.

Finally, the Brier Score (BS) and Significance Score (SS) (Brier, 1950; Fraedrich and Leslie, 1987), are estimated to assess the probability density function (PDF) for the simulated and observed daily data during the three seasons. The BS represents the mean square error of the probability and SS represents the smallest cumulative probability of the observation and simulation distribution in each equal sequence of values. BS and SS are given as follows:

$$BS = \frac{1}{N}\sum_{i=1}^{N}\left(P_i^{sim} - P_i^{obs}\right)^2\,, \qquad (4)$$

$$SS = \sum_{i=1}^{N} Minimum\left(P_i^{sim}.P_i^{obs}\right)\,, \qquad (5)$$

where N is the number of intervals, P_i^{sim} is the probability density value of the simulated precipitation at interval i, and P_i^{obs} is the probability density value of the observed precipitation at interval i. The smaller/larger BS/SS indicates the ability of the RegCM5 scheme to simulate the probability density distribution

4 Results and Discussion

The results are analyzed for the period of (2001-2009); the year 2000 is used as a spin-up period. The simulated precipitation is compared to the observed PP7 data.

4.1 Error-based Evaluation

To evaluate the different RegCM5 configurations over the UBNB, Fig. 3, and Table 3 show the evaluation results of the simulated precipitation due to the seven scenarios. Fig. 3a shows the mean monthly precipitation, which represents the mean annual cycle over the UBNB. The annual mean of the PP7 is about 1232 mm. Most of the RegCM5 simulations follow the observed precipitation pattern but there is a high overestimation, especially the S1 that uses the Grell scheme. It is also noticed that the overestimation is reduced when changing the microphysics scheme from SUBEX to NoTo indicating that the SUBEX overestimates the large-scale precipitation over the UBNB. For NoTo scenarios, both Emanuel and Tiedtke (S5 and S6) are closer to the PP7 than Kain-Fritsch (S7), especially at the onset of the rainy seasons (FMAM & JJAS). The NoTo not only corrects the overestimation but also reduces the significance between the CCs.

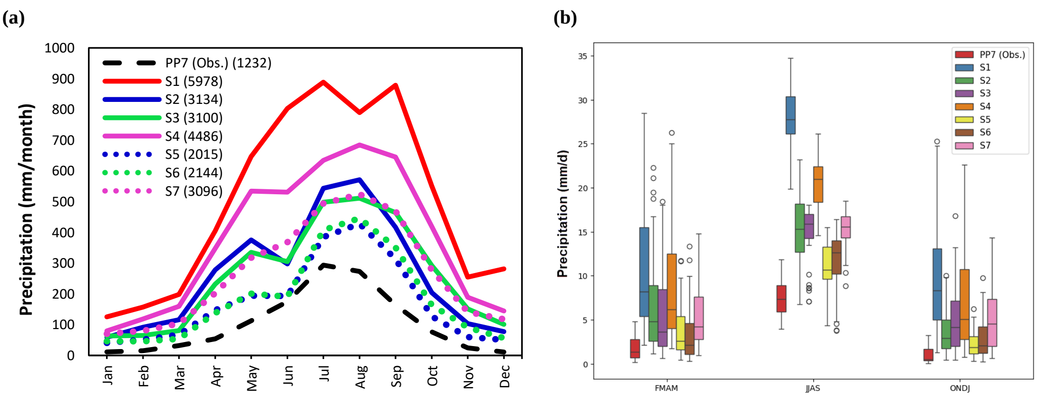

Figure 3. Simulations of precipitation over UBNB; (a) the mean monthly, and (b) boxplots of the monthly mean during rain and dry seasons.

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To analyze the variation of the three climate seasons (FMAM, JJAS, and ONDJ) over the UBNB, the monthly mean precipitation boxplots are calculated (Fig. 3b). It is noticed that NoTo (S5, S6, and S7) succeeded to reduce the precipitation range. In addition, it captures the low rainfall values in the wet season (JJAS). S5 & S6 boxplots are also closer to the PP7 boxplots than the other scenarios. Table 3 reports the estimated statistical criteria that investigate the error of the model simulations of the mean areal precipitation over the basin. It is found that the criteria for the simulations are out of the accepted ranges except for the S5, which has a satisfactory performance for the Bias% according to (Moriasi et al., 2007) and recorded the best value of the RSR.

Table 3. Error-based statistical criteria and its accepted range

Scenario	Bias%	RSR
	Bias% < ±75	0.0 ≤ RSR ≤ 0.7
S1	339	4.60
S2	153	2.10
S3	149	2.00
S4	261	3.25
S5	66	1.00
S6	76	1.20
S7	155	1.90

4.2 Spatiotemporal Evaluation

The part 2 scenarios (S5, S6, and S7), which use the NoTo microphysics scheme, are selected to evaluate the performance of the RegCM5 through analyzing the spatial pattern and the intra-annual variability for the three seasons. Figure 4 shows the seasonal mean of the observed and simulated precipitation and Fig. 5 shows the Bias% with respect to PP7 observation data. The model captures the high precipitation locations in the central and southern mountainous regions of the basin but with high overestimation, especially in the Kain-Fritsch scenario. However, the model overestimated the eastern and south-western regions which are considered semiarid and receive low rainfall compared to the central and southern regions. Emanuel, which has the lowest overestimation, underestimated the precipitation in the western region in JJAS with a negative bias of about 10%. In the FMAM season, Tiedtke has a slightly lower overestimation than Emanuel.

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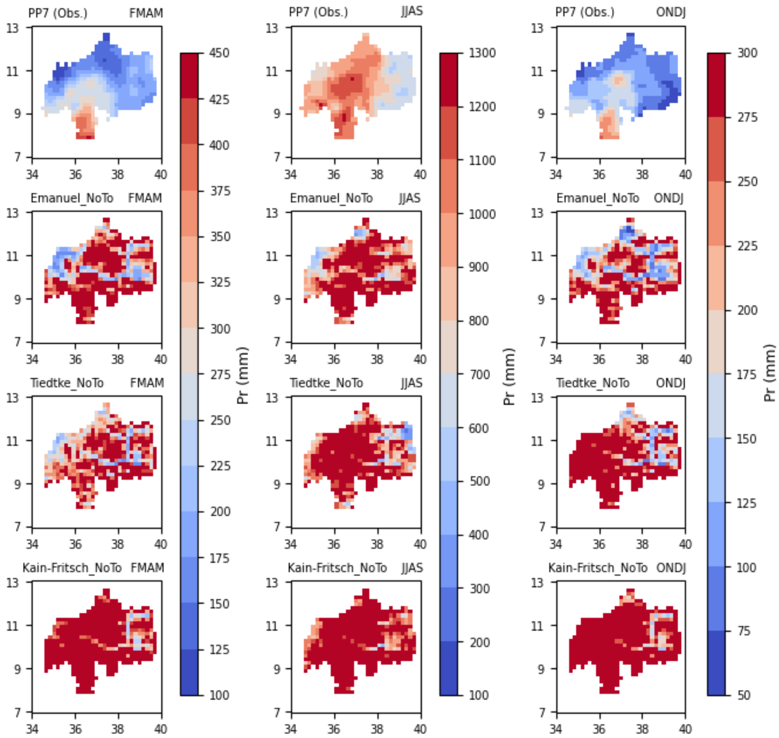

Figure 4. Seasonal mean precipitation over the UBNB for (FMAM, JJAS, and ONDJ) at (left, middle, and right) columns.

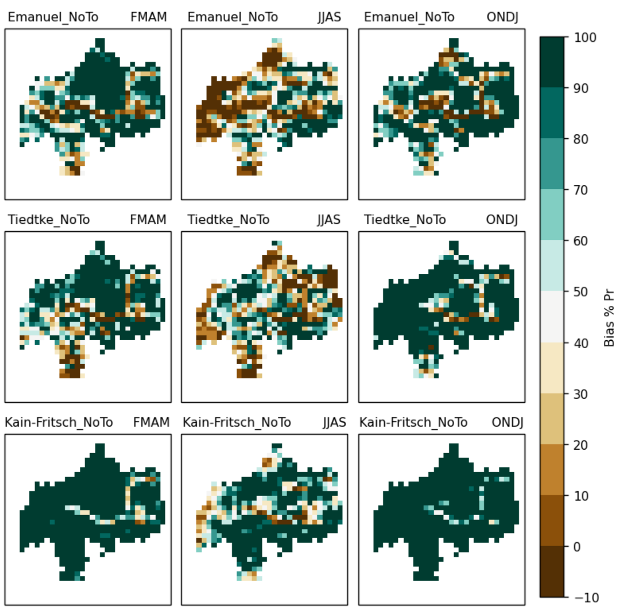

Figure 5. Seasonal mean precipitation percent bias (Bias%) with respect to the PP7 observation data over the UBNB during the three seasons (FMAM, JJAS, and ONDJ) at (left, middle, and right) columns.

Figure 6 represents the spatial variation of the correlation coefficient between the monthly mean time series of the simulated precipitation of S5, S6, and S7 and PP7 observed precipitation during the three seasons. The correlation ranges from 0.46 to

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0.77 showing a moderate to relatively good relationship between the simulated and observed precipitation. This indicates that the model captures the temporal variability reasonably well, but the model configurations still need an enhancement.

The spatial patterns of correlation provide critical insight into areas where the model exhibits deficiencies. For FMAM season, weak to moderate correlations dominate most of the basin and the eastern regions exhibit a lack of strong correlation. In the east of UBNB, short rains during FMAM are largely influenced by localized convective systems, which are difficult to simulate accurately. In JJAS, the model shows higher correlations in the west, while a negative correlation over the southwestern part.

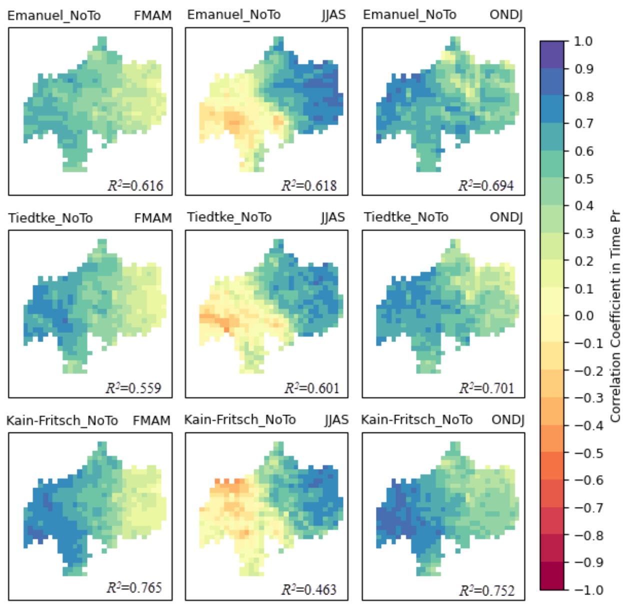

Figure 6. Correlation coefficient with respect to the PP7 observation data over the UBNB during the three seasons (FMAM, JJAS, and ONDJ) at (left, middle, and right) columns.

The weak correlation in these parts of the UBNB; eastern/southwestern during FMAM/JJAS, reflects the deficiency of the model to simulate the large-scale circulation associated with the rainfall generation during these seasons. During the FMAM rains over Ethiopia, the large-scale convection in the lower troposphere is fostered by the downward bent of the subtropical westerly jet (SWJ) at upper levels (Zeleke et al., 2016). Similarly, (Fekadu, 2015) highlighted that the interaction of the SWJ with deep troughs in the easterly flow enhances upward motion and moisture convergence, which is critical for rain production during FMAM. For the major long rains during JJAS, the southwestern UBNB is exposed to westerly rains for a longer time than the eastern and northeast parts (Mellander et al., 2013) benefiting from lower tropospheric southwesterlies from the Atlantic (Nicholson, 2017) due to the windward side of the Ethiopian Highlands. These westerly rains are attributed to the large-scale circulation such as the tropical easterly jet (TEJ) and the Eastern Africa Low-Level Jet (EALLJ). TEJ and EALLJ with the quasi-permanent high-pressure systems over the South Atlantic and South Indian Ocean together affect the quality of the JJAS rain season (Camberlin, 2009; Mohamed et al., 2005). The formation and movement of these systems, along with their interactions with local topography and atmospheric conditions, are essential in driving precipitation patterns. For example, large-scale features like the TEJ and shifts in the position of troughs can create instabilities that result in significant rainfall (Yin et al., 2023). As a result, the FMAM (JJAS) rainfall is longer over northern and northeastern (southwestern) parts of the UBNB (Birhan et al., 2019).

Finally, the PDFs are analyzed to assess the daily precipitation characteristics simulated in these selected scenarios. The PDFs are shown for the PP7 and the selected three RegCM5 simulations in Fig. 7a, b, and c during the FMAM, JJAS, and ONDJ respectively. The simulations couldn't capture the PDF of PP7, especially the low and mid precipitation intensity, which is

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very clear during the wet season (JJAS), Fig. 7b. However, the PDF of Emanuel_NoTo, (S5), is closer than the other simulations. Tiedtke_NoTo, (S6), slightly enhances the daily precipitation representation during the FMAM, Fig. 7a.

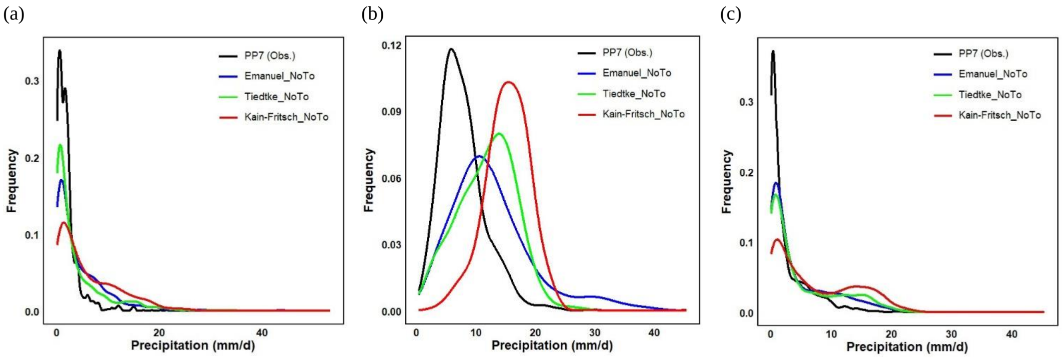

Figure 7. The PDF of the daily precipitation over the UBNB during seasons; (a) FMAM), (b) JJAS, and (c) ONDJ.

The BS and SS scores are reported in Table 4 to evaluate the PDFs. Emanuel_NoTo (S5) has the lowest BS and the highest SS (best results) during JJAS and ONDJ, while for FMAM, the best BS and SS found when using Tidetke_NoTo (S6). This demonstrates the visualization interpretation from Fig. 7. The intensity of precipitation events is also influenced by the positioning and dynamics of upper-level jets and troughs (Qi et al., 2023). Therefore, RegCM5 may face challenges in accurately representing these complex interactions due to limitations in parameterizations and resolution. Refining the spatial scale increases the natural variability of the precipitation challenging the detection of forced signals (Giorgi, 2002). Hence, at such high resolution simulation, hydrostatic dynamic may struggle to correctly parameterize interactions between local and large-scale circulations. It should be also noted that the observed data may be affected by significant uncertainties. The PP7 is a merge between gauges, collected from data summaries provided by the World Meteorological Organization (WMO), and satellite data. The reported records of rain gauges that cover the UBNB are not error free, since not all the zero readings occurred but there is a possibility that rainfall occurred but was not reported (Keshta et al., 2019).

Table 4. Scores of PDFs of the simulated daily precipitation over the UBNB

Scenario	BS			SS		
	FMAM	JJAS	ONDJ	FMAM	JJAS	ONDJ
Emanuel_NoTo	0.0010	0.0007	0.0008	1.17	1.35	1.57
Tiedtke_NoTo	0.0006	0.0010	0.0009	1.31	1.25	1.50
Kain-Fritsch_NoTo	0.0017	0.0024	0.0017	0.96	0.64	1.26

Overall, the Emanuel with NoTo succeeded to simulate the UBNB precipitation, especially the JJAS, which represents ~70% of the total annual precipitation over the UBNB. However, the model configuration requires enhancement to reduce the bias in the other seasons (FMAM and ONDJ) and generally improve the spatiotemporal pattern over the UBNB. Using the new dynamic core option, MOLOCH non-hydrostatic, involved in the RegCM5 may enhance capturing the observed rainfall variability. The non-hydrostatic dynamic core improves the representation of mesoscale convective systems and tropical storms (Giorgi, 2019). Thus it can resolve fine-scale atmospheric processes circulations in regions with complex terrain and convective precipitation systems such as the UBNB. (Silué et al., 2024) found that using MOLOCH non-hydrostatic improves the simulation of precipitation intensity, diurnal cycles, and the representation of mesoscale convective systems compared to hydrostatic core. They also found that using the PBL scheme of the University of Washington (UW) (Bretherton et al., 2004) instead of its counterpart, Holtslag, showed a better representation of boundary-layer dynamics and vertical mixing. UW employs higher-order turbulence parameterizations and showed outperformance in capturing vertical profiles of temperature, humidity, and wind, leading to improved precipitation simulations during the rainy season (JJAS) over West Africa. Counting for such update can also improve the precipitation simulation over the UBNB.

6 Conclusions

In this research, we investigated the performance of the RegCM5 (hydrostatic dynamical core), using the advancement of the spatiotemporal resolution of the ERA5, to simulate the spatiotemporal variability of the precipitation over the UBNB for the wet and dry seasons. The model captures the general pattern of the observed rainfall, although it is overestimated compared to PP7 observation data. The non-convective precipitation is highly overestimated. The NoTo microphysics scheme outperforms the SUBEX in representing the non-convective precipitation and reduces the difference between the total precipitation scenarios. Exploring the better performance of NoTo than SUBEX, which had widely been used in earlier studies, especially over East Africa, is considered one of the research novelty. Emanuel CC over land demonstrates a relatively accurate representation of convective precipitation, which dominates rainfall in UBNB, especially during the long rain season (JJAS). During JJAS, the model spatially captures the high rainfall locations in central and southern, however, it underestimated the western UBNB with a negative bias of up to 10%. Due to the high overestimation, the model couldn't capture the low and mid intensities, which is clearly noticed in the daily PDFs.

Comparing the temporal correlation between the simulations and observation data spatially provides critical insight into areas where the model exhibits deficiencies. The model couldn't simulate the rainfall pattern over the eastern (southwestern) during FMAM (JJAS) with weak to negative correlation. Over these specific UBNB regions, the interaction of upper-level circulations such as SWJ (TEJ) with lower-level weather patterns is the dominant process that affects rainfall generation during the FMAM (JJAS). Hence, the model may fail to effectively simulate atmospheric dynamics like moisture transport, or jet stream interactions.

In conclusion, the model reasonably succeeded to simulate the precipitation over the UBNB using the Emanuel with NoTo, since it reproduces the UBNB mean annual close to the PP7 observation data with an accepted Bias%. The success of the model in capturing the spatial variability of the JJAS that represents the highest proportion of the UBNB annual precipitation (~70%) is promising for future enhancement. To enhance the model configuration, we recommend using the new dynamic core option of MOLOCH non-hydrostatic that can play a role in resolving these upper-atmosphere processes reducing biases in simulating the precipitation. In addition, we recommend to refine the physical parameterizations of the RegCM5 (e.g., PBL schemes).

Code and 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., 2023a). The model input data is available at http://clima-dods.ictp.it/regcm4. The ERA5 reanalysis data is available at https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels for the initial and boundary conditions, and https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels for the SST data. The observed precipitation data (PP7) used in this research are provided by the Egyptian Ministry of Water Resources and Irrigation (WMRI) and cannot be shared publicly due to data restrictions. The results and codes used to produce the plots for all the simulations presented in this paper are uploaded to Zenodo at https://doi.org/10.5281/zenodo.7548172 (Keshta, 2025).

Author contribution: EK was responsible for software development, formal analysis, investigation, data curation, writing the original draft, and visualization. EK and DA provided the resources. DA, AME, and MAG supervised the research. All authors contributed equally to the conceptualization, methodology, validation, and writing—review and editing.

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References

Abdelwares, M., Haggag, M., Wagdy, A., and Lelieveld, J.: Customized framework of the WRF model for regional climate simulation over the Eastern Nile basin, Theor Appl Climatol, 134, 1135–1151, 2018.

Abtew, W., Melesse, A. M., and Dessalegne, T.: El Niño Southern Oscillation link to the Blue Nile River Basin hydrology, Hydrol Process, 23, 3653–3660, 2009.

Amin, D. and Kotb, A.: Assessment of the Skill of Seasonal Meteorological Forecasts in the Eastern Nile, Nile Water Science & Engineering Journal, 8, 2015.

Birhan, M. W., Raju, U. J. P., and Kenea, SamuelT.: Estimating the role of upper Blue Nile basin moisture budget and recycling ratio in spatiotemporal precipitation distributions, J Atmos Sol Terr Phys, 193, 105064, 2019.

Bretherton, C. S., McCaa, J. R., and Grenier, H.: A New Parameterization for Shallow Cumulus Convection and Its Application to Marine Subtropical Cloud-Topped Boundary Layers. Part I: Description and 1D Results, Mon Weather Rev, 132, 864–882, 2004.

Brier, G. W.: Verification of Forecasts Expressed in terms of Probability, Mon Weather Rev, 78, 1–3, 1950.

Camberlin, P.: Nile Basin Climates, in: The Nile: Origin, Environments, Limnology and Human Use, edited by: Dumont, H. J., Monographiae Biologicae, Springer, 307–333, 2009.

Camberlin, P. and Philippon, N.: The East African March–May Rainy Season: Associated Atmospheric Dynamics and Predictability over the 1968–97 Period, J Clim, 15, 1002–1019, 2002.

Conway, D.: The Climate and Hydrology of the Upper Blue Nile River, Geogr J, 166, 49–62, 2000.

Conway, D. and Hulme, M.: Recent fluctuations in precipitation and runoff over the Nile sub-basins and their impact on main Nile discharge, Clim Change, 25, 127–151, 1993.

Coppola, E., Giorgi, F., Mariotti, L., and Bi, X.: RegT-Band: a tropical band version of RegCM4, Clim Res, 52, 115–133, 2012.

Diro, G. T., Grimes, D. I. F., and Black, E.: Large Scale Features Affecting Ethiopian Rainfall, in: African Climate and Climate Change: Physical, Social and Political Perspectives, edited by: Williams, C. J. R. and Kniveton, D. R., Springer Netherlands, Dordrecht, 13–50, 2011.

Elsanabary, M. H. and Gan, T. Y.: Wavelet Analysis of Seasonal Rainfall Variability of the Upper Blue Nile Basin, Its Teleconnection to Global Sea Surface Temperature, and Its Forecasting by an Artificial Neural Network, Mon Weather Rev, 142, 1771–1791, 2014.

Elsanabary, M. H. and Gan, T. Y.: Evaluation of climate anomalies impacts on the Upper Blue Nile Basin in Ethiopia using a distributed and a lumped hydrologic model, J Hydrol (Amst), 530, 225–240, 2015.

Elsanabary, M. H. and Yew, T.: Evaluation of Climate Anomalies Impacts on the upper Blue Nile Basin in Ethiopia using a Distributed and a Lumped Hydrologic Model, J Hydrol (Amst), 530, 225–240, https://doi.org/10.1016/j.jhydrol.2015.09.052, 2015.

Emanuel, K. A.: A Scheme for Representing Cumulus Convection in Large-Scale Models, Journal of Atmospheric Sciences, 48, 2313–2329, 1991.

https://doi.org/10.5194/egusphere-2025-532
Preprint. Discussion started: 14 April 2025
© Author(s) 2025. CC BY 4.0 License.

Endris, H. S., Omondi, P., Jain, S., Lennard, C., Hewitson, B., Chang'a, L., Awange, J. L., Dosio, A., Ketiem, P., Nikulin, G., Panitz, H.-J., Büchner, M., Stordal, F., and Tazalika, L.: Assessment of the Performance of CORDEX Regional Climate Models in Simulating East African Rainfall, J Clim, 26, 8453–8475, 2013.

Fekadu, K.: Ethiopian Seasonal Rainfall Variability and Prediction Using Canonical Correlation Analysis (CCA), Earth Sciences, 4, 112–119, 2015.

Fraedrich, K. and Leslie, L. M.: Evaluation of Techniques for the Operational, Single Station, Short-Term Forecasting of Rainfall at a Midlatitude Station (Melbourne), Mon Weather Rev, 115, 1645–1654, 1987.

Giorgi, F.: Dependence of the surface climate interannual variability on spatial scale, Geophys Res Lett, 29, 14–16, 2002.

Giorgi, F.: Thirty Years of Regional Climate Modeling: Where Are We and Where Are We Going next?, Journal of Geophysical Research: Atmospheres, 124, 5696–5723, 2019.

Giorgi, F. and Marinucci, M. R.: A Investigation of the Sensitivity of Simulated Precipitation to Model Resolution and Its Implications for Climate Studies, Mon Weather Rev, 124, 148–166, 1996.

Giorgi, F., Marinucci, M. R., and Bates, G. T.: Development of a second generation regional climate model (RegCM2). Part I: Boundary layer and radiative transfer processes., Mon Weather Rev, 121, 2794–2813, 1993.

Giorgi, F., Coppola, E., Giuliani, G., Ciarlo, J., Pichelli, E., Nogherotto, R., Raffaele, F., Malguzzi, P., Davolio, S., Stocchi, P., and Drofa, O.: RegCM-NH V5 code, https://doi.org/10.5281/zenodo.7548172, January 2023a.

Giorgi, F., Coppola, E., Giuliani, G., Ciarlo`, J. M., Pichelli, E., Nogherotto, R., Raffaele, F., Malguzzi, P., Davolio, S., Stocchi, P., and Drofa, O.: The Fifth Generation Regional Climate Modeling System, RegCM5: Description and Illustrative Examples at Parameterized Convection and Convection-Permitting Resolutions, Journal of Geophysical Research: Atmospheres, 128, e2022JD038199, 2023b.

Grell, G. A.: Prognostic Evaluation of Assumptions Used by Cumulus Parameterizations, Mon Weather Rev, 121, 764–787, 1993.

Gudoshava, M. and Semazzi, F. H. M.: Customization and Validation of a Regional Climate Model Using Satellite Data Over East Africa, Atmosphere (Basel), 10, 2019.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N.: The ERA5 global reanalysis, Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049, 2020.

Hoffmann, L., Günther, G., Li, D., Stein, O., Wu, X., Griessbach, S., Heng, Y., Konopka, P., Müller, R., Vogel, B., and Wright, J. S.: From ERA-Interim to ERA5: The considerable impact of ECMWF's next-generation reanalysis on Lagrangian transport simulations, Atmos Chem Phys, 19, 3097–3214, https://doi.org/10.5194/ACP-19-3097-2019, 2019.

Holtslag, A. A. M., Bruijn, E. I. F. De, and Pan, H.-L.: A High Resolution Air Mass Transformation Model for Short-Range Weather Forecasting, Mon Weather Rev, 118, 1561–1575, 1990.

Janjić, Z. I.: The Step-Mountain Eta Coordinate Model: Further Developments of the Convection, Viscous Sublayer, and Turbulence Closure Schemes, Mon Weather Rev, 122, 927–945, 1994.

Kain, J. S.: The Kain–Fritsch Convective Parameterization: An Update, Journal of Applied Meteorology, 43, 170–181, 2004.

Kalmár, T., Pieczka, I., and Pongrácz, R.: A sensitivity analysis of the different setups of the RegCM4.5 model for the Carpathian region, International Journal of Climatology, 41, E1180–E1201, 2021.

Keshta, E.: A Multi-Component Model for Long-Term River Flow Forecasting. M.Sc. Thesis, M.Sc. Thesis, Ain Shams University, Cairo, Egypt, 2020.

© Author(s) 2025. CC BY 4.0 License.

Keshta, E.: Precipitation Parameterizations in RegCM5 for the Upper Blue Nile Basin: Codes and data , https://doi.org/10.5281/zenodo.15164540, February 2025.

Keshta, E., Gad, M. A., and Amin, D.: A Long–Term Response-Based Rainfall-Runoff Hydrologic Model: Case Study of The Upper Blue Nile, Hydrology, 6, 22, 2019.

Koné, B., Diedhiou, A., Touré, N. E., Sylla, M. B., Giorgi, F., Anquetin, S., Bamba, A., Diawara, A., and Kobea, A. T.: Sensitivity study of the regional climate model RegCM4 to different convective schemes over West Africa, Earth System Dynamics, 9, 1261–1278, 2018.

Li, B., Huang, Y., Du, L., and Wang, D.: Sensitivity experiments of RegCM4 using different cumulus and land surface schemes over the upper reaches of the Yangtze river, Front Earth Sci (Lausanne), 10, 2023.

Mellander, P.-E., Gebrehiwot, S. G., Gärdenäs, A. I., Bewket, W., and Bishop, K.: Summer rains and dry seasons in the upper Blue Nile Basin: the predictability of half a century of past and future spatiotemporal patterns., PLoS One, 8, e68461, 2013.

Mohamed, Y. A., van den Hurk, B. J. J. M., Savenije, H. H. G., and Bastiaanssen, W. G. M.: Hydroclimatology of the Nile: results from a regional climate model, Hydrol Earth Syst Sci, 9, 263–278, 2005.

Moriasi, D. N., Arnold, J. G., Liew, M. W. Van, Bingner, R. L., Harmel, R. D., and Veith, T. L.: Model Evaluation Guidlines for Systematic Quantification of Accuracy in Watershed Simulations, Trans ASABE, 50, 885−900, 2007.

NFC.: Nile Forecasting System (NFS), Version 6.0. Manual, Nile Forecast Center (NFC), Ministry of Water Rsources and Irrigation (MWRI): Giza, Egypt, 2009.

Nicholson, S. E.: Climate and climatic variability of rainfall over eastern Africa, Reviews of Geophysics, 55, 590–635, 2017.

Nikulin, G., Jones, C., Giorgi, F., Asrar, G., Büchner, M., Cerezo-Mota, R., Christensen, O. B., Déqué, M., Fernandez, J., Hänsler, A., van Meijgaard, E., Samuelsson, P., Sylla, M. B., and Sushama, L.: Precipitation Climatology in an Ensemble of CORDEX-Africa Regional Climate Simulations, J Clim, 25, 6057–6078, 2012.

Nogherotto, R., Tompkins, A. M., Giuliani, G., Coppola, E., and Giorgi, F.: Numerical framework and performance of the new multiple-phase cloud microphysics scheme in RegCM4.5: precipitation, cloud microphysics, and cloud radiative effects, Geosci Model Dev, 9, 2533–2547, 2016.

Oleson, K., Lawrence, D., Bonan, G., Drewniak, B., Huang, M., Koven, C., Levis, S., Li, F., Riley, W., Subin, Z., Swenson, S., Thornton, P., Bozbiyik, A., Rosie, F., Heald, C., Kluzek, E., Lamarque, J.-F., Lawrence, P., Leung, L., and Yang, Z.-L.: Technical description of version 4.5 of the Community Land Model (CLM), 2013.

Pal, J. S., Small, E. E., and Eltahir, E. A. B.: Simulation of regional-scale water and energy budgets: Representation of subgrid cloud and precipitation processes within RegCM, Journal of Geophysical Research: Atmospheres, 105, 29579–29594, 2000.

Qi, H., Lin, C., Peng, T., Zhi, X., Cui, C., Chen, W., Yin, Z., Shen, T., and Xiang, Y.: Diurnal Characteristics of Heavy Precipitation Events under Different Synoptic Circulation Patterns in the Middle and Lower Reaches of the Yangtze River in Summer, Atmosphere (Basel), 14, 2023.

Rientjes, T., Haile, A. T., and Fenta, A. A.: Diurnal rainfall variability over the Upper Blue Nile Basin: A remote sensing based approach, International Journal of Applied Earth Observation and Geoinformation, 21, 311–325, 2013.

Segele, Z. T. and Lamb, P. J.: Characterization and variability of Kiremt rainy season over Ethiopia, Meteorology and Atmospheric Physics, 89, 153–180, 2005.

Segele, Z. T., Leslie, L. M., and Lamb, P. J.: Evaluation and adaptation of a regional climate model for the Horn of Africa: rainfall climatology and interannual variability, International Journal of Climatology, 29, 47–65, 2009.

Shahin, M.: Ch2. Physiography of the Nile Basin, in: Hydrology of the Nile, Elsevier Netherlands, Amsterdam, 15–57, 1985.

Siam, M. S. and Eltahir, E. A. B.: Climate change enhances interannual variability of the Nile river flow, Nat Clim Chang, 7, 350–354, 2017.

Silué, F., Diawara, A., Koné, B., Diedhiou, A., Kouassi, A. A., Kouassi, B. K., Yoroba, F., Bamba, A., Kouadio, K., Tiémoko, D. T., Yapo, A. L. M., Koné, D. I., and Famien, A. M. L.: Assessment of the Sensitivity of the Mean Climate Simulation over

https://doi.org/10.5194/egusphere-2025-532
Preprint. Discussion started: 14 April 2025
© Author(s) 2025. CC BY 4.0 License.

West Africa to Planetary Boundary Layer Parameterization Using RegCM5 Regional Climate Model, Atmosphere (Basel), 15, 2024.

Tariku, T. B. and Gan, T. Y.: Regional climate change impact on extreme precipitation and temperature of the Nile river basin, Clim Dyn, 51, 3487–3506, 2018a.

Tariku, T. B. and Gan, T. Y.: Sensitivity of the weather research and forecasting model to parameterization schemes for regional climate of Nile River Basin, Clim Dyn, 50, 4231–4247, 2018b.

Tiedtke, M.: A Comprehensive Mass Flux Scheme for Cumulus Parameterization in Large-Scale Models, Mon Weather Rev, 117, 1779–1800, 1989.

Yin, J., Yuan, J., Peng, J., Cao, X., Duan, W., Nan, Y., Mao, M., and Feng, T.: Role of the subtropical westerly jet wave train in the eastward-moving heavy rainfall event over southern China in winter: A case study, Front Earth Sci (Lausanne), 11, 2023.

Zaroug, M. A. H., Eltahir, E. A. B., and Giorgi, F.: Droughts and floods over the upper catchment of the Blue Nile and their connections to the timing of El Niño and La Niña events, Hydrol Earth Syst Sci, 18, 1239–1249, 2014.

Zeleke, T., Giorgi, F., Mengistu Tsidu, G., and Diro, G. T.: Spatial and temporal variability of summer rainfall over Ethiopia from observations and a regional climate model experiment, Theor Appl Climatol, 111, 665–681, 2013.

Zeleke, T., Yeshita, B. D., and Agidew, F. M.: Evaluation of a Regional Climate Model for the Upper Blue Nile Region, in: Topics in Climate Modeling, edited by: Hromadka, T. and Rao, P., IntechOpen, Rijeka, https://doi.org/10.5772/64954, 2016.

Zeng, X., Zhao, M., and Dickinson, R. E.: Intercomparison of Bulk Aerodynamic Algorithms for the Computation of Sea Surface Fluxes Using TOGA COARE and TAO Data, J Clim, 11, 2628–2644, 1998.