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REVIEW

Assessment of WRF model simulations of extreme rainfall events in West Africa: a comprehensive review

**Anselem Onyejuruwa · Zhenghua Hu ·
Charles Anosike · Abu Reza Md. Towfiqul Islam ·
Dinesh Madhushanka**

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Abstract The need to advance operational capacities in numerical weather prediction models across West Africa is becoming increasingly urgent, given the rising frequency and intensity of extreme rainfall events in the region, particularly in Nigeria. This study conducted a systematic review to investigate the sensitivity and performance of the weather research and forecasting (WRF) model in simulating extreme rainfall events in Nigeria, employing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist for data filtering. The study synthesizes findings, revealing significant latitudinal variations in rainfall occurrences and an increasing trend in high rainfall amounts. Additionally, the WRF model's capacity for short-range and probabilistic rainfall forecasting is highlighted. Other key takeaways include critical challenges related to model configurations, such as physics parameterization, initial lateral and boundary conditions, and model resolution. Notably, the study uncovered a research gap in simulating deep convective systems (e.g., Mesoscale convective systems (MCSs)), which are vital and could serve as a proxy for extreme rainfall prediction in Nigeria. Despite certain limitations affecting the performance of the WRF model in most of the selected studies, it remains a valuable tool for both operational and research purposes. Its potential applications include realistic weather simulations for quantitative rainfall predictions. The study provides valuable insights into the current state of extreme rainfall events in Nigeria, using the WRF model. Therefore, we recommend future studies focusing on multiple WRF experiments to explore the rainfall-associated dynamics across Nigeria.

A. Onyejuruwa · Z. Hu (✉) · D. Madhushanka
School of Ecology and Applied Meteorology, Nanjing
University of Information Science & Technology,
Nanjing 210044, China
e-mail: zhhu@nuist.edu.cn

A. Onyejuruwa
e-mail: ans_iyke@yahoo.com

D. Madhushanka
e-mail: r.m.d.karunarathna@gmail.com

A. Onyejuruwa · C. Anosike
National Weather Forecasting and Climate Research
Center, Nigerian Meteorological Agency, Abuja, Nigeria
e-mail: c.anosike@nimet.gov.ng

Z. Hu
Collaborative Innovation Center on Forecast
and Evaluation of Meteorological Disasters, Nanjing
University of Information Science & Technology,
Nanjing 210044, China

A. R. M. T. Islam
Department of Disaster Management, Begum Rokeya
University, Rangpur 5400, Bangladesh
e-mail: towfiq_dm@brur.ac.bd

A. R. M. T. Islam
Department of Development Studies, Daffodil
International University, Dhaka 1216, Bangladesh

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Introduction

Mesoscale convective systems (MCSs) highly contribute to extreme rainfall events in the tropics (Yuan & Houze, 2010). In recent years, the frequency and intensity of unprecedented extreme rainfall episodes have increased. The variability, trends, and impacts of precipitation climatology and extensive rainfall events have been studied by researchers globally and within regions of West Africa (Akinsanola & Ogunjobi, 2014; Engel et al., 2017; Gbode et al., 2019a; Maranan et al., 2019; Ogolo & Matthew, 2022; Taylor et al., 2017). In Nigeria, research indicates a significant increase in the intensity of rainfall extremes that affect livelihoods (Akinola & Yin, 2019; Akinsanola & Aroninuola, 2016; Gbode et al., 2019a; Okorie, 2015; Owoseni et al., 2019; Enete, 2014). For instance, the extreme rainfall events of June 12, 2016, and September 29, 2012, across major cities in Nigeria caused devastating losses to lives and property (Akinola & Yin, 2019; Akinsanola & Aroninuola, 2016; Ibrahim & Afandi, 2014; Maranan et al., 2019).

Accurate and quantitative rainfall forecasting plays a vital role in policy-making for socio-economy development (Olaniyan et al., 2022). However, predicting extreme rainfall events have proven challenging; even short-range forecasts of severe occurrences has shown less accuracy (Olaniyan et al., 2021). Igri et al. (2015) noted that severe rainfall forecasts are particularly tasking due to their small spatiotemporal scale and the inherently non-continuous nature of the driving dynamics. Omotosho et al. (2000) and Omotosho & Abiodun (2007) suggested that the adequacy of wet southwesterly flow from the South Atlantic, daily variability of moisture advection, and low-level moisture transport were found to be responsible for intensified rainfall over Nigeria. Additionally, the spatial distribution and location of moisture flux divergence and wind shear in relation to the Africa Easterly Jet (AEJ) and Convective Available Potential Energy (CAPE) contribute to the maintenance of extreme rainfall events (Olaniyan et al., 2021).

Most global numerical weather prediction model struggles to accurately predict extreme rainfall events due to their low horizontal resolution (Ajibola et al., 2020; Raj et al., 2019). Regional numerical weather prediction (NWP) models could help fill significant lapses in rainfall forecasting, especially in West Africa, where quality ground observation data is lacking (Engel et al., 2017). The convective signature of West African rainfall presents a challenge for forecasting intense rainfall events in the region. High-resolution or convective-permitting regional models, such as the weather research and forecasting (WRF) model, which have been found to replicate extreme rainfall events significantly in various studies. For instance, there is a growing number of research on extreme rainfall simulations in WRF models both globally (Castorina et al., 2022; Chen et al., 2023; Ferreira et al., 2014; Gorja et al., 2023; Mazzoglio et al., 2022; Thomas et al., 2023), and within West Africa (Flaounas et al., 2011; Gbode et al., 2019a, b; Kouadio et al., 2020; Tanessong et al., 2017). Akinola and Yin (2019) provide focused information on WRF cloud properties from two extreme rainfall events in Nigeria. However, a comprehensive study evaluating the performance and limitations of this numerical model's rainfall simulation in Nigeria is still lacking. Therefore, this current study utilized the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) systematic review approach scheme to analyze studies on the WRF model (model framework described in the "Domain study" section) in the simulation of extreme rainfall events. This systematic review approach enhances the quality and confidence of explicitly reported techniques, allowing them to be regenerated and assessed (Page et al., 2021).

The specific objective of this study is to investigate the performance of the WRF model in simulating extreme rainfall events in Nigeria. Furthermore, analyzes the sensitivity of different parameterization physics schemes combinations in WRF model in reproducing rainfall amounts. Finally, operational rainfall forecasters and research may benefit from the study as it hopes to address related questions regarding the predictability of rainfall events in the WRF model: (i) How well can the WRF model capture a deep convective system in Nigeria? (ii) Which WRF model physics dominate in the production and formation of rainfall processes over West Africa? The other part of this work is arranged as follows: the "Domain study" section describes the study area; the "Method" section shows the methods and model description; the "Results" section shows the results in the different categories; the "Discussion" and "Conclusion" sections and are the discussion and conclusion, respectively.

Domain study

The West African region is located between 20°W and 20°E longitude and 0° to 25°N latitude (Fig. 1a). The area can be divided into two distinct climatic zones: the Guinea Coast and the Sahel (Ajibola et al., 2020). Nigeria is situated on the eastern flank of West Africa, bordered by Benin Republic to the west, Niger Republic and Lake Chad to the north, Cameroon to the east, and the Atlantic Ocean to the south. Figure 1b shows the latitudinal variation in very heavy rainfall days (> 20 mm) in Nigeria, which decreases with increasing latitude (Owoseni et al., 2019). The R20mm value for rainfall days reaches up to 2200 mm/day in coastal regions and ≤ 600 mm/day in the Sahel region of Nigeria. The region experiences fluxes of wet (southwesterly) and dry (northeasterly) winds, which emerge from the Atlantic Ocean and the Saharan Desert (Ogwang et al., 2020). These two trade winds are responsible for the positioning and evolution of summer monsoon rainfall in Nigeria (Audu et al., 2021), as shown in Fig. 1b.

Method

We adopted a systematic search and review methodology. We employed the PRISMA checklist guide (Page et al., 2021) to filter via selection criteria and quality assessment of eligibility and inclusions to achieve the best studies for this current research (Fig. 2).

Data search was initialized with no caveat on the start date until November 20, 2023. Searches were re-run after 14 days to include newly published articles. These searches were done in Web of Science, Scopus, Google Scholar, and Springer-Link archive engines. The results from the search were coded into an Excel 2016 spreadsheet (Ose, 2016), and the other co-authors performed a similar search, sharing their output as pre-coded. All search results were placed on the Excel spreadsheet for unification. The result contains information on the study's characteristics, such as author(s) name, citation, abstract, title, acceptance, and publication dates, and so on.

Identification

We applied the search items (words) differently with mixed Boolean operators. The first search used ("WRF" OR "weather research and forecasting") AND ("model simulation of extreme rainfall events" OR "Nigeria"), and the second, ("Performance of WRF model" OR "extreme rainfall events") AND ("Nigeria"). This method helps to reduce the number

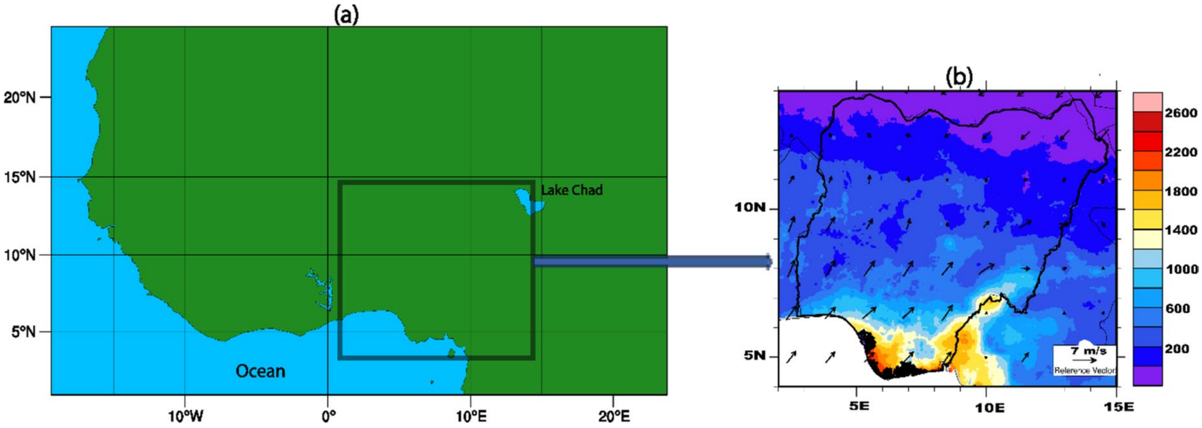

Fig. 1 **a** Mercator WRF-map projection of West Africa and Nigeria (innermost polygon). **b** Very heavy rainfall days (i.e., rainfall > R20mm) (shaded) from Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS), and wind vector (m/s) from the Fifth Generation European Centre for Medium-range Weather Forecast Reanalysis (ERA5) at 925 hPa Averaged over Nigeria for 1983–2022

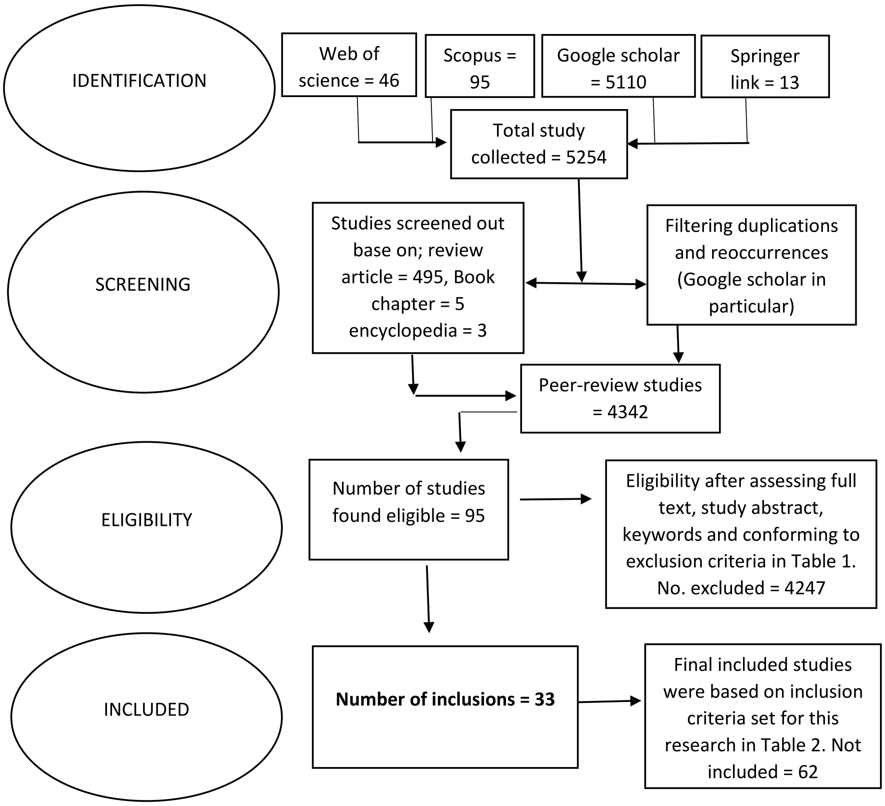

Fig. 2 Step-by-step application of PRISMA checklist guide

of study scope outliers (seen in all databases except Google Scholar) and accommodates studies with relevant research terms. The search recognized 46 studies on the Web of Science, 95 in Scopus, 5110 in Google Scholar, and 13 from the Springer-Link database.

Screening

A total of 5,254 identified studies were screened for duplications and reoccurrences. This was particularly evident in the studies retrieved from Google Scholar, due to the search engine's lack of specific filtering functions. Studies were also excluded after removing reviewed articles, book chapters, and encyclopedia publications. Overall, only English-language peer-reviewed journals were considered eligible, as they are assumed to have a broader readership.

Eligibility

Studies full text, abstract, and keywords were assessed for eligibility based on conformity on specific criteria. The exclusion criteria defined for this study is shown in Table 1.

Inclusion

The final inclusions were studies that met the inclusion requirement through their focused objective and methodology as outlined in Table 2.

Selection analysis and categorized

The quality and re-assessment of included studies were further carried out by two independent reviewers. This diagnostic measure will hopefully improve the confidence in the final included study. Consequently, the data were synthesized and categorized based on study motivation, study challenges, objectives of the research, model, and data used. The final selected or included study is categorized in Table 3.

Table 1 Overview of exclusion criteria

Conditions	Exclusion measures
i	Extreme rainfall studies outside the Nigeria domain
ii	Studies on climate future or projections
iii	Numerical Model other than deterministic regional climate model, i.e., only limited area models (LAM), e.g., WRF model
iv	Numerical studies that focused on rainfall variability, i.e., long-term or climatological precipitation simulations
v	Studies with method and data from downscaling, i.e., no studies using various downscaling method or interpolated techniques on global numerical weather prediction models, such as European Centre for Medium-range Weather Forecast (ECMWF), and Global Forecast System (GFS) models, etc

Table 2 Overview of inclusion criteria

Conditions	Inclusion requirement
1	WRF model rainfall simulation studies over West Africa
2	Cases of extreme rainfall in Nigeria
3	WRF model sensitivity performance study in West Africa
4	Rainfall trends and impact studies across Nigeria

Table 3 Overview of categories adopted for this study

S/N	Category	Domain or study coverage
1	Extreme rainfall events in Nigeria; occurrence, frequency, and impact	Nigeria
2	WRF's capability of simulating extreme rainfall in West Africa, Nigeria	West Africa
3	Sensitivity performance of model configurations in WRF model	West Africa
4	Verification data and methodology for model validation	West Africa

WRF description

The WRF model was developed by the Mesoscale and Meteorology Division of the National Center for Atmospheric Research (NCAR) (Skamarock et al., 2008, 2021). This mesoscale, non-hydrostatic numerical weather system is designed for atmospheric research and operational forecasting. It comprises multiple dynamical cores, allowing computational parallelism and system flexibility. The Advance Research WRF (ARW) dynamical core is built on equations that are fully compressible and Eulerian with a run-time hydrostatic option (Ooyama, 1990). The model employs terrain-following, hydrostatic-pressure vertical coordinate with the top of the model as a constant pressure surface and allows for multi-nesting, as well as moving nest options (Laprise, 1992). The Arakawa C-grid horizontal staggering is used (Skamarock et al., 2008).

The nesting method helps to specifically focus on a limited area to solve primitive equations on a high-resolution grid (Castorina et al., 2022). The WRF model can be employed to run both real and idealized case with different source of lateral boundary condition data. It can adjust different parameterization physics schemes for processes in the atmosphere. These include microphysics, cumulus or convective physics, planetary boundary layer, longwave and shortwave radiation options, and land surface physics (Chen et al., 2023). These physical parameterizations are used to analyze physical processes with simple approximations to reduce the number of uncertainties in that atmospheric pattern. With this, the selection of the optimal physical parameterization for weather and climate WRF simulation is essential. The WRF model is designed to run effectively on parallel distributed memory of high-performance computing systems (Zhong et al., 2023). Which increases processing

Table 4 Outlook of some commonly use WRF model design configurations

Configuration	Options (data, physics-schemes, versions, source)
WRF-Variants	Advance Research WRF (ARW), WRF-Chemistry, WRF-Hydrology, WRF-Urban, WRF-Large Eddy Simulation (LES), WRF-Solar, WRF-FIRE
Map projection	Mercator, lambert
Initial and boundary condition data	ECMWF (ERA5, and ERA-Interim), Final Global Analysis (FNL), Model for Ozone and Related Chemical Tracers (MOZART), Model for Simulating Aerosol interactions and Chemistry (MOSAIC), Goddard Chemistry Aerosol Radiation and Transport (GOCART)
Land use data	Moderate Resolution Imaging Spectroradiometer (MODIS), United State Geological Survey (USGS)
Model resolution	Choose suitable resolution in km or meters
Microphysics/cloud scheme	Goddard, WRF-single-moment-class5 (WSM5), WRF-single-moment-class6 (WSM6), Thompson, WRF-double-moment-class6 (DM6), Morrison
Cumulus/ convective scheme	Kain-Fritsch, Betts-Miller-Janji (BMJ), Grell-Freitas Ensemble, New Tiedtke (nTDK), New Simplified Arakawa-Schubert (nSAS) Schemes
Planetary boundary layer	Yonsei University (YSU), Mellor-Yamada-Janjic (MYJ), Asymmetric Convection Model 2 (ACM2), Mellor-Yamada Nakanishi Niino 2.5 & 3 (MYNN), Quasi-normal Scale Elimination (QNSE) Schemes
Shortwave and longwave physics	Dudhia, Rapid Radiative transfer Model (RRTM), Rapid Radiative transfer Model Global models (RRTMG), Community Atmospheric Model (CAM)
Land surface	Unified Noah, Noah-Multiparameterization (MP)

speed for resolving complex atmospheric equations for various users. However, the WRF model is computationally demanding, especially running large domains at fine model resolution.

The WRF model has evolved from different versions. Currently, at the time of this study, WRF version 4.5 is the latest. The ARW model can be assessed from the earlier version till present are available.[1] Druyan et al. (2009) have been cited as the first study of WRF over the West Africa region by Noble et al. (2014). Table 4 describes assumed commonly used configurations for WRF experiment designs in simulations in West Africa.

Results

We found 5254 studies from our search with four database science engines as earlier described, using the study's major focus objective terms "performance of WRF model simulation of extreme rainfall events in Nigeria." The full identity and characteristics of the 33 included studies. The studies is categorized into four groups.

Extreme rainfall events in Nigeria

Like every other region in the Tropics, Nigeria experiences pronounced climate variability, which is evident in the high frequency and intensity of extreme rainfall events across the region (studies in Table 5). In most cases, this leads to flooding, resulting in damages such as land cover degradation and infrastructure damage (Abiodun et al., 2017; Akinsanola & Ogunjobi, 2014). In this category, we found 18 studies from the overall inclusion focusing rainfall events in Nigeria (Table 5). Positive trends in related heavy rainfall activities were reported in nine studies (Audu et al., 2021; Babatolu et al., 2014; Dike et al., 2020; Ogolo & Matthew, 2022; Okoloye et al., 2013; Ogwang et al., 2020; Owoseni et al., 2019; Udosen, 2012; and Umar, 2012), indicating an increase in positive rainfall trends in Nigeria. Regarding extreme rainfall in Nigeria, Agada and Nirupama (2015), Agogbuo et al., (2017), Akinola & Yin (2019), Doan et al. (2023), Gbode et al. (2023), Ibrahim and Afandi (2014), Maranan et al. (2019), Olaniyan et al. (2021), and Vizy and Cook (2023) investigated high intensity rainfall events. These extreme events have been reported to increase in both frequency and intensity since the 1980s. Babatolu et al. (2014), Dike et al. (2020), Okoloye et al. (2013), and Udosen (2012) revealed a further increase in trends between 2005

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[1] https://www2.mmm.ucar.edu/wrf/users/wrf_files/

Table 5 Summary of studies included extreme rainfall (frequency, intensity, and occurrence) events in Nigeria

S/N	Title/authors	Extreme event/evaluation period	Event description	Event location
1	Extreme rainfall events in the West Africa Sahel: Understanding storm development over the Damergou gap using convection-permitting simulations in the Weather Research and Forecasting model. (Vizy & Cook, 2023)	July 19, 2001	High rainfall event	Northern-Sahel Nigeria
2	Rainfall Trends in Uyo-Akwa Ibom State and its Implication on Urban Flooding. (Udosen, 2012)	1977–2010	High rainfall and flood events	South-coastal Nigeria
3	Spatial and temporal analysis of observed trends in extreme precipitation events in different climatic zones of Nigeria. (Ogolo & Matthew, 2022)	1983–2017	Rainfall trend; high rainfall events	Entire Nigeria
4	Interactions between Convection and a moist Vortex Associated with an extreme rainfall event over Southern West Africa. (Maranan et al., 2019)	June 12, 2016	High rainfall amount	Southern Nigeria
5	Heavy Rainfall/Flash Flood Events Forecasting in Africa: Nigeria as a case study. (Ogwang et al., 2020)	1971–2014	High Rainfall period	Entire Nigeria
6	Short-Range Rainfall Prediction over Nigeria Using the Weather Research and Forecasting Model.(Ibrahim & Afandi, 2014)	September 29, 2012	High rainfall event	Entire Nigeria
7	Verification of multiresolution model forecasts of heavy rainfall events from 23 to 26 August 2017 over Nigeria. (Gbode et al., 2023)	August 23–26, 2017	High rainfall event	Entire Nigeria
8	Evaluation of trends, cycles and effects of extreme rainfall events on hydraulic design over Nigeria. (Owoseni et al., 2019)	1975–2015 period	Rainfall Trends; frequency and intensity	Entire Nigeria
9	Variability and trends of daily heavy rainfall events over Niger River Basin Development Authority Area in Nigeria. (Babatolu et al., 2014)	1941–2010	Trend increase in the frequency of heavy rainfall	Northern Nigeria
10	Tracking urban footprint on extreme precipitation in an African megacity. (Doan et al., 2023)	May 30, 2006	High rainfall event	South-coastal Nigeria

Table 5 (continued)

S/N	Title/authors	Extreme event/evaluation period	Event description	Event location
11	Evaluation of selected numerical weather prediction models for a case of widespread rainfall over central and southern Nigeria. (Agogbuo et al., 2017)	March 21, 2015	High rainfall event	Entire Nigeria
12	A serious flooding event in Nigeria in 2012 with specific focus on Benue state: a brief review. (Agada & Nirupama, 2015)	March 2012	High rainfall event	Central Nigeria
13	An Assessment of the role of ice hydrometeor-types in WRF bulk microphysical schemes in simulating two heavy rainfall events over southern Nigeria. (Akinola & Yin, 2019)	June 12, 2016, and September 29, 2012, events	High rainfall events	Southern Nigeria
14	Intensification of summer rainfall extremes over Nigeria during recent decades. (Dike et al., 2020)	1975–2013	Increase trend in total precipitation and R20mm	Entire Nigeria
15	Analysis of extreme rainfall events and risk of drought and flood occurrences in Nigeria. (Umar, 2012)	1901–2000	High rainfall occurrences	Entire Nigeria
16	Rainfall variability and the recent climate extremes in Nigeria. (Okoloye et al., 2013)	2007–2011	Increase climate extreme trend	Entire Nigeria
17	Assessment of spatial distribution and temporal trends of precipitation and its extremes over Nigeria. (Audu et al., 2021)	1979–2013	High Rainfall indices	Entire Nigeria
18	Impact of Moisture Flux and Vertical Wind Shear on Forecasting Extreme Rainfall Events in Nigeria. (Olaniyan et al., 2021)	July 1–3, 2014	High rainfall event	Nigeria

and 2010. Given the increasing warming trend and its potential influence on rainfall variability and anomalies, along with concern about a potential increase in the frequency and intensity of high rainfall events, it is crucial to evaluate and incorporate regional climate models (RCMs) for both research and operations.

WRF capability of simulating extreme rainfall in West Africa

Most extreme rainfall episodes in West Africa are associated with mesoscale convective systems (Maranan et al., 2018, 2019; Nicholson, 2013). Moreover, their prediction can be challenging due to the complex synoptic and sub-synoptic features influenced by surface inhomogeneities such as vegetation and orography (Ajibola et al., 2020). Most GCM precipitation simulations with coarse to medium resolution indicate limitations in accuracy due to the non-inclusion of local factors in the driving data (Ajibola et al., 2020; Raj et al., 2019). Studies have shown that increasing the resolution of driving data can improve the simulation of extreme rainfalls in the GCMs (Ajibola et al., 2020; Castorina et al., 2022). Most extreme rainfall events in West Africa, particularly in Nigeria, were localized (Akinola & Yin, 2019; Akinsanola & Aroninuola, 2016; Engel et al., 2017; Ibrahim & Afandi, 2014). Regional climate models (RCMs) are limited area NWP models capable of simulating atmospheric and hydrological processes, when coupled with high resolution features of local components such as topography, surface condition, and land-sea interaction information (Noble et al., 2014). In this context, we found 20 studies among the included archives that assessed the ability of the WRF model to reproduce extreme rainfall events, as indicated in Table 6.

As alluded to in earlier references, WRF simulations' performance can vary with seasons, location, and even variables of interest. Flaounas et al. (2011), Tanessong et al. (2014), Igri et al. (2015), Gbode et al., (2019a, b, 2021), Vizy and Cook (2019), and

Table 6 Included studies for the WRF's capability to simulate extreme rainfall category

S/N	Title/author(s)	Model variant
1	Extreme rainfall events in the West African Sahel: Understanding storm development over the Damergou gap using convection-permitting simulations in the Weather Research and Forecasting model. (Vizy & Cook, 2023)	WRF-ARW
2	Short-Range Rainfall Prediction over Nigeria Using the Weather Research and Forecasting Model. (Ibrahim & Afandi, 2014)	WRF-ARW
3	Verification of multiresolution model forecasts of heavy rainfall events from 23 to 26 August 2017 over Nigeria. (Gbode et al., 2023)	WRF-ARW
4	Tracking urban footprint on extreme precipitation in an African megacity. (Doan et al., 2023)	WRF-Urban
5	An Assessment of the Role of Ice Hydrometeor-Types in WRF Bulk Microphysical Schemes in Simulating Two Heavy Rainfall Events over Southern Nigeria. (Akinola & Yin, 2019)	WRF-ARW
6	Evaluation of probabilistic precipitation forecast determined from WRF forecasted amounts. (Tanessong et al., 2014)	WRF-ARW
7	WRF high resolution simulation of an extreme rainfall event over Douala (Cameroon): a case study. (Tanessong et al., 2017)	WRF-ARW
8	Potential effects of Land Use Land Cover Change on streamflow over the Sokoto Rima River Basin. (Achugbu, et al., 2022b)	WRF-Hydro
9	Evaluation of selected numerical weather prediction models for a case of widespread rainfall over Central and Southern Nigeria. (Agogbuo et al., 2017)	WRF-ARW
10	Potential of the Coupled WRF/WRF-Hydro Modeling System for Flood Forecasting in the Oueme River (West Africa). (Quenum et al., 2022)	WRF-Hydro
11	Understanding the summertime diurnal cycle of precipitation over sub-Saharan West Africa: regions with daytime rainfall peaks in the absence of significant topographic features (Vizy & cook, 2019)	WRF-ARW
12	Sensitivity of different physics schemes in the WRF model during a West African monsoon regime. (Gbode et al., 2019a)	WRF-ARW
13	Simulation of wet and dry West African monsoon rainfall seasons using the Weather Research and Forecasting model. (Gbode et al., 2019b)	WRF-ARW
14	The sensitivity of WRF daily summertime simulations over West Africa to alternative parameterizations. Part II: Precipitation. (Noble et al., 2017)	WRF-ARW
15	Assessing the performance of WRF model in predicting high-impact weather conditions over Central and Western Africa: an ensemble-based approach. (Igri et al., 2018)	WRF-ARW
16	Added-value of 3DVAR data assimilation in the simulation of heavy rainfall events over West and Central Africa. (Igri et al., 2015)	WRF-ARW
17	Regional climate modelling of the 2006 West African monsoon: Sensitivity to convection and planetary boundary layer parameterization using WRF. (Flaounas et al., 2011)	WRF-ARW
18	Does convection-permitting simulate better rainfall distribution and extreme over Guinean coast and surroundings? (Kouadio et al., 2020)	WRF-ARW
19	Modeling the spatiotemporal response of dew point temperature, air temperature and rainfall land use cover change over West Africa. (Achugbu et al., 2022a)	WRF-ARW
20	Assessment of WRF land surface model performance over West Africa. (Achugbu et al., 2020)	WRF-ARW

Kouadio et al. (2020) evaluated the capability of the WRF model in simulating the WAM rainfall. The West African Monsoon (WAM) regime produces over 2500 mm of rainfall annually in the region (Raj et al., 2019). Studies have explained that the major drivers for WAM rainfall are the dynamic features (Biasutti, 2019; Sylla et al., 2010); hence, their proper representation in the WRF model will benefit proper simulation of WAM rainfall. The WRF experiments performed better in presenting these drivers: Saharan heat low (SHL), zonal wind, African easterly waves (AEWs), African easterly jet (AEJ), and surface temperature in these studies (Flaounas et al., 2011; Igri et al., 2015; Gbode et al., 2019a, b, 2021); other atmospheric parameters such as geopotential height and relative vorticity have also been shown to be connected to rainfall during this period (Vizy & Cook, 2019). The WRF capability was assessed for the 2010 WAM wet season, and the result is based on probabilistic evaluation, and it indicates that a rainfall event has a high probability of occurring (Tanessong et al., 2014), and Kouadio et al. (2020) assessed the impact of fine and coarse WRF resolutions in simulating the WAM of 2014. Both resolutions were able to replicate the seasonal scale rainfall; however, the simulation using the convectively resolved scale resolution presented a more realistic extreme rainfall than the parameterized simulation.

For high impact-base rainfall events, the West African domain is one region in the tropics that is dominated by deep convective activities (Maranan et al., 2019; Rajeevan et al., 2010). Studies have cited extreme rainfall events within West Africa with devastating impacts (Akinsanola &Aroninuola 2016; Engel et al., 2017; Gbode et al., 2019a; Maranan et al., 2019). Akinola and Yin (2019) and Ibrahim and Afandi (2014) demonstrate the ability of the WRF model to realistically reproduce the extreme rainfall event of September 29, 2012, in Nigeria. Some of these high rainfall events are triggered by high thermodynamic values, especially at low-level atmospheres; for example, accurate WRF simulations of convective available potential energy (CAPE) and relative humidity have been associated with heavy rainfall in experiments (Tanessong et al., 2017; Vizy & Cook, 2023). Furthermore, extreme rainfall associated with AEWs was better simulated (Noble et al., 2017) even in both the convective scale (≤ 4 km) and the non-convective scale (> 4 km) (Gbode et al., 2023). Most localized extreme rainfall episodes may be influenced by land changes; reports indicate that deforestation increases rainfall activity (Abiodun et al., 2008). On the contrary, other documentations suggest that afforestation could induce and potentially increase the extreme rainfall events, leading to flooding (Abiodun et al., 2013). Achugbu et al., (2020, 2022a, b), Kouadio et al. (2020), and Doan et al. (2023) evaluated rainfall events attributed to urbanization and afforestation in WRF model simulations. In a sensitivity test, WRF-urban was activated, showing that higher rainfall was simulated over the urban areas than the non-urban in the WRF model (Achugbu et al., 2022a; Doan et al., 2023). The findings in Achugbu et al. (2022a) support the claim that potential increase in afforestation will lead to more in rainfall events. The updated/recent land data incorporated into the WRF model correlate well with observed rainfall data. Furthermore, a sophisticated parameterized land surface model physics with appropriate vegetation formulation can realistically capture rainfall events (Achugbu et al., 2020). The changes in land cover can also hamper the hydrological flow regime, hence may lead to distortion in streamflow and evaporation rate. WRF-Hydro were used in Achugbu et al. (2022b) and Quenum et al. (2022), findings shows that the streamflow and rainfall follow similar patterns, but differ during onsets.

Despite the capacity of the WRF model demonstrated in these studies, most authors have suggested conducting multi-case WRF model experiments (e.g., across different seasons and rainfall events) to further evaluate specific variables of interest. However, this limitation has been attributed to computational costs (Agogbuo et al., 2017; Doan et al., 2023; Flaounas et al., 2011; Gbode et al., 2023; Ibrahim & Afandi, 2014; Kouadio et al., 2020; Tanessong et al., 2014).

Sensitivity performance of model design configurations in WRF-ARW model

For West Africa to experience sustainable socioeconomic development, it is critical to accurately forecast periods of intense and extensive rainfall. The forecasting of these events remains a challenge over the region (Olaniyan et al., 2021). Hence, it is important to identify optimized model configurations, particularly non-constant (dynamic) options that would better simulate rainfall events across this region.

This involves several experimental perturbations in the parameters, physics, and domain resolution built into the model. Here we evaluate numerical studies on the sensitivity performance of different configuration options in WRF model simulation of rainfall and its associated meteorological factors. Fourteen (14) studies were linked to this part, as shown in Table 7. Flaounas et al. (2011), Noble et al. (2014), Igri et al. (2018), Akinola and Yin (2019), Gbode et al., (2019a, b, 2021), Achugbu et al. (2020), Kouadio et al. (2020), and Doan et al. (2023) evaluated the WRF performance sensitivity to different model physics. Gbode et al., (2019a, b) and Igri et al. (2015) examined the performance of WRF using different and combining initial and lateral boundary condition data sources, while fluctuations in land covers and impacts of domain resolutions (fine and coarse) were investigated in Achugbu et al., (2020, 2022b) and Gbode et al., (2023; Kouadio et al., 2020), respectively.

The issue concerning unresolved sub-grid-scale processes was attributed to horizontal resolution (Gbode et al., 2019a). The WRF model simulations with high resolution had a better production of extreme rainfall (Kouadio et al., 2020), whereas Gbode et al. (2023) find no significant difference between the simulations of convective resolved scale and the parameterized (> 4 km) in their spatial rainfall distribution. The quality and source of the model's initial and lateral boundary condition (ILBC) data could influence the performances of the designed model experiment (Di et al., 2015). Improved spatial–temporal resolution reanalysis ERA products data from the European Centers for Medium-Range Weather Forecasts (ECMWF) archives as driving data in different WRF model experiments (Gbode et al., 2019a, b), could boost reduce uncertainties in the model output. Notwithstanding, WRF experiment using three-dimensional variational data assimilation (DA) (3DVAR), which incorporates both satellite and ground observation, better deals with the issue of ILBC (Igri et al., 2015). Finally, Gbode et al., (2019a, b, 2021), Akinola and Yin (2019), Igri et al. (2018), and Noble et al. (2017) investigated the sensitivity of various model physics parameterizations by varying them in different experiments while maintaining other model configurations for an unbiased assessment. These model physics include microphysics (MP), cumulus (CU), planetary boundary layer (PBL), and land surface model (LSM) (see Skamarock et al. (2021) for the WRF model physics parameterization scheme's full names and descriptions). The fundamental difference in the performance of the various parameterization schemes is their different mathematical assumptions and formulations. The study Gbode et al. (2019a), conducted a robust WRF experiment of 27 simulations over West Africa to identify optimized WRF model configurations for forecasting rainfall events and its associated dynamics. The combination of MP's Goddard, PBL's MYJ, and CU's BMJ schemes outperformed others based on the applied statistic. Similarly, this model configuration was performed well in other studies (Gbode et al., 2019b, 2021). The different WRF physics parameterization performances are validated and evaluated for optimization using various statistical methods for ranking (see next sub-section).

Verification data and methodology for model validation

Model validation is critical to advance the evaluation and to gauge the model's ability to provide accurate simulations. However, there might be limitations in verification results due to lack of standards in reference data and systematic error in data interpolation techniques. With this, studies have used two reference data in their work to improve the confidence of model results (Akinsanola & Zhou, 2019; Gbode et al., 2019a, b). This will increase the verification results' credibility. We found 14 papers in this category (see Table 8) that used different verification techniques to calculate the margin of error or model prediction skill.

Achugbu et al., (2022a, b), Akinola and Yin (2019), Gbode et al. (2019a), Ibrahim and Afandi (2014), and Igri et al., (2015, 2018), adopt one or two and/or all of these methods; root mean square error (Rmse), mean bias (Mb), mean absolute error (Mae), standard deviation (Std), and correlation coefficient (R). Agogbuo et al. (2017) and Tanessong et al. (2014) used the probabilistic forecast base contingency table. The percentage bias and Nash–Sutcliffe efficiency index (Achugbu et al., 2022b), Hovmoller diagram (Doan et al., 2023), fractional skill score (Gbode et al., 2023), average percentage difference (Gbode et al., 2021), and added value (Kouadio et al., 2020) were all applied in assessing performances in different WRF model experiment. The Tropical

Table 7 Studies on the sensitivity performance of different WRF physics schemes in simulating heavy rainfall

S/N	Article	Sensitivity focus	Options
1	Sensitivity of different physics schemes in the WRF model during a West African monsoon regime. (Gbode et al., 2019a)	Model physics and ILBC data	MP (WSM5, Goddard), PBL (YSU, MYJ, MYNN2.5), CU (KF, BMJ, GF, nTDK, nSAS, nGF) / ERA-Interim, GFS-FNL
2	Regional climate modelling of the 2006 West African monsoon: Sensitivity to convection and planetary boundary layer parameterization using WRF. (Flaounas et al., 2011)	Model physics	PBL (MYJ, YSU), CU (GR, KF, GR3D)
3	Does convection-permitting simulate better rainfall distribution and extreme over Guinean coast and surroundings? (Kouadio et al., 2020)	Model physics and domain resolution	MP (Morrison, new Thompson, WSM6), PBL (ACM2, MYJ, YSU)
4	An Assessment of the Role of Ice Hydrometeor-Types in WRF Bulk Microphysical Schemes in Simulating Two Heavy Rainfall Events over Southern Nigeria. (Akinola & Yin, 2019)	Model physics	MP (WSM5, WSM5, Morrison, WDM6)
5	Modeling the spatiotemporal response of dew point temperature, air temperature and rainfall land use cover change over West Africa. (Achugbu et al., 2022a)	Land cover data	MODIS, USGS
6	Assessing the performance of WRF model in predicting high-impact weather conditions over Central and Western Africa: an ensemble-based approach. (Igri et al., 2018)	Model physics	CU (KF, BMJ, GD3D, Modified Tiedtke, nGFS), MP (Lin, WSM5, Dudhia, Ferrier, Thompson, Morrison), LSM (Unified-Noah, RUC, Plein and Xiu)
7	Simulation of wet and dry West African monsoon rainfall seasons using the Weather Research and Forecasting model. (Gbode et al., 2019b)	Model physics and ILBC data	MP (WSM5, Goddard), PBL (YSU, MYJ, MYNN2.5), CU (BMJ, nTDK, nSAS)
8	The sensitivity of WRF daily summertime simulations over West Africa to alternative parameterizations. Part II: Precipitation. (Noble et al., 2017)	Model physics	PBL (ACM2, MYJ, MYNN, YSU), LSM (PX, Unified-Noah, RU, 5L thermal diffusion), CU (KF, GD)
9	Added-value of 3DVAR data assimilation in the simulation of heavy rainfall events over West and Central Africa. (Igri et al., 2015)	ILBC data	Data assimilation (DA), No-DA
10	Potential effects of Land Use Land Cover Change on streamflow over the Sokoto Rima River Basin. (Achugbu et al., 2022b)	Model design and land cover	REFKDT Values (0.5, 0.6, 0.7, 1.0, 1.5, 3) / Updated-MODIS data
11	Assessment of WRF land surface model performance over West Africa. (Achugbu et al., 2020)	Model physics	Land surface model (Noah, Noah-MP, CLM4, Noah-MP GW)
12	Tracking urban footprint on extreme precipitation in an African megacity. (Doan et al., 2023)	Model physics	Urban_phy, NoUrban_phy
13	Impacts of global warming on West African Monsoon rainfall. (Gbode et al., 2021)	Model physics	MP (Goddard, WSM5), PBL (MYJ, MYNN2.5, YSU), CU (BMJ, nTDK, nSAS)
14	Verification of multiresolution model forecasts of heavy rainfall events from 23 to 26 August 2017 over Nigeria. (Gbode et al., 2023)	Domain resolution	WRF-2 km, WRF-6 km, WRF-18 km

Table 8 Included studies and validation methods in model and data verification

S/N	Article reference	Evaluation method equations	Model/data type
1	Achugbu et al. (2022a)	Root mean square error, $Rmse = \sqrt{\Sigma''_{i=1}(r_x - o_x)^2 / \mathrm{n}}$ $\mathrm{r_x}$ = Observed data o_x = model data n = Total amount of data points used for the analysis $\overline{\mathrm{o_x}}$ = Model mean $\overline{\mathrm{r_x}}$ = Observed mean	WRF/TRMM, GPCP
2	Achugbu et al. (2022b)	*Percentage Bais,* $PBais = \Sigma''_{x=1}\left(\mathrm{t_x}^{\mathrm{a}} - \mathrm{t_x}^{\mathrm{b}}\right)/\Sigma''_{x=1}\mathrm{t_x}^{\mathrm{b}} \times 100$ *Nash–Sutcliffe efficiency index,* $NSE = 1 - \Sigma''_{x=1}\left(t_x^a - t_x^b\right)^2/\Sigma''_{x=1}\left(t_x^b - t^{\eta}\right)^2$ Correlation, $R = \frac{\Sigma^{\mathrm{n}}_{\mathrm{x=1}}(\mathrm{r_x} - \overline{\mathrm{r_x}})(\mathrm{o_x} - \overline{\mathrm{o_x}})}{\sqrt{\Sigma^{\mathrm{n}}_{\mathrm{x=1}}(\mathrm{r_x} - \overline{\mathrm{r_x}})^2}\sqrt{\Sigma^{\mathrm{n}}_{\mathrm{x=1}}(\mathrm{o_x} - \overline{\mathrm{o_x}})^2}}$	WRF-hydro/Station-gauge
3	Achugbu et al. (2020)	$Rmse = \sqrt{\Sigma''_{i-1}\left(r_x - o_x\right)^2}/n,$ $R = \frac{\Sigma^{\mathrm{n}}_{\mathrm{x=1}}(\mathrm{r_x} - \overline{\mathrm{r_x}})(\mathrm{o_x} - \overline{\mathrm{o_x}})}{\sqrt{\Sigma^{\mathrm{n}}_{\mathrm{x=1}}(\mathrm{r_x} - \overline{\mathrm{r_x}})^2}\sqrt{\Sigma^{\mathrm{n}}_{\mathrm{x=1}}(\mathrm{o_x} - \overline{\mathrm{o_x}})^2}}$ $Std = \sqrt{\Sigma\left(\mathrm{r_i} - \overline{\mathrm{r_x}}\right)^2}/\mathrm{n}$	WRF/GPCP, TRMM
4	Agogbuo et al. (2017)	$Accuracy$ = (Hit + Correct-ve) / Total $Bias$ = (Hit + False_Alarm) / (Hit + Miss)	WRF, UKMet/Station-gauge, ECMWF, GFS
5	Akinola and Yin (2019)	$Rmse = \sqrt{\Sigma''_{x=1}\left(r_x - o_x\right)^2}/n$ $MB = \frac{1}{n}\Sigma^n_{x=1}\left(r_x - o_x\right)$	WRF-version3.8/TRMM
6	Doan et al. (2023)	Hovmoller diagram	WRF-version3.9.1/CMORPH, GPCP
7	Gbode et al. (2019a)	$MB = (\Sigma''_{x=1}(r_\mathrm{x} - o_\mathrm{x}))/\mathrm{n}$ $MAE = \frac{1}{n}\Sigma^n_{x=1}(\mathrm{r_x} - \mathrm{o_x})$ $R = \frac{\Sigma^n_{x=1}(\mathrm{r_x} - \overline{\mathrm{r_x}})(o_\mathrm{x} - \overline{o_\mathrm{x}})}{\sqrt{\Sigma^n_{x=1}(\mathrm{r_x} - \overline{\mathrm{r_x}})^2}\sqrt{\Sigma^n_{x=1}(o_\mathrm{x} - \overline{o_\mathrm{x}})^2}}$	WRF-version3.8.1/CMORPH, GPCP, TRMM
8	Gbode et al. (2021)	Average percentage difference	WRF-version3.8.1/TRMM, GPCP
9	Gbode et al. (2023)	$FSS = 1 - (\mathrm{MSE_x} / \mathrm{MSE_{(x)re}})$ MSE = mean standard error $MSE_{(x)re}$ = reference for each for each neighborhood length, x	WRF-version4.2, UKmet / GPM

Table 8 (continued)

S/N	Article reference	Evaluation method equations	Model/data type
10	Ibrahim and Afandi (2014)	$MB = \frac{1}{n}\sum_{x=1}^{n}\left(r_x - o_x\right)$ $Rmse = \sqrt{\Sigma_{x=1}^{\prime\prime}\left(r_x - o_x\right)^2}/n$ $MB\% = (MB / \bar{\upsilon}_o) \times 100$ $Rmse\ \% = (Rmse / \bar{\upsilon}_o) \times 100$	WRF / Station-gauge
11	Igri et al. (2015)	$Rmse = \sqrt{\sum{\prime\prime}_{x=1}\left(\mathrm{r_x} - \mathrm{o_x}\right)^2}/\mathrm{n}$ $MB = \frac{1}{n}\Sigma^{\mathrm{n}}{}_{\mathrm{x=1}}(\mathrm{r_x} - \mathrm{o_x})$ $R = \frac{\Sigma^{\mathrm{n}}{}_{\mathrm{x=1}}\left(\mathrm{r_x} - \overline{\mathrm{r_x}}\right)\left(\mathrm{o_x} - \overline{o_x}\right)}{\sqrt{\Sigma^{\mathrm{n}}{}_{\mathrm{x=1}}\left(\mathrm{r_x} - \overline{\mathrm{r_x}}\right)^2}\sqrt{\Sigma^{\mathrm{n}}{}_{\mathrm{x=1}}\left(o_x - \overline{o_x}\right)^2}}$	WRF-version3.3/TRMM
12	Igri et al. (2018)	$Rmse = \sqrt{\sum{\prime\prime}_{x=1}(\mathrm{r_x} - \mathrm{o_x})^2}/\mathrm{n}$ $MB = \frac{1}{n}\Sigma^{\mathrm{n}}{}_{\mathrm{x=1}}(\mathrm{r_x} - \mathrm{o_x})$ $R = \frac{\Sigma^{\mathrm{n}}{}_{\mathrm{x=1}}\left(\mathrm{r_x} - \overline{\mathrm{r_x}}\right)\left(\mathrm{o_x} - \overline{o_x}\right)}{\sqrt{\Sigma^{\mathrm{n}}{}_{\mathrm{x=1}}\left(\mathrm{r_x} - \overline{\mathrm{r_x}}\right)^2}\sqrt{\Sigma^{\mathrm{n}}{}_{\mathrm{x=1}}\left(\mathrm{o_x} - \overline{o_x}\right)^2}}$	WRF-version3.3/TRMM
13	Kouadio et al. (2020)	$Addedvalue(av) = ((V_{\varrho o1} - V_{o\beta})^2$ $-(V_{\varrho o2} - V_{o\beta})^2)/\max((V_{\varrho o1} - V_{o\beta})^2 \bullet (V_{\varrho o2} - V_{o\beta})^2)$ $V_{\varrho o1}$ = model with coarse resolution $V_{\varrho o2}$ = model with fine resolution $V_{o\beta}$ = observations	WRF-DA/TRMM, CHIRPS
14	Tanessong et al. (2014)	Correct-alarm ration, $CAR = \mathrm{Hit} / (\mathrm{Hit} = \mathrm{f})$ Hit ratio, $Hr = \mathrm{Hit} / (\mathrm{Hit} + \mathrm{m})$ False-alarm ration, $Far = \mathrm{f} / (\mathrm{f} + \mathrm{c})$ Miss ration, $Mr = \mathrm{m} / (\mathrm{m} + \mathrm{f})$	WRF-version 3.3/GPCP, TRMM

Rainfall Measuring Mission (TRMM) was employed by nine of these studies (Table 8), and six studies used the Global Precipitation Climatology Project (GPCP) as reference data. However, only three studies used station data to verify and validate model output, as depicted in Fig. 3. This could be due to the poor ground gauge network and lack of high temporal resolution data over the region (Akinola & Yin, 2019; Gbode et al., 2021; Maranan et al., 2019).

Discussion

The motivation behind this study is the need for a numerical method to accurately forecast extreme rainfall events in Nigeria. The WRF numerical weather prediction (NWP) model is increasingly recognized for short-range, probabilistic and, seasonal rainfall forecasting in West Africa (e.g., Gbode et al., 2019a, b; Ibrahim & Afandi, 2014; Tanessong et al., 2014). Figure 1 b depicts the climatological spatial distribution of very heavy rainfall occurrences in Nigeria, describing the latitudinal variation of rainfall and impacts over the region (Ogolo & Matthew, 2022; Owoseni et al., 2019). A consensus among the studies on rainfall trends, agree on the increasing rainfall trends in the region, particularly since the 1980s, which were linked to the gradual recovery of rainfall patterns in the Sahel region (Akinsanola & Zhou, 2019; Babatolu et al., 2014; Dike et al., 2020; Okoloye et al., 2013; Quenum et al., 2021; Udosen, 2012). Hence, underscoring the regions vulnerability to severe flooding and its socio-economic impacts.

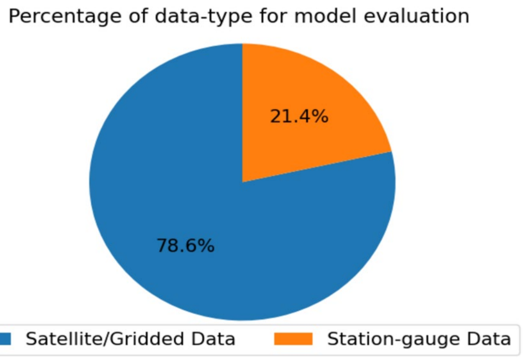

Fig. 3 Percentage ratio of station-gauge and satellite/gridded data for model validation

Reported extreme rainfall cases are highest in the southern Nigeria (Agogbuo et al., 2017; Akinola & Yin, 2019; Gbode et al., 2023; Ibrahim & Afandi, 2014; Maranan et al., 2019; Olaniyan et al., 2021), largely linked to the abundance of maritime flow into the continent (Olaniyan et al., 2021). The adverse impacts of most of these extreme rainfall events were devastating (Agada & Nirupama, 2015; Akinola & Yin, 2019).

The work by Druyan et al. (2009) employed the WRF model as a regional model during the AMMA Special Observing Period project. This referred study is the novel application of WRF model in West Africa. Since then, several have utilized the WRF model in the region, particularly in Nigeria, as shown in Table 6. Despite this, the WRF model is not used for operational purposes in the national meteorological services, but the Consortium for Small-scale Modeling (COSMO) (Olaniyan et al., 2015). However, this review study only focusses on the application of WRF models. Table 6 also highlights various WRF variant studies, although WRF-Chem studies were excluded in final inclusion, because none of its identified study focus on rainfall events. Interestingly, studies outside the domain had compared the performances of WRF-ARW and WRF-Chem in simulating parameters associated with extreme rainfall events (Chen et al., 2023; Yahya et al., 2016). These studies have suggested better performance with WRF-Chem.

Notwithstanding, the WRF-ARW model has demonstrated the ability to reproduce rainfall events in West Africa (Table 5). WRF model performance can be evaluated based on how well it represents precipitation and its associated synoptic and sub-synoptic conditions. High rainfall activities occur more frequently during the WAM. The key components driving the WAM includes AEJ, TEJ, AEWs, SHL, LLWS, AEWs, in particularly, have been linked to various convective activities in West Africa (Gbode et al., 2019a; Noble et al., 2014, 2017; Vizy & Cook, 2019, 2023). In most of their findings, the WRF model successfully simulated the westward movement of precipitation associated with AEWs. However, an earlier study suggested that not all heavy rainfall is associated with AEWs (Taleb & Druyan, 2003), instead the position of AEJ is often a determinant of rainfall across the West African domain (Achugbu et al., 2020; Flaounas et al., 2011; Gbode et al., 2019b; Igri et al., 2018). These studies have demonstrated WRF's capability to accurately reproduce WAM's dynamics parameters well. Other atmospheric instabilities and local conditions whose perturbation strongly influences extreme rainfall phenomena were also examined as a measure for WRF performance. Most of these synoptic and local conditions were realistically reproduced in the WRF model (Akinola & Yin, 2019; Gbode et al., 2019a, b; Ibrahim & Afandi, 2014; Igri et al., 2015; Tanessong et al., 2017; Vizy & Cook, 2023). The model simulated CAPE values suggests that CAPE is not a good predictor for extreme rainfall (Vizy & Cook, 2023); they argued that extreme rainfall events could occur even at CAPE < 2000 J/kg.

Surface cover and land change significantly influence the rate and magnitude of extreme rainfall events due to surface-atmosphere interaction (Williams & Kniveton, 2012). Urbanization which reduces evapotranspiration can increased sensible heat flux, resulting in an urban heat island effect (Hao et al., 2023). This effect triggers low-level convergence, creating favorable conditions for moisture inflow (Achugbu et al., 2022a; Doan et al., 2023). The WRF model simulations have showed a decrease/increase rainfall amount over afforestation/deforestation areas (Achugbu et al., 2022a; Doan et al., 2023; Odoulami et al., 2019). Changes in land cover and long-term updated topography data can vary results of precipitation simulations in the WRF model (Achugbu et al., 2020; Kouadio et al., 2020; Vizy & Cook, 2023).

The application of WRF-hydro variant has shown a reasonable simulation of streamflow when compared with precipitation pattern (Achugbu et al., 2022b; Quenum et al., 2022). Generally, streamflow and precipitation follow a similar pattern when there is little or no land cover changes. Although streamflow may not correlate exactly with the onset of precipitation. This performance of WRF-hydro is consistent with findings from studies conducted in other region (Kerandi et al., 2017; Uribe et al., 2020).

The sensitivity of different configurations in WRF model experiment design plays a crucial role in determining model performance. A study Di et al. (2015) emphasized that the ability of the WRF model to accurately predict weather events depends primarily on the model's physical processes, initial and boundary input data, and model design equations. However, the model's performance varies depending on location, season, model physics, and the variable of interest (Gbode et al., 2019a, b; Kumar et al., 2014). Physics parameterization is a method of approximating physical processes at various scales in a model through simplified procedures (Zhong et al., 2023). Table 7 highlights that most WRF sensitivity studies have focused on physics parameterization schemes. This is because physical schemes have been identified as a major source of bias in high-resolution models (Rajeevan et al., 2010). The WSM5 and Goddard MP schemes were found to be highly sensitive when combined with other model physics schemes, as noted by Noble et al. (2017), Akinola and Yin (2019), and Gbode et al., (2019a, b, 2021). The performance of these simple MP physics schemes suggest that complex or double-moment MP schemes do not necessarily outperform single-moment schemes.

The improved nSAS and nTDK CU schemes demonstrated distinct performance characteristics when activated in non-convective permitting domains (i.e., horizontal resolution > 4 km), especially when coupled with the MYJ PBL scheme and other schemes (Flaounas et al., 2011; Gbode et al., 2019a, b, 2021). For the land surface model physics (LSM), the Noah and Noah-MP LSM schemes were outperformed by the updated Noah-MP GW scheme (Achugbu et al., 2020). Moreover, research on WRF LSM sensitivity remains limited compared to studies on CU, PBL, and MP schemes, in addition, Igri et al., (2015) opined that rainfall dependency on LSMs is relatively weak. Some authors have argued which WRF model physics are most influential in producing high rainfall. Doan et al. (2023) and Kouadio et al. (2020) finds the PBL to be more sensitive than the MP. However, this conclusion may not be definitive, as only a limited number of physics schemes were tested, and different schemes could yield different results.

The Initial and boundary condition data, along with land-use and land-cover input data play a pivotal role in model simulation outcome. Doan et al. (2023) and Kouadio et al. (2020) noted that model's performance is more reactive to the sources and formulations of ILBC data than to changes in physical schemes and model horizontal resolution respectively.

On the other hand, previous NWP studies in West Africa have emphasized the need for improved domain resolution to enhance weather forecasting accuracy (Afiesimama et al., 2006; Klein et al., 2015), as extreme rainfall events are often localized. Advances in computing have enabled simulations at higher convective-permitting model resolutions. A model horizontal resolution of ≤ 4 km allows for cumulus processes to be explicitly resolved (Doan et al., 2023; Vizy & Cook, 2023), leading to the deactivation of the cumulus scheme in the explicit convective domain. Kouadio et al. (2020) found that explicit-scale WRF experiments reproduced higher rainfall intensity compared to non-convective scale simulations. Similar results were observed by Vizy and Cook (2019), who used convective-permitting models to analyze the daily rainfall cycle during WAM maxima. However, in a more recent study, Gbode et al. (2023) discovered that a convective-permitting simulation at 2 km resolution performed comparably to a 6 km WRF run (Gbode et al., 2023).

In improving model results, Ibrahim and Afandi (2014) suggested the assimilation of observed station data in the model. Igri et al. (2015) assimilated satellite and station data as inputs in a WRF experiment and found that the DA experiment improved the representation of rainfall amounts.

Model performance evaluation can be either objective or subjective and is dependent on the verification technique and the region of interest (Agogbuo et al., 2017; Gbode et al., 2019a; Lupo & Market, 2002). Quantitative rainfall forecasting remains a challenge, primarily because rainfall is often embedded in mesoscale bands, making it difficult to represent accurately in initial model conditions derived from global data (Tanessong et al., 2014). This limitation has caused conventional model verification methods to encounter a “double penalty” when results are slightly displaced in space, leading to both misses and false alarms (Ebert, 2008; Rossa et al., 2008).

To verify numerical model long-term simulations, such as during the WAM period, statistical metrics such as MAE, MB, Pearson correlation, and RMSE should be synthesized to create a comparative Model Skill Score (MSS) evaluation (Gbode et al., 2023). This approach was adopted by Gbode et al. (2019b). Most of the studies summarized in Table 8 employed the point-to-point nearest-neighbor approach. However, this method has limitations due to uncertainties arising from imbalances and irregular spatial reference gauges.

Qualitatively, a deterministic binary process can be used to verify model performance based on rainfall occurrence or non-occurrence. Agogbuo et al. (2017) and Tanessong et al. (2014) utilized contingency table elements for probabilistic forecast verification and established their relationship with quantitative forecasts. Tanessong et al. (2014) found that quantitative rainfall forecasts are preferable for sub-regional point assessments compared to probabilistic estimates. Thus, it can be inferred that a skillful probabilistic rainfall forecast over a region can be validated based on the quantitative rainfall forecast values within subregions. This conclusion is consistent with the findings of Gallus and Segal (2004).

The low percentage of station data used for model performance evaluation underscores the challenge posed by sparse data networks and poor data quality over the study domain, as shown in Fig. 3. Validation of model forecasts with station data is considered essential for boosting confidence, particularly for NWP models. However, relying solely on station observations for model output comparison may still raise doubts (Agogbuo et al., 2017). Combining station-gauge data with satellite data can improve the reliability of performance results (Simmons et al., 2004). Overall, by addressing the identified limitations and leveraging the strengths of the WRF model, its application in the region can effectively enhance the accuracy of high rainfall forecasts, ultimately supporting sustainable development and resilience in the region.

Conclusion

This study delved into extensive review research on investigating WRF model performance in simulating rainfall events in West Africa, with a specific focus over Nigeria using four science database engines. The PRISMA checklist guide protocol was adopted for a systematic process in the identification, screening, eligibility, and final inclusions. Out of 5254 identified documents, only 33 qualified for inclusion and analysis following the study’s set criteria. The findings underscore the escalating impacts of severe flooding from intense extreme rainfall attributed to climate change. The increasing trend and high occurrence of extreme rainfall events, especially in southern Nigeria, have been linked to convective instabilities and specific atmospheric conditions. The study has shed light on the performance of the WRF model rainfall forecasting in West Africa, emphasizing the need for a numerical approach to predict accurate extreme rainfall events.

Despite the considerable success of the WRF model in representing rainfall events and its associated synoptic conditions, there are limitations and challenges. The sensitivity studies revealed concerns regarding different model configurations, particularly physical parameterization schemes, initial and lateral boundary conditions, and the influence of domain resolution in model simulation results. The differences in model physical schemes have been suggested as the primary source of model bias in most RCMs, due to their varying assumption and formulations. Data assimilation processes are shown to correct model biases that may have been caused by global ILBC data, which directly influence the model dynamics.

The review discusses the objective and subjective model performance verification techniques. Challenges related to sparse networks and poor station data quality emphasize the importance of combining station data with gridded satellite data to achieve reliable verification results. Notably, the study observed that insufficient computational power constrains most of the studies to embarked on a single case study or a single-period WRF simulation experiments, limiting robust performance evaluation.

In essence, this review work will contribute to the understanding the WRF model's capabilities and limitations in simulating extreme rainfall episodes in West Africa. Finally, the study recommends specific WRF model configurations for performance optimization, including physics parameterization combinations (Goddard-MYJ-BMJ), ILBC (ERA5 hourly data), and static/topographic data (updated MODIS).

Addressing the earlier questions: (1) No study has been identified that employed the WRF model to simulate deep convective systems, such as MCSs, over Nigeria. This is recognized as a research gap, as MCSs contribute the majority of rainfall during the WAM season; (2) both the MP and PBL schemes contribute distinctly to the total distribution of moisture in the atmosphere, particularly in the tropics; however, the PBL is noted to dominate the rainfall processes.

The insights from this study can guide future research and improvements in forecasting techniques and provide realistic weather simulations for quantitative rainfall prediction in Nigeria, ultimately aiding in mitigating the adverse impacts of extreme rainfall and associated flooding.

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Author contribution A.O. conceptualized, collected data, analyzed, and wrote main manuscript text, Z.H. supervised and edited, C.A. revised and edited writing, A.R.M.T.I. collected data, revised and edited manuscript, D.M. collected data and edited revised manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval Not applicable.

Competing Interests The authors declare no competing interests.

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