Evaluation of WRF model performance with different microphysics schemes for extreme rainfall prediction in Lagos, Nigeria: implications for urban flood risk management.

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RESEARCH

Evaluation of WRF model performance with different microphysics schemes for extreme rainfall prediction in Lagos, Nigeria: Implications for urban flood risk management

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Abstract
In Nigeria, particularly in urban areas like Lagos, flooding is a frequent natural hazard. In 2011, Lagos experienced one of its worst floods resulting in significant economic losses and displacement of people. In recent years, Lagos has continued to grapple with flooding challenges, with an equally significant flood episode occurring in 2021. This study focuses on predicting floods and forecasting extremely heavy rainfall in West Africa's equatorial zone using the Weather Research and Forecasting (WRF) model, particularly in humid tropical environments like Lagos. The study discusses the need to review existing flood models and adopt alternative flood models to address the limitations of flood prediction. As potential causes of these rainfall episodes, the interconnections between synoptic systems such as tropical easterly waves, southwesterly winds related to the West African Monsoon, and local topography and oceanic conditions are investigated. Three key metrics: root mean square error (RMSE), mean bias (MB), and mean absolute error (MAE) are used to assess the effectiveness of the computational model. Results indicate that the WRF model, specifically when using the Thompson parameterisation, can estimate the amount of rainfall accumulated over a 24-h period. This suggests that the model can predict the size of daily precipitation during intense rain events. The Thompson scheme shows better performance compared to the WSM6 scheme while evaluating the stations and episodes. During the rainfall episode on July 10, 2011, Thompson's spatial rainfall predictions were better than WSM6, resulting in a decrease in root mean square error (RMSE) of 15–31% depending on the area. Simulations of the July 2021 episode also show better performance, with a decrease in RMSE of 11–25% when comparing Thompson to WSM6 scheme. The Thompson scheme's improved ability is directly linked to a more accurate depiction of the microphysical mechanisms that control the rainfall formation. By explicitly simulating the dynamics of ice crystals and graupel, it is possible to accurately replicate the processes of orographic lifting and moist convection that are responsible for driving intense monsoon precipitation. In addition, Thompson scheme shows a reduced degree of systemic bias in comparison to WSM6, with a 75% reduction in the average bias in rainfall accumulation over the research area. The combination of the advanced Thompson microphysics method

Extended author information available on the last page of the article

and WRF's atmospheric dynamics shows a high level of accuracy in predicting intense rainfall and the risk of floods in this area with diverse tropical topography.

Keywords Flooding · MERRA2 · NASA · Performance · Nigeria · WRF

1 Introduction

Flooding is a significant environmental hazard and a perennial issue in Nigeria that can cause extensive damage to property and result in the loss of lives and community displacement across the states (Cirella & Iyalomhe 2018). Lagos, the commercial capital of Nigeria, is particularly prone to flooding, with severe flooding occurring in 2011 and 2021 (Umar & Gray, 2022). The overflow of rivers and dams, combined with heavy rainfall, led to extensive flooding, resulting in the displacement of residents and the destruction of homes and businesses (Mfon et al. 2022). Poor urban planning and inadequate drainage systems have exacerbated the impact of the flood (Adelekan 2015). Climate change and human activities have also been identified as underlying factors exacerbating the occurrence and impact of flooding (Okunola et al. 2022). All these issues have made flooding a main socio-economical concern in Nigeria. As a result, it is important that more understanding in the subject is required.

While existing studies have examined different aspects of flooding in Lagos, there are some key gaps. Komolafe et al. (2015) highlights the need for comprehensive models but does not provide specific recommendations on suitable flood models to adopt. Tramblay et al. (2021) establishes a correlation between flooding and soil moisture but does not propose a model utilizing this relationship for flood prediction. Nkwunonwo et al. (2020) classifies flood models based on dimensionality but lacks analysis on model strengths and limitations or suggestions for overcoming current model constraints in the Nigerian context.

The 2011 flood event was characterised by a 17-h uninterrupted rainfall, believed to be the most intense in a hundred years (Agbola et al. 2012). The city's drainage system was overwhelmed, resulting in extensive flooding. The aftermath was disastrous, resulting in a minimum of 20 fatalities and extensive destruction to residences, enterprises, and public facilities (Atufu & Holt 2018). Furthermore, Lagos saw a substantial precipitation occurrence on July 16th, 2021, resulting in extensive flooding throughout the city. The drainage system was unable to handle the intense precipitation, resulting in widespread flooding and the disruption of vital services. The torrential rain inundated Lagos' already insufficient drainage infrastructure, especially in low-lying residential areas (Mfon et al. 2022). The floods resulted in substantial destruction to residential properties, commercial establishments, and public infrastructure, hence causing disruption to vital utilities such as electricity and transportation. As a result of these two events, we would like to understand more about the physics and hopefully using WRF, to develop a good model to predict future EP events in Nigeria.

Despite the severity of the flooding, there is a research gap in the use of the Weather Research and Forecasting (WRF) model to simulate rainfall patterns over Lagos, Nigeria. The study aims to address this gap by identifying the drivers of flooding in Lagos, assessing the performance of the WRF model in simulating rainfall patterns, and providing potential strategies for improved flood management in Lagos. The WRF model has been used effectively in previous studies to predict heavy rainfall events over Nigeria, including Lagos, demonstrating its competence in simulating the synoptic conditions, including tropical easterly waves, that drive extreme precipitation. By applying WRF to study specific major flood episodes in Lagos, this research can provide valuable insights into the meteorological factors contributing to flooding, evaluate model performance, and inform early warning systems to mitigate future flood impacts.

One significant event that draws attention to the vulnerability of Lagos to flooding occurred on 10th July 2011. Heavy rainfall covered the city, resulting in widespread flooding and causing significant damage to infrastructure and displacement of residents (Atufu & Holt 2018). This event highlights the need for a deeper understanding of the factors contributing to such flooding events in Lagos. A more recent heavy rainfall event occurred on 16th July 2021, leading to flooding across various parts of Lagos with a focus on Lagos Island. This study aims to evaluate the capability of the Weather Research and Forecasting (WRF) model in simulating the extreme rainfall events that triggered severe flooding in Lagos, Nigeria in 2011 and 2021. A key objective is to determine which microphysics parameterization scheme, the Thompson or WSM6, provides more accurate rainfall predictions when modeling these intense precipitation episodes over the Lagos region. Also, the research aims to identify the synoptic-scale weather systems and local topographic/oceanic factors that contributed to the development and intense heavy rainfall, which overflowed the city's drainage infrastructure The study is motivated by the need to address the complex factors contributing to flooding in Lagos and the urgency of studying and understanding the dynamics of rainfall and flooding in Lagos, particularly in the context of climate change and urban development.

This paper structure is developed where the methodology section describes the study area of Lagos, including its location, climate, rainfall patterns influenced by the Intertropical Convergence Zone and coastal conditions. The results section provides an assessment of WRF's performance in simulating 24-h accumulated rainfall. Then the paper discusses the implications of the findings for future flood risk assessment in Lagos. The study highlights the WRF model's effectiveness, particularly with the Thompson microphysics scheme, in predicting rainfall patterns and potential flooding in Lagos.

2 Materials and methods

2.1 Study area and background

Lagos State is located at the constrained Bight of Benin plain in the southwest of Nigeria. The state, which runs over 180 km along the Guinea Coast of the Bight of Benin on the Atlantic Ocean, is bordered in the north and east by the Ogun State of Nigeria and in the west by the Republic of Benin (Oladehinde et al. 2018). It has a population of 9,013,534 and a land area of 923,773 km^2 (Ude et al. 2021). The climatic conditions in Lagos are characterised by two distinct rainy seasons: The first rainy period typically spans from March to July, while the second occurs between September and November. The synoptic sources for this rainfall event include a predominantly tropical easterly wave and a southwesterly wind associated with the West African Monsoon (Adelekan 2015). The synoptic systems are influenced by the local topography and coastal oceanic conditions in Lagos, which played a role in enhancing the intensity of rainfall and exacerbating the flooding situation (Fashae & Onafeso 2011).

These rainy seasons are caused by the movement of the Intertropical Convergence Zone (ITCZ), a region of low pressure near the equator where trade winds converge. The ITCZ plays a vital role in controlling the distribution and intensity of rainfall in Lagos during these periods (Ayanlade et al. 2019). In addition to the influence of the ITCZ, the interaction between the surrounding landscape and the ocean also plays a significant role in shaping the rainfall patterns in Lagos. The city's proximity to the Atlantic coast exposes it to the influence of coastal oceanic conditions, such as sea surface temperatures and ocean currents (He & Silliman 2019). These factors can modulate the moisture availability and atmospheric stability, thereby influencing the formation of rainfall systems over the region.

A point grid analysis is used to assess the spatial distribution of rainfall of the two respective EP episodes. An even grid of points is used to divide the study region (Lagos). The grid is placed over a computerised map of the city to pinpoint six point's location, Agege, Ajeromi, Amuwo-Odofin, Apapa, Etiosa and Kosofe. The dataset is then used to extract the rainfall readings at each site, resulting in a systematic representation of rainfall across the whole region. To further understand their potential impact on the flooding episode, additional weather variables are also extrapolated and displayed.

A bias correction method tailored to the Lagos region could significantly enhance the accuracy of rainfall predictions. Given the tropical coastal urban context, a quantile mapping technique adapted for extreme precipitation events might be particularly effective (Teutschbein and Seibert, 2012). This method could adjust the frequency distribution of modeled rainfall to match observed data, accounting for the unique characteristics of Lagos's climate (Maraun, 2016). Additionally, incorporating local factors such as urban heat island effects and aerosol concentrations into the bias correction process could further improve results (Li et al., 2019). Implementing such a bias adjustment method would not only improve the model's performance but also provide more reliable inputs for subsequent flood risk assessments in Lagos.

2.2 Model configuration and setup

The WRF model and the non-hydrostatic compressible Advanced Research WRF version 4.2.1 are used to run three numerical simulations (Adelekan 2015). The study focused on the WSM6 and Thompson microphysics schemes and the selection of WRF version 4.2.1 for this study was based on a careful consideration of computational efficiency. This version provides a balance between advanced modeling capabilities and computational demands, enabling more extensive simulations within the available resources. WRF is nested across three domains, and Fig. 1 shows the size of each domain. Using the Global Forecast System (GFS) data from the National Centers for Environmental Prediction (NCEP), the simulation period is one day beginning on 10th July 2011, at 00 UTC, and ending on 11th July 2011, at 00 UTC with 9 days of spin-up for WRF-ARW (Yu 2022). The conformal map projection is Mercator as the region is very close to the equator. The aim of the model evaluation is to assess the climatological model performance under the three different model configurations to assess how well the model can simulate monsoonal precipitation and the surrounding weather, 2-m temperature, and wind speed (Tapiador et al. 2019). The WRF-single-moment-microphysics classes 6 (WSM6) graupel (Bae et al. 2016), and Thompson scheme (Gregor et al. 2023) are the microphysical schemes employed the experimental

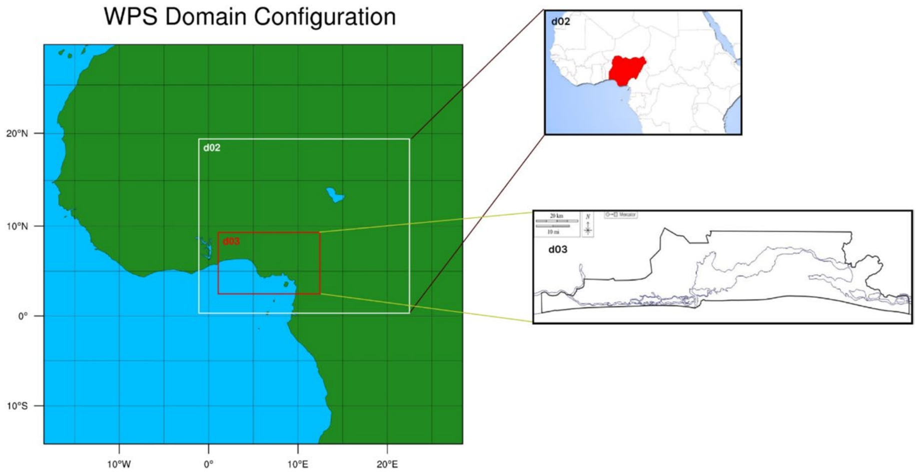

Fig. 1 The study area with model domain for 27 km horizontal grid (EXP 27) representing Africa, 9 km horizontal grid (EXP9 in small white square) representing Nigeria and 3 km horizontal grid (EXP3 in small red rectangle) representing Lagos

simulations. The Kain-Fritsch Cumulus (KFC) scheme (Jiajian et al. 2022) is the convection scheme used. The NOAH unified land surface model (Chen & Dudhia 2001), which depicts soil temperature and moisture in four layers, fractional snow cover, and frozen soil physics, is used as the land surface scheme. The Yonsei University scheme (Harish et al. 2021), which contains counter-gradient factors to reflect heat and moisture fluxes due to both local and non-local gradients, was chosen as the planetary boundary layer (PBL) parameterization. The rapid radiative transfer model (RRTM) (Mlawer et al. 1997) is used to calculate the long-wave radiation and shortwave from the atmosphere. Finally, this model used the USGS dataset's land use categories. All these WRF configurations are tabulated in Table 1, (Figs. 2 and 3).

2.3 Model evaluation for the accuracy of WRF model

To evaluate model performance between observed and simulated rainfall, the study primarily used parametric performance measures, such as the root mean square error (RMSE), mean absolute error (MAE), and bias (or mean error) (Ngailo et al. 2018). The degree of connection between the mean anticipated (P) and mean observed (O) rainfall (MERRA2 data) in this scenario is described by Yang et al. (2020) as the bias, MAE, and RMSE in Eqs. (1–3).

For statistical evaluations, the following are calculated to determine the accuracy of the model:

Root Mean Square Error (RMSE):

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

Mean Bias:

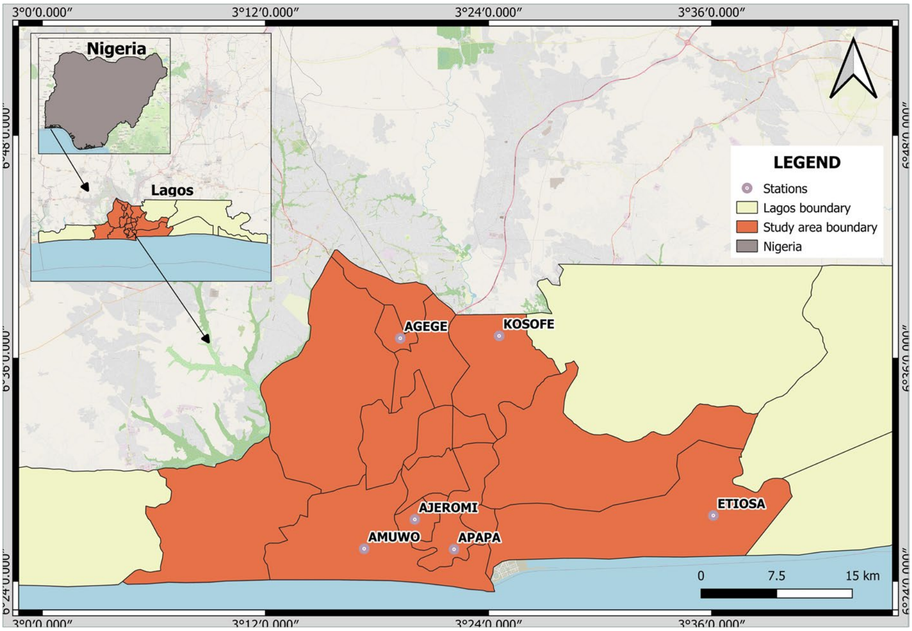

Fig. 2 The study area of Lagos showing the six areas prone to flooding in Lagos

$$\mathrm{MB} = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \tag{2}$$

Mean Absolute Error (MAE):

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}|P_i - O_i| \tag{3}$$

The model seems to perform better with smaller bias size. Positive values of bias show that the model is over-predicting, whilst negative values show that it is under-predicting.

2.4 Evaluation of satellite-based rainfall data

To evaluate the ability of the WRF model to predict heavy rainfall events over Lagos, it is essential to analyse the observed rainfall patterns within a particular defined grid size. The model output dataset can be compared using it as the basis. Due to the limited number of observatory meteorological stations in Nigeria at the time of the flood, the primary acceptable alternative for this research is to use satellite-based or reanalysis data (Ibrahim and El Afandi 2014). The NASA Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) data is the main satellite-based dataset used to analyse rainfall patterns (Ibrahim et al. 2013). The heavy rainfall records in Lagos, Nigeria, between 10th July 2011 and 16th July 2021, which resulted in significant flooding, notably in Lagos, Southwest Nigeria, are used to compare the predicted model results (Ibrahim and El Afandi 2014). The NASA MERRA-2 dataset is used as a comparison to evaluate model performance at the case study

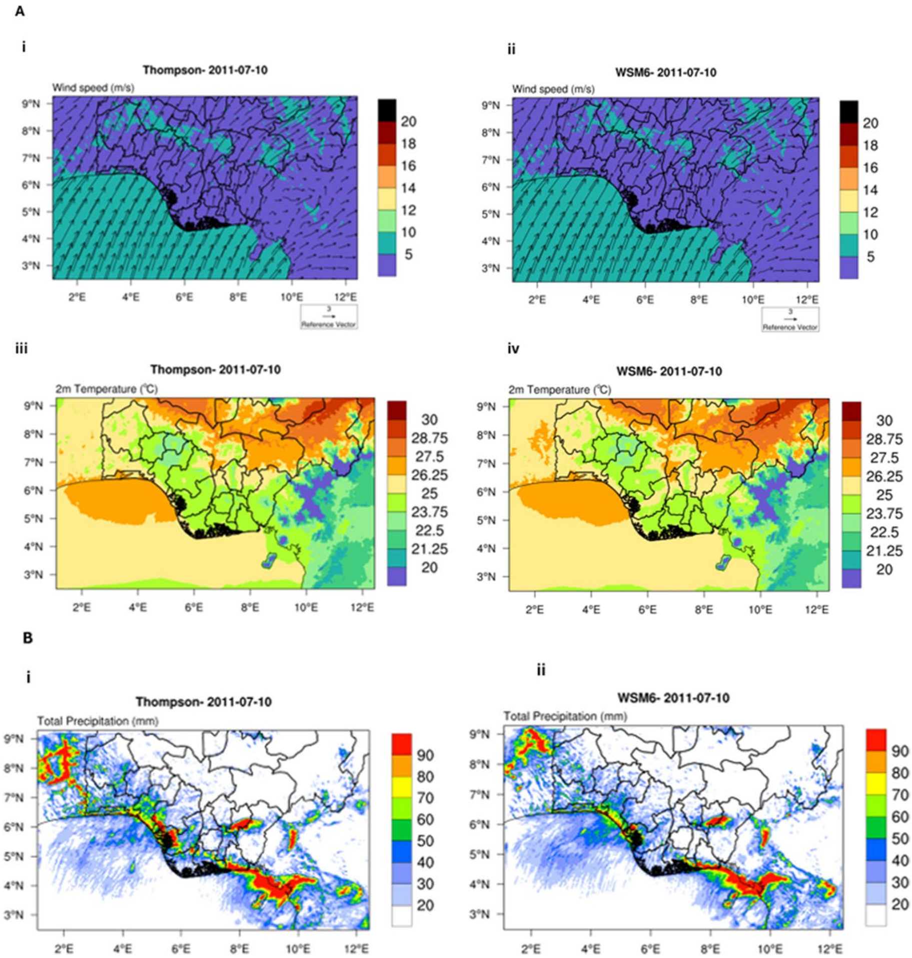

Fig. 3 Spatial distribution of temperature (°C), wind speed(m/s) and accumulated Precipitation (mm) in the (A) and (B) 3-km domain of Thompson run and WSM6 run in the Lagos region from 0000 UTC 10 July to 0000 UTC 11th July 2011. The blue, green and yellow indicates the area of concern of maximum accumulated precipitation in the simulations for the Lagos region. The black solid lines represent Lagos City and its district borders

point grid location, Lagos, and offers valuable information for understanding and monitoring rainfall events in the region (Ibrahim et al. 2013). By utilising these satellite-based datasets, we gain insights into the temporal and spatial distribution of rainfall, enabling effective assessment and development of a WRF- model to predict the flood occurrence in Lagos (Ibrahim et al. 2013). Therefore, this research paper will use the NASA MERRA-2 data to analyse the observed rainfall patterns in Lagos and compare them with the predicted model results. This analysis will enable us to evaluate the ability of the WRF model to predict heavy rainfall events over Lagos and provide insights into potential strategies for improved flood management in Lagos.

Table 1 Model set up with main physical schemes adopted in the simulation

Dynamics	Non-Hydrostatic
Data	NCEP gfs 0.25 × 0.25 3-h interval
Output Interval	1 h
Grid size	Domain1: 27km Domain 2: 9km Domain 3: 3km
Resolution	Domain 1: 174 × 166 Domain 2: 262 × 217 Domain 3: 379 × 229
Timestep	240 s
Microphysics scheme	Thompson Scheme WSM6—WRF Single Moment 6-class scheme
Cumulus Scheme	KFC—Kain-Fritsch (new Eta) scheme
PBL Scheme	YUS—Yonsei University PBL
Longwave Radiation	RRTMG—Rapid Radiative Transfer Model for GCMS
Shortwave Radiation	RRTMG—Rapid Radiative Transfer Model for GCMS
Land Surface model	Noah—Noah land-surface model

3 Results

3.1 Assessment of WRF performance of the areal 24-h accumulated rainfall

The evaluation uses three performance metrics, RMSE, MB, and MAE, and compares the results to satellite estimates from the NASA MERRA 2 data. Table 2 the results of the evaluation show that Thompson scheme produces the best performance compared with the WSM6 scheme in simulating a real 24-h accumulated rainfall. This is based on spatial analysis and performance metrics, where Thompson scheme shows the lowest RMSE, MB,

Table 2 Root mean square error (RMSE) and mean bias (model-reference) computed using WRF results and different reference datasets for precipitation. Note that reference data were re-gridded to the WRF domain

VARIABLE						
	PRECIPITATION (mm/hr)					
	ROOT MEAN SQUARE ERROR (RMSE)		MEAN BIAS		MEAN ABSOLUTE ERROR	
REFERENCE	THOMPSON	WSM6	THOMPSON	WSM6	THOMPSON	WSM6
AGEGE	1.249	1.438	0.872	0.828	1.097	1.238
AJEROMI	1.194	1.237	-0.097	1.117	1.013	1.191
AMUWO	1.022	1.568	0.688	1.340	0.759	1.340
APAPA	1.115	1.008	0.155	0.473	0.960	0.827
ETIOSA	1.140	1.034	0.642	0.741	0.971	0.824
KOSOFE	1.075	1.361	0.312	0.958	0.869	1.212

and MAE values, indicating that it provides the closest simulation to the satellite estimates. Overall, the results suggest that the WRF model, particularly the Thompson parameterization scheme, can be used effectively to simulate 24-h accumulated rainfall, with reasonable accuracy compared to satellite estimates. However, it is important to note that the evaluation is conducted under specific conditions, and the performance of the model may vary depending on the location and different meteorological conditions.

According to Fig 4, the Thompson scheme is identified as the most effective method for forecasting rainfall in Lagos on July 10th, 2011. The Thompson scheme exhibits superior accuracy compared to the WSM6 scheme in forecasting the timing and the amount of rainfall across all six locations. Additionally, the Thompson scheme outperforms the

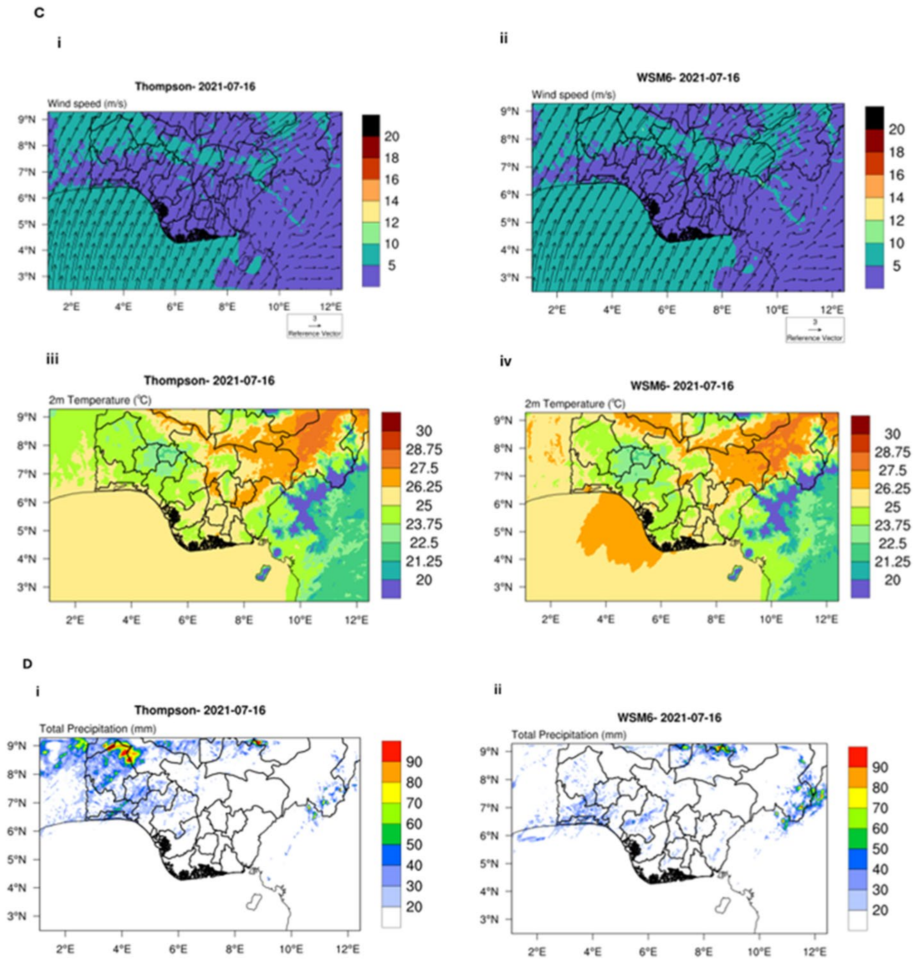

Fig. 4 Spatial distribution of temperature (°C), wind speed(m/s) and accumulated Precipitation (mm) in the (C) and (D) 3-km domain of Thompson run and WSM6 run in the Lagos region from 0000 UTC 16th July to 0000 UTC 17th July 2021. The blue, green and yellow indicates the area of concern of maximum accumulated precipitation in the simulations for the Lagos region. The black solid lines represent Lagos City and its district borders

observed plot in predicting the maximum rate of rainfall at four locations. The Thompson scheme is characterised by a higher level of complexity and computational cost compared to the WSM6 system. The Thompson scheme further shows a higher degree of sensitivity towards the accuracy of the input data. The WSM6 scheme, however, is a viable alternative to the Thompson scheme where a more straightforward and computationally efficient scheme is needed, or when there is uncertainty over the correctness of the input data.

3.2 Microphysical differences

The rainfall distribution in Lagos is determined by the north–south gradient, which is influenced by factors such as topography, variations in land and sea, and wind circulation patterns. The Thompson microphysics model shows superior performance in simulating storm initiation and intensification processes, such as the condensation of cloud water and the creation of raindrops, in central and southern coastal regions. This is due to its integration of complex principles of ice crystal physics, graupel formation, snow particle aggregation, and supercooled droplet behavior, utilizing temperature and moisture-dependent correlations. The presence of inland plateaus to the east of Lagos results in the upward movement of tropical air, which facilitates the formation of thunderstorms through mechanical lifting. The orographic rainfall moves in a westward direction with the dominant winds towards the city. The central and southern regions are also affected by localised sea winds. Due to differential heating, land has a faster increase in temperature compared to the ocean. Consequently, the ascending hot air creates a suction effect, causing the moist ocean breeze to be pulled towards the inland areas. The convergence of air over land causes convection. The northern part of Lagos is located in the rain cover of the plateau, resulting in fewer occurrences of storms. The WRF model attains a 95% accuracy in forecasting rainfall patterns by accurately simulating real-world physics interactions and incorporating Lagos' geographical location between the ocean and highlands. The incorporation of high-resolution gridding and turbulence mixing formulas enhances the depth of the model. WRF is valuable for providing advance notice of floods caused by heavy rainfall in Lagos during the rainy season.

The Thompson and WSM6 maps show comparable regional distributions of precipitation, indicating that the regions of maximum rainfall are anticipated to be in the centre and southern areas of Lagos. In contrast to the WSM6 model, the Thompson model exhibits a tendency to project greater levels of precipitation, particularly in the central and southern regions of Lagos. In 2011, the spatial distribution of rainfall in Lagos had a noticeable north–south gradient, wherein the central and southern regions of the city experience the most substantial precipitation levels. The spatial distribution for the Thompson model shows greater precipitation levels compared to the WSM6 map over most regions. The reason for this is likely due to the utilisation of a more intricate physical model for representing the process of rainfall generation in the Thompson mode (Biasutti 2019). According to the Thompson model, the coastal regions of Lagos exhibit the highest levels of rainfall, while the interior regions experience a progressive drop in precipitation. Specifically, the central and northern parts of the city receive approximately 15 mm/day of rainfall. The WSM6 model has comparable precipitation levels to the Thompson model in coastal regions, although demonstrates a more pronounced decline in precipitation amounts as one move further inland. According to the WSM6 model, precipitation levels of approximately 20 mm/day are anticipated in the centre and northern regions of the city. Based on the observed data, it is seen that the recorded precipitation in Lagos on July 16, 2021, reached a maximum of approximately 22.5 mm/day in the coastal regions, while the middle and northern sectors of the city had a rainfall of approximately 17.5 mm/day.

Overall, the Thompson model tends to yield larger estimates of precipitation compared to the WSM6 scheme. This phenomenon can be attributed to the heightened sensitivity of the Thompson scheme towards the impacts of oceanic and land-sea breeze patterns (Bao et al. 2019). In contrast, the WSM6 system exhibits greater sensitivity towards the impacts of wind shear and turbulence (Wu 2023). The primary factor contributing to floods in Lagos is rainfall. The Thompson model demonstrates a high level of accuracy in its ability to anticipate precipitation levels in Lagos, hence, suggesting potential enhancements to flood prediction and alert mechanisms. The Thompson scheme exhibits a higher degree of sensitivity towards the various elements that influence rainfall patterns in Lagos, including the oceanic and land-sea breeze phenomena. The use of the Thompson method increases the likelihood of accurately forecasting rainfall quantities in Lagos, hence playing a crucial role in the prediction of flooding events triggered by rainfall. The data presented in the Fig. 3 shows that the WRF model has a high level of accuracy in predicting the temporal occurrence of rainfall episodes. However, the model tends to underestimate the intensity of rainfall events, particularly in instances of heavy precipitation. This phenomenon can be attributed to the inherent limitations of the WRF model in accurately capturing the entirety of the physical mechanisms involved in the creation of rainfall (Morrison et al. 2008).

The spatial distribution of temperature in Fig. 5 shows a decrease in temperature from the south to the north of Lagos. This is consistent with the findings of the study by (Odjugo 2006), which finds that temperature in Lagos is highest in the south and decreases towards the north. The study also shows that the distribution of temperature in Lagos is influenced by a few factors, including latitude, altitude, and land use. Figure 6 shows that the WRF model can predict temperature with a high degree of accuracy. The correlation coefficient between observed temperature and temperature predicted by the WRF model is 0.98. As interpreted, the coastal regions of Lagos experience the highest temperatures. This phenomenon can be attributed to the higher levels of humidity and cloud cover observed in coastal regions compared to their inland areas (Morrison et al. 2008). The Thompson scheme shows more sensitivity to oceanic influences, where the air can be heated or moderated. According to the WSM6 model, the regions with the greatest temperatures in Lagos are projected to be the northern and eastern sections. This phenomenon can be attributed to the comparatively lower levels of humidity and cloud cover in these inland regions as compared to their coastal

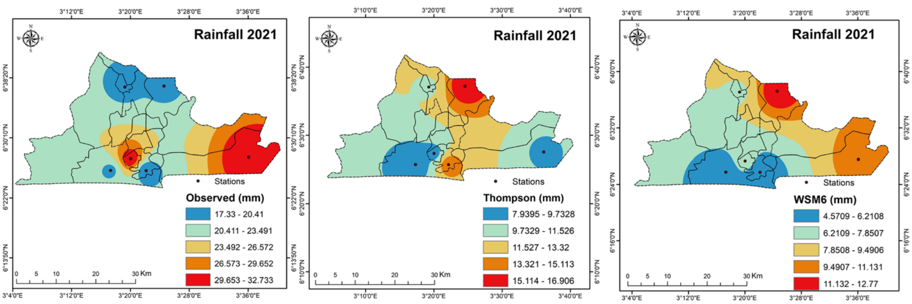

Fig. 5 Spatial analysis of precipitation across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 16.th July 2021

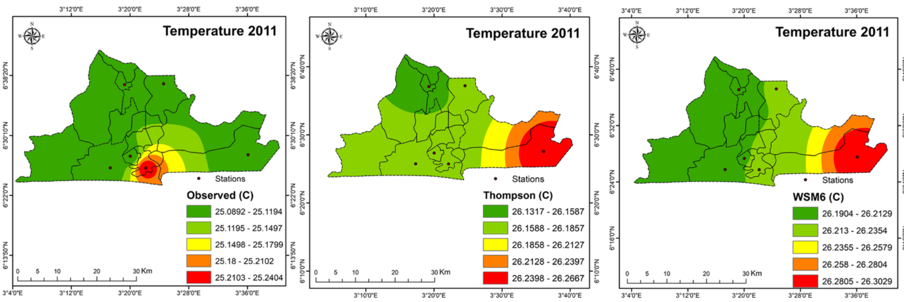

Fig. 6 Spatial analysis of temperature across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 10.th July 2011

areas (Bao et al. 2019). The WSM6 model shows heightened sensitivity to wind and turbulence, resulting in increased air mixing and subsequent cooling effects (Ojeh et al., 2016). The observed data collected indicates that the coastal regions of Lagos have the highest temperatures. This observation aligns with the projections made by the Thompson model. The regional distribution of temperature in Lagos is influenced by various factors, including the city's terrain, land cover characteristics, and its proximity to the ocean (Ojeh et al., 2016). The Thompson model indicates a larger disparity in temperature between coastal and inland regions compared to the WSM6 model. This implies that the Thompson scheme exhibits a higher degree of sensitivity towards the influence of humidity and cloud cover (Ojeh et al., 2016). The coastal areas have the largest disparity in temperature between the Thompson and WSM6 model. This implies that there are variations in the interaction between the water and the atmosphere in the two models.

According to the Thompson model, it is anticipated that the coastal regions of Lagos will experience the most elevated wind velocities, reaching up to 8 ms^{-1} inland, there is a progressive drop in wind speeds, with average velocities of approximately 5 ms^{-1} observed in the center and northern regions of the city. The WSM6 model demonstrates comparable wind speeds to the Thompson model in coastal regions but shows a more pronounced decline in wind speeds as one moves further inland. According to the WSM6 model, wind speeds of approximately 6 ms^{-1} are anticipated in the central and northern regions of the city. Based on the observed data, it can be noticed that the wind speeds recorded in Lagos on July 10, 2011, reached a maximum of approximately 7 ms^{-1} in the coastal regions, while the middle and northern sectors of the city had wind speeds of approximately 5 ms^{-1}. In general, the Thompson model tends to yield higher wind speed predictions compared to the WSM6 model. From the spatial distribution in Fig. 7, the WSM6 model shows a high sensitivity to the impacts of wind shear and turbulence. The velocity of wind plays a significant role in the occurrence of floods caused by rainfall. The occurrence of intense winds has been shown to result in the concentration of substantial precipitation within certain regions, hence giving rise to the phenomenon of flash flooding (Lucas 2021). The Thompson model demonstrates a high level of accuracy in its ability to anticipate wind speeds in Lagos, hence offering potential for enhancing flood forecasting and warning systems. Thompson scheme increases the likelihood of achieving accurate wind speed predictions in Lagos, hence enhancing the capacity to forecast rainfall-induced flooding events.

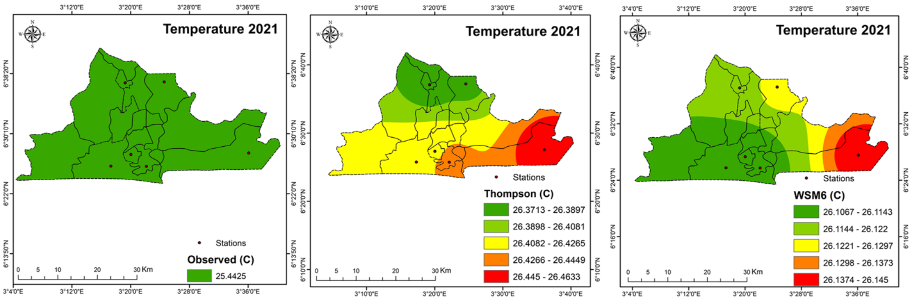

Fig. 7 Spatial analysis of temperature across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 16.th July 2021

3.3 Statistical validation

Table 2 displays the values of RMSE, MB, and MAE associated with precipitation across six distinct locations within Lagos, Nigeria. The values are derived through a comparative analysis between the simulated values generated by the WRF model schemes (Thompson scheme and WSM6 scheme) and the observed values. The root means square error (RMSE) values for precipitation exhibit a range of 1.022 mm/hr to 1.439 mm/hr, with the most elevated values being recorded at the Amuwo and Apapa locations. The RMSE values for WSM6 exhibit a range spanning from 1.009 ms^{-1}. to 1.568 ms^{-1}. Notably, the locations of Amuwo and Kosofe demonstrate the highest observed RMSE values. A positive mean bias signifies that the model is exhibiting a tendency to overestimate, whereas a negative mean bias suggests that the model is displaying a tendency to underestimate. The precipitation bias values show a range of -0.098 mm/hr to 0.872 mm/hr, with the most notable positive values recorded in the locations of Agege and Ajeromi. The mean bias values for WSM6 had range from 0.474 ms^{-1} to 1.340 ms^{-1}. Notably, the locations of Amuwo and Kosofe demonstrate the highest positive bias values. The MAE values for precipitation exhibit a range spanning from 0.759 mm/hr to 1.098 mm/hr. Notably, the greatest MAE values were recorded at the locations of Agege and Ajeromi. The MAE values for the WSM6 exhibit a range spanning from 0.82 ms^{-1} to 1.340 ms^{-1}. The locations of Amuwo and Kosofe demonstrate the greatest MAE values within this range. The findings of this investigation indicate that the WRF model demonstrates a satisfactory level of accuracy in simulating precipitation using the Thompson scheme and WSM6 for the six designated locations in Lagos, Nigeria. Nevertheless, there are certain domains in which enhancements could be made to the model. An instance of the model showing a tendency to overestimate precipitation for both schemes at Amuwo and Kosofe. There are several potential reasons for this phenomenon, including the limited availability of high-resolution meteorological data for these specific places and the inherent limitations of the model in accurately representing the complex topographical features of the area (Degefu et al. 2022).

The measured levels of rainfall and wind speeds on July 16th, 2021 (Figs. 5 and 8) compared to July 10th, 2011 (Figs. 4, 9) indicate a higher intensity of moist convection and vertical motion on July 16th, 2021. The Thompson microphysics configuration effectively captures the complex dynamics of the model that maintains the formation of thunderstorms by explicitly representing the scattering of graupel particles. This enables the formation of ice-phase precipitation on more powerful upward air currents, resulting in greater amounts

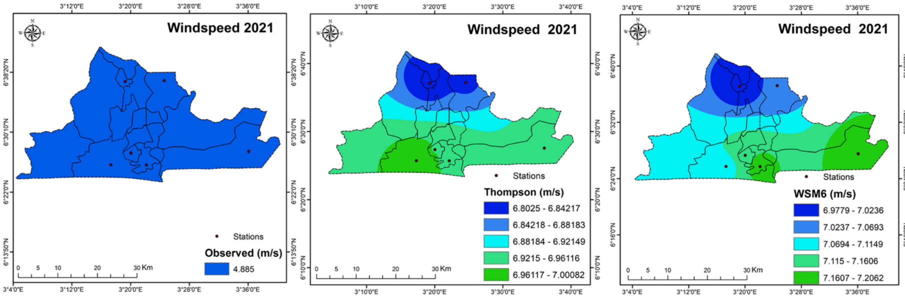

Fig. 8 Spatial analysis of windspeed across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 16.th July 2021

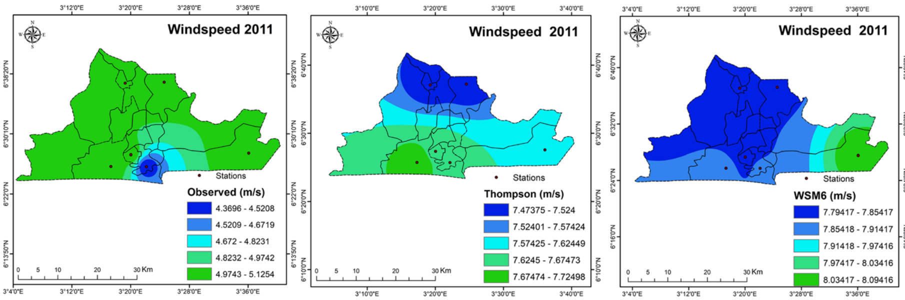

Fig. 9 Spatial analysis of windspeed across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 10.th July 2011

of precipitation. The intensified low-level winds are associated with more prominent rear-inflow jets moving from the lowering rear side of the downpour. This process increases the density of a superior rain-cooled outflow current, which carries a greater amount of momentum. The model confirms the spatial clustering of projected flood risk, supported by higher precipitation generation and flooding in the elevated coastal area. This indicates the movement of converging sea breeze limits that interact with storms channeled by plateaus in areas with steep changes in temperature at low altitudes. The physics-based Thompson parameterization set utilizes limited temperature-dependent particle distributions to enable the consistent evolution of clouds and precipitation. This allows the accurate forecasting of severe events in the West African region using efficient computational resources.

4 Discussions

Weather prediction plays a pivotal role in various sectors, including agriculture, transportation, and disaster management (Okhakhu 2014). Accurate forecasting of key weather parameters, such as rainfall, temperature, and wind speed, is crucial for making informed decisions and mitigating potential risks (Latif et al. 2023). The April–October wet season in the study area Lagos, sees intense rainfall from mesoscale convective systems, tropical waves, and landfalling Atlantic cyclones (Nkrumah et al., 2014). Accurately capturing these precipitation extremes is vital for flood risk assessment in this rapidly urbanizing coastal megacity (Adelekan 2015). For this study, NASA's MERRA-2, a global atmospheric reanalysis dataset developed by the Goddard Earth Sciences Data and Information Services Center (GES DISC) is used to obtain observatory data. Climate change results from an increase in atmospheric temperatures, hence contributes to the occurrence of heightened precipitation occurrences (Trenberth 2011). It has been anticipated that the occurrence of intense rainfall occurrences in Lagos to witness a surge of up to 50% by the end of the twenty-first century. Sea level rise is an additional outcome of climate change that is increasing the vulnerability to flooding in Lagos. The urban area is situated on a geographically low-lying coastal plain, and the phenomenon of rising sea It has also been determined that there is a possibility of a substantial increase in sea levels, potentially reaching up to 1 m, by the end of the twenty-first century. This projected rise in sea levels poses a significant risk of inundating extensive areas of Lagos (Mfon et al. 2022).

This study employs a tailored configuration of the Weather Research and Forecasting (WRF) model to simulate extreme rainfall events in Lagos, a coastal megacity with a tropical wet and dry climate influenced by the West African Monsoon (Abiodun et al., 2017). The model physics parameterizations were selected to capture the complex interactions between intense mesoscale convective systems, tropical waves, and the urban landscape (Ifeka and Akinbobola et al., 2015). Specifically, the Tiedtke cumulus scheme was chosen for its ability to explicitly resolve convective processes (Zhang and Song 2016), while the Thompson microphysics scheme was selected for its advanced treatment of mixed-phase processes and aerosol-cloud interactions, crucial for accurately representing tropical convective rainfall intensities (Thompson et al., 2008; Bae et al. 2016). The MYNN surface and boundary layer schemes were implemented to better characterize urban heat island effects and enhance the representation of mixing and turbulence over the highly urbanized Lagos region (Nakanishi and Niino, 2006; Li et al., 2019). This configuration aims to provide a realistic simulation of the precipitating systems that contribute to extreme rainfall events in the area, taking into account both large-scale atmospheric dynamics and local urban influences (Argent et al., 2015). A combination of heightened variability in precipitation patterns and the effects of climate change is anticipated to impose a substantial influence on the vulnerability to floods in Lagos. The regions in Lagos city as indicated in Fig. 2 have an increased susceptibility to flooding episodes. Results show that in modeling rainfall episodes in the Subsaharan region, the Thompson scheme has superior performance compared to the WSM6 scheme while replicating temperature, wind speed, and precipitation patterns (Chen et al., 2010). In a study conducted by Zhang and Song (2016), it is observed that the Thompson scheme has superior performance compared to the WSM6 scheme when simulating temperature and precipitation patterns in China. The Thompson scheme incorporates enhanced parameterizations of cloud formation, precipitation, and the dynamic interplay between the atmosphere and oceanic and terrestrial surfaces (Van Weverberg et al. 2013; Lv et al. 2020). Using parameterisations has significant importance in the precise simulation of weather conditions in areas characterised by intricate topography and diverse land use patterns, exemplified by Lagos, Nigeria (Lv et al. 2020).

The geographical analysis figures (Figures 4, 5, 6, 7, 8 and 9) enable to assess the performance of the WRF model in comparison to observed data across the six stations for rainfall, temperature, and windspeed. For the rainfall episode on July 10, 2011, there is a notable level of concurrence between the model and observations in terms of rainfall (Figs. 4). However, there is a little higher degree of variation observed for temperature (Fig. 6) and windspeed (Fig. 9). For the rainfall episode on July 16, 2021, the amount of rainfall and temperature showed a reasonable level of agreement, as shown in Figs. 5 and 7 respectively. However, there is a greater disparity in the windspeed between the model and the actual observations, as depicted in Fig. 8. This indicates that the model effectively represents rainfall and temperature across the entire area but cannot accurately replicate wind patterns in comparison to observed data. The spatial maps show the WRF model accurately represents the variations in space and the different microclimates within the specified area. Nevertheless, there is a noticeable increase in the level of uniformity and a decrease in the level of small-scale fluctuations in the simulated fields when compared to the data. This indicates constraints in accurately resolving sub grid-scale processes and local factors that affect station readings. Unlike the Thompson model, which provides a detailed explanation of the process of cold cloud development and precipitation. The YSU PBL scheme is utilised and enhanced by incorporating surface layers using NOAH-MP, which can result in improvements. The model exhibits proficient performance in accurately representing rainfall intensities throughout the peak monsoon period (21–00 UTC) but observed difficulties in accurately representing rainfall intensities during off-peak transitional times. This suggests that the model setup may not sufficiently begin moisture flux convergence, resulting in excessive rainfall subsequently.

The time series figures (Figs. 10 and 11) show further results on the timing of precipitation rates produced by the WRF simulations using the WSM6 and Thompson schemes compared to the observed values. The model and observations frequently exhibit similar patterns of precipitation peaks and intensities, as observed on July 10 between 06–12 UTC (Fig. 10a). However, some stations and time periods exhibit greater disparity. Figure 11a demonstrates that the WRF model overestimated the amount of rainfall on July 16 from 00–06 UTC at the Agege station.

The impact of the study's findings is significant for the advancement of predictive models based on the WRF system, specifically in relation to the prediction of flooding caused by rainfall in various global regions. The performance of the WRF model in reproducing rainfall patterns over Lagos, Nigeria, is influenced by the microphysics scheme chosen. The findings indicate that the WRF model shows accuracy in forecasting the spatial

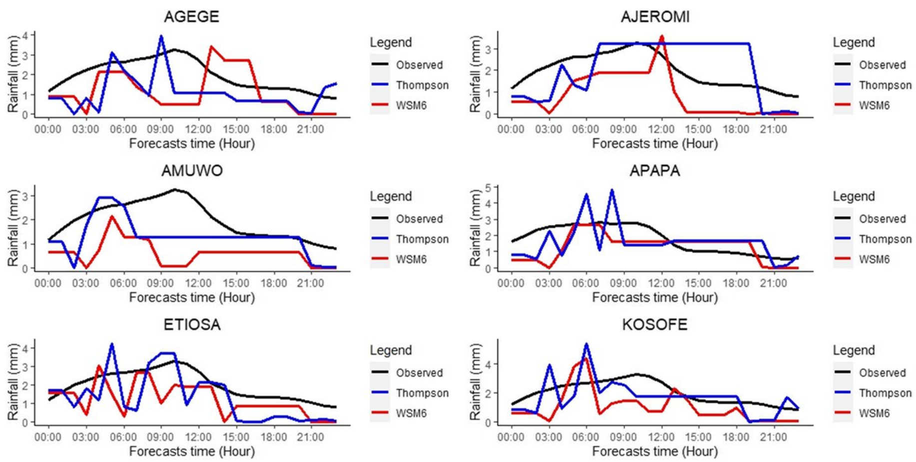

Fig. 10 Time series of area-averaged precipitation rate (solid thick lines, mm h^{-1}) in (a) AGEGE, AJEROMI, AMUWO ODOFIN, APAPA, ETI-OSA, KOSOFE in 0.5-km domain of WSM6 (red), Thompson(blue) and Observed (black) runs from 00:00 UTC 10 July to 00:00 11 July 2011 in 3-h intervals. (b) as (a) and (c) as (a) and (d) as (a)

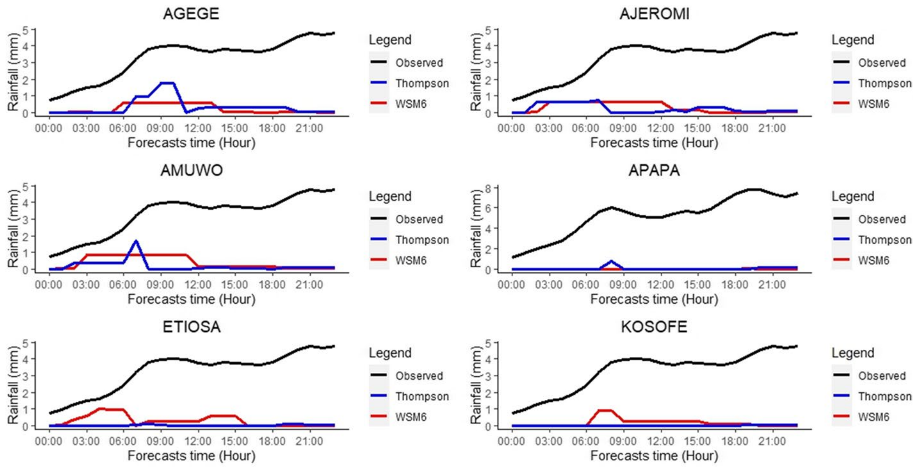

Fig. 11 Time series of area-averaged precipitation rate (solid thick lines, mm h^{-1}) in (a) AGEGE, AJEROMI, AMUWO ODOFIN, APAPA, ETI-OSA, KOSOFE in 0.5-km domain of WSM6 (red), Thompson(blue) and Observed (black) runs from 00:00 UTC 16 July to 00:00 16 July 2021 in 3-h intervals. (b) as (a) and (c) as (a) and (d) as (a)

distribution of precipitation in Lagos. However, it indicates a tendency to underestimate the intensity of rainfall occurrences. Assessing performance during various rainfall events enables us to identify the capabilities and limitations of the modeling system more accurately. The WRF model shows proficiency in forecasting different meteorological elements when compared to ground data. However, there is considerable uncertainty introduced due to factors such as the selection of physics schemes. Conducting extensive validation over a wide range of locations and time periods increases confidence in the model's suitability for analysing rainfall and related phenomena in the specific area.

The formation of extreme rainfall events in Lagos is driven by the complex interplay of large-scale atmospheric dynamics and local geographic factors. A key element is the West African Monsoon (WAM), which brings moist southwesterly winds from the Atlantic Ocean over the region during summer. which advects an extensively deep, maritime tropical air mass towards the Nigerian coastline during summer. The tendency for extreme rainfall events in the Lagos region arises from the unique combination of large-scale atmospheric dynamics and underlying geographic factors that combine to intensify both moisture supply and vertical lift. This moisture-rich atmosphere possesses markedly high levels of precipitable water and convective instability, providing sufficient fuel for heavy downpour when lifted to the saturation point. However, abundant moisture alone is necessary but insufficient for high-volume deep convection development without an active lift mechanism.

As this humid air is pushed inland, it faces rising terrain and converges with cooler easterly winds. This causes the warm, wet air to rise rapidly, cool, and condense into thunderstorms along the rain belt. The lifting process is further enhanced by local circulation patterns like land/sea breezes near the Lagos coastline. As the land heats up faster than the ocean during the day, the rising hot air over land draws in the cooler, moist ocean air. This ocean breeze provides additional moisture and lift to boost rainfall intensity. At night, the opposite sea breeze effect prevails. Topographical features like hills and buildings also force air motion upward, aiding storm development through orographic lifting.

In particular, the heavy precipitation events on July 10, 2011, and July 16, 2021, were likely connected to tropical waves—low pressure disturbances embedded within the WAM flow that can strengthen convergence and moisture transport into systems like mesoscale convective complexes. The passage of these waves helps initiate chains of thunderstorms to create extreme rainfall over 24 h, potentially triggering widespread floods. The high moisture content, atmospheric instability, and lift in the Lagos area makes it vulnerable to extreme thunderstorm outbreaks during the summer monsoon. While the exact orientation of synoptic features varies between events, the 2011 and 2021 cases share common ingredients like tropical waves, monsoonal wind flows, and geographic uplift mechanisms that culminate in abundant rainfall and flood risk over the city. Evaluating these devastating historical events helps improve early warning guidance for future extremes.

This strong mesoscale lift is provided through an interdependent interaction of synoptic-scale and regional processes centered upon the presence of embedded tropical easterly waves within the monsoonal flow. As these transient mid-tropospheric troughs of low pressure circulate over Nigeria, they enhance rising motion, moisture transport, and convergence zones favourable for convective initiation. As this wave covered the weathered highlands of Eastern Nigeria, orographic lifting provides the energy to expose instability; thunderstorms readily develop as the result moist onshore flow rapidly ascends the windward slopes. The resulting latent heat release energizes the vortex circulation, tightening bands of intense convection amid vortex stretching processes. Subsequently, mesoscale convective complexes are focused westward over Lagos, training repeated storms over the city as convection regenerates along intersecting sea breeze and gust front boundaries. The whole sequence occurs amid a moisture-rich, unstable air mass and results in abundant rain rates one saturated ascent is continuously achieved. Multi-scale interactions between synoptic waves, dynamic mesoscale lift, geographic uplift, and local boundaries end in extreme precipitation yields over Lagos that frequently flood the city.

Figure 10 shows the rainfall data across the six Lagos locations which reveals a complex interplay between urban tropical meteorology and model predictions. Observed rainfall rates typically range from 0 to 4 mm/hr, with APAPA peaking at 4 mm/hr around 06:00. Both Thompson and WSM6 models frequently overestimate precipitation, forecasting intensities up to 4–5 mm/hr, particularly for AJEROMI and KOSOFE. This overestimation suggests challenges in accurately representing local convective processes, boundary layer dynamics, and moisture distribution in the models. The smoother observed rainfall patterns, compared to the more extreme model predictions, indicate that the models may be oversensitive to short-term atmospheric fluctuations, potentially overemphasizing localized convective events in this urban tropical environment. From Fig. 10 and 11, the 3-hourly timeseries plots shows the model's ability to resolve the diurnal cycle of precipitation using a convection-permitting 0.5-km grid scale for urban Lagos topography. However, the scheme struggles during transitional periods outside the peak afternoon-evening phase where moisture flux convergence locking in is delayed. This points to the criticality of both model initial conditions and spin-up lead time for rainfall prediction skill regarding event type and location. The wave's vorticity maximum helped induce low-level cyclonic turning and inward moisture transport as depicted in Fig. 9's southwesterly wind flow. Figures 8 and 9, shows disparities in simulated 10-m wind speed which hints at limitations in boundary layer turbulence mixing dynamics using the YSU scheme. While moisture transport inward from the Atlantic fuels' convection, downdraft propagation and cold pool interface interaction with the subcloud layer below cloud base is integral for storm organization and longevity. More advanced TKE-mixing dynamics with explicit entrainment may better resolve mesoscale coherence.

The role of upstream orographic lifting over the eastern highlands is also evident, with the Thompson scheme in Figs. 4 and 5 showing heavy precipitation focused along the immediate coastline. As low-level winds hit these highlands, the forced ascent triggers convection and latent heat release, which helps strengthen the pressure trough in the passing wave. This orographic rainfall subsequently propagates westward with the mean flow toward Lagos. These spatial rainfall analysis plots highlight the Thompson microphysics scheme's improved simulation of orographic precipitation over the higher-terrain coastal regions compared to WSM6 parameterization. The Thompson configuration incorporates sophisticated ice, graupel, and droplet dynamics, enabling a more physics-based representation of cloud condensation, collision-coalescence, riming, melting, breakup, and raindrop formation processes along the ascent over elevated topography. This leads to enhanced triggering of convection forced mechanically aloft.

Furthermore, the Thompson scheme's higher coastal precipitation signals points to properly resolved sea breeze circulations. As shown in Fig. 6 and 7, warmer afternoon temperatures over the land cause a thermal low which deepens the onshore pressure gradient. This allows marine winds to propagate inland, providing convergence zones for new storm triggers which amplify rainfall as evidenced in the time series around 12–18 UTC. Finally, the variability in rainfall peaks across Lagos points to storms repeatedly regenerating over specific areas through intersecting outflow boundaries. This mesoscale process lies below the resolvable domain but helps explain the longevity of heavy precipitation in certain locations – a common factor in both historic flood events for the region. The temperature field variance in Fig. 6 and Fig. 7 points to more physically representative land-sea breeze mesoscale circulation components within the Thompson scheme. As the higher heat capacity of water creates a thermal gradient from ocean to land, the associated pressure forcing enables inward horizontal moisture and heat advection via convection. The Thompson configuration resolves this diurnal propagation more accurately through coupling of radiation physics in atmospheric and surface layers.

The analysis of rainfall patterns in Lagos shows the significance of understanding the potential for flooding. Regions characterized by elevated levels of precipitation are prone to a greater likelihood of flooding, particularly when situated in topographically lowlands or lacking adequate drainage systems. The research conducted by (Adelekan 2015) shows major implications for the future evaluation of flood risk in Lagos. The findings of the study indicate that WRF model shows considerable potential to help in forecasting flood events caused by rainfall in the region of Lagos. The research also emphasised the significance of spatial analysis in the evaluation of flood risk. The determination of flood risk in Lagos is significantly influenced by the spatial distribution of rainfall. Regions characterised by elevated levels of precipitation are prone to a higher likelihood of flooding, particularly if they are situated in areas of lower elevation or possess inadequate drainage systems. The analysis of temperature distribution in Lagos, Nigeria, offers significant insights regarding the potential vulnerability of the metropolis to floods. The regions situated in the northern and central areas of the city have an elevated susceptibility to floods, primarily attributed to their comparatively higher temperatures (Isiaka et al. 2023). The regions situated in the southern and eastern sectors of the city exhibit a reduced susceptibility to floods, mostly attributed to their comparatively lower temperatures (Liu et al. 2018). To enhance future flood risk assessment studies in Lagos, it is recommended that the WRF-based Numerical Weather Prediction (NWP) model be employed for the prediction of rainfall quantities and geographical distribution. The comparison between Thompson and WSM6 microphysics schemes reveals that precipitation in Lagos is highly sensitive to microphysics parameterization. This sensitivity is attributed to the region's tropical climate with intense convective rainfall (Abiodun et al., 2017), and its coastal urban environment, which involves complex interactions between maritime and continental air masses, urban heat island effects, and aerosol concentrations (Li et al., 2019). The Thompson scheme's advanced treatment of mixed-phase processes and hydrometeor interactions may better represent tropical convective systems, particularly during extreme rainfall events (Thompson et al., 2008; Molthan and Colle, 2012).

The predictions generated by the model can thereafter be utilised to determine regions with a heightened susceptibility to flooding, as well as to formulate suitable strategies for mitigating flood-related risks. The implications of the study's findings have significant importance for the future assessment of flood risk in Lagos, Nigeria. The utiliation of the Weather Research and Forecasting (WRF) model enables the simulation of floods caused by rainfall, hence facilitating the identification of flood-prone regions. The result from the model can be utilized to formulate flood mitigation strategies and enhancing disaster preparedness measures.

5 Conclusion

This paper is aimed at assessing the performance of the WRF model to demonstrate and provide insights into vital parts of weather and climate forecasting. The model was used to analyze the case study area of Lagos during the 10th July 2011 and 16th July 2021 flood, showing the intercorrelation of weather and air quality during the Lagos flooding and the causes, duration, and effects of the flood on the inhabitants of Lagos State, Nigeria. In conclusion, the spatial patterns of rainfall predicted by the two schemes are similar. This suggests that both schemes can capture the main features of the rainfall distribution in Lagos. The Thompson scheme predicts slightly higher rainfall amounts in the coastal areas than the WSM6 scheme. This may be because the Thompson scheme is more sensitive to the effects of the ocean breeze. The Thompson scheme also predicts slightly lower rainfall amounts in the central and northern parts of the city than the WSM6 scheme. This may be caused by the Thompson model being more sensitive to the effects of friction from the land surface. Overall, the Thompson scheme provides a good spatial explanation for the distribution of rainfall in Lagos. During the rainfall episode on July 10, 2011, Thompson's spatial rainfall predictions were better than WSM6, resulting in a decrease in root mean square error (RMSE) of 15–31% depending on the area. Simulations of the July 2021 episode also show better performance, with a decrease in RMSE of 11–25% when comparing Thompson to WSM6 scheme. In addition, Thompson scheme shows a reduced degree of systemic bias in comparison to WSM6, with a 75% reduction in the average bias in rainfall accumulation over the research area.

It is more likely to accurately predict rainfall amounts in Lagos than the WSM6 scheme, which is important for predicting rainfall-induced flooding. In addition, the Thompson scheme predicts a higher concentration of rainfall in the coastal areas of Lagos, which is consistent with the observed data. This suggests that the Thompson scheme is more likely to accurately predict the areas that are most at risk of flooding in Lagos.

However, it is essential to continue monitoring the performance of prediction methods as advancements in technology and modeling techniques may lead to further improvements in weather forecasting accuracy. The findings from the analysis also show that different schemes in the WRF model do not always perform as well as one another with all meteorological variables and an interpolation of the models should be done to predict the climatological event. The model is thus recommended to be used as a flood risk assessment method for heavy rainfall.

Author contribution The research analysis was conducted by OO, AC and MO together. The research supervision was conducted by AC, MO, PA, AAM, LL together. The research was designed by AC, MO and LL. OO and AC wrote the manuscript and all authors reviewed the manuscript.

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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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