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Evaluation of global data sources as boundary conditions for rainfall simulation by WRF model at Hue city in period of 2015-2025

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***Abstract*—The Weather Research and Forecasting (WRF) model is a powerful tool for simulating and forecasting weather, particularly heavy rainfall events. In this study, the WRF model was applied to simulate rainfall over Hue City using two global data sources as boundary conditions: the Global Forecast System (GFS) of the U.S. National Centers for Environmental Prediction and the Integrated Forecasting System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF). A total of 59 heavy rainfall events in Hue during the period 2015–2025 were selected for simulation. The results, including both rain total over the study area and rain patterns at selected stations, were compared with observations to assess accuracy and the ability to reproduce the spatiotemporal characteristics of rainfall. The findings indicate that differences in boundary conditions from the two global forecast systems significantly affect rainfall simulation outcomes. Accordingly, the study provides initial insights into the suitability of each dataset for rainfall simulation and forecasting applications in Hue City.**

Keywords— WRF, GFS, IFS, Hue, Rainfall

I. INTRODUCTION

The Weather Research and Forecasting (WRF) model is one of the most widely used numerical weather simulation tools, applied extensively in weather forecasting and regional climate research. With its high degree of customization and flexible configuration, WRF allows the use of various physical parameterization schemes and input datasets to simulate extreme weather phenomena such as heavy rainfall, tropical storms, and flash floods. The accuracy of the model largely depends on the quality of input data, including both initial conditions and boundary conditions.

Numerous studies, both domestic and international, have demonstrated that the choice of input data source significantly influences the performance of the WRF model. Globally, Srivastava et al. (2023) showed that using the WRF model to enhance the spatial resolution of ERA5 reanalysis data substantially improved the ability to simulate extreme rainfall events in the United States [1]. Capecchi (2021), using input data from ECMWF, indicated that regional models have a better capacity to reproduce heavy rainfall characteristics than global models in Italy [2]. Similarly, Yan and Gallus (2016) compared the rainfall forecasting capabilities of the WRF, NAM, and GFS models over the United States, and found that WRF demonstrated a clear advantage at higher rainfall thresholds [3].

In Vietnam, at the national scale, Tran Anh Duc et al. (2025) evaluated heavy rainfall forecasts over Vietnam for the period 2019–2025, comparing ECMWF IFS and WRF–ARW simulations with data assimilation. The results indicated that using a high-resolution model combined with data assimilation is essential to improve forecast accuracy in complex topography areas [4]. Similarly, Nguyen Thi Nga et al. (2021) assessed the quantitative precipitation forecasting capability in 2020 using the global IFS model and the high-resolution regional WRF–ARW model for northern Vietnam. Their findings showed that rainfall forecast in this region remains limited; however, the WRF model with data assimilation significantly improved accuracy for heavy rainfall thresholds in 1–3-day forecasts, providing more effective support for operational heavy rainfall forecasting [5].

Hue City and Central Vietnam are frequently affected by prolonged heavy rainfall events, which often lead to flooding and cause severe economic losses. Most current studies primarily use GFS data as the input source for the WRF model. Previous works, such as those by Nguyen Thi Thanh et al. (2024), Nguyen Tien Toan et al. (2018), and Do Huy

Duong et al. (2005), applied WRF with GFS boundary conditions to simulate major rainfall events in Central Vietnam, achieving encouraging results [6][7][8]. Notably, Nguyen Tien Thanh et al. (2022) successfully simulated rainfall and streamflow in the Ta Trach Reservoir Basin (Thua Thien Hue) during the 2020 flood season using ERA5 reanalysis data as input [9].

However, detailed comparisons of the impacts of different input datasets – particularly between GFS and IFS – remain limited and require further investigation. Therefore, this study aims to evaluate the influence of two widely used global datasets, GFS and IFS, on rainfall simulation results using the WRF model for Hue City during major rainfall events. The simulation outputs are compared with observed rainfall data to assess their accuracy and ability to reproduce rainfall characteristics, thereby providing insights to support the selection of appropriate input data for weather forecasting and disaster prevention in Central Vietnam.

II. STUDY AREA AND DATA

A. *Study Area and Period*

The study was conducted in Hue City, located in Central Vietnam. This area is characterized by a distinctive topography, where the Truong Son Mountain Range runs close to the coastline, creating an abrupt transition from high mountainous terrain to low-lying coastal plains. The steep terrain and proximity of the mountains to the sea enhance orographic rainfall effects due to the interaction between topography and moist airflow, especially during the rainy season. Rainfall is mainly concentrated within the three-month rainy season from September to November, featuring prolonged and intense precipitation events that frequently cause flooding, severely impacting livelihoods, agriculture, urban infrastructure, and transportation.

The criteria for selecting rainfall events include high rainfall totals, long-lasting precipitation, and significant impacts on the study area. In addition to identifying the timing and characteristics of each event, the study also compiles and classifies the main synoptic weather patterns – such as tropical storms, tropical depressions, cold surges, and easterly disturbances – which are the primary causes of heavy rainfall in this region. The analysis period spans from 2015 to 2025, aiming to clarify the relationships between large-scale atmospheric conditions and local rainfall characteristics, as well as to evaluate the WRF model's performance when using different input datasets, namely GFS and IFS.

A total of 59 heavy rainfall events occurring between January 2015 and June 2025 were selected as the basis for analysis and simulation. These events were identified using official meteorological and hydrological records published in the annual reports *"Hydro-Meteorological Characteristics"* by the Vietnam Meteorological and Hydrological Administration (VMHA). Detailed information on the weather systems responsible for each rainfall event is presented in Table I.

TABLE I. RAINFALL-FORMING WEATHER SYSTEMS

No	Weather Pattern	Number of Rainfall Events	Percentage (%)
1	Cold surge combined with tropical cyclone or tropical depression	6	10.17%
2	Tropical cyclone or tropical depression with direct impact	14	23.73%
3	Cold surge combined with upper-level easterly winds	21	35.59%
4	Cold surge combined with tropical depression or cyclone, tropical convergence zone, and upper-level easterly winds	9	15.25%
5	Cold surge	1	1.69%
6	Cold surge combined with tropical convergence zone	2	3.39%
7	Tropical convergence zone combined with tropical depression	2	3.39%
8	Cold surge combined with tropical convergence zone and upper-level easterly winds	1	1.69%
9	Other weather patterns	3	5.08%
	Total	59	100%

B. *Data Used*

In this study, two primary input datasets were used to run the WRF model: data from the Global Forecast System (GFS) and data from the Integrated Forecasting System (IFS) developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). In addition, observed rainfall data were used to evaluate the simulation results.

The GFS input data are global forecast outputs produced by the National Centers for Environmental Prediction (NCEP) of the United States. In this study, GFS data with a spatial resolution of 0.25° (~28 km) in GRIB2 format were used to provide the initial and boundary conditions for the WRF model. Data fields at the analysis time (F000) and every 6-hour interval were continuously collected from January 2015 to June 2025, resulting in a total of 15,215 files with an approximate volume of 5,028 GB.

The IFS input data used in this study are ERA5 reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), with a spatial resolution of 0.1° (~9 km) in GRIB format. The ERA5 dataset used in this research includes two types: (1) Single-level data, representing surface meteorological fields such as precipitation, surface temperature, 10 m wind, and surface pressure; and (2) Pressure-level data, containing variables such as wind, temperature, and humidity at standard pressure levels ranging from 1000 hPa to 100 hPa. The data were extracted corresponding to the selected rainfall events identified during the 2015–2025 study period.

The observed rainfall data were obtained from the network of meteorological and hydrological stations in Hue region and were used as reference data to evaluate the model's accuracy. The stations include: A Luoi and Thuong Nhat – located in the western mountainous area of Thua Thien Hue Province, characterized by highly dissected terrain; Nam Dong – situated in the midland zone, representing a transition between mountains and plains; and Hue – representing the coastal plain area, with relatively flat and low-lying terrain (Fig. 1). The diversity of topographic conditions among these stations enables a comprehensive assessment of the model's performance under different terrain settings. The data were provided by the National Center for Hydro-Meteorological Forecasting (NCHMF) (Table II).

TABLE II. OBSERVATIONAL STATIONS USED

No	Station	Station Longitude	Station Latitude
1	A Luoi	107.283333	16.216667
2	Thuong Nhat	107.686241	16.129444
3	Nam Dong	107.718333	16.168333
4	Hue	107.583336	16.433332

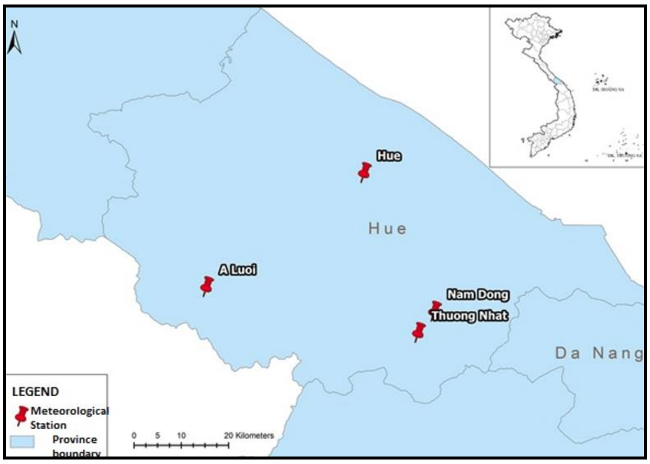

Fig. 1. Observational Stations in the Study Area

III. MODEL CONFIGURATION

After defining the study area, selecting the spatial – temporal simulation range, and determining the input datasets, this section further presents the specific configuration parameters and model structure used in the study.

A. *WRF Model Configuration for the Study Area*

1) Physical Parameterization Schemes

During the simulation process, the physical parameterization schemes play a crucial role in determining meteorological characteristics, particularly rainfall behavior. To ensure consistency in comparing the performance of the two input datasets (GFS and IFS), all model runs were conducted using the same physical configuration.

The selected physical schemes were chosen to suit the characteristics of the study area – a region with complex terrain and a tropical monsoon climate – and were also based on recommendations from previous studies conducted in Vietnam and Southeast Asia. Specifically, the configuration includes: the Kessler microphysics scheme, the Kain–Fritsch cumulus parameterization scheme, the RRTMG shortwave/longwave radiation schemes, and the YSU planetary boundary layer scheme, with a total of 51 vertical levels and a model top at 50 hPa (~20 km).

Maintaining the same set of physical parameterization schemes throughout all simulation runs is essential to ensure that any differences in the simulated rainfall results – if present – originate from the input datasets rather than from variations in the model configuration.

2) Model Domain Configuration

To enable detailed simulation of heavy rainfall events, the WRF model was configured with three nested domains having spatial resolutions of 15 km, 5 km, and 1.67 km, respectively, following a downscaling ratio of 5:3. The specific configuration of the model domains is illustrated in Figure 2:

The outermost domain (D01) consists of 160 × 140 grid points, covering the entire East Sea (South China Sea) region, with coordinates ranging from 5.53° to 24.07°N latitude and 98.97° to 121.03°E longitude.

The middle domain (D02) consists of 151 × 151 grid points with a spatial resolution of 5 km. It is centered over Thua Thien Hue Province and covers the area from 12.78° to 19.44°N latitude and 104.37° to 111.30°E longitude.

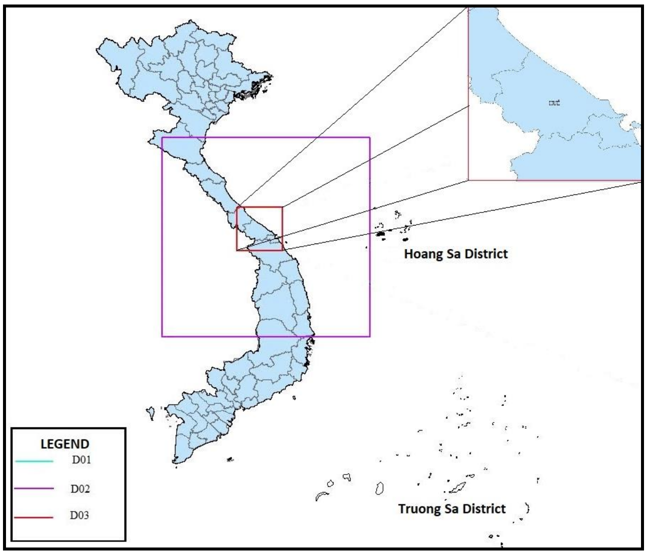

Fig. 2. Domains D01, D02, and D03 (left) and Domain D03 (right)

The innermost domain (D03) has the highest spatial resolution of 1.67 km, consisting of 100 × 100 grid points, focusing on a detailed simulation of Hue City and its surrounding areas. It spans from 15.65° to 17.11°N latitude and 106.86° to 108.38°E longitude. The center of D03 is located directly over Hue City, while D01 is configured to cover the entire East Sea (South China Sea) to ensure appropriate boundary conditions for the inner domains.

3) Topography and Land Cover Data

The topography and land cover data used in the WRF model were obtained from standard global datasets, including GMTED2010 (Global Multi-resolution Terrain Elevation Data 2010) and MODIS (Moderate Resolution Imaging Spectroradiometer), and processed through the geogrid module of the WRF Preprocessing System (WPS). Specifically:

The topographic data were derived from the GMTED2010 (Global Multi-resolution Terrain Elevation Data 2010) dataset, with a spatial resolution of 30 arc-seconds (approximately 1 km). This dataset was jointly developed and updated by the U.S. Geological Survey (USGS) and the National Geospatial-Intelligence Agency (NGA) around 2010–2011. GMTED2010 provides highly detailed and globally consistent elevation information, making it suitable for regions with complex terrain.

The land use/land cover data were obtained from the MODIS 20-category dataset, with a similar spatial resolution of approximately 1 km, representing the average land cover conditions. The classification system follows the IGBP (International Geosphere–Biosphere Program) standard, comprising 20 land cover types, including forest, agricultural land, urban areas, and water bodies. The version used in this study has enhanced capability to identify lakes and lagoon areas.

The soil type data are divided into two layers – a surface layer and a subsurface layer – with a spatial resolution of 30 arc-seconds (approximately 1 km). The classification follows the USGS soil taxonomy, consisting of about 16 major soil groups, such as sand, clay, loam, and sandy loam. In addition, multi-year mean soil temperature data are also provided to support the initialization of land surface conditions in the model.

By utilizing modern, high-resolution datasets, the WRF model is able to accurately represent the diverse topographic features of the Hue City region – which encompasses coastal plains, lagoon systems, and western mountain ranges – thereby enhancing the reliability and accuracy of the meteorological simulation results.

4) Initial and Boundary Conditions

The initial conditions (IC) and boundary conditions (BC) for the model were provided by the two global datasets, GFS and IFS. In the *namelist.input* file, the boundary conditions were updated at 6-hour intervals (*interval_seconds = 21600s*). The global model data were interpolated into the three nested domains with a parent_grid_ratio of 1:3:3, where the outermost domain has a spatial resolution of 15 km.

5) Preprocessing Tools and Workflow

All input data were processed using the WPS, which consists of three main steps:

- geogrid: processes topography and land cover data and generates the model spatial grid.
- ungrib: decodes global GFS/IFS data (in GRIB2/GRIB format) into an intermediate format readable by WRF.
- metgrid: interpolates the global data into the coordinate system and grid structure of the WRF model.

This process ensures that the global meteorological data are properly synchronized with the WRF simulation grid over the Hue City region. The differences in spatial and temporal resolution, as well as in the forecasting algorithms between GFS and IFS, represent potential factors contributing to the discrepancies in WRF-simulated rainfall results.

The model was tested with a total of 59 heavy rainfall events, each simulated twice, corresponding to the two input datasets: GFS and IFS. The computation process showed an average simulation time of approximately 10 minutes for each hour of real-world weather. The model was configured with a time step of 6 seconds and produced output results at 1-hour intervals.

B. Evaluation Methodology

To evaluate the performance of the WRF model in simulating rainfall using the two input datasets, GFS and IFS, the study compared the simulated results with observed rainfall data from meteorological stations in the Hue City area. The evaluation was conducted from both quantitative and qualitative perspectives – using statistical indicators for numerical assessment and visual analysis through graphical comparisons.

1) Quantitative Evaluation: The statistical indicators were used to quantify the errors and correlation between the simulated and observed rainfall data.

a) MAE (Mean Absolute Error) – measures the average magnitude of the differences between the simulated and observed rainfall values.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|P_i - O_i\right| \qquad (1)$$

b) RMSE (Root Mean Square Error) – evaluates the average deviation while accounting for the severity of larger errors (due to squaring). It is more sensitive to large discrepancies, and a smaller RMSE indicates higher model accuracy.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(P_i - O_i\right)^2} \qquad (2)$$

c) ME (Mean Error) – represents the average difference between the simulated and observed values. This indicator shows whether the model tends to overestimate (positive ME) or underestimate (negative ME) compared to observations. The closer the ME is to zero, the smaller the model bias. However, since ME only reflects the average difference, positive and negative errors may offset each other; therefore, it should be used in combination with other metrics (such as MAE and RMSE) for a more comprehensive evaluation.

$$ME = \frac{1}{n}\sum_{i=1}^{n}\left(P_i - O_i\right) \qquad (3)$$

d) PBIAS (Percent Bia) – represents the relative difference between the simulated total rainfall from the model and the observed total rainfall.

$$PBIAS = \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)}{\sum_{i=1}^{n} O_i} * 100 \qquad (4)$$

This indicator is used to evaluate the bias tendency of the model: a positive PBIAS value indicates that the model overestimates rainfall, while a negative PBIAS value indicates underestimation.

Where:

P_i:: simulated rainfall value at point *i*

O_i: observed rainfall value at point *i* n: total number of data points (spatial or temporal)

These statistical indicators have been widely applied in numerous meteorological simulation and forecasting studies in Vietnam. For instance, Truong Ba Kien et al. (2023) [10] employed ME, MAE, and RMSE to evaluate the rainfall forecast quality of the WRF model at 150 meteorological stations nationwide; Mai Khanh Hung (2020) [11] used ME and RMSE to assess rainfall forecast errors from a numerical weather prediction model for Ha Nam and Nam Dinh provinces in 2019; and Vu Van Thang (2017) [12] applied these indicators to analyze the forecasting performance of summer rainfall over Southern Vietnam and the Central Highlands.

However, no officially published classification threshold system currently exists to determine what constitutes a "good" or "poor" value for these statistical indicators in WRF-based rainfall simulations, particularly for the Central Vietnam region.

Therefore, in this study, to facilitate the aggregation and comparison of results among different stations and between models, the errors were categorized into three quantitative ranges as follows: Error ≤ 5 mm; Error between 5–10 mm and Error > 10 mm.

This classification is not intended to evaluate the model's quality as "good" or "poor," but rather to provide a consistent basis for comparison. The selected thresholds were determined based on empirical experience, the characteristics of the study area, and by referring to approaches from several international studies (Willmott & Matsuura, 2005; Moriasi et al., 2007) [13][14], as well as practical applications in domestic research.

2) Qualitative Evaluation: In this study, the qualitative assessment was conducted through visual analysis of comparative graphs between the WRF-simulated rainfall results (using the two input datasets, GFS and IFS) and the observed data at meteorological stations within the Hue City area. Unlike conventional approaches that rely solely on time series comparisons, this study focuses on:

- Total rainfall of the 59 heavy rainfall events during 2015–2025: analyzing the similarities and differences between simulated and observed values to identify the model's ability to reproduce the actual intensity and spatial extent of rainfall…
- Statistical indicators (ME, MAE, RMSE): illustrating the error trends for each rainfall event and the differences between the two input datasets, GFS and IFS.

Presenting the results through bar charts and comparative plots enables the assessment of the model's error trends across consecutive rainfall events, its ability to reproduce total rainfall for each event as well as for the entire study period, and the distinct differences between WRF-GFS (WRF using GFS input) and WRF-IFS (WRF using IFS input). This approach helps clarify the impact of input data sources on simulation quality. The qualitative analysis provides a visual perspective that complements the quantitative evaluation, while also identifying periods and conditions under which the model performs effectively or ineffectively in simulating rainfall over Hue City.

IV. RESULTS AND DISCUSSION

In this section, the study focuses on presenting and analyzing the WRF-simulated rainfall results using two global boundary condition datasets – GFS and IFS – for the period 2015–2025 in Hue City, specifically referred to as WRF-GFS and WRF-IFS. The analyses were conducted from two perspectives: (i) Evaluation using statistical indicators (ME, MAE, RMSE) to quantify the model's overestimation or underestimation tendencies and its ability to reproduce rainfall patterns; and (ii) Evaluation based on the total rainfall of 59 major rainfall events, aimed at determining the degree of discrepancy between simulated and observed rainfall.

1) Evaluation Based on ME, MAE, and RMSE Indicators

To evaluate the performance of the global model datasets used as boundary conditions for the WRF model in rainfall simulation, three commonly used statistical indicators were applied: Mean Error (ME), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE). These metrics were employed to analyze the model's overall performance and its ability to reproduce observed rainfall patterns.

TABLE III. RMSE-BASED EVALUATION CLASSIFICATION

Station	Model	Error (≤5)	Error (5-10)	Error (>10)
A Luoi	GFS	26	27	6
	IFS	26	22	11
Hue	GFS	27	24	8
	IFS	26	22	11
Nam Dong	GFS	17	32	10
	IFS	21	22	16
Thuong Nhat	GFS	22	27	10
	IFS	17	26	16

According to the RMSE-based evaluation (Table III), at the A Luoi and Hue stations, both WRF-GFS and WRF-IFS models produced comparable overall error levels; however, the WRF-GFS model exhibited fewer events falling within the high-error range (>10 mm) compared to WRF-IFS. Specifically, WRF-IFS recorded up to 11 events with RMSE >10 mm, while WRF-GFS registered only 6 to 8 events in the same range.

At the Nam Dong and Thuong Nhat stations – both characterized by complex terrain and high rainfall amounts – the WRF-GFS model also demonstrated greater stability, with significantly fewer high-error events (>10 mm) compared to WRF-IFS. The WRF-IFS model recorded up to 16 events with RMSE >10 mm at these two stations, indicating a notable discrepancy in rainfall simulation over topographically sensitive areas.

Although in certain periods the WRF-IFS model produced results closer to observations, overall – based on the RMSE values and the number of high-error events – the WRF-GFS model demonstrated greater stability, particularly at mountainous stations such as Nam Dong and Thuong Nhat. This finding should be carefully considered when selecting input datasets for heavy or extreme rainfall forecasting applications in Central Vietnam.

According to the MAE-based evaluation (Table IV), the WRF-GFS model demonstrated a clear advantage over WRF-IFS across all four stations. Specifically, the number of events with MAE ≤ 5 mm in WRF-GFS ranged from 52 to 55 events per station, which is 3–5 events higher than that of WRF-IFS.

TABLE IV. MAE-BASED EVALUATION CLASSIFICATION

Station	Model	Error (≤5)	Error (5-10)	Error (>10)
ALuoi	GFS	55	3	1
	IFS	49	9	1
Hue	GFS	54	5	0
	IFS	51	8	0
NamDong	GFS	52	6	1
	IFS	49	9	1
ThuongNhat	GFS	53	5	1
	IFS	48	10	1

In contrast, the WRF-IFS model had a greater number of events within the 5–10 mm error range, indicating that its average error was generally higher than that of WRF-GFS. Both models recorded very few events with large errors (MAE > 10 mm); however, WRF-GFS consistently maintained better stability, with a higher number of events falling within the low-error range.

At the Hue station, both WRF-GFS and WRF-IFS achieved high accuracy, with no events recording MAE > 10 mm. However, WRF-GFS performed slightly better, with a greater number of events having MAE ≤ 5 mm, indicating a closer agreement with observations.

Overall, according to the MAE indicator, which reflects the average deviation between simulated and observed rainfall, the WRF-GFS model exhibited greater stability and higher performance compared to WRF-IFS across all stations. This result is consistent with the previous RMSE analysis, indicating that WRF-GFS has a clear advantage in simulating overall rainfall with smaller errors, particularly during moderate to heavy rainfall events.

TABLE V. ME - BASED EVALUATION CLASSIFICATION

Station	Model	Error (≤5)	Error (5-10)	Error (<0)	Error (>10)
A Luoi	GFS	36	1	22	0
	IFS	32	1	26	0
Hue	GFS	26	0	33	0
	IFS	24	1	34	0
Nam Dong	GFS	29	0	30	0
	IFS	23	1	35	0
Thuong Nhat	GFS	29	0	30	0
	IFS	31	1	27	0

The ME indicator (Table V) reflects the bias trend between simulated and observed rainfall—positive values indicate that the model overestimates rainfall, while negative values indicate underestimation. Therefore, events with ME < 0 reveal that the model tends to predict lower rainfall than observed, which is particularly important when evaluating heavy rainfall events...

The results show that both WRF-GFS and WRF-IFS exhibited a significant number of events with negative ME values, indicating that the models underestimated rainfall compared to observations. At the Hue and Nam Dong stations, the number of events with ME < 0 reached 30–35, accounting for a large proportion of the entire simulation period.

Overall, the WRF-GFS model showed smaller mean deviations at three stations – A Luoi, Hue, and Nam Dong – with a greater number of events having |ME| ≤ 5 mm compared to WRF-IFS. At the Thuong Nhat station, WRF-IFS performed slightly better, with 31 events within the |ME| ≤ 5 mm range compared to 29 events for WRF-GFS; however, the difference was insignificant.

Thus, the ME analysis indicates that the WRF-GFS model generally produced simulations closer to observations than WRF-IFS, particularly at stations located in complex terrain areas such as A Luoi and Nam Dong. However, the fact that both models frequently underestimated actual rainfall – as reflected by the high proportion of events with ME < 0 – is noteworthy. This highlights the need for model calibration, especially for heavy rainfall, extreme precipitation events, or composite synoptic systems associated with intense rainfall.

Based on the RMSE, MAE, and ME error indicators at the four observation stations – A Luoi, Hue, Nam Dong, and Thuong Nhat – the WRF-GFS model generally demonstrated greater stability and reliability compared to WRF-IFS. In particular, for the MAE indicator, WRF-GFS showed a significantly higher number of rainfall events with errors less than or equal to 5 mm, outperforming WRF-IFS at all stations.

Regarding the RMSE indicator, both models showed comparable overall performance; however, WRF-GFS consistently exhibited fewer events with errors greater than 10 mm compared to WRF-IFS.

Based on the ME indicator, both WRF-GFS and WRF-IFS showed a tendency to underestimate actual rainfall in many events. However, WRF-GFS maintained a smaller average bias, with fewer negative ME events (indicating underestimation) compared to WRF-IFS at most stations…

Thus, in most rainfall simulation cases, the WRF-GFS model demonstrated higher quantitative reliability compared to WRF-IFS, although WRF-IFS could still produce better results in certain specific rainfall events.

Throughout the study period, a total of 59 heavy rainfall events were simulated and analyzed. However, only a selected number of meteorologically distinctive events were chosen for detailed presentation (Fig. 2, 3, and 4). These representative cases are primarily associated with synoptic systems such as tropical storms, tropical depressions, or the interaction between cold surges and tropical weather phenomena…

To visualize the results and compare the forecasting performance of the WRF-GFS and WRF-IFS models, graphs of the evaluation indicators (RMSE, MAE, ME) are presented for each representative rainfall event. These charts clearly illustrate the magnitude of errors between the model simulations and actual observations, while also providing a detailed insight into the performance of each model under different meteorological conditions.

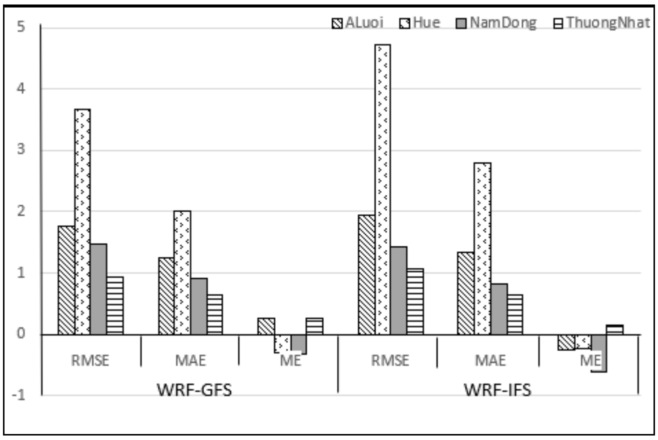

Fig. 3. Evaluation Indicators for the 12/2024 Rainfall Event

Based on the RMSE, MAE, and ME indicators, the WRF-GFS model provided more accurate rainfall forecasts than WRF-IFS for the December 2024 rainfall event (Fig. 3). Specifically, WRF-GFS showed lower errors at most stations, particularly at Hue and A Luoi, as reflected by its smaller RMSE and MAE values compared to WRF-IFS. The ME indicator revealed that WRF-GFS exhibited less bias, whereas WRF-IFS tended to underestimate rainfall, consistent with the total rainfall charts where WRF-IFS values were generally lower than observations, especially at Nam Dong. This indicates that WRF-GFS more effectively reproduced actual rainfall under heavy precipitation conditions in Central Vietnam.

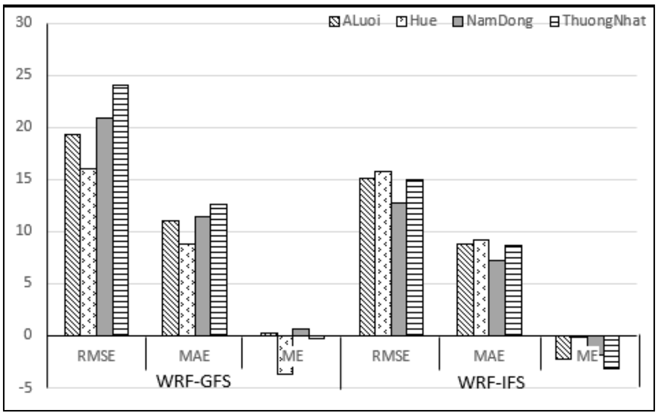

Fig. 4. Evaluation Indicators for the 10/2020 Rainfall Event

During the 10/2020 heavy rainfall event (Fig. 4), the WRF-IFS model generally provided forecasts closer to observations than WRF-GFS at most stations, as indicated by lower RMSE and MAE values, particularly at Nam Dong and A Luoi. The WRF-GFS model exhibited higher absolute and root mean square errors, especially at Nam Dong (RMSE-GFS = 20.94 compared to RMSE-IFS = 12.80). The ME indicator shows that WRF-IFS tended to produce negative values (indicating underestimation), whereas WRF-GFS was closer to zero or slightly positive.

Overall, WRF-IFS exhibited smaller average errors, but WRF-GFS performed better in heavy rainfall areas such as A Luoi and Thuong Nhat, consistent with the trends shown in the total rainfall charts.

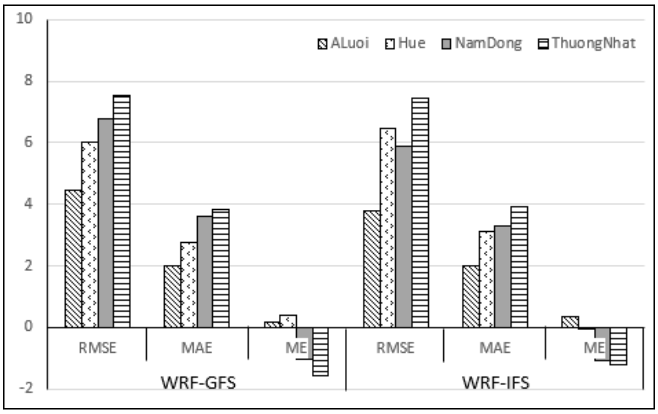

Fig. 5. Evaluation Indicators for the 11/2015 Rainfall Event

In the 11/2015 rainfall event (Fig. 5), the performance of the WRF-GFS and WRF-IFS models was generally comparable, although differences were observed across specific locations.

At the A Luoi station, the WRF-IFS model exhibited a lower overall error (RMSE = 3.77 compared to 4.45), while WRF-GFS had an ME value closer to zero (0.15 vs. 0.33), indicating less bias. At the Hue station, both RMSE and MAE were lower for WRF-GFS, suggesting that this model provided more accurate rainfall forecasts.

In contrast, at the Nam Dong and Thuong Nhat stations, both models underestimated the observed rainfall, as indicated by the strong negative ME values (particularly for WRF-GFS at Thuong Nhat, where ME = –1.56). However, WRF-IFS produced more stable results at these two stations, with both RMSE and MAE values lower than those of WRF-GFS.

The error trend indicated by the ME values shows that WRF-GFS tended to overestimate rainfall at the A Luoi and Hue stations, whereas WRF-IFS provided closer estimates at Hue but showed notable underestimation at Nam Dong and Thuong Nhat.

It can be seen that the chart analysis results serve as an important basis for evaluating the applicability of the models in rainfall forecasting and for guiding future improvements aimed at enhancing forecast accuracy in subsequent studies.

2) Evaluation Based on Total Rainfall

The summary of rainfall event classifications for the 2015–2025 period (Table VI) shows that both GFS and IFS boundary datasets, when used in the WRF model, still exhibited notable discrepancies compared to observations. However, the degree of deviation varied across different stations.

TABLE VI. RAINFALL CLASSIFICATION BY TOTAL

Station	Model	Good (≤25)	Acceptable (25-50)	Unsatisfactory (>50)
A Luoi	GFS	20	16	23
	IFS	20	10	29
Hue	GFS	12	17	30
	IFS	15	14	30
Nam Dong	GFS	16	15	28

Station	Model	Good (≤25)	Acceptable (25-50)	Unsatisfactory (>50)
	IFS	15	17	27
Thuong Nhat	GFS	15	13	31
	IFS	12	12	35

- A Luoi Station: Both WRF-GFS and WRF-IFS achieved 20 out of 59 events (≈34%) classified as *"good."* However, GFS had a greater number of "acceptable" events (16 compared to 10), while IFS recorded more "unsatisfactory" events (29 compared to 23). This indicates that at A Luoi, the WRF-GFS model demonstrated greater stability in terms of total rainfall simulation compared to WRF-IFS.
- Hue Station: The results were fairly balanced. IFS had a higher number of "good" events (15 compared to 12) and a similar number of "acceptable" events (14 versus 17), yet both models recorded up to 30 out of 59 "unsatisfactory" events (≈51%). This reflects the common difficulty in accurately simulating heavy rainfall over the central plain region.
- Nam Dong Station: WRF-GFS performed slightly better in terms of the number of *"good"* events (16 compared to 15), while WRF-IFS had more *"acceptable"* events (17 versus 15). The number of *"unsatisfactory"* events was relatively similar between the two datasets (28 and 27). Thus, at Nam Dong, the simulation performance of WRF-GFS and WRF-IFS was nearly equivalent.
- Thuong Nhat Station: This station recorded the highest errors. WRF-GFS achieved 15 "good" and 13 "acceptable" events, whereas WRF-IFS had only 12 "good" and 12 "acceptable" events. Both datasets had over 50% of events classified as *"unsatisfactory,"* with WRF-IFS reaching as many as 35 out of 59 events (≈59%).

General Remarks: There was no clear overall superiority between the two datasets, WRF-GFS and WRF-IFS, across all stations. WRF-GFS tended to be more stable at the A Luoi and Thuong Nhat stations, while WRF-IFS performed slightly better at Hue and Nam Dong. However, the proportion of *"unsatisfactory"* events remained very high for both datasets (≈45–60%), highlighting the challenge of accurately reproducing heavy rainfall using the WRF model when only the global boundary conditions are changed. These findings suggest that additional methods, such as bias correction, data assimilation, or the use of more suitable physical parameterization schemes, are needed to improve simulation quality.

Based on a total of 59 rainfall events during the 2015–2025 period, the dominant weather systems were classified into nine main categories. The evaluation of the WRF model's simulation performance using the two boundary condition datasets, GFS and IFS, was conducted according to the criterion that an event is considered successful when at least two stations recorded PBIAS ≤ 25%. The results revealed notable differences between the two datasets (Table VII).

TABLE VII. EVALUATION BY RAINFALL PATTERNS

No	Weather Pattern	Number of Rainfall Events	Simulation Performance of WRF-GFS and WRF-IFS
1	Cold surge combined with tropical cyclone or tropical depression	6	Equivalent
2	Tropical cyclone or tropical depression with direct impact	14	WRF-GFS performs better
3	Cold surge combined with upper-level easterly winds	21	WRF-GFS slightly better
4	Cold surge combined with tropical depression or cyclone, tropical convergence zone, and upper-level easterly winds	9	WRF-IFS performs better
5	Cold surge	1	Both failed to simulate
6	Cold surge combined with tropical convergence zone	2	Both failed to simulate
7	Tropical convergence zone combined with tropical depression	2	WRF-GFS performs better
8	Cold surge combined with tropical convergence zone and upper-level easterly winds	1	WRF-GFS significantly better
9	Other weather patterns	3	Equivalent
	Total	*59*	

Among the analyzed weather patterns, the combination of cold surge and upper-level easterly winds was the most common type. Within this group, the WRF model using GFS input data demonstrated better rainfall simulation performance compared to IFS, although the accuracy of both models remained limited.

For weather patterns directly influenced by tropical storms or depressions – which typically cause widespread heavy rainfall – the WRF-GFS model continued to show a clear advantage. Its ability to reproduce rainfall events under these conditions indicates that WRF-GFS possesses higher sensitivity in capturing the circulation characteristics of tropical cyclone systems.

In contrast, for complex combined weather patterns – including cold surges, tropical depressions or storms, tropical convergence zones, and upper-level easterly winds – the model using IFS input data produced better simulation results. This suggests that WRF-IFS may more effectively capture large-scale interactions and upper-atmospheric structures. However, since the number of rainfall events within this category was relatively limited, the results require further verification to confirm their stability and reliability.

In some less frequent but well-defined weather patterns, such as the combination of cold surge and tropical convergence zone, the WRF-GFS model produced fairly satisfactory simulation results. However, due to the low occurrence frequency of these events, the findings should be considered indicative rather than conclusive.

Conversely, for single-type weather patterns such as pure cold surges or weak combinations of cold surges with other factors, both datasets failed to produce successful simulations. This reflects the limitations of the model in handling weakly dynamic systems or poorly defined synoptic patterns under the given input conditions.

Overall, WRF-GFS tended to simulate more accurately than WRF-IFS under well-defined, large-scale, and organized weather systems such as tropical storms, depressions, or easterly flows, whereas WRF-IFS appeared to perform better in multi-factor composite patterns. These results suggest that the selection of boundary conditions should take into account the dominant synoptic characteristics of each rainfall event within the simulation domain.

Focusing on the analysis of representative rainfall events not only allows for a more accurate assessment of the forecasting capability of the WRF-GFS and WRF-IFS models but also enables the research team to visualize the total rainfall of each event through graphical representations. This approach helps illustrate the differences between simulated and observed results, thereby evaluating model performance in specific meteorological situations and providing a foundation for improving rainfall forecast accuracy in future studies.

The 12/2024 rainfall event (Fig. 6) was caused by the interaction between a cold surge and upper-level easterly winds. During this event, the WRF-GFS model provided better forecasts than WRF-IFS at most stations – particularly at A Luoi, Nam Dong, and Thuong Nhat – where WRF-GFS produced rainfall values closer to observations, while WRF-IFS showed a notable underestimation. However, at the Hue station, both models performed reasonably well, with only minor differences between simulated and observed rainfall. Overall, underestimation was the dominant trend in this event, especially pronounced in WRF-IFS. Therefore, WRF-GFS was assessed to perform better in simulating rainfall for this cold surge–easterly wind combination event.

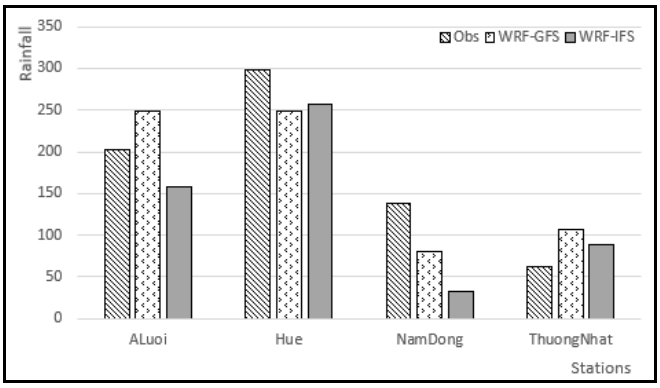

Fig. 6. Total Rainfall Chart for the 12/2024 Event

The 10/2020 rainfall event (Fig. 7) was one of the most intense rainfall episodes, caused by a complex combination of weather systems, including a cold surge, tropical depression or storm, tropical convergence zone, and upper-level easterly winds. During this event, the WRF-GFS model simulated rainfall closely matching observations at most stations – such as A Luoi, Nam Dong, and Thuong Nhat – with relatively small errors. In contrast, the WRF-IFS model tended to underestimate rainfall, particularly at high-rainfall sites like Thuong Nhat and A Luoi, where discrepancies reached hundreds of millimeters. At the Hue station, however, WRF-IFS produced results closer to observations than WRF-GFS. Overall, WRF-GFS was assessed to perform better in this event, as it more accurately captured extreme rainfall magnitudes across the region, while WRF-IFS exhibited a significant underestimation bias in such complex synoptic conditions.

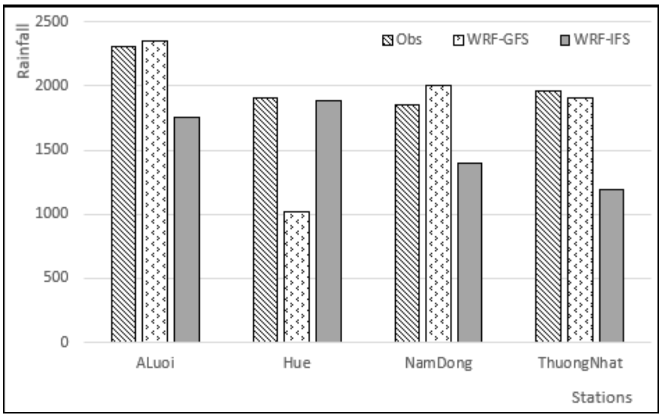

Fig. 7. Total Rainfall Chart for the 10/2020 Event

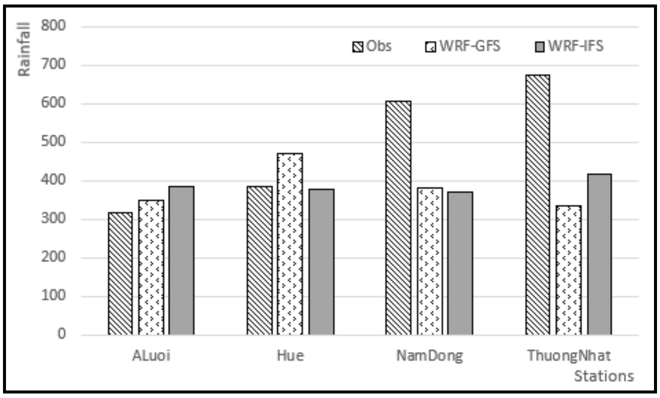

Fig. 8. Total Rainfall Chart for the 11/2015 Event

The 11/2015 rainfall event (Fig. 8) featured intense precipitation concentrated in Nam Dong and Thuong Nhat. Overall, the WRF-IFS model simulated rainfall more accurately than WRF-GFS at A Luoi and Thuong Nhat; however, both models significantly underestimated rainfall at locations with very high observed totals. This indicates that under non-typical synoptic conditions, the models tend to underpredict rainfall and fail to accurately represent the spatial distribution of extreme precipitation.

V. CONCLUSION

The study successfully configured the WRF model to simulate rainfall over Hue City, focusing on a total of 59 major rainfall events during the 2015–2025 period. Two global boundary condition datasets were compared: GFS and IFS (ERA5 reanalysis data from ECMWF). The simulation results were evaluated using statistical indicators (ME, MAE, RMSE), total rainfall analysis, and assessments based on dominant synoptic weather patterns.

The main findings can be summarized as follows:

- Regarding the error indicators (ME, MAE, RMSE): the model using GFS boundary conditions exhibited lower average errors and greater stability compared to IFS in most rainfall events, particularly at mountainous stations such as A Luoi and Thuong Nhat. Both models showed a tendency to underestimate rainfall (negative ME values); however, WRF-GFS generally maintained smaller errors in the majority of cases.

- Regarding total rainfall (based on the PBIAS indicator): neither dataset demonstrated complete superiority; however, WRF-GFS performed better under large-scale, well-organized weather systems such as tropical storms, depressions, or easterly flows. In contrast, WRF-IFS tended to simulate composite or more complex synoptic patterns more accurately. Nevertheless, the proportion of rainfall events meeting the "acceptable" criterion (PBIAS ≤ 25%) was only about 40–55%, highlighting the limitations of relying solely on different boundary conditions without applying bias correction or data assimilation techniques.

- Regarding synoptic characteristics: WRF-GFS proved to be more suitable for rainfall events associated with tropical storms, tropical depressions, or easterly flows, whereas WRF-IFS was better at capturing more complex interactions between cold surges and the intertropical convergence zone (ITCZ). These results suggest that the selection of input datasets should be flexible and tailored to the dominant synoptic conditions of each meteorological scenario.

Recommendations and Future Model Development Directions: It is necessary to integrate model correction techniques (bias correction), data assimilation, and improvements in physical parameterization schemes to enhance simulation accuracy. Additionally, the use of IFS data should be further explored – although IFS showed higher errors in certain situations, it still holds significant potential when combined with data assimilation or model bias-adjustment techniques.

Practical Application: The WRF model using GFS boundary conditions can be prioritized for regional-scale heavy rainfall forecasting in the Hue area, particularly under strong and well-defined synoptic conditions such as tropical storms or tropical depressions.

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REFERENCES

[1] A. Srivastava, P. Ullrich, D. Rastogi, P. Vahmani, A. Jones, và R. Grotjahn, "Assessment of WRF (v 4.2.1) dynamically downscaled precipitation on subdaily and daily timescales over CONUS," *EGU General Assembly 2023*, 2023, doi: 10.5194/egusphere-2022-1382.

[2] Capecchi, V., "Reforecasting Two Heavy-Precipitation Events with Three Convection-Permitting Ensembles", *Weather and Forecasting*, 36(3): 769-790, 2021. doi:10.1175/WAF-D-20-0130.1.

[3] H. Yan and W. A. Gallus, "An Evaluation of QPF from the WRF, NAM, and GFS Models Using Multiple Verification Methods over a Small Domain," *Weather and Forecasting*, vol. 31, pp. 1363–1379, 2016, doi: 10.1175/WAF-D-16-0020.1.

[4] T. A. Duc, M. V. Khiem, M. K. Hung, D. D. Quan, D. T. Trang, H. G. Nam, L. R. Hole, and D. D. Tien, "Skill validation of high-impact rainfall forecasts over Vietnam using the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS) and dynamical downscaling with the Weather Research and Forecasting model (WRF-ARW)," *Atmosphere*, vol. 16, no. 2, Art. no. 224, 2025. doi: 10.3390/atmos16020224.

[5] N. T. Nga, T. Cong, K. H. Mai, and D. D. Tien, "Đánh giá kĩ năng dự báo mưa định lượng từ mô hình quy mô toàn cầu và khu vực phân giải cao cho khu vực Bắc Bộ," *Tạp chí Khí tượng Thủy văn*, vol. 730, pp. 79–92, 2021, doi: 10.36335/VNJHM.2021(730).79-92. (In Vietnamese).

[6] N. T. Thanh, T. D. Thức, N. Đ. Nam, D. H. Nhung, và N. T. Thủ, "Mô phỏng mưa lớn bằng hệ thống mô hình WRF/WRF-Hydro: Trường hợp nghiên cứu cho lưu vực sông Vệ - Trà Khúc, tỉnh Quảng Ngãi," *Tạp chí Khoa học Biến đổi Khí hậu*, no. 32, pp. 113–118, Dec. 2024. (In Vietnamese).

[7] T. T. Nguyễn, T. Công, T. P. Phạm, và T. A. Vũ, "Đánh giá khả năng dự báo mưa lớn của mô hình WRF do hình thế không khí lạnh kết hợp với gió đông trên cao cho khu vực Trung Trung Bộ," *Tạp chí Khoa học ĐHQGHN: Các Khoa học Trái đất và Môi trường*, vol. 34, no. 1S, pp. 133–137, 2018. (In Vietnamese).

[8] Đ. H. Dương, "Khả năng dự báo mưa lớn ở Việt Nam bằng mô hình WRF," *Tạp chí Khí tượng Thủy văn*, vol. 535, no. 07, pp. 40–44, 2005. (In Vietnamese).

[9] N. T. Thành, P. M. Long, and D. T. Hieu, "Rainfall and runoff simulation in Ta Trach reservoir basin using WRF and SWAT models," *Journal of Hydrology*, vol. 600, p. 126529, 2022.

[10] T. B. Kiên, P. T. T. Ngà, T. D. Thức, P. T. M. Linh, and V. V. Thăng, "Đánh giá chất lượng dự báo mưa định lượng của mô hình WRF cho khu vực Việt Nam," *Tạp chí Khí tượng Thuỷ văn*, no. 738, pp. 1–11, 2022. (In Vietnamese).

[11] M. K. Hưng, D. D. Tiến, L. V. Sơn, B. T. Hải, P. T. P. Dung và D. Đ. Quân, "Đánh giá chất lượng dự báo mưa từ mô hình số trị cho khu vực Hà Nam và Nam Định trong năm 2019," *Tạp chí Khí tượng Thủy văn*, vol. 715, pp. 37–48, 2020, doi:10.36335/VNJHM.2020(715).37-48. (In Vietnamese).

[12] V. V. Thăng, V. Thế Anh, T. D. Thức, T. B. Kiên và N. V. Hiệp, "Đánh giá khả năng dự báo mưa mùa hè của mô hình WRF đối với khu vực Nam Bộ và Nam Tây Nguyên khi có bão trên Biển Đông," *Tạp chí Khoa học Biến đổi Khí hậu*, số 2, pp. 43–51, 06/2017. (In Vietnamese).

[13] C. J. Willmott and K. Matsuura, "Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance," Climate Research, vol. 30, no. 1, pp. 79–82, 2005.

[14] D. N. Moriasi, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith, "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations," Trans. ASABE, vol. 50, no. 3, pp. 885–900, 2007.