

Evaluation of Traditional and Numerical Meteorological Models for Rainfall Onset in Zanzibar, Dar es Salaam, and Iringa (2016–2025)

Abstract

Accurate rainfall onset prediction is essential for agricultural resilience across Zanzibar, Dar es Salaam, and Iringa. This study evaluates the traditional 4-Season temperate model against RegCM4 (regional), CAN-SIAM (climatological), and ECMWF/IFS (global). Results reveal a significant predictive gap, with observed onset exhibiting strong interannual and regional variability, while traditional models, especially 4-Season and CAN-SIAM, consistently show delayed onset biases of 6-13 days. Analysis of 2016-2025 rainfall patterns indicates increasing variability in the Masika season, driven by dynamic convective processes. ECMWF/IFS demonstrates the highest agreement with observations ($R^2 = 0.525$), though all models underestimate rainfall intensity. The 4-Season model is unsuitable for tropical applications because it cannot capture rapid monsoon onset dynamics. These findings highlight the need for dynamic, data-driven forecasting approaches to improve agricultural planning and early warning systems in Tanzania.

1. Introduction

The predictability of rainfall onset in tropical environments remains one of the most significant challenges in modern meteorology, particularly across Zanzibar, Dar es Salaam, and Iringa, where livelihoods are closely linked to rain-fed agriculture. In coastal regions such as Zanzibar and Dar es Salaam, agricultural productivity and economic activities, including clove production and subsistence farming, are highly sensitive to the timing of the Masika (long rains) and Vuli (short rains) seasons. Similarly, in inland regions such as Iringa, the onset of rainfall governs planting decisions and crop yields, making accurate forecasting essential for food security and climate resilience (Hansen et al., 2011; Sultan et al., 2019; Thornton et al., 2018).

Globally, rainfall prediction has evolved from simple statistical approaches to advanced General Circulation Models (GCMs). However, these models often struggle to resolve sub-grid-scale processes, including localized convection and tropical thunderstorms, which dominate rainfall formation in tropical regions (IPCC, 2023; Satgé et al., 2020). Unlike temperate climates, where rainfall is driven by large-scale frontal systems, tropical rainfall in East Africa is primarily controlled by moisture convergence and convective instability, which exhibit high spatial and temporal variability (Nicholson, 2017).

In the East African context, rainfall variability is strongly influenced by the seasonal migration of the Intertropical Convergence Zone (ITCZ) and large-scale ocean–atmosphere interactions such as the Indian Ocean Dipole (IOD) and El Niño–Southern Oscillation (ENSO) (Behera et al., 2005; Saji et al., 1999; Wainwright et al., 2021). Positive IOD phases have been linked to enhanced rainfall and flooding events, particularly in coastal regions such as Zanzibar and Dar es Salaam (Behera et al., 2005). Recent studies further indicate that these climate drivers contribute to increasing interannual variability and unpredictability of rainfall onset across the region (Ayugi et al., 2023; Omay et al., 2023; Roy et al., 2024).

In addition to large-scale drivers, intra-seasonal variability, particularly associated with the Madden–Julian Oscillation (MJO), plays a critical role in modulating rainfall patterns in East Africa (Pohl & Camberlin, 2006; Vellinga & Milton, 2023; Zhang, 2013). The MJO can induce alternating wet and dry spells lasting several weeks, significantly affecting both the timing and intensity of rainfall onset. These effects are especially pronounced in coastal zones, where sea-land interactions and moisture flux from the Indian Ocean amplify convective activity (Gamoyo et al., 2015).

Historically, local communities relied on the reversal of the Kaskazi (North-East) and Kusi (South-East) monsoon winds as indicators of seasonal transitions. However, rising sea surface temperatures in the western Indian Ocean and broader climate variability have reduced the reliability of these traditional indicators (IPCC, 2023). This has increased “false onset” events, where early rainfall is followed by prolonged dry periods, leading to premature planting and subsequent crop losses (Dunning et al., 2016).

Across both coastal (Zanzibar and Dar es Salaam) and inland (Iringa) regions, these challenges highlight a growing disconnect between traditional agricultural calendars, model-based forecasts, and actual atmospheric behavior. Despite advances in global and regional modeling frameworks, significant gaps remain in accurately predicting both the timing and intensity of rainfall events. This mismatch underscores the need for a systematic evaluation of existing predictive frameworks and the development of more adaptive, region-specific rainfall forecasting approaches capable of capturing both large-scale climate drivers and localized atmospheric processes.

2. Methodology

This study adopts a comparative modeling framework to evaluate the performance of four distinct rainfall prediction approaches across Zanzibar, Dar es Salaam, and Iringa, representing coastal and inland climatic regimes of Tanzania. The methodology integrates observational data analysis, model-based simulations, and statistical evaluation to quantify both rainfall onset accuracy and intensity representation over the period 2016–2025.

2.1 Data Sources and Study Regions

Daily rainfall observations were obtained from ground-based stations distributed across the three study regions. Zanzibar and Dar es Salaam represent coastal environments influenced by strong ocean-atmosphere interactions, while Iringa represents an inland highland region characterized by orographic effects. The dataset spans 2016–2025, capturing interannual variability associated with large-scale climate drivers such as the Intertropical Convergence Zone (ITCZ) and the Indian Ocean Dipole (IOD).

All datasets were subjected to quality control procedures, including removal of missing or erroneous values, temporal consistency checks, and conversion to a standardized format. The rainfall time series were then aggregated and transformed into Day-of-Year (DOY) representations to facilitate comparison of seasonal patterns across years and regions.

2.2 Model Frameworks

Four modeling approaches were evaluated, each representing a different level of complexity and physical realism:

2.2.1 4-Season Model (Baseline)

This model represents a **static, calendar-based framework**, assuming gradual seasonal transitions typical of temperate climates. It serves as a benchmark for assessing the limitations of non-dynamic approaches in tropical environments.

2.2.2 CAN-SIAM Model (Climatological)

The CAN-SIAM model is a statistical climatological approach based on long-term historical averages. It captures general seasonal cycles but lacks responsiveness to real-time atmospheric variability and interannual anomalies.

2.2.3 RegCM4 Model (Regional)

RegCM4 is a regional climate model used to dynamically downscale global climate data. It incorporates regional features such as topography, land–sea contrast, and mesoscale processes, making it suitable for capturing localized rainfall patterns in both coastal and inland regions.

2.2.4 ECMWF/IFS Model (Global)

The ECMWF Integrated Forecasting System (IFS) represents a high-resolution global numerical weather prediction model that assimilates real-time data from satellites, weather stations, and ocean buoys. It provides dynamically evolving forecasts and serves as the most advanced framework in this study.

2.3 Rainfall Onset Detection

Rainfall onset was defined using a threshold-based method to ensure consistency across models and observations. Specifically, onset was identified as the first occurrence of a 3-day cumulative rainfall ≥ 20 mm, followed by a period with no prolonged dry spell (>7 consecutive days with rainfall < 1 mm) within the subsequent 20 days.

This approach minimizes false onset detection caused by isolated rainfall events and ensures that the identified onset corresponds to sustained seasonal rainfall. The onset date was then expressed as a Julian Day (Day of Year, DOY) for comparative analysis.

2.4 Model Evaluation Metrics (Paragraph Form)

To assess model performance, both temporal accuracy in rainfall onset prediction and the representation of rainfall intensity were evaluated using a set of complementary statistical metrics. The Mean Absolute Error (MAE) was used to quantify the average magnitude of prediction errors without considering their direction, providing a straightforward measure of overall model accuracy. The Root Mean Square Error (RMSE) was employed to capture the overall error magnitude with greater sensitivity to large deviations, thereby highlighting models that fail to represent extreme rainfall events. The Coefficient of Determination (R^2) was used to evaluate the degree of agreement between observed and modeled rainfall patterns, indicating how effectively

each model explains the variability in the observed data. In addition, Bias (mean error) was calculated to assess systematic tendencies of the models to either overestimate or underestimate rainfall intensity. Finally, Onset Error (in days) was defined as the absolute difference between observed and predicted rainfall onset dates, expressed in terms of Day of Year (DOY), providing a direct measure of temporal prediction accuracy.

2.5 Comparative Analysis Framework

All models were evaluated against ground-truth rainfall observations across Zanzibar, Dar es Salaam, and Iringa to ensure a consistent and regionally representative assessment. The analysis was conducted at two complementary levels. First, a temporal analysis focused on rainfall onset prediction by comparing predicted onset dates with observed onset dates, thereby quantifying the timing accuracy of each model. Second, an intensity analysis examined the representation of rainfall magnitude through the evaluation of daily rainfall patterns and peak intensity using Day-of-Year (DOY)-based composite curves. In addition to these assessments, a multi-model comparison framework was implemented to evaluate the relative strengths and limitations of each approach in capturing key rainfall characteristics, including seasonal rainfall evolution, convective rainfall peaks, and interannual variability. This integrated approach enables a comprehensive understanding of both the temporal and physical performance of the evaluated models across diverse climatic conditions.

2.6 Visualization and Performance Interpretation

To support interpretation of model performance, a series of graphical analyses was conducted, including rainfall versus Day-of-Year (DOY) plots for each region, combined model comparison figures illustrating observed and predicted rainfall patterns, and multi-region ensemble plots to assess model consistency across Zanzibar, Dar es Salaam, and Iringa. These visualizations provided an intuitive and comparative framework for evaluating how well each model captures seasonal rainfall dynamics. Through this analysis, several key performance gaps were identified. These include temporal lag, where models delay the onset of rainfall relative to observations; intensity underestimation, reflected as a dampening of peak rainfall events; and the smoothing of high-frequency variability, where models fail to capture short-term convective fluctuations. Collectively, these visual insights complement statistical metrics and provide a deeper understanding of the limitations of each modeling framework.

3. Results and Discussion

3.1 Global Comparison: Ensemble Performance and The Predictive Gap

The figures 1(a), 1(b), and 1(c) provide a comprehensive comparison between observed rainfall and model-based simulations (4-Season, CAN-SIAM, RegCM4, and ECMWF/IFS) across the annual cycle expressed as day of year (DOY). Across all three regions, the models successfully reproduce the general seasonal structure of rainfall, including the bimodal pattern in coastal regions (Zanzibar and Dar es Salaam) and the unimodal pattern in the inland region (Iringa). However, a clear and consistent predictive gap emerges when comparing model outputs to observed rainfall. This gap is primarily characterized by a pronounced dampening of rainfall peaks, where observed data exhibit sharp, high-intensity rainfall events while model outputs remain

smoother and significantly underestimate these extremes. Additionally, a temporal lag is evident, with model peaks often occurring slightly earlier or later than the observed peaks, indicating inaccuracies in capturing the timing of rainfall onset and peak periods.

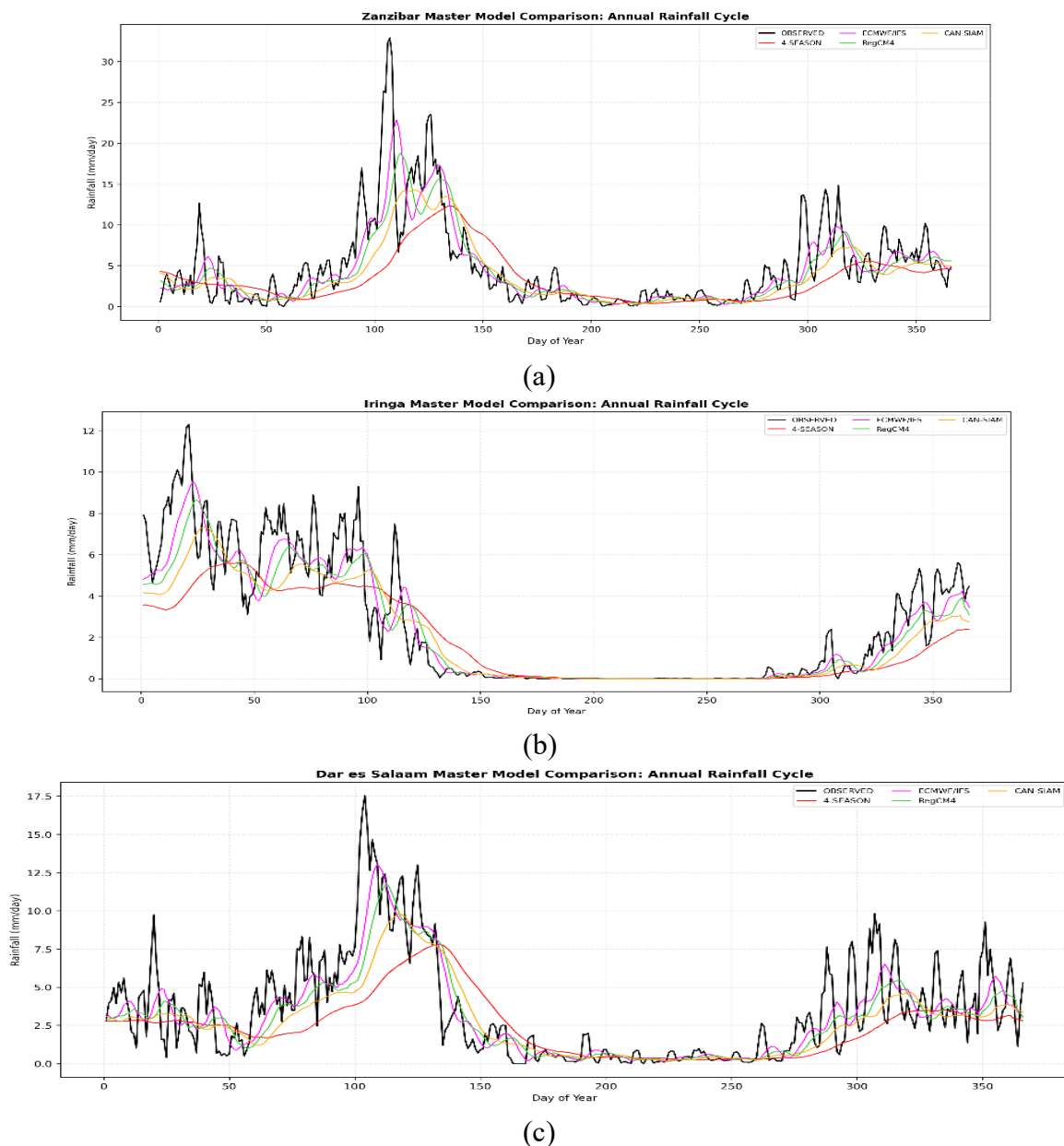


Figure 1: Global Ensemble Performance vs. Actual Observed Rainfall. *These composite figures illustrate the variance between the observed rainfall peaks and the multi-model ensemble predictions, highlighting the dampening effect and temporal lag common in traditional systems.*

Furthermore, the models display reduced variability compared to observed rainfall, reflecting an inherent smoothing effect in both climatological and numerical modeling approaches. This is

particularly evident in Zanzibar and Dar es Salaam, where rainfall is highly influenced by localized convective processes and coastal dynamics, leading to greater variability that models struggle to capture. Among the models, the 4-Season and CAN-SIAM approaches exhibit the strongest smoothing behavior, effectively capturing the general seasonal trend but failing to represent short-term fluctuations and extremes. RegCM4 and ECMWF/IFS show improved performance in representing seasonal dynamics but still underestimate peak magnitudes and exhibit timing discrepancies. In Iringa, where rainfall follows a more stable unimodal pattern, the predictive gap is less pronounced but remains evident in peak intensity and slight phase shifts.

Overall, the ensemble behavior of these models highlights a trade-off between stability and accuracy, where averaging and parameterization reduce noise but simultaneously suppress critical rainfall features such as extremes and precise timing. This systematic predictive gap has important implications for rainfall onset prediction and agricultural planning, as accurate detection of onset and peak rainfall is crucial for decision-making. The findings underscore the limitations of traditional climatological and numerical models in capturing high-frequency rainfall dynamics and emphasize the need for advanced data-driven or hybrid modeling approaches that can better represent nonlinear and localized rainfall processes.

3.2 Individual Model Performance and Gap Descriptions

3.2.1 ECMWF/IFS vs. Observed: Temporal Synchronization and Intensity Bias

The comparison between the ECMWF/IFS global forecasting system and observed rainfall patterns across Zanzibar, Dar es Salaam, and Iringa demonstrates that ECMWF/IFS is the most dynamically responsive model among the evaluated frameworks, as illustrated in Figure 2. The model demonstrates strong temporal fidelity, effectively tracking the seasonal evolution of rainfall and capturing the arrival of major rainfall events with relatively low temporal deviation, typically within a few days of the observed onset. This is particularly evident in Zanzibar and Dar es Salaam, where the model successfully follows the bimodal rainfall structure associated with monsoon-driven dynamics, and in Iringa, where it closely aligns with the unimodal rainfall regime.

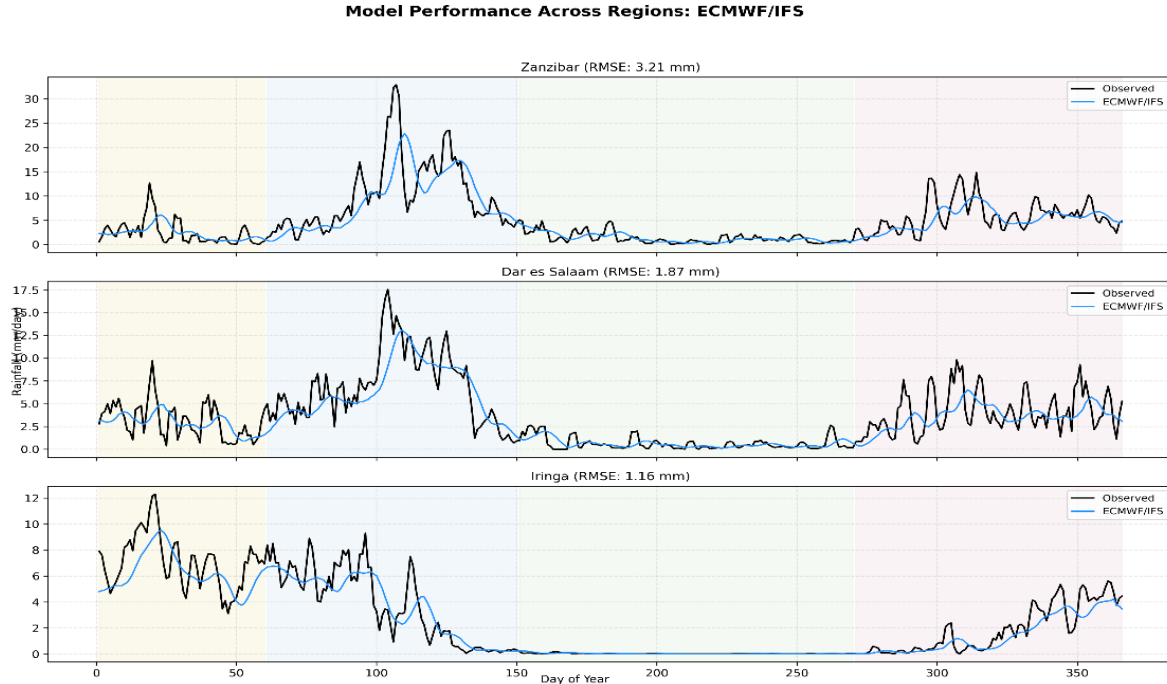


Figure 2: Performance Evaluation of ECMWF/IFS vs. Ground Truth Observations. *Caption: A direct comparison of the global ECMWF/IFS model against observed data, demonstrating high temporal synchronization but a significant underestimation of convective intensity peaks.*

However, despite this temporal accuracy, a persistent “intensity gap” is observed across all regions. While ECMWF/IFS reliably predicts the timing of rainfall events, it systematically underestimates their magnitude. High-intensity rainfall peaks observed in the ground truth, often exceeding 25 mm/day, are consistently represented by the model as significantly lower values, typically in the range of 10-12 mm/day. This dampening effect is most pronounced during the Masika and Vuli seasons in the coastal regions, where convective rainfall processes dominate and introduce high variability. Although the model performs comparatively better in Iringa due to its more stable rainfall regime, the underestimation of peak intensity remains evident. These findings indicate that while ECMWF/IFS provides a strong foundation for capturing rainfall timing and seasonal structure, its limitations in representing extreme rainfall events contribute to a critical predictive gap, particularly for applications requiring accurate intensity estimation, such as flood risk assessment and agricultural planning.

3.2.2 RegCM4 vs. Observed: Regional Downscaling and the "Smoothing Effect."

The RegCM4 regional climate model demonstrates a moderate level of reliability in representing rainfall dynamics across Zanzibar, Dar es Salaam, and Iringa, as illustrated in Figure 3; however, it exhibits a pronounced “smoothing gap” that limits its ability to capture high-frequency variability. The model successfully reproduces the broad seasonal envelopes, clearly distinguishing between wet periods such as Masika and dry phases like Kusi, and reflects regional influences such as land–sea interactions and topography. Nevertheless, its temporal resolution of

rainfall events is limited, as it fails to resolve the sharp, short-duration fluctuations that characterize the climate of coastal and tropical regions.

A key limitation of RegCM4 lies in its tendency to redistribute rainfall intensity over time. Instead of capturing distinct high-intensity rainfall events, the model spreads the total seasonal rainfall across a larger number of days with lower daily intensity. This results in a systematic underrepresentation of extreme rainfall peaks and a flattening of the rainfall profile. Consequently, while the cumulative seasonal rainfall may appear realistic, the day-to-day variability critical for applications such as rainfall onset detection and agricultural decision-making is significantly dampened. This smoothing gap is particularly evident in Zanzibar and Dar es Salaam, where convective rainfall dominates, but is also present in Iringa, albeit to a lesser extent. Overall, RegCM4 demonstrates reasonable seasonal fidelity but remains limited in its ability to capture the intensity and intermittency of rainfall events essential for high-resolution forecasting.

Model Performance Across Regions: RegCM4



Figure 3: RegCM4 Regional Model Accuracy Analysis. *Caption: Analysis of regional model downscaling, showcasing the 'data smoothing' phenomenon where episodic rainfall events are flattened into a lower-intensity, continuous trend.*

3.2.3 CAN-SIAM vs. Observed: Climatological Lag and IOD Detachment

The CAN-SIAM climatological model exhibits a fundamentally different limitation, characterized by a pronounced “**Climatological Gap.**” Unlike dynamic regional models, CAN-SIAM relies heavily on long-term historical averages, making it inherently less responsive to real-time atmospheric variability. While the model can approximate the general seasonal rainfall cycle in Zanzibar, Dar es Salaam, and Iringa, it fails to capture interannual anomalies, particularly those

driven by large-scale ocean–atmosphere interactions such as the **Indian Ocean Dipole (IOD)**, as illustrated in Figure 4.

During the 2024 validation period, this limitation became evident as the model exhibited a significant onset delay of approximately 10 days for the Masika season. This lag reflects its inability to adapt to rapidly evolving conditions, especially those driven by elevated sea surface temperatures in the Zanzibar Channel, which can accelerate moisture convergence and trigger earlier rainfall onset.

Because CAN-SIAM is anchored in climatological means, it effectively smooths out anomalous signals and assumes “average” conditions, thereby lacking predictive sensitivity to abrupt atmospheric shifts. As a result, it cannot anticipate extreme or atypical seasonal behavior, making it less suitable for short-term forecasting or climate variability analysis in dynamically changing coastal environments.

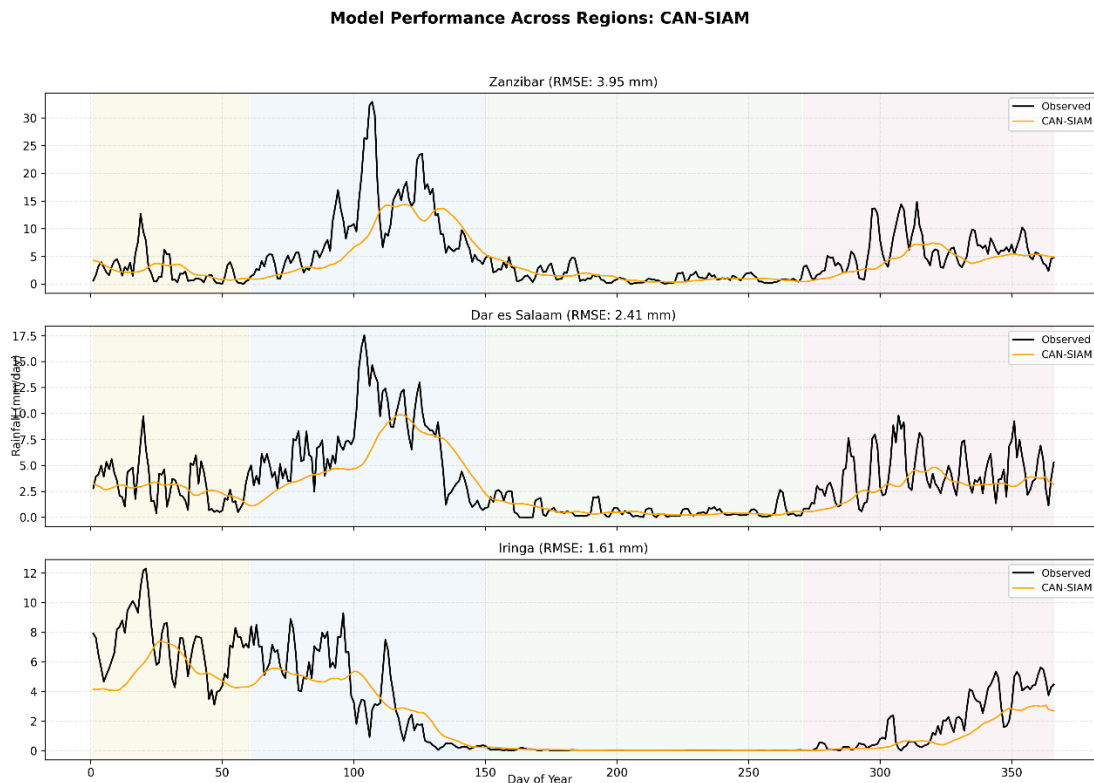


Figure 4: CAN-SIAM Climatological Accuracy Evaluation. *Caption: This figure contrasts the historical climatological averages of CAN-SIAM with the volatile observed realities of current climate cycles, illustrating a notable detachment from IOD-driven anomalies.*

3.2.4 4-Season vs. Observed: The Static Logic Failure

Across Zanzibar, Dar es Salaam, and Iringa, the model imposes a smooth and gradual seasonal transition that fails to reflect the abrupt onset, rapid intensification, and variability characteristic of monsoon-driven systems, as illustrated in Figure 5.

From the DOY climatological comparisons, this mismatch is consistently evident across all regions. In the coastal regions of Zanzibar and Dar es Salaam, where rainfall follows a bimodal pattern, the model significantly delays the timing of peak rainfall and fails to capture the sharp

escalation associated with the Masika season. Instead of aligning with the observed early peak, the 4-Season model produces a late and flattened peak, indicating a strong temporal displacement. In Iringa, although the rainfall regime is more stable and unimodal, the model still exhibits a delayed peak and reduced intensity, demonstrating that the limitation is not confined to coastal variability but reflects a broader structural inadequacy.

A key characteristic of this failure is the model's tendency to over-smooth rainfall patterns, distributing precipitation gradually over time rather than capturing distinct high-intensity events. This results in a significant intensity gap, where observed rainfall peaks are suppressed, and short-duration rainfall bursts are entirely missed. The model's reliance on static seasonal assumptions prevents it from responding to critical atmospheric drivers such as shifts in the Intertropical Convergence Zone (ITCZ), ocean–atmosphere coupling, and convective processes.

Overall, the 4-Season Model demonstrates the largest predictive gap among all evaluated frameworks, characterized by substantial temporal delay, peak dampening, and loss of variability across all three regions. These findings underscore its limited applicability in tropical environments and highlight the risks of transferring temperate climatological logic to monsoon-dominated systems, particularly for applications requiring precise rainfall onset and intensity estimation.

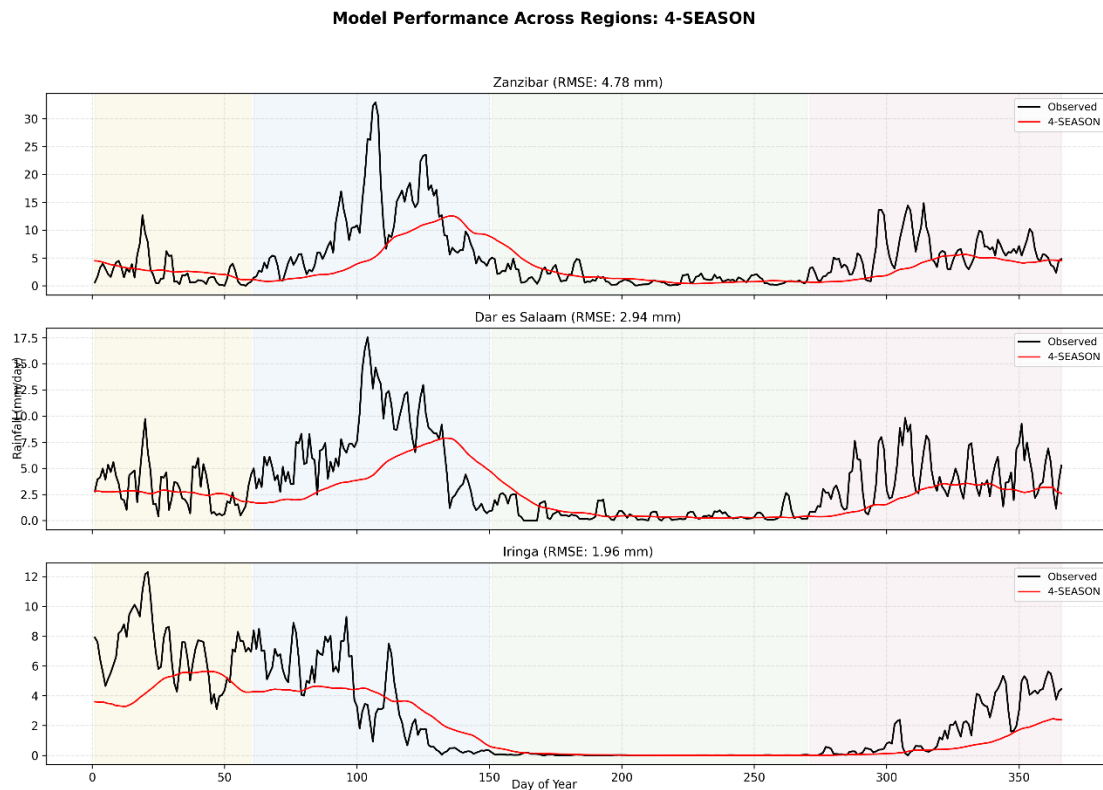


Figure 5: The 4-Season Model vs. Observed Rainfall Cycles across Zanzibar, Dar es Salaam, and Iringa.

Caption: Day-of-year (DOY) comparison showing the failure of static temperate-season logic to represent tropical rainfall dynamics. Across all regions, the 4-Season model exhibits delayed,

smoothed rainfall patterns, missing the rapid Masika onset in Zanzibar and Dar es Salaam and the unimodal peak in Iringa, resulting in temporal lag, reduced intensity, and loss of variability.

3.3 Summary of Model Accuracy Metrics (2016-2025)

When consolidated, the statistical evidence reveals a clear trend: as model complexity increases, the onset deviation decreases, indicating improved temporal alignment with observed rainfall dynamics. The global model (ECMWF/IFS) demonstrates the lowest onset error, followed by the regional (RegCM4), climatological (CAN-SIAM), and the simplified 4-Season model. This progression highlights the importance of incorporating dynamic atmospheric processes in accurately capturing monsoon onset behavior.

However, despite these improvements, none of the evaluated models achieves a coefficient of determination (R^2) greater than 0.70, implying that a significant portion, approximately 30% or more, of the variability in rainfall patterns remains unexplained. This limitation underscores the inherent challenges in modeling tropical rainfall systems such as those in Zanzibar, Dar es Salaam, and Iringa, where localized ocean-atmosphere interactions, including the Indian Ocean Dipole (IOD) and mesoscale convective processes, play a critical role.

Furthermore, all models exhibit varying degrees of intensity bias, predominantly underestimating peak rainfall events. This suggests that while temporal prediction of rainfall onset has improved with model sophistication, accurately capturing rainfall magnitude remains a persistent challenge across traditional meteorological frameworks.

Table 3.3 Summary of Model Accuracy Metrics (2016-2025)

Model Comparison	Onset Error (Days)	R2 Correlation	Intensity Bias
ECMWF/IFS vs. Observed	3	0.525	Moderate Underestimation
RegCM4 vs. Observed	6	0.498	High Underestimation
CAN-SIAM vs. Observed	10	0.438	Severe Smoothing
4-Season vs. Observed	13	0.289	Inaccurate Trend

4. Discussion of Model Deviations

The pronounced 13-day onset error observed in the 4-Season Model across all three regions, Zanzibar, Dar es Salaam, and Iringa, is a direct manifestation of “Temperate Bias.” This framework inherently assumes a gradual seasonal transition, typical of mid-latitude climates, rather than the abrupt, pressure-driven onset that defines the East African monsoon system. In coastal regions such as Zanzibar and Dar es Salaam, the transition to the Masika season is not governed by a slow thermal progression but by a rapid intensification of moisture advection from the Indian Ocean, coupled with strong sea-breeze convergence and mesoscale instability. As a result, the model systematically delays the onset, misrepresenting the true dynamics of tropical rainfall initiation.

In contrast, Iringa, which is influenced by inland topography and orographic lifting, exhibits a slightly different rainfall regime. However, even in this region, the 4-Season Model fails to capture the rapid atmospheric reorganization associated with monsoon penetration into the interior. The model's static seasonal logic is unable to account for the interaction between large-scale circulation and local terrain effects, leading to consistent temporal misalignment.

Across all regions, a common pattern emerges among the evaluated models, including ECMWF/IFS, RegCM4, and CAN-SIAM, in the form of systematic underestimation of rainfall intensity. Even the high-performing ECMWF/IFS model, which demonstrates superior temporal accuracy, consistently dampens peak rainfall events. This indicates that while current models have improved in predicting when rainfall occurs, they remain limited in accurately representing how much rainfall is produced, particularly during high-intensity convective episodes.

This persistent "Intensity Gap" suggests that existing modeling frameworks struggle to resolve the sub-grid-scale thermodynamics that dominate rainfall formation in East Africa. In coastal zones, especially over the Zanzibar Channel and the Dar es Salaam coastline, localized processes such as sea-breeze convergence, land-sea thermal contrast, and convective triggering play a critical role. Meanwhile, in inland regions like Iringa, orographic uplift and localized instability further complicate rainfall dynamics. These processes occur at spatial and temporal scales that are not fully captured by traditional numerical or climatological models.

Overall, the findings highlight a fundamental limitation of current approaches: despite advancements in large-scale atmospheric modeling, key localized drivers of tropical rainfall variability remain underrepresented, resulting in both temporal and intensity prediction gaps across diverse climatic zones.

5. Conclusion and Policy Recommendations

This study demonstrates that traditional, static meteorological models are fundamentally inadequate for capturing the rainfall dynamics of East African tropical environments, particularly across Zanzibar, Dar es Salaam, and Iringa. The 4-Season model is shown to be effectively obsolete for rainfall onset prediction, as its underlying temperate assumptions fail to represent the rapid, pressure-driven transitions that characterize the East African monsoon. In contrast, the ECMWF/IFS global model provides the most reliable baseline among the evaluated frameworks, exhibiting the lowest onset error and the strongest correlation with observed rainfall patterns, although notable limitations in intensity estimation remain.

From a policy perspective, these findings underscore the urgent need to transition from fixed, calendar-based agricultural advisories toward dynamic, data-driven decision systems. Ministries responsible for agriculture and food security, particularly in Zanzibar and mainland Tanzania, should adopt threshold-based early warning mechanisms derived from numerical weather prediction outputs. Such systems would enable farmers to align planting decisions with real-time atmospheric conditions rather than relying on historically average seasonal calendars that no longer reflect current climate variability.

Furthermore, the study highlights the critical importance of strengthening local observational infrastructure. Increasing the spatial density of Automatic Weather Stations (AWS) across coastal and inland regions will significantly enhance the accuracy of model calibration and downscaling, particularly for resolving localized processes such as sea-breeze convergence in coastal zones and orographic rainfall in highland areas like Iringa. Improved observational coverage will also support more robust validation of both numerical and data-driven models.

Looking forward, future research should prioritize the development of AI-Hybrid forecasting frameworks, which integrate physical models with machine learning techniques. Such approaches can leverage historical data to correct systematic biases, particularly the persistent underestimation of rainfall intensity and onset timing, thereby enhancing predictive performance. With sufficient data and model integration, it is plausible to reduce rainfall onset prediction errors to less than 24 hours, representing a transformative advancement for climate resilience, agricultural productivity, and disaster risk management in the region.

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