AI-Assisted GFS Bias Correction and Multiscale Spectral Nudging Framework for Tropical Cyclone Genesis Prediction

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Abstract

Tropical cyclone (TC) prediction in the Indonesian Maritime Continent remains challenging due to complex atmospheric interactions and limitations of global numerical models. This study integrates Random Forest-based Global Forecast System (GFS) bias correction using ERA5 reanalysis with spectral nudging in a nested Weather Research and Forecasting (WRF) model. The framework is evaluated for three tropical cyclones: Cempaka (2017), Flamboyan (2018), and Senyar (2025), using different spectral nudging configurations (N0, N1, and N2). Results demonstrate improvements in cyclone position prediction, with minimum mean errors of 142 km for Cempaka (N2), 178 km for Flamboyan (N1), and 233 km for Senyar (N1), compared with 303 km, 200 km, and 288 km from Raw GFS, respectively. However, improved positioning does not necessarily enhance intensity prediction. These findings highlight the case-dependent effectiveness of spectral nudging and the potential of integrating AI-based bias correction with regional atmospheric modeling to improve tropical cyclone prediction near the equator.

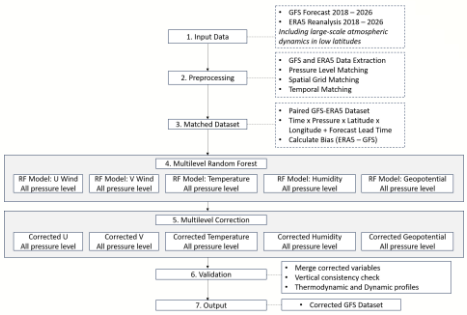
Keyword: Tropical cyclone genesis; bias correction; AI; Spectral nudging; WRF model.

Introduction

Tropical cyclone (TC) prediction near Indonesia remains challenging due to weak Coriolis forcing and complex multiscale atmospheric interactions (Yulihastin et al., 2023). Nevertheless, several TCs have developed near the equator, including Vamei (2001), Cempaka (2017), Seroja (2021), and Senyar (2025). Accurate prediction requires improved representation of large-scale circulation and mesoscale processes. The Weather Research and Forecasting (WRF) model has been widely used for TC simulations. Spectral nudging improves large-scale circulation representation while preserving regional atmospheric processes (Moon et al., 2018; Delfino et al., 2022; Huang et al., 2025). However, its effectiveness near the equator remains uncertain, while biases in Global Forecast System (GFS) data may further reduce prediction accuracy.This study integrates Random Forest-based GFS bias correction using ERA5 reanalysis with spectral nudging in a two-domain nested WRF model. Six configurations (N0–N5) are evaluated to assess their effects on TC genesis, track, and intensity prediction. The framework aims to improve tropical cyclone forecasting in near-equatorial regions.

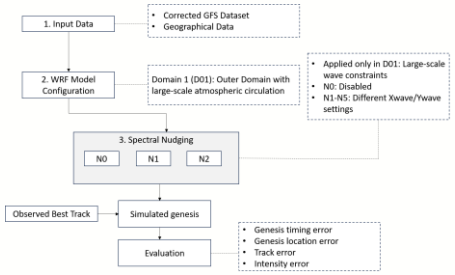
Research Method

GFS forecast data (2018–2024) with 0.25° spatial resolution and forecast lead times F00–F120 are used as atmospheric inputs, including zonal wind, meridional wind, temperature, relative humidity, and geopotential at multiple pressure levels. ERA5 reanalysis serves as the reference for bias correction. Both datasets are harmonized spatially, temporally, and vertically



Picture 1. Workflow of multilevel GFS correction

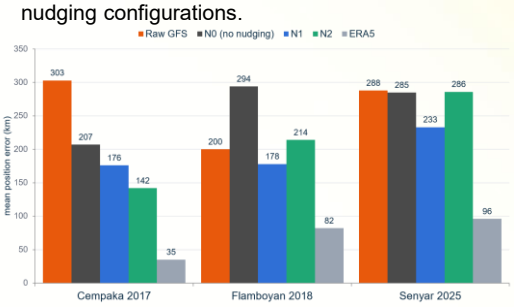
A Random Forest (RF) algorithm estimates GFS biases relative to ERA5, with corrected fields calculated by adding predicted biases to the original GFS data. The corrected atmospheric fields are subsequently processed to generate initial and boundary conditions for WRF simulations.The Advanced Research WRF (ARW) model employs two nested domains: an outer domain (D01) representing large-scale atmospheric circulation and an inner domain (D02) resolving regional atmospheric processes. Physical parameterizations include WSM6 microphysics, Kain–Fritsch cumulus, RRTMG radiation, YSU planetary boundary layer, revised MM5 surface layer, and Noah land surface schemes. Spectral nudging is applied to D01 to constrain large-scale circulation while preserving mesoscale processes in D02. Sensitivity experiments compare a control simulation without nudging (N0) against different spectral nudging configurations (N1–N5), varying zonal and meridional wave settings.Tropical cyclone genesis and evolution are evaluated against IBTrACS best-track data. Genesis identification considers low-pressure circulation and near-surface wind patterns.



Picture 2. Workflow of WRF simulation using spectral nudging for genesis forecast of tropical cyclone

Discussion & Result

Figure 3 compares the mean tropical cyclone (TC) position errors at 6-hourly intervals for Cempaka (2017), Flamboyan (2018), and Senyar (2025). For Cempaka, N2 achieves the lowest error of 142 km, representing a 53% improvement over Raw GFS (303 km). For Flamboyan, N1 reduces the error to 178 km, compared with 200 km for Raw GFS and 294 km for N0. Similarly, N1 provides the best performance for Senyar, reducing the error to 233 km from 288 km for Raw GFS. Overall, N1 demonstrates the most consistent improvement, while N2 performs best for Cempaka. These findings indicate that spectral nudging can improve TC track prediction, although its effectiveness varies among cyclone events and nudging configurations.



Picture 3. Mean position error over the evaluation window, for three cases of TC impacting Indonesia region

Conclusion

This study demonstrates that spectral nudging in a two-domain nested WRF model with AI-assisted GFS bias correction can improve tropical cyclone (TC) track prediction over the Indonesian region, although its effectiveness varies across events. For Cempaka (2017), N2 achieved the lowest mean position error of 142 km, representing a 53% improvement over Raw GFS. Meanwhile, N1 provided the best performance for Flamboyan (2018) and Senyar (2025), reducing position errors to 178 km and 233 km, respectively. However, improvements in track accuracy were not always accompanied by better intensity representation, and prediction errors varied throughout the simulation periods. These findings highlight the case-dependent effectiveness of spectral nudging and the importance of selecting appropriate configurations. Further investigation of environmental steering flow, vorticity, and moisture convergence, along with evaluation across additional cyclone events, is recommended to improve tropical cyclone genesis and track prediction near the equator.