

Abstract and Aim

This study examines the efficacy of numerical weather prediction (NWP) models using the Greenko observation dataset collected from 2023 to 2025, comprising data from nine locations and 17 wind turbines. The dataset provides high-resolution wind speed measurements, enabling a thorough assessment of forecasting accuracy. Statistical diagnostics, including mean bias error (MBE), root mean square error (RMSE), and other metrics, are used to assess systematic biases, random errors, and differences in variance between NWP outputs and observed values. The results demonstrate that, although NWP models accurately capture general temporal trends in wind variability, they reduce the accuracy of turbine performance simulations. The analysis focuses on identifying systematic biases and discrepancies that affect forecast reliability. By comparing model outputs with site-specific observations, the study examines how local terrain and environmental conditions influence predictive accuracy. The overarching goal is to strengthen reproducible forecasting frameworks, incorporate effective bias-correction methods in future work, and support climate-resilient energy planning. In essence, this work compares NWP forecasts with observational data and quantifies the errors that limit the reliability of operational wind-energy forecasting.

Keywords: Wind energy forecasting, NWP bias, Greenko dataset, statistical validation, NCUM-Gx

Data

- **Greenko wind observation dataset (2023–2025)** from 17 turbine clusters across diverse terrain.
- Hub-height measurements **80–106 m**
- **NCUM-G model outputs (NCMRWF)** at 50 m, extrapolated to hub height for consistency.

Methodology

- **Statistical diagnostics:** Biases, RMSE, and MAE
- Fitted **Weibull distribution** to observed and modeled wind speeds for energy potential assessment
- Compared forecasts on **daily, diurnal, and monthly scales** to capture temporal variability
- Identified **site-specific biases** and quantified various errors.

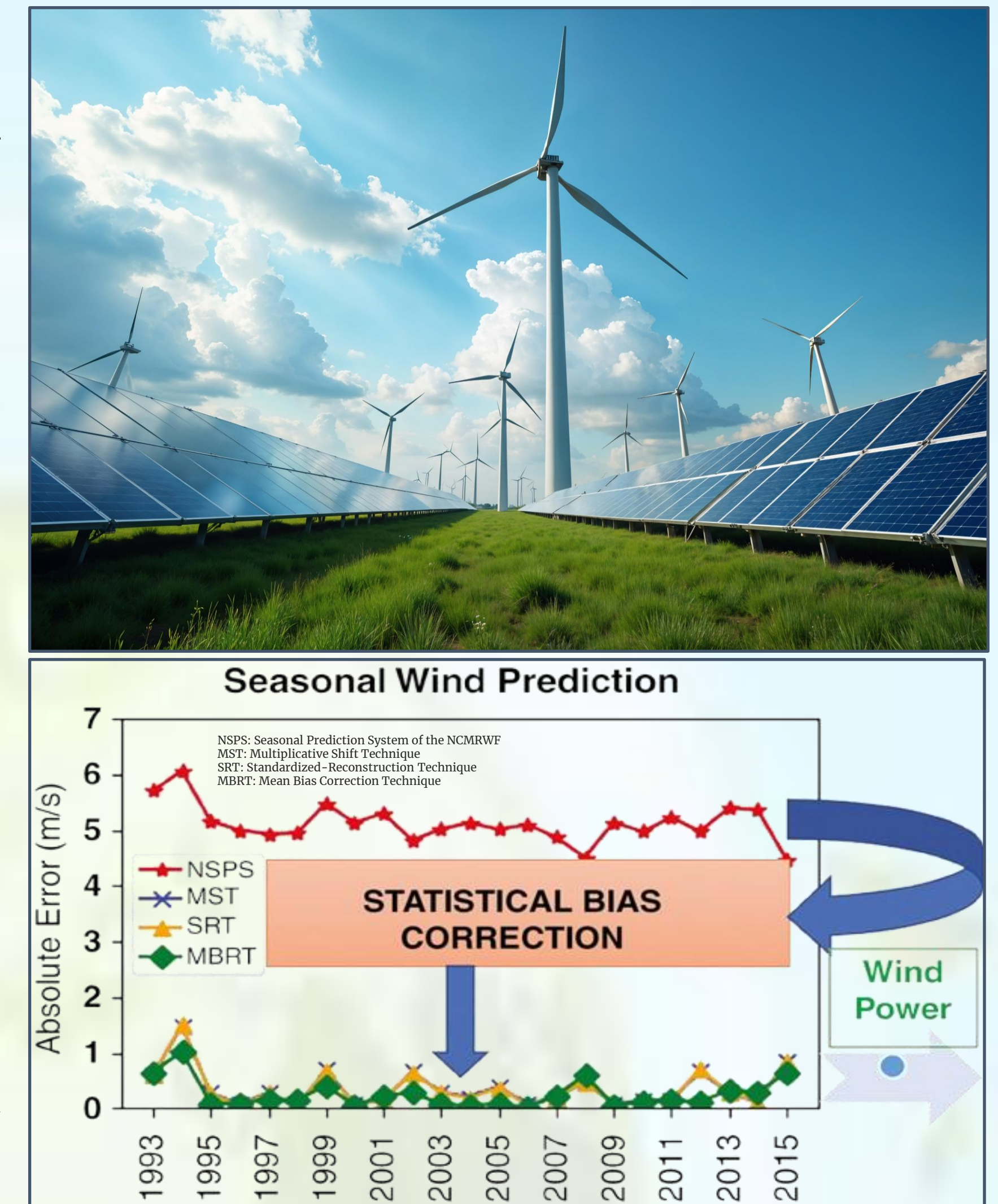


Figure 1: Details and techniques of the NCUM_G wind datasets.

Results

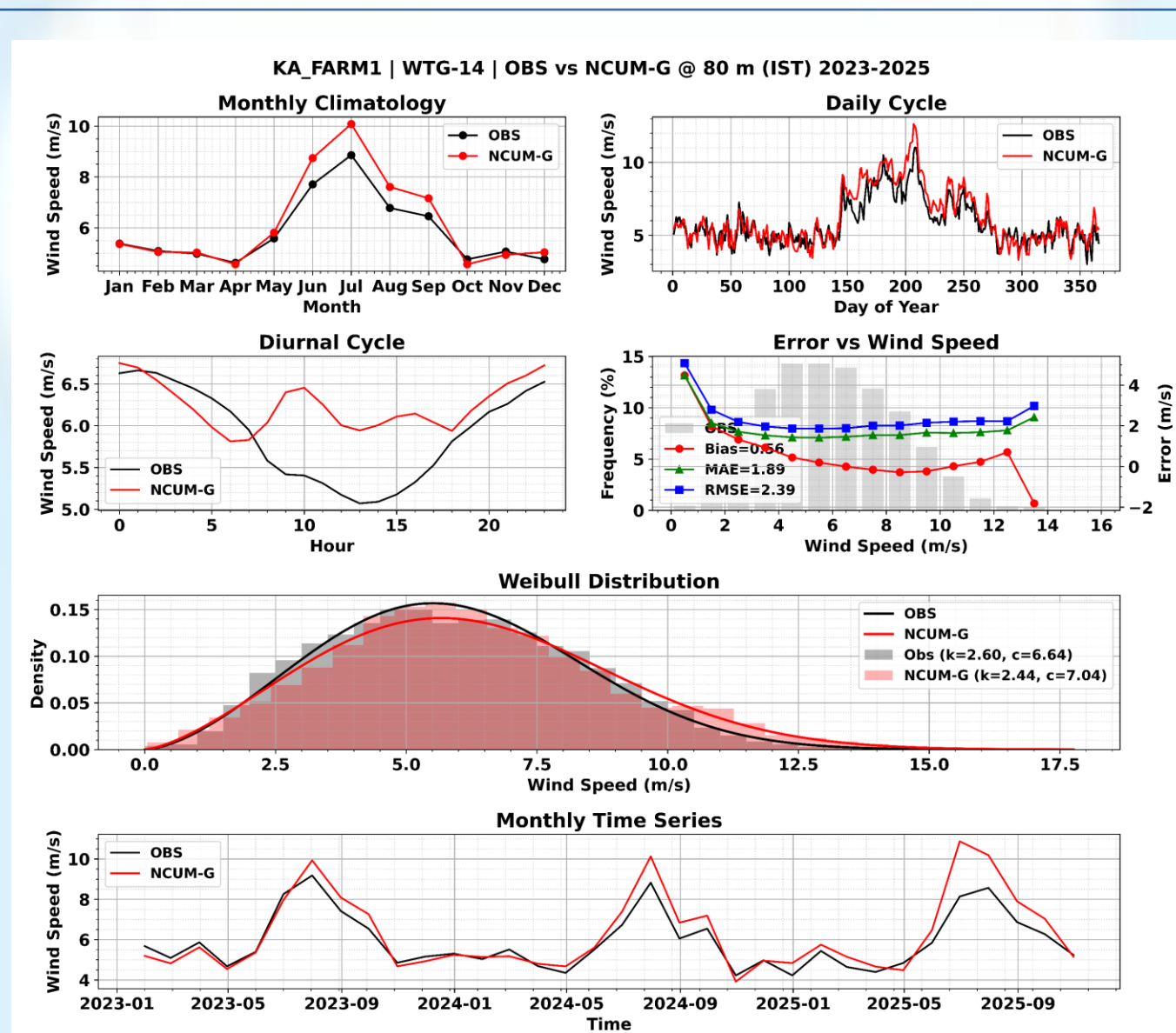


**Figure 2: All Diagnostics of GREENKO vs NCUM_G datasets.
(Best Performing)**

- **Daily pattern:** Observed winds rise during daytime hours and decline at night; NWP flattens these variations.
- **Farm differences:** Coastal farms (KA, GJ) show stronger daytime peaks, while inland farms (MP, TN) have weaker cycles.

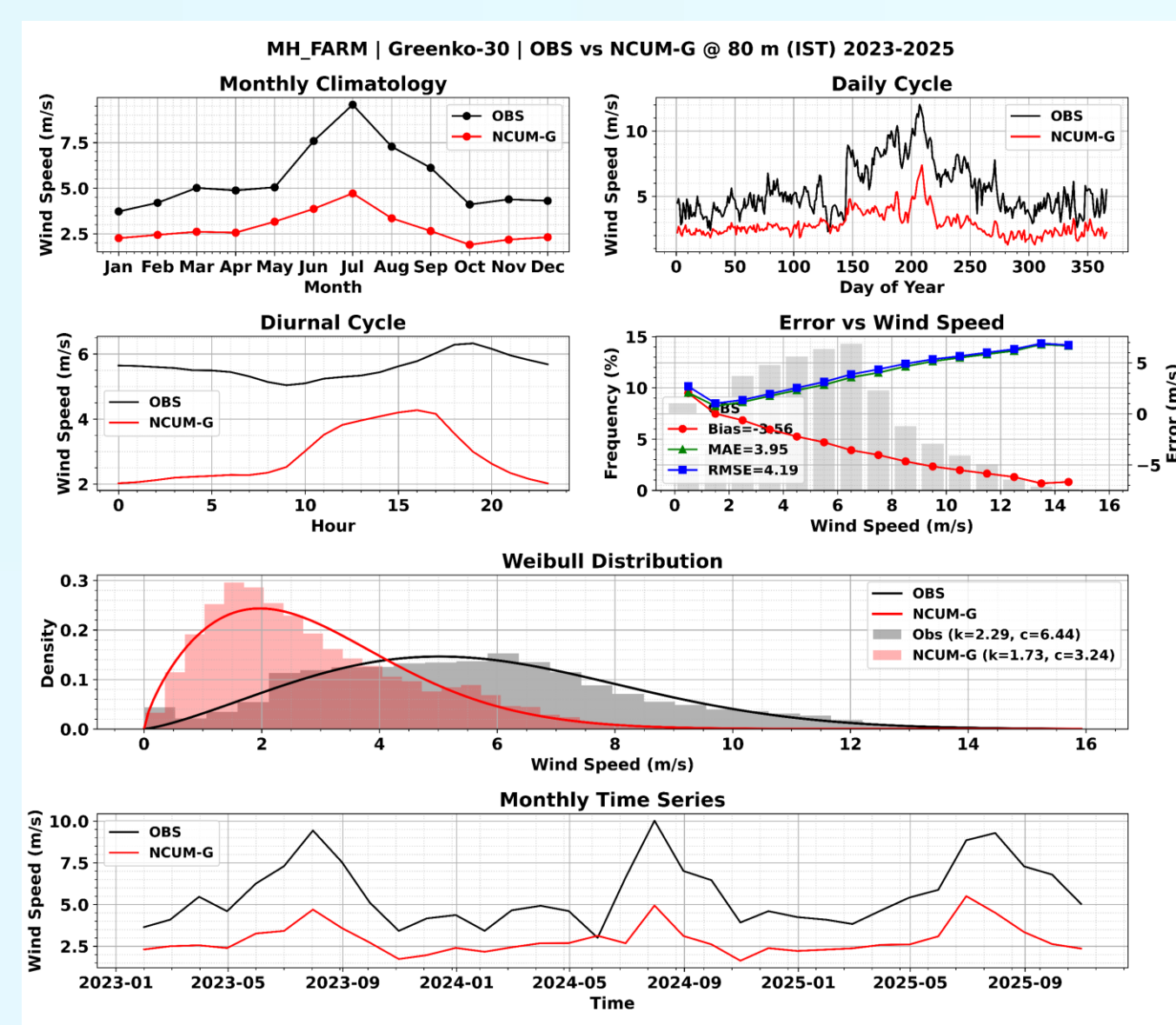


Figure 3: All Diagnostics of GREENKO vs NCUM_G datasets. (Worst performing)

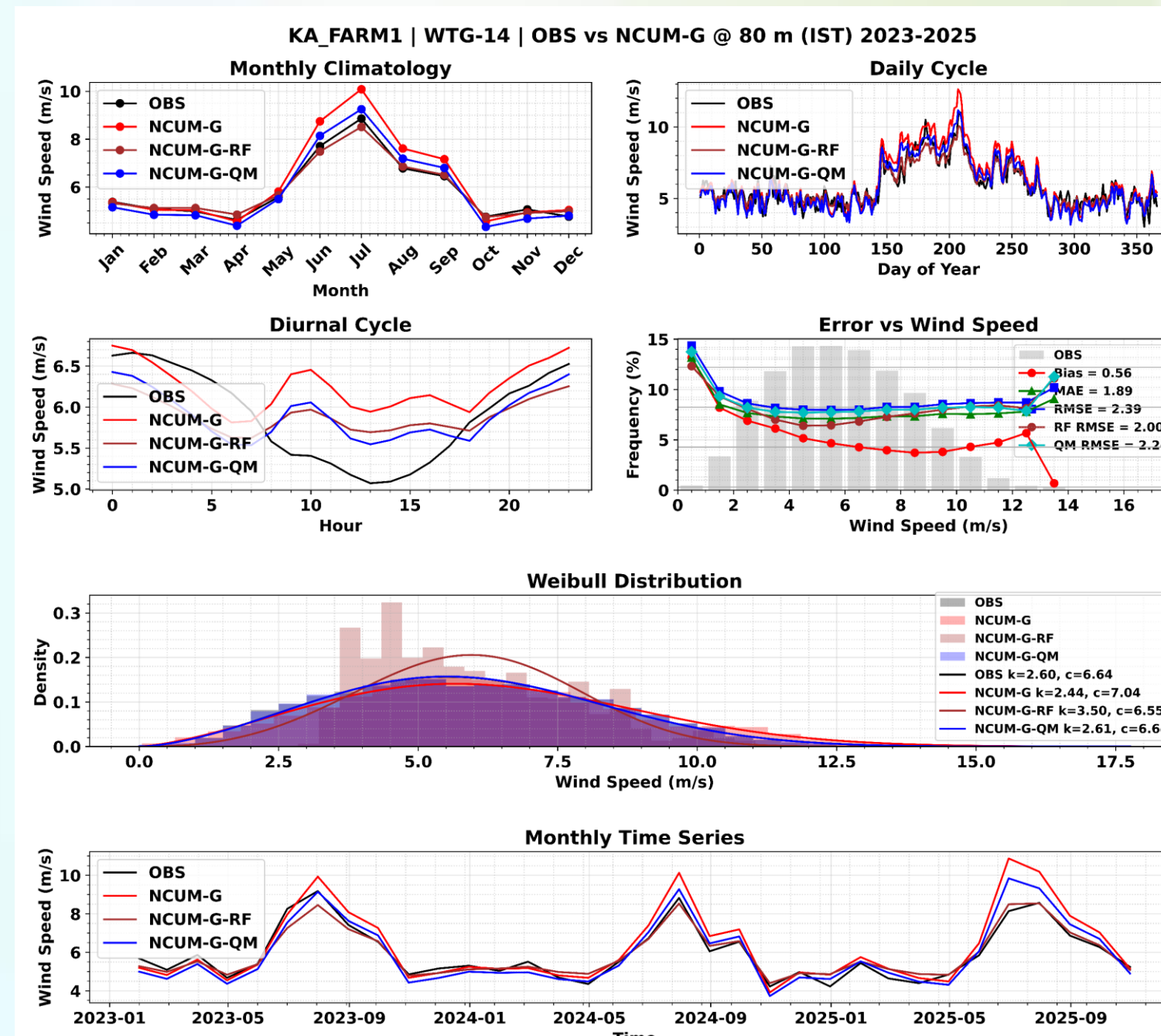


Figure 4: All Diagnostics of GREENKO vs NCUM_G datasets.

- **NCUM-G Strengths:** Captures large-scale wind trends and seasonal cycles.
- **Limitations:** Consistently overestimates wind speeds, reduces variance, and shows site-specific biases.
- **Insight:** Strong Weibull fit, but scale bias inflates strong wind predictions.
- Need adaptive bias-correction & terrain-aware modeling.

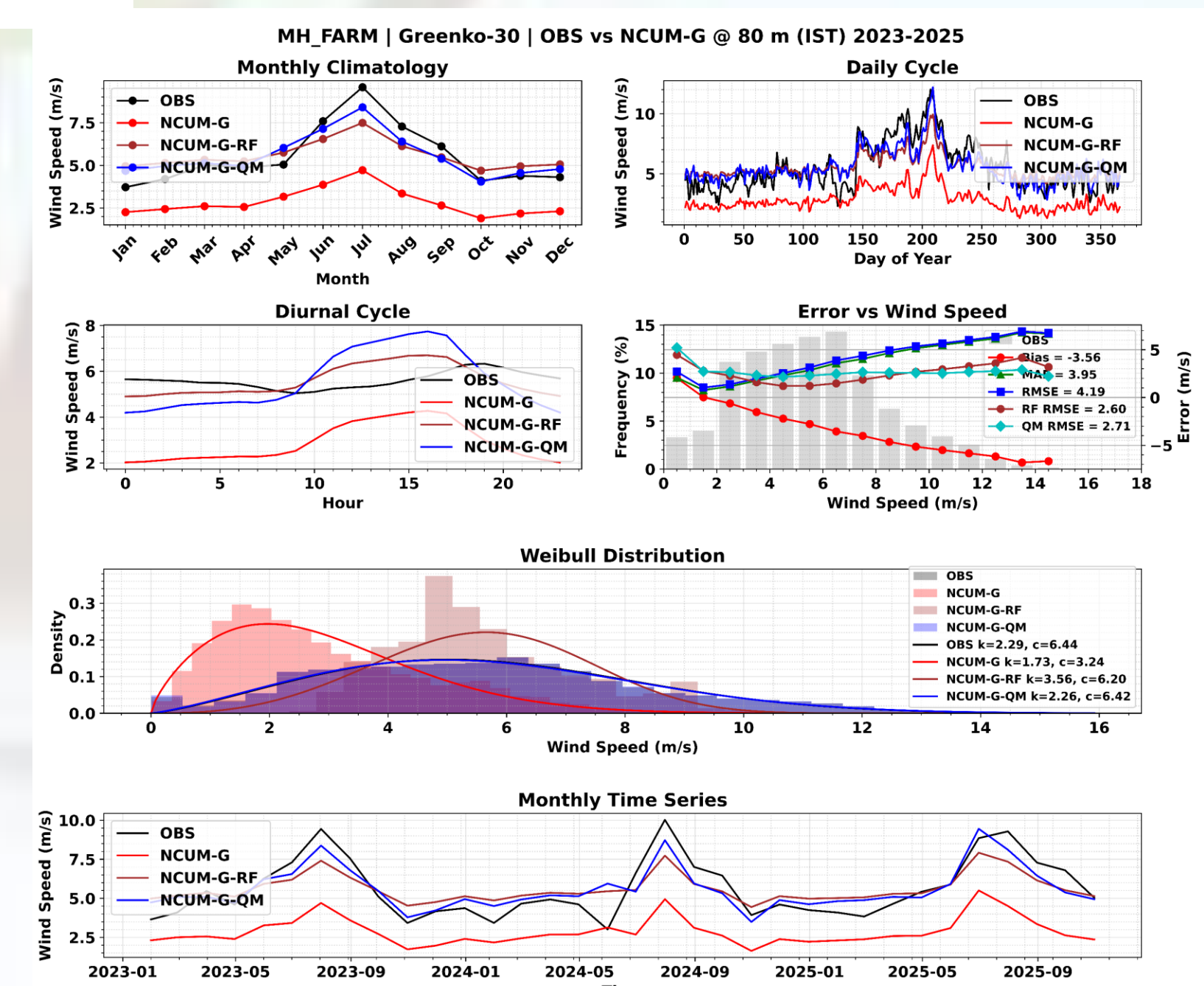


Figure 5: All Diagnostics of GREENKO vs NCUM_G datasets.

After Bias Correction using AI/ML Techniques

- **Correction impact:** RF consistently reduces RMSE, while QM performs better at some farms.
- **Farm variability:** The largest improvements occur at **MH_FARM** and **AP_FARM1**.

Farms	Bias	NWP MAE	RMSE NWP	RF RMSE	QM RMSE	RF Improvement (%)	QM Improvement (%)
AP_FARM1	1.26	1.99	2.53	1.93	2.07	23.72	17.79
AP_FARM2	1.03	2.07	2.64	2.04	2.24	22.73	15.15
KA_FARM1	0.73	1.93	2.43	1.98	2.24	20.58	7.82
KA_FARM2	-0.40	2.18	2.76	2.40	2.73	13.04	1.09
MP_FARM1	-0.26	2.49	3.08	2.79	3.13	9.42	-1.62
RJ_FARM	0.68	2.65	3.40	2.76	3.02	18.82	11.18
GJ_FARM	1.13	2.33	2.89	2.57	2.82	11.07	2.42
MH_FARM	-3.83	4.18	4.40	2.66	2.74	39.55	37.73
TN_FARM	-0.66	2.61	3.34	3.07	3.42	8.08	-2.40

Conclusion

- **Baseline:** NWP forecasts capture seasonal/diurnal wind variation but show high RMSE & MAE.
- **Bias Correction:** QM reduces errors significantly, while QM+RF delivers the best improvements across most farms.
- **Site-Specific Gains:** Largest improvements at MH_FARM, AP_FARM1, AP_FARM2; smaller but consistent gains at KA_FARM1, RJ_FARM, TN_FARM.
- **Takeaway:** QM+RF is the most efficient and reliable corrective method, combining statistical bias correction with ML refinement for operational wind forecasting.

References and Acknowledgments

1. Singh, P., Kumar, S., Ashrit, R. *et al.* Wind speed and power forecasting: Evaluating NCMU-G model performance. *J Earth Syst Sci* **134**, 20 (2025). <https://doi.org/10.1007/s12040-024-02485-y>
2. National Centre for Medium Range Weather Forecasting (NCMRWF)(2024). NCMRWF annual report 2023-24. Retrieved from <https://www.ncmrwf.gov.in>
3. We acknowledge the GREENKO group for providing the turbine observational dataset for the study period.

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