Verification of Numerical Weather Prediction Products for Marine Weather Services

1. Introduction

A comprehensive verification of **10-meter wind** speed forecasts over the Indian Ocean region used for the marine weather services are carried out by using various Numerical Weather Prediction model's forecast. The NWP models used are Global Forecast System (GFS), Global Ensemble Forecast System (GEFS), Japan Meteorological Agency (JMA), National Center for Environmental Prediction (NCEP), and National Centre for Medium Range Weather Forecasting (NCMRWF) Unified Model (NCUM), along with the Multi-Model Ensemble (MME) of these 5 models. The verification process involves comparing these model predictions with observations obtained from buoys and ships. Through this analysis, we aim to assess the accuracy and reliability of the models, particularly focusing on the performance of the MME, in capturing the observed 10-meter wind conditions at a specific location over the Indian Ocean.

In addition to evaluating model performance against sparse observations, a comparative analysis of the model's accuracy in depicting the 10-meter wind field is also performed. The assessment includes a detailed examination of how well each model aligns with the analysis field of 10-meter wind, providing insights into the model's proficiency in representing the underlying atmospheric conditions over the specified region.

2. Operational models and observation

The NWP division of the Indian Meteorological Department (IMD) currently utilize many global forecast models output available from various national and international meteorological Agencies. The information about these operational global models is briefly provided in the following section.

Table 1. Below is a summary of table outlining the different models used here:

S. No.	Operational Global Models	Operating Organization	Resolution
1.	Global Forecasting System (GFS)	India Meteorological Department (IMD), India	12 km
2.	Global Ensemble Forecasting System (GEFS)	India Meteorological Department (IMD), India	12 km
3.	Global Forecasting System (GFS)	Japan Meteorological Agency (JMA), Japan	25 km
4.	Global Forecasting System (GFS)	National Centre for Environment Prediction (NCEP), USA	25 km
5	Unified Model	National Centre for Medium-Range Weather Forecasting (NCMRWF), India	12 km

2.1 **Observational data used from Buoys and Ships**

Observational data from buoys and ships in the Indian domain used for the verification purpose are available through various channels, including the Global Telecommunication System (GTS). In the GTS, a worldwide network of telecommunication links facilitates the exchange of meteorological and other environmental information among meteorological organizations globally. Buoys are equipped with sensors measuring atmospheric and oceanic parameters, and their real-time data is transmitted via satellite communication systems to meteorological centers. Similarly, ships contribute observational data through onboard instruments during their voyages. Ship data is transmitted through various means, including the use of the NAVTEX (Navigational Telex) system, which broadcasts navigational and meteorological warnings and forecasts to ships at sea. This comprehensive system ensures that observational data from buoys and ships are shared and utilized for accurate weather forecasting and analysis in the Indian region, contributing to improved maritime safety and operational planning.

The observations data including 10m wind from buoys and ships are directly collected from the GTS. The data available in the GTS are decoded on real-time basis for verification purpose. The horizontal visibility data available from ships in real-time are also utilized for the qualitative verification of MME based forecast visibility.

2.2 **10m Wind Speed**

The Sea area within the expanded geographical range spanning from longitude 30°E to 120°E and latitude 35°S to 35°N is depicted in **Figure 1**. This sea area has been subdivided into smaller labelled boxes (A00 to G35). The average 10m wind speed across each box is calculated using data from the GFS, GEFS, NCUM, JMA, and NCEP models and then the MME forecast is also prepared by averaging the above 5 models.

The MME forecast wind speed is then illustrated in Figure 1, with various colors indicating different wind speeds as per the legend. These visualizations extend up to a seven-day forecast, serving as valuable tools for operational forecasters. Additionally, wind speed and direction data from buoys are presented in the form of blue wind bars, along with ships with black wind bars.

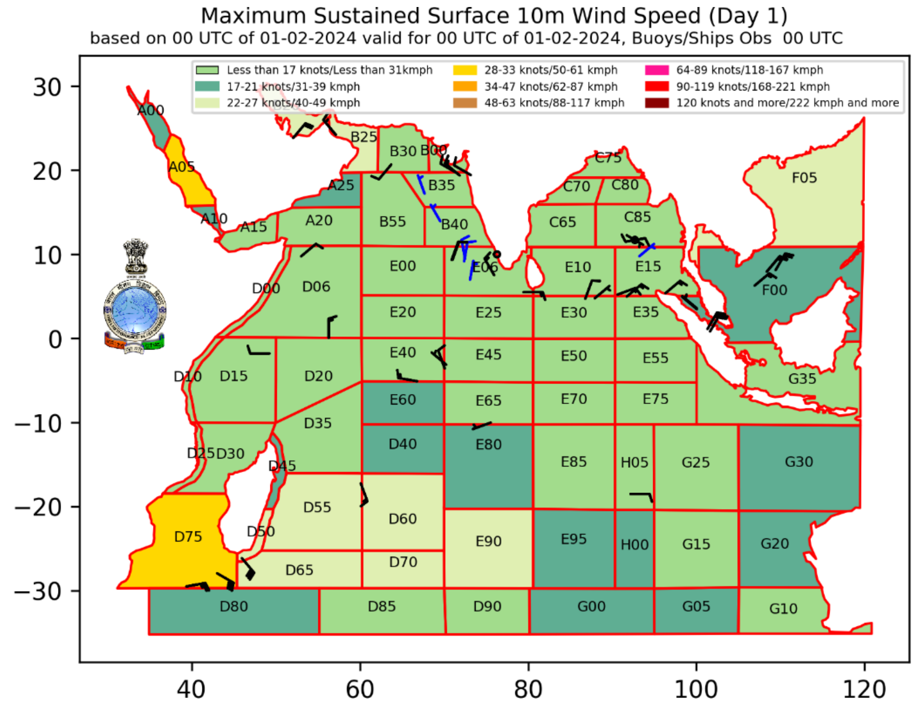

Figure 1: Sample plot for Day-1 operational MME forecast 10m wind speed (knots) average over the respective box area overlay of buoys (blue) and ships observations (black).

2.3 Horizontal Visibility: Model-based products often lack reliable visibility information during adverse weather conditions. Consequently, visibility is evaluated using rainfall distribution, detailed in Table 2. This table also includes spatial distribution of rainfall, estimated visibility ranges measured in nautical miles/kilometres, with the forecast presented in visibility categories.

Table 2: Horizontal Visibility estimation from Rainfall distribution

Spatial distribution of rainfall/Intensity of Rainfall (RF)	Estimated Visibility	Category for Visibility
Fair/Dry Weather	≥ 31.25 nm (≥50 km)	Excellent
mainly Dry (RF <2.5mm)	12.5-31.25 nm (20-50 km)	Very Good
Scattered	6.25-12.5 nm (10-20km)	Good
Fairly widespread	2.5-6 nm (4-10 km)	Moderate
Widespread	1.25-2.5 nm (2-4 km)	Poor
Fairly widespread/ widespread with 1% heavy rainfall	< 1.25 nm (<2 km)	Very Poor

The MME product for model-based visibility is also generated. We utilize a method that involves computing the spatial distribution of rainfall over grid points exceeding 2.5 mm and tallying the number of such points for each model within the shapefile region. To generate the MME spatial distribution, we aggregate the grid points where rainfall surpasses 2.5 mm across all considered models, then divide this sum by number of models times the total number of grid points within the specific shapefile region. This provides the percentage distribution of grid points within the shapefile region. Subsequently, the region is further categorized based on this distribution as Fair/isolated (1-25%), scattered (26-50%), fairly widespread (51-75%), and widespread (76-100%). Table 2 is then utilized to provide the number for estimated visibility.

Figure 2 illustrates the estimated visibility derived from the MME. Only the day-1 forecast is shown, aligning with the available observations from ships. The observations from ships data are superimposed as blue numbers in km over their respective latitude and longitude locations.

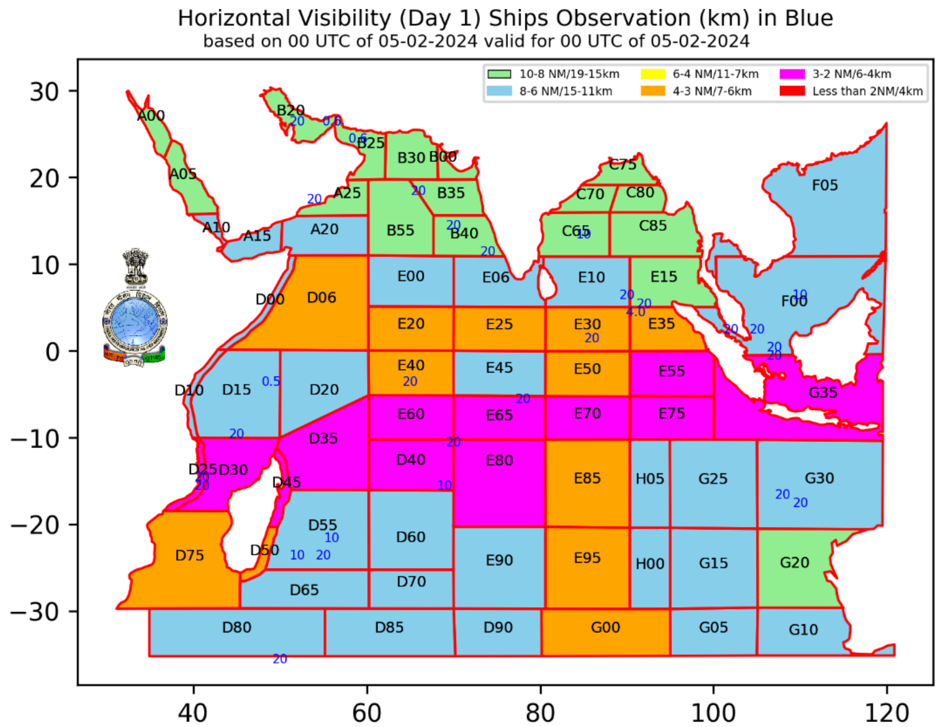

Figure 2: Sample plot for Day-1 operational MME visibility forecast overlay of ships visibility observations (Blue) in km.

Figures 1 and 2 depict the spatial distribution of buoys and ships, emphasizing the limited in-situ observations across the ocean, with ships being the primary source of in-situ visibility. Given this, the verification in the report will specifically concentrate on 10 m wind speeds.

3. Verification of buoys data for the November, December 2023 & January 2024

Figure 3 presents the monthly statistical computations of models based on buoy observations. Data from the three months (November and December 2023 & January 2024) are employed to calculate the RMSE, and this same data is made available to forecasters in real-time for specific locations of buoys. The figure conveys crucial information to forecasters, indicating that MME products offer greater reliability compared to individual models. This is further emphasized in the RMSE, where the black-colored MME exhibits lower errors in comparison to any individual model.

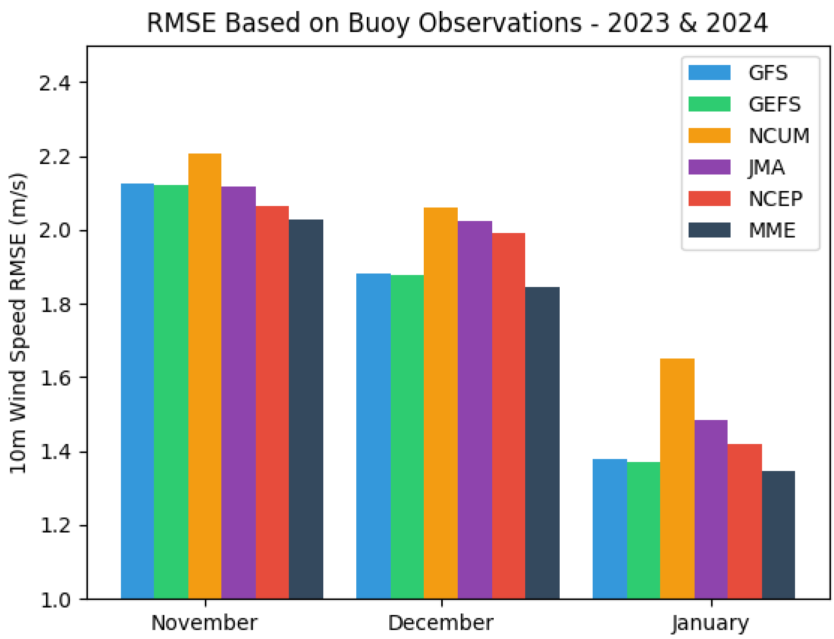

Figure 3: RMSE for model forecasts relative to buoys observations for November, December 2023 and January 2024.

The scatter plot analysis of 10m wind speed models against observations reveals crucial insights into their performance. Points along the 45-degree line (dark black dotted line) indicate perfect agreement, serving as a benchmark for model accuracy. Clusters around this line signify accurate predictions, while deviations above or below suggest positive or negative biases, respectively. The spread of points reflects variability in model performance, with a tight cluster indicating consistency and accuracy. Comparative analysis between models highlights those with consistent biases, and the Multi-Model Ensemble (MME) can be assessed against individual models. In summary, the scatter plot visually captures agreement, biases, and variability, offering valuable information for model evaluation and enhancement strategies. In addition, incorporating a regression line with its corresponding R-squared value and slope enhances the scatter plot analysis, providing a quantitative measure of the relationship between model predictions and observations.

Most red dots lie to the right of the lines, indicating a model overestimation bias. MME exhibits less bias and a narrower spread compared to other models. Also, the higher R-squared value observed for the Multi-Model Ensemble (MME) in the scatter plot indicates a stronger correlation between the ensembles predictions and buoy observations.

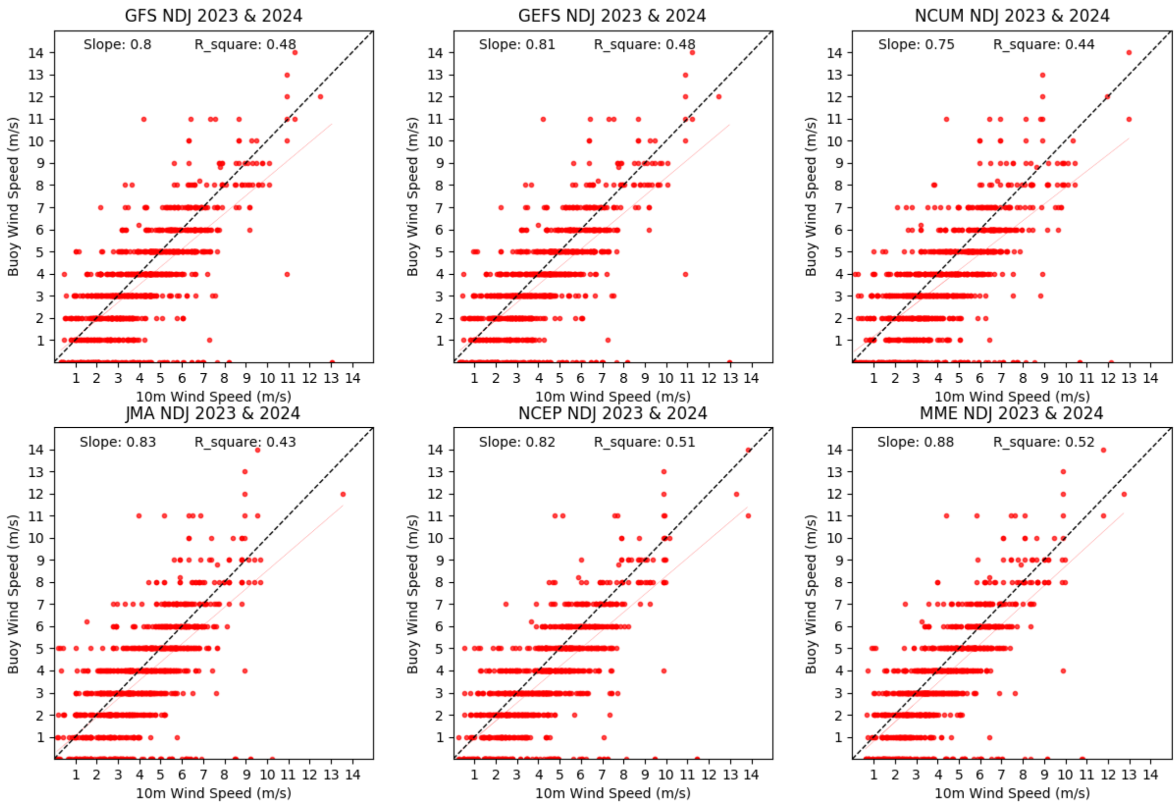

Figure 4: Scatter Plots of Model Forecasts Relative to Buoy Observations (Nov 2023 - Jan 2024). The figure displays scatter plots comparing model forecasts (GFS, GEFS, NCUM, JMA, NCEP, and MME) to buoy observations for November and December 2023, and January 2024.

Figures 5-10 are routinely updated and shared with forecasters in real-time. These visuals depict a comparison between wind speed data from buoy (3m) observations and the wind speed forecasts from models for day-1 to day-5 forecast. In our analysis, it is important to note that while the buoy observations provide 10m wind speed data, the models wind speed forecasts are utilized at the 10m level. Though we recognize the difference in measurement heights, our focus remains on assessing the models performance against observed 10m wind speeds for comprehensive model evaluation and verification.

The specific Figure 5 below compares model wind speed with buoy observations recorded at 03 UTC. The dataset includes observations from the last 3 hours. The x-axis distinctly presents data in 3-hour intervals, categorized by latitude, longitude, hours, and minutes. The models wind speed data is extracted for the locations from the buoys. The consistent bias in the observed black dots and models symbols in the figure can be clearly seen due the hight difference of data utilized. Bias of the models increase with the forecast hours from day-1 to Day-5.

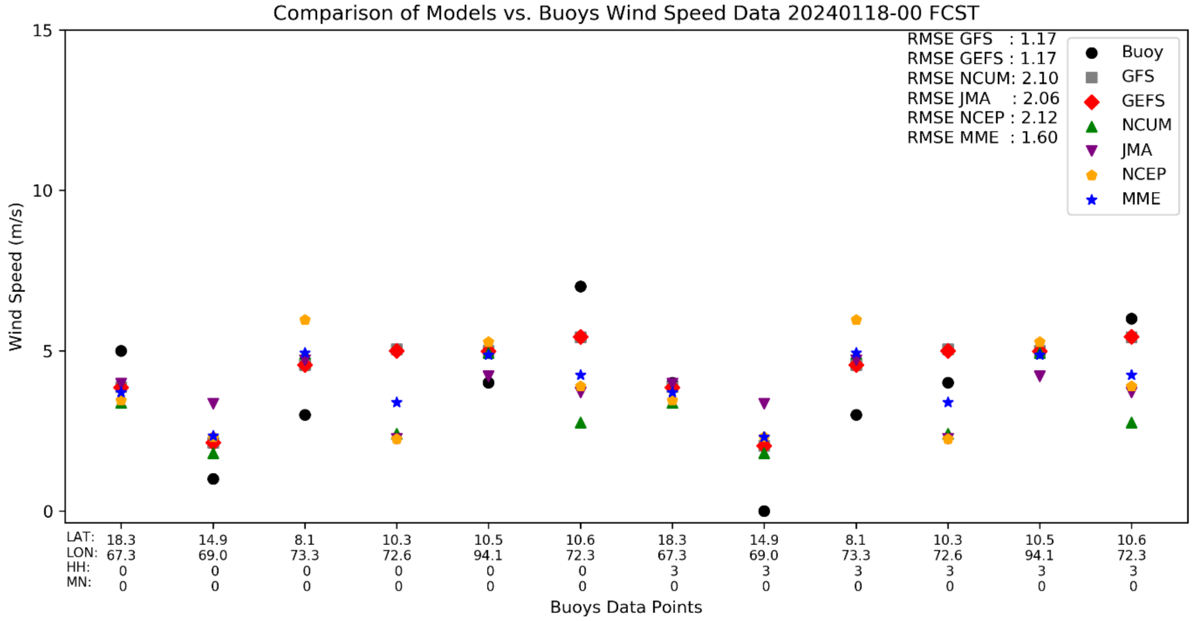

Figure 5 shows how well the models predict the 10m wind speed comparing with respect to the wind speed (3m) data collected from buoys.

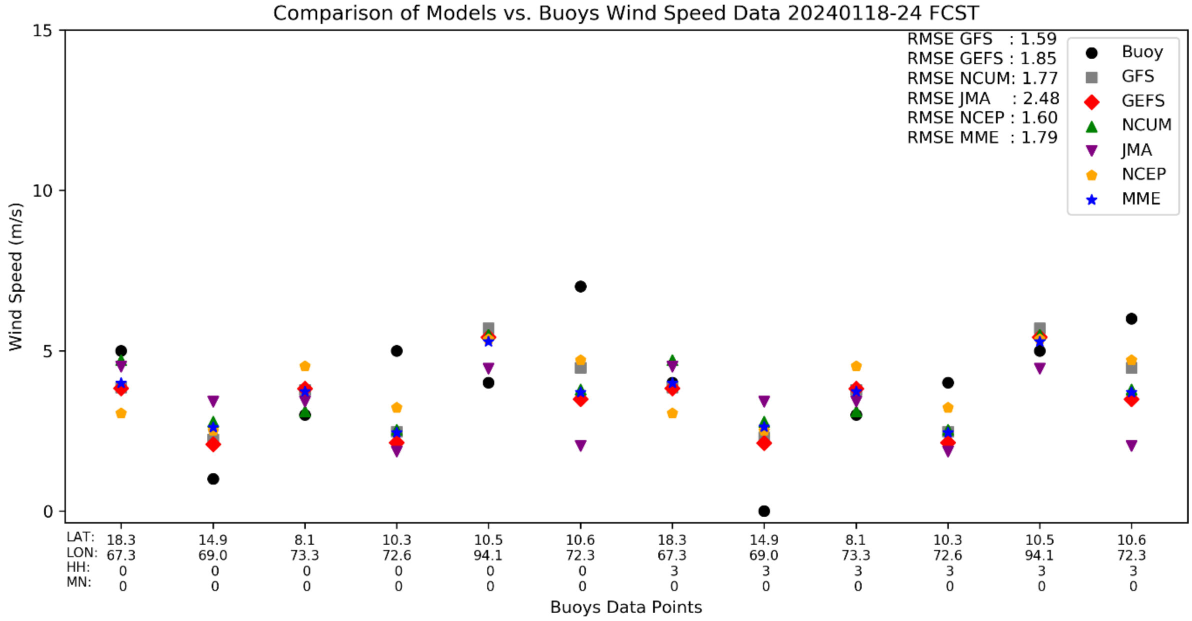

Figure 6 shows how well the models predict 24-hours forecast for 10m wind speed comparing with respect to the wind speed (3m) data collected from buoys.

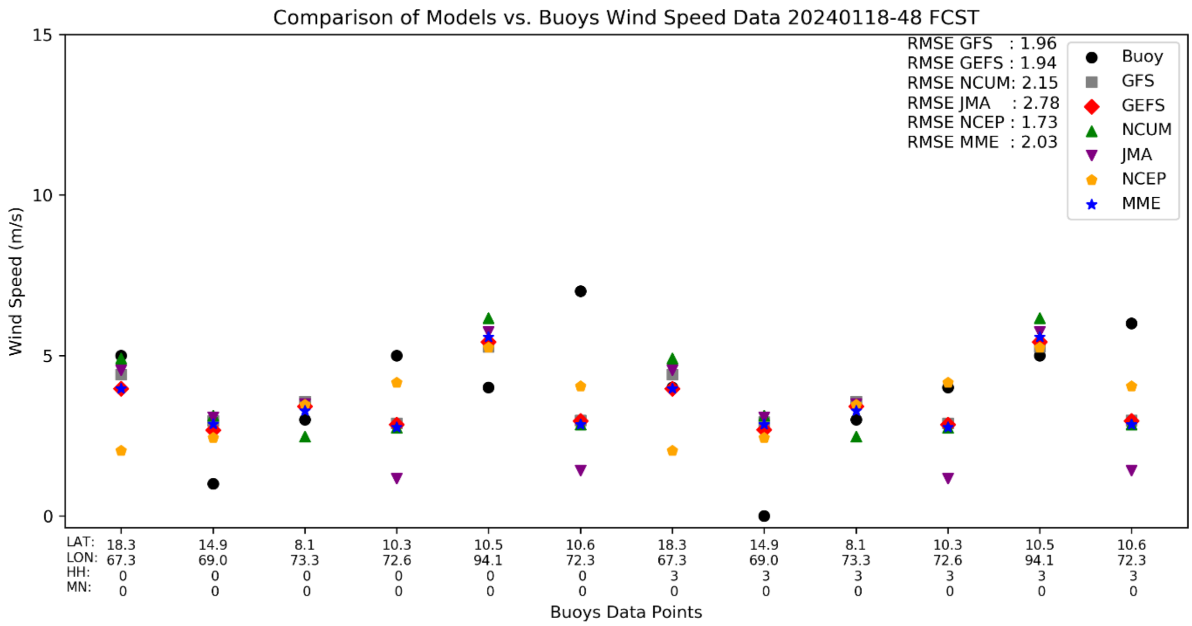

Figure 7 shows how well the models predict 48-hours forecast for 10m wind speed comparing with respect to the wind speed (3m) data collected from buoys.

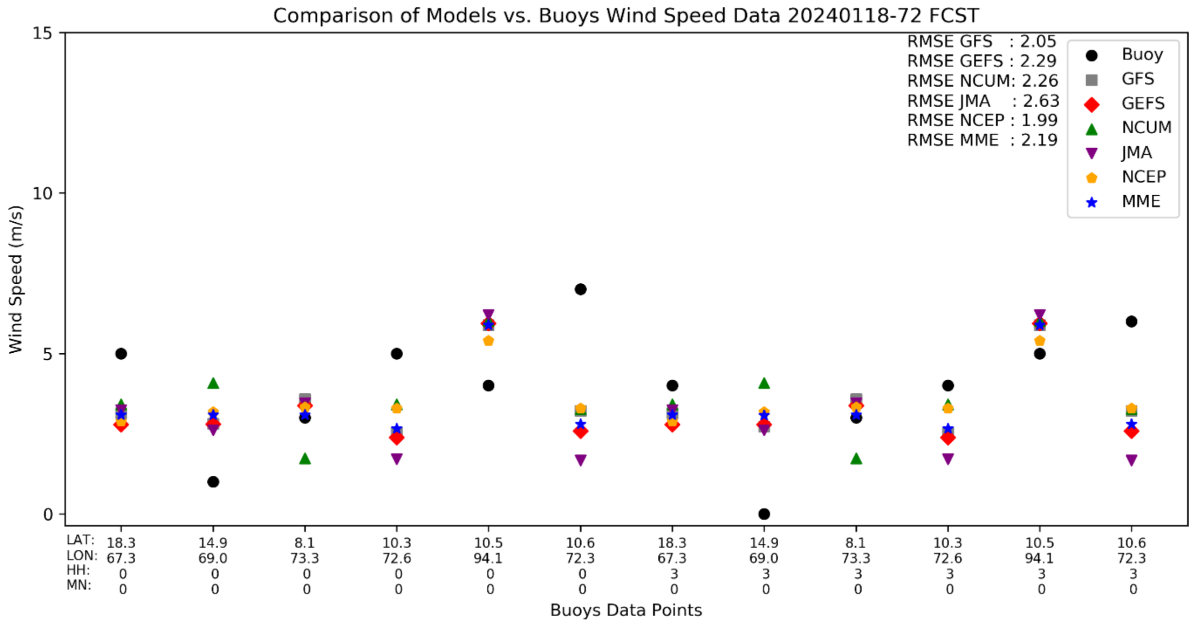

Figure 8 shows how well the models predict 72-hours forecast for 10m wind speed comparing with respect to the wind speed (3m) data collected from buoys.

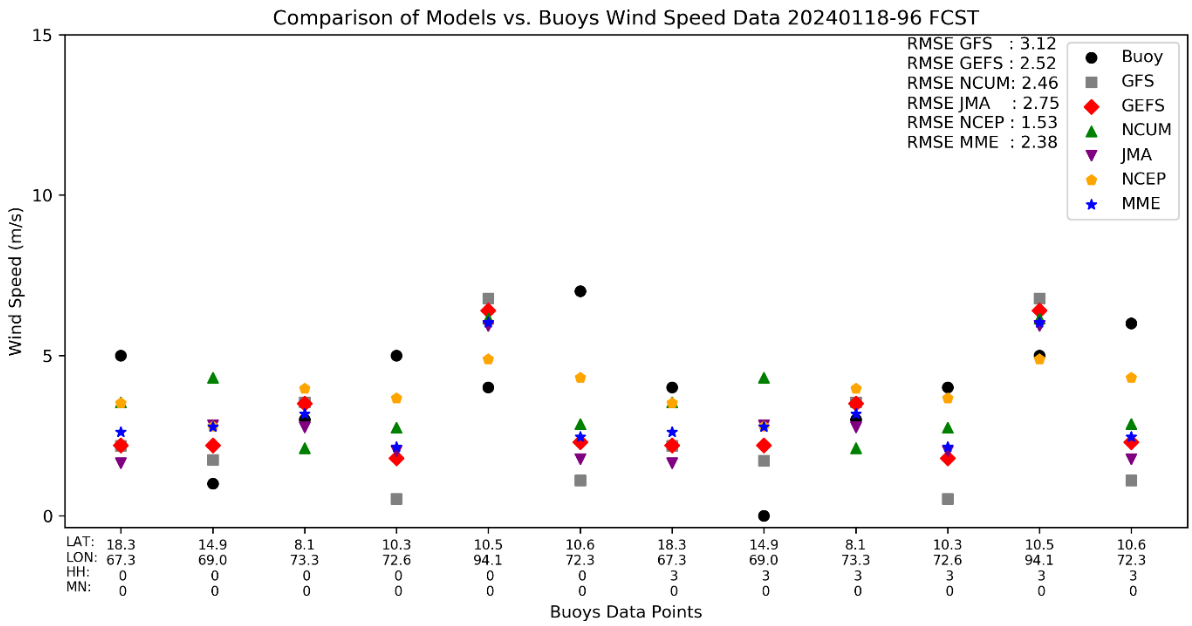

Figure 9 shows how well the models predict 96-hours forecast for 10m wind speed comparing with respect to the wind speed (3m) data collected from buoys.

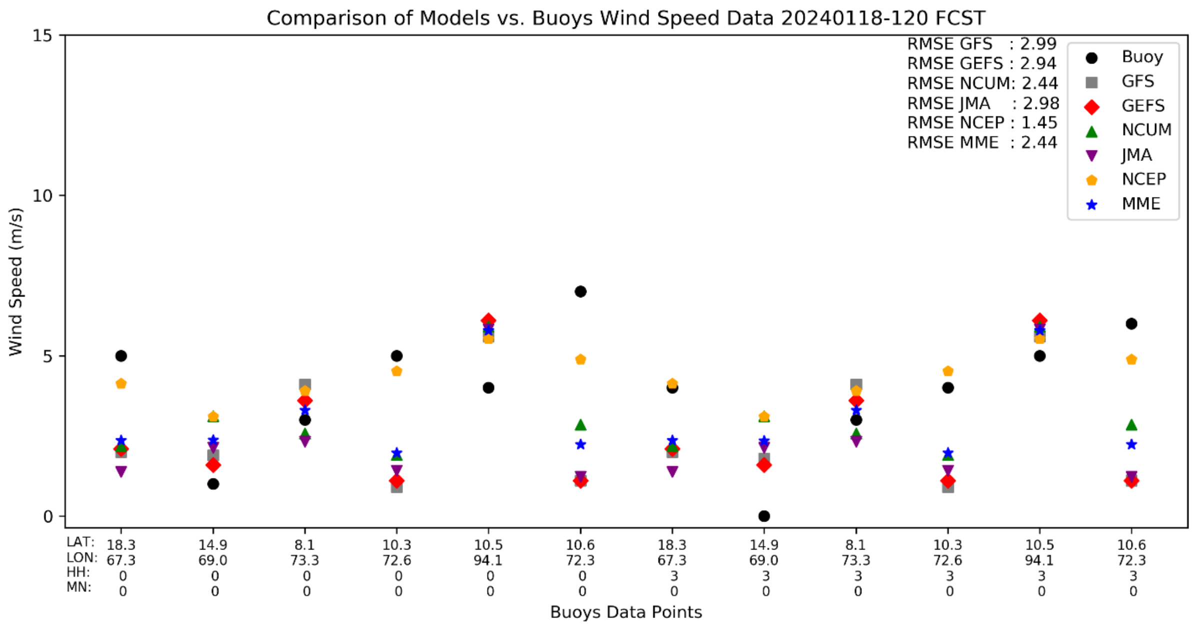

Figure 10 shows how well the models predict 120-hours forecast for 10m wind speed comparing with respect to the wind speed (3m) data collected from buoys.

4. Verification of Ships data for the November, December 2023 & January 2024

Figure 11 presents the monthly statistics of models based on ships observations. Daily data for the period from 01 November 2023 to 31 January 2024 are used to calculate the RMSE for each locations of ships. The figure conveys that MME products offer greater reliability compared to individual models. This is further emphasized in the RMSE, where the black-colored MME exhibits lower errors in comparison to any individual model.

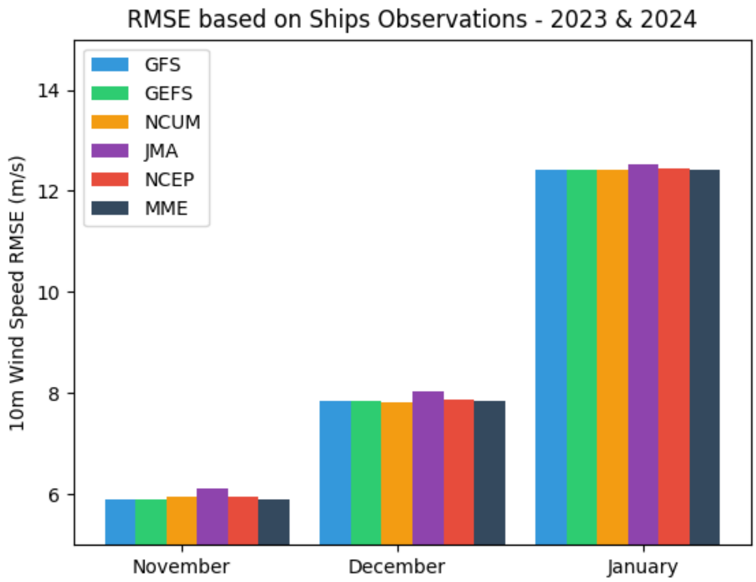

Figure 11: RMSE for model forecasts relative to buoys observations for November, December 2023 and January 2024.

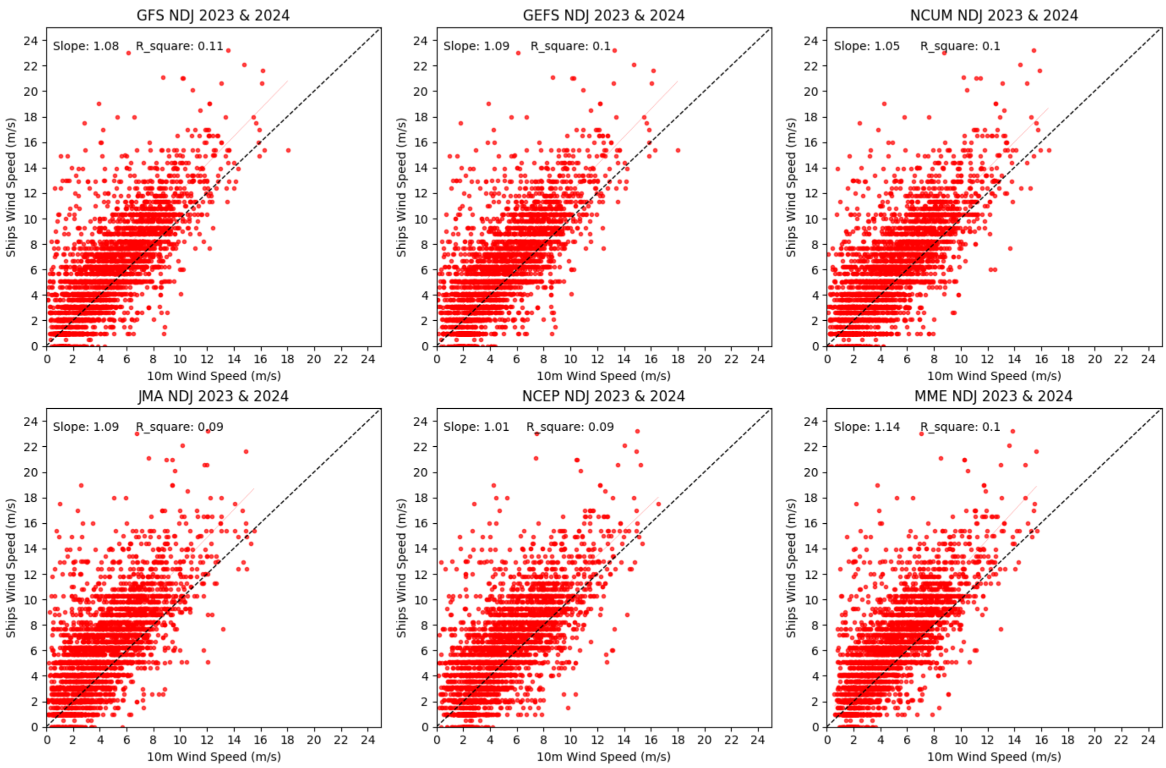

Figure 12: Scatter plots of model forecasts relative to ships observations (Nov 2023 - Jan 2024). The figure displays scatter plots comparing model forecasts (GFS, GEFS, NCUM,

JMA, NCEP, and MME) to ships observations for November and December 2023, and January 2024.

The Scatter plot illustrate the ships vs models (GFS, GEFS, NCUM, JMA, NCEP and MME) wind speed. The points in red dots above the black dotted line suggest model underestimation, while points below imply overestimation. The spread around the line signifies variability in model performance. In Figure 12, most red dots lie to the left of the regress line (light red), indicating a model underestimate the observed values. In other words, the model predicts lower values than what is observed via ships. MME exhibits less bias and a narrower spread compared to other models.

Figures 13-18 are routinely updated and shared with forecasters in real-time. These visuals depict a comparison between wind speed data from ships observations and the wind speed forecasts from models for day-1 to day-5 forecast.

The specific Figure 13 below compares model wind speed with ships observations recorded at 03 UTC. The dataset includes observations from the last 3 hours. The x-axis distinctly presents data in 3-hour intervals, categorized by latitude, longitude, hours, and minutes. The models wind speed data is extracted for the locations from the ships. The consistent bias in the observed black dots and models can be clearly seen. Also the bias of the models forecast from Day-1 to Day-5 increase with the forecast hours as illustrated in Figures 13-18.

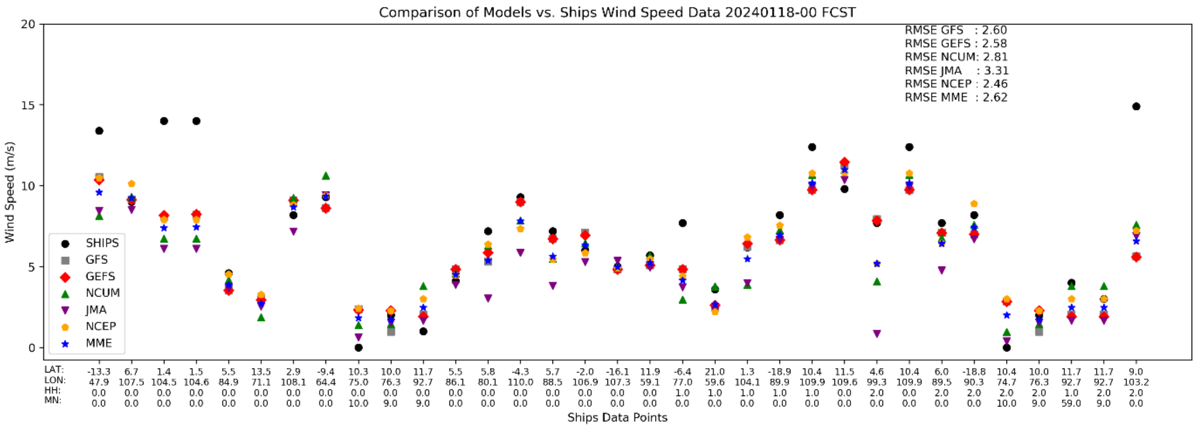

Figure 13 shows how well the models predict for 10m wind speed comparing with respect to the wind speed data collected from dynamics ships.

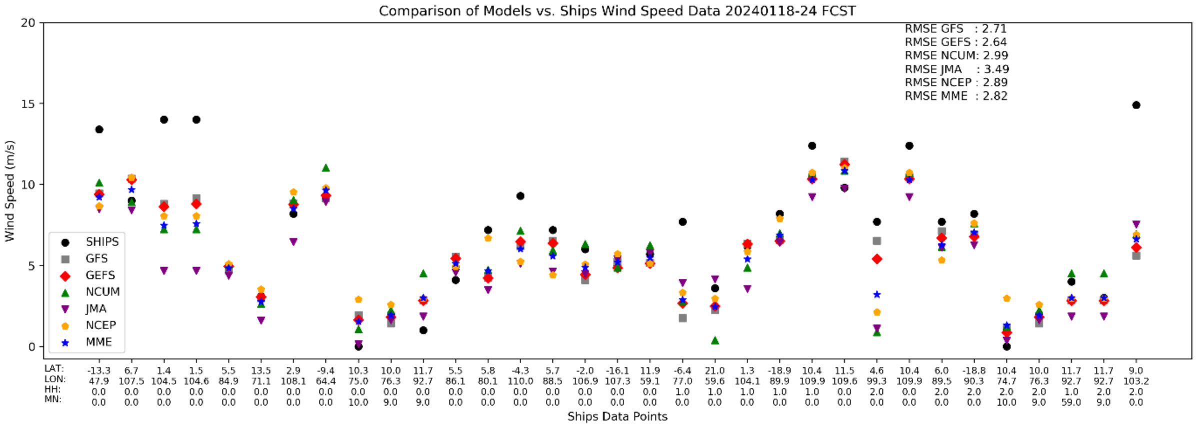

Figure 14 shows how well the models predict 24- hours forecast for 10m wind speed comparing with respect to the wind speed data collected from dynamics ships.

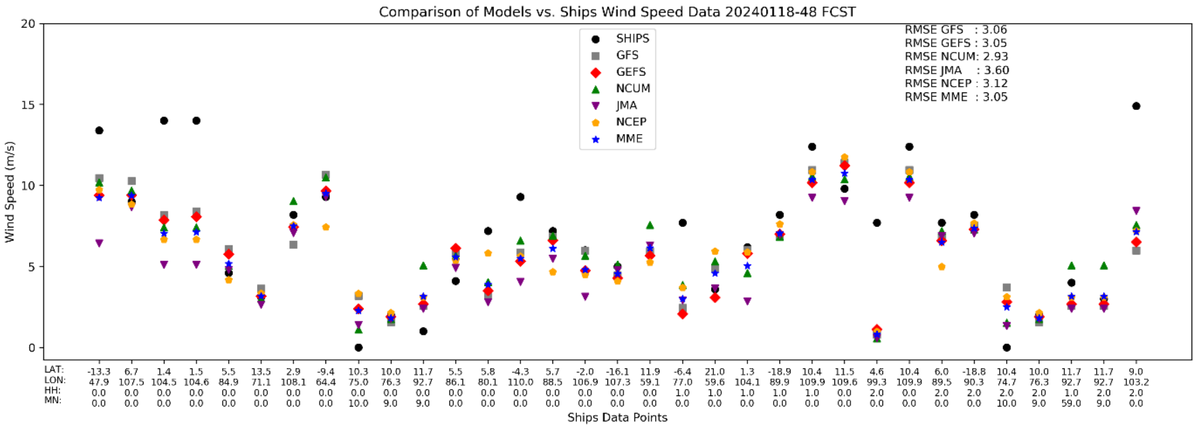

Figure 15 shows how well the models predict 48- hours forecast for 10m wind speed comparing with respect to the wind speed data collected from dynamics ships.

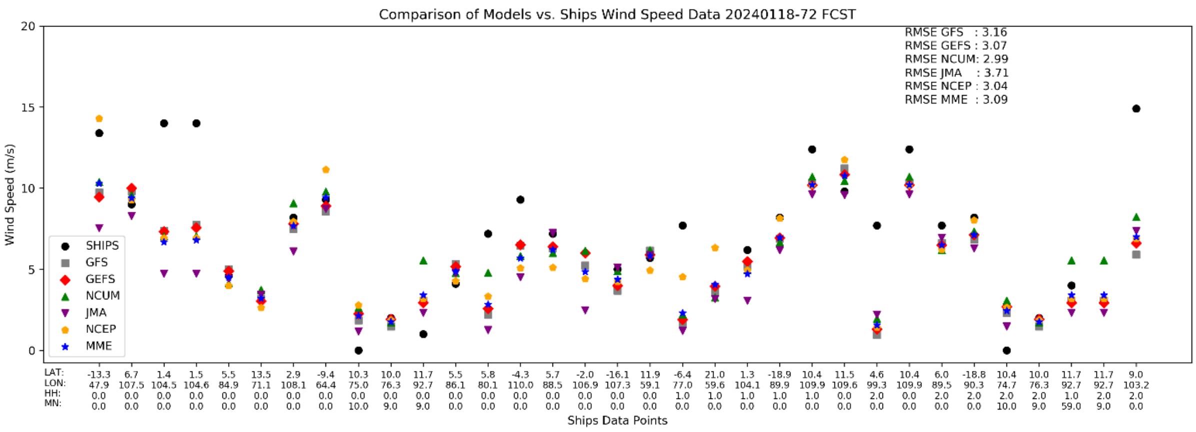

Figure 16 shows how well the models predict 72-hours forecast for 10m wind speed comparing with respect to the wind speed data collected from dynamics ships.

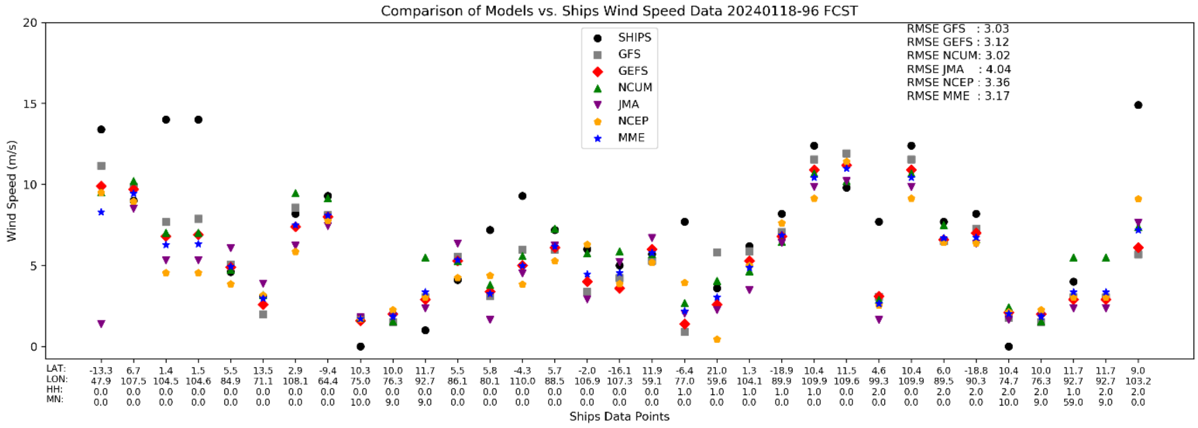

Figure 17 shows how well the models predict 96-hours forecast for 10m wind speed comparing with respect to the wind speed data collected from dynamics ships.

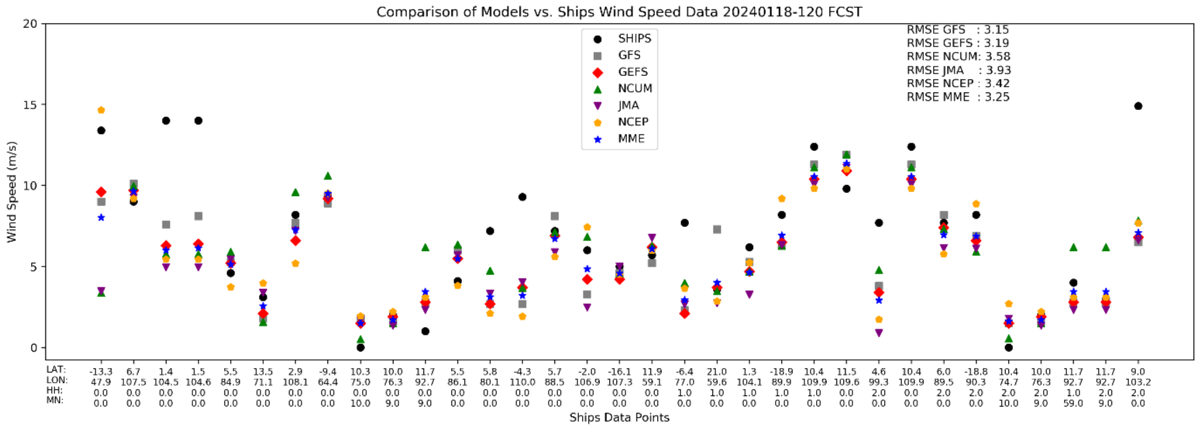

Figure 18 shows how well the models predict 120-hours forecast for 10m wind speed comparing with respect to the wind speed data collected from dynamics ships.

5. **Models wind speed comparison based on analysis field.**

Over the ocean, where we have limited observational data, we used the analysis field to check how accurately different models predict wind speeds. By comparing the models with this reference field, we discovered where the models tend to underestimate or overestimate wind speeds, giving us valuable insights into their performance. This assessment is conducted in real-time for models such as GFS, GEFS, NCUM, JMA, NCEP, and ECMWF, providing forecast bias information for up to five days.

Figures 19-24 are regularly updated and shared with forecasters in real-time. These figures compare the wind speed bias from various operational models GFS, GEFS, NCUM, JMA, NCEP, and ECMWF with respect to respective analysis for days 1 to 5.

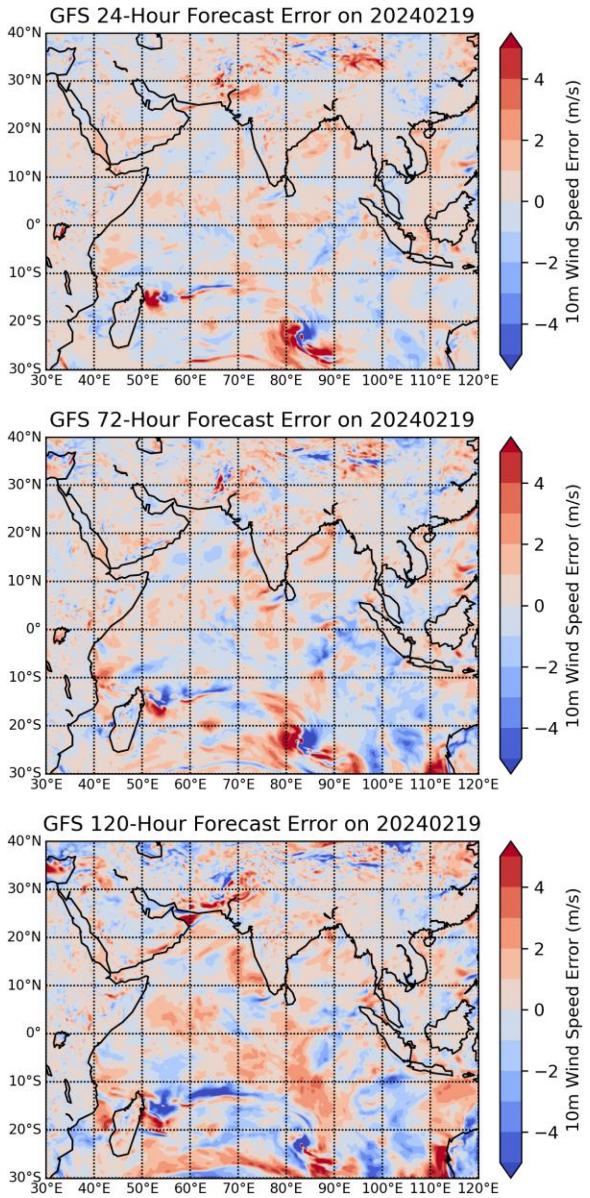

Figure 19: Bias Error of GFS Models from the Analysis Field in the Forecast for Days 1 to 5.

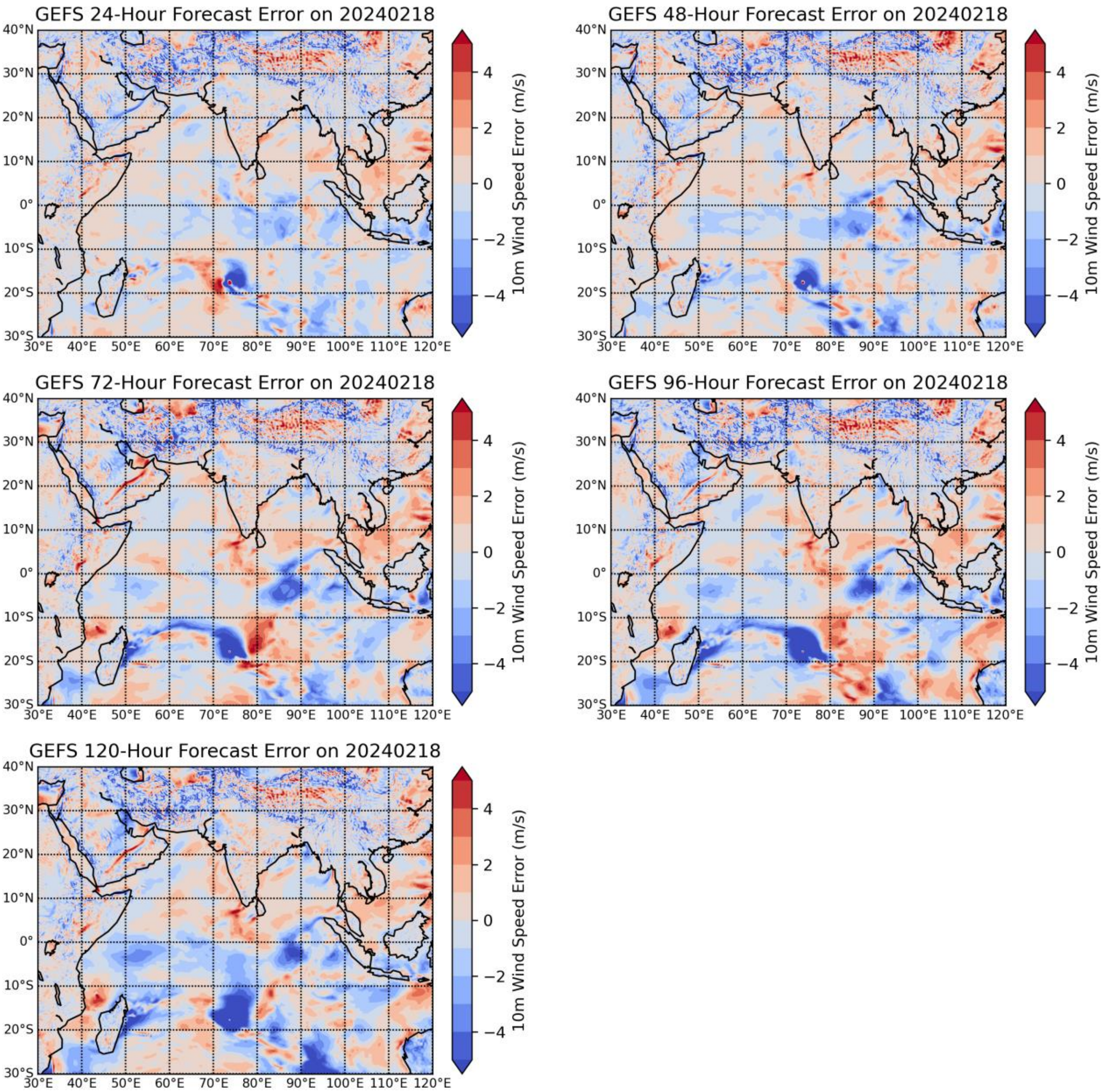

Figure 20: Bias Error of GEFS Models from the Analysis Field in the Forecast for Days 1 to 5.

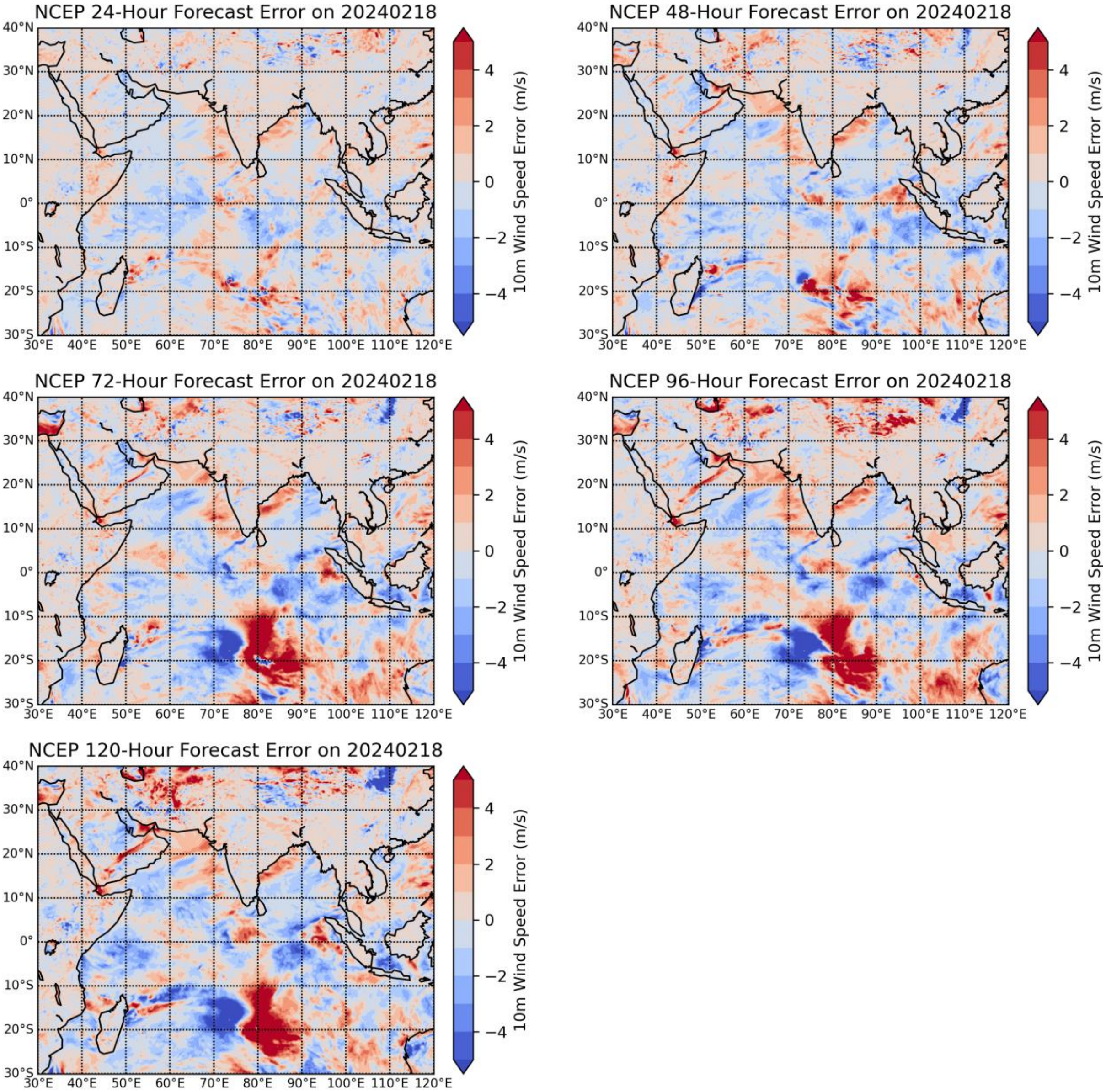

Figure 21: Bias Error of NCE Models from the Analysis Field in the Forecast for Days 1 to 5.

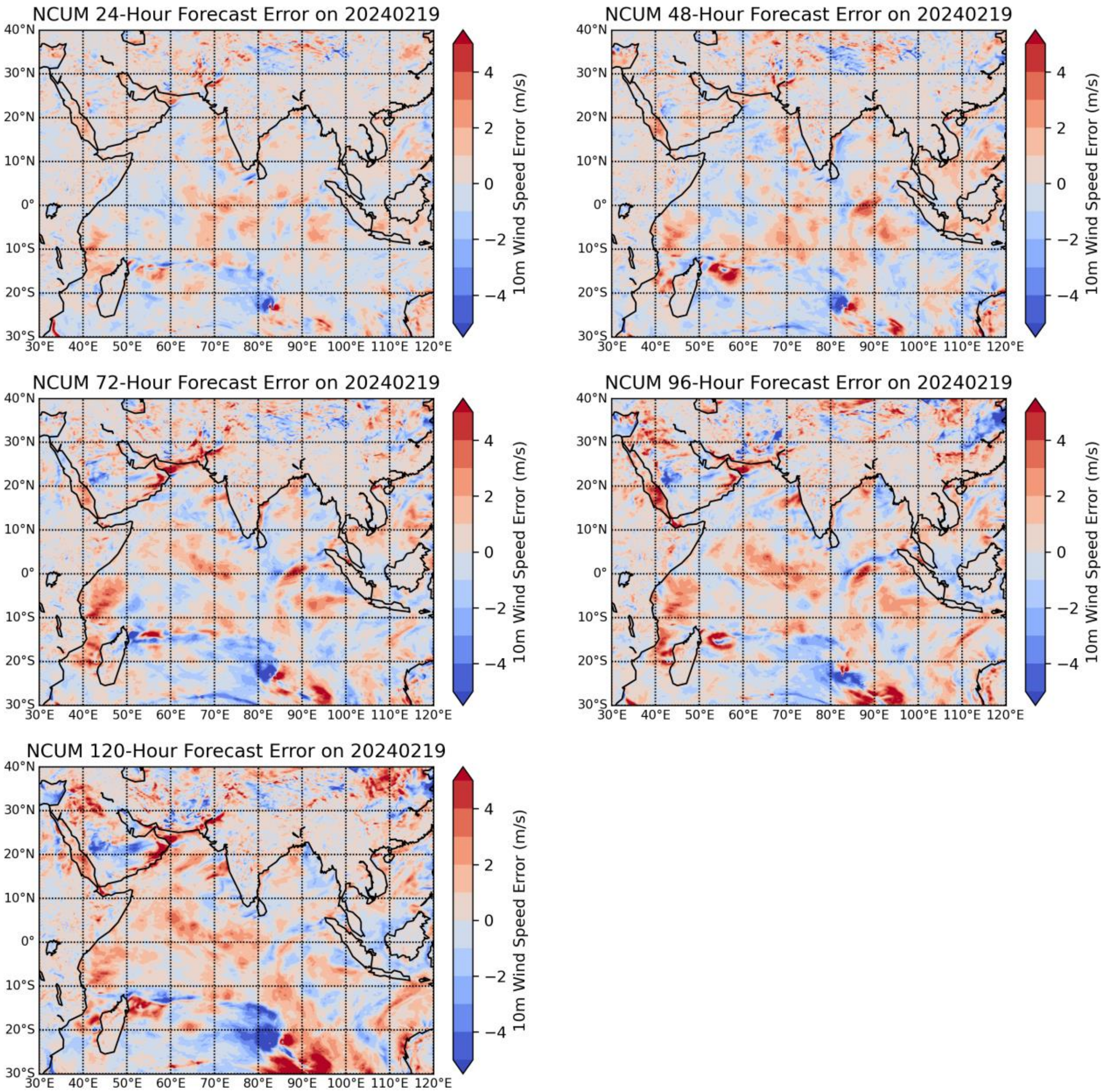

Figure 22: Bias Error of NCUM Models from the Analysis Field in the Forecast for Days 1 to 5.

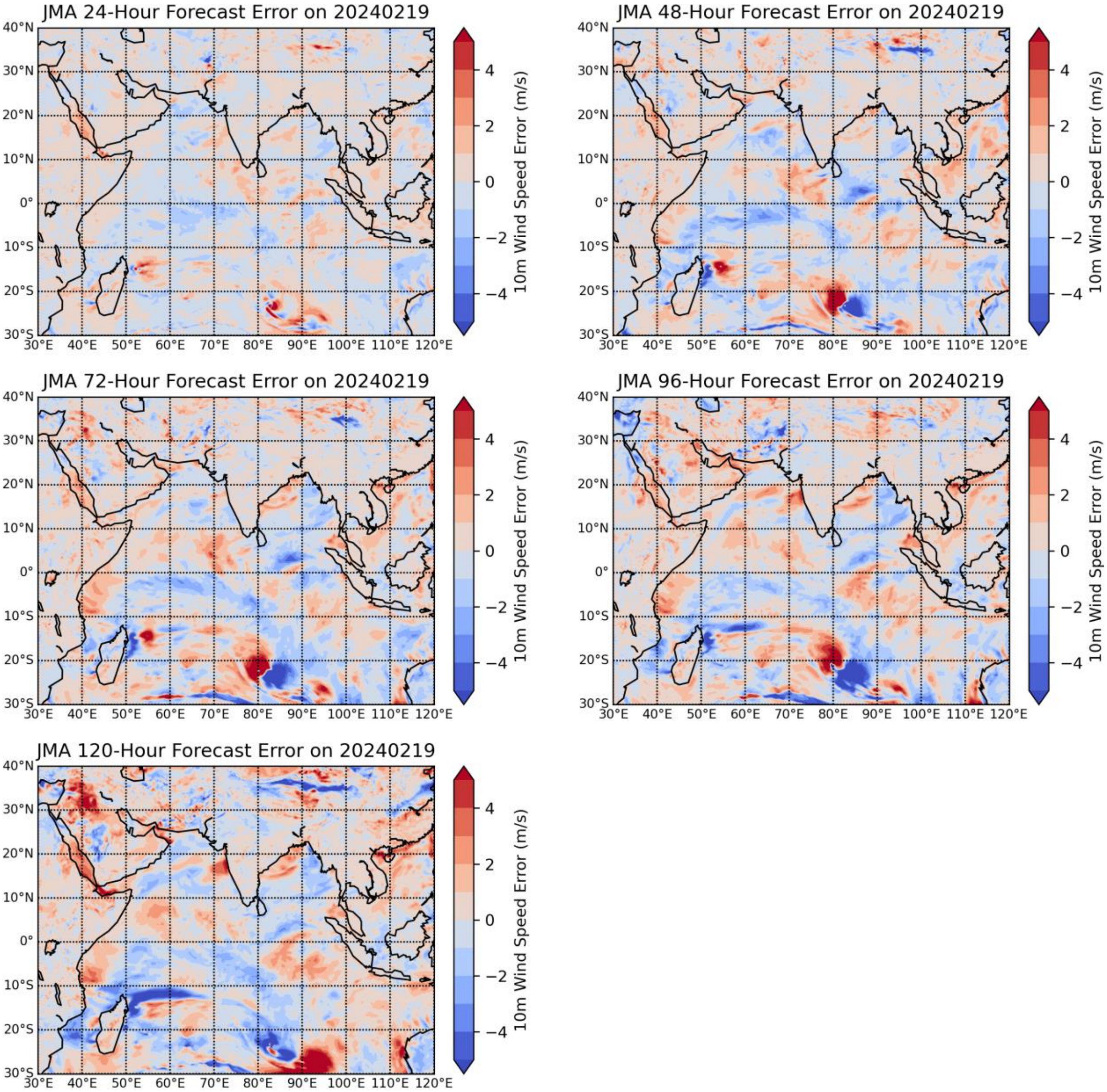

Figure 23: Bias Error of JMA Models from the Analysis Field in the Forecast for Days 1 to 5.

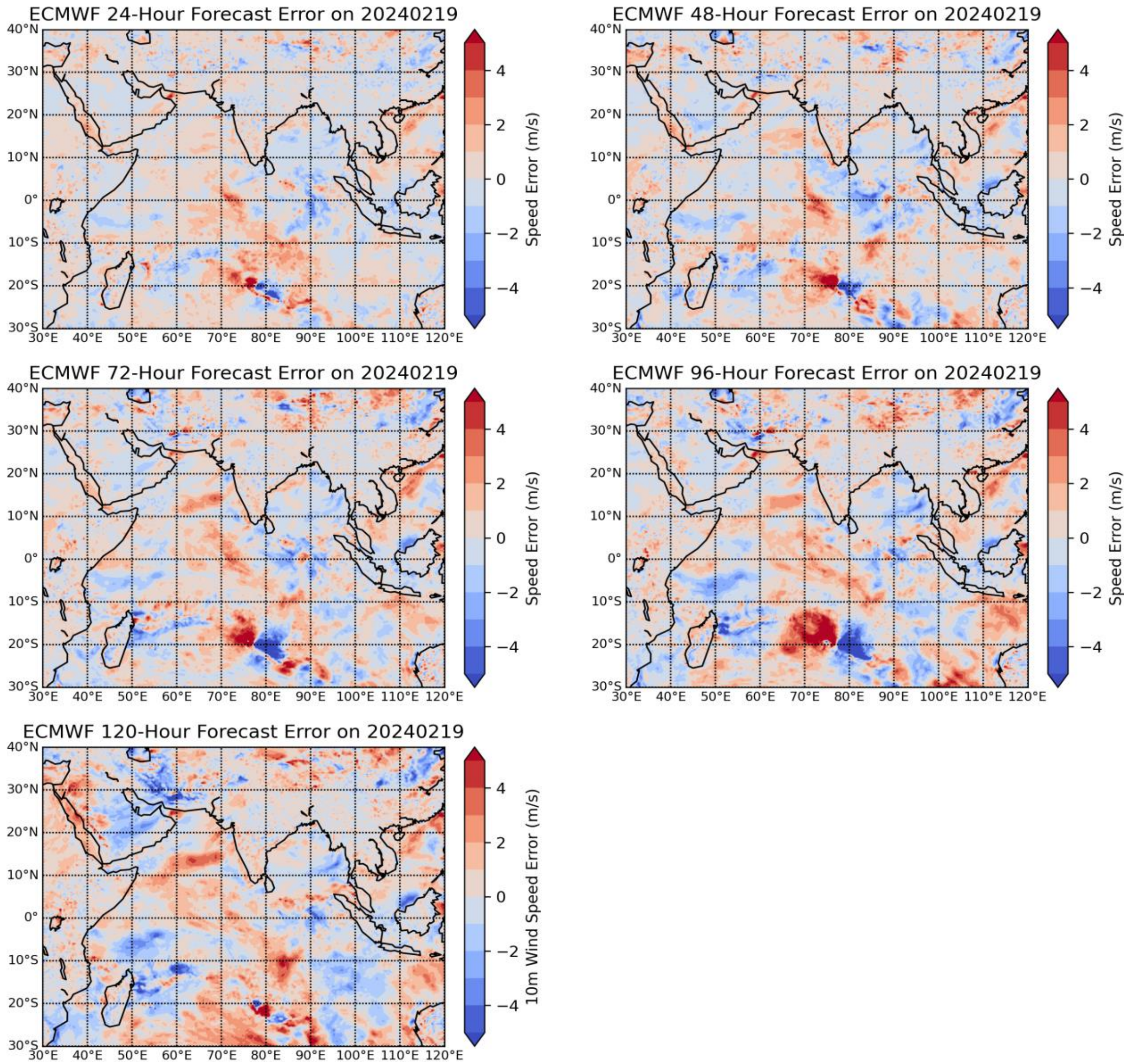

Figure 24: Bias Error of ECMWF Models from the Analysis Field in the Forecast for Days 1 to 5.

In short, the bias from the analysis field indicated that the lowest bias comparing to the other models can be seen in GFS, GEFS, and the largest bias is shown by the NCUM model for all the five days. Most of the models overestimating over the Comorin area.

6. Summary

The comprehensive report presents a thorough evaluation of 10m wind speed predictions from various numerical weather models (GFS, GEFS, NCUM, JMA, NCEP, and MME) through real-time comparisons with buoy and ship observations. The analysis involves scatter plots, statistical metrics, and spatial assessments to understand model accuracy, biases, and performance across different scenarios. Key findings include a visual representation of model-observation agreement, identification of biases, and a detailed spatial analysis of model performance. The report emphasizes the reliability of the Multi-Model Ensemble (MME) and provides valuable insights for forecasters to enhance the precision of wind speed predictions in operational forecasting.