A robust error correction method for numerical weather prediction wind speed based on Bayesian optimization, Variational Mode Decomposition, Principal Component Analysis, and Random Forest: VMD-PCA-RF (version 1.0.0)

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Abstract. Accurate wind speed prediction is crucial for the safe and efficient utilization of wind resources. However, current single-value deterministic numerical weather prediction methods employed by wind farms do not adequately meet the actual needs of power grid dispatching. In this study, we propose a new hybrid forecasting method for correcting 10-meter wind speed predictions made by the Weather Research and Forecasting (WRF) model. Our approach incorporates Variational Mode Decomposition (VMD), Principal Component Analysis (PCA), and five artificial intelligence algorithms: Deep Belief Network (DBN), Multilayer Perceptron (MLP), Random Forest (RF), eXtreme Gradient Boosting (XGBoost), light Gradient Boosting Machine (lightGBM), and the Bayesian Optimization Algorithm (BOA). We first construct WRF-predicted wind speeds using the Global Forecast System (GFS) model output based on prediction results. We then perform two sets of experiments with different input factors and apply BOA optimization to tune the four artificial intelligence models, ultimately building the final models. Furthermore, we compare the aforementioned five optimal artificial intelligence models suitable for five provinces in southern China in the wintertime: VMD-PCA-RF in December 2021 and VMD-PCA-lightGBM in January 2022. We find that the VMD-PCA-RF evaluation indices exhibit relative stability over nearly a year: correlation coefficient (R) is above 0.6, Forecasting Accuracy (FA) is above 85 %, mean absolute error (MAE) is

32 below 0.6 m s^{-1}, root mean square error (RMSE) is below 0.8 m s^{-1}, relative mean absolute error (rMAE)

33 is below 60 %, and relative root mean square error (rRMSE) is below 75 %. Thus, for its promising

34 performance and excellent year-round robustness, we recommend adopting the proposed

35 VMD-PCA-RF method for improved wind speed prediction in models.

36 **1 Introduction**

37   Sustainable energy plays a vital role in reducing carbon footprint and increasing system reliability

38 (Hanifi et al., 2020). As renewable energy sources have a negligible carbon footprint, they have

39 become the preferred choice for many industries in the power sector (Dhiman and Deb, 2020). Among

40 these sources, wind energy is a crucial low-carbon energy technology with the potential to become a

41 sustainable energy source (Tascikaraoglu and Uzunoglu, 2014). In 2022, the global wind power

42 capacity reached 906 GW, with a 9 % year-on-year increase due to a newly installed capacity of 77.6

43 GW. The global onshore wind market increased by 68.8 GW while facing a 5 % growth decline

44 compared to the previous year. Such change is attributed to a slowdown in China and the U.S., the

45 world's two largest wind markets that account for over two-thirds of the world's onshore wind farm

46 installations (Joyce and Feng, 2023). The instability and unpredictability of wind power generation can

47 lead to instability in the power system. In addition, the decline of the wind energy market also makes it

48 more challenging to improve the accuracy of wind speed forecasts. An accurate wind speed prediction

49 method is needed to reduce the instability risk of power system and the economic loss of wind power

50 enterprises (Huang et al., 2019). Therefore, accurate and stable wind speed prediction (WSP) is very

51 important for the safe and stable operation of the power grid system and for improving the utilization

52 rate of wind energy and economic development (Guo et al., 2021; Xiong et al., 2022; Tang et al.,

53 2021).

54   Current WSP algorithms are primarily categorized into physical algorithms (Zhao et al., 2016),

55 statistical algorithms (Wang and Hu, 2015; Barthelmie et al., 1993), machine learning (ML) algorithms

56 (Huang et al., 2019; Salcedo-Sanz et al., 2011; Ma et al., 2020), and hybrid algorithms (Deng et al.,

57 2020; Xu et al., 2021; Zhao et al., 2019; Xiong et al., 2022; Tang et al., 2021). Physical methods, such

58 as numerical weather prediction (NWP), are commonly used in wind speed forecasting. NWP, which

59 accounts for atmospheric processes and physical laws, solves discrete mass, momentum, and energy

60 conservation equations along with other fundamental physical principles, establishing itself as a widely

61 adopted and reliable physical method. Currently, the High-resolution Limited Area Model (HIRLAM)

62 (Služenikina and Männik, 2016), the European Center for Medium-Range Weather Forecast (ECMWF)

63 model, the fifth-generation mesoscale model (MM5) (Salcedo-Sanz et al., 2009), and the Weather

64 Research and Forecasting Model (WRF) (Skamarock et al., 2021) are extensively utilized for wind

65 speed prediction. However, NWP modeling faces challenges due to the selection of parameterization

66 schemes, such as model microphysics and systematic errors, which exhibit temporal and spatial

67 differences and uncertainties. These uncertainties hinder the accuracy of NWP models in wind speed

68 prediction, making it difficult to meet the rising demands of the grid system (Zhao et al., 2019; Xu et

69 al., 2021).

70   Studies have demonstrated that enhancing the accuracy of numerical weather prediction (NWP)

71 models and correcting prediction errors can effectively minimize the errors associated with wind speed

72 prediction. These research endeavors have typically sought to optimize the physical and dynamic

73 parameters of the NWP model (Cheng et al., 2013), refine the model structure (Jiménez and Dudhia,

74 2012), or improve the accuracy of model inputs through preprocessing and denoising techniques (Xu et

75 al., 2015). Additionally, improving initial field error through methods, such as target observation and

76 data assimilation (Williams et al., 2013), can also minimize wind speed errors predicted by NWP

77 models.

78   Physical methods are generally more appropriate for long-term wind speed prediction, such as

79 those 48-72 hours in advance, while their practical application in short-term forecasting is limited

80 (Zhao et al., 2019; Deng et al., 2020; James et al., 2018). In contrast, statistical methods utilize

81 historical data to establish a relationship between input and output variables and are therefore

82 well-suited for short-term wind speed prediction. They are usually time series models, such as

83 Autoregressive Moving Average (ARMA) (Erdem and Shi, 2011) and Autoregressive Integrated

84 Moving Average (ARIMA) (Wang and Hu, 2015). Whereas filtering models (Cassola and Burlando,

85 2012; Chen and Yu, 2014), machine learning models (Hu et al., 2013), and hybrid models (Huang et al.,

86 2019) have been gradually developed to further improve wind speed prediction accuracy.

87   With purely statistical models becoming less suitable for wind speed predictions beyond 6 hours,

88 the use of a combination of physical and statistical methods has gained growing interest (Zjavka, 2015;

89   Xu et al., 2021). The error correction model improves the accuracy of the NWP model by training on

90   the relationship between the NWP predictor variables and the observed correlation variables (Sun et al.,

91   2019). However, traditional error prediction models rely solely on historical wind speed sequences as

92   input factors (Deng et al., 2020; Guo et al., 2021) and do not incorporate the characteristic

93   meteorological factors forecasted by the WRF model. Studies have shown that considering all relevant

94   historical meteorological factors can lead to more accurate predictions compared to only taking into

95   account historical wind speed (Zhang et al., 2019c). Therefore, it is crucial to include meteorological

96   characteristic factors as input in the prediction model.

97   For an error prediction model, wind speed is the most important input factor. Traditionally, the

98   error prediction model uses historical wind speed data as input, without any feature selection. Feature

99   selection methods, such as filtering methods, are commonly used in time series analysis. Currently,

100 empirical mode decomposition (EMD) (Liu et al., 2018; Guo et al., 2012), ensemble empirical mode

101 decomposition (EEMD) (Wang et al., 2017), wavelet decomposition (WD) (Zhang et al., 2019b),

102 variational mode decomposition (VMD) (Hu et al., 2021; Zhang et al., 2019a), and other filtering

103 methods are used to select key features in the wind speed data. As mentioned above, studies have

104 shown that these feature selection methods can effectively extract the hidden features in the wind speed

105 series to improve wind speed prediction accuracy. However, despite the effectiveness of wind speed

106 filtering methods in wind speed prediction, only a few studies have applied these methods to the

107 correction of wind speed errors in NWP forecasting (Xu et al., 2021; Li et al., 2022).

108   In addition, traditional error correction methods generally adopt linear regression (Dong et al.,

109 2013), multiple linear regression (Liu et al., 2016), machine learning (Salcedo-Sanz et al., 2011), and

110 deep learning algorithms (Zhang et al., 2019c). However, the efficacy of machine learning and deep

111 learning algorithms is highly dependent on the selection of model parameters (Guo et al., 2021; Xiong

112 et al., 2022). The Bayesian optimization algorithm (Li and Shi, 2010; Guo et al., 2021) is considered a

113 relatively advanced algorithm for optimizing model parameters and has been widely used in MATLAB

114 and Python packages.

115   In this study, we investigate a multi-step wind speed forecasting model that combines NWP

116 simulation and an error correction strategy. We present two sets of experiments divided into three steps:

117 (1) we use the first group of experiments to extract hidden features from various meteorological

118 elements forecasted by NWP; The second group of experiments mainly focuses on the wind speed

119 forecast of NWP, and the VMD-PCA algorithm is used to extract the hidden features in the forecasted

120 wind speed; each set of experimental input factors is matched with the actual 10-meter wind speed data

121 of 410 stations in time and space; (2) we employ four advanced machine learning algorithms optimized

122 by the BOA algorithm, and DBN deep learning algorithm to train the two groups of experiments and

123 perform 5-fold cross-validation; and (3) we analyze six distinct wind speed error indicators to compare

124 and identify the most suitable wind speed error correction schemes for the five southern provinces

125 (Yunnan, Guizhou, Guangxi, Guangdong, Hainan) in winter and throughout most of the year. The

126 remainder of this paper is organized into sections discussing the effects of the BOA-VMD-PCA

127 approach, the interpretability of RF feature importance, and the stability analysis of the proposed

128 models.

2 Data and methods

2.1 Data

131 The observed data comes from the China Meteorological Administration land data assimilation

132 system (CLDAS-V2.0) real-time product data set. According to the description of the documents on the

133 official website (https://data.cma.cn/data/cdcdetail/dataCode/NAFP_CLDAS2.0_RT.html), the dataset

134 is constructed through the integration of multiple sources, including ground and satellite data, and is

135 refined using advanced techniques such as multi-grid variational assimilation, physical inversion, and

136 terrain correction. This dataset exhibits superior quality in comparison to other products, offering

137 higher spatial and temporal resolutions. The target observation data includes 2-m air temperature, 2-m

138 specific humidity, 10-meter wind speed, surface pressure, and precipitation. These data are processed

139 by the China Meteorological Public Service Center to equivalent latitude and longitude grid scale,

140 covering a geographical range of 15-32.97°N and 94-120.97°E. The spatial resolution of the grid is

141 $0.03° \times 0.03°$ (3km by 3km) and the temporal resolution is 1 hour. China Meteorological Public

142 Service Center applied the nearest neighbor interpolation for precipitation and bilinear interpolation for

143 the other four meteorological elements with downscaling from 3km to 410 sites. We select the

144 10-meter wind speed data of 410 sites, as illustrated in Fig. 1.
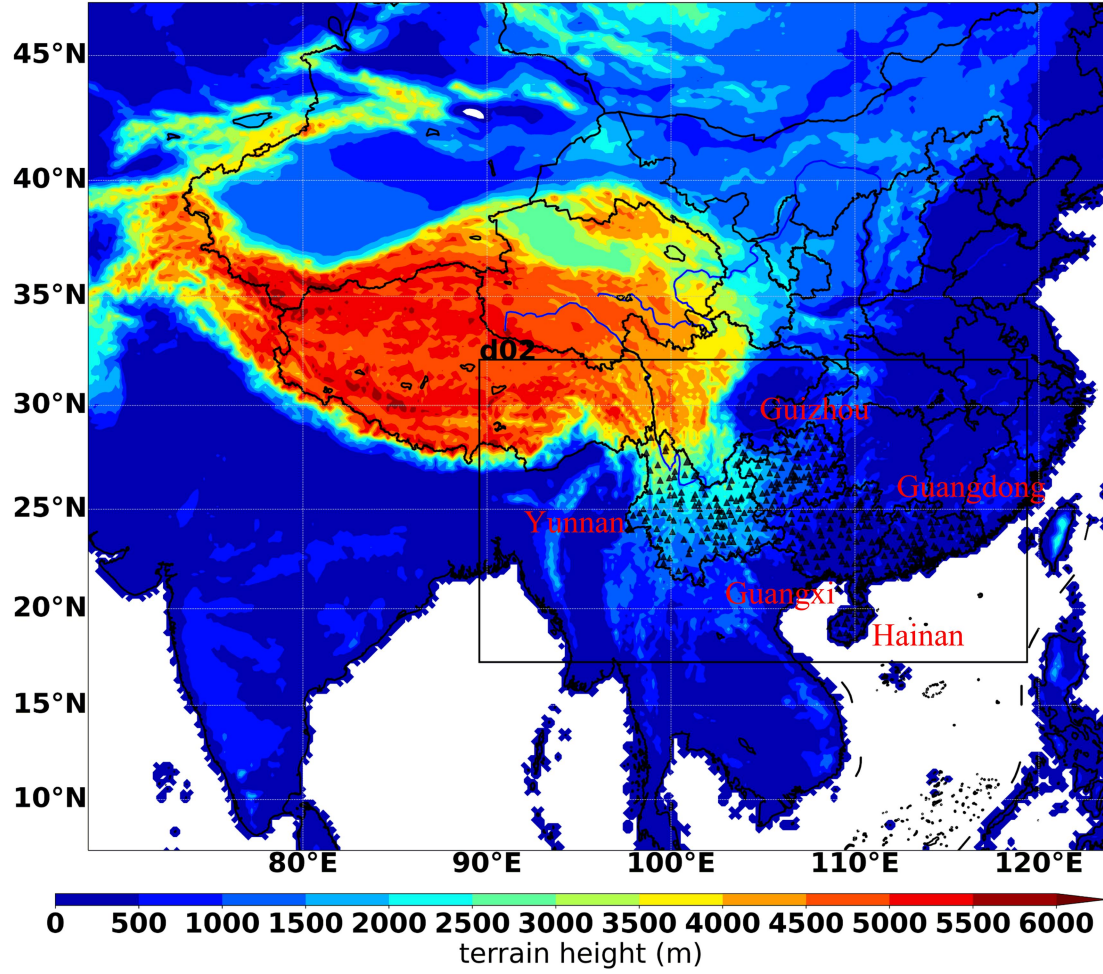
Figure 1. WRF model simulation area elevation diagram. (d02 represents the nested area of the second layer of the WRF model, and the black triangles represent the meteorological sites).

2.2 Methods

2.2.1 WRF simulation

The WRF 4.2 model (Skamarock et al., 2021), developed by the National Center for Atmospheric Research (NCAR), represents a new generation of mesoscale numerical models with numerous applications in research forecasting. When forecasting meteorological elements, the WRF model normally uses the GFS data developed by the National Centers for Environmental Prediction (NCEP). We use the WRF model in combination with daily GFS data resolution of 0.25° × 0.25°. The GFS data used by us is released at 06:00 UTC with forecasting every 3 hours for a total duration of 90 hours. We selected the 24-h forecasting data from the WRF-resulted file after a spin-up time of 18 hours. The GFS data as the initial field and lateral boundary conditions for the WRF model. Surface

159   static data, such as terrain, soil data, and vegetation coverage, are derived from the Moderate

160   Resolution Imaging Spectroradiometer (MODIS) satellite with a resolution of 15 seconds

161   (approximately 500 meters). Incorporating a two-layer grid nesting configuration, the forecast area is

162   illustrated in Fig. 1. The WRF configuration process is detailed in Table 1. Given that the time scale of the

163   the meteorological station data in the study area is 1 hour, the forecast data time interval of the WRF

164   model is also set to 1 hour. As a widely used numerical weather forecast model, the WRF model is

165   suitable for weather studies from a few meters to several thousand kilometers. Therefore, this paper

166   uses the WRF model to predict 10-meter wind speed as the input factor for the error correction model.

167

168   **Table 1. WRF configuration scheme**

Model (Version)	WRF (V4.2)	
Domains	D1	D2
Horizontal grid points	600*500	967*535
Δx (km)	9	3
Vertical layers	58	
Longwave radiation	RRTMG (Iacono et al., 2008)	
Shortwave radiation	RRTMG (Iacono et al., 2008)	
Land surface	Noah LSM (Chen et al., 1997)	
Surface layer	MYJ (Janjić, 1994)	
Microphysics	Thompson (Thompson et al., 2008)	
Boundary layer	MYJ (Janjić, 1994)	
Cumulus	Tiedtke (Tiedtke, 1989; Zhang et al., 2011)	

169

170   **2.2.2 Variational mode decomposition**

171   As a new filtering method, VMD is robust in feature selection. The VMD algorithm decomposes a

172   time series signal into several intrinsic mode functions (Isham et al., 2018). The sum of the modes

173   equals the original signal, and the sum of the bandwidths is the smallest. The analysis signal is

174   calculated using the Hilbert transform to estimate the modal bandwidth. The optimization model is

175   described as

176
$$\left\{ \min_{\{u_k\},\{\omega_k\}} \left\{ \sum_{k=1}^{K} \| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) u_k(t) \right] e^{-j\omega_k t} \right|_2^2 \right\} s.t. \quad \sum_{k=1}^{K} u_k = v \right. \quad (1.1)$$

177   where K is the total number of modes, u_k is the decomposed K-th mode, w_k is the corresponding

178   center frequency, and v is the time-series signal, representing the wind speed sequence predicted by the

179   WRF model in this study.

180   The above-constrained problem can be transformed into an unconstrained problem using the

181 Lagrangian function:

$$L\left(\{u_k\},\{\omega_k\},\lambda\right)=\omega_k^{n+1}=\frac{\int_0^\infty \omega\left|\hat{u}_k(\omega)\right|^2 d\omega}{\int_0^\infty \left|\hat{u}_k(\omega)\right|^2 d\omega}\sum_{k=1}^K \|\partial_t\left[\left(\delta(t)+\frac{j}{\pi t}\right)u_k(t)\right.$$

182

183

184 $$\left.\times\right]e^{-j\omega_k t}\|_2^2 + \| v(t)-\sum_{k=1}^K u_k(t)\|_2^2 + \left\langle \lambda(t), v(t)-\sum_{k=1}^K u_k(t)\right\rangle \tag{1.2}$$

185   where α is the penalty parameter and $\lambda(t)$ is the Lagrange multiplier.

186   Then we update u_k, w_k, and λ using the alternating direction method of the multiplier:

187 $$\hat{u}_k^{n+1}(\omega)=\frac{\hat{v}(\omega)-\sum_{i\neq k}\hat{u}_i(\omega)+\dfrac{\hat{\lambda}(\omega)}{2}}{1+2\alpha\left(\omega-\omega_k\right)^2} \tag{1.3}$$

188 $$\omega_k^{n+1}=\frac{\int_0^\infty \omega\left|\hat{u}_k(\omega)\right|^2 d\omega}{\int_0^\infty \left|\hat{u}_k(\omega)\right|^2 d\omega} \tag{1.4}$$

189 $$\hat{\lambda}^{n+1}(\omega)=\hat{\lambda}^n(\omega)+\tau\left[\hat{v}(\omega)-\sum_{k=1}^K \hat{u}_k^{n+1}(\omega)\right] \tag{1.5}$$

190   where τ is the update parameter.

191   When the accuracy (left side of the following expression) meets the following condition, u_k, w_k

192 and λ would stop updating:

193 $$\sum_{k=1}^K \frac{\|\hat{u}_k^{n+1}-\hat{u}_k^n\|_2^2}{\|\hat{u}_k^n\|_2^2}<\varepsilon \tag{1.6}$$

194 where ε is the tolerance of the convergence criterion.

195   The VMD algorithm is implemented to decompose the wind speed signal predicted by the WRF

196 model. When using multiple sub-signals instead of the original signal, more features of the wind speed

197 can be obtained. Therefore, it is beneficial to improve the prediction accuracy when using the

198 sub-signal as input to the error correction model (Xu et al., 2021; Li et al., 2022).

199 **2.2.3 Principal Component Analysis**

200   Subsequences obtained by VMD usually have several illusory components. Using PCA to extract

201 the principal components of subsequences increases the number of features input to the model and

202 reduces the dimension of the data decomposed by VMD. When principal components (PCs) are used as

203   the input of the error prediction algorithm, the PCs fully reflect the characteristics of the subsequence

204   and reduce the model complexity. The PCs y_k, $k=1, 2, …, K$ of the subsequence matrix U and the

205   cumulative contribution rate η_n of the first n principal components are expressed as:

206 $$y_k = c_k' U \tag{1.7}$$

207 $$\eta_n = \frac{\sum_{k=1}^{n} \lambda_k}{\sum_{k=1}^{K} \lambda_k} \tag{1.8}$$

208   where c_k is the corresponding characteristic unit vector, with $k=1, 2, …, K$; λ_k is the characteristic

209   root, with $\lambda_1 \geq \lambda_2 \geq … \geq \lambda_K$.

210   **2.2.4 Evaluation indicators**

211   There are many commonly used predictive effect evaluation indicators. This article uses the

212   following evaluation indicators: correlation coefficient (R), root mean square error (RMSE), mean

213   absolute error (MAE), relative root mean square error (rRMSE), relative mean absolute error (rMAE),

214   Forecasting Accuracy (FA). Six error indicators are used to evaluate the correction results of short-term

215   wind speed forecasts of wind farms. The formula for calculating the error index is as follows:

216 $$R = \frac{\sum_{i}^{n}(y_i - \bar{y})(\hat{y}_i - \bar{\hat{y}})}{\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}\sqrt{\sum_{i=1}^{n}(\hat{y}_i - \bar{\hat{y}})^2}} \tag{1.9}$$

217 $$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2} \tag{1.10}$$

218 $$MAE = \frac{1}{n}\sum_{i=1}^{n}|\hat{y}_i - y_i| \tag{1.11}$$

219 $$rRMSE = \left[\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2} \bigg/ \left(\frac{1}{n}\sum_{i=1}^{n}y_i\right)\right] \times 100\% \tag{1.12}$$

220 $$rMAE = \left(\frac{1}{n}\sum_{i=1}^{n}|\hat{y}_i - y_i| \bigg/ \left(\frac{1}{n}\sum_{i=1}^{n}y_i\right)\right) \times 100\% \tag{1.13}$$

221
$$FA = N_r / N_f \qquad\qquad (1.14)$$

222 Among them, n represents the number of samples, $\hat{y}_i$ represents the i-th predicted value, y_i

223 represents the i-th actual value; N_r represents the number of wind speed absolute errors not greater than

224 1 m s^{-1}, and N_f represents the number of research samples.

225

226 **2.2.5 Proposed hybrid forecasting algorithms**

227   This study used five machine learning algorithms to conduct ten experiments following two main

228 paths. The first path involves increasing the meteorological variables possibly related to wind speed in

229 the forecast field. The correlation between the WRF-predicted 10-m wind speed and the observed wind

230 speed is the highest. The purpose of the second experimental path is using the VMD-PCA algorithm to

231 dig out the hidden wind speed characteristics of the 10-meter forecast wind speed, reduce the input of

232 other meteorological factors such as WD_{10} and D_2, and further prove that the VMD-PCA algorithm is

233 effective before correcting the WRF-predicted wind speed. The overarching goal is to achieve accurate

234 correction of the forecast field wind speed. The flowchart of the artificial intelligence models used to

235 correct the WRF predicted wind speed for the two main experimental paths is illustrated in Fig. 2 and

236 comprises the following three steps:

237   Step 1. Data fusion, cleaning, and standardization: As depicted in Fig. 2, this paper proposes two

238 distinct experimental paths, with the primary difference being the selection of input variables. In

239 Experiment 1, as shown in Fig. 2, 12 sets of data are selected from the WRF forecast field, including

240 altitude (HGT), 10-meter wind speed (WS_{10}), latitude (LAT), longitude (LON), surface pressure (PRS),

241 relative humidity (RH), 10-meter meridional wind (V_{10}), 10-meter zonal wind (U_{10}), 2-meter

242 temperature (T_2), 2-meter dew point temperature (D_2), 10-meter wind direction (WD_{10}), and hourly

243 precipitation (PRE). Experiment 2 derives 8 sets of data by reducing the selected WRF field forecast

244 data to include only altitude, 10-meter wind speed, latitude, longitude, surface pressure, relative

245 humidity, 2-meter temperature, and hourly precipitation. The focus is on unearthing hidden

246 characteristic information of forecast wind speed. In this experiment, the wind speed is decomposed

247 into 9 Intrinsic Mode Functions (IMFk, k=0, 1, 2, …, 8) using VMD. Subsequently, a low-dimensional

248 wind speed vector is extracted from the 9 IMF components via PCA dimensionality reduction (pca0,

249 pca1, pca2), and all data are concatenated to construct the input factors for the model in Experiment 2.

250   The time points in the dataset where missing values are located are eliminated. Experiment 1

251   (Experiment 2) standardizes 12 sets of meteorological elements (8 sets of meteorological elements in

252   Fig. 3, 9 IMF components, and three PCA vectors in Fig. 4) and wind speed observation data,

253   respectively. Standardization addresses the issue of varying meteorological factor values during

254   training, which may result in different contributions. In this paper, the 24-hour forecast data correspond

255   to the observation data of the subsequent 24 hours. The dataset spans from 00:00 on December 1, 2021,

256   to 23:00 on February 28, 2022, totaling 2160 hours and encompassing 410 weather stations.

257   Consequently, the original dataset comprises 2160*410 samples, with each sample containing 12

258   meteorological features in Experiment 1 and 20 input features in Experiment 2. While similar past

259   studies for wind speed correction from NWP models usually use several years for training and at least

260   one year for testing whereas our periods are shorter, the size of our data set is sufficient. For example,

261   Sun et al. 2019 used a data set that contained 1827 days, from January 2012 to December 2016, using

262   143 grid points with a resolution of 0.5°*0.5° predicted by ECMWF, followed by 24 features for each

263   sample, with a training set size of 1827*143*24 for each prediction time. Meanwhile, the size of our

264   training set is about 2160*410*12. Therefore, even though it only took us a month to train, for this

265   project, we trained millions of data; Second, the training data we used here was obtained through daily

266   operational runs of numerical weather forecasting, so it would have taken several years to get an equal

267   amount of training data.

268   Step 2. BOA optimization of AI models and cross-validation: In this study, the dataset is

269   partitioned into training, validation, and test sets in accordance with the time series. February 2022

270   serves as the training and validation sets, while December 2021 and January 2022 constitute the test set.

271   The training and validation sets are divided based on five-fold cross-validation. Both experiments

272   employ five machine learning algorithms (DBN, MLP, RF, XGBoost, and LightGBM) to construct

273   distinct machine learning models. Concurrently, this paper utilizes the BOA algorithm to tune the

274   parameters of all models, except for DBN, resulting in the optimal hyperparameters for each model.

275   Step 3. Model evaluation and error analysis: The trained machine learning models are applied to

276   the test set to obtain the revised wind speed data, and ultimately, the accuracy of all models is assessed

277   through the wind speed evaluation index. The ultimate goal here is to identify the best wind speed

278   correction model suitable for the entire year. Accordingly, the generalization of all models is evaluated

279   across other seasonal months of the year, culminating in the selection of the best model.

281   **Figure 2. Flowchart of the AI model used to correct WRF-predicted wind speeds in the two main**

282   **experimental pathways.**

283
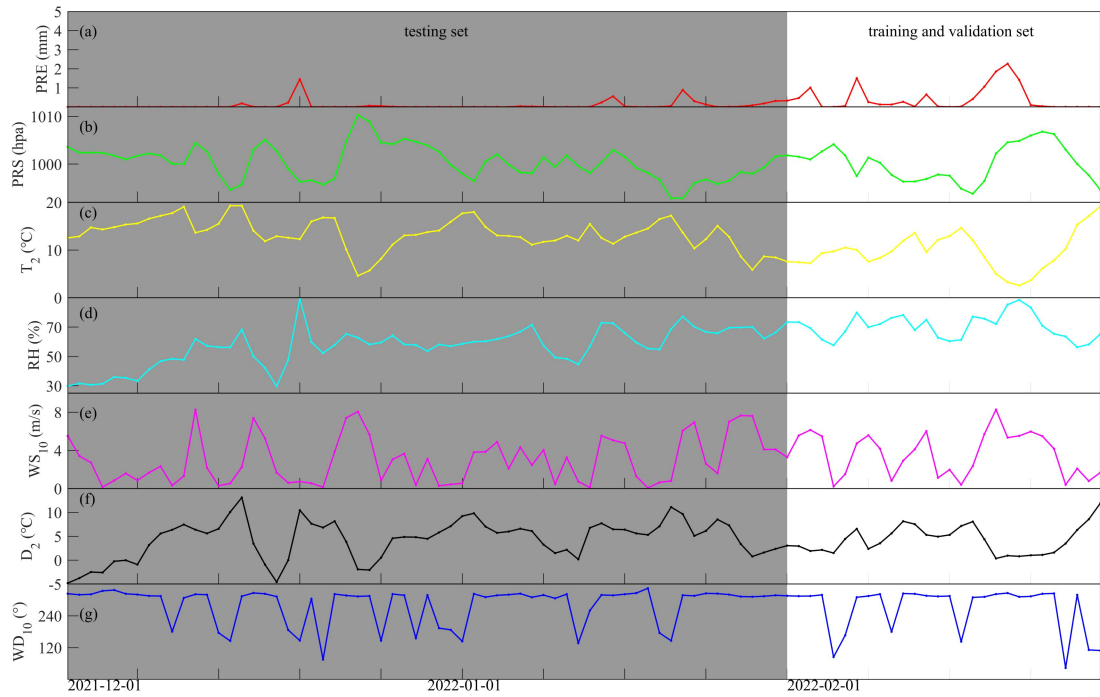
Figure 3. **Daily average hourly rainfall (a), surface pressure (b), 2-meter temperature (c), 2-meter relative humidity (d), 10-meter wind speed (e), 2-meter dew point temperature (f), and 10-meter wind direction (g) which are located at Guangdong Lechang Station from December 1, 2021, to February 28, 2022. (February 2022 represents the training and verification sets, and December 2021 to January 2022 represents the testing set).**
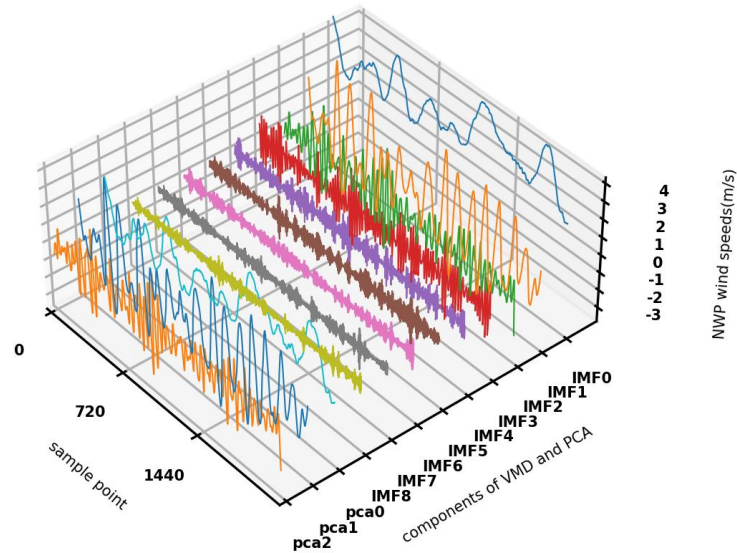
Figure 4. **Three-dimensional view of 12 wind speed components after VMD and PCA processing of the 10-meter forecast wind speed at Lechang Station in Guangdong from December 1, 2021, to February 28, 2022.**

296

3 Results

3.1 Experiment 1 evaluation

In Experiment 1, the BOA optimization algorithm was applied to five AI models to correct the 10-meter wind speed forecasted by WRF. There were 12 meteorological element features to establish five different AI models (see Table S1 for the hyper-parameters of the five AI models). The training, validation, and testing results for 10-meter wind speed are shown in Figs. S1-5 in the supplementary material. It is clear from Table 2 that all models, except the DBN model, can fit the training set data well. The DBN model exhibits the weakest performance on both the training and validation sets. Alternatively, the LightGBM and XGBoost models demonstrate superior prediction performance on the training set compared to the validation set. The scatters of the training sets of these two models accumulate on the 1:1 diagonal, indicating slight overfitting. As shown in Figs. S1-5d, f, considering different evaluation indices, the revision effects of the five models in two months demonstrate that RMSE in January 2022 is generally lower than in December 2021; FA in January 2022 is generally higher than in December 2021; R in January 2022 is generally lower than in December 2021. Overall, the prediction performance of the five models in January 2022 surpassed that in December 2021. Furthermore, the LightGBM and RF models exhibited the best performance among the five models in the two-month test sets, while the DBN model had the least effective correction effect.

As illustrated in Fig. 5a, b, WS_{10} showed the strongest positive correlation with WS_{obs}, with the highest R of 0.51, which was consistent with the highest variable importance value of 31 % (23 %) in experiment 1 (experiment 2). In addition to WS_{10}, experiment 1 (experiment 2) also had another three dominant variables namely, LAT, HGT, and LON, with importance values of 16 % (14 %), 15 % (15 %), and 15 % (13 %), respectively. Meanwhile, in experiment 2, IMF0 and pca0 generated by the VMD-PCA algorithm have a good importance value of 9 % and 4 %, and the R values of them with WS_{obs} are as high as 0.47 and 0.45.

Concerning the importance of RF characteristics (Fig. 5a, c), it is indisputable that the 10 m wind speed predicted by WRF plays a dominant role in correcting the actual wind speed. The ones following are latitude, longitude, and topographic height, which represent spatial geographic information, and the

324   actual wind speed is closely related to geographic information. Subsequently, relative humidity is of

325   lesser importance. The distribution of the humidity field typically correlates with the movement of the

326   atmosphere, which is also closely related to wind speed. Certain meteorological elements, such as

327   rainfall, 2 m dew-point temperature, and 2 m temperature, contribute less importance.

328   **Table 2. Table of evaluation indices of wind speed error trained and verified by 10 models in February 2022**

Model	training set			validation set		
	R	RMSE(m s^{-1})	FA	R	RMSE(m s^{-1})	FA
VMD-PCA-lightGBM	0.96	0.33	0.99	0.88	0.53	0.94
VMD-PCA-XGBoost	0.96	0.31	1.00	0.87	0.54	0.94
VMD-PCA-RF	0.89	0.52	0.94	0.86	0.57	0.93
VMD-PCA-DBN	0.74	0.75	0.87	0.74	0.75	0.87
VMD-PCA-MLP	0.84	0.60	0.91	0.81	0.66	0.90
lightGBM	0.93	0.41	0.98	0.88	0.54	0.94
XGBoost	0.96	0.31	0.99	0.87	0.56	0.93
RF	0.89	0.52	0.94	0.86	0.57	0.93
DBN	0.76	0.73	0.88	0.76	0.73	0.88
MLP	0.85	0.59	0.92	0.83	0.62	0.91

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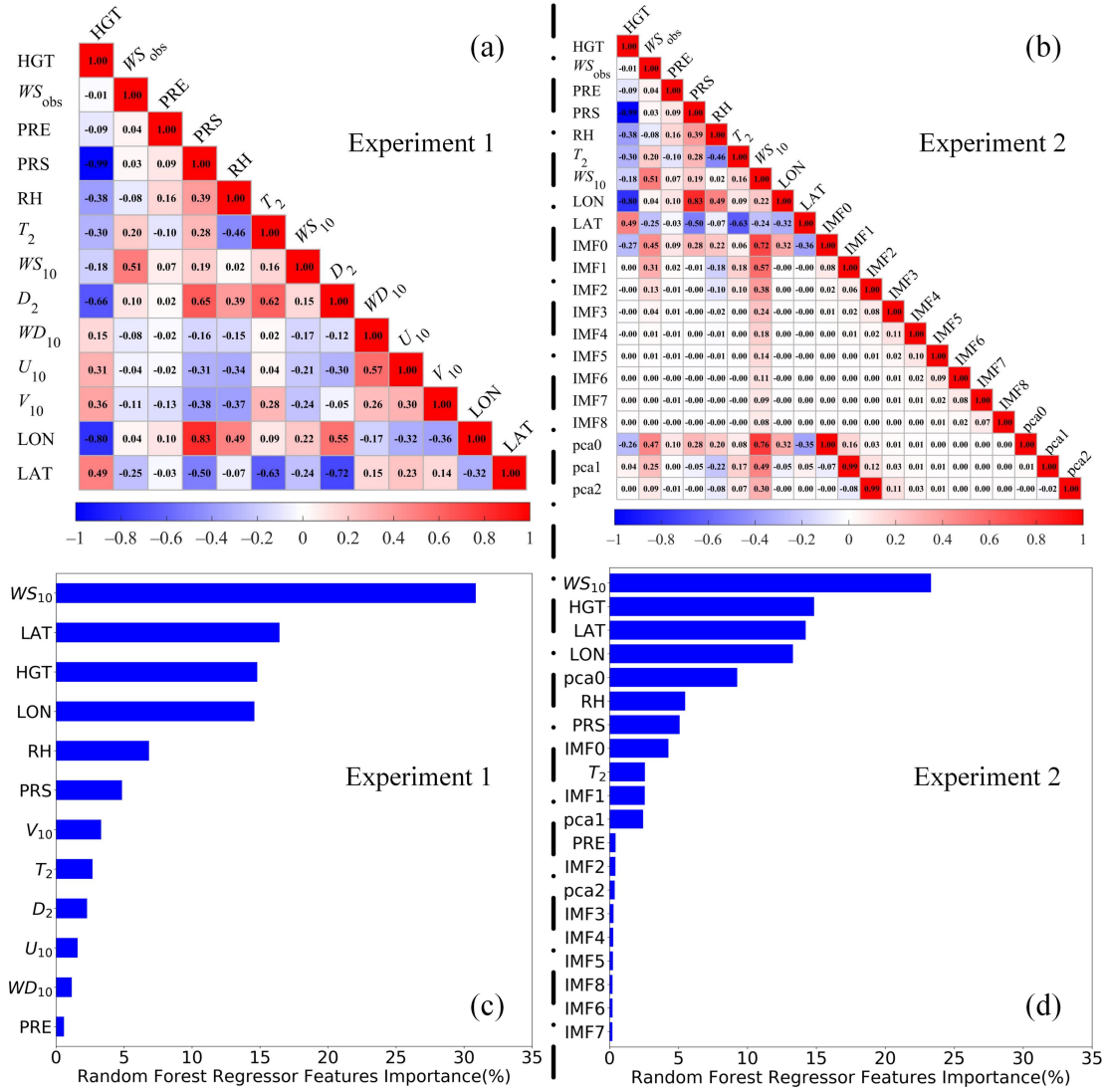
Figure 5. Schematic diagram of correlation coefficients (represented the WS$_{10}$ and input variables) and feature importance (calculated by the scikit-learn python package) for two sets of experiments. (a) and (c) represent experiment 1, and (b) and (d) represent experiment 2.

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3.2 Experiment 2 evaluation

Experiment 2 builds upon Experiment 1, concentrating on the predicted 10-meter wind speed by the WRF model. We use the VMD algorithm to decompose the predicted wind speed into 9 components and use the PCA algorithm to extract the main 3 principal components. In the RF feature importance analysis (Fig. 5b, d), it is evident that the VMD algorithm can decompose IMF0 and IMF1, with contributions surpassing those of 2-meter temperature and precipitation, respectively. The importance of the pca0 component, after PCA principal component extraction, reaches up to 8%. What

342   is particularly interesting is that in the correlation analysis, the correlation values between the IMF0

343   and pca0 components and the actual wind speed are 0.50 and 0.51, which are second only to the

344   forecasted wind speed.

345   From the indices (RMSE, FA, R) of the training set and validation set shown in Table 2, in

346   comparison to the above five artificial intelligence methods, the training results of VMD-PCA-DBN

347   are relatively inferior. VMD-PCA-lightGBM and VMD-PCA-XGBoost models still train the processed

348   data effectively. According to the scatter density figure (Fig. 6a, Fig. 7a), the scatters are relatively

349   concentrated on the 1:1 line. From the indicators (RMSE, FA, R) of the testing set shown in Figs.

350   S6-8d, f and Figs. 6-7d, f, the test results of the five models in Experiment 2 in December 2021 and

351   January 2022 show that the error indices of RMSE and FA of each model exhibit a minimal difference

352   in two months. Nonetheless, disregarding the R results, the performance of the five models in

353   December 2021 is inferior to that in January 2022. The diurnal variation scatter plot of two months is

354   tested. As is shown in Figs. S6-8d, f and Figs. 6-7d, f, the red scatters represent the nighttime wind

355   speed, which is more concentrated on the 1:1 line. In contrast, the blue scatters represent the afternoon

356   wind speed, which is slightly away from the 1:1 line. This suggests that the correction effect of the five

357   models (VMD-PCA-lightGBM, VMD-PCA-XGBoost, VMD-PCA-RF, VMD-PCA-DBN, and

358   VMD-PCA-MLP) exhibits a noticeable diurnal variation.

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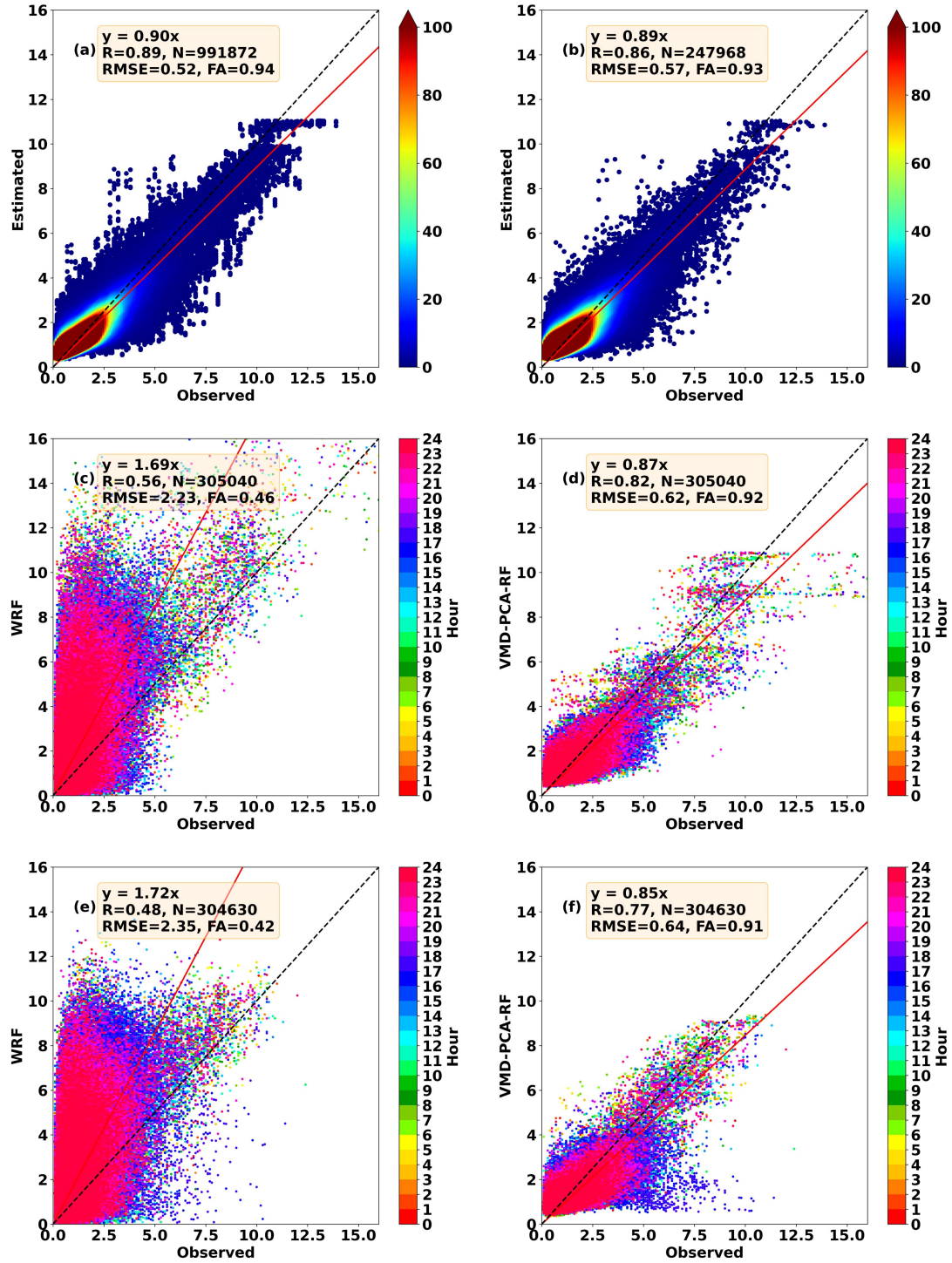
Figure 6. The scatter density map compared with the actual 10-meter wind speed: (a) 10-fold cross-validation training set of VMD-PCA-RF model in February 2022, (b) 10-fold cross-validation validation set of VMD-PCA-RF model in February 2022. The 24-hour scatter map compared with the actual 10-meter wind speed: (c) WRF forecasts in December 2021, (d) VMD-PCA-RF model forecasts in December 2021, (e) WRF forecasts in January 2022, and (f) VMD-PCA-RF model forecasts in January 2022. (The time is UTC + 08:00.)

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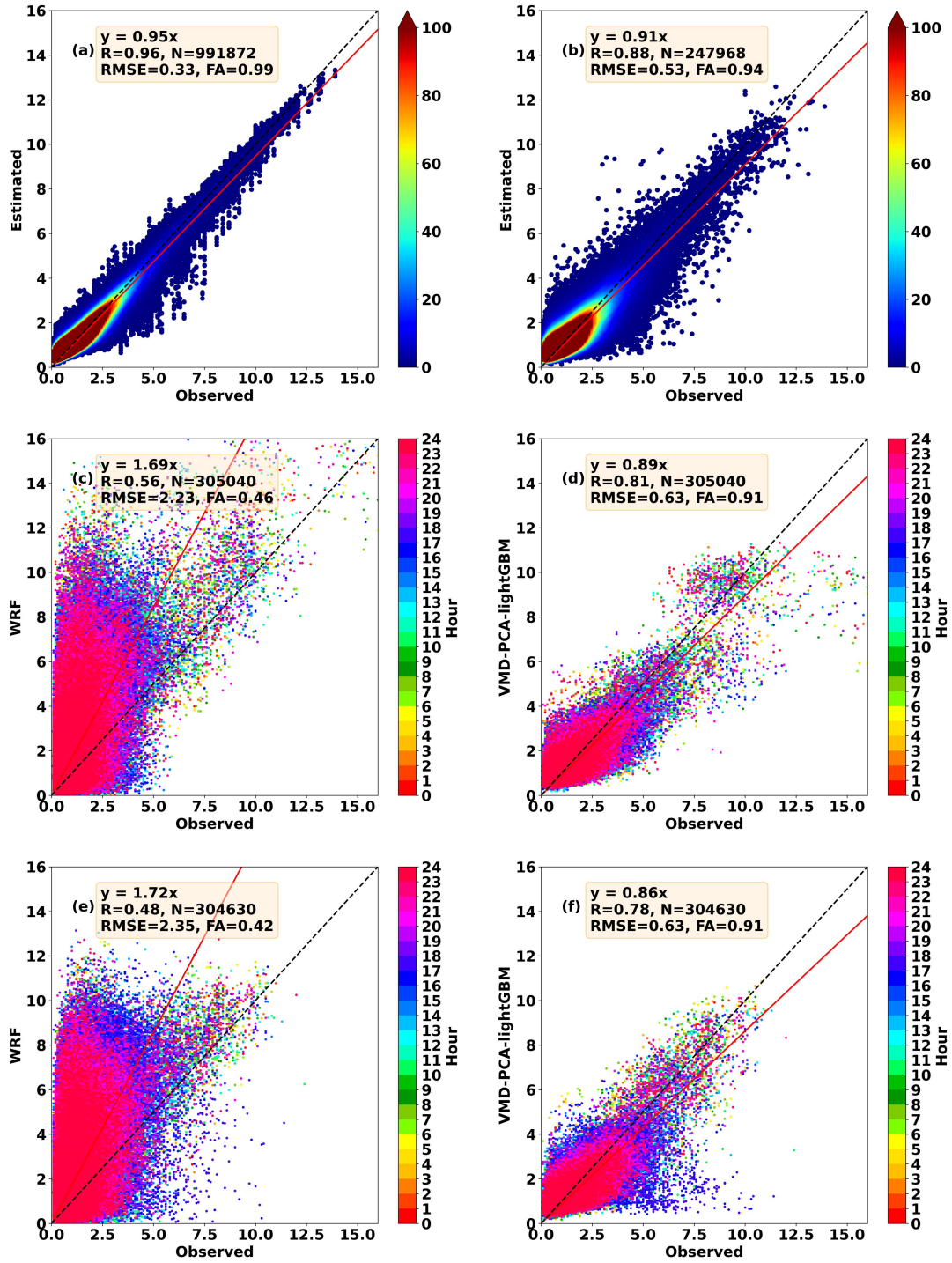
Figure 7. The scatter density map compared with the actual 10-meter wind speed: (a) 10-fold cross-validation training set of VMD-PCA-lightGBM model in February 2022, (b) 10-fold cross-validation validation set of VMD-PCA-lightGBM model in February 2022. The 24-hour scatter map compared with the actual 10-meter wind speed: (c) WRF forecasts in December 2021, (d) VMD-PCA-lightGBM model forecasts in December 2021, (e) WRF forecasts in January 2022, and (f) VMD-PCA-lightGBM model forecasts in January 2022. (The time is UTC + 08:00.)

3.3 Comparison of the two experiments

Firstly, all 10 models effectively corrected the 10-meter wind speed forecasted by WRF. Table S2 and Table S3 represent the evaluation indices of wind speed errors predicted by 10 models in December 2021 and January 2022. From the two tables, it is evident that the VMD-PCA-RF and VMD-PCA-lightGBM models have the best performance in December 2021 and January 2022, respectively, with the most comprehensive performance of the forecast indicators. The MAE, RMSE, rMAE, rMAE, and FA for the two models VMD-PCA-RF (VMD-PCA-lightGBM) were 0.46 m s^{-1} (0.45 m s^{-1}), 0.62 m s^{-1} (0.63 m s^{-1}), 37.36 % (34.75 %), 50.39 % (48.65 %), and 91.79 % (91.49 %) in December 2021 (January 2022). Additionally, based on the analysis of the Taylor chart (Fig. 8e, f) of 10 models in Fig. 8, it can also be seen that the scatter distance of VMD-PCA-RF and VMD-PCA-lightGBM models is closest to the observed black dotted line and the black triangle position. The two models show that the standard deviation is close to the observed wind speed, with the lowest RMSE and the highest R. Secondly, in the comparison of cumulative probability distributions, all models passed Kolmogorov's 5 % confidence interval test when the interval of wind speed is 0.5 m s^{-1} (Fig. 8a, d). However, when the interval of wind speed is 0.2 m s^{-1} (Fig. 8b, e), the VMD-PCA-lightGBM model deviated from Kolmogorov's 5 % confidence interval detection in December 2021. This indicates that the VMD-PCA-RF model has a better predictive effect than the VMD-PCA-lightGBM model in December 2021 when the actual wind speed is within the range of 0.4 m s^{-1}-0.8 m s^{-1}.
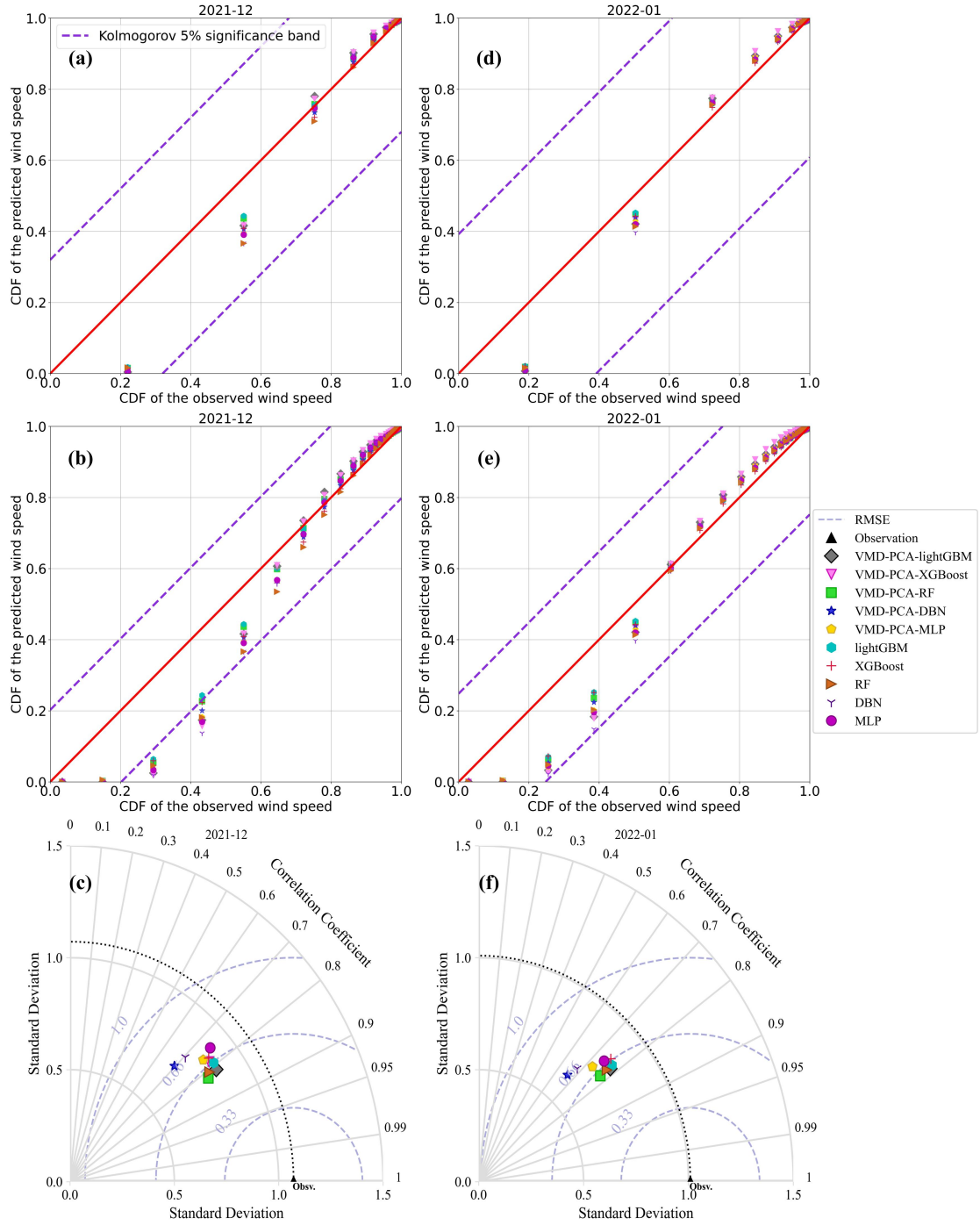
Figure 8. The cumulative distribution probability scatter plots of the actual wind speed and the predicted wind speed of 10 models in wind speed intervals of 0.5 m s⁻¹ ((a) represents December 2021, (d) represents January 2022) and 0.2 m s⁻¹ ((b) represents December 2021, (e) represents January 2022) respectively; Taylor distribution map ((c) represents December 2021, (f) represents January 2022).

3.4 Spatial-temporal variations in the best models

Based on our comparative analysis results, we conclude that the best performing combination models in December 2021 and January 2022 are VMD-PCA-RF and VMD-PCA-lightGBM respectively. Fig. 9 and Fig. S9 shows the diurnal variation corrections of the two best models for a given month, as well as the diurnal variation of wind speed in the original WRF forecast. The wind speed of the original WRF numerical weather forecast shows a noticeable overestimation, which is confirmed in Fig. 7c and 7e. The scatters of WRF forecast predominantly deviate towards the upper left corner, with relatively low correlation coefficients, 0.56 and 0.23, respectively. Furthermore, the wind speed forecast by WRF displays obvious diurnal variation traits, characterized by large errors between afternoon and evening, specifically between 11:00 and 20:00 (Fig. 9a, Fig. S9a). Moreover, the actual average wind speed in January 2022 deviates from the range of one standard deviation of the WRF forecast wind speed at 17:00 and 18:00 (Fig. S9a). This demonstrates that the wind speed forecast by WRF is inaccurate and exhibits substantial diurnal variation errors.

After the best model was corrected, the error of diurnal variation was significantly reduced (Fig. 9b, Fig. S9b). First, the average wind speed corrected by the best model is essentially consistent with the actual average wind speed curve, with minimal error and no diurnal variation. Second, the one standard deviation range of the corrected and actual wind speeds is also well-matched, indicating that the corrected and actual wind speed distributions are consistent. The correction effect at 16:00 and 17:00 on January 2022 is suboptimal, which may be due to the insufficient generalization of the training model and the excessive fluctuation of the actual wind speed at these two-time points.

The FA (Fig. 10a, Fig. S10a) and RMSE (Fig. 10b, Fig. S10b) distribution of WRF forecast 10-meter wind speed at 410 stations in the five southern provinces shows that the 10-meter wind speed prediction effect of the WRF model in Yunnan is superior to that in the other four provinces. In the regions of Hainan, Guangxi, and Guangdong, the number of sites with a RMSE for 10-meter wind speed forecast in December 2021 ranging from 5.6 to 6.0 m s^{-1} was significantly higher than in January 2022, especially in coastal areas (Fig. 10b, Fig. S10b). In the Yunnan area, the FA of most WRF forecast station 10-meter wind speeds exceeds 40 %, and the RMSE value is mostly below 2.4 m s^{-1}. Conversely, in other regions, such as Guangxi, Guangdong, and Hainan, the terrain is relatively flat. The FA of the 10-meter wind speed forecast by WRF is as low as 30 % at some stations, and the

431   RMSE reaches up to 5.4 m s^{-1}. However, after the VMD-PCA-RF and VMD-PCA-lightGBM models

432   are corrected, the FA of most stations in the five southern provinces is as high as 90 %, and the RMSE

433   is as low as 0.6 m s^{-1}. Moreover, in Guangxi, Guangdong, and Hainan, where the WRF forecast effect

434   is subpar, the accuracy of the corrected 10-meter wind speed by VMD-PCA-RF

435   (VMD-PCA-lightGBM) is significantly improved.

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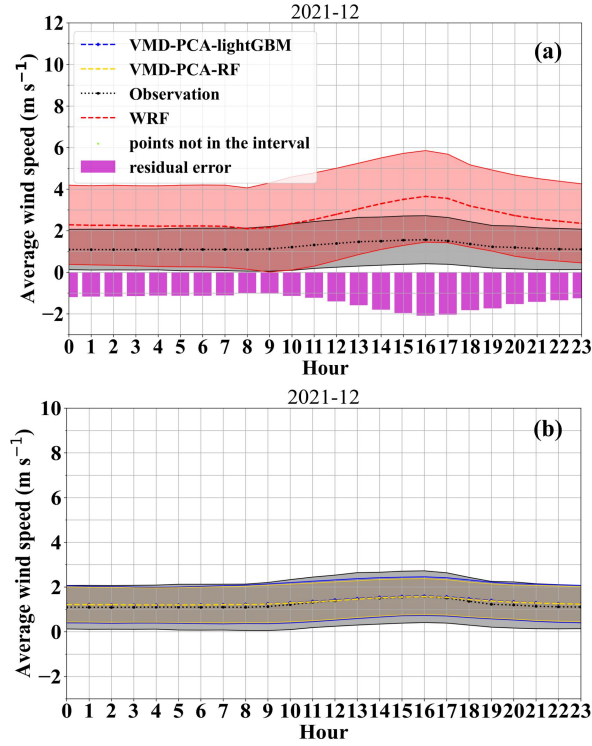
437   **Figure 9. VMD-PCA-lightGBM, VMD-PCA-RF, and WRF daily variation of predicted and actual wind**

438   **speeds in December 2021. (The shading areas represent an interval of 1 standard deviation, which is a 68%**

439   **confidence interval. The time is UTC + 08:00.)**

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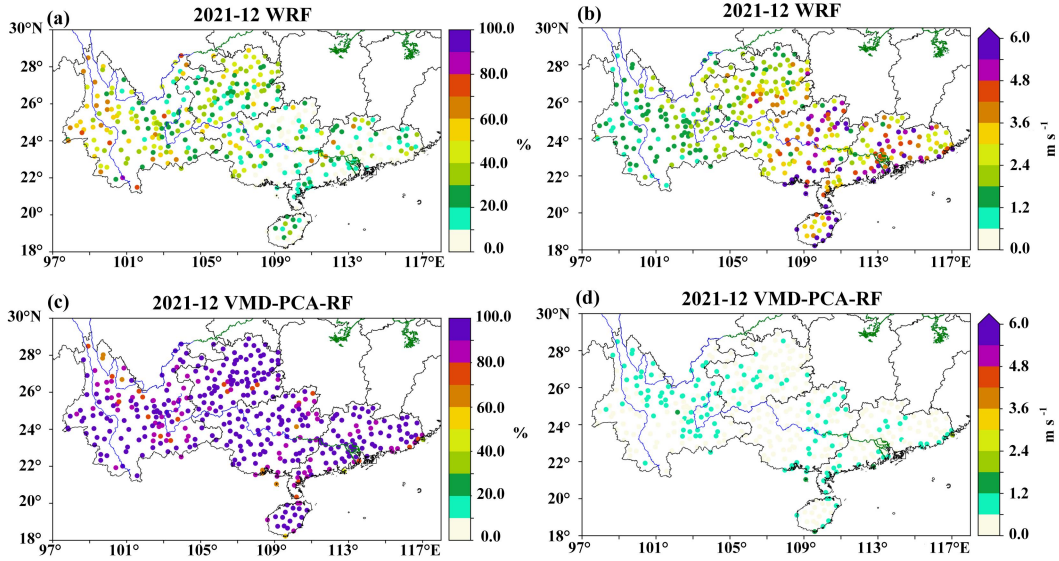
Figure 10. FA ((a), (c)) and RMSE ((b), (d)) distribution maps of VMD-PCA-RF and WRF models on 410 sites in five southern provinces in December 2021.

4. Discussion

4.1 The effects of BOA-VMD-PCA

It is shown in Table S1 that the hyper-parameters of the 10 models in the two experiments are different. Since the DBN model is not added to the scikit-learn Python learning package, it is challenging to call the BOA algorithm for tuning parameters. Apart from the DBN model, all the other models are optimized using the BOA algorithm. From the various evaluation indicators in Table S2 and Table S3, the DBN model, which does not use the BOA algorithm to adjust the model parameters to obtain an optimal parameter configuration, yields the worst prediction results in December 2021 and January 2022. Moreover, studies (Xiong et al., 2022) also have shown that BOA can further improve the model's prediction accuracy by configuring optimal hyper-parameters. The hyper-parameters such as the number of neurons and learning rate in the hidden layer, significantly impact the model's performance. When the same model is applied to different data sets of two experiments, the BOA adaptively obtains the optimal combination of hyper-parameters, overcoming the limitations of manual parameter adjustment (Guo et al., 2021). This suggests that the selection of model hyper-parameters introduces considerable uncertainty in our prediction results. Therefore, the choice of optimization model parameters represents one source of uncertainty in the correction results, which entails the

460 complexity of parameter selection. However, a more advanced parameter tuning method, such as the

461 BOA tuning algorithm, is essential.

462 The VMD is used to obtain unknown but meaningful features hidden in the 10-meter wind speed

463 sequences predicted using WRF models (Li et al., 2022). In addition, the PCA can extract important

464 components of anemometer subsequences. When the stationary subsequence serves as an input to the

465 error correction model, it contains more valuable information than the previous non-stationary wind

466 speed sequences (Xu et al., 2021).

467 The complexity of the input factors in this study is one of the sources of uncertainty in the process

468 of correcting WRF prediction results. The input factors of the two experiments are not identical. In the

469 second set of experiments, the input of meteorological factors is reduced based on the first set of

470 experiments, while component information of the 10-meter wind speed predicted by WRF is increased.

471 Multiple wind speed components processed by VMD-PCA and noise reduction are introduced. Among

472 them, the importance of pca0 and IMF0 introduced is approximately 5 %. In the 13-month test sets, the

473 correction accuracy of experiment 2 is no less than the results of experiment 1 (Figs. S11, 12),

474 indicating that the 10-meter wind speed components introduced by the VMD-PCA contribute

475 positively to the correction results.

476

477 **4.2 RF feature importance**

478 To further understand the feature importance ranking of the RF models, we divided the model

479 prediction results and actual wind speeds of the 410 stations into 20 equal parts according to terrain

480 height above sea level (Fig. 11). First of all, the actual wind speed in December 2021 and January 2022

481 varies with the height of the station, showing that the lower the height of the station, the more

482 significant the change of wind speed. This relationship is associated with the wind speed profile of the

483 atmosphere, where wind speed increases as height decreases. Secondly, the wind speed during the day

484 is generally greater than the wind speed at night, which is related to the turbulent motion of the

485 atmosphere during the day. Solar radiation causes the atmosphere to mix, resulting in convective

486 movement. The 10-meter wind speed at night is affected by the cooling radiation of the surface, and the

487 atmosphere is relatively stable.

488   The 10-meter wind speed predicted by WRF has the highest feature importance in the correction

489   process of the RF models. Input factors with distinct geographic information, such as latitude,

490   longitude, and height, rank highly in feature importance. Similarly, when Sun et al. 2019 used machine

491   learning to correct the 10-meter wind speed predicted by the numerical weather prediction model

492   ECMWF, the characteristic weight of the 10-meter wind speed predicted by the model was the highest,

493   followed by the sea-land factor. Also, as the 10-meter wind speed forecast by WRF increases, the

494   instability of the 10-meter wind speed corrected by the 10 machine learning models gradually increased,

495   and the correction accuracy gradually decreased (Fig. 12). This partly explains the higher importance

496   of the 10-meter wind speed forecast by WRF.

497   With 1 km as the center, the measured 10-meter wind speed is more variable in areas where the

498   station terrain height increases or decreases. However, the pink box of the 10-meter wind speed

499   predicted by WRF becomes wider as the station terrain height decreases (Fig. 11). The distance

500   between the gray box and the pink box is greater as the station terrain height decreases. It shows that

501   the 10-meter wind speed predicted by WRF has less accuracy with the station terrain height decreases.

502   The VMD-PCA-RF and VMD-PCA-lightGBM models significantly reduce the variability of the

503   10-meter wind speed predicted by WRF. When the height of the station increases or decreases at 1 km,

504   the correction intensity tends to increase gradually. This further explains the higher importance of the

505   height factor in the RF model training.

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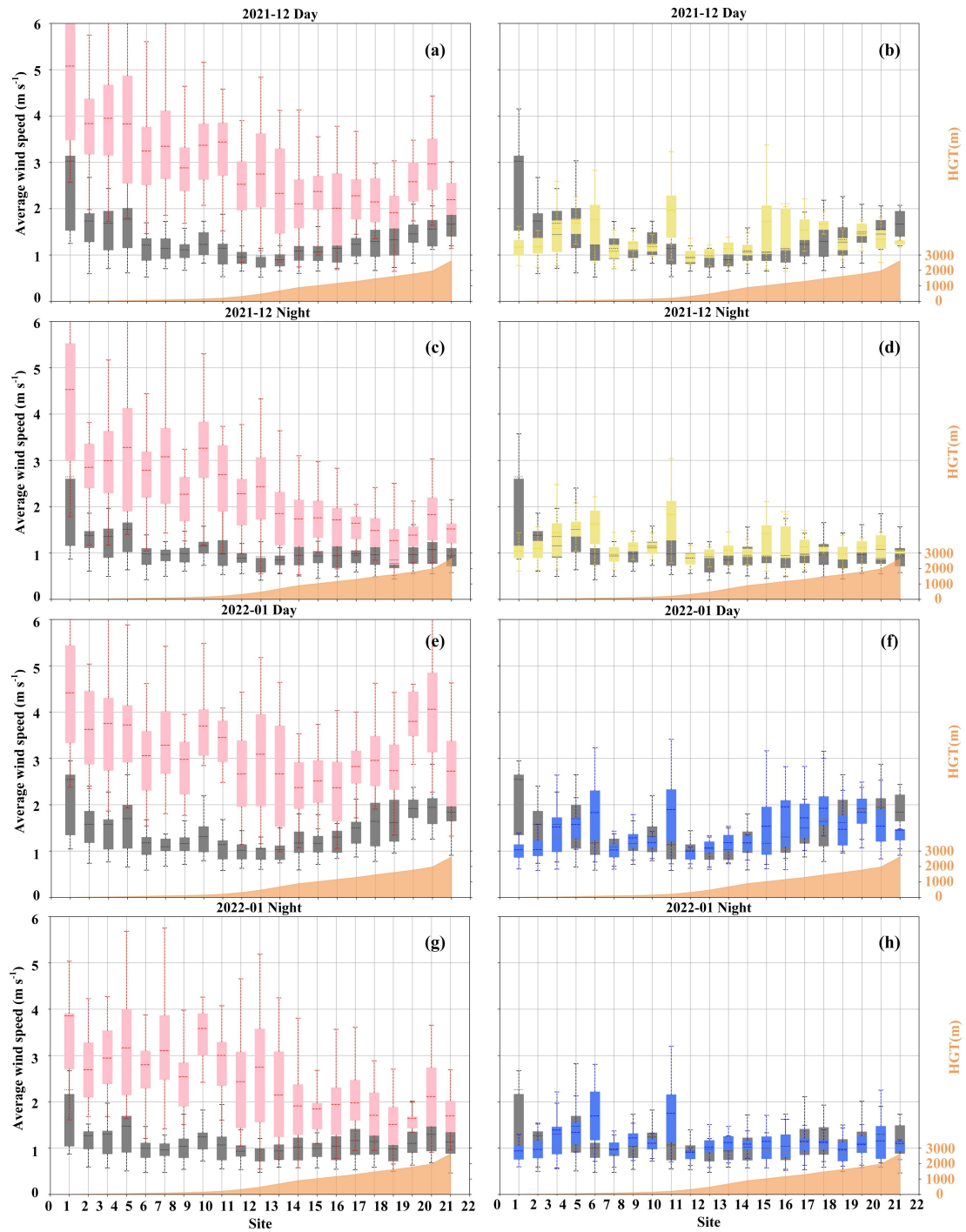
507 **Figure 11. The boxplots of the predicted wind speeds of the VMD-PCA-RF (yellow), VMD-PCA-lightGBM**

508 **(blue), and WRF (pink) models at 20 stations at different height intervals, and the boxplots of the actual**

509 **wind speeds (gray).**

510

(a)

(b)
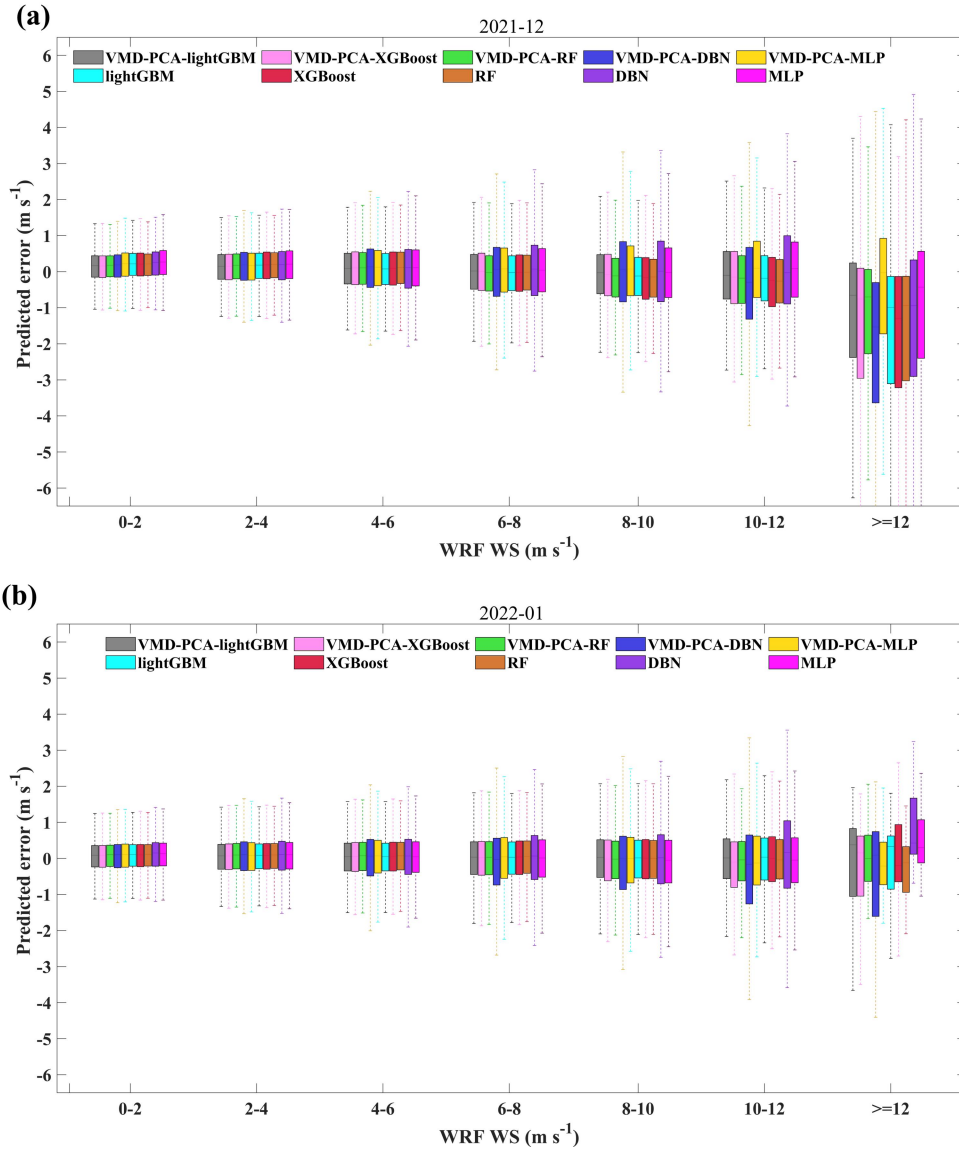
Figure 12. The prediction error boxplots of 10 models in different WRF prediction intervals.

4.3 Stability analysis of the proposed models

In order to identify the best model of the five southern provinces and assess the model's stability, we evaluated all 10 models over 13 different months. Fig. 13 shows the evaluation histogram of the 10-meter wind speed predicted by the 10 models in Experiment 1 and Experiment 2, as well as the actual wind speed in various months. Meanwhile, Fig. S11 and Fig. S12 can more effectively illustrate the daily changes of the revised results of 10 models in 13 different months. As shown in Fig. 13, the evaluation indices of the model trained in Experiment 2, after VMD-PCA processing, outperform those of the model trained in Experiment 1. The RF model demonstrates exceptional robustness, while the

522 MLP model exhibits the poorest performance. VMD-PCA-RF evaluation indices are relatively stable

523 across the 13 months, with a correlation coefficient R above 0.6, FA above 85 %, MAE below 0.6 m s^{-1},

524 RMSE below 0.8 m s^{-1}, rMAE below 60 %, and rRMSE below 75 %. However, the robustness of the

525 VMD-PCA-lightGBM and VMD-PCA-XGBoost models is inferior to that of the VMD-PCA-RF, with

526 all six evaluation indices performing worse than the VMD-PCA-RF as the seasons and months change.

527 In general, VMD-PCA-lightGBM is the superior wind speed correction model for the winter, and

528 VMD-PCA-RF performs the best throughout the entire year in the five southern provinces. In cases

529 where ample machine CPU and other hardware resources, as well as training time, are available, we

530 recommend using VMD-PCA-lightGBM for modeling each season. However, when dealing with

531 limited resources such as a laptop and constrained training time, we recommend using VMD-PCA-RF

532 to train data for a single month, as this yields the most robust correction results.
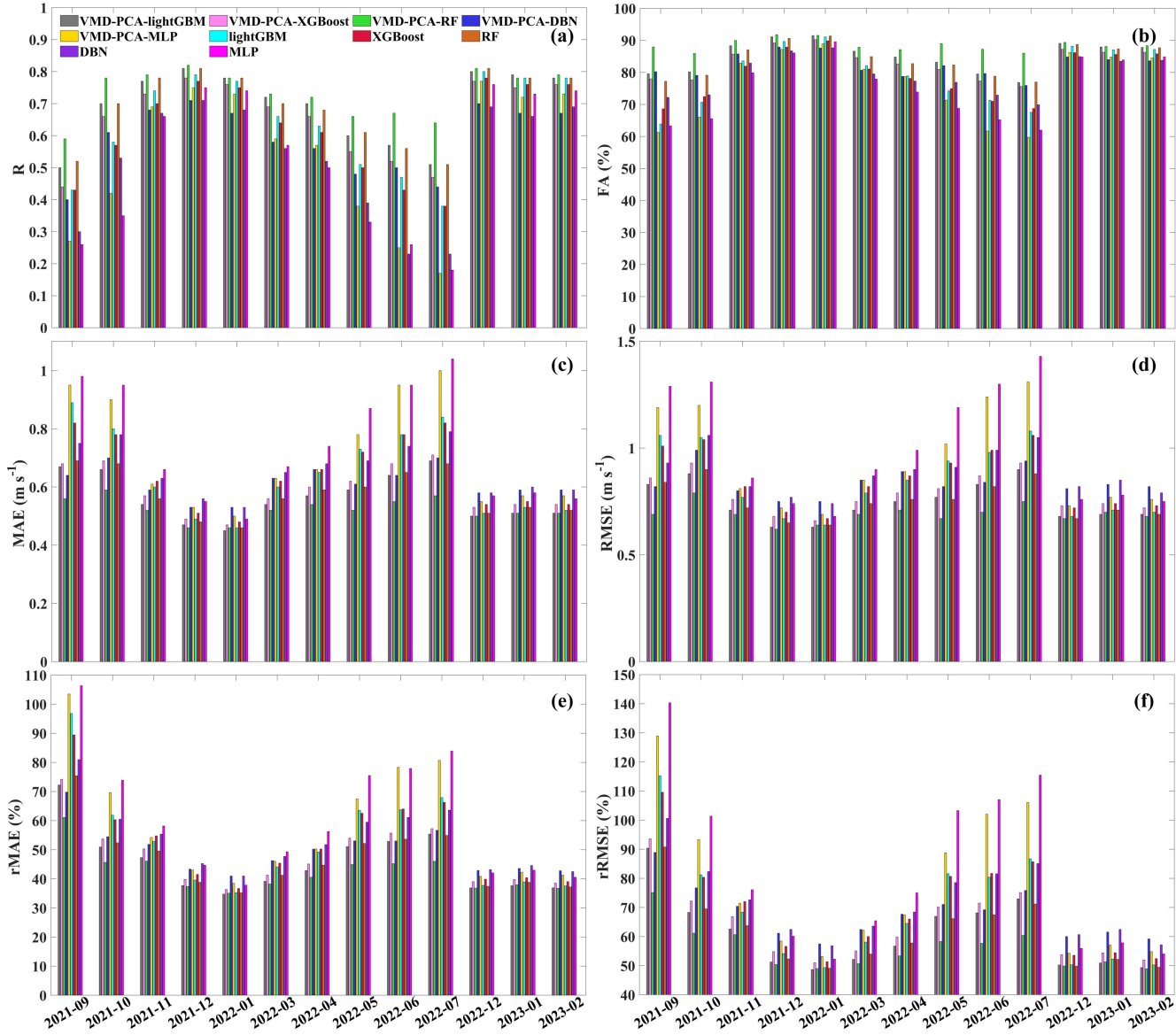
Figure 13. Evaluation histograms of 10-meter wind speed predicted by 10 models in different months in Experiment 1 and Experiment 2 ((a), (b), (c), (d), (e), and (f) represent R, FA (%), MAE (m s⁻¹), RMSE (m s⁻¹), rMAE (%), and rRMSE (%) respectively).

5. Conclusions

In an effort to enhance the wind speed prediction performance for wind farms, this study developed a WRF-based multi-step wind speed prediction model. A hybrid error correction strategy combining BOA, VMD, PCA, and RF (LightGBM) is proposed to increase the accuracy of WRF simulations. The first group of experiments used various meteorological elements as input factors in a control experiment. In the second group of experiments, the wind speed sequence predicted by the

WRF model was decomposed into multiple IMFs using the VMD algorithm for feature extraction. A principal component analysis method is used to extract meaningful principal components from these subsequence IMFs to improve computational efficiency. In the error correction model, RF (lightGBM) and other algorithms are used to train the relationship between different input factors and the actual wind speed error, respectively.

Through a case analysis of 410 stations in five southern provinces in China, the following conclusions can be drawn: (1) The machine learning models tuned by the BOA-VMD-PCA algorithm exhibit a positive impact on wind speed error correction; (2) Feature importance analysis revealed that the top eight contributing factors for correcting WRF forecasted wind speed include WRF forecast 10-meter wind speed (WS_{10}), latitude, longitude, altitude, pca0 (pca0 physically represents the lowest frequency wind speed series after PCA treatment of all IMF_k (k=0, 1, 2, …, 8) sub-series with reduced dimension), humidity, pressure, IMF0 (IMF0 physically represents the wind speed stationary series with a specific lowest center frequency after the original wind speed series has been processed by VMD); (3) VMD-PCA-RF and VMD-PCA-lightGBM are the most suitable wind speed correction algorithms for December 2021 and January 2022, respectively. The MAE, RMSE, FA, rMAE, rRMSE, and R of the corrected wind speed and the actual wind speed are 0.46 (0.45), 0.62 m s^{-1} (0.63 m s^{-1}), 37.36 % (34.75 %), 50.39 % (48.65 %), 91.79 % (91.49 %), and 0.82 (0.78); and (4) The proposed wind speed correction model (VMD-PCA-RF) demonstrates the highest prediction accuracy and stability in the five southern provinces in nearly a year and at different heights. VMD-PCA-RF evaluation indices for 13 months remain relatively stable: R is above 0.6, FA is above 85 %, MAE is below 0.6 m s^{-1}, RMSE is below 0.8 m s^{-1}, rMAE is below 60 %, and rRMSE is below 75 %. In future research, the proposed VMD-PCA-RF algorithm can be extrapolated to the 3 km grid points of the five southern provinces to generate a 3km grid-corrected wind speed product.

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Code availability

The code and model are available as a free-access repository on Zenodo at https://doi.org/10.5281/zenodo.8108889 (Zhou, 2023).

Data Availability

The data is available as a free-access repository on Zenodo at https://doi.org/10.5281/zenodo.8108889 (Zhou, 2023).

Author contributions

SZ developed the software, visualized the data, and prepared the original draft. SZ and YG developed the methodology and carried out the formal analysis. XX and SZ validated data. SZ, YG, XX, ZD, and YL reviewed and edited the text. All authors have read and agreed to the published version of the paper.

Competing interests

The authors declare that they have no conflict of interest.

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