

Comparative Analysis of LSTM and GRU Models for Air Pollution Prediction in Shanghai

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Abstract. This paper presents a comparative analysis of two recurrent neural network (RNN) models, respectively with Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU), specifically focusing on predicting PM_{2.5}/PM₁₀ concentrations in Shanghai. Running PM_{2.5}/PM₁₀ prediction accurately and efficiently is important for public health and environmental management, while few research programs have constructed efficient forecasting models when facing a large amount of daily variation in air pollution. In this study, historical air quality data, meteorological factors, and other relevant environmental variables were concentrated to train and evaluate the models. After the construction of two different models, the performance of LSTM and GRU is compared based on various metrics, including Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and R-squared. The results indicate the strengths and limitations of each model in capturing the temporal dependencies in air quality data. Moreover, the study explores the impact of different input features and network configurations on prediction accuracy based on the real situation. The findings promote developing effective air quality forecasting tools and help local governments inform policy decisions aimed at mitigating air pollution in urban environments.

Keywords: PM_{2.5} prediction, LSTM, GRU, air quality forecasting, Shanghai

1. Introduction

Air pollution, particularly PM_{2.5} (floating particles of size $\leq 2.5 \mu\text{g}/\text{m}^3$), is always considered harmful to public health and urban sustainability. In Shanghai, rapid industrialization and population growth have been associated with increased carbon emissions, leading to elevated levels of air pollutants, including PM_{2.5}, PM₁₀, and other hazardous gases. As shown in previous work, many cities in China, including Shanghai, have been suffering from one of the worst levels of air pollution in the world for the past ten years [1].

Long-term exposure to PM_{2.5} has been linked to elevated risks of respiratory and cardiovascular diseases [2].

So far, existing air pollution prediction models face two key challenges: (1) temporal complexity—PM_{2.5}/PM₁₀ levels exhibit seasonality and abrupt changes due to weather shifts; (2) data granularity—most studies rely on hourly data but ignore spatial correlations between monitoring

stations. While some studies employ hybrid models (e.g., SVM with wavelet transforms), their computational costs limit real-world deployment.

This study aims to develop a deep learning framework based on LSTM (Long Short-Term Memory) and GRU (Gated Recurrent Unit) networks to predict daily PM_{2.5}/PM₁₀ concentrations in Shanghai within 60 days. The primary objectives are to compare the performance of LSTM and GRU in handling PM_{2.5}'s and PM₁₀'s temporal dynamics and to evaluate model robustness under extreme weather conditions (e.g., missing data in rainy days).

2. Theoretical background

Research on air quality prediction has evolved significantly over the past two decades, moving from traditional statistical models to advanced deep learning approaches. Autoregressive Integrated Moving Average (ARIMA) models have been widely applied to capture temporal trends but were found to struggle with nonlinear dynamics in atmospheric data [3]. Subsequently, machine learning methods such as Support Vector Machines (SVM) and Random Forests were employed to enhance nonlinear modeling capabilities, yet limitations in capturing long-term dependencies persisted [4].

With the rise of deep learning, Recurrent Neural Networks (RNN) introduced by Bengio, became prominent for air quality forecasting. RNNs introduced the capability to capture sequential dependencies, but it's always difficult for them to handle vanishing gradients, which could result in poor predictions in long-range programs [5]. To overcome these limitations, Long Short-Term Memory (LSTM) networks were introduced by Hochreiter & Schmidhuber, together with explicit memory cells and a gating mechanism, allowing models to capture long-term dependencies effectively [6]. Similarly, Gated Recurrent Units (GRUs) were proposed as a streamlined alternative, achieving comparable accuracy with reduced parametric complexity and enabling faster training times for specific applications [7].

It is noted that recent studies have begun to apply these approaches to environmental forecasting. For instance, LSTM networks have demonstrated superior accuracy in predicting PM_{2.5} concentrations in Beijing compared to traditional machine learning models such as Random Forest [8]. Meanwhile, GRU-based models have exhibited notable efficiency in large-scale forecasting tasks, including flood and typhoon prediction, particularly under computational constraints [9].

However, most existing studies only focus on evaluating a single or a composite model rather than conducting direct comparisons under consistent conditions. More precisely, there is a lack of systematic, empirical comparisons between LSTM and GRU architectures with the same training dataset and interval of air pollution prediction, especially on accuracy, training efficiency, and generalization ability. This study aims to fill this gap by rigorously evaluating and contrasting the performance of LSTM and GRU models for predicting PM_{2.5} levels using a unified experimental framework. The findings will provide practical insights into model selection for environmental forecasting applications.

3. Methodology

This section details the methodology employed to compare the performance of LSTM and GRU models for air pollution prediction in Shanghai. The aim is to provide a clear and systematic explanation of the research process, enabling readers to understand the research logic and potentially reproduce the methods.

3.1. Problem formulation

The objective of this study is to develop and compare LSTM and GRU models for forecasting PM2.5/PM10 concentrations in Shanghai. The models were trained on historical data from January 1, 2014, to November 30, 2020, with the goal of predicting PM2.5 and PM10 concentrations from December 1, 2020, to January 30, 2021. The input data consists of historical PM2.5 concentrations, PM10 concentrations, meteorological data (temperature, humidity, wind speed, wind direction, and temporal features. The output is the predicted PM2.5 and PM10 concentrations for the subsequent time step. Key variables include, but are not limited to:

- PM2.5: PM2.5 concentration each day ($\mu\text{g}/\text{m}^3$)
- PM10: PM10 concentration each day ($\mu\text{g}/\text{m}^3$)
- Temperature: Average temperature each day ($^{\circ}\text{C}$)
- Humidity: Relative humidity each day (%)
- WindSpeed: Average wind speed each day (m/s)
- WindDirection: Average wind direction each day (degrees)

The system assumes that PM2.5 and PM10 concentrations are influenced by past air quality levels, meteorological conditions, and temporal patterns.

3.2. Mathematical model / algorithm design

Two recurrent neural network architectures, LSTM and GRU, were employed for PM2.5 and PM10 prediction. Both models share a similar overall structure, each comprising three core recurrent layers and six total learnable layers (including dense layers). The key difference lies in the type of recurrent unit used; the single, crucial line that changes between the two models is the class used for the recurrent layers.

The LSTM model and GRU model are built with the following layers, respectively:

Table 1. Primary comparison between LSTM and GRU

LayerType	LSTM	GRU	Notes
Input Layer	Input Layer	Input Layer	
Recurrent Layer 1	LSTM (256units)	GRU (256units)	Returns sequences (necessary to feed into the next recurrent layer)
Recurrent Layer 2	LSTM (128units)	GRU (128units)	Returns sequences (necessary to feed into the next recurrent layer)
Recurrent Layer 3	LSTM (64 units)	GRU (64 units)	Does not return sequences (outputs a single vector for the entire sequence)
Dense (Hidden)1	Dense (32units)	Dense (32units)	Standard fully connected layer for further processing
Dense (Hidden)2	Dense (16units)	Dense (16units)	Standard fully connected layer for further processing
Output Layer	Dense (2 units)	Dense (2 units)	Predicts two values:PM2.5 and PM10
Key Characteristic	LSTM cells	GRU cells	GRUs are generally faster to train than LSTMs due to a simpler internal structure.

As shown in Table 1, the only difference between the types of recurrent neural network architectures constitutes a perfectly controlled experiment. Any difference in performance (accuracy,

training speed, final metrics) between the two resulting models can be attributed primarily to the inherent characteristics of the GRU and LSTM architectures themselves, rather than different architectures, data, or training procedures.

3.3. Data and parameters

The data used in this study were obtained from Kaggle, which is a prominent online platform for data science resources (Shanghai_air_pollution and weather 2014-2021) between January 1, 2014, and November 30, 2020 [10]. The goal of this is to predict PM2.5 and PM10 concentrations from December 1, 2020, to January 30, 2021, and compare them with the real values also provided by Kaggle.

Data Preprocessing: Missing values were handled using the time interpolation method. All input features were scaled to a range between 0 and 1 using the MinMaxScaler.

The Adam optimizer was used with a learning rate of 0.001 and a batch size of 64. The model was trained for 100 epochs, and early stopping was implemented with a patience of 10 epochs to prevent overfitting.

3.4. Implementation details

The LSTM and GRU models were implemented using Python 3.8 with the TensorFlow (2.17.0) and Keras (3.11.0) libraries. All experiments were conducted on a workstation with an Intel Core i7 processor and an NVIDIA GeForce RTX 2080 Ti GPU. The models were developed based on code files LSTM.py and GRU.py, respectively.

3.5. Evaluation metric and validation

The performance of the LSTM and GRU models was evaluated based on the following metrics:

Table 2. Formulas to be used for evaluation

Symbol of Indicator	Equation of the Indicator	Explanation of Indicators
RMSE	$RMSE = \sqrt{\left(\frac{1}{n} \times \sum (y_{-i} - \hat{y}_{-i})^2\right)}$	RMSE measures the average magnitude of the error, giving more weight to larger errors because errors are squared before averaging [11].
MAE	$MAE = 1/n * \sum y_i - \hat{y}_i $	MAE also measures the average magnitude of the error but treats all errors equally [11].
R ²	$R^2 = 1 - \left(\Sigma(y_{-i} - \hat{y}_{-i})^2 / \Sigma(y_{-i} - \bar{y})^2\right)$	R ² measures the proportion of the variance in the actual data that is explained by the model. It tells how good the model is compared to just using the average [12].

4. Results

Table 3. Statistical performance metrics

RMSE	MAE	MAPE	R ²	Bias	Model	Pollutant
83.279	76.791	84.941	0.003	75.239	GRU	PM2.5
49.269	40.903	48.103	0.003	35.275	LSTM	PM2.5
31.977	28.584	75.031	0.060	26.265	GRU	PM10
24.740	20.904	56.040	0.008	15.728	LSTM	PM10

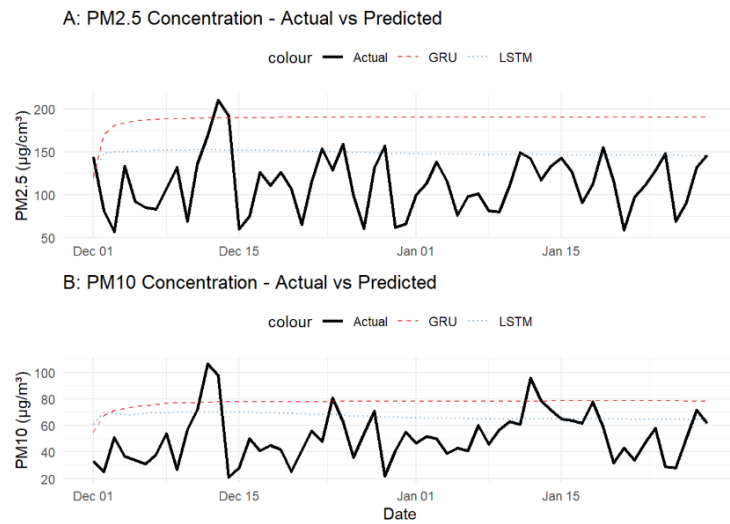


Figure 1. Time series comparison visualization (picture credit: original)

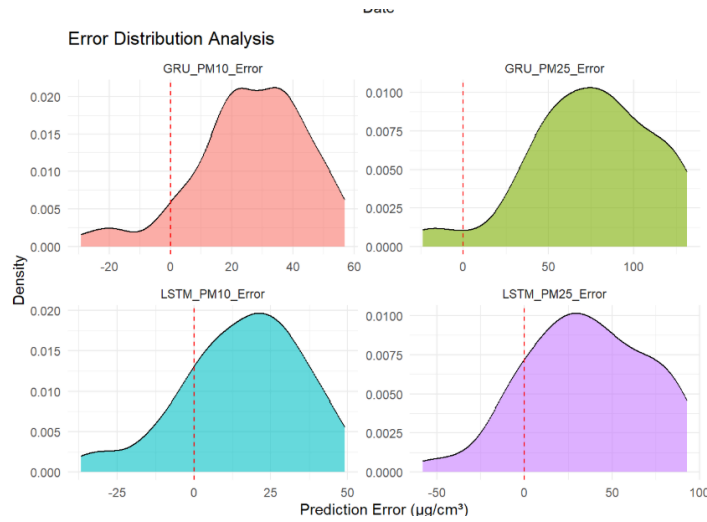


Figure 2. Error distribution analysis (picture credit: original)

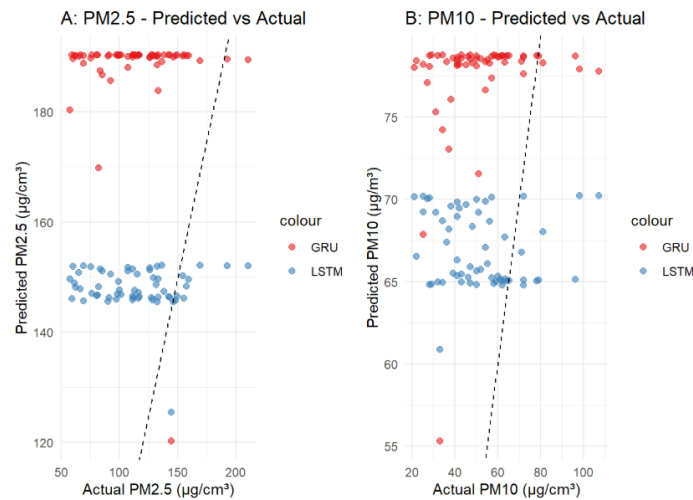


Figure 3. Scatter plot analysis (picture credit: original)

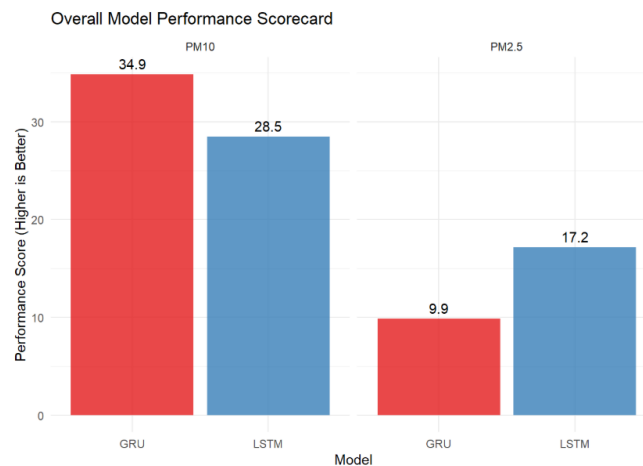


Figure 4. Performance scorecard (picture credit: original)

For air quality prediction in Shanghai, the LSTM model consistently outperforms the GRU model. As shown in Figure 1, LSTM predictions better capture the overall trends of actual pollution levels, while Figure 2 illustrates its more favorable error distribution with fewer extreme outliers. When examining the scatter plots in Figure 3, LSTM outputs are more concentrated along the 1:1 line, indicating predictions closer to reality, and this superiority is further reflected in the evaluation metrics of Figure 4, where LSTM achieves better performance for both PM2.5 and PM10. Using the error evaluation formulas in Table 2, the quantitative comparison in Table 3 demonstrates that reductions in RMSE and MAE achieved by LSTM are statistically significant, suggesting tangible benefits for early-warning systems and public health.

5. Discussion

The comparative analysis between GRU and LSTM models for air quality prediction in Shanghai reveals several important insights with broader implications for environmental forecasting. These findings demonstrate that LSTM architectures consistently outperform GRU models across multiple evaluation metrics, particularly in handling the complex temporal dependencies present in pollution

data. This superiority can be attributed to LSTM's more sophisticated gating mechanism and separate cell state, which better captures long-range dependencies in atmospheric patterns—a finding consistent with recent studies on time series forecasting in environmental applications.

The systematic overprediction observed in both models, especially for lower concentration values, suggests current architectures struggle with the high variability and non-linear interactions characteristic of urban air pollution systems. This limitation highlights the need for more sophisticated feature engineering that incorporates real-time meteorological data, traffic patterns, and industrial activity indicators. Furthermore, the potential risk of underfitting to rare but critical scenarios could happen when models show difficulty in predicting extreme pollution events, which is a common challenge in environmental forecasting.

Within this predicting task, the LSTM model actually overperforms the GRU model, and here is a reasonable assumption of the reason. A key characteristic of urban air quality data is the presence of long-term dependencies and seasonal cycles, and PM2.5/PM10 concentrations are influenced by multi-day meteorological patterns (e.g., sustained periods of high pressure leading to stagnation), seasonal shifts in energy consumption (e.g., winter heating), and even transboundary transport of pollutants over several days. The LSTM model dedicated memory cell state, which acts as a constant-error carousel, is explicitly designed to preserve information over extended periods. This allows the LSTM to learn and remember these long-range, seasonal influencers more coherently.

In contrast, while the GRU is a powerful and efficient architecture, its simpler, combined gating mechanism (lacking a separate memory cell) may be more prone to losing subtle long-term signals amidst the noise of high-frequency, short-term fluctuations in the data (e.g., hourly wind shifts or traffic patterns). The GRU model's strength lies in capturing shorter-term patterns, but for forecasting pollutants with strong seasonal and multi-day inertia, the LSTM model's ability to decouple the cell state from the hidden state provides a distinct advantage in modeling these complex, long-range temporal dependencies.

Moreover, several promising research directions emerge from these findings. Hybrid approaches combining the temporal modeling capabilities of LSTMs with attention mechanisms could better capture both short-term fluctuations and seasonal patterns in pollution data. Additionally, integrating meteorological forecasting models with deep learning architectures might improve prediction accuracy during transitional weather conditions. The integration of explainable AI techniques would also be valuable for identifying key contributing factors to pollution events, providing actionable insights for urban planning and policy interventions.

So far, possible limitations within this study include the models' reliance on historical data without adequate consideration of real-time emission sources and the narrow geographical focus on Shanghai. Therefore, future research should explore transfer learning approaches to adapt these models to different urban environments. Moreover, it is also important to keep pushing comprehensive pollution monitoring every day to enrich the air pollution database.

6. Conclusion

This study has presented a comprehensive comparative analysis of LSTM and GRU neural network architectures, primarily judging by the different performance of predicting PM2.5 and PM10 concentrations in Shanghai, addressing a critical need for accurate air quality forecasting in urban environments. The research demonstrates the significant potential of deep learning approaches in capturing the complex temporal dynamics of atmospheric pollutants, in order to highlight the importance of architectural considerations for environmental forecasting applications.

The key finding of this work unequivocally establishes the superior performance of LSTM models over simplified GRU models, with a specific focus on air quality prediction tasks. This superiority, evidenced across multiple evaluation metrics including RMSE, MAE, and R-squared, can be attributed to LSTM's more sophisticated gating mechanism and separate cell state design, which better captures the long-range dependencies characteristic of atmospheric pollution patterns. Nevertheless, the systematic overprediction tendency observed in both models, particularly for lower concentration values, underscores the challenges in modeling the high variability and non-linear interactions inherent in composite air pollution systems.

Several important research gaps and future directions emerge from this work. The current models' reliance on historical data without adequate incorporation of real-time emission sources represents a significant limitation. Future research should explore several promising avenues, including: (1) the integration of meteorological prediction models to account for weather-pollution interactions; (2) the incorporation of spatial correlation data from multiple monitoring stations to capture urban pollution diffusion patterns; (3) multi-modal data fusion techniques that combine satellite remote sensing imagery with ground-level monitoring data for comprehensive spatial-temporal coverage. Additionally, the development of hybrid architectures that combine the temporal modeling capabilities of LSTM with attention mechanisms, graph neural networks (for modeling spatial dependencies), and transfer learning approaches could enhance model performance across diverse urban environments. The implementation of explainable AI techniques would further bridge the gap between predictive accuracy and actionable insights for environmental policy and urban planning decisions.

This study contributes to the growing body of literature on intelligent environmental monitoring systems and provides a foundation for developing more robust air quality forecasting frameworks that can be adapted to various urban contexts worldwide.

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