Supplementary information for

Wind-Aware, Time-Scale Adaptive $PM_{2.5}$ Spatiotemporal Forecasting with Spatial Regularization

Guyu Zhao[a,b] , Shuo Zhang[a,b] , QiMing Liu[a,b] and Hongdou He[a,*]
[a]School of Information Science and Engineering, Yanshan University, Qinhuangdao
[b]The Key Laboratory for Software Engineering of Hebei Province, Qinhuangdao

*Corresponding Author
He Hongdou, E-mail: hhd@ysu.edu.cn

Table S1. Parameter Explanations for PM2.5 Prediction Model

Parameter	Explanation
AQI (Air Quality Index)	A single numerical indicator that integrates multiple pollutant concentrations (e.g., $PM_{2.5}$, PM_{10}, O_3) to represent overall air quality. It helps track general pollution levels and provides indirect insights into $PM_{2.5}$ trends.
CO (Carbon Monoxide)	Concentration of Carbon Monoxide, mainly from vehicle exhaust and combustion sources. CO often co-occurs with $PM_{2.5}$ in urban areas, indicating shared emission origins.
NO_2 (Nitrogen Dioxide)	A reactive nitrogen gas produced mainly by fossil fuel combustion. It is a precursor to secondary particulate formation and correlates with traffic-related $PM_{2.5}$ emissions.
O_3 (Ozone)	A secondary pollutant formed through photochemical reactions involving NO_x and VOCs. Ozone levels influence the oxidative environment and the formation of secondary $PM_{2.5}$.
PM_{10} (Particulate Matter 10)	Particulate matter with diameter ≤10μm, which includes $PM_{2.5}$. PM10 trends often move with PM2.5 and can indicate broader particle pollution.

$PM_{2.5}$（Particulate Matter 2.5）	Fine particulate matter with diameter ≤2.5μm. It poses significant health risks and is the core target variable in the prediction model.
SO_2 (Sulfur Dioxide)	A gaseous pollutant from industrial processes and coal combustion. SO_2 can react in the atmosphere to form sulfate particles, contributing to $PM_{2.5}$ levels.
t2m (2-meter Temperature)	Near-surface air temperature at 2 meters. It influences atmospheric mixing, stability, and chemical reaction rates, all of which affect $PM_{2.5}$ dynamics.
d2m (2-meter Dew Point Temperature)	Dew point temperature at 2 meters, reflecting ambient humidity. High dew points are associated with enhanced aerosol hygroscopic growth and secondary PM formation.
V10 (10-meter North-South Wind Component)	Meridional (north-south) wind component at 10 meters altitude. It affects pollutant transport and regional dispersion of $PM_{2.5}$.
u10 (10-meter East-West Wind Component)	Zonal (east-west) wind component at 10 meters altitude. Together with V10, it determines wind-driven horizontal movement of air pollutants.
tp (Total Precipitation Rate)	Total precipitation rate in millimeters per hour. Rainfall helps remove $PM_{2.5}$ from the air through wet deposition.
sp (Surface Pressure)	Surface atmospheric pressure, indicating synoptic weather conditions. It influences boundary layer height and the vertical mixing of pollutants, thus affecting $PM_{2.5}$ accumulation.

Table S2. Optimal parameter values used in the experiments.

Hyperparameters	Values
Training epoch	100
Input sequence length	168
Hidden dimension	64
Mid-layer channel	32
Number of heads	4
Window size	8
Wind-bias scale	0.5
Number of experts	4
Top-U temperature	0.5
Number of prototypes	50
Cluster-softmax temperature	1.0
Dynamic-adj temperature	0.5
Static–dynamic fusion α init	0.1
Laplacian-reg weight	0.1
Learning rate	1e-4
Weight decay	1e-3

Table S3. Air Quality Level Classification Based on the "Technical Regulations for Ambient Air Quality Index"

Level	PM2.5 concentration range (μg/m³)
Excellent	0-35
Good	36-75
Light Pollution	76-115
Moderate Pollution	116-150
Heavy Pollution	151-250
Severe Pollution	>250

Table S4. Sensitivity Analysis of the Neighborhood Size k in kNN Graph Construction

K	1h		6h		12h		24h	
	MAE ↓	RMSE ↓	MAE ↓	RMSE ↓	MAE ↓	RMSE ↓	MAE ↓	RMSE ↓
2	4.637	7.300	8.932	13.568	11.056	16.985	13.057	19.677
4	**4.614**	**7.181**	**8.387**	**13.065**	**10.769**	**16.152**	**12.896**	**19.333**
6	4.635	7.204	8.654	13.548	11.036	16.835	13.202	19.712
8	4.659	7.259	8.854	13.882	11.532	17.002	13.636	20.051

Fig.S1. Distribution of Stations in the Beijing-Tianjin-Hebei Region

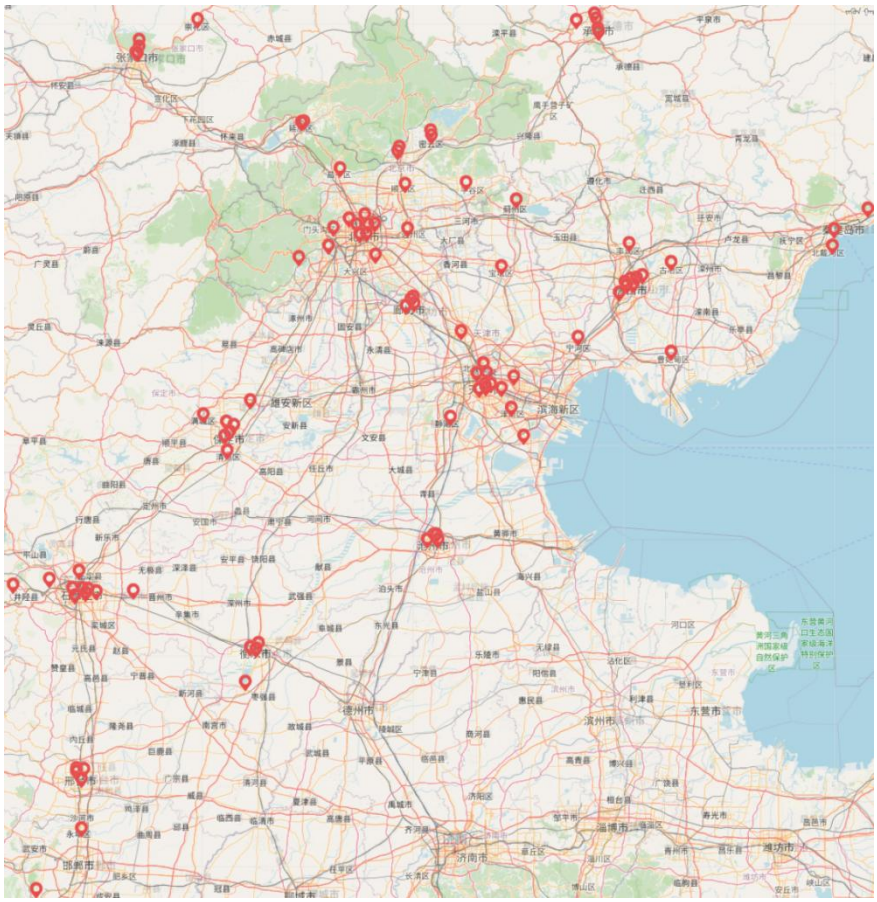

Fig.S2. Time Convolution Block structure

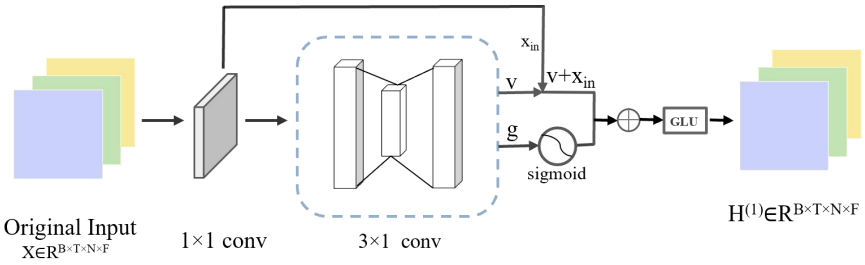

Fig.S3. Comparison of city-level MAPE for hourly $PM_{2.5}$ forecasts in the BTH region.

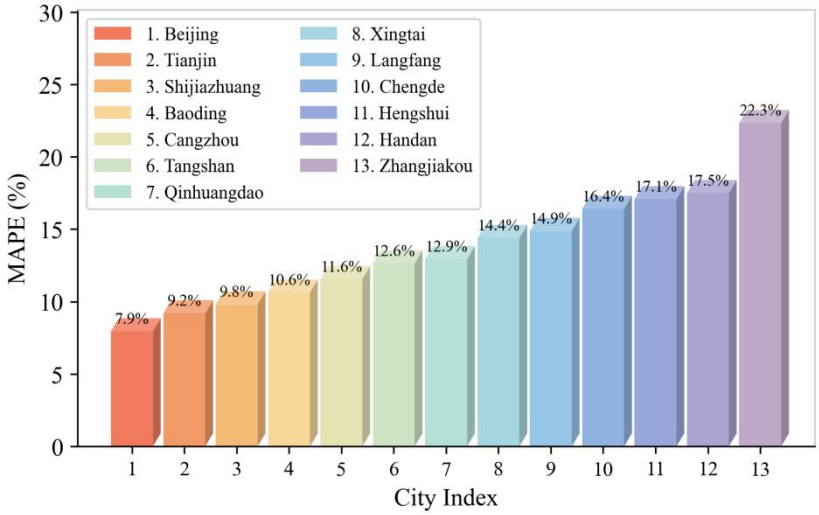

Fig.S4. Comparison of observed and forecasted city-level average $PM_{2.5}$ concentrations across all monitoring stations in selected cities within the BTH region (April~1--2, 2023). The horizontal axis represents date and hour, and the vertical axis shows $PM_{2.5}$ concentration. The solid blue line indicates the observed average, and the dashed green line represents the forecasted average.

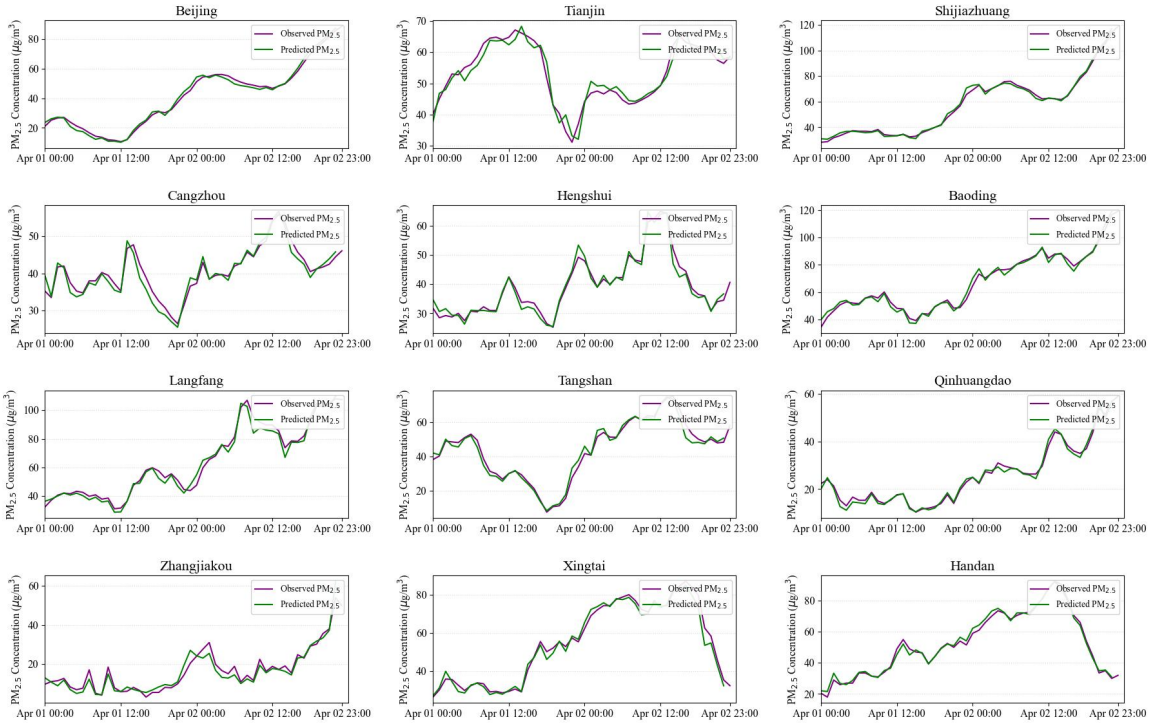

Fig.S5. Contour maps comparing $PM_{2.5}$ forecasts at different lead times with ground-truth observations. Results are shown for 1h, 6h, 12h, and 24h forecasts across cities in the BTH region under varying pollution levels.