Table S1. Geographic information for the 36 prefecture-level cities included in this study. The table lists the province, city identifier, longitude, and latitude of each city in Northeast China. The coordinates represent the city-level locations used for spatial mapping and city-centered buffer analyses. Chaoyang City in Liaoning Province is denoted as ChaoyangLN, and Yichun City in Heilongjiang Province is denoted as YichunHLJ to avoid ambiguity with other cities of the same name.

Province	City ID	Longitude (deg E)	Latitude (deg N)
Heilongjiang	Harbin	127.9536	45.634
Heilongjiang	Qiqihar	124.5348	47.6968
Heilongjiang	Jixi	132.2779	45.6289
Heilongjiang	Hegang	130.8028	47.6397
Heilongjiang	Shuangyashan	132.6036	46.7153
Heilongjiang	Daqing	124.7012	46.3417
Heilongjiang	YichunHLJ	129.2036	47.8029
Heilongjiang	Jiamusi	132.159	47.2366
Heilongjiang	Qitaihe	130.9352	45.8794
Heilongjiang	Mudanjiang	129.8902	44.5918
Heilongjiang	Heihe	126.9946	49.2536
Heilongjiang	Suihua	126.636	46.8907
Heilongjiang	Daxinganling	124.2199	52.322
Jilin	Changchun	125.5782	44.281
Jilin	Jilin	126.8421	43.5762
Jilin	Siping	124.3871	43.4837
Jilin	Liaoyuan	125.3058	42.8102
Jilin	Tonghua	125.9486	41.9523
Jilin	Baishan	127.286	42.0685
Jilin	Songyuan	124.4717	44.8004
Jilin	Baicheng	123.0089	45.3433
Jilin	Yanbian	129.1226	43.1405
Liaoning	Shenyang	123.1367	42.0919
Liaoning	Dalian	122.1813	39.5898
Liaoning	Anshan	123.0158	40.7115
Liaoning	Fushun	124.6552	41.8334

Liaoning	Benxi	124.5681	41.23
Liaoning	Dandong	124.3945	40.5396
Liaoning	Jinzhou	121.6098	41.4582
Liaoning	Yingkou	122.4512	40.3883
Liaoning	Fuxin	121.9531	42.2791
Liaoning	Liaoyang	123.246	41.1813
Liaoning	Panjin	121.994	41.0656
Liaoning	Tieling	124.1709	42.6425
Liaoning	ChaoyangLN	120.0115	41.5095
Liaoning	Huludao	120.2027	40.6169

Table S2. City-level monitoring stations used in this study. The table lists the province, city, number of national air-quality monitoring stations, and station names for the 36 prefecture-level cities in Northeast China.

Province	City	Number of stations	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8	Station 9	Station 10	Station 11	Station 12
	Dandong	4	Zhou Cheng Chang	Cai Zhuan	Yuan Bao Shan Shui Chang	Shi Yan Xiao Xue								
	Dalian	10	Gan Jing Zi	Zhou Shui Zi	Xing Hai San Zhan	Qing Ni Wa Qiao	Fu Jia Zhuang	Qi Xian Ling	Lv Shun	Jin Zhou	Kai Fa Qu	Shuang D Port		
	Fushun	6	Zhan Qian	Xin Hua	Dong Zhou	Wang Hua	Shui Ku	Shen Fu Xin Cheng						
	Chaoyang	4	Yi Jian Gou Jian Chang	Yuan Lin Guan Li Chu	Mian Fen Chang	Long Cheng Nong Ye Yuan Qu								
	Benxi	6	Da Yu	Xi Hu	Dong Ming	Cai Tun	Wei Ning	Zhi Ye Bing Yuan						
	Shenyang	11	Hui Shan	Er Mao	Tai Yuan Jie	Xiao He Yan	Wen Yi Lu	Bei Ling	Pao Bing Xue Yuan	Zhang Shi	Dong Ruan	Hun Nan Er	Liaoning University	
	Panjin	3	Kai Fa Qu	Xing Long Tai	Ding Xiang									
Liaoning	Yingkou	4	Ying Kou Da Xue	Zhi Wu Yuan	Xi Pao Tai	San Shui Chang								
	Huludao	4	Hu Lu Dao Shi Xi Shan Po	Lian Shan Qu Zheng Fu	Hua Gong Yi Yuan	Xin Qu Gong Yuan								
	Liaoyang	4	Liao Hua	Er Ling Yi Xue Zhan	Yuan Lin Xiao Qu	Gang Guan Chang								
	Tieling	4	Gang Chang	Ben Zhan	Shui Le Yuan	Jin Sha Jiang								
	Jinzhou	5	Nan Shan	Kai Fa Qu	Bai Gu Shui Chang	Jian Ce Zhan	Bei Hu Gong Yuan							

	Fuxin	5	Huan Bao Ju	Nong Ye Yuan Qu	Ren Min Gong Yuan	Gong Ye Yuan Qu	Yu Long Xin Cheng Zi Zhan					
	Anshan	7	Qian Shan Gong Yuan	Shen Gou Si	Zhong Xin Zhan	Tai Ping Zi Zhan	Tie Xi	Kai Fa Qu	Ming Da Xin Qu			
	Jilin	7	Feng Man	Ha Da Wan	Dong Ju Zi	Dian Li Xue Yuan	Jiang Bei	Jiang Nan Gong Yuan	Nong Ke Yuan			
	Siping	3	Jian Ce Zhan	Yi Shang Dian	Jing Yuan							
	Yanbian	3	Yan Bian Yi Yuan	Fu You Yi Yuan	Zhao Yang Chuan Zhen Yi Yuan							
	Songyuan	2	Jiang Nan	Jiang Bei								
Jilin	Baicheng	2	Municipal Environmental Protection Bureau	Taobei District Environmental Protection Bureau								
	Baishan	2	Huan Bao Ju	Xi Feng								
	Liaoyuan	2	Huan Bao Ju	Wu Shui Chu Li Chang								
	Tonghua	2	Guang Ming	Tie Lu								
	Changchun	10	Shuai Wan Zi	Shi Pin Chang	Ke Che Chang	You Dian Xue Yuan	Lao Dong Gong Yuan	Yuan Lin Chu	Jing Yue Tan	Jing Kai Huan Wei Chu	Gao Xin Qu Guan Wei Hui	Dai Shan Gong Yuan
	Qitaihe	3	Hu Tou Gou	Huan Bao Ju	Xin Jian							
	Yichun	3	Tangwang he	Zhong Xin Yi	Lin Guan Ju							

			National Park	Yuan										
	Jiamusi	5	Si Feng	Jia Fang	Huan Bao Ju	Fa Dian Chang	Shi Yi Zhong							
	Shuangyashan	4	Miao Pu	Shuang He Cun	Huan Bao Ju	Nan Xiao Shi								
	Harbin	12	Ling Bei	Tai Ping Hong Wei Gong Yuan	Dong Li He Ping Lu	Dao Wai Cheng De Guang Chang	Nan Gang Xue Fu Lu	Xiang Fang Hong Qi Da Jie	Dao Li Jian Guo Lu	Ping Fang Dong Qing Chang	Song Bei Shang Da	A Cheng Hui Ning	Hu Lan Shi Zhuan	Provincial Academy of Agricultural Sciences
	Daxing'anling	2	Huan Bao Ju	Gong An Ju										
Heilongjiang	Daqing	5	Sa Er Tu Qu	Rang Hu Lu Qu	Long Feng Qu	Hong Gang Qu	Da Tong Qu							
	Mudanjiang	5	Wen Hua Guang Chang	Huan Bao Da Lou	Di Yi Yi Yuan	Ji Che Chang	Di Yi Zhong Xue							
	Suihua	2	Party and Government Office Center	Ren He Dong Jie										
	Jixi	4	Qi Xiang Ju	Huan Bao Ju	Zi Lai Shui Gong Si	Bai Jiu Chang								
	Hegang	4	Wu Hao Shui Ku	Ha Pi Fen Gong Si	Si Da Ji Dian	Dong Shan Zhi Ban Chang								
	Heihe	3	Di Zhen Ju	Jiao Tong Ju	Dang Xiao									
	Qiqihar	5	Fu Qu Huan Bao Ju	An Ju Xiao Qu	Zhong Xin Guang Chang	Nong Mu Che Liang Chang	Municipal Environmental Monitoring Station							

Table S3. ERA5meteorological variables used as model predictors. The table lists the variable name, physical meaning, unit, and whether the variable is instantaneous, accumulated, or derived.

Variable	Full name	Unit	Type / note
BLH	Boundary layer height	m	ERA5 surface variable; instant
T_d	2 metre dewpoint temperature	K	ERA5 surface variable; instant
p_s	Surface pressure	Pa	ERA5 surface variable; instant
SSRD	Surface short-wave (solar) radiation downwards	J m^{-2}	ERA5 surface variable; accumulated
T	2 metre temperature	K	ERA5 surface variable; instant
TCC	Total cloud cover	0–1	ERA5 surface variable; instant
TP	Total precipitation	m	ERA5 surface variable; accumulated
u_{10}	10 metre U wind component	m s^{-1}	ERA5 surface variable; instant
v_{10}	10 metre V wind component	m s^{-1}	ERA5 surface variable; instant
RH	Relative humidity	%	Derived from t2m and d2m

Table S4. Annual mean $PM_{2.5}$ concentrations and daily exceedance statistics in Northeast China from 2015 to 2025. Annual mean $PM_{2.5}$ was calculated from hourly observations averaged over all cities. Exceedance days were defined as days with daily mean $PM_{2.5}$ concentrations exceeding 75 μg m^{-3}. Regional exceedance days were calculated using the regional daily mean $PM_{2.5}$ concentration averaged across all cities, representing region-wide pollution episodes. City-day exceedance counts were obtained by identifying exceedance days for each city separately and then summing all city-day exceedance events over the region, representing the cumulative city-level exceedance burden.

Year	Annual mean $PM_{2.5}$(μg m^{-3})	Regional exceedance days (d)	City-level exceedance counts (city-days)
2015	48.437	52	2173
2016	39.631	22	1359
2017	39.361	40	1496
2018	32.498	10	771
2019	39.442	26	711
2020	33.076	29	1063
2021	29.708	14	724
2022	26.214	9	459
2023	29.200	8	721
2024	29.196	7	645
2025	29.201	12	736

Table S5. The weather-normalized and meteorological components during regional $PM_{2.5}$ exceedance days. Exceedance days were defined as days with regional daily mean $PM_{2.5}$ concentrations exceeding 75 μg m^{-3}. Regional daily values were calculated by averaging hourly values across all cities. For each year, $PM_{2.5}$, PM_emi, and PM_met were averaged only over exceedance days. PM_emi > 75 days denotes exceedance days when the weather-normalized component alone exceeded the daily $PM_{2.5}$ standard.

Year	Exceedance days	Mean $PM_{2.5}$	Mean PM_{emi}	Mean PM_{met}	PM_{emi} > 75 days
2015	52	111.981	69.542	42.439	19
2016	22	99.950	64.091	35.859	1
2017	40	97.038	61.536	35.503	3
2018	10	79.622	47.518	32.105	0
2019	26	103.642	48.574	55.068	0
2020	29	97.234	59.193	38.040	0
2021	14	90.617	42.579	48.038	0
2022	9	86.935	46.020	40.915	0
2023	8	93.360	49.259	44.100	0
2024	7	107.956	47.069	60.886	0
2025	12	87.016	50.853	36.163	0

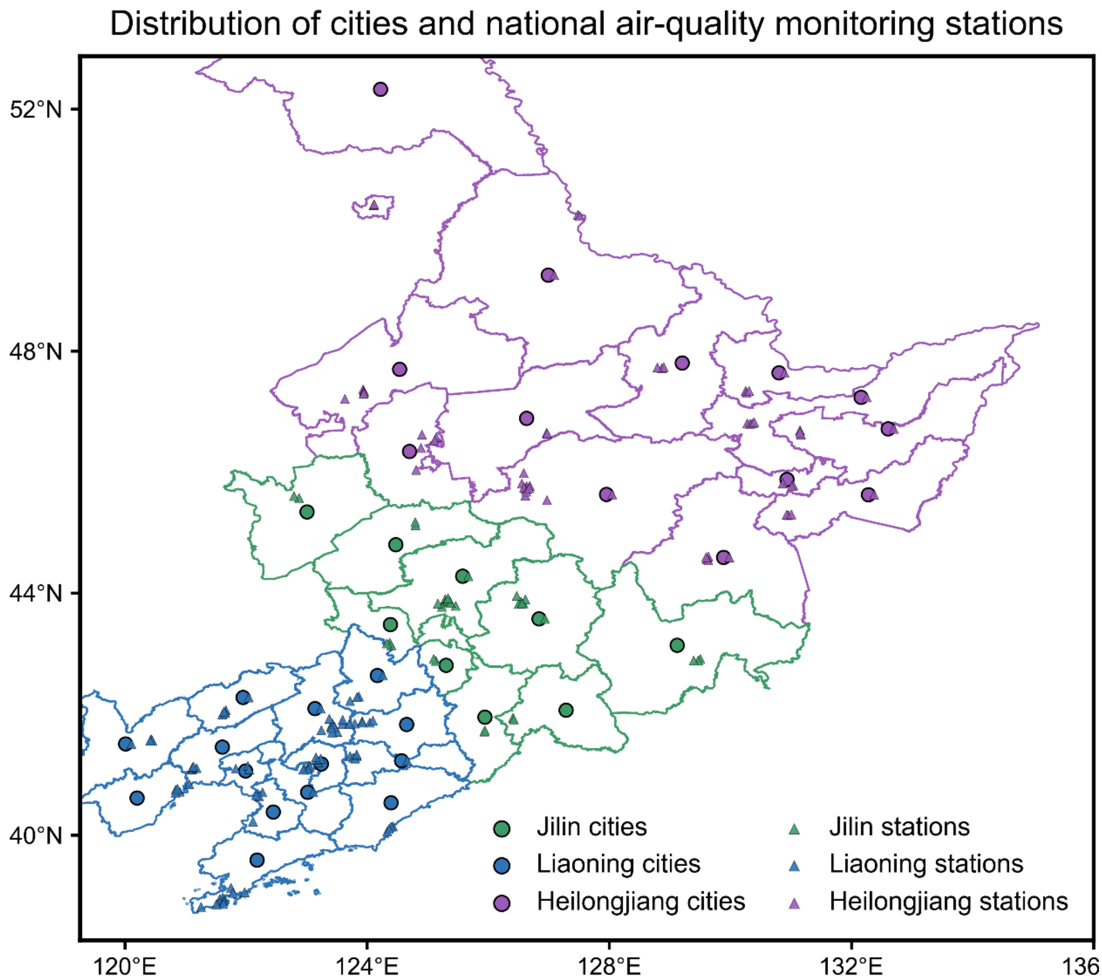

Figure S1. Spatial distribution of study cities and national air-quality monitoring stations in Northeast China. Circles represent the 36 prefecture-level cities included in the analysis, while triangles indicate national air-quality monitoring stations. Colors distinguish the three provincial regions: Liaoning, Jilin, and Heilongjiang.Table 1. Cities and national air-quality monitoring stations included in Northeast China.

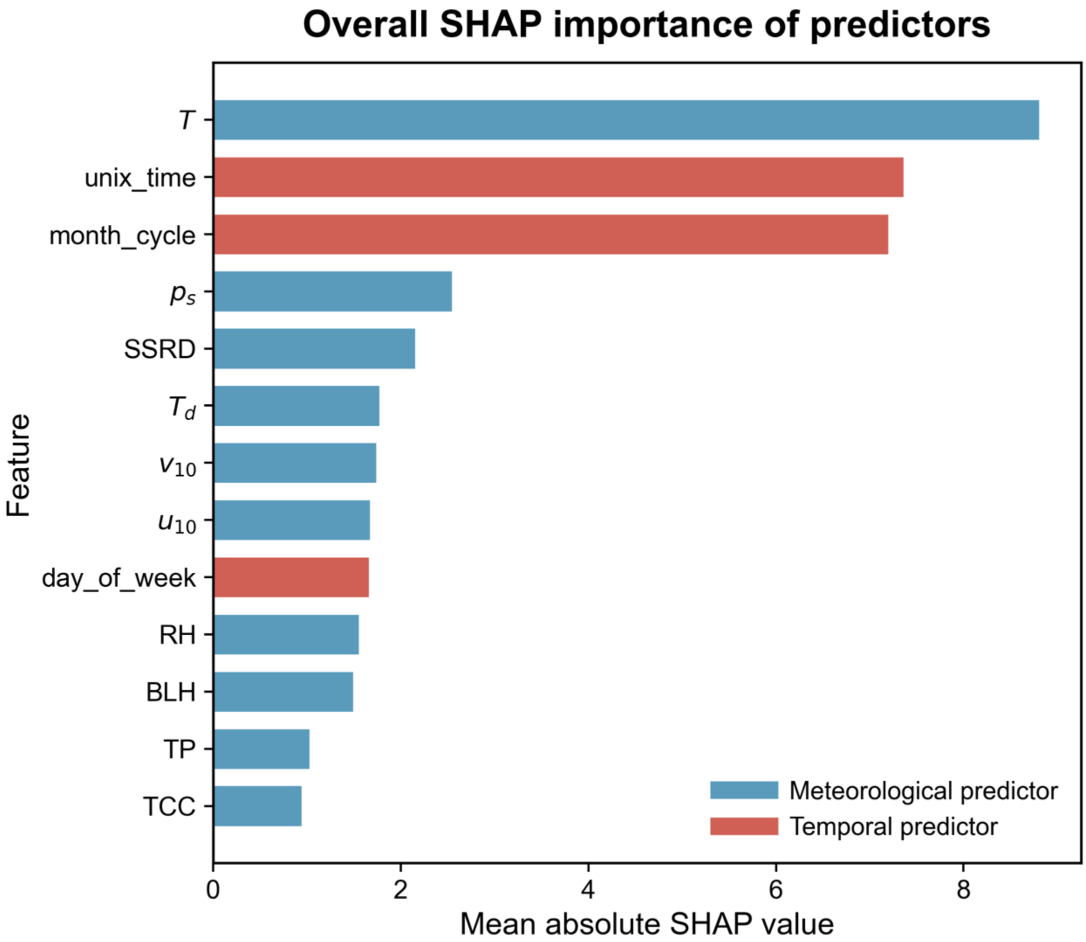

Figure S2. Overall SHAP importance of predictors in the LightGBM model. Predictor importance is quantified using mean absolute SHAP values across sampled observations and cross-validation folds. Blue and red bars represent meteorological and temporal predictors, respectively, with larger values indicating stronger average contributions to $PM_{2.5}$ prediction. The month_cycle term represents the combined contribution of month_sin and month_cos.