This paper describes a Bayesian hierarchical approach to predict short-term concentrations of particle pollution in an urban environment, with application to inhalable particulate matter (PM$_{10}$) in Greater London. We developed and compared several spatiotemporal models that differently accounted for factors affecting the spatiotemporal properties of particle concentrations. We considered two main source contributions to ambient measurements: (i) the long-range transport of the secondary fraction of particles, which temporal variability was described by a latent variable derived from rural concentrations; and (ii) the local primary component of particles (traffic- and non-traffic-related) captured by the output of the dispersion model ADMS-Urban, which site-specific effect was described by a Bayesian kriging. We also assessed the effect of spatiotemporal covariates, including type of site, daily temperature to describe the seasonal changes in chemical processes affecting local PM$_{10}$ concentrations that are not considered in local-scale dispersion models and day of the week to account for time-varying emission rates not available in emissions inventories. The evaluation of the predictive ability of the models, obtained via a cross-validation approach, revealed that concentration estimates in urban areas benefit from combining the city-scale particle component and the long-range transport component with covariates that account for the residual spatiotemporal variation in the pollution process.

**Keywords:** Bayesian analysis; exposure modelling; geostatistics; time series; urban particle pollution
non-traffic emissions, and secondary particles formed by atmospheric physical and chemical processes, such as condensation of vapourised material or by-product of the oxidation of gases, mainly during the course of long-range transport of pollutants. In this paper, we worked with point-referenced time series (daily) and considered several hierarchical models that differently accounted for the relative contribution of regional and local sources affecting the spatiotemporal properties of PM. Specifically, we considered:

(1) A time-varying latent regional process for capturing the long-range transport of PM. In our study, regional PM concentrations were estimated through direct measurement of rural background concentrations, using an additive approach as suggested by Lenschow et al. to account for the relative contribution of regional and local sources affecting the spatiotemporal properties of PM. Specifically, we considered:

A spatial local process for capturing the additional urban and local primary PM component. In our application, a local-scale air pollution dispersion model was used to describe this component.

Moreover, we accounted for selected space- or time-varying factors, which could have a direct influence on the pollution process or could be used as proxies for other unmeasured variables. We applied our proposed methodology to model inhalable PM in Greater London (UK), namely particles with a diameter \( \leq 10 \mu m \) (PM10), one of the air pollutants of most concern for public health that has been linked to a range of serious cardiovascular and respiratory health effects.20–22

We assessed the predictive performance of the models using a cross-validation approach.

Finally, we compared our approach with the one typically used in the literature on spatiotemporal modelling of air pollution, including random intercepts to account for spatial and temporal dependencies.

MATERIALS AND METHODS

Data Description

The PM10 data (\( \mu g/m^3 \)) were daily average concentrations (midnight to midnight) collected in the years 2002–2003 (728 days). This period was selected to include several pollution episodes (i.e. periods of elevated PM10) and the 2003 European heat wave.23 The data were log-transformed to achieve a Gaussian distribution. They came from three sources:

1. Mass concentration measurements from the London Air Quality Network (LAQN; www.londonair.org.uk): This monitoring network had 76 PM10 sites in 2002–2003, with some of these also affiliated with the www.londonair.org.uk): This monitoring network had 76 PM10 sites. We selected 45 of these sites for the study, 8 of which were suburban sites (located from 1 to 5 m from a major carriageway) and 4 were kerbside sites (located within 1 m of a major road carriageway).

2. Day of the week, which accounted for unknown changes in emissions between weekdays and weekend days, because emission inventories are not time-varying but only contain annual totals. The indicator variable for day of the week was categorised as Monday–Friday, Saturday and Sunday or Public Holiday.

3. Average daily temperature to describe seasonal changes in chemistry between primary and regional secondary PM10. Other meteorological variables were not considered as these are used in the ADMS-Urban model; however, this does not include secondary PM10 formation, and thus daily mean temperature was used as a surrogate for such processes. Over the 2002–2003 years, the average temperature, recorded at London Heathrow, was 11.9 °C, with daily mean ranging between −1.3 and 28.2 °C.

Exploratory Data Analysis

Figure 1 presents the geographical location of the 45 monitoring sites across Greater London by site type. As we found little difference between the PM10 concentrations at suburban and urban background sites, we aggregated these two categories.

Figure 2 shows the correlation of daily data for pairs of monitoring sites as a function of their separation distance. The correlations were generally high, also over long distances (\( \geq 30,000 \) m), indicating that factors other than distance may have a role in explaining the spatial variability of PM10 levels.

Figure 3 presents the daily levels of PM10 across the 45 monitoring sites sorted from the top to the bottom by decreasing longitude, during the 2 year in study.30 The daily values are displayed according to the terciles computed on the global data set to ensure the comparability of the time series and assigned to low (brown), medium (pale green) and high (green) categories of PM10 concentrations. The bottom of the plot shows the daily median values across all the time series. The PM10 pollution episodes that London experienced during February, March, April, August, September and November 2003 are clearly visible. These episodes were mainly caused by secondary PM10 from distant sources, with summer episodes also being linked to photochemistry.31 The November 2003 episode was associated with Guy Fawkes Night fireworks and bonfires.32

The analysis via cross-correlogram of the time series of PM10 concentrations observed in Greater London and the local component of PM10 captured from ADMS-Urban output, presented in Figure 4, shows that the correlation was relatively high and positive at lag 0 (same day pollution levels), suggesting that the numerical model captured the time variation of PM10 observed at monitoring sites.

Modelling Approach

We denoted \( Z(t,s) \) as the log-transformed daily PM10 concentrations, with \( t = 1,\ldots,728 \) (days) and \( s = 1,\ldots,n = 45 \) (sites of the pollutant monitoring
network. We assumed that the observed monitoring data were characterised by measurement error defined by a zero-mean Gaussian white noise process. We specified a Gaussian likelihood for $Z(t, s)$:

$$Z(t, s) \sim N(\mu(t, s), \sigma^2(s))$$

where $\mu(t, s)$ represents the mean process driven by covariates varying over space and time and $\sigma^2(s)$ is the site-specific measurement error variance. We considered a class of different nested statistical formulations for the mean space–time process, $\mu(t, s)$, that differently accounted for factors affecting the spatiotemporal properties of particle concentrations.

Model I represented a simple statistical structure where the daily measurements at each monitoring site were assumed to be a function of a residual mean concentration across the urban area and a latent pollutant process described by the long-range transported proportion of particulate. The time-varying latent regional process was included assuming that concentrations at the city scale derive largely from information borrowed from rural measurements. It assumed the form:

$$\mu(t, s) = a + \mu_{\text{lrt}}(t)$$

where $a$ is the residual intercept and $\mu_{\text{lrt}}(t)$ represents the mean of the latent process.

In particular, let $j$ denote several available rural background monitoring sites around the metropolitan area, with $j = 1, \ldots, J$. We assumed that the time series of pollution data from the rural monitoring sites are a reflection of an underlying long-range transport of particles into the urban area, measured with error:

$$\mu_{\text{lrt}}(t; j) \sim N(\mu_{\text{lrt}}(t), \sigma^2_{\text{lrt}}(j))$$

In our application, this latent process was driven by the two time series of PM10 measured at the Harwell and Detling rural background sites ($j = 1, 2$).

This simple model accounted for the temporal variability of the pollution process, but did not incorporate a spatial structure. The model describes the main hypothesis in the definition of air pollution exposure in ecological time series studies, where the pollution estimates for a given study region, are generally free from a spatial dimension, although these studies typically use averaged ambient pollutant levels from one or more background monitoring stations to represent the exposure experienced by a study population.

Model II added to the constant, $a$, the local city primary PM10 component described by ADMS-Urban, $\ell(t, s)$:

$$\mu(t, s) = a + b_1(s)\ell(t, s)$$

A spatially varying coefficient model was used for this component to capture the effect of site. We assumed $(b_1, b_2, \ldots, b_J)^T$ to be distributed according to a zero-centred multivariate Gaussian distribution $\beta_j \sim \text{MVN}(0, \sigma^2 H(q))$, where $\sigma^2 > 0$ is the spatial effect variance parameter and $H$ represents the spatial correlation matrix.

Figure 1. Location and siting characteristics of the air quality monitoring sites in Greater London selected for the study.

Figure 2. Correlation between pairs of monitoring sites as a function of their separation distance.
described by an exponential function \( f(d, \varphi) = \exp(-\varphi d) \), where 
\( d = ||s - s'|| \) and \( ||.|| \) indicates the Euclidean distance between two generic sites \( s \) and \( s' \), and \( \varphi \) is the (non-negative) decay parameter that represents the rate of decline of spatial correlation among sites over distance. This spatial structure for the ADMS-Urban output provided a realistic representation of the spatial variability observed in the explorative analysis. However, we would expect a poor performance of this model as it did not account for the temporal variability in the pollution process.

Model III included both the regional and the local primary PM10 components:

\[
\mu(t, s) = a + \mu_{\text{reg}}(t) + \beta_1(s) \epsilon(t, s) \quad (5)
\]

Model IV was performed to explore the effect of the set of covariates (without regional and local PM10 components):

\[
\mu(t, s) = a + \beta_2 \text{type}(s) + \beta_3 \text{dow}(t) + \beta_4(t) \text{temp}(t) \quad (6)
\]

where type is the type of site, dow is the day of the week and temp is the temperature. In particular, we used site type to represent possible difference in concentration levels, as road and kerb sites are likely to have higher concentrations as they are closer to traffic source of pollution;
daily mean temperature to describe chemical processes affecting local PM$_{10}$ concentrations that are not considered in local-scale dispersion models and day of week to account for time-varying emission rates that are not described in emissions inventories. In Eq. (6), the fixed-effects coefficients $\beta_1$ and $\beta_2$ are unknown parameters for the variables site type and day of the week. The vector $\mu(t) = (\mu_1(t), \ldots, \mu_d(t))^T$ is the dynamic parameter associated with the temperature built according to a Gaussian second-order random walk (RW2), which was found provide the best smoothness prior for this variable. It assumed the form: $\mu_i(t) \sim N(\mu_i(t - 1) - \beta_1 x_i(t), \sigma^2_d)$ for $t = 1, \ldots, T - 2$, where $\sigma^2_d$ is the variance. A RW2 acts as a smoothness prior based on the second difference and penalises deviations from a linear trend.\textsuperscript{35} This prior, for regular time-point provides enough flexibility because of its invariance under addition and it is computationally convenient because of its Markov properties.\textsuperscript{36} The choice of this prior followed an initial explorative analysis where we found that the relationship between temperature and PM$_{10}$ concentrations (not shown) was potentially well described by a cubic smoothing spline. The RW2 is a discrete-time analogue of a cubic smoothing spline.\textsuperscript{37}

Model V finally represented the full model that accounted for the regional and local PM$_{10}$ components and for the covariates:

$$
\mu(t, s) = \alpha + \mu_{\text{lt}}(t) + \beta_1 s(t, s) + \beta_2 \text{type}(s) + \beta_3 \text{dist}(t) + \beta_4 t(t) \text{temp}(t)
$$

Parameter Priors and Implementation

A Gaussian prior distribution with mean zero and variance $10^3$ was assigned to the intercept $\alpha$, and to the fixed-effects coefficients $\beta_1$ and $\beta_2$. To ensure identifiability, we fixed the first category of these two parameters as zero ($\beta_{1,1} = 0$ and $\beta_{3,1} = 0$). The same Gaussian prior was chosen for the mean of the latent background process. Weakly informative inverse-Gamma hierarchical priors were specified for the error variance parameters $\sigma^2(t)$ and $\sigma^2(s, t)$ with $\text{IG}(t, 0.1)$ and $\text{IG}(c, d, t) = 1, \ldots, s$, setting the hyperpriors $(a, b, c, d)$ as $\text{IG}(0.1)$. Similarly, inverse-Gamma priors were specified for the between-site variance component $\sigma^2$ and the variance of the RW2 $\sigma^2_d$ with hyperpriors $\text{IG}(1, 0.1)$. We assumed a discrete uniform prior distribution for the decay parameter $\varphi$ as suggested by Diggle and Ribeiro,\textsuperscript{38} with range chosen based on prior beliefs about the minimum and maximum correlation at the smallest and largest distances. Typically, locations close in space are assumed to be characterised by a stronger degree of correlation, but we did not want to assume a strong prior on it and we allowed for a range of correlation between 0.10 and 0.99. For large separation distances, we specified a range between 0.01 and 0.65.

The models were implemented in WinBUGS,\textsuperscript{39} a freely available software to perform Bayesian inference via Markov chain Monte Carlo (MCMC) simulation method.\textsuperscript{40} Two parallel MCMC chains with different starting values were run for each model. We ran 60,000 iterations with 50,000 burn-in and thinned the Markov chains by a factor of 10, resulting in samples of size 2000 to estimate the posterior distributions for the parameters of interest. Posterior correlation was reduced by a grand mean centring of the covariates.\textsuperscript{41} Convergence was assessed by checking the trace plots of the samples, the estimated kernel density plots, the autocorrelation functions, and a Monte Carlo errors <5% of the posterior standard deviation.

Comparison with Models Implemented with Varying Intercepts

The model formulation proposed in our paper deviates from the standard spatiotemporal statistical models that include varying intercepts (baseline concentrations) that are spatially or temporally correlated.\textsuperscript{45,6,14,16} The most common setting assumes that the spatial and temporal dependences are introduced into the modelling in the form of random effects. Thus, pollution concentrations characterised by a Gaussian likelihood are typically related to a trend surface model together with additive-independent random spatiotemporal effects that in a simple implementation can assume the form:

$$
\mu(t, s) = BX(t, s) + \theta(t) + \eta(s) + \epsilon(t, s)
$$

(8)

Here, $B$ is a vector of regression coefficients associated with the covariates $X(t, s)$. The residual is partitioned into a temporal, $\theta(t)$, a spatial, $\eta(s)$, and an independent process $\epsilon(t, s)$, which is Gaussian with zero mean and $\sigma^2(\epsilon)$ variance. As a comparison with our approach, we have considered a model implementation within this classical framework using the same set of data.

We developed five nested hierarchical structures that incorporated separable random space and time effects. The first model was given by:

Model Ia:

$$
\mu(t, s) = \theta(t) + \eta(s)
$$

(9)

The parameters $\theta(t) = (\theta_1, \ldots, \theta_T)^T$ should capture the residual temporal dynamics characterising the pollutant process. This temporal process was described using an autoregressive first-order non-stationary model as daily dependence in air particulate concentrations can be expected,\textsuperscript{8} and was built as $\theta(t) \sim \text{AR}(1)$ for $t = 1, \ldots, T - 1$. The term $\eta(s) = (\eta_1, \ldots, \eta_s)^T$ represents a spatially varying intercept that we assumed described by a zero-centred Gaussian process with variance $\sigma^2$ and an exponential correlation function that depend upon the intersite distance and the parameter $\varphi$ quantifying the correlation decay.

Model IIa also included the latent regional process defined as in Eq. (3): Model IIIa:

$$
\mu(t, s) = \theta(t) + \eta(s) + \mu_{\text{lt}}(t, s)
$$

(10)

Model IIIa added to the random effects of the urban local component of PM$_{10}$ described by ADMS-Urban:

Model IIIa:

$$
\mu(t, s) = \theta(t) + \eta(s) + \mu_{\text{lt}}(t, s)
$$

(11)

The space-varying slope $\mu_{\text{lt}} = (\mu_{1,1}, \mu_{2,1})^T$ was built according to a Bayesian isotropic kriging\textsuperscript{84} as specified in our main analysis. Model IVa incorporated both the long-range and the local components of PM$_{10}$:

Model IVa:

$$
\mu(t, s) = \theta(t) + \eta(s) + \mu_{\text{lt}}(t, s)
$$

(12)

Model Va included exclusively the spatiotemporal random intercepts and the covariates type site, day of the week and daily mean temperature:

Model Va:

$$
\mu(t, s) = \theta(t) + \eta(s) + \mu_{\text{lt}}(t, s)
$$

(13)

Similar to the main analysis, we also tried to implement a full model as:

Model V:

$$
\mu(t, s) = \theta(t) + \eta(s) + \mu_{\text{lt}}(t, s)
$$

(14)

However, it resulted overparameterised and yielded implausible predictions, and thus we decided not to present the results from this model. Models Ia–Va were specified assuming for the variance parameters $\sigma^2$ and $\sigma^2_d$ inverse-Gamma priors $\text{IG}(1, 0.1)$. The other priors were specified as in the main analysis.

Performance Assessment

To compare our models, we partitioned the monitoring network into three sets of sites following these steps: (i) we stratified the 45 sites by type (urban/suburban, roadside and kerbside sites), (ii) we chose a random sample of nine sites, representative of the entire network (with respect to the number of sites of each type) as validation data for testing the models, and (iii) we retained the other 36 sites as training data to fit the models. We repeated steps (i)–(iii) three times (so each site entered into the validation data once).

To evaluate the predictive performance of the models, we compared the predicted PM$_{10}$ concentrations against the observed measurements on the validation set via the following indices: the empirical coverage of 90% credible intervals (90% CI) coupled with their average length, the squared correlation coefficient ($R^2$) and the root mean square error (RMSE).\textsuperscript{14} Lower values of RMSE indicate more similarity among predicted values and observed values. To obtain these indices, for each model we used the full posteriors from each Markov chain and we combined the predicted values from the three sets. This same procedure was used to summarise the results for the parameters evaluation.

Sensitivity Analysis

Sensitivity analysis was performed in order to:

(1) Assess the performance of our modelling approach in urban environments that have a monitoring network less dense than in London. The EU Air quality directive (2008/50/EC) stipulates the minimum population-dependent measurement requirements for EU cities. With 36 European cities with populations above 1 million and 9 above 2 million,\textsuperscript{42}
we considered that testing the methodology on a sample of 10 measurement sites (matching the minimum number of monitoring sites for a city of 2.75 million population) would provide an assessment of applicability in a typical city. A city of 2.75 million would be smaller than the total area of Greater London. To this end, we considered the north-west boroughs in Greater London only and selected 10 sites as training set and 3 sites as validation set, representative of 3 site types, following the methodology described for the main analysis.

(2) Investigate whether results remained essentially unchanged in the presence of different prior distributions. We considered commonly used inverse-Gamma priors for the variance parameters (measurement errors) $\sigma^2$ and $\sigma_0^2$: $\text{IG}(0.1,0.1)$ and $\text{IG}(0.001,0.001)$. For the spatial effect variance parameter, $\sigma^2$, and the random walk variance parameter, $\sigma^2$, we tested the prior $\text{IG}(0.001,0.001)$.

RESULTS
Predictive Performance
Table 1 shows the cross-validation summary statistics. The results are reported on the original scale correcting for bias after logarithmic transformation. Moving from model I to model V, we noted a progressive improvement in the prediction capability, with exception of model II. However, we found that the validation indices improved heavily when the site-specific local component, described by ADMS-Urban output, was included in addition to the regional background component (as an example, the RMSE described by ADMS-Urban output, was included in addition to the indices improved heavily when the site-specific local component, except for model II. However, we found that the validation indices improved heavily when the site-specific local component, described by ADMS-Urban output, was included in addition to the regional background component (as an example, the RMSE decreased from 11.11 for model II to 5.11 for model III). The incorporation of the selected covariates in models IV and V produced an additional increase in the cross-validation performance.

Figure 5 shows the Taylor diagrams for the models, over (a) the whole study period and (b) a 2003 heat-wave event (days from 4 to 13 August 2003). This diagram represents a useful method for evaluating predictive performance, as it visualises simultaneously the centred RMSE (it is centred because the mean values of the observed and predicted data are subtracted first), the correlation coefficient ($R$) and the standard deviation of the observed and predicted values. In detail, the observed variability (i.e. the standard deviation) is plotted on the x-axis (specifically, the magnitude of the variability is measured as the radial distance from the origin of the plot), $R$ is shown on the grey arc, whereas the RMSE is indicated by the concentric brown dashed lines emanating from the observed point. The Taylor diagram performed on the entire study period (plot a) showed a quite similar performance of the models from 3 to 5, with model V be the best as presenting the highest correlation, the least RMSE and a reasonable similar variability compared with the observations, and the poor performance of model II was also confirmed. However, the Taylor diagram obtained on a 10-day heat-wave event (plot b) to assess how the models performed in capturing these events, pointed out differences, with models II and model V performing worst in comparison to models I and III. This result could be explained by the fact that the heat-wave events of 2003 were dominated by the long-rang transport component.

### Table 1. Predictive performance by model (on original scale).

| Models | Average Coverage RMSE $R^2$ |
|--------|-----------------------------|
|        | width 90% CI   | 90% CI |             |              |
| Model I | 23.67 0.91       | 5.26 0.58 |
| Model II | 45.55 0.88       | 11.11 0.04 |
| Model III | 21.51 0.91       | 5.11 0.61 |
| Model IV | 22.20 0.89       | 5.04 0.61 |
| Model V  | 20.40 0.89       | 4.75 0.63 |

Abbreviations: CI, credible intervals; RMSE, root mean square error.

### Table 2. Predictive performance of the models implemented using spatiotemporal varying intercepts (on original scale).

| Models | Average Coverage RMSE $R^2$ |
|--------|-----------------------------|
|        | width 90% CI   | 90% CI |             |              |
| Model Ia | 28.58 0.89       | 7.37 0.64 |
| Model IIa | 29.90 0.88       | 7.58 0.64 |
| Model IIIa | 28.43 0.92       | 6.84 0.65 |
| Model IVa | 28.59 0.91       | 6.89 0.64 |
| Model Va  | 27.18 0.91       | 6.05 0.64 |

Abbreviations: CI, credible intervals; RMSE, root mean square error.

Figure 5. Taylor diagrams showing the predictive performance of the five hierarchical models related to: (a) the entire period of study and (b) a 2003 heat-wave event (from 4 to 13 August 2003).
Instead, we found a strong effect of the site type described by mean concentration, for the fixed effects and for the variance parameters. The residual maximum distance.

| Parameters                      | Model I          | Model II         | Model III         | Model IV         | Model V          |
|---------------------------------|------------------|------------------|-------------------|------------------|------------------|
|                                  | Mean 90% CI      | Mean 90% CI      | Mean 90% CI       | Mean 90% CI      | Mean 90% CI      |
| s (intercept)                   | 3.243 3.242, 3.244 | 3.315 3.309, 3.322 | 3.251 3.252, 3.253 | 3.325 3.302, 3.347 | 3.253 3.251, 3.254 |
| \( \beta_{23} \) (road site)    | \(- \)           | \(- \)           | \(- \)            | \(- \)           | \(- \)           |
| \( \beta_{23} \) (kerb site)   | \(- \)           | \(- \)           | \(- \)            | \(- \)           | \(- \)           |
| \( \beta_{32} \) (Saturday)    | \(- \)           | \(- \)           | \(- \)            | \(- \)           | \(- \)           |
| \( \beta_{32} \) (Sunday or Public Holiday) | \(- \) | \(- \) | \(- \) | \(- \) | \(- \) |
| \( \sigma^2_i \) (range among sites of the posterior mean of variance) | 0.061–0.202 0.163–0.168 | 0.038–0.074 0.048–0.052 | 0.033–0.050 0.032–0.074 |
| \( \sigma^2_r \) (spatial effect variance for the local PM component) | \(- \) | \(- \) | \(0.066 0.024, 0.152\) | \(0.041 0.040, 0.042\) | \(0.042 0.041, 0.043\) |
| \( \sigma^2_{s2} \) (second order random walk variance for the temperature) | \(- \) | \(- \) | \(- \) | \(1.111 0.950, 1.300\) | \(0.006 0.005, 0.007\) |

Abbreviations: CI, credible intervals.

**Table 4.** Predictive performance by model obtained in the sensitivity analysis (on original scale).

| Models         | Coverage 90% CI | Average width 90% CI | RMSE  | \( R^2 \) |
|----------------|-----------------|----------------------|-------|-----------|
| Model I        | 0.93            | 31.52                | 6.91  | 0.52      |
| Model II       | 0.87            | 47.01                | 11.36 | 0.02      |
| Model III      | 0.92            | 29.62                | 6.65  | 0.57      |
| Model IV       | 0.89            | 28.54                | 6.65  | 0.53      |
| Model V        | 0.88            | 23.29                | 5.38  | 0.61      |

Abbreviations: CI, credible intervals; RMSE, root mean square error.

Sensitivity Analysis Results

Table 4 describes the results related to the predictive ability of our modelling approach on a restricted number of monitoring sites in north-west London. We found that the indices were consistent with those reported in the main analyses (Table 1).

We performed also an assessment of the sensitivity of findings to prior details and these analyses showed that the results were quite robust to these choices.

**DISCUSSION**

We have presented a Bayesian spatiotemporal approach for modelling particulate pollution concentrations in urban area for health risk studies. We combined air monitoring data with the output from a local-scale air pollution model and explicitly solved the problem of incorporating regional pollution concentrations within the city-scale assessment. Moreover, we assessed the effects of covariates to account for the residual spatiotemporal variation of particle concentrations. We evaluated the predictive performance of these statistical structures through a robust procedure of cross-validation that allowed us to compare the daily predictions with the observed PM\(_{10}\) concentrations within three validation sets of sites, which represented different urban environment (i.e. site types).

In particular, we applied our modelling approach to predict PM\(_{10}\) concentrations in Greater London, using a latent regional pollution process derived by rural sites to describe the long-range transport PM\(_{10}\) component and the output from ADMS-Urban to capture the local primary PM\(_{10}\) component.

ADMS-Urban is widely used for estimating urban-scale air pollution for regulatory purposes and in epidemiological air pollution studies.\(^{46,47}\) We found that the exclusive use of ADMS-Urban to predict the PM\(_{10}\) concentrations produces poor results. So far, although the inclusion of ADMS-Urban, in addition to a regional latent process, increases the predictive performance of the models, we suggest that the use of this deterministic output to measure the population exposure to PM in short-term epidemiological studies should be enhanced with the combination of other information sources characterising the study area, such as site-type or time-varying emission factors linked to day of the week, as evidenced by the strength of the covariates in our models.

In this implementation, we adopted an indicator variable for site types that is actually quite crude. The use of a more localised index of sites better reflecting land use and building geometry (canyon orientation for example) by utilising GIS techniques may further improve our model performance.
The final aim of our study was to assess air PM exposure models to use in short-term health effects studies in London. We therefore worked with the dense monitoring network available owing to the city size and the legal structures for local air quality management. To assess the applicability of our approach in urban environment with smaller number of monitoring sites, we performed a sensitivity analysis restricting the study area to a part of London matching the minimum requirements in EU directives. The results suggested that our approach will also perform well in smaller urban environments with more sparse monitoring networks, which are typical of many European cities.

Methodologically, the models presented here deviate from the standard space–time statistical modelling approach, which typically presents varying intercepts.4,6,8,14,16 As we were including in our models a set of covariates characterised by spatial and temporal variation, we assumed only time- and space-varying regression coefficients. To assess the plausibility of our approach in comparison with a classical modelling scenario, we developed five models, with independent spatiotemporal random effects. We assessed the predictive capability of these structures, and we found that our methodology, applied in an urban environment, performed better than the classical approach. This evidence suggests that, in context where local and urban primary emissions together with regional background data are not available, the inclusion in the models of independent error distributions is able to capture spatial and temporal dependencies. However, in context of analysis, where the researchers can perform extra modelling efforts, our proposed models perform better than a classical approach.

Finally, the hierarchical methodology that we proposed in this study provided a flexible way to model daily PM. This approach could also be applied to other environmental space–time processes (e.g. to model time series of different ambient primary or secondary pollutants) and used to predict non-daily data (e.g. hourly).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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