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DISPERSION PARAMETERS IN A WIND TUNNEL AND IN THE FIELD: ANALYSING THOMPSON'S 1991 WIND TUNNEL DATA FOR ISOLATED STACKS WITH IFDM, AND ITS APPLICATION TO BUILDING DOWNWASH MODELLING

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Abstract: In 1991, R.S.Thompson published 320 ground level concentration (glc) profiles measured in the US EPA meteorological wind tunnel; 311 glc profiles were for a source located near a building, 9 profiles over downwind distances from 50 mm to 10000 mm for isolated stacks ranging in height from 37.5 mm till 450 mm. First, we examined the measurements for an isolated stack. Glc-profiles were computed using the IFDM lateral and vertical dispersion parameters $\sigma_y(x)$ and $\sigma_z(x)$ for a neutral boundary layer as published by Bultynck-Malet in 1972. Only a minor change to these dispersion parameters was needed to reproduce all measured concentrations with a regression equation:
Observed Concentration = 0.9506 times Modelled Concentration.
Explained variance $R^2 = 0.9798$
This analysis links dispersion parameters in the field with those found in a wind tunnel. Implicitly, this also defines the scale between the wind tunnel and the field.
Next, we investigated the measured glc-profiles C(x,0,0,Hs) for a stack with height Hs in the presence of a building. We illustrate that these glc-profiles can be reproduced using a set of plumes that have a log-normally distributed height. These results could improve building downwash in bi-Gaussian models of the future.

Key words: *Bultynck-Malet, stability parameters, IFDM, atmospheric dispersion experiments, ground-level concentrations, isolated stack, wind tunnel****.***

INTRODUCTION

When analysing measured ground-level concentrations of heavy metals at industrial sites whose current impact exceeds the target values imposed for the year 2012 by the European Air Quality Daughter Directive 2004/207/EC, we found that these elevated concentrations were due not to unknown (fugitive) sources as assumed initially, but to small emissions released from small stacks on the roofs of the factory buildings (Lefebvre *et al.*, 2010).

It is known that fragments of plumes, released from stacks on building roofs, are often captured by the air stream passing over the building, and are dragged towards the ground within a distance of a few building heights or less. As a result, the ground-level concentration of pollutants in such a plume can be very high. Depending upon the heat content in such a plume and the thermal stratification of the air near the ground, ground-level concentrations in such plumes can be tens to hundreds of times greater than they would have been if the plume were not influenced by the turbulent flow over the building, as is illustrated by the atmospheric dispersion SF6 tracer experiments of Guenther *et al.* (1990), who emitted SF6 through the buoyant plume of a 35 MPH natural gas compressor turbine.

Field experiments are expensive. Their results are often hard to interpret as ambient atmosphere is usually rapidly changing and its complex structure might be not fully captured by the limited set of meteorological measurements that can be performed. A wind tunnel provides a more controlled environment for atmospheric dispersion experiments, even allowing duplication of experiments and performing series of dispersion experiments using a wide range of building and stack configurations under the same meteorological conditions, something that is impossible in ambient air.

A series of such experiments was conducted by R.S.Thompson (1990), who published 320 ground level concentration (glc) profiles measured in the US EPA meteorological wind tunnel: 311 glc profiles were for a source located near a building and 9 profiles over downwind distances from 50 mm to 10000 mm for isolated stacks ranging in height from 37.5 mm till 450 mm.

Air quality models are indispensable tools for cost effective air quality management. Good models guarantee that emission controls, including stack height, that are implemented to respect current or future air quality standards, will result in the desired ambient air quality without waste of money on undersized or oversized air cleaning installations. However, despite more than 40 years of model development and improvement, the state of the art for modelling building downwash effects in bi-Gaussian models at short distances from the building is rather poor, as illustrated by Olesen *et al.* (2009), who analysed the performance of several state-of-the-art models on the Thompson data set.

In order to help industry to meet the future air quality standards, we needed some model able to predict ground-level concentrations at very short distances from buildings with short stacks. Therefore, a parameterisation of the Thompson dataset seemed a useful tool.

STANDARD BI-GAUSSIAN FORMULAS

Equation (1) is the bi-Gaussian plume equation for the distribution C [kg/m^{-3}] in a plume of the mass Q [kg/s^{-1}] that originates from the top of a stack of height H_S. The origin of the co-ordinate system with axes x, y, z is at the foot of the stack. x, y and z are in respectively the along wind direction, the horizontal and the vertical cross-wind direction. $u(H_S)$ is the wind speed at stack orifice height.

$$C(x,y,z,H_S) = \frac{Q}{2\pi\ u(H_S)\sigma_y(x)\sigma_z(x)} \exp\left(-\frac{1}{2}\left\{\frac{y}{\sigma_z(x)}\right\}^2\right) \sum_{i=\{-1,1\}} \exp\left(-\frac{1}{2}\left\{\frac{H_S - iz}{\sigma_z(x)}\right\}^2\right) \qquad (1)$$

The summation is needed because the material in the plume is reflected at ground-level. The functions $\sigma_y(x)$ and $\sigma_z(x)$ are the standard deviation of the mass distribution at a distance x from the plume origin. We consider them having a form:

$$\sigma_y(x) = a\, x^{\alpha} \tag{2a}$$

$$\sigma_z(x) = b\, x^{\beta} \tag{2b}$$

where the coefficients a and b, and the exponents α and β depend upon terrain type and atmospheric stability. Table 1 gives the values a , b, α, β for the Bultynck-Malet stability classification system (see later paragraph.)

If z=0 and y =0, equation (1) gives the ground-level concentration profile under the plume axis and can be simplified to

$$C(x, y=0, z=0, H_S) = C(x, H_S) = \frac{Q}{\pi\ u(H_S)\sigma_y(x)\sigma_z(x)} \exp\left(-\frac{1}{2}\left\{\frac{H_S}{\sigma_z(x)}\right\}^2\right) \tag{3}$$

SOURCE STRENGTH AND VERTICAL WIND SPEED PROFILE

Description of the wind-tunnel

The test section of the US EPA meteorological open-circuit wind tunnel is 3.7 m wide, 2.1 m high and 18 m long. For the Thompson 1990 experiments, the floor is covered with gravel coated panels, the gravel stones being up to 10 mm diameter.

Source strength

Thompson reports ‘dimensionless’ concentrations (non-D Conc), obtained by multiplying the measured concentrations with $u_\infty * H_b^2/Q$, where u_∞ is the free flow wind speed in the tunnel, H_b is the height of the building used in the building downwash experiments and Q is the source strength. Practically, this means that the concentration reported by the Gaussian transport and diffusion equation for a unit source strength must be multiplied with $4*(150^2)$.

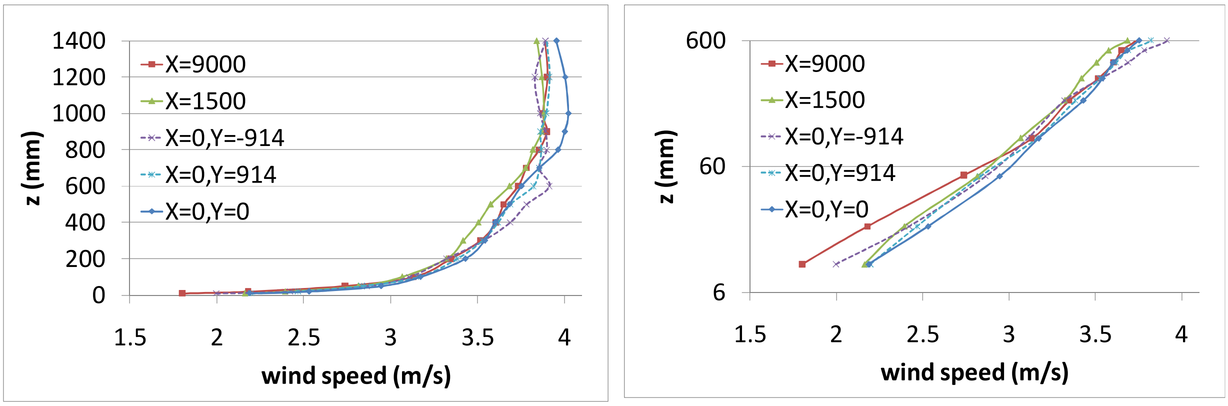

Figure 1: Vertical wind speed profiles in wind tunnel in absence of building at stack (X=0) and some crosswind /downwind distances

Wind speed profile

The wind speed in the wind-tunnel boundary layer, measured (Figure 1) at nine positions between heights z 10 till 700. The increase in height can be fitted equally well by the exponential law (equation (4a)) as by the logarithmic law (eq.(4b)):

$$u(z) = 2.2\ (z/10)^{0.136} \qquad u(z)=0.35\ \ln[(z-2.62)/0.015] \qquad (4a)-(4b)$$

The free-stream wind speed is 4 m/s, which, according to the above relation, is reached at z = 800. (Wind speed at z=75 is about 3 m/s.)

DISPERSION PARAMETERS IN THE FIELD AND WIND TUNNEL

The Bultynck-Malet Stability Classification system

Table 1 summarizes the Bultynck-Malet stability classification system. It is based on the bulk-Richardson number[3] S determined by the difference of the potential temperature between 114 m and 8 m and the square of the wind speed at 69 m, determined along a 120 m high meteorological tower over a sub-urban park-like (conifer trees) terrain in Mol, Northern Belgium. The dispersion parameters[4]$\sigma_y(x)$ and $\sigma_z(x)$ have been determined from wind fluctuations at 69 m. For each stability class, wind fluctuations have been measured for at least 30 different periods where the meteorological parameters remained

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[3] S is actually the bulk-Richardson number where all physical constants have been removed.

[4] Bultynck-Malet first determined analytical formulae that express $\sigma_y(x)$ and $\sigma_z(x)$ as a function of the bulk-Richardson number S and the stability parameters for neutral stability, next they derived the discrete scheme given in Table 1.

quite constant over one hour each. The system can be correlated to meteorological observations from lower heights, in which case altitude of the sun above the horizon and wind speed are the most relevant parameters for day time conditions and wind speed (and to a lesser extend cloudiness) are relevant during night time conditions. The dimensions of the correlated functions are ‘production or loss of heat at ground’, divided by the third power of the wind speed.

Initial assumption on scales

Because the rate of dispersion is not a linear function of downwind distance (see later paragraph), we must make an assumption on the scale of the wind-tunnel. We assume that the wind-tunnel is a 1/1000 scale model of the field. This is a rather arbitrary decision. If the assumption is very wrong, we will find a great difference between the dispersion parameters derived in the field and those needed to replicate the observed concentration ground-level concentrations in the wind-tunnel.

Dispersion parameters for the wind tunnel and results

Using the values $a(E_3)$and $b(E_2)$ from Table 1, equations (2a) and (2b) give the dispersion parameters for the wind tunnel observations (scale up to fields size) with following values for a and b:

$$a(hs) = a(E_3) - 0.0001(4.5hs+500) \qquad (5a)$$

$$b(hs) = b(E_2) + 0.0001(4.5hs-0.0005(hs-150)\hat{}2) \qquad (5b)$$

The resulting reproduction of the observed ground-level concentrations can be seen in Figure 2. Visual agreement is excellent, as is confirmed by the regression equation: observed = 0.9506 reproduced and by the explained variance R^2 = 0.9798. The dependence of the values of a and b in equations (5a) and (5b) could be related to changes of the wind speed profile along the wind tunnel (which are visible on Figure 1) and are not necessarily of the same nature in the field.

So the dispersion parameters for the wind tunnel experiments are found to be in between field dispersion parameters for neutral and slightly stable atmosphere over park-like suburban terrain. The values of the coefficients a and b found for the wind tunnel assuming a 1/1000 scale (Table 2) are between those found in the field by Bultynck and Malet for slightly stable to neutral stability. *The exponents α and β, that define the decrease of the ground-level concentrations with distance after the maximum ground-level concentration has been reached, are found to be the same for wind tunnel and the Mol terrain.*

Coefficients a and b for the wind tunnel length-scale

Equations (5a)- (5b) give values for the coefficients a and b in equations (2a)-(2b) that are valid for field scale values of x, y and z where x and y are in the range from 10 m to 30 km and z is in the range of 1 to 1000 m.

Now look at the ground-level concentration profile for H =188 m in Figure 2. The maximum calculated nonD-concentration is found at x = 3200 m, and is 0.103. At this place, $\sigma_y(x)$ = 230 m and $\sigma_z(x)$ = 188 m.

Next, consider the same plume using wind tunnel lengths. The ground-level concentration profile for H =0.188 m (Figure 2) has a measured maximum nonD-concentration at x = 3.200 m. At this place, one expects $\sigma_y(x)$ = 0.230 m and $\sigma_z(x)$ = 0.188 m, because basically, all distances are divided by 1000.

However, using equations (5a)-(5b), one finds: $\sigma_y(x) = (a(3.2)^{\alpha}) = 0.98$ m and $\sigma_z(x) = b(3.2)^{\beta} = 0.96$ m, which is respectively 4 and 7 times larger than allowed by the similarity-requirement of the material distribution in the plume between the two length scales. The problem is easily solved. If x is scaled down by a factor 1000, x^{α} shrinks by only a factor $(0.001)^{\alpha}$. For α=0.796, this factor is 4.09 times too large, and for β =0.711, the factor is 7.362 too large. Consequently, for use on the millimeter length scale of the wind tunnel, the coefficients a and b to be used in equations (2a)-(2b) must be divided by respectively $(0.001)^{\alpha}$ and $(0.001)^{\beta}$.

Determining the wind tunnel scale for the Mol terrain

We can now look for which scales equations (5a) and (5b) give a value for the coefficients a and b as close as possible to those, observed in the field by Bultynck-Malet, and find:

- a close match with dispersion under neutral conditions is found for the 200 mm stack at a scale 1÷ 2026 , where eqs. (5a)-(5b) give; $a(hs)$=0.425 and $b(hs)$=0.512, compared with $a(E_3)$=0.418 and $b(E_3)$=0.52 in Table 1;
- a close match with dispersion under slightly stable conditions is found for the 250 mm stack at a scale 1÷586 , with $a(hs)$=0.309 and $b(hs)$=0.38, compared to $a(E_2)$=0.297 and $b(E_2)$=0.382 in Table 1.

So the initial guess of a 1÷1000 scale is close to the geometric average of the above two scales.

The wind speed exponents in wind tunnel and (Mol) field are however different, the increase with height in the wind tunnel being less steep than in the field.

Fortunately, the question of the scale between wind tunnel and the field is crucial only when one uses wind tunnel data to determine values for coefficients in equations for use in the field or inversely. This is, in this paper, not our intention to do.

The lesson to remember from all this, is that the coefficients of the dispersion parameters in equations (2a)-(2b) depend upon the distance scale they have been determined for. *The values of the exponents α and β however are scale invariant.*

PROPOSED FORMULA FOR BUILDING DOWNWASH PLUMES

Based on own visual observations of water vapour plumes from small heating installations (dwellings) in urban and rural regions during winter time, it seemed logical to investigate whether the impact of a plume subject to building downwash could be computed by replacing the single plume by a set of sub-plumes, having a log-normal type distribution of height and pollutant mass[5]. This paper only gives some elements of the formulas found. Using the bi-Gaussian transport and dispersion equation form, the ground-level concentration due to such a set of sub-plumes is of the form:

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[5] In PRIME, the plume is split in two plumes only, one carrying a part of the pollutant mass inside the cavity, the other plume being outside the cavity. In our approach, the concept of ‘cavity’ is not used, but the mathematical formulas we find to describe the ground-level concentrations can be used to quantify some properties of that ‘cavity’ concept.

Table 1: The Bultynck-Malet stability classification system, as determined along a 120 m high meteorological tower over a sub-urban park-like (conifer trees) terrain in Mol, Northern Belgium

Stability class	Index E_i	$\sigma_y(x)=a(E_i)x^\wedge\alpha$		$\sigma_z(x)=b(E_i)x^\wedge\beta$		criterion (‡)		Exponent of wind speed profile
		a	***α***	***b***	***β***	***S>0***	***S<0***	
stable	E1	0.235	0.796	0.311	0.711	λ > 2.75		0.53
sightly stable	E2	0.297	0.796	0.382	0.711	1.75 <= λ <= 2.75		0.4
neutral	E3	0.418	0.796	0.52	0.711	λ <= 1.75 .or.	λ <= 2.	0.33
slightly unstable	E4	0.586	0.796	0.7	0.711		2 <= λ <= 2.75	0.23
unstable	E5	0.826	0.796	0.95	0.711		2.75 <= λ < = 3.3	0.16
very unstable	E6	0.946	0.796	1.321	0.711		λ > 3.30	0.1
storm	E7	1.043	0.698	0.819	0.669	wind speed (69m) > 11 m/s		0.33

‡ : λ = log10 (abs (S) * 10 ^6

with: S =(((T(114m) - T(8m)) / (114. - 8.)) + (0.0098)) / (wind speed (69m)^ 2)

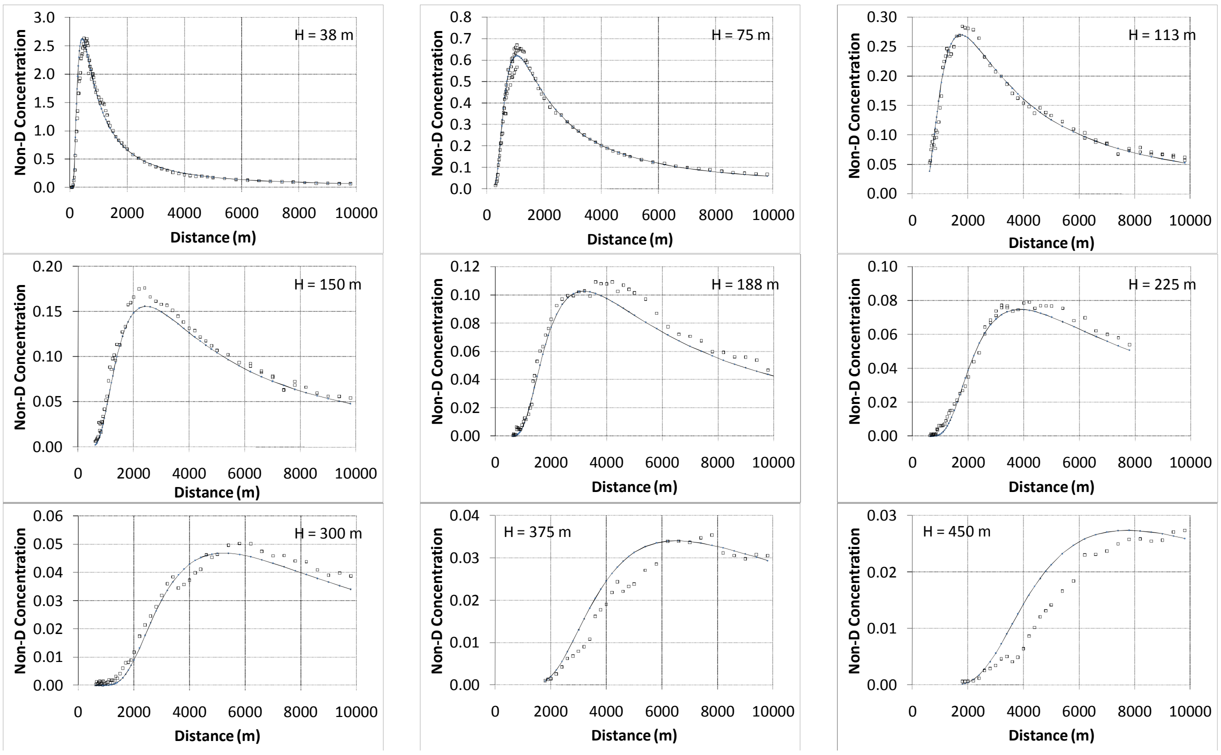


Figure 2: Reproduced (line) and observed (dots) ground-level concentrations measured in the wind tunnel for isolated stacks with heights ranging from 38 m to 450 m (assuming a 1mm ÷ 1m scale)

Table 2: Coefficients of dispersion parameters in the field (Bultynck-Malet) and in the wind tunnel, assuming a scale 1÷1000. Values of comparable magnitude in the Field and in the Wind tunnel are connected by arrows

	Field			Wind tunnel	
Field	a	b	H_stack	a	b
E2	0.297	0.382			
			38	0.441	0.350
			75	0.424	0.367
			113	0.407	0.385
			150	0.391	0.402
			188	0.373	0.419
			225	0.357	0.435
			300	0.323	0.468
			375	0.289	0.500
			450	0.256	0.532
E3	0.418	0.52			

$$C(x_{receptor-S},0,0,H_{S},H_{building},X_{S-building})=\int_{-\infty}^{+\infty}\frac{Q_{zp}}{\pi u(h_{zp})\sigma_y(x^*)\sigma_z(x^*)}\exp\left(-\frac{1}{2}\left\{\frac{h_{zp}}{\sigma_z(x^*)}\right\}^2\right)dz_p \qquad (6)$$

where the subscript z_p refers to the log-normal type distribution and x^* is a virtual distance takes into account the increased turbulence near the building, and, for some stack-building configurations, additional mixing of streamlines over a small interval along the plume trajectory. The log-normal type distribution is defined by:

$$\exp\,(\,\ln(h_0\,)-|z_p\,|\,\sigma_h(x^{**}))$$

Due to the absolute sign around the eccentricity variable z_p, all heights are smaller (or at most equal to) h_0. Nevertheless, we call h_0 the 'median' height of the plume set. We use $\Sigma(x)$ to denote the distance between h_0 and exp ($\ln(h_0\,)-\sigma_h(x^{**})$). Using these symbols, 68% of the pollutant mass emitted is assigned to plumes at heights between h_0 and $h_0-\Sigma(x)$.

For each sub-plume, the transport wind speed $u(h_{zp})$ and the coefficients a and b of the dispersion parameters are computed using the sub-plume height h_{zp} in equations (4a)-(5a)-(5b).

REPRODUCING GROUND-LEVEL CONCENTRATIONS FOR PLUMES SUBJECT TO BUILDING DOWNWASH

Figure 3 shows ground-level concentration profiles for plumes of several stack heights with and without building. The stacks, ranging in height from 1 to 2.5 times the (cubicle) building height (150mm), are located on the downwind side of the building.

Upwind displacement of the virtual source is about 250 mm, the 'median' plume height h_0 is 50 mm below the stack orifice. $\Sigma(x)$ reaches a maximum of 50 mm at the location of the maximum ground-level concentration.

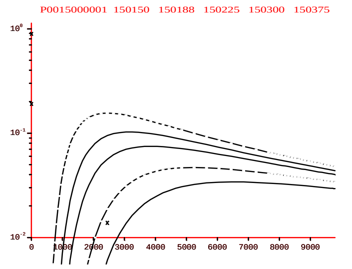
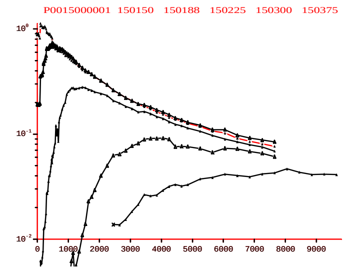
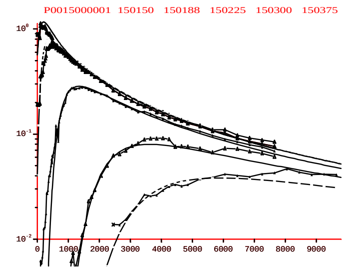
without building, reproduced by equations (5a),(5b)	measured with cubical building, stacks at wind downward side of building	measured + reproduction by equation (6)
		

Figure 3: Ground-level concentration profile for emissions through stacks of 150, 188,225, 300 and 375 mm.

CONCLUSIONS

In the last part of this paper, we showed that the ground-level concentrations, measured in a wind tunnel under a plume subject to building downwash, can be reproduced using a set of bi-Gaussian plumes. Leaving some details apart, these plumes have a lognormal-type distribution of height and pollutant mass. In the model we are developing, each sub-plume is subject to dispersion as if there was no building in the wind tunnel.

Therefore, we determined in the first part of the paper the dispersion parameters needed by a bi-Gaussian model to reproduce the observed ground-level concentrations for wind tunnel plumes of different heights in absence of a building.

Finally, we investigated the relation between dispersion on the length scale of a wind tunnel and on the length scale of field (or ambient atmosphere). A scale ratio of 1 mm wind tunnel to 1 m in the field in both x, y and z direction was found to be a good approximation.

As a result, incorporating this in a bi-Gaussian plume model could strongly increase the capacity of the model of predicting pollutant concentrations in the vicinity of buildings neighbouring emission sources.

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