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Spatially-varying surface roughness and ground-level air quality in an operational dispersion model ☆

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ABSTRACT

Urban form controls the overall aerodynamic roughness of a city, and hence plays a significant role in how air flow interacts with the urban landscape. This paper reports improved model performance resulting from the introduction of variable surface roughness in the operational air-quality model ADMS-Urban (v3.1). We then assess to what extent pollutant concentrations can be reduced solely through local reductions in roughness. The model results suggest that reducing surface roughness in a city centre can increase ground-level pollutant concentrations, both locally in the area of reduced roughness and downwind of that area. The unexpected simulation of increased ground-level pollutant concentrations implies that this type of modelling should be used with caution for urban planning and design studies looking at ventilation of pollution. We expect the results from this study to be relevant for all atmospheric dispersion models with urban-surface parameterisations based on roughness.

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1. Introduction

It has been estimated that over 1 billion people are exposed to poor air quality, and that it causes 1 million premature deaths each year (World Health Organization, 2005; United Nations, 2010). In principle, there are four ways to reduce exposure to poor urban air quality and improve the health of the inhabitants of a city: reduce overall emissions (Mayer, 1999); increase the depositional sink for pollutants (Nowak et al., 2000); relocate people and/or polluting industries (i.e., better segregation between pollutant sources and vulnerable populations) (Okuda et al., 2011); or improve the ventilation of city neighbourhoods and streets (Vardoulakis et al., 2011).

The ventilation of a city is intricately linked with urban form because urban form (i) controls the overall aerodynamic roughness of the urban area, (ii) produces specific quasi-stationary modifications to the impinging flow (e.g., venturi effects, cross-wind flows, wakes, vortices, etc), and (iii) interacts with the radiative and turbulent energy transfer between surface and atmosphere, and effects heat storage in the underlying surface or buildings. Surface aerodynamic roughness is a function of the spatial density, orientation and height of obstacles to the wind and plays a significant role in how air flow interacts with the urban landscape (Mahrt, 1999; Holland et al., 2008; Di Sabatino et al., 2010; Salizzoni et al., 2011). Historically, few users had the computational power to model spatially varying roughness, hence single (fixed) values were adopted (Rotach, 1993; Kastner-Klein et al., 2004). However, it is now possible to account for the effects of variable surface roughness using models that run on desktop computers (Edussuriya et al., 2011; Millward-Hopkins et al., 2011; Soulhac et al., 2011).

In classical, one-dimensional, boundary-layer theory, surface roughness is parameterized through the roughness length (z_0), which is equivalent to the height where the mean wind speed becomes zero (Seinfeld and Pandis, 2006; Holland et al., 2008; Li et al., 2009). is approximately one thirtieth of the height of the surface roughness elements, with values ranging from 1.5 m for large urban areas, to 0.5 m for open suburbia and 0.1 m for parkland (Rotach, 2001; Hang and Li, 2011; Wania et al., 2012). Roughness length varies greatly from the dense, compact and often high-rised city centres to the more homogeneous areas found on the outskirts, especially those of older European cities (Grimmond and Oke, 1999; Roth, 2000; Ng et al., 2011). Spatially-variable roughness creates

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horizontal variations in turbulence and the local mean flow, both of which can affect pollutant dispersion.

Overall, the degree to which an urban form promotes the removal and dilution of pollutants is encapsulated in the concept of 'urban breathability' (Bottema, 1997; Monks et al., 2009; Buccolieri et al., 2010; Panagiotou et al., 2013), which is defined by Neophytou et al. (2005) and Buccolieri et al. (2011) as a parameter indicating the potential of a city to ventilate itself through the exchange of pollutants, heat, moisture and other scalars with the atmosphere above. Operational dispersion modelling does not explicitly simulate the urban canopy and its exchange with the planetary boundary layer above, but attempts to capture "breathability" through canyon parameterisations and aerodynamic roughness.

ADMS-Urban is a tool for modelling air quality at a city-wide scale, and can include industrial, domestic and traffic emissions. Many recent studies have verified the accuracy of the model (Courthold and Whitwell, 1998; Righi et al., 2009; Mohan et al., 2011), while others have used it to assess the effects of climate change on air quality (Athanassiadou et al., 2010) or to estimate background urban carbon monoxide concentrations (Leuzzi et al., 2010). Additionally, many local authorities use ADMS-Urban to evaluate changes in air quality associated with major infrastructural developments, or to assess the potential impact of traffic management schemes (Oduyemi and Davidson, 1998), or changes in fleet composition (Rexeis and Hausberger, 2009).

The current version of ADMS-Urban allows users to model the spatial variation of surface roughness over a given modelling domain. In previous versions of the model, users were restricted to specifying a single roughness value for the entire urban area, or else modelling the spatial variation of terrain height together with the surface roughness. ADMS-Urban is proprietorial model code, although details of the algorithms are available via the company website and are based on research published in various journal articles (Carruthers et al., 2001). It is a steady-state quasi-Gaussian plume model, which contains the FLOWSTAR model (Belcher and Hunt, 1998) for calculating the spatial variation of flow field and turbulence parameters that drive the dispersion. FLOWSTAR calculates the perturbations to the mean wind speed boundary layer profile, u, which is formulated as:

$$u(z) = \frac{u_*}{\kappa} \left[\ln\left(\frac{z + z_0}{z_0} \right) + \psi(z, z_0, L) \right] \tag{1}$$

This formulation illustrates that the mean wind speed at height z is a function of surface roughness z_0, stability through the function ψ, and the friction velocity u_* (κ is the von Kármán constant and L is the Monin-Obukhov length).

It is useful to note at this point that the expression for the mean wind speed used in ADMS-Urban (1) does not allow for the displacement of the wind speed profile to above the urban canopy. Instead, the local value of z_0 represents the mixing close to the surface, and is related to the building height. An alternative formulation, that includes this zero-plane displacement height, d, is given by:

$$u(z) = \frac{u_*}{\kappa} \left[\ln\left(\frac{z - d}{z_0} \right) + \psi(z, z_0, L, d) \right] \tag{2}$$

This paper has two aims.

- To assess changes in model performance resulting from the implementation of variable roughness values in ADMS-Urban, and
- To use the best model representation to assess the air-quality benefits of improving ventilation.

Based on the literature discussed above, our hypothesis is that selectively decreasing surface roughness for part of the built-up urban area will improve ventilation and hence reduce local pollutant concentrations. To examine our hypothesis, we must undertake the first evaluation of the effect of spatially-varying roughness in ADMS-Urban. To aid interpretation of the modelling, we will work in the framework of the Gaussian Plume Equation (GPE, see Seinfeld and Pandis (2006) ch. 18), a commonly used version of which is:

$$C(x,y,z) = \frac{q}{2\pi\sigma_y\sigma_z\langle u \rangle} \exp\left(-\frac{y^2}{2\sigma_y^2} \right) \left[\exp\left(-\frac{(h-z)^2}{2\sigma_z^2} \right) + \exp\left(-\frac{(h+z)^2}{2\sigma_z^2} \right) \right] \tag{3}$$

where C is the concentration at point (x,y,z) (kg m^{-3}) which is directly proportional to q, the mass emission rate (g s^{-1}) (Turner, 1994). σ_y is the standard deviation of Gaussian distribution function in direction y (m), σ_z is the standard deviation of Gaussian distribution function in direction z (m), $\langle u \rangle$ is the wind speed (m s^{-1}) averaged over the vertical and horizontal domain of the dispersion model, and h is the effective plume release height (m), which for road vehicles is taken as 1 m in ADMS-Urban. The σ parameters depend principally on the travel time of the pollutant from the source and the relevant components of the turbulent velocities, which near the ground depend principally on the surface friction velocity, which in turn is a function of surface roughness. The domain-average wind, $\langle u \rangle$, depends on the geostrophic wind and surface roughness. Both the plume spread and mean wind speed depend on stability effects.

The effect of changing roughness on ground-level pollutant concentrations near a ground-level source will therefore depend on the relative sensitivities to z_0 of σ_z and σ_y on the one hand (see the appendix), and of $\langle u \rangle$, sensitivities which will tend to have opposing effects on pollutant concentrations at a given point. This is discussed further below where we refer to the opposing effects as being the *turbulent mixing* (i.e., the σ_z and σ_y) *sensitivity* and the *horizontal ventilation* (the $\langle u \rangle$ *sensitivity*).

2. Model set-up, evaluation, and effects of variable roughness

As our test case, we use a modelling scenario for central Birmingham, UK. The model area of interest covered 6.5 km^2 of Birmingham city centre (UK grid reference for the bottom-left corner − 406274, 285376), containing over 300 road sources (Fig. 1). ADMS-Urban allows for the effects of street canyons when modelling pollutant concentrations, and many of the roads in the area of interest were classified as canyons with heights varying from 5 to 20 m. The 2008 emission inventory built into ADMS-Urban was used to model traffic emissions, while background pollutant concentrations were obtained from the UK government's Automatic Urban and Rural Network (AURN) of air quality monitors, where one monitor is situated within the city centre (www.uk-air.defra.gov.uk). Annual mean backgrounds of 34.8 μg m^{-3} and 23.1 μg m^{-3} were adopted for NO$_x$ and NO$_2$, respectively. One year of hourly sequential meteorological data from Coleshill Met station (inset, Fig. 1) was used in the model runs. We follow standard practice in choosing a meteorological station close to, but not inside the urban area of interest (Oke, 2006). This is because meteorological data from within an urban area have well-known problems of representativeness. The ADMS-Urban modelling suite, used in this study, includes a meteorological pre-processor that accounts for the change in roughness associated with moving from rural to urban land cover.
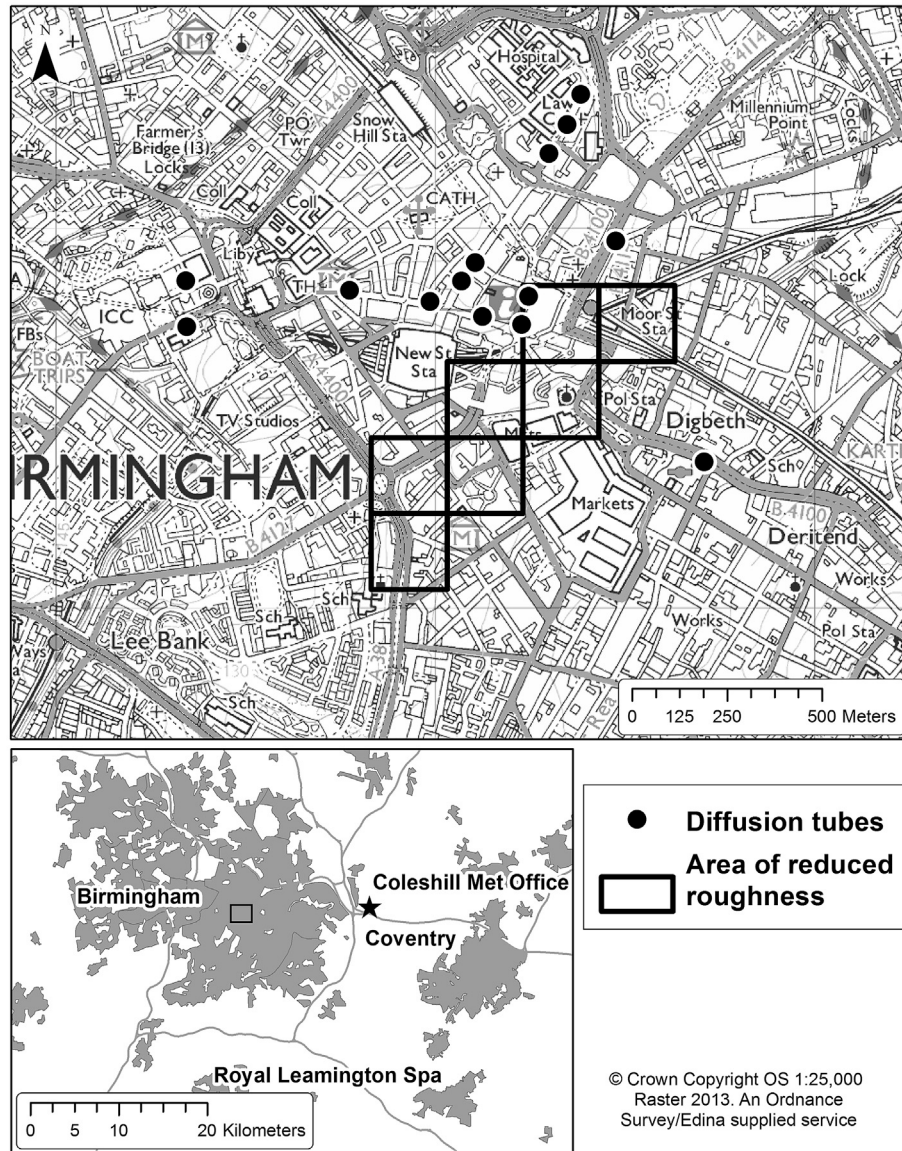
Fig. 1. A map of Birmingham City centre with the diffusion tubes and area of reduced roughness illustrated. The smaller inset map highlights where the area of interest was situated within Birmingham, along with the relative position of the Coleshill meteorological station.

Observed pollutant concentrations were obtained from NO_2 diffusion tube data, made available by Birmingham city council. The exposure time of the diffusion tubes was four to five weeks, and the concentrations were calculated in accordance with guidelines from DEFRA (2009). Fourteen diffusion tubes were included in the study. The coordinates of the diffusion tubes were defined as receptors and ADMS-Urban was used to simulate annual mean concentrations at these specific points.

ADMS-Urban version 3.1 was initially run with a single fixed roughness value of 1.5 m, which is representative of a large city centre (Wieringa, 1993); the model was then run again using a variable roughness file over the same area. The variable roughness file was created by Brade (2011) from airborne LIDAR data and digital map data in a GIS at 200 m spatial resolution. The file comprised 168 points with a mean roughness value of 1.44 m. Urban surface roughness is, in principle, also a function of wind direction, because the roughness is affected by the orientation of buildings with respect to the wind; this wind-direction-dependence was not accounted for in the current study.

Table 1 compares the mean of the observed and modelled concentration data over all sites (Oreskes et al., 1994). Table 2 summarises related statistics, as calculated by the 'openair' software package (Carslaw and Ropkins, 2012).

Tables 1 and 2 clearly indicate that both models have a tendency to over-estimate the observed NO_2 concentrations. The likely explanation for this is that the background concentrations were taken from within the urban area modelled (as opposed to using rural values), which will lead to some double counting of pollution. Whilst improvements to the model set up would be possible, the main aim of this paper is to assess the change in model behaviour

Table 1
Summary of mean concentration ($\mu g\ m^{-3}$) of NO_2 over all sites.

	Observed	Fixed surface roughness	Variable surface roughness
Mean	44.2	53.6	50.0

Table 2
Summary of statistics relating to the ability of the ADMS-Urban model to predict the observed concentrations at the 14 receptors used in the study. Note that the Index of Agreement provides an overall indicator of model quality; the parameter ranges between −1 and +1, with values approaching +1 representing better model performance.

Definition of surface roughness parameter	Proportion of points within a factor of two of the observed data (FAC2)	Mean bias (MB)	Mean gross error (MGE)	Normalised mean bias (NMB)	Normalised mean gross error (NMGE)	Root mean square error (RMSE)	Pearson correlation coefficient (r)	Index of agreement
Fixed	100%	9.4	9.8	0.21	0.22	13.8	0.67	0.07
Variable	100%	5.8	6.8	0.13	0.15	9.6	0.72	0.35

due to the inclusion of a spatially varying surface roughness file, in order to assess its suitability for modelling changes to building density within an urban area. The statistics clearly indicate that better model performance was achieved when using variable as opposed to fixed surface roughness. ADMS-Urban was therefore re-run with variable surface roughness across the area of interest to a regular grid of receptors (90 by 90) to create a 'base case' against which subsequent runs could be compared.

3. Reduced roughness scenarios

To assess whether, through the horizontal ventilation effect, a significant reduction in pollutant concentrations could be achieved without reducing emissions, a sizeable area of Birmingham city centre was modelled with a reduced roughness length. Selected values in the spatially varying roughness file were reduced for two modelled scenarios: z_0=0.5 m and z_0=0.1 m (Fig. 2), corresponding, roughly, to replacement of buildings with urban parkland and grassland, respectively (Turner, 1994). (Note that this study does not take explicit account of the effects of vegetation on air pollution (see, e.g., Donovan et al. (2005); Pugh et al. (2012)) other than through modification of the roughness length). Street canyons were also removed from ADMS-Urban over the corresponding area. The spatially varying differences between the "base case" and the z_0=0.1 m case are given in Table 3. (Results for the z_0=0.5 m case are similar in pattern but smaller in magnitude.) The extra computational power required to generate output for 8100 receptors meant that representative meteorology, based on annual mean values of

meteorological variables, was used in place of the hourly sequential data that had been used in the model evaluation. Wind direction was therefore input as 200°, wind speed 3.8 m s^{-1}, temperature 9.8 °C and cloud cover as 5.3 Oktas. Table 3 shows that there was an overall mean increase in pollutant concentration in all of the squares for NO$_2$, and in most of the squares for NO$_x$, with a very small decrease in squares D and H. Maximum NO$_2$ increases in most squares (row 3 of Table 3); this is because most of the maximum concentrations in the base case do not occur near streets modelled as street canyons by ADMS-Urban.

The difference between the "base case" and the runs with roughness reduced to 0.1 m can also be seen in Fig. 3. The black areas indicate an increase in ground-level NO$_2$ and NO$_x$ concentrations whilst the grey areas indicate a decrease in concentrations. The difference in the maximum concentration is far greater for NO$_x$ than it is for NO$_2$, but the increases are less spread out and more focused on street corridors. This is to be expected as the primary source for NO$_x$ is traffic emissions, while NO$_2$ concentrations can be increased when NO reacts with O$_3$. In spite of this, concentration increases at ground level dominate for both pollutants.

The case-study NO$_2$ concentration contour was generated at 4-m increments from ground level up to a height of 20 m above ground level, across each square. For all the squares with reduced roughness length (A to G), reducing roughness increased pollutant concentrations below 5 m but reduced concentrations above that height (Fig. 4). In the two sample squares where the roughness length had not been not reduced (H and I), the model runs with
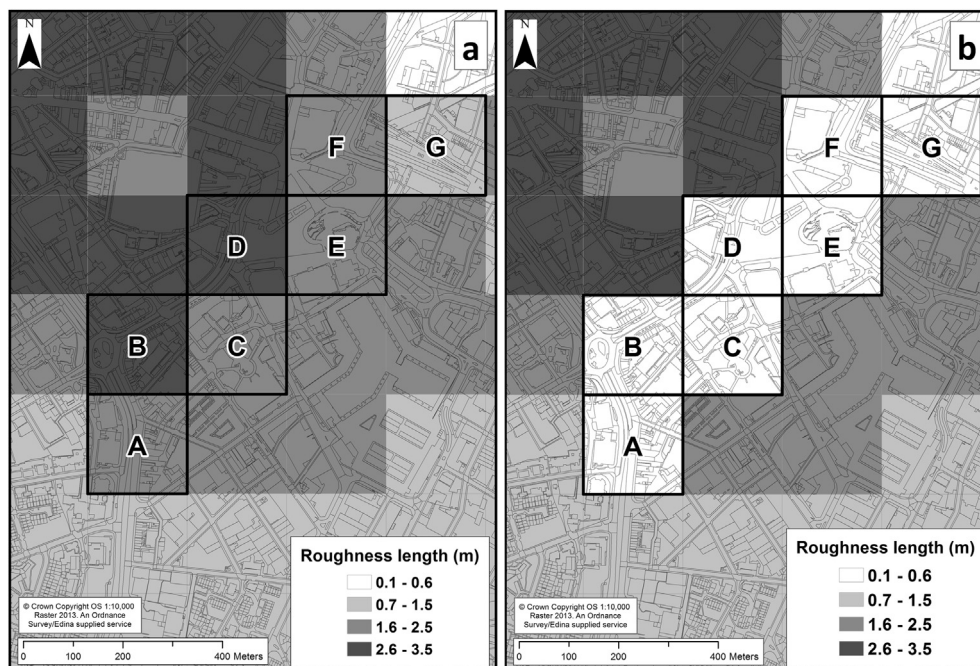
Fig. 2. Variable surface roughness. Figure 2a shows the urban roughness of Birmingham city centre at present, while Figure 2b highlights the reduction in surface roughness (m) to simulate an urban parkland. The roughness length has been decreased initially to 0.5 m, and then to 0.1 m, diagonally through the squares A to G. Each square is 200 × 200 m.

Table 3
ADMS-Urban results (μg m^{-3}) for 'base case' and runs adopting reduced surface roughness values. The letters on the top row relate to the squares in Figs. 2 and 3. The results from two extra squares, H and I, were used to reference additional pollutant changes (Fig. 3). The values are summarized for each square at *ground level*. The differences in concentration relate to the modified results minus the unmodified results.

	A	B	C	D	E	F	G	H	I
Base case (unmodified) roughness length, m	1.7	3.1	2.0	2.5	2.1	2.3	1.3	3.0	0.4
Modified roughness length, m	0.1	0.1	0.1	0.1	0.1	0.1	0.1	3.0	0.4
Difference in maximum NO$_2$ concentration	12.0	11.0	2.7	−1.8	13.7	0.7	4.0		1.9	3.4
Difference in minimum NO$_2$ concentration	−0.8	−0.9	0.1	1.3	−0.3	0.1	0.1		0.7	1.2
Mean NO$_2$ change (increase) over square	2.4	4.8	1.8	1.6	2.3	2.2	3.2		1.2	2.2
Difference in maximum NO$_x$ concentration	80.5	72.3	28.8	−37.4	17.7	−9.8	8.4	−36.0	4.1
Difference in minimum NO$_x$ concentration	−0.7	−0.7	0.5	1.0	−0.2	−0.1	1.6		1.5	1.1
Mean NO$_x$ change (increase) over square	11.4	14.7	7.8	−0.2	7.3	7.8	7.9		−0.2	2.0

reduced roughness in the other sample squares had higher pollutant concentrations at all heights (Fig. 4).

3.1. Seasonal variations

To assess the impact of seasonal variations, meteorological data from the Coleshill site for the months of February and August were again used. Typical meteorological days were compiled for each month and the model re-run. The biggest differences between the two months were temperature and wind speed (February: wind speed 6 m s^{-1}, direction 250°, cloud 4 oktas, temperature 7.8°C; August: wind speed 2.5 m s^{-1}, direction 225°, cloud 3.5 oktas, temperature 14.3°C). The results for the seasonal runs (Table 4)

bracket the annual average results given in Table 3. In all cases, reducing surface roughness increases mean ground-level NO$_2$ concentrations in boxes A-I. The effect is smallest in the February case, when wind speeds are high and temperatures moderately low (i.e., neutral stability).

4. Discussion

The localized reduction in roughness length from a maximum of 3.1 m–0.1 m has resulted in a localized increase in ground-level concentrations (and due to mass conservation, reduction in concentrations above ground-level). The effects seen are not uniform, due to the heterogeneous nature of the street plan for Birmingham city centre, and different volumes of traffic along each street, but patterns are consistent. Following our discussion around Equations (1) and (2), we can say that, for our case study, the *turbulent mixing* effect dominates over the *horizontal ventilation* effect. Modelled concentrations above ground-level (above about 5 m) decrease when roughness is reduced, consistent with a redistribution of pollutant through reduced vertical mixing when roughness is reduced. Overall, the effect of decreasing surface roughness in the model is to worsen ground-level air quality, which would thus increase calculated human exposure. This is true in our case study even though the built environment parameterisation used in the model includes street canyons. We would expect the removal of street canyons when roughness is reduced to increase the *horizontal ventilation* effect beyond that expected from simple inspection of the log–wind profile (Equation (1)).

The outcome of our modelling may be counter-intuitive but can be explained in terms of the model formulation. In neutral conditions the plume spread (σ_y and σ_z) in Equation (3) depends on the travel time of the pollutant from the source, which is determined by the distance from the source and wind speed at plume height and the relevant component of the root mean square turbulent velocities. For example, in ADMS-Urban at a distance X close to the
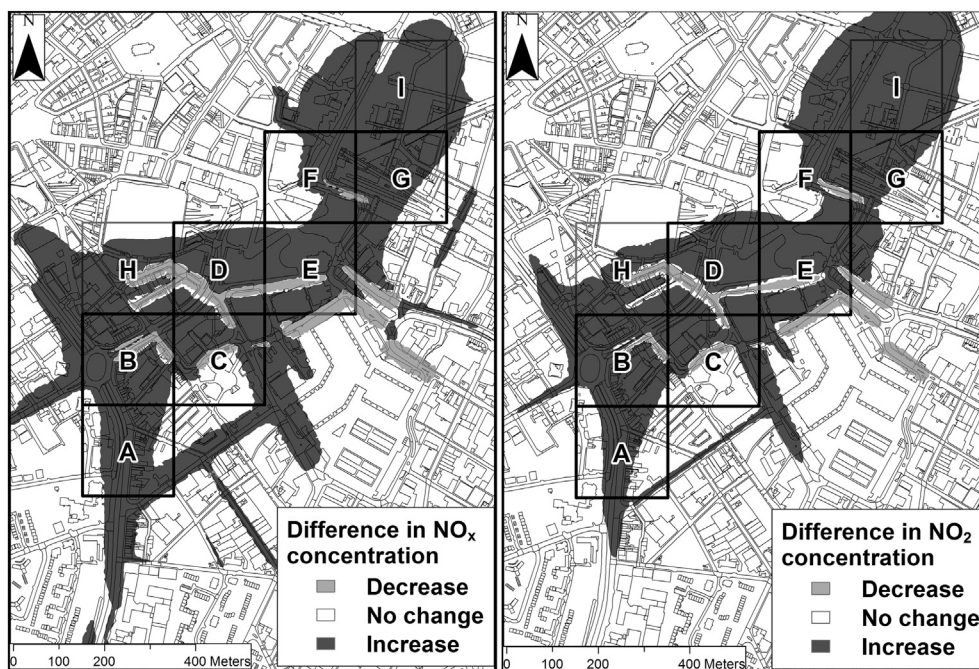
Fig. 3. The difference between the 'base case' and the model run in which surface roughness was reduced to 0.1 m. The black areas indicate where concentrations are higher in the model run with the modified roughness values. Both NO$_x$ and NO$_2$ concentrations are in μg m^{-3} and are based on the annual mean. Statistics from the seven lettered squares (A to G) can be seen in Table 3, along with additional squares H and I. Areas with no change have been defined as plus or minus 1 μg m^{-3}.
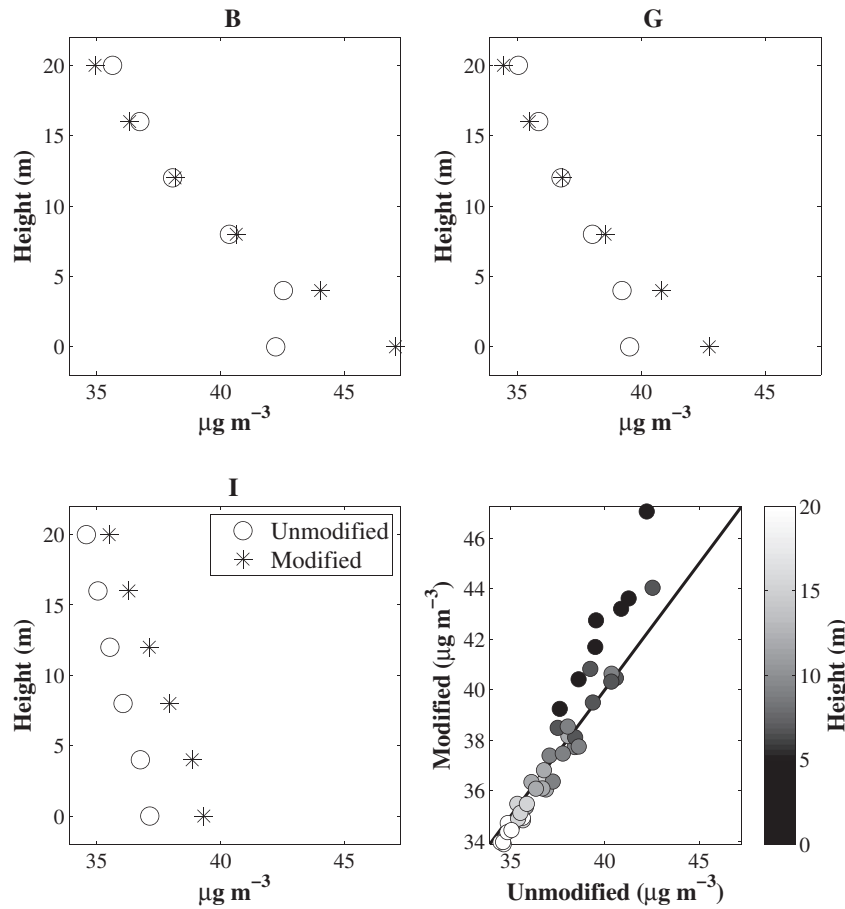
Fig. 4. The difference between the 'base case' and the model run in which the surface roughness was reduced to 0.1 m at different heights for the mean NO$_2$ concentration across each square. It can be seen that for the modified roughness case there is a higher pollutant concentration at ground level, but this decreases with height more than with the unmodified roughness case. The two squares (H and I) where there was no modification to the roughness length had higher concentrations at all heights when the roughness had been modified across the other squares. The bottom right scatter plot includes the results from the seven modified squares, with higher pollutant concentration towards the ground. It can also be seen that closer to the ground the concentrations for the modified roughness results are significantly higher. Squares B and G were chosen because they are representative of all of the modified squares.

source when the average wind speed is $\langle u \rangle$, the expression for the vertical plume spread can be approximated as:

$$\sigma_z \sim \sigma_w t \sim u_* \frac{X}{\langle u \rangle} \tag{4}$$

Table 4
ADMS-Urban results ($\mu g\ m^{-3}$) for 'base case' and runs adopting reduced surface roughness values for the two months of February and August. The letters on the top row relate to the squares in Figs. 2 and 3. The values are summarized for each square at *ground level*. The differences in concentration relate to the modified results minus the unmodified results. There was a significant increase in pollutant concentration in all of the squares in August, but very little in February.

		A	B	C	D	E	F	G
Aug	Difference in maximum NO$_2$ concentration	24.9	25.7	26.5	12.4	34.4	26.2	37.5
	Difference in minimum NO$_2$ concentration	−1.3	−1.1	−2.2	−1.8	−2.6	−2.9	−0.7
	Mean NO$_2$ change (increase) over square	3.4	5.4	3.4	1.6	4.3	2.1	4.1
Feb	Difference in maximum NO$_2$ concentration	3.2	2.9	3.2	1.5	3.9	3.2	4.2
	Difference in minimum NO$_2$ concentration	0	0	0.1	0	0.1	0	0.1
	Mean NO$_2$ change (increase) over square	0.4	0.7	0.6	0.2	0.6	0.4	0.5

Focussing, for simplicity, on plume centreline concentrations by ignoring both the exponential terms in (3) and the mixing in the transverse direction, which is of less significance than vertical mixing for line sources, we can deduce from (3) and (4) that:

$$1/C \sim \langle u \rangle \sigma_z \sim u_* X \tag{5}$$

Since increasing surface roughness increases u_* for a given geostrophic windspeed, the concentration will decrease with increasing roughness, or increase with decreasing roughness. Taking account of σ_y and also any stability effects in the expressions for σ_z and σ_y — as is done within ADMS-Urban, of course — does not change the general result that increasing roughness generally reduces maximum surface concentrations for surface emissions in this model formulation.

The presence of buildings in an urban area generates a very complex flow field that cannot be modelled explicitly in ADMS-Urban. Rather than such an obstacle-based approach, ADMS-Urban assumes a roughness-based approach. One fundamental assumption of the roughness-based approach in ADMS-Urban is that the physical presence of the building is ignored. This means that in a highly built up area, where the buildings may contribute a large proportion of volume of the space occupied, the concentration predicted solely by the increased mixing due to the

presence of buildings would lead to an underestimate of the predicted concentrations. In order to account for this, ADMS-Urban includes a relatively simple treatment of street canyons, based on the Operational Street Pollution Model (OSPM), in which the build-up of pollutants between buildings is taken into account in particular parts of the domain. Note, however, that *this increase in concentrations within the canyon is not accounted for outside the canyon* and that only a relatively small fraction of the urban landscape can be treated in this way in the model (see, for example, the areas of 'street canyon' shown by decreases in air pollutant concentrations in Fig. 3). Another aspect of the problem is that there is no allowance for the vertical displacement of the wind profile in the model (see Equation (3)), and the lower windspeeds and turbulence levels between the buildings, as seen for example, in wind tunnels (Di Sabatino et al., 2008; Carruthers et al., 2011). This effect would be diminished in the ventilation corridor.

Sections of the city downwind of the area of change were also adversely affected (Squares H and I, Fig. 3). The model outcome suggests that, when implementing an urban ventilation corridor, there needs to be an "exit" for air pollution, otherwise there will be significant increases in pollution concentrations — and hence exposure — in built-up areas just downwind. Overall, however, the simplifications inherent in a roughness-based approach — and the additional simplificiations inherent in the locally one-dimensional closure of a roughness-based surface scheme — should make us sceptical of the realism of any of the model results presented here.

5. Conclusions

Implementation of an option to model variable roughness within the air pollution dispersion model ADMS-Urban has improved model performance, although this does have the penalty of a significant increase in run time. We have used the new variable-roughness facility in ADMS-Urban to examine reduced roughness scenarios (without reducing emissions). Our case-study model produces increased ground-level pollutant concentrations for reduced surface roughness, both locally in the area of reduced roughness and downwind of that area. We discuss this modelling outcome from the perspective of Gaussian dispersion, and introduce a *turbulent mixing* effect and a *horizontal ventilation* effect, whose sensitivities to changing roughness are such that they act in opposite ways on ground-level pollutant concentrations. In our case study, the *turbulent mixing* effect dominates. Since the model predicts that reducing roughness has the (at first glance) perverse effect of increasing ground-level pollutant concentrations, we caution against using this type of modelling for urban planning and design studies in which the concept of breathability is important.

We expect the results from this study to be relevant for all atmospheric dispersion models with urban-surface parameterisations based on 1-D roughness-based closure schemes. To the extent that such models reflect actual atmospheric behaviour, the results presented are most relevant to those post-industrial "shrinking" cities (e.g., Kabisch (2007)) in which plots of land next to transport corridors become vacant and derelict. However, there are well-known limitations of 1-D roughness-based closure schemes near the surface of urban areas (e.g., Oke (2006)). We hope that the model case study reported here illustrates the caution with which modelling based on 1-D roughness-based closure should be viewed when undertaking urban redevelopment, and that our modelling will stimulate discussion and CFD analyses to investigate further this type of behaviour with a view to improving the performance of air-quality dispersion models.

Appendices

A. Appendix

For Equation (3), and with $\sigma_z \propto z_0$, we may examine the effects of small perturbations in a parameter value, say, $\langle u \rangle$, or z_0 (effectively σ_z) by using the partial differential of C with respect to the parameter. For example, a small change in mean wind speed $\langle u \rangle$ will cause a change in C:

$$\Delta C \big|_{\langle u \rangle} = \frac{\delta C}{\delta \langle u \rangle} \Delta \langle u \rangle = \left(-\frac{\Delta \langle u \rangle}{\langle u \rangle} \right) C. \tag{6}$$

That is, the relative change in $\langle u \rangle$ reduces (due to the minus sign) the pollutant concentration by the same relative amount, which is the well-known dependence of pollutant dispersion on wind speed. We can derive a similar relationship for σ_z, which is slightly more complicated:

$$\Delta C \big|_{\sigma_z} = \frac{\delta C}{\delta \sigma_z} \Delta \sigma_z = \frac{\Delta \sigma_z}{\sigma_z} C \left[\frac{\left(\frac{z-h}{\sigma_z}\right)^2 e^{-\frac{(z-h)^2}{2\sigma_z^2}} + \left(\frac{z+h}{\sigma_z}\right)^2 e^{-\frac{(z+h)^2}{2\sigma_z^2}}}{e^{-\frac{(z-h)^2}{2\sigma_z^2}} + e^{-\frac{(z+h)^2}{2\sigma_z^2}}} - 1 \right]$$

$$= \frac{\Delta \sigma_z}{\sigma_z} C \cdot [A - 1] \tag{7}$$

If the first term in the square bracket is ignored, the relationship would be the same as that for wind speed. By letting $A = 1$, we can find the critical height z_{crit}, below which $A < 1$ and above which $A > 1$. Therefore in the domain where $z < z_{crit}$, a small increase in σ_z will cause C to reduce, and a small decrease of σ_z will cause C to increase. This is consistent with the modelling results in which a decrease of z_0 (thus a decrease of σ_z because $\sigma_z \propto z_0$) caused C to increase for small z (Fig. 4). Note that A is larger than 1 for $z > z_{crit}$ and a small decrease of σ_z will cause C to decrease in this part of the domain.

Under the conditions given in the manuscript ($h = 0.5$ m or 1 m), several values of z_{crit}/σ_z are calculated and shown in Table A.1. The results show that z_{crit} is larger than σ_z.

Table A.1
Value of z_{crit}/σ_z for different conditions.

	$\sigma_z = 1$ m	$\sigma_z = 2$ m	$\sigma_z = 3$ m	$\sigma_z = 4$ m
$h = 0.5$ m	1.17	1.10	1.07	1.05
$h = 1.0$ m	1.92	1.42	1.27	1.20

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