ENHANCED “URBAN BREATHABILITY” LEADS TO DETERIORATION IN GROUND-LEVEL AIR-QUALITY

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Abstract

Generally, there are four strategies to reduce exposure to poor urban air quality and improve the health of the inhabitants of a city: reduce overall emissions; increase the depositional sink for pollutants; relocate people and/or polluting industries or improve the ventilation of city neighbourhoods and streets.

The ventilation of a city is intricately linked with urban form because urban form controls the overall aerodynamic roughness of the urban area, produces specific quasi-stationary modifications to the impinging flow and interacts with the radiative and turbulent energy transfer between the surface and the atmosphere. 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.

This paper reports on changes in model performance resulting from the introduction of variable surface roughness values in ADMS-Urban (v3.1) before going on to assess whether significant reductions in pollutant concentrations can be achieved simply through local reductions in these values. ADMS-Urban was initially used to model NO_x and NO_2 concentrations across Birmingham City Centre, UK, using a file derived from airborne LiDAR data in which roughness values ranged from 0.4 to 3.1m. The model was then re-run with a modified surface roughness file in which selected values near the city centre were reduced to 0.1m to represent a change in landuse to urban parkland.

Our results show that reducing surface roughness in the city centre would increase ground-level pollutant concentrations, both locally in the area of reduced roughness and downwind of that area. We discuss our results in terms of vertical stirring and horizontal ventilation effects and in this instance conclude that the vertical stirring effect dominates. Since the model predicts that reducing surface roughness to enhance ‘urban breathability’ has the unexpected 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 roughness.

Key words: *Air quality, ADMS-Urban, Street canyons, Urban breathability, Surface roughness*

INTRODUCTION

Urban form plays an inherent role in the ventilation of a city because urban form (i) controls the overall aerodynamic roughness of the urban area, (ii) interacts with the radiative and turbulent energy transfer between the surface and the atmosphere, and affects heat storage in the underlying surface or buildings, and (iii) produces specific quasi-stationary modifications to the impinging flow (e.g., venturi effects, cross-wind flows, wakes, vortices, etc). 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).

In classical, one-dimensional, boundary-layer theory, surface roughness is parameterized through the roughness length (Z_0), which corresponds to the height where the mean wind speed becomes zero (Seinfeld and Pandis, 2006; Holland et al., 2008; Li et al., 2009). Z_0 is approximately one thirtieth of the height of the surface roughness elements, with values ranging from 1.5 m for dense urban areas, 0.5 m for open suburbia and 0.1 m for parkland (Rotach, 2001; Hang and Li, 2011; Wania et al., 2012).

Horizontal variations in turbulence and flow are created by spatially variable roughness, both of which can affect pollutant dispersion. Overall, the degree to which an urban form promotes the removal and dilution of pollutants is captured in the theory of urban breathability (Bottema, 1997; Buccolieri et al., 2010), 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.

In previous versions of the ADMS-Urban, 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. The current version of the model allows users to model the spatial variation of surface roughness values over a given modelling domain. ADMS-Urban 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:

$$\bar{u}(z) = \frac{u_*}{\kappa}[ln\left(\frac{Z + Z_0}{Z_0}\right) + \psi(Z, Z_0, L)] \qquad (1)$$

This equation 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_* (*K* is the von Kármán constant and *L* is the Monin-Obukhov length).

Our research has two aims.

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

Our hypothesis is that selectively decreasing roughness for part of the built-up urban area will improve ventilation and hence reduce local pollutant concentrations.

MODEL SET-UP, VERIFICATION AND EFFECTS OF VARIABLE ROUGHNESS

Central Birmingham in the UK was used as our test case modelling scenario. The observed pollutant concentrations were obtained from NO_2 diffusion tube data, made available by Birmingham city council. The coordinates of 14 diffusion tubes were defined as receptors within ADMS-Urban and the model was then used to simulate annual mean concentrations at these specific points using a single fixed roughness of 1.5 m, which is representative of a large city centre (Wieringa, 1993). Verification was then repeated using a variable roughness file derived from airborne LiDAR data. Table 1 compares the mean of the observed and modelled data, over all sites.

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

	Observed	**Fixed surface roughness**	**Variable surface roughness**
Mean	44.2	53.6	50.0

Table 1 indicates that the model has a tendency to over-estimate the observed NO_2 concentrations, although further improvements to the model set up would be possible. The aim of this paper however, is to assess the change in model behaviour 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 therefore indicate that better model performance was achieved when using a variable surface roughness. This version of the model was therefore re-run to a regular grid of receptors (90 x 90) to represent “base case” conditions.

URBAN BREATHABILITY

To assess whether 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 a spatially varying roughness file were reduced for a modelled scenario, where $Z_0 = 0.1$m in squares A – G (Figure 1), corresponding, roughly, to replacement of buildings with urban parkland and grassland (Turner, 1994).

The difference between the “base case” and the run with reduced roughness can be seen in Figure 1. The red areas indicates an increase in ground-level NO_x concentration, whilst the green areas indicate a decrease in concentration. 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, pollutant concentration increases at ground level dominate for both NO_2 and NO_x.

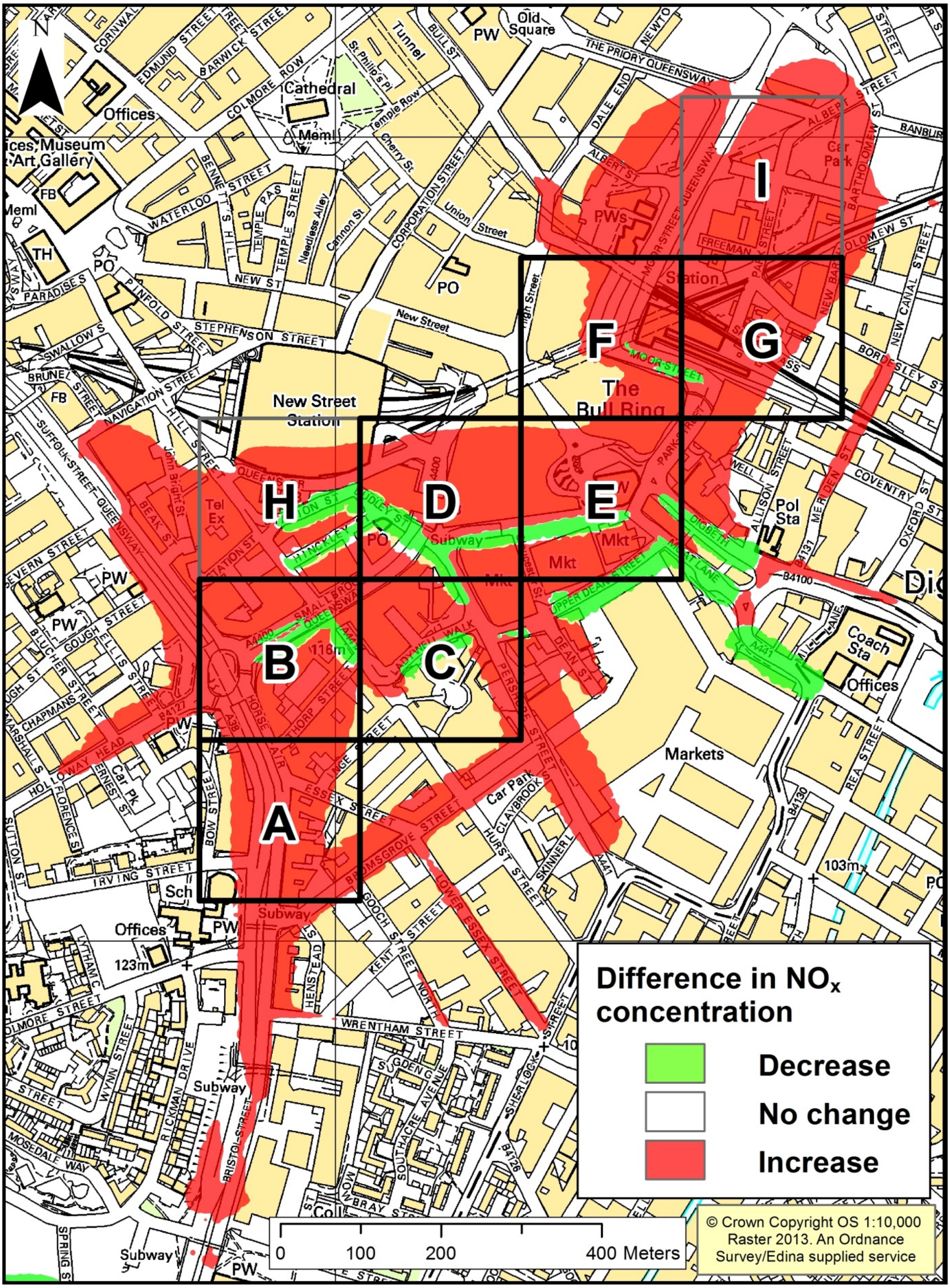

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Figure 1: The difference between the “base case” model and run in which the surface roughness was reduced to 0.1 m. The red areas indicate where concentrations are higher in the model run with the modified roughness. NO_x concentrations are in $\mu g\ m^{-3}$ and are based on the annual mean. Each square is 200 m by 200 m. Areas with no change have been defined as plus or minus 1 $\mu g\ m^{-3}$.

DISCUSSION

A localized increase in ground-level concentrations (and due to mass conservation, reduction in concentrations above ground level) occurred due to the localized reduction in roughness length. Due to the heterogeneous nature of the street plan for Birmingham city centre, and different volumes of traffic along each street, the effects seen are not uniform. For our case study we can say that the turbulent mixing effect dominates over the horizontal ventilation effect. Concentrations above ground-level (above about 5 m) decrease when roughness is reduced, consistent with a redistribution of pollutant through reduced vertical mixing. Overall, considering that most human exposure will be at heights below 5 m, the effect of improving "urban breathability" is to make exposure to air pollutants worse, although breathability is not synonymous with exposure.

This result may appear counter-intuitive but an explanation is forthcoming in terms of the model formulation. In neutral conditions the σ parameters in equation 2 depend on the travel time of the pollutant from the source, which depends on the wind speed at effective plume height h, given by $\left(\frac{u_*}{\kappa}\right)\ln\left(\frac{h}{z_0}\right)$ and the relevant component of the root mean square turbulent velocities. For example, in ADMS-Urban at a distance X close to the source when the average wind speed is U, the vertical plume spread can be approximated:

$$\sigma_z \sim \sigma_w t \sim u_* X/U \tag{2}$$

So, since increasing roughness increases u_* for a given geostrophic wind speed, 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 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 in ADMS-Urban cannot be modelled on a building-by-building basis. ADMS-Urban represents the presence of buildings by assuming the spreading of emissions over a larger vertical extent than in the absence of buildings i.e. increased surface roughness; for ground level sources this reduces the concentrations. One fundamental assumption in this 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 models street canyons, where the build-up of pollutants between buildings is taken into account. It is important to note however that this increase in concentrations within the canyon is not accounted for outside the canyon. Another aspect of the problem is that there is no allowance for the vertical displacement of the wind profile in the model, and the lower wind speeds 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, Figure 1). This 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.

CONCLUSIONS

ADMS-Urban has improved model performance when the spatially-varying roughness option is utilized, although this does come at the cost of a substantial increase in run time. We have used the new variable-roughness facility in ADMS-Urban to model an increase in urban breathability (i.e., reducing roughness in an area without reducing emissions). Our case-study model results indicate that reducing the roughness would increase ground-level pollutant concentrations, both locally in the area of reduced roughness and downwind of that area. We discuss these results in terms of 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. The model predicts that reducing roughness to enhance "urban breathability" has the (at first glance) perverse effect of increasing ground-level pollutant concentrations. We therefore 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 roughness. 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. We hope that the results reported here will stimulate discussion and CFD analyses to investigate further this type of behaviour.

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