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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.

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:

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

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.