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URBAN CANOPY FLOW FIELD AND ADVANCED STREET CANYON MODELLING IN ADMS-URBAN

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Abstract: Two new modules have recently been added to the ADMS-Urban dispersion model to improve the model predictions of concentrations in urban areas. The urban canopy module calculates a spatially varying flow field due to variations in building density and geometry at neighbourhood scales. The advanced street canyon module allows for detailed calculation of the effects of a wide range of individual street canyon geometries on the dispersion of pollution from road sources. This extended abstract gives an overview of the formulations used for the modules and presents validation of the modules at monitoring sites in central London. The results presented show that the new modules capture the observed variation of concentration with wind speed and direction at in-canyon monitoring sites better than previous modelling approaches, with a corresponding increase in correlation between modelled and observed concentrations. Work is ongoing to validate the model in a wider range of canyon geometries in Hong Kong.

Key words: *street canyon, urban canopy, ADMS-Urban, validation, flow*

INTRODUCTION

In urban areas, high traffic flows and congestion lead to large pollutant emissions. The resultant concentrations depend on the morphology of the urban area; wind speeds at ground level reduce where there are densely packed buildings and street canyons, resulting in increased concentrations. Further, the urban fabric alters the local climate so that the temperature gradient is rarely stable.

Previously, the widely-used ADMS-Urban dispersion model (McHugh *et al.*, 1997) accounted for urban meteorology by using a generic boundary layer flow profile adjusted for the increase in turbulence generated by buildings and applying a minimum to the Monin-Obukhov length to restrict stability conditions. However, it is generally accepted that as wind approaches a built-up urban area, the profile is displaced vertically by a height related to the mean height of the buildings, while the flow within the building canopy is slowed by the buildings (Belcher *et al.* 2013), as depicted in Figure 1. ADMS-Urban has now been developed to explicitly include a *spatially-varying urban canopy module* which incorporates above-canopy displaced flow and turbulence profiles linked to in-canopy profiles, allowing the flow field within urban areas to be characterised on a neighbourhood-by-neighbourhood basis.

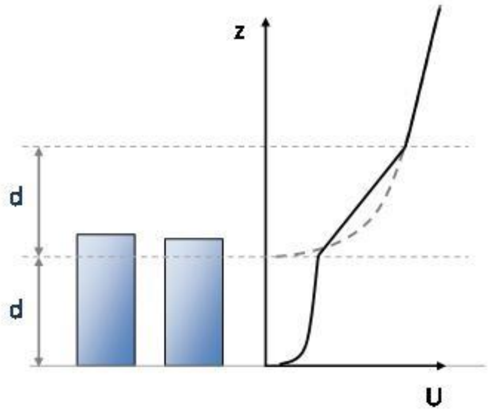

Figure 1 Diagram of urban canopy vertical profile of velocity relative to displacement height *d*. The dashed line represents the standard velocity profile displaced upwards by *d*.

Within street canyons, there may be channelling of the flow and a recirculation region driven by the component of the above-canopy flow perpendicular to the street; for street canyons with high aspect ratios, flow velocities may reduce significantly near the ground. As part of the model's explicit treatment of road traffic emissions, ADMS-Urban has included a canyon model which is a modification to the original Danish Operational Street Pollution Model (OSPM) formulation (Berkowicz *et al.* 1997). This simple model can estimate the increase of concentrations within a symmetric street canyon with height/width ratio of order 1, but does not calculate any effects of a street canyon on concentrations outside the canyon, includes only a limited vertical variation of concentration and is unsuitable for tall or asymmetric canyons. In addition, it does not take into account the presence of pavements, instead spreading the road emissions throughout the width of the canyon. The new ADMS-Urban *advanced street canyon module* allows for a wide variety of canyon geometries to be considered, with smooth transitions of concentrations between open and built-up areas. It includes consideration of tall and/or asymmetric canyons and restricts emissions to a subset of the canyon width in order to take account of pavements. It has been developed based on a combination of CFD, wind tunnel and field data and theoretical considerations.

The following sections cover the formulations of the urban canopy and advanced canyon modules, describe the set-up of the extended ADMS-Urban model for a study area in central London, present comparisons between modelled and monitored concentrations at 29 sites and discuss the results.

FORMULATION

Urban canopy

The urban area is characterised by gridded values of the average building height, the average street canyon width ($\hat{g}$), the ratio of the plan area of buildings to grid cell area (λ_P) and, for a user-specified set of wind direction sectors, the ratio of the frontal area of buildings to grid cell area (λ_F). Grid cell dimensions are set so that these parameters are able to represent the features of distinct urban neighbourhoods (typically 500 m to 2 km). The urban canopy module follows MacDonald et al. (1998) in calculating an effective roughness z_{0b} and a displacement height d from these input data.

The full urban canopy vertical velocity profile consists of three sections as shown in Figure 1: above twice the displacement height (‘above-building’), below the displacement height (‘below-building’) and a transition region between these two regions. For the ‘above-building’ section, the standard ADMS velocity profile as described in the ADMS technical specification documents (CERC, 2012) is displaced upwards by d and a modified friction velocity is used, which is calculated using the local roughness z_{0b}. Below the displacement height a logarithmic velocity profile is applied, with a ‘below-building’ roughness z_{0s} of 0.1 m, which represents the effect on the flow of small obstacles which may be present at street level. The effective friction velocity for the below-building flow is calculated by matching the below-building velocity at the displacement height to a fraction $(1 - \lambda_P)^2$ of the above-building velocity at twice the displacement height. A linear interpolation is performed in the transition region between the below-building velocity at the displacement height and the above-building velocity at twice the displacement height.

The full urban canopy vertical profile of turbulence consists of two sections: above and below the displacement height. Above the displacement height, the standard ADMS stability-dependent turbulence profiles are displaced upwards by d and the modified friction velocity related to the local roughness z_{0b} is used. Below the displacement height, the turbulence velocities decay towards the ground according to $\exp(-(d - z)/2\hat{g})$, where z is the height above ground level.

The effects of the urban canopy module are divided into four regimes according to the values of z_{0b} and d. For the lowest values of d, below 1 mm, no urban canopy flow calculations are performed, while for the highest values of d, greater than the maximum of 2 m and half the average building height, full urban canopy flow calculations are performed as described below. Two intermediate regimes are defined: for low values of d, less than the maximum of 1 m and a tenth of the average building height, a ‘standard’ ADMS flow profile with the local roughness z_{0b} is used, known as the ‘no displacement’ solution; while for moderate values of d the flow is interpolated between the no displacement and full urban canopy profiles to give a ‘low displacement’ solution.

Advanced canyon

A street canyon is characterised according to the values of the following parameters for each side of the road centreline: building height, distance from road centreline to canyon wall and length of road with adjacent buildings. These values are processed to obtain average canyon height H, total canyon width g and porosity α, which is defined as 1 – (length of road with adjacent buildings)/(total length of road). A road will be modelled using the advanced canyon module if at least one side has a canyon height of 1 m or more and the road has adjacent buildings extending for 5 m or more. Canyon walls may be present on one or both sides of a road.

The ADMS advanced street canyon module uses the concept of superposing component sources to represent different aspects of street canyon dispersion. Five component sources are used in the advanced canyon system, which are subject to different wind directions, have various source definitions and regions of influence, as summarised in Table 1 and shown diagrammatically in Figure 2. The weightings given to each source vary according to the canyon properties and the wind direction relative to the canyon axis. Information about the standard ADMS-Urban road and volume source types can be found in the ADMS technical specification (CERC, 2012).

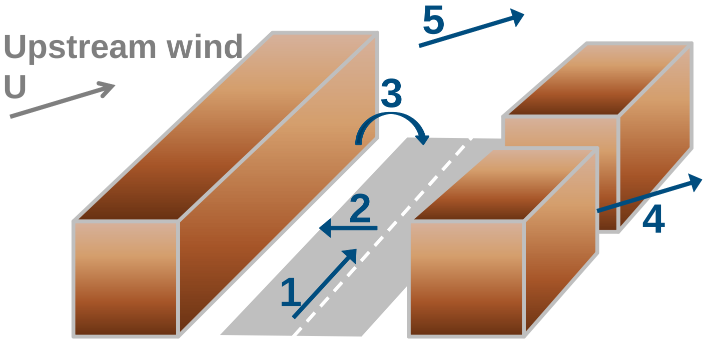

Figure 2 Diagram of the five component sources used in the ADMS-Urban advanced street canyon module

The procedure for calculating weightings q_i for the component sources is as follows: an initial balance between pollutants trapped within the canyon (q_{12}) and dispersing through the walls of the canyon (q_4) is calculated based on the square of the overall porosity, i.e. $q_4 = \alpha^2$. An adjustment is applied to increase q_4 and reduce the in-canyon weightings if the canyon is shallow ($H/g < 1$), giving $q_4 = \alpha^2/(\alpha^2 + (1 - \alpha^2)(H/g)^{0.5})$. The in-canyon weighting is then divided between the along-canyon and across-canyon components according to wind direction: $q_1 = q_{12}\max(1 - \gamma\sin^2(\Delta\varphi)),0)$ where γ is a parameter based on a critical angle and $\Delta\varphi$ is the angle between the wind direction and the canyon axis, and $q_2 = q_{12}-q_1$. If the upstream canyon wall is lower than the downstream canyon wall, the across-canyon source q_2 is reduced and the non-canyon source q_4 is increased. Similarly, if the downstream canyon wall is lower than the upstream canyon wall, the along-canyon source q_1 is reduced and the non-canyon source q_4 is increased. Finally, the canyon-top weighting q_5 is set equal to the in-canyon weighting, $1 - q_4$, and the recirculation weighting q_3 is set equal to the across-canyon weighting q_2.

Table 1 Summary of component sources used in the ADMS-Urban advanced street canyon module

Source	Canyon effect	Type	Wind direction	Region of influence
1. Along canyon	Channelling along canyon	Road with wall reflections	Along canyon	Within canyon
2. Across canyon	Direct dispersion across canyon by circulating flow	Simplified road	Across canyon	Within canyon
3. Recirculation	Recirculation of pollution trapped within canyon	Well-mixed	n/a	Within canyon
4. Non-canyon	Dispersion through gaps between buildings	Road	Upstream	Within and outside canyon
5. Canyon-top	Dispersion out of the top of the canyon	Volume	Upstream	Outside canyon

MODEL SET-UP

A study area of around 10 km x 15 km in central London has been selected for preliminary model validation, encompassing 29 continuous monitoring sites of which 21 are classified as roadside or kerbside, and 8 as background. CERC's standard approach to modelling London was used, with measured meteorology from Heathrow airport and upwind background concentrations from rural sites, as described in Carslaw *et al.* (2013), although the current work used updated meteorology, background concentrations and emissions data appropriate to the chosen study year of 2012.

Buildings data for the study area were processed to obtain urban canopy and advanced canyon parameter values using GIS tools. The urban canopy grid resolution is 1 km and the average building height across the study region is 15 m. 1742 out of 1962 roads use the advanced canyon module, with average canyon height 17.5 m and width 24.2 m. Around 17% of the canyons are fully asymmetric, with a canyon wall on only one side.

Four model configurations have been run for comparison: 'No canyon' has all roads modelled without any street canyon effects; 'Basic canyon' uses the simple canyon model previously implemented in ADMS-Urban; 'Urban canopy' uses the new urban canopy flow field module with basic canyons; and 'Advanced canyon and urban canopy' uses both of the new modules simultaneously.

RESULTS

Numerical and graphical comparisons between the modelled and measured concentrations have been created using the open-source tools openair (Carslaw and Ropkins, 2011) and the MyAir Model Evaluation Toolkit (Stidworthy *et al.*, 2013). The comparisons presented focus on NO_x and NO_2 concentrations, as these pollutants are primarily affected by the emissions from the nearest road source for roadside sites and are consequently strongly influenced by street canyon properties.

Model evaluation statistics for NO_x and NO_2 concentrations across all sites for the five model configurations are given in Table 1. The statistics presented for comparison are annual average concentration (Mean, μgm^{-3}), normalised mean square error (NMSE), correlation (R), fraction of modelled concentrations within a factor of two of the measured concentration (Fac2) and fractional bias (Fb). A graphical comparison of modelled and measured annual average NO_2 concentration at each monitoring site for the three primary modelled options is shown as a scatter plot in Figure 3.

Polar plots are a useful graphical tool for comparing the variation of concentrations with wind speed and direction predicted by a model with those measured at a site. The 'CD9' monitoring site in central London is a kerbside site on Euston road, which is a busy main road with an annual average daily traffic flow of around 48 000 vehicles. A map showing the monitor location relative to local roads and buildings is shown in Figure 4. The properties of the canyon at this site are an average porosity of 0.26 and height/width ratio of 0.96. Polar plots of the measured and modelled NO_2 concentrations from three model configurations, using measured wind speed and direction data from Heathrow airport, are shown in Figure 5.

Table 2 Model evaluation statistics for NO_x and NO_2 concentrations (μgm^{-3}) across 29 measurement sites for four ADMS-Urban configurations (refer to text for details). Statistics calculated using the MyAir Model Evaluation Toolkit.

Data			**NO_x**					**NO_2**		
	Mean	**NMSE**	**R**	**Fac2**	**Fb**	**Mean**	**NMSE**	**R**	**Fac2**	**Fb**
Observed	170.8	0.00	1.00	1.00	0.00	70.8	0.00	1.00	1.00	0.00
No canyon	109.0	1.67	0.41	0.61	-0.44	53.8	0.76	0.36	0.73	-0.27
Basic Canyon	130.4	1.10	0.53	0.67	-0.27	61.5	0.53	0.49	0.79	-0.14
Urban Canopy	141.5	0.97	0.55	0.68	-0.19	65.2	0.49	0.50	0.79	-0.08
Advanced Canyon & Urban Canopy	129.9	0.91	0.64	0.69	-0.27	63.1	0.39	0.62	0.81	-0.11

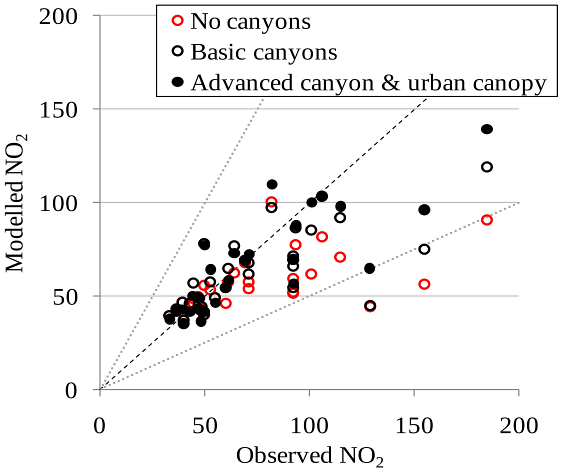

Figure 3 Scatter plot of modelled versus observed annual average NO_2 concentrations (µgm^{-3}) at 29 sites in central London, for three modelled configurations.

Figure 4 Map showing CD9 monitoring site location relative to local buildings (green outlines) and roads (red lines). Map extends approximately 500 m.

DISCUSSION AND CONCLUSIONS

Table 2 and Figure 3 show that the use of either the basic or advanced canyon module significantly improves the ADMS-Urban predictions of NO_x and NO_2 at the London monitors considered in this study relative to no inclusion of street canyon effects. When using the new urban canopy module with the basic canyon approach, concentrations generally increase, although inspection of the results on a site-by-site basis indicates that around 17% of annual averages decrease; this highlights the spatial variation of the urban canopy flow field which can both increase and decrease wind speeds relative to the basic flow. Use of the advanced canyon module leads to a significant improvement in correlation and NMSE for both NO_x and NO_2 relative to the basic canyon case, showing that the new module is more accurately capturing complex features of the flow and dispersion within street canyons. The annual average NO_2 concentrations from the new modules shown in Figure 3 are particularly encouraging, because not only are previously underestimated concentrations now higher, but also, in some cases, those that were previously overestimated have now been reduced. The polar plots for the CD9 site given in Figure 5 show improved variation of concentration with wind direction and speed at this kerbside, in-canyon receptor when the advanced canyon and urban canopy modules are used.

The advanced canyon module accounts for asymmetry, unlike the old canyon module. Inspection of results for monitors located within one-sided ‘canyons’ are encouraging. Results from further validation of the advanced canyon module against field study and wind tunnel experimental data for a line source with a noise barrier, forming an asymmetric canyon, can be found in Heist *et al.* (2014). Additional validation of the modules in the more challenging urban environment of Hong Kong, where canyon height to width ratios can be significantly greater than one, is currently ongoing.

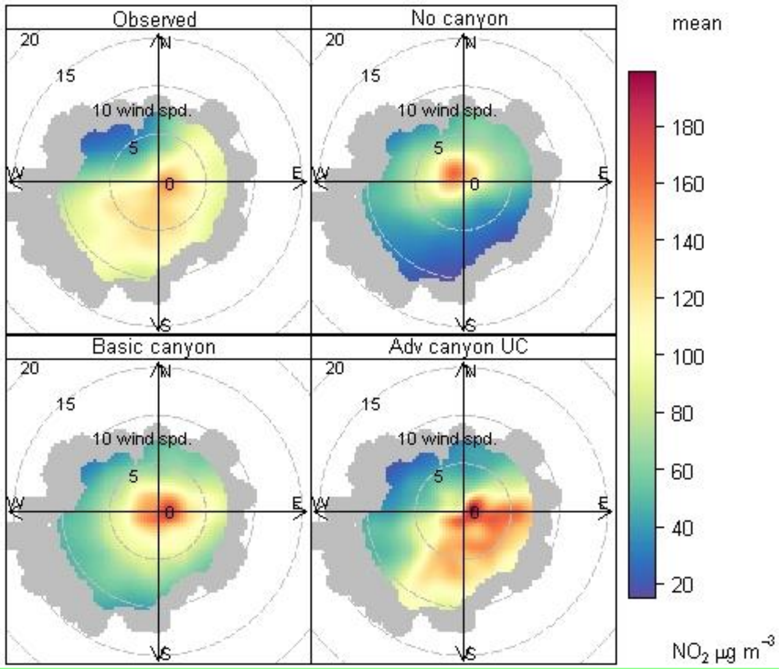

Figure 5 Polar plots of measured and modelled NO_2 concentrations (μgm^{-3}) at the CD9 roadside site. Key to headings: ‘Observed’: measured concentration; ‘No canyon’: modelling with no canyon effects; ‘Basic canyon’: modelling with basic canyon effects; and ‘Adv canyon UC’: modelling with advanced canyon and urban canopy effects. Combinations of wind direction and wind speed which occur for fewer than 8 hours in the year are greyed out.

The addition of new features to a practical and widely-used dispersion model challenges developers to balance the complexity of capturing advanced physics, for example improving the modelling of an individual street canyon, with the requirement to maintain realistic run times for modelling a wider urban area. The results presented in this paper demonstrate that this has been achieved.

ACKNOWLEDGEMENTS

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