Urban canopy flow field and advanced street canyon modelling in ADMS-Urban

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16th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
8-11 September 2014
Varna, Bulgaria

CERC
Cambridge Environmental Research Consultants
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Background: Urban Canopy

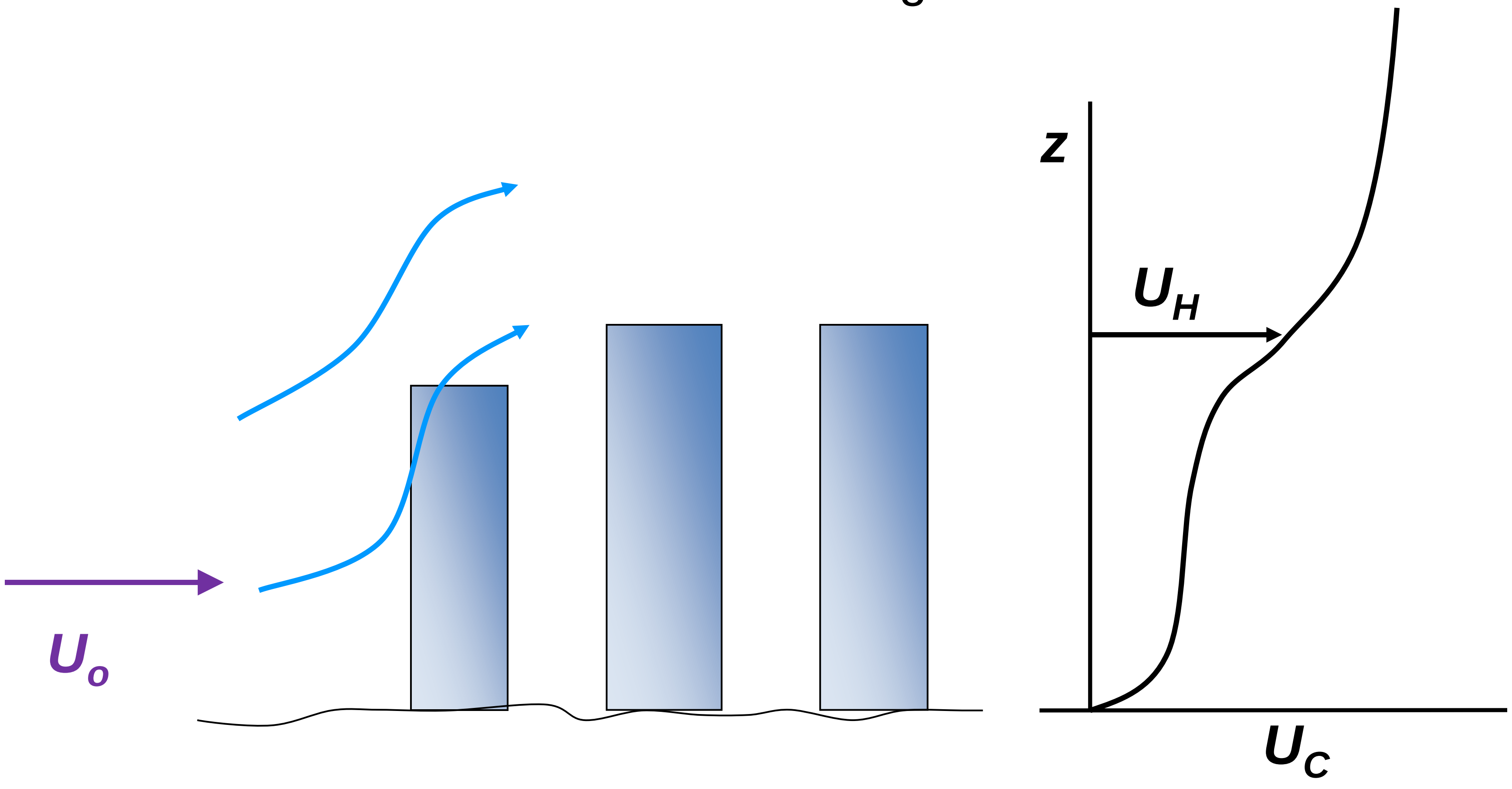
- Urban architecture affects local air flow
- Important to use urban flow characteristics for accurate calculation of pollutant dispersion
- Earliest historic studies (CFD, wind tunnel and field experiments) used regular arrays of cubic obstacles to represent urban buildings
- Some later extensions to real urban areas with irregular arrays and non-cubic buildings
- CERC parameterisation based on published experimental data and theoretical considerations

Background: Advanced Canyon

- Many modern urban areas feature closely-packed tall buildings which form street canyons
- Existing dispersion models for street canyons, eg. OSPM, were developed based on ‘European’ urban geometries
  - Canyon heights and widths of similar magnitude
  - Symmetric properties on each side of a canyon
- Choice required between canyon and non-canyon modelling
- A comprehensive model for street canyons should include:
  - Tall canyons (height/width > 1)
  - Asymmetric canyons: height, width, building density
  - Pavements and traffic lanes
  - Smooth transition between non-canyon and canyon modelling

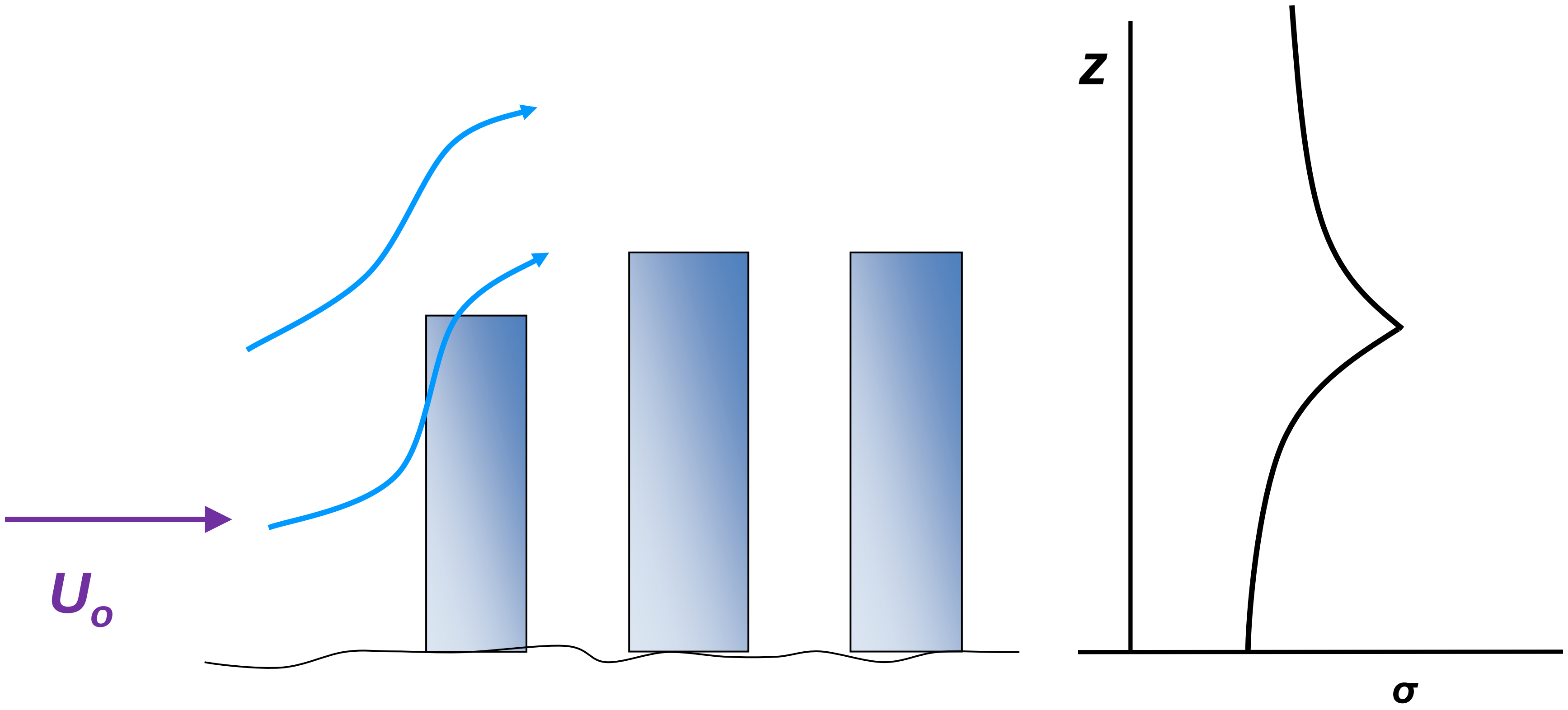
Urban Canopy
Theory: Velocity

- Upstream wind velocity profile is displaced above the buildings
- Velocities are reduced below the buildings



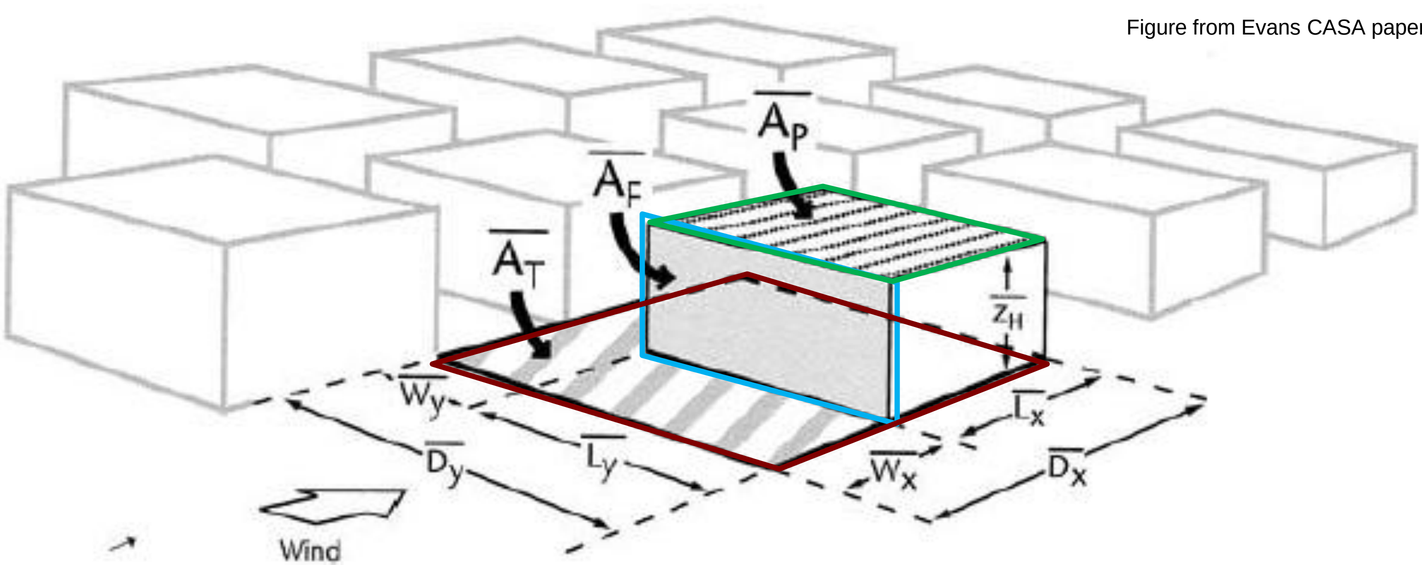
Urban Canopy
Theory: Turbulence

- Turbulent velocities are reduced below the buildings



Urban Canopy
Theory: Characterisation of urban area

Figure from Evans CASA paper

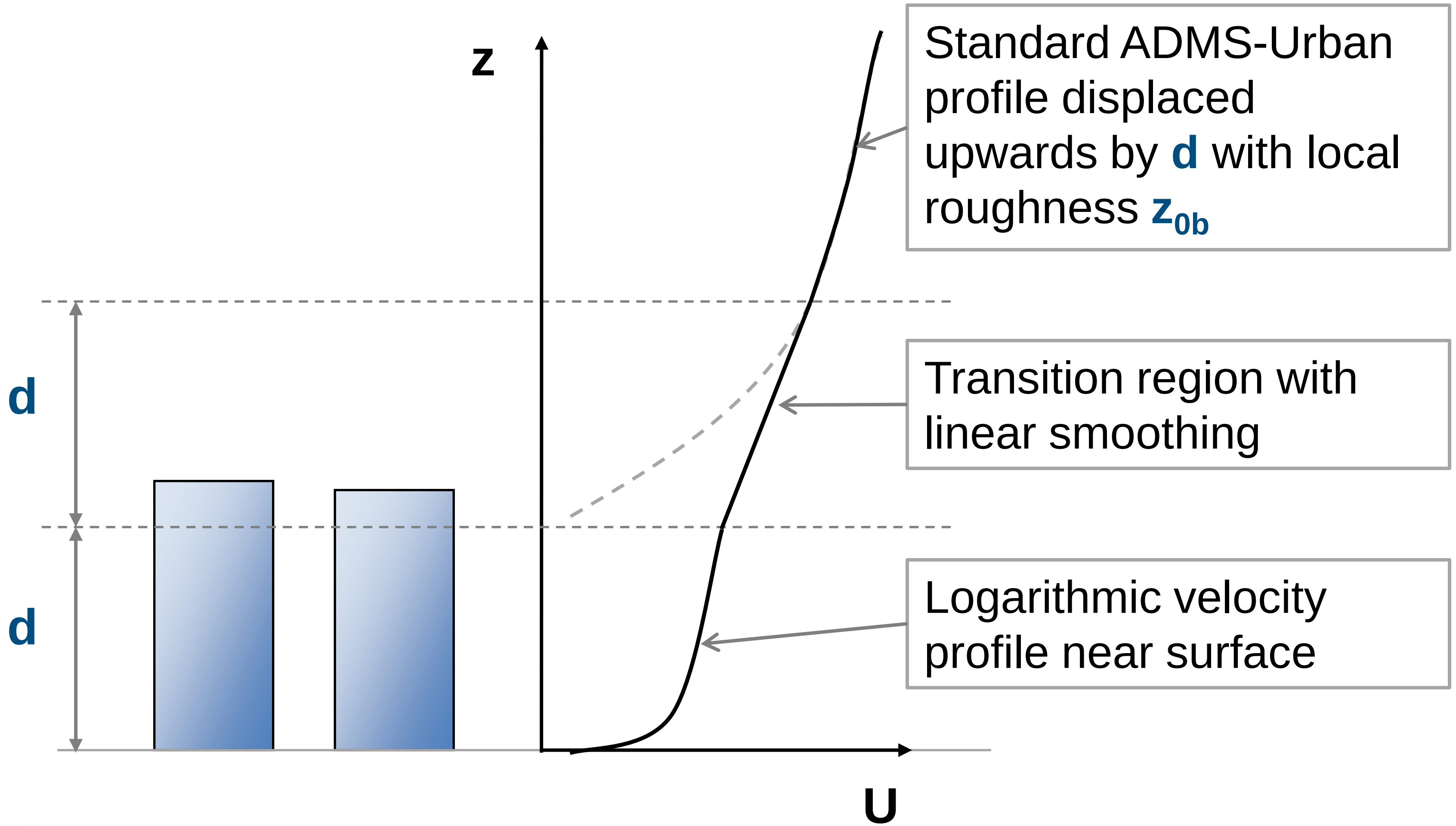


- Effective roughness z_{0b} and displacement height d calculated relative to average building height H using plan and frontal area fractions λ_P and λ_F
- $\lambda_P = A_P/A_T$
- $\lambda_F = A_F/A_T$
- $d/H = 1 + (\lambda_P - 1)\alpha^{-\lambda P}$
- $z_{0b}/H = (1-d/H)\exp\{-(0.5\beta C_D\lambda_F(1-d/H)/\kappa^2)^{-0.5}\}$

Macdonald *et al.* 1998 *Atmos. Environ*. **32**:1857-1864

Implementation in ADMS-Urban: Velocity

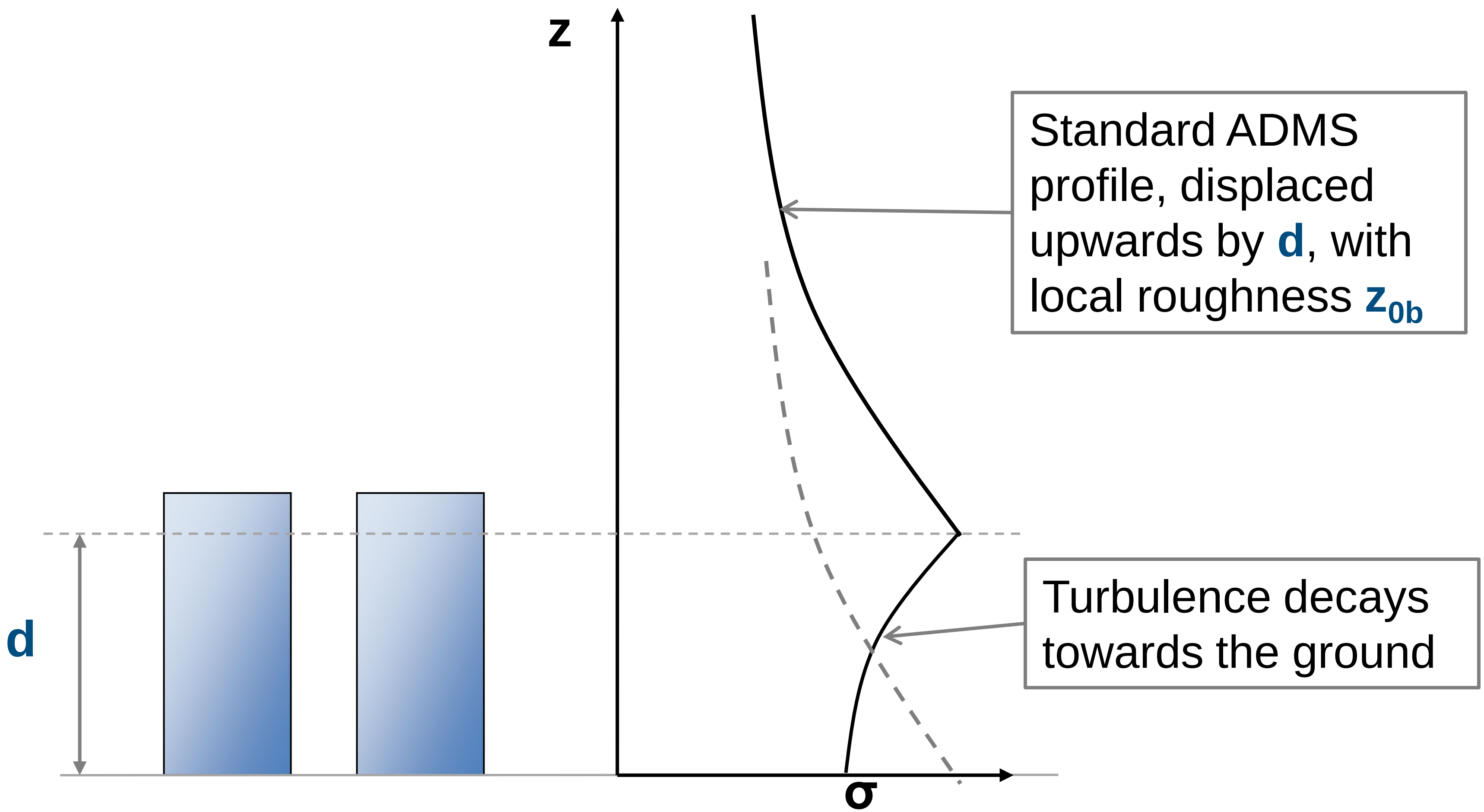
Three-part velocity profile: above 2x displacement height, below displacement height and transition region.



Details of standard ADMS velocity profiles can be found at http://www.cerc.co.uk/environmental-software/technical-specifications.html

Urban Canopy
Implementation in ADMS-Urban: Turbulence

Two part profile: above and below displacement height



Details of standard ADMS turbulent velocity profiles can be found at
http://www.cerc.co.uk/environmental-software/technical-specifications.html

Implementation in ADMS-Urban: Flow regimes

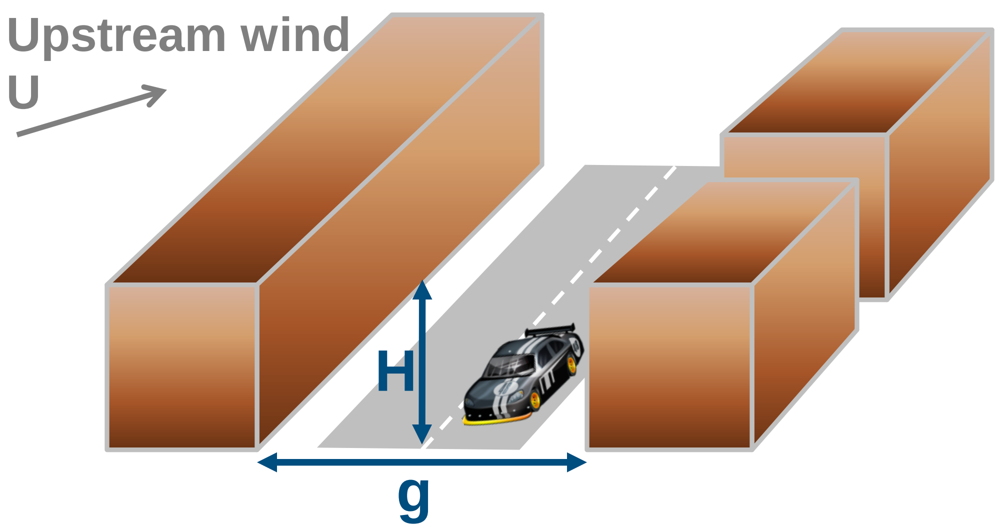
- **Full urban canopy** if displacement height **d** > max(2 m, H/2)
  - Full urban canopy flow profiles
  - Effective roughness length due to buildings $\mathbf{z_{0b}}$ < **d**/2
- **Low displacement** if displacement height **d** < max(2 m, H/2)
  - Interpolation between full urban canopy and no displacement
- **No displacement** if displacement height **d** < max(1 m, H/10)
  - Standard ADMS-Urban flow profiles with local roughness $\mathbf{z_{0b}}$
- **No urban canopy** if displacement height **d** < 1 mm
  - Standard ADMS-Urban flow profiles used

Theory: Canyon properties

Each side of the canyon has properties

- Whether there is a canyon wall: minimum height and building length
- Height: average, minimum and maximum
- Width: from road centreline to canyon wall
- Porosity: proportion of canyon wall without buildings ie. 1-(building length/total length)

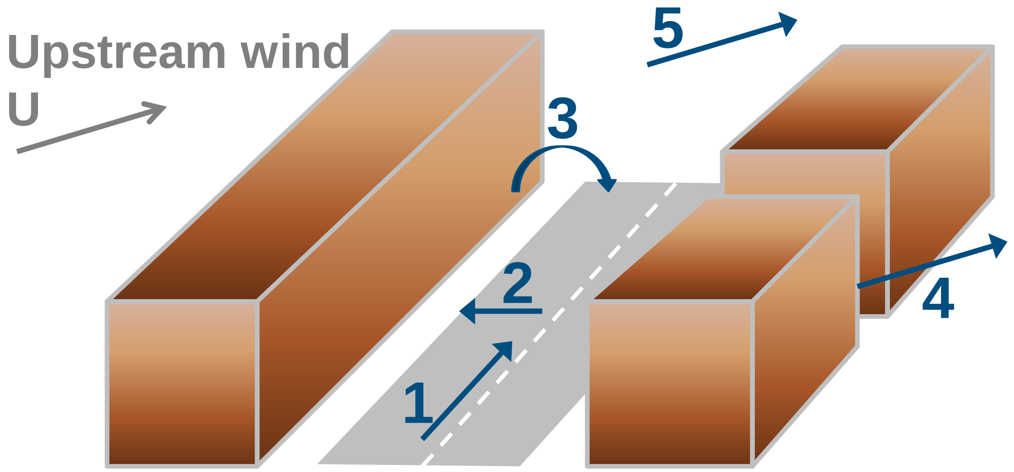
These are combined to find total canyon width (wall to wall) **g**, average height **H** and overall porosity **α**



Advanced Canyon
Theory: Canyon effects

5 principal effects of street canyons on dispersion

1. Pollutants are channelled **along** street canyons
2. Pollutants are dispersed **across** street canyons by circulating flow at road height
3. Pollutants are trapped in **recirculation** regions
4. Pollutants leave the canyon through gaps between buildings as if there was **no canyon**
5. Pollutants leave the canyon from the **canyon top**

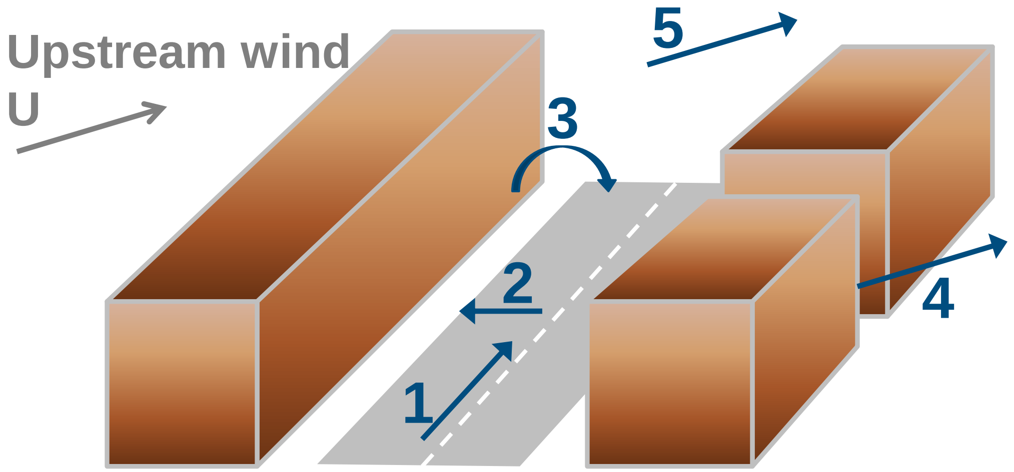


Advanced Canyon
Theory: Component sources

Each effect is modelled using a component source, with differing

- Source **geometry**
- Source **dispersion** type
- **Wind direction**
- **Region of influence**
- Source strength

The final concentration is the weighted sum of contributions from the component sources



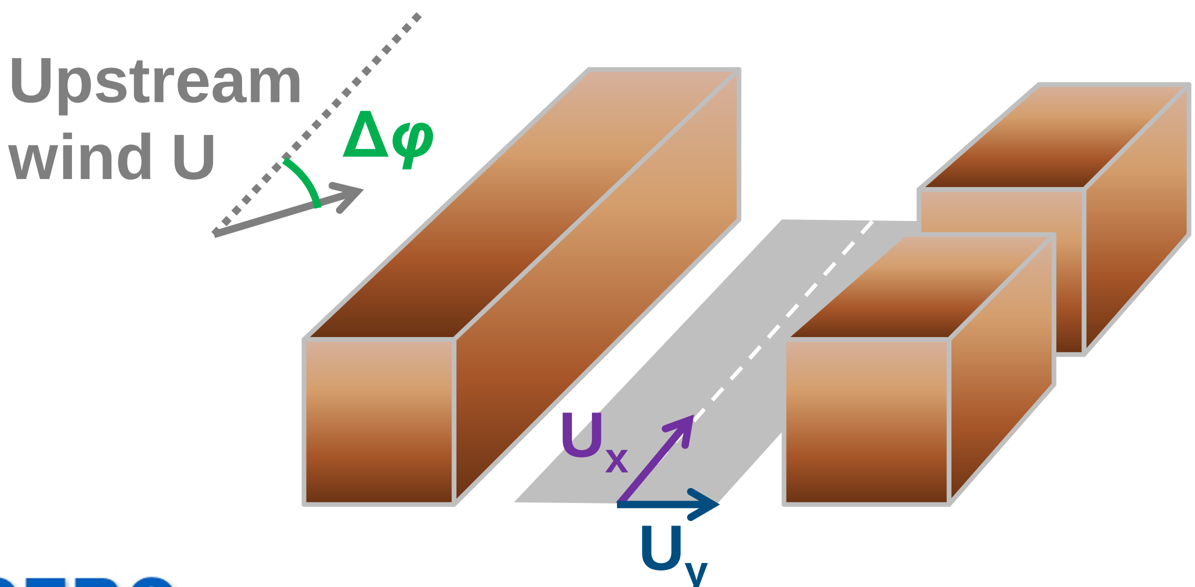
Advanced Canyon

ADMS-Urban Implementation: Canyon flow

- Upstream wind is split into components parallel and perpendicular to the canyon axis
- Perpendicular component is further reduced in magnitude due to recirculation $\hat{h}(z)$ and obstacles (user-defined factor η)

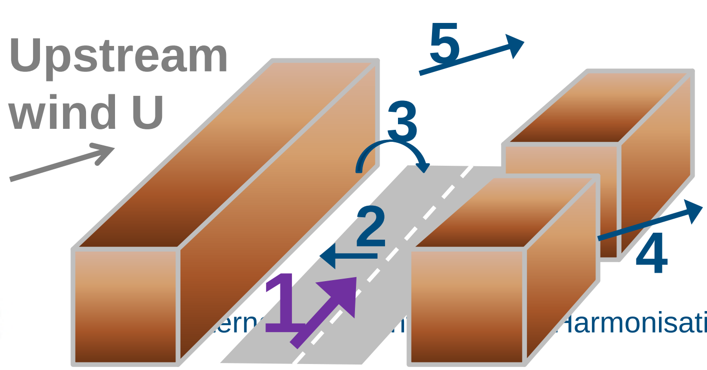
$$U_x(z) = U(z) \cos \Delta\varphi$$

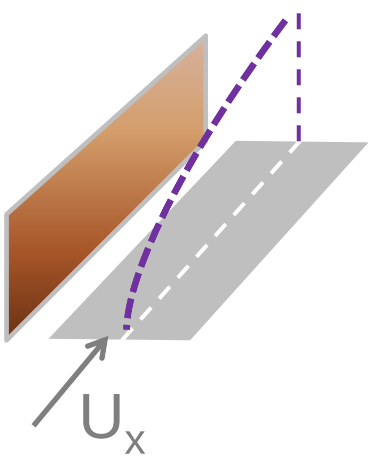
$$U_y(z) = U(z)\, \eta\, \hat{h}(z) \sin \Delta\varphi$$



Advanced Canyon
ADMS-Urban Implementation: S1 Along canyon

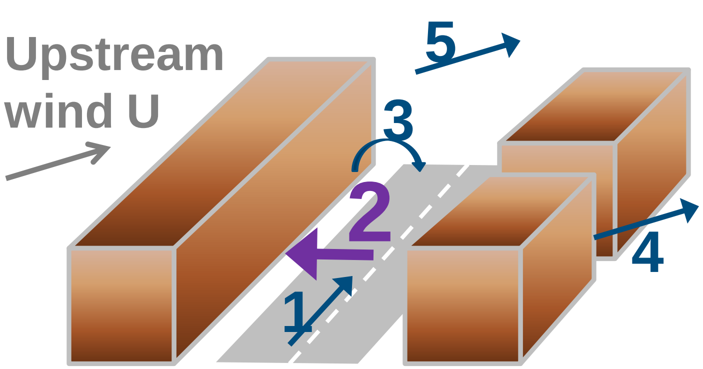
- Pollution is advected and dispersed by flow channelled along the canyon
  - **Geometry**: standard road
  - **Dispersion**:
    - standard ADMS-Urban road with width limit due to canyon walls and simplified calculation of mean plume height
    - well-mixed across canyon after a reflection reaches the opposite wall
    - option to set a constant segment length to obtain constant along-canyon concentration
  - **Wind direction**: along canyon
  - **Region of influence**: within canyon

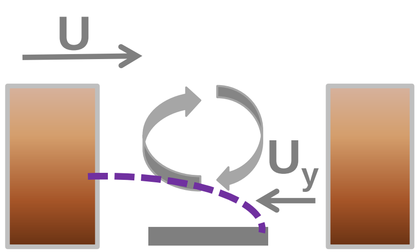




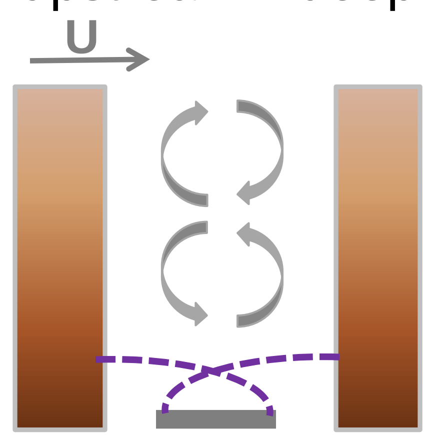
Advanced Canyon
ADMS-Urban Implementation: S2 Across canyon

- Pollution is dispersed across the canyon by circulating flow
- Deeper canyons have more complex flow structures
  - **Geometry**: standard road
  - **Dispersion**: well-mixed along road, analytical integration across road to output point
  - **Wind direction**: across canyon, opposite direction to upstream if a shallow canyon, both opposite and in line with upstream if deep
  - **Region of influence**: within canyon





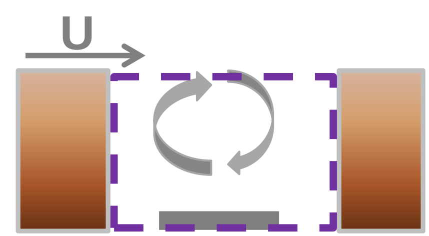
Shallow canyon: single circulation



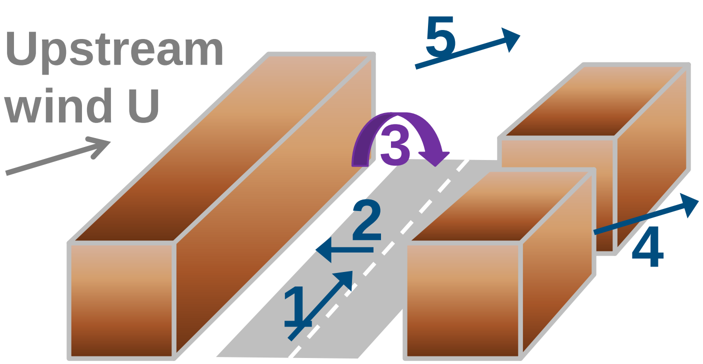
Deep canyon: multiple circulation

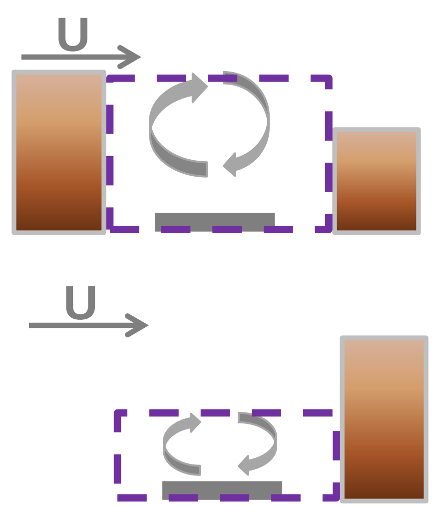
Advanced Canyon
ADMS-Urban Implementation: S3 Recirculation

- Pollution can be trapped within the canyon by the recirculating flow
  - **Geometry**: full width of canyon, height depends on **H** and **g**
  - **Dispersion**: well mixed, analytical solution
  - **Wind direction**: n/a
  - **Region of influence**: within canyon

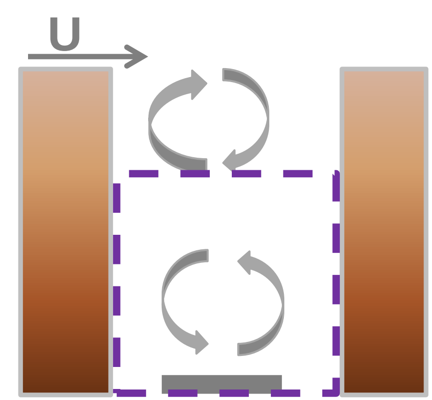


Shallow symmetric canyon





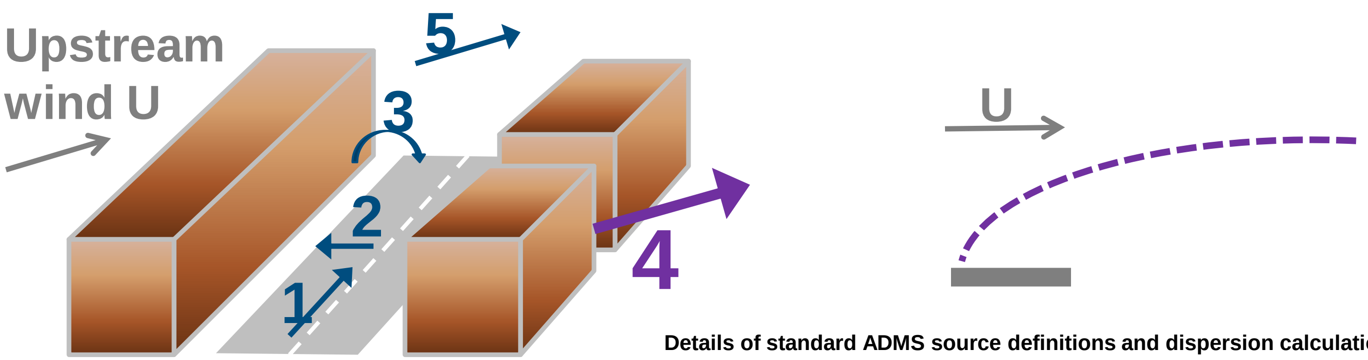
Shallow asymmetric canyons



Deep symmetric canyon

Advanced Canyon
ADMS-Urban Implementation: S4 Non-canyon

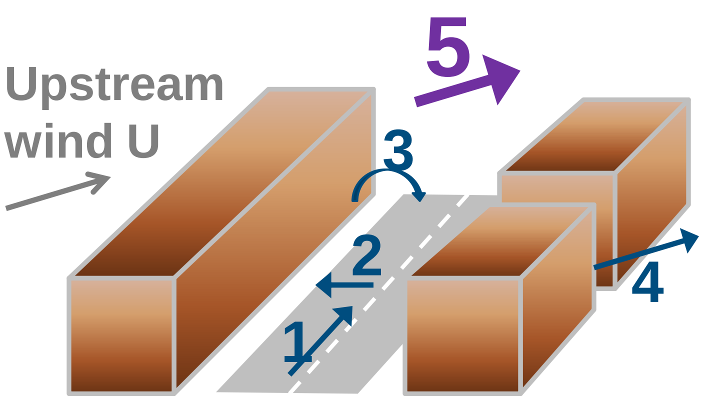
- Some of the pollution from the road disperses through gaps between buildings in the canyon walls
- Allows for transition from open to built-up roads
  - **Geometry**: standard road
  - **Dispersion**: standard ADMS-Urban road
  - **Wind direction**: upstream
  - **Region of influence**: inside and outside canyon

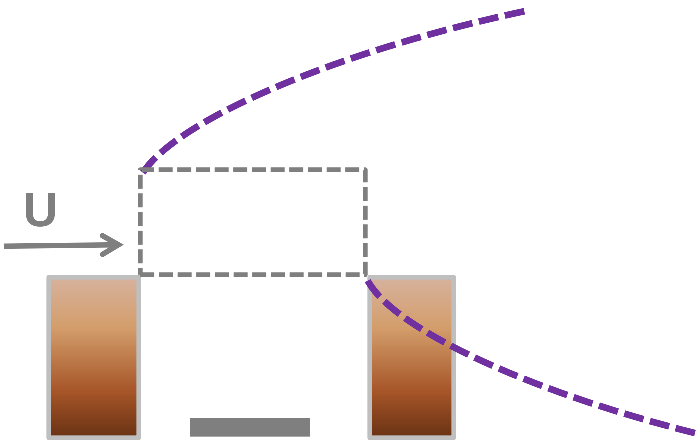


Details of standard ADMS source definitions and dispersion calculations can be found at http://www.cerc.co.uk/environmental-software/technical-specifications.html

Advanced Canyon
ADMS-Urban Implementation: S5 Canyon top

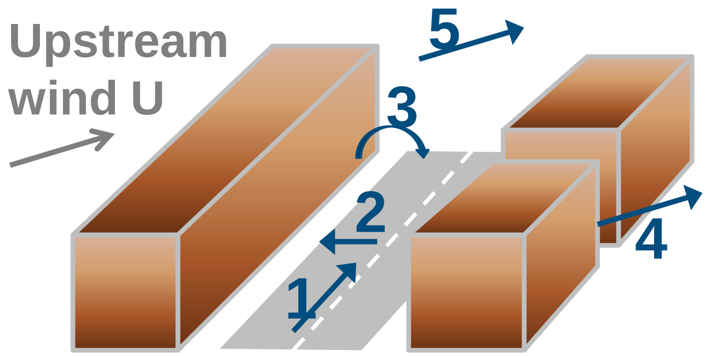
- Pollution leaves the canyon from the top
  - **Geometry**: volume source with canyon width, depth depends on canyon height
  - **Dispersion**: standard ADMS-Urban volume source
  - **Wind direction**: upstream
  - **Region of influence**: outside canyon





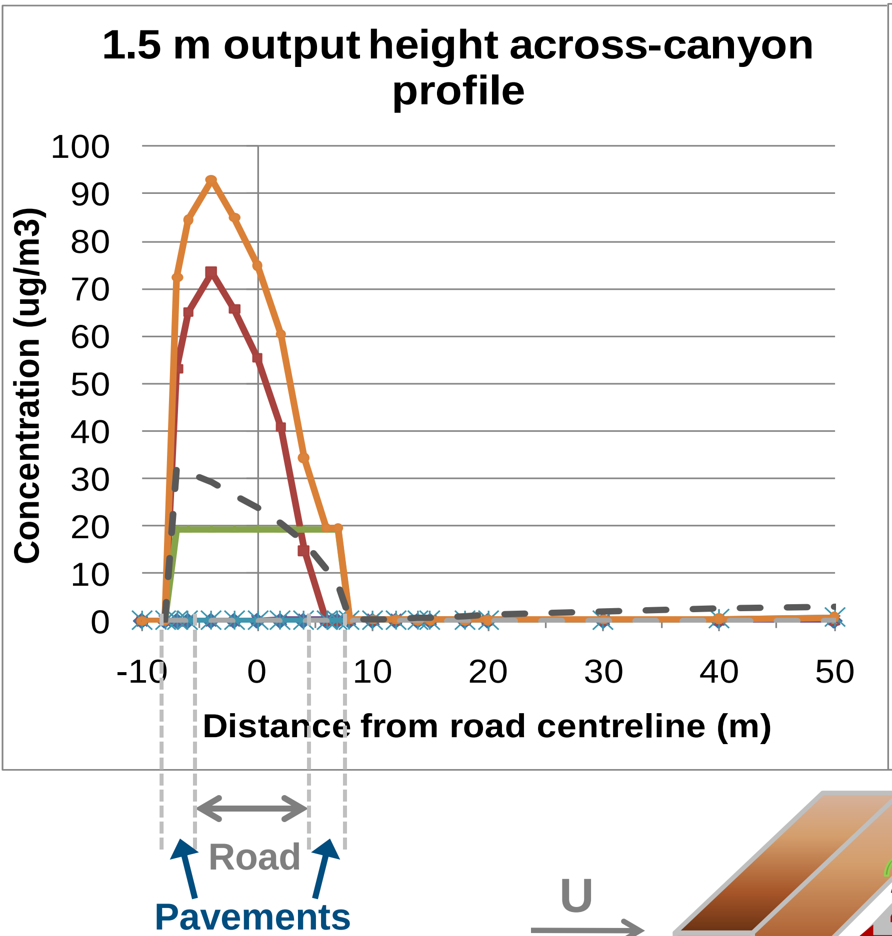
ADMS-Urban Implementation: Source weightings

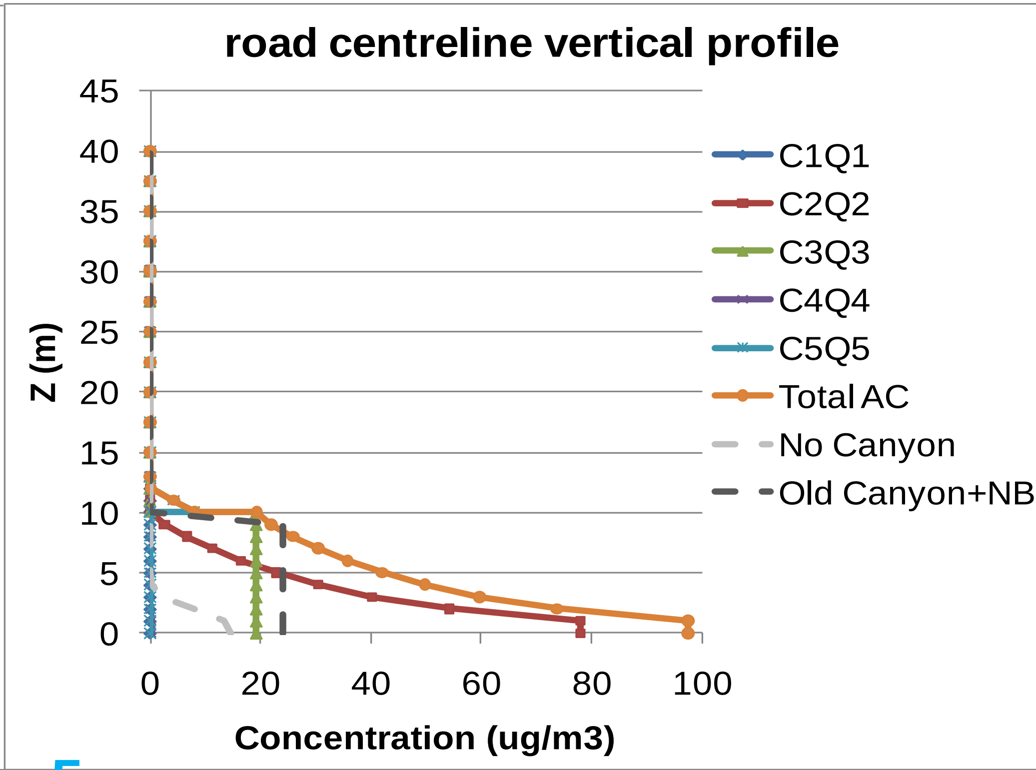
- Balance between in-canyon (**S1,S2**) and non-canyon (**S4**) weighting based on porosity squared
- Non-canyon increased if the canyon is shallow
- In-canyon divided between along-canyon (**S1**) and across-canyon (**S2**) based on wind direction relative to canyon axis
- In-canyon (**S1, S2**) may be reduced due to canyon asymmetry
- Canyon-top (**S5**) equal to in-canyon (1-**S4**)
- Recirculation (**S3**) equal to across-canyon (**S2**)

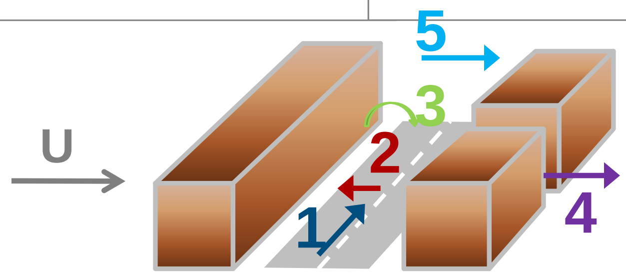


Example concentration profiles

- Shallow symmetric canyon, perpendicular wind







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ADMS-Urban model set-up for London

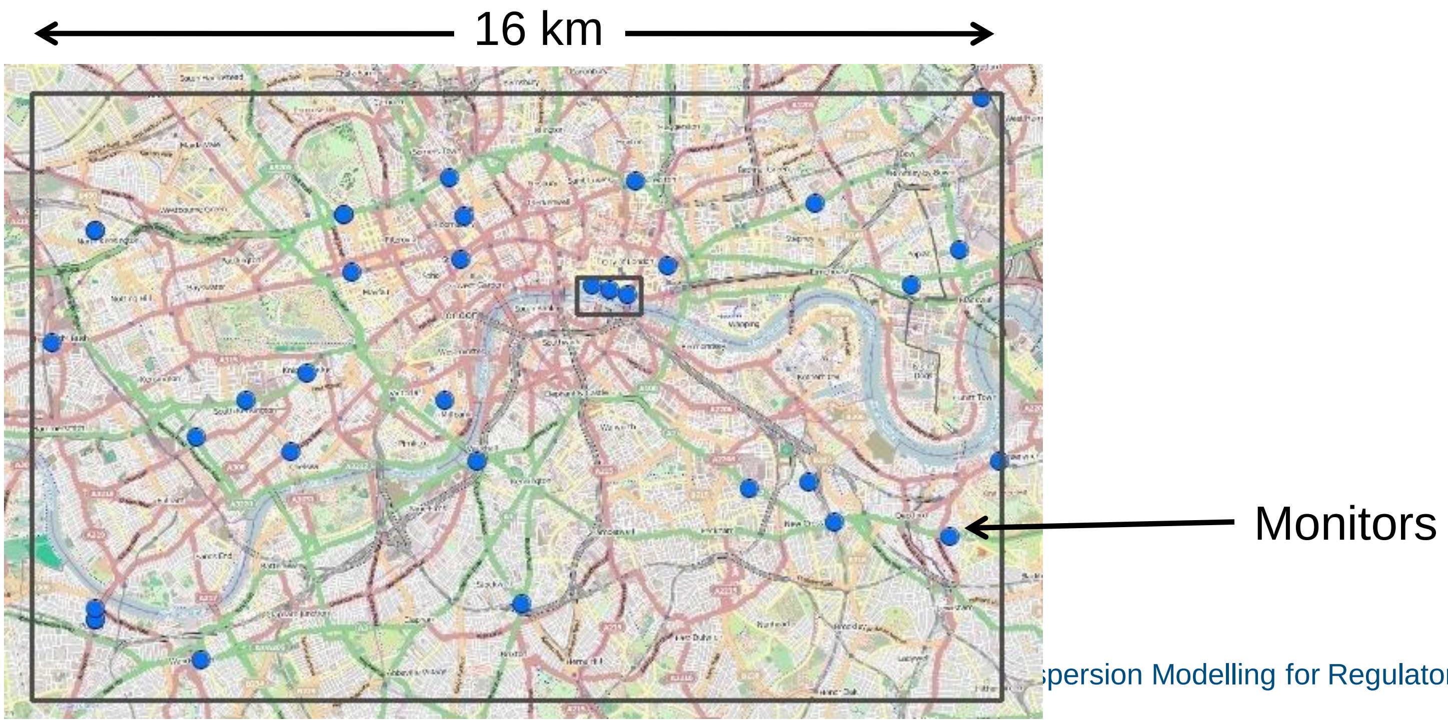
Input data

- Standard ADMS-Urban modelling approach for London
  - Measured meteorological data from Heathrow airport
  - Measured upwind rural background concentrations
  - London Atmospheric Emissions Inventory (LAEI) emissions data
  - Modelling year 2012
  - Modelling domain 10x15 km central London

- Model configurations tested
  - **No canyon**: no street canyon modelling
  - **Basic canyon**: existing ADMS-Urban street canyon model
  - **Advanced canyon & Urban Canopy**: Urban Canopy flow field with new street canyon modelling

Monitoring network

- 29 monitors located within the ‘buildings data’ area
- Monitor information (values, locations, heights) available from web
- Data for NO_x, NO_2, PM_{10}, $PM_{2.5}$, O_3
- 21 kerbside/roadside, 8 urban background
  - Some of the urban background sites are within canyons
- Monitor heights generally less than or equal to 3 m



Tools used for analysis

- MyAir Toolkit for Model Evaluation
  http://www.cerc.co.uk/environmental-software/myair-toolkit.html
- openair
  http://www.openair-project.org/Downloads/Default.aspx

Polar plots

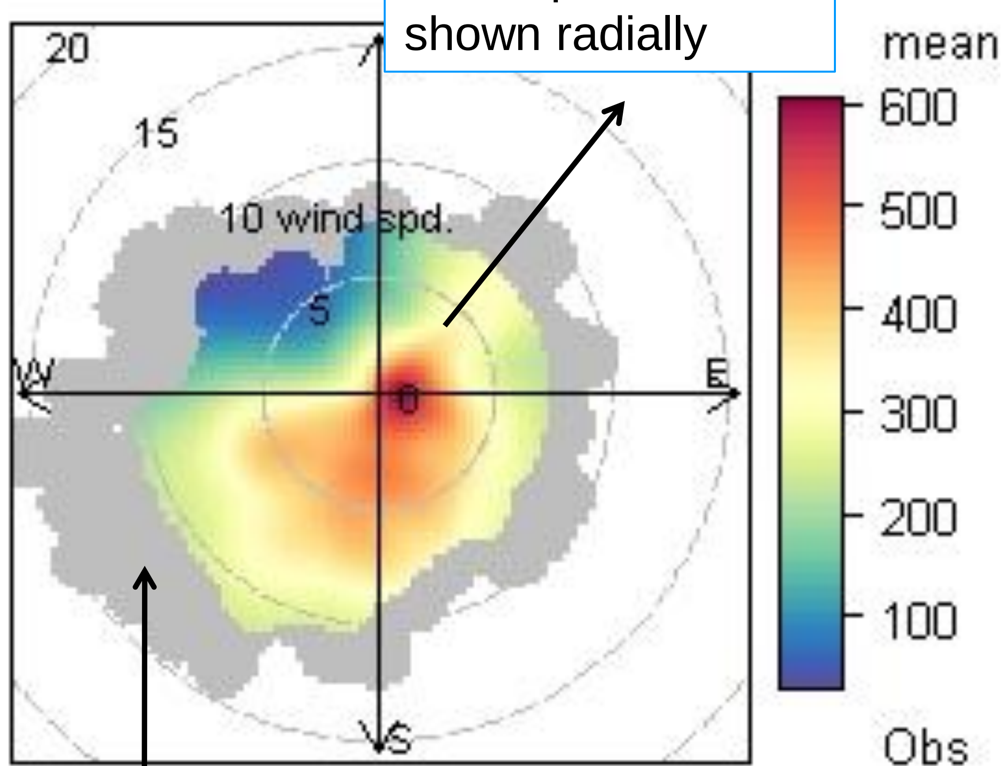
Example shows observed NO_x concentrations at a single receptor

Hourly data binned according to wind speed and direction

Colour indicates average concentration for each bin

Observations at this site indicate high concentrations for a range of wind speeds and restricted wind directions

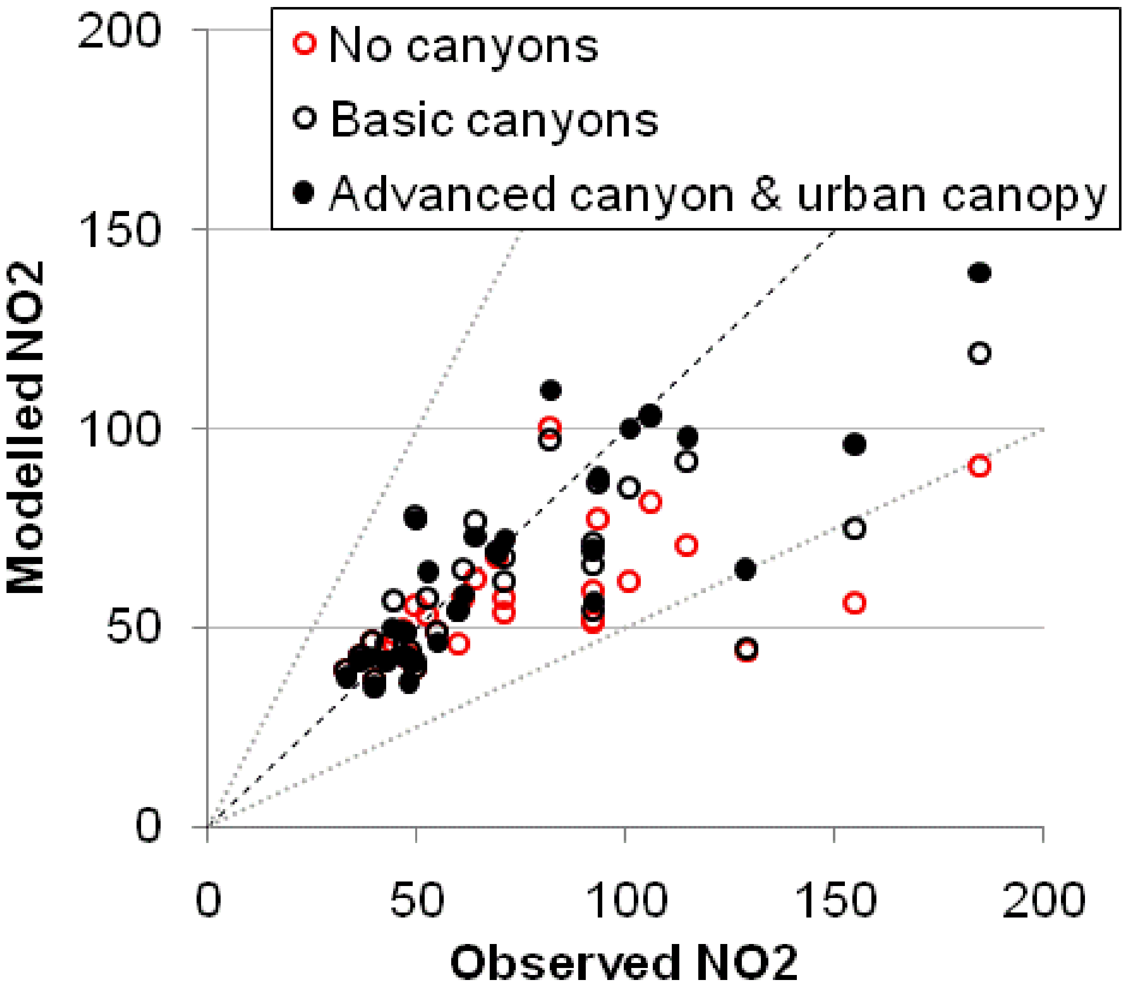
Wind speed in m/s shown radially



Concentration bins with <8 entries shown in grey

Validation Results

Mean NO_2 concentrations scatter plot



- All sites shown
- When canyons are modelled, means usually increase, giving a better estimate
- Modelling canyons does not affect the lower concentration sites

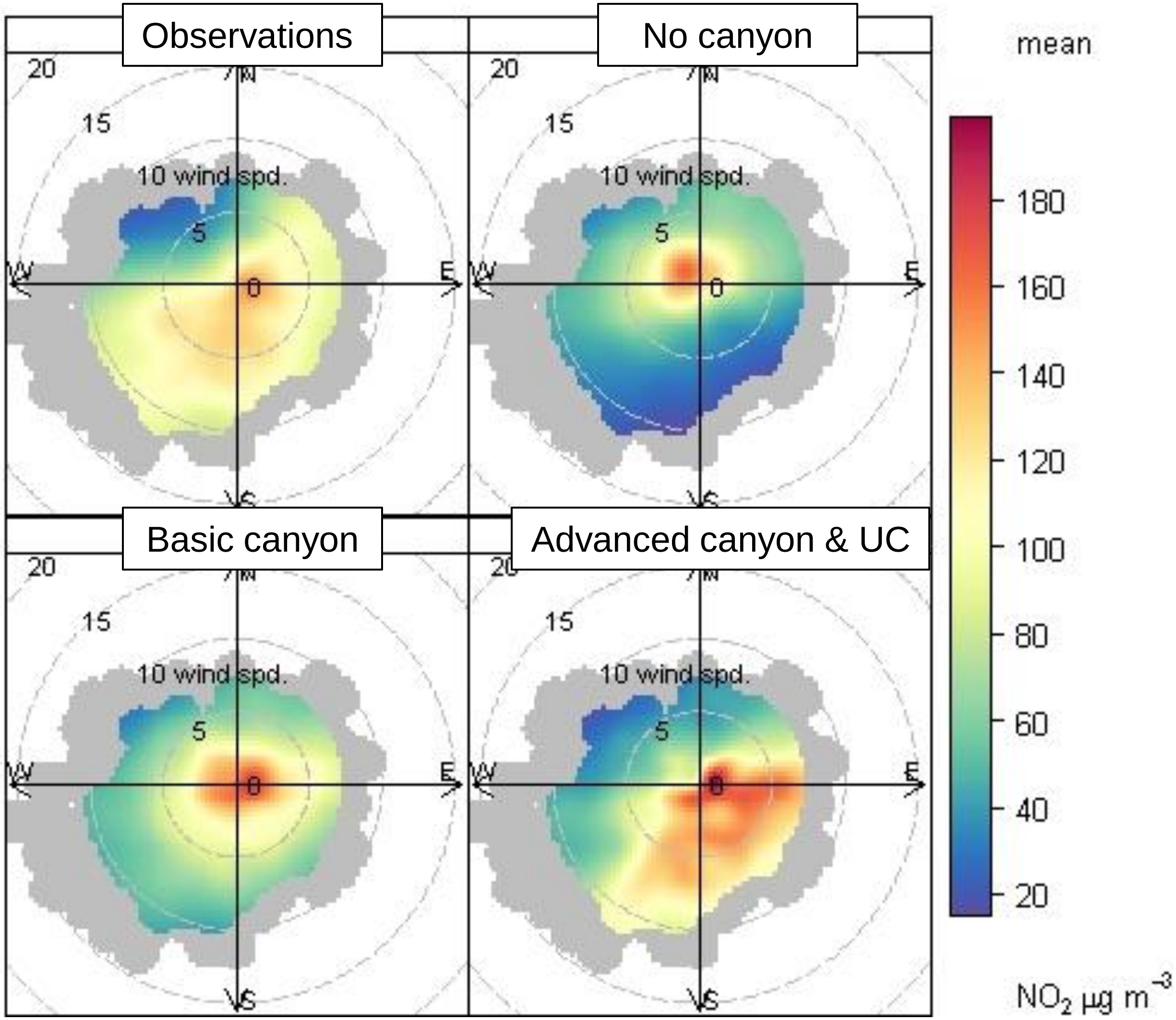
NO_2 concentration statistics

- Data for all sites for whole year
- Best statistics highlighted

Data	Mean	NMSE	R	Fac2	Fb
Observed	70.8	0.00	1.00	1.00	0.00
No Canyon	53.8	0.76	0.36	0.73	-0.27
Basic Canyon	61.5	0.53	0.49	0.79	-0.14
Advanced Canyon & Urban Canopy	**63.1**	**0.39**	**0.62**	**0.81**	**-0.11**

Validation Results
Polar plots: Full canyon

- Consider a receptor ‘CD9’ within a standard canyon (H/g = 0.96, porosity = 0.26)



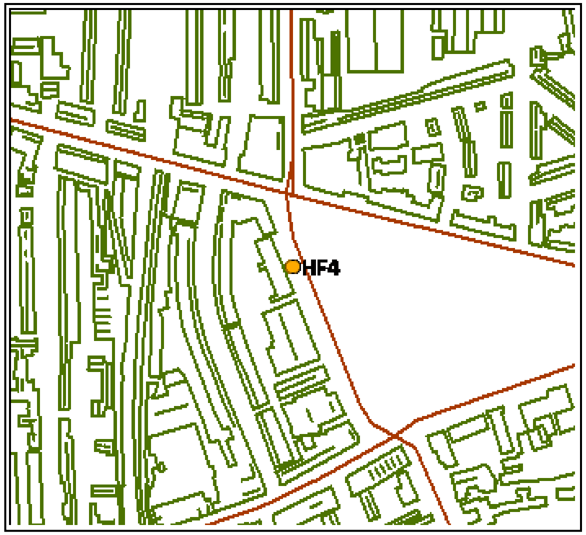
- Wind from North West gives low concentrations and from the South East gives high concentrations due to presence of canyon
- ‘No canyon’ and ‘Basic canyon’ runs predict similar concentrations in all directions

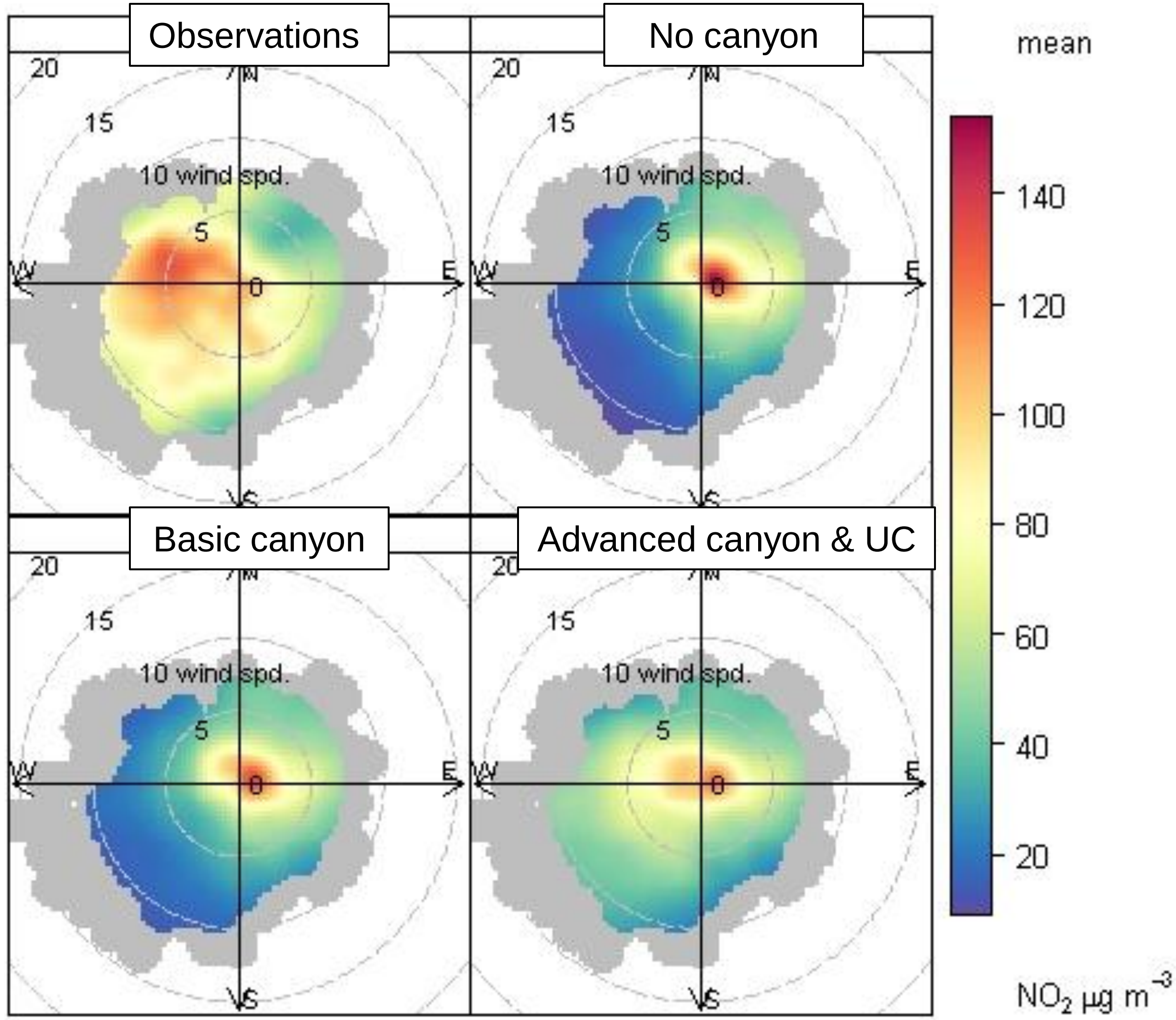
NO_2 concentrations

Validation Results

Polar plots: Asymmetric canyon

- Consider a receptor ‘HF4’ within an asymmetric canyon (H = 15 m)





- Wind from West gives high concentrations and from the East gives lower concentrations due to presence of asymmetric canyon
- ‘No canyon’ and ‘Basic canyon’ runs predict wind from East giving higher values

NO_2 concentrations

Conclusions

- New modules for modelling urban canopy flow field and advanced street canyon effects have been added to ADMS-Urban

- Validation ongoing in London and Hong Kong

- Model to be released in 2015

Acknowledgements

The urban canopy and advanced street canyon modules have been developed in collaboration with researchers from the Hong Kong University of Science and Technology, supported by the Hong Kong Environmental Protection Department.

香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Environmental Protection Department
The Government of the Hong Kong Special Administrative Region