Modelling air quality in complex urban environments: latest developments in ADMS-Urban

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Cambridge Environmental Research Consultants
Environmental Software and Services

Contents

- ADMS-Urban basics
- Urban Canopy flow
- Street canyon dispersion
- Chemistry
- Ongoing developments/Opportunities

ADMS-Urban Model Capabilities

- ADMS-Urban is designed to model dispersion from a wide range of urban sources
- Gaussian type model with point, line area, road and grid sources; non-Gaussian vertical profile of concentration in convective conditions
- Concentration calculated at high resolution (<10m)
- Includes meteorological pre-processor
- Options for different chemical mechanisms
- Considers effects of complex terrain: surface elevation and roughness
- ***Allows for the effects of buildings; fully integrated street canyon model;***
- Integration with Geographical Information Systems (GIS) and an Emissions Inventory Database (EMIT)
- Used in many major cities for air quality management, air quality forecasting etc: e.g. London, Budapest, Rome, Barcelona, Beijing, Shanghai, Singapore, Cape Town, Hong Kong, Kuala Lumpur

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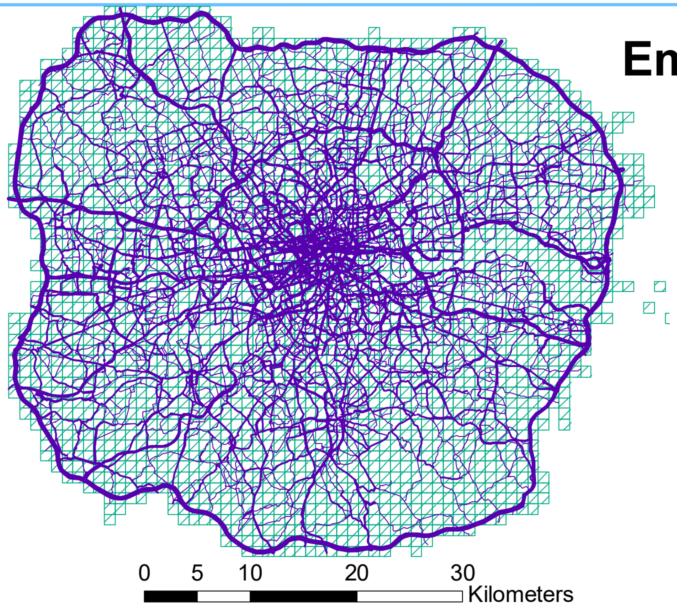
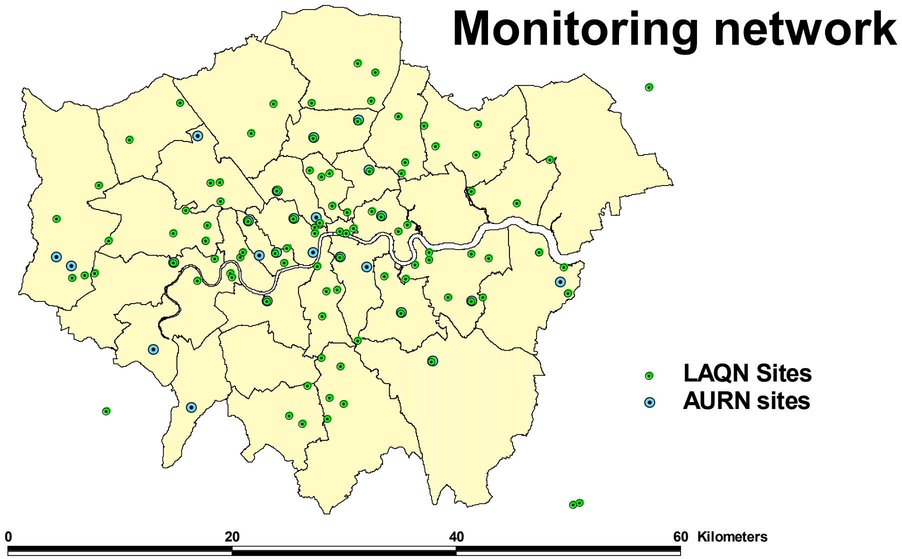
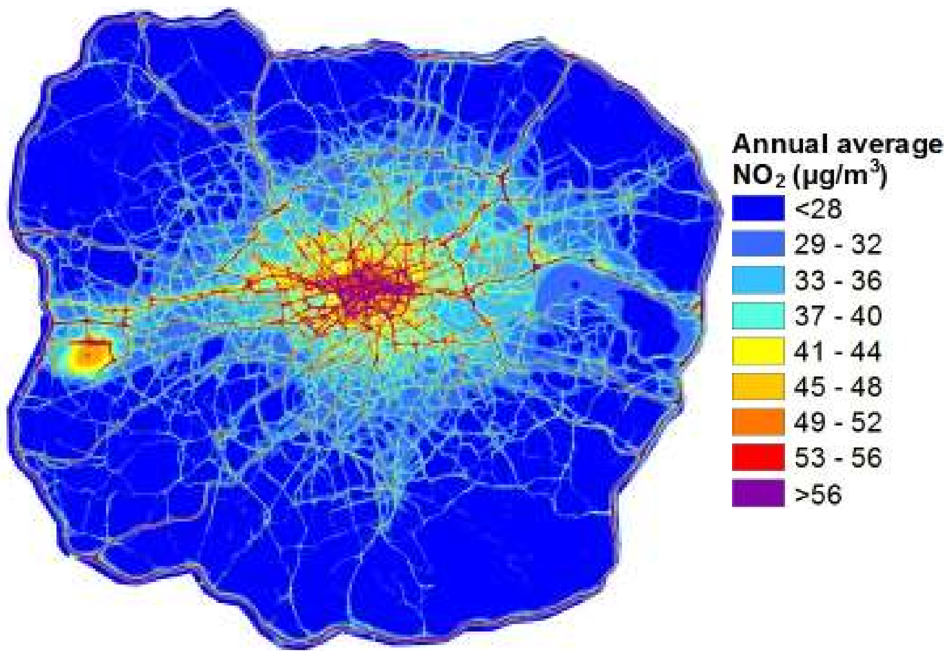
Example of the use of ADMS-Urban





Modelled annual average NO_2 concentrations 2012



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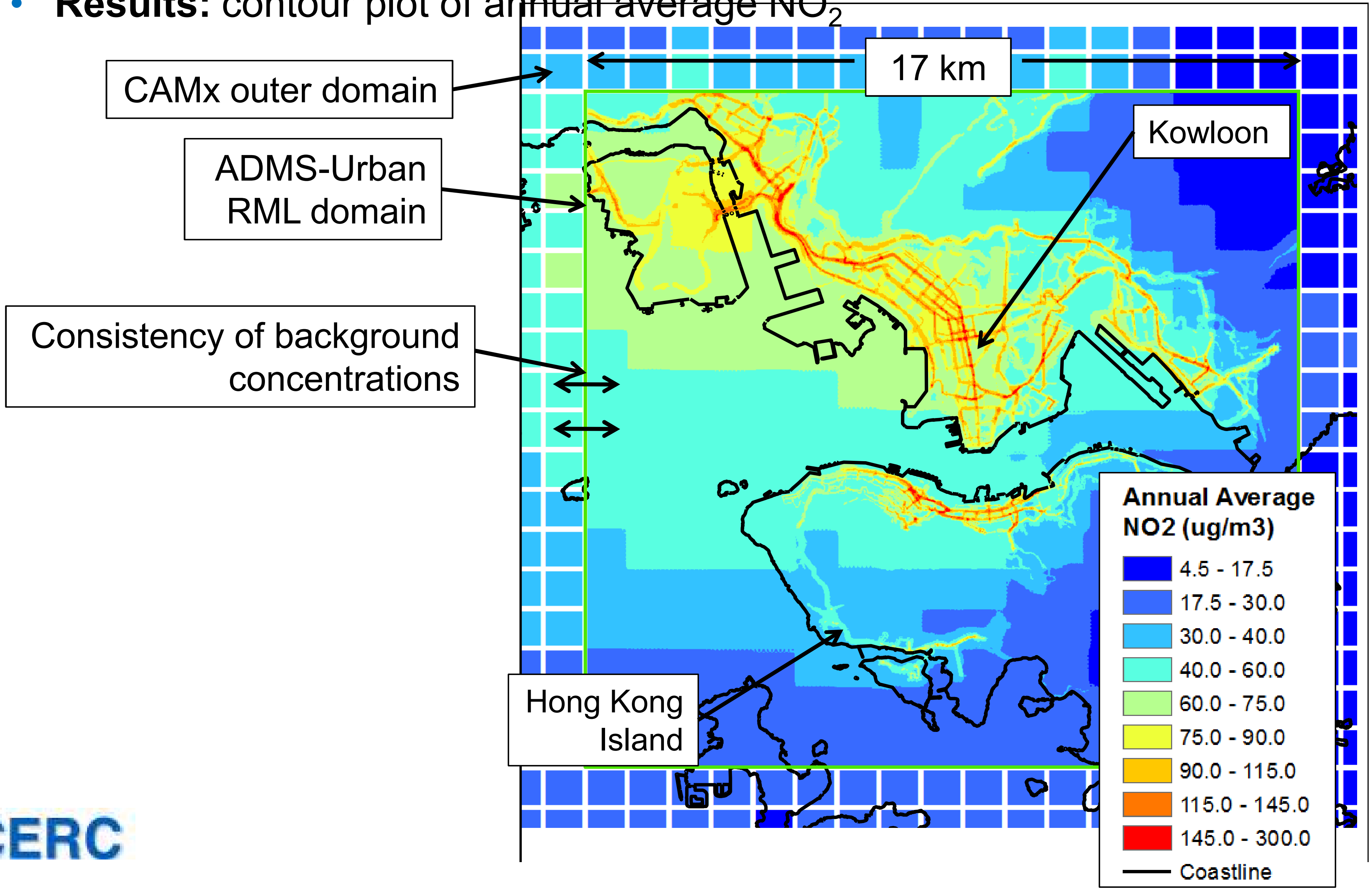
ADMS-Urban Regional Model Link

- **Results:** contour plot of annual average NO_2



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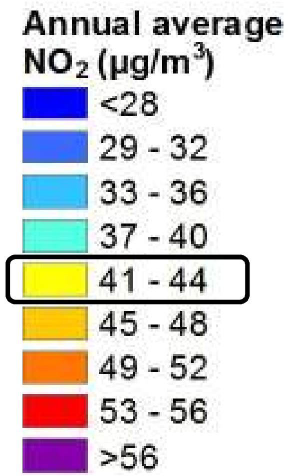
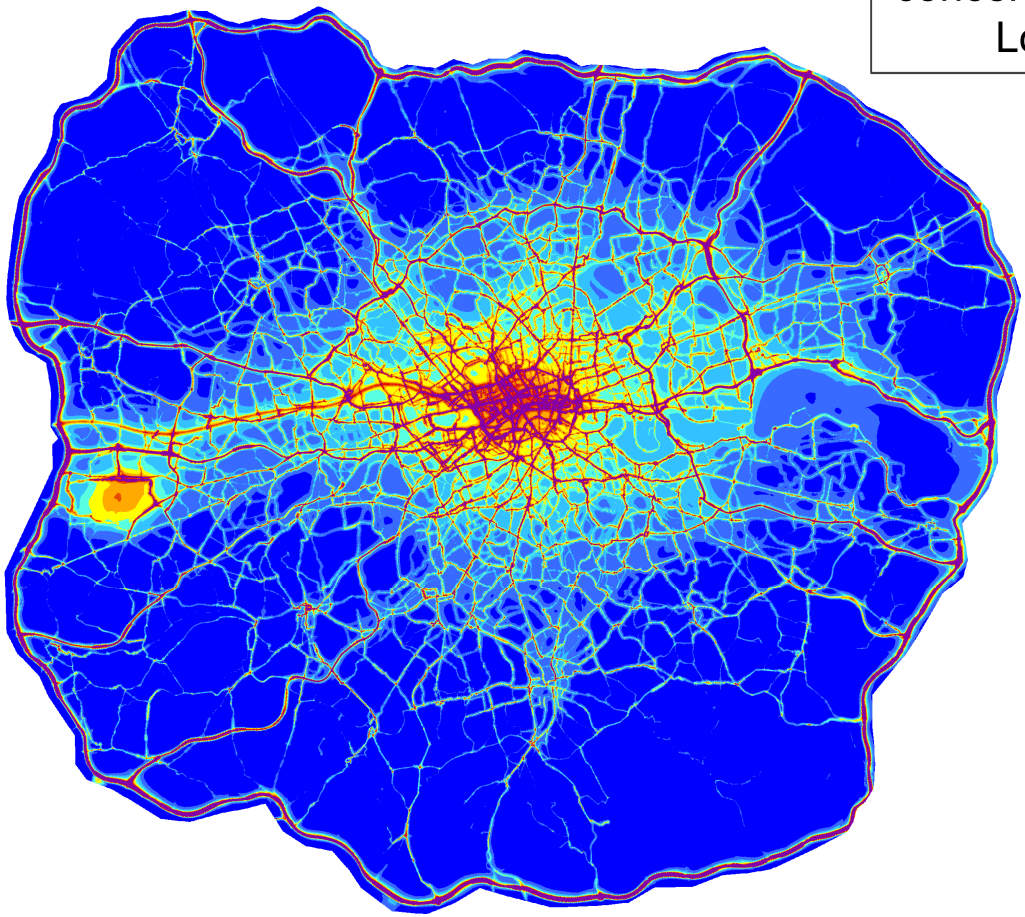
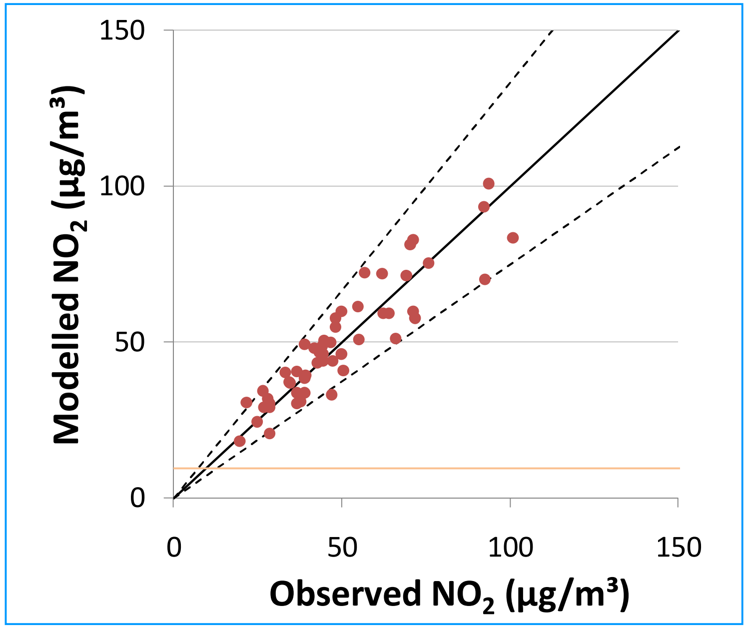
Example and validation using ADMS-Urban

- Given accurate inputs (e.g. adjusted to account for real-world emissions) comparison with measurements at roadside and background sites good for long term averages.

Long-term average NO_2 concentrations in Greater London (2012)







Recent Developments of ADMS-Urban at local scale

- Allowance for neighbourhood scale effect of urban canopy on flow
- Advanced street canyon model. Former street canyon model used in ADMS-Urban (OSPM) is highly idealized – limited variation of concentration with height; no pavements: road width is canyon width; on:off
- Tunnels, elevated roads .....
- ADMS approach is to include essential physics but to use simplifying parameterizations so that model is practical to run for planning and policy scenarios etc.

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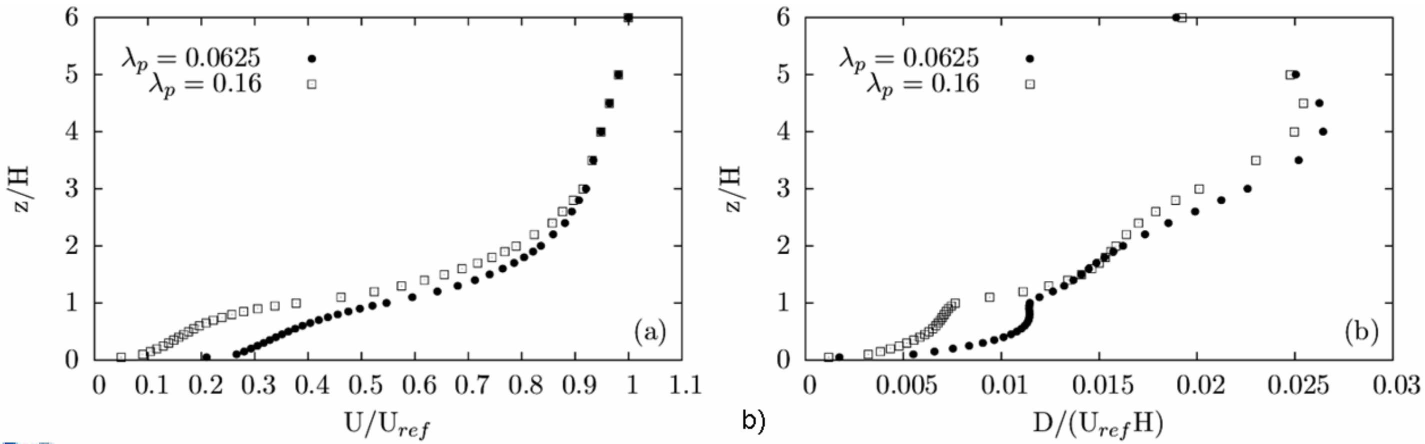
Background: Urban Canopy Flow

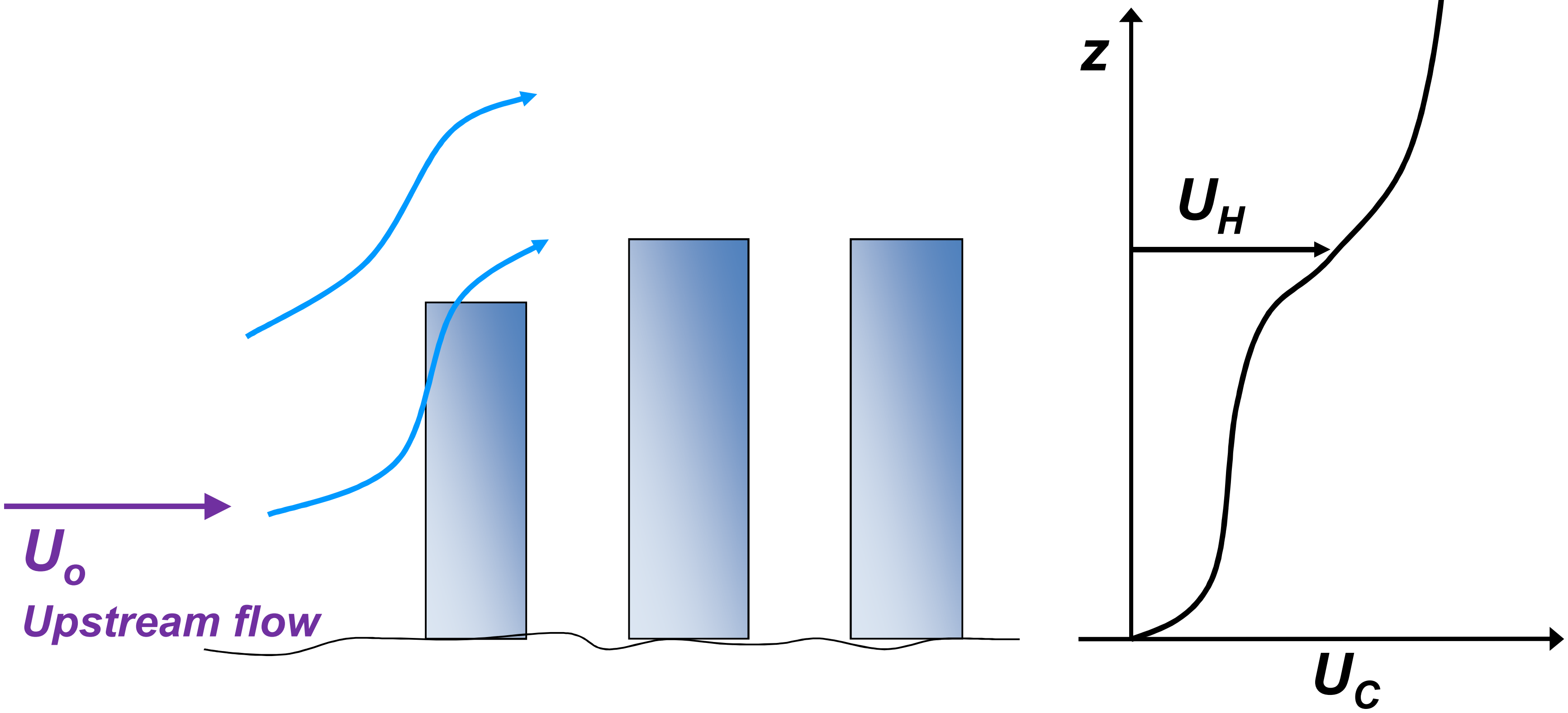
- Urban architecture affects local air flow
- Important to use urban flow characteristics for accurate calculation of pollutant dispersion
- Many studies (CFD, wind tunnel and field experiments) have used regular arrays of cubic obstacles to represent urban buildings
- Also some studies of real urban areas with irregular arrays and non-cubic buildings
- Parameterisation based on published experimental and wind tunnel data, CFD and theoretical considerations



a) b)

Urban Canopy Flow: Velocity

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



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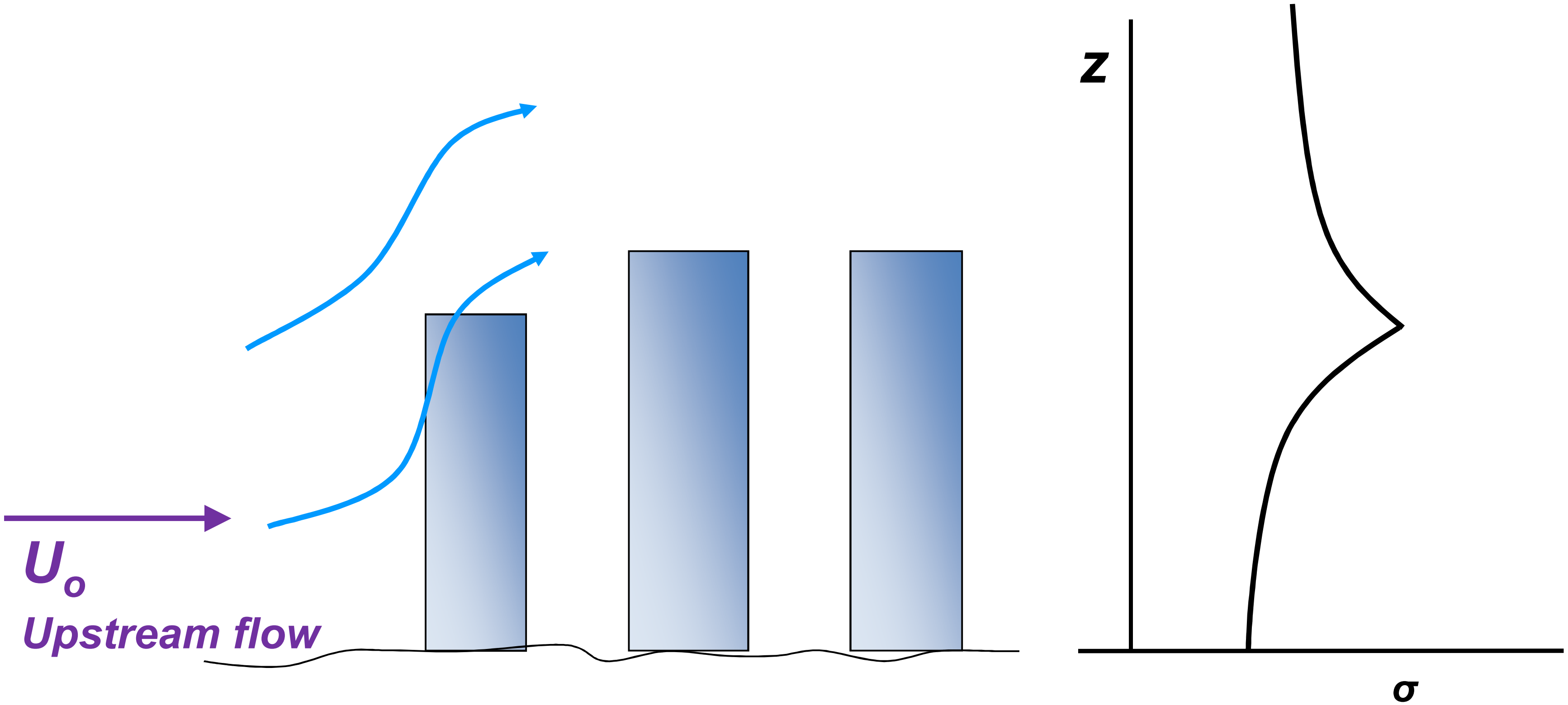
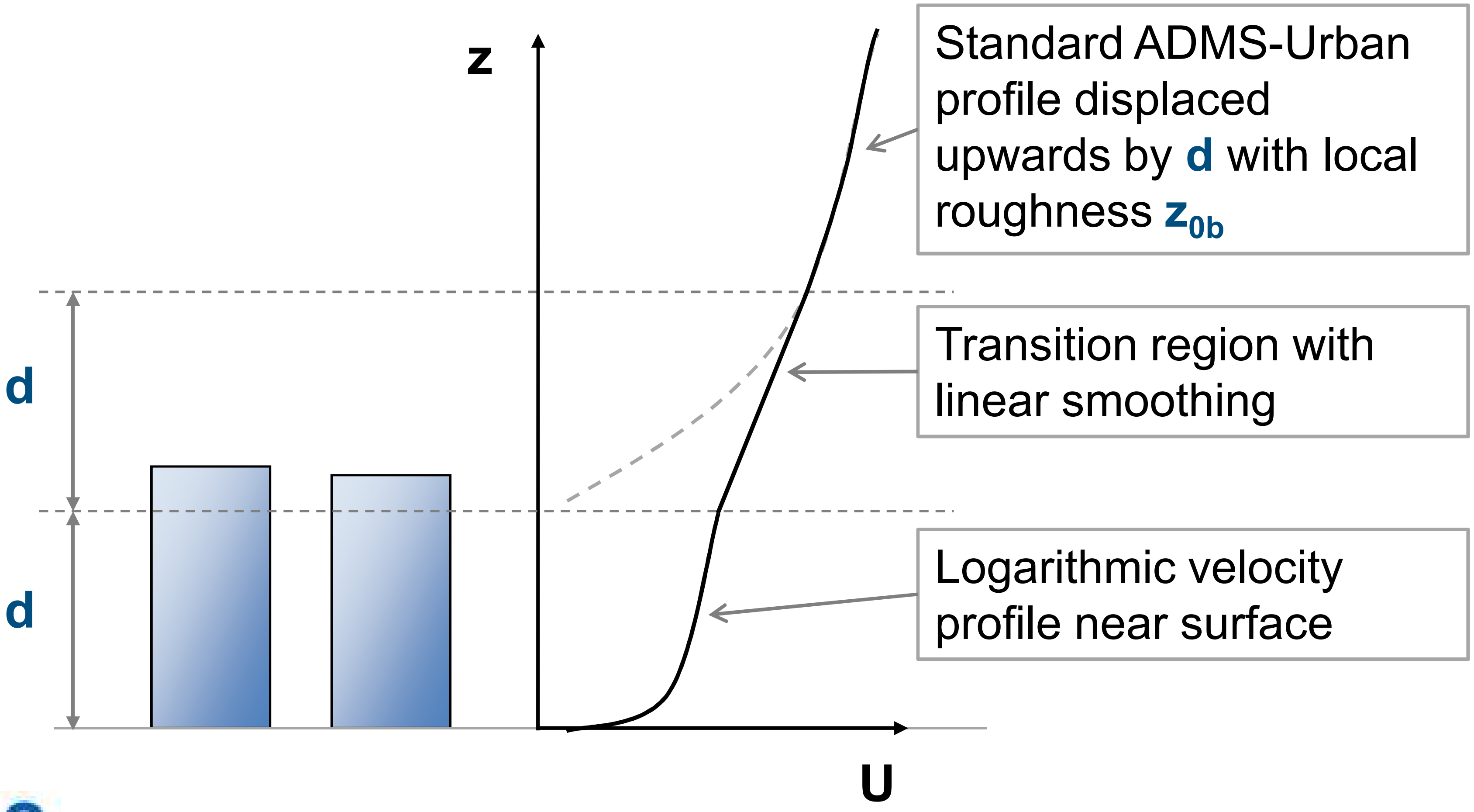
Urban Canopy Flow: Turbulence

- Turbulent velocities are enhanced in shear layer near building tops and reduced below the average building height



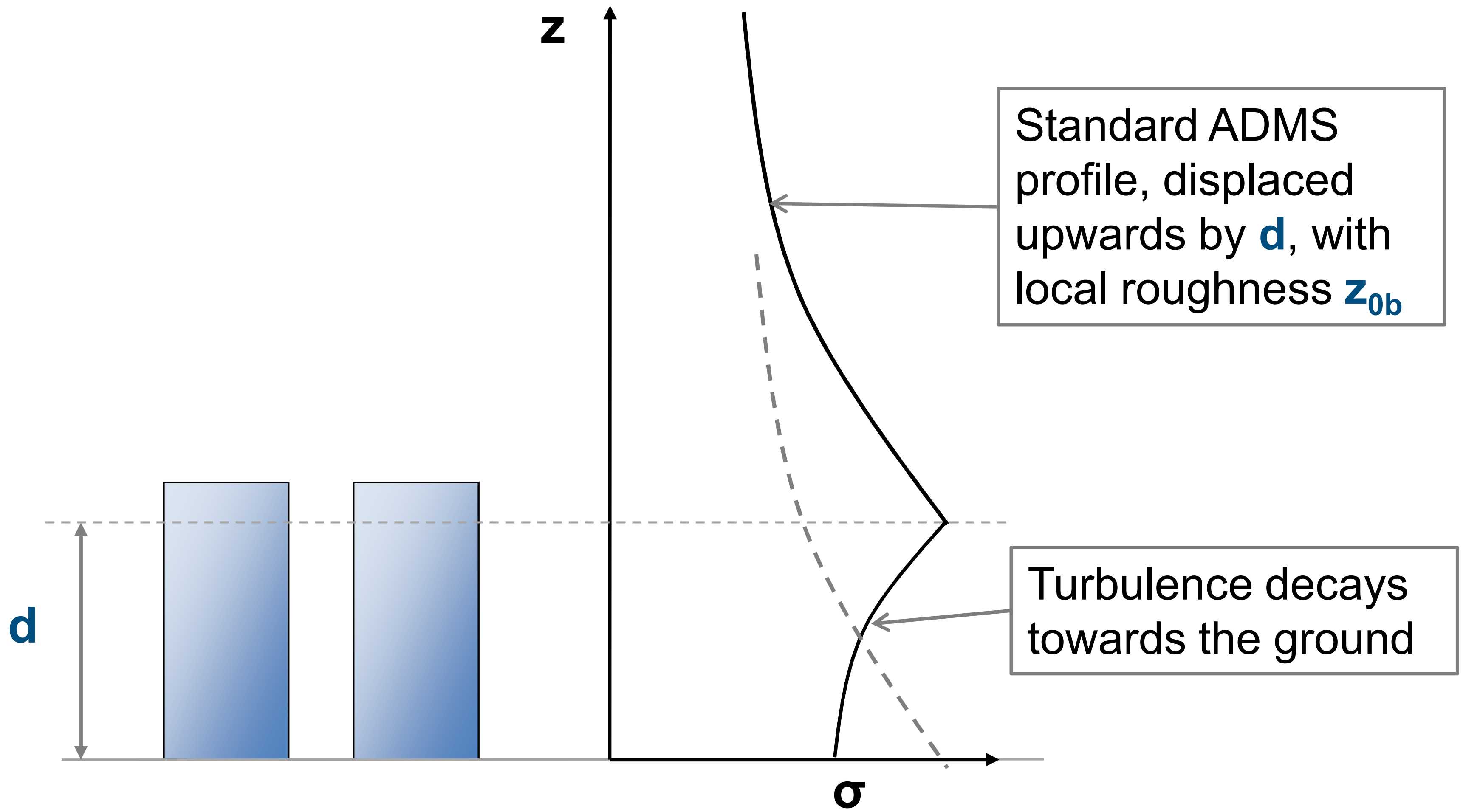
Urban Canopy Flow:
Implementation in ADMS-Urban: Velocity

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



Urban Canopy Flow:
Implementation in ADMS-Urban: Turbulence

Two part profile: above and below displacement height

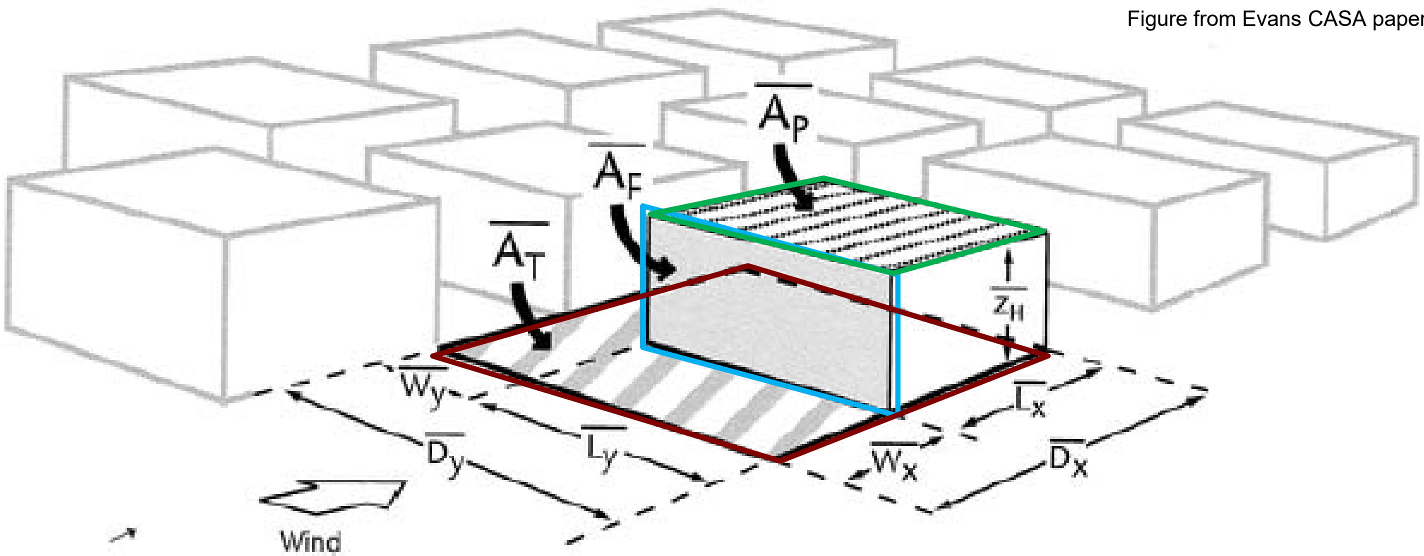


Details of standard ADMS turbulent velocity profiles can be found at
http://www.cerc.co.uk/environmental-software/technical-specifications.html

Urban Canopy Flow:

Implementation in ADMS: Characterisation of urban area

Figure from Evans CASA paper

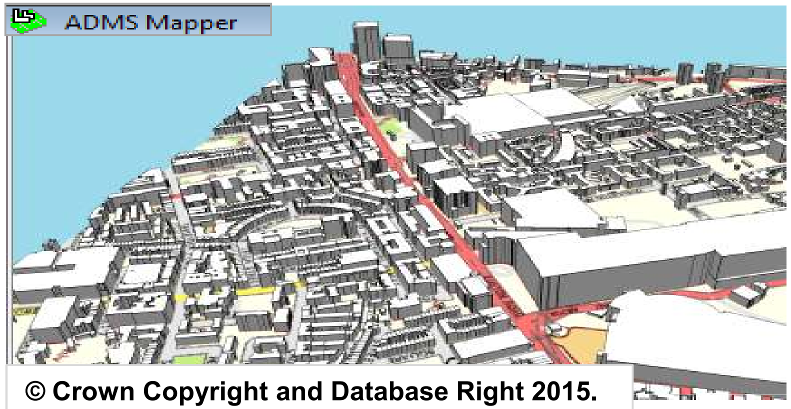


- Effective roughness $\mathbf{z_{0b}}$ and displacement height $\mathbf{d}$ calculated relative to average building height $\mathbf{H}$ using plan and frontal area fractions λ_P and λ_F
- $\lambda_P = A_P/A_T$
- $\lambda_F = A_F/A_T$
- $d/H = 1 + (\lambda_P - 1)\alpha^{-\lambda P}$
- $z_{0b}/H = (1\text{-}d/H)\exp\{-(0.5\beta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

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

Urban Canopy Flow Summary

- Requires 3D buildings data as input; ArcGIS Tools available to pre-process buildings data



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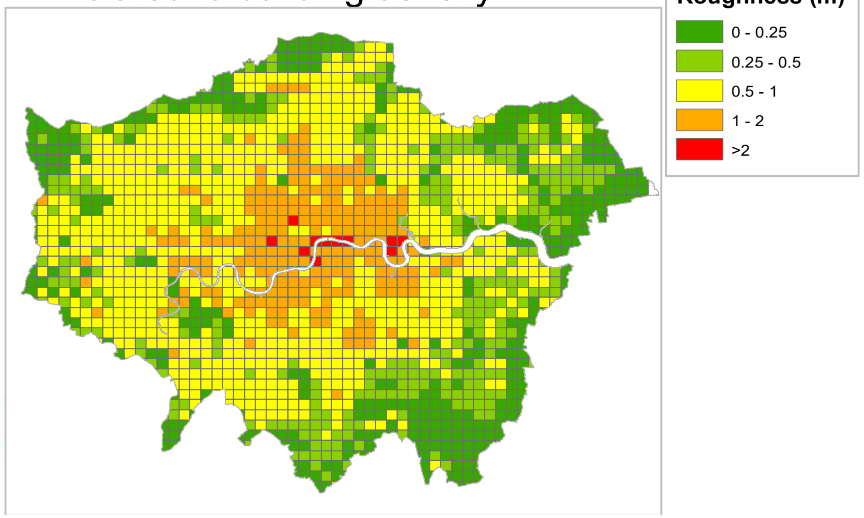
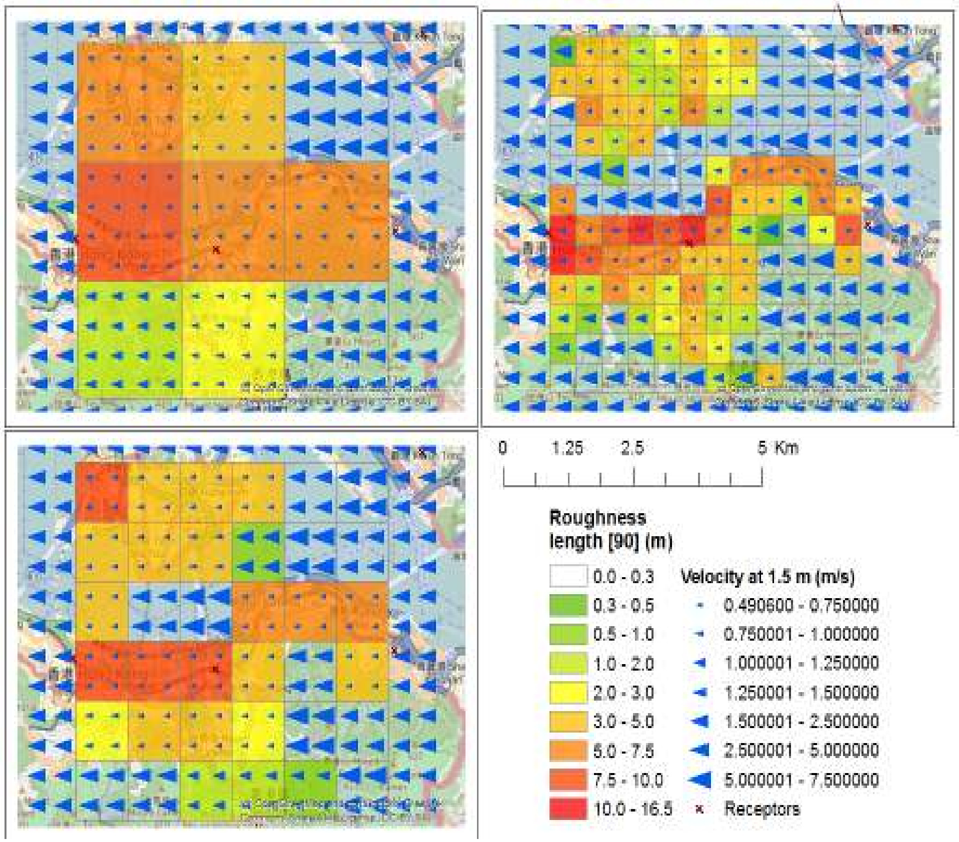
Ordnance Survey (Digimap Licence)

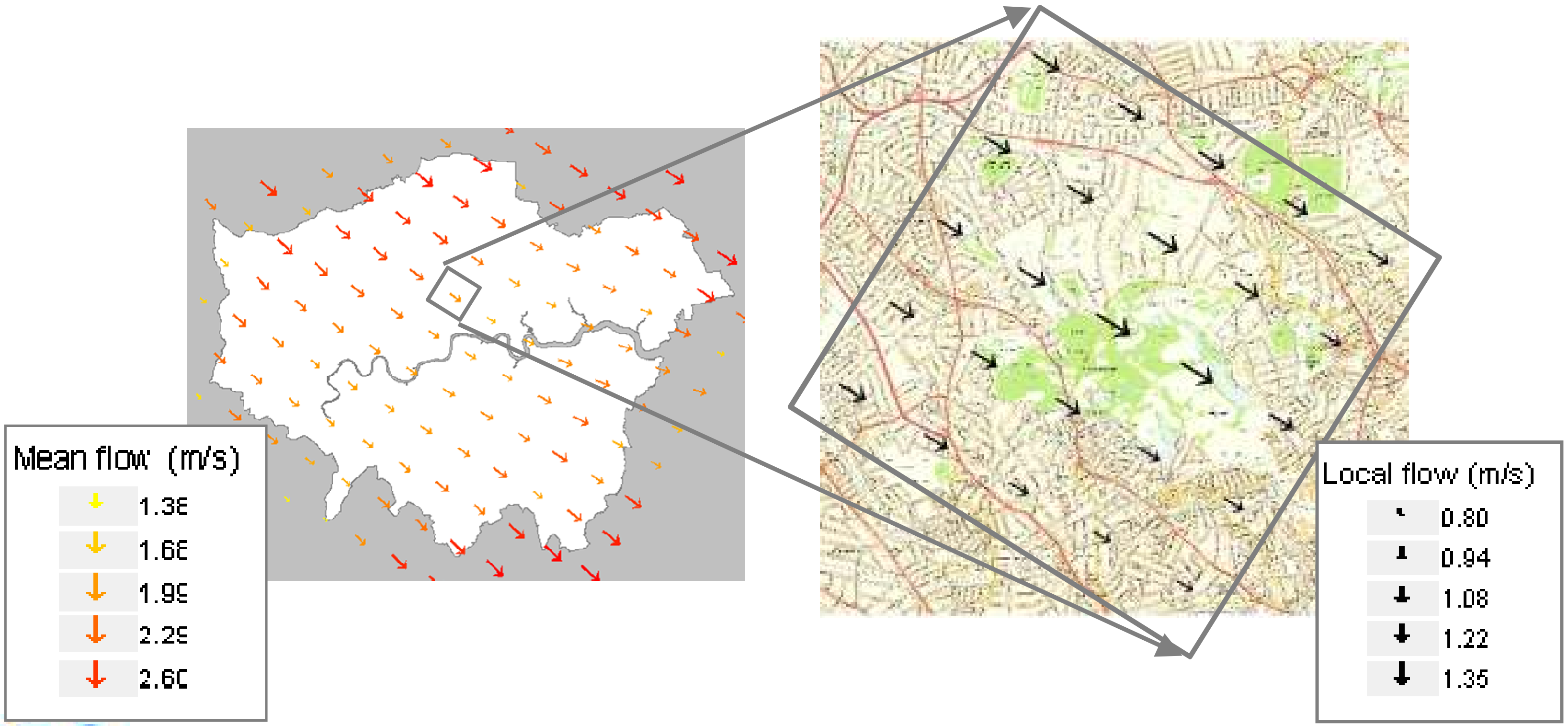
- Model calculates the spatial variation of roughness length, giving a spatial variation of wind speed related to building density





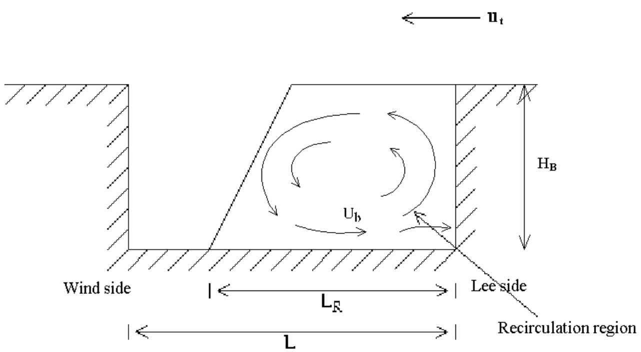
Urban Canopy Flow:
Example flow field: London

- 5 km resolution flow field from WRF
- 1 km resolution urban canopy flow field from ADMS-Urban



Background: Canyon Flow and dispersion

- 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 traditional '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
- Improved modelling of street canyons was required to include:
  - Tall canyons (height/width > 1)
  - Asymmetric canyons: height, width, building density
  - Smoother transition between non-canyon and canyon modelling
  - Allowance for pavements (no emissions) and road lanes



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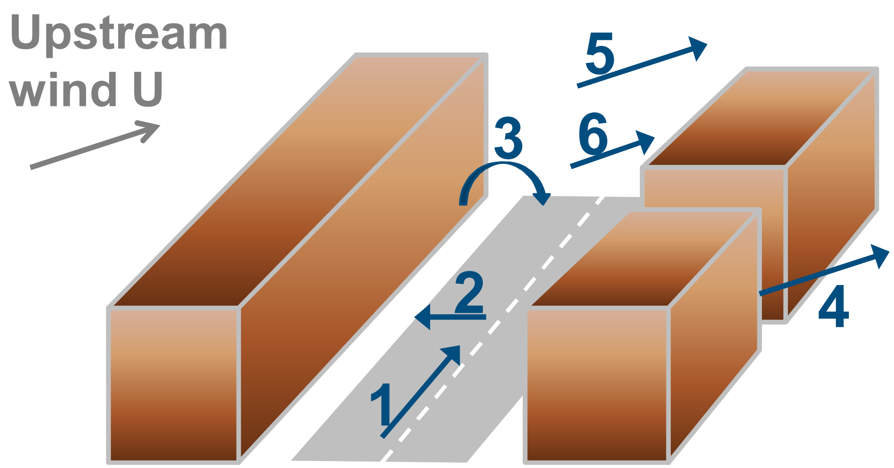
Street canyon dispersion effects

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**
6. Pollutants enter/leave the canyon from the **canyon end**



Model Implementation - Characterising street canyon properties

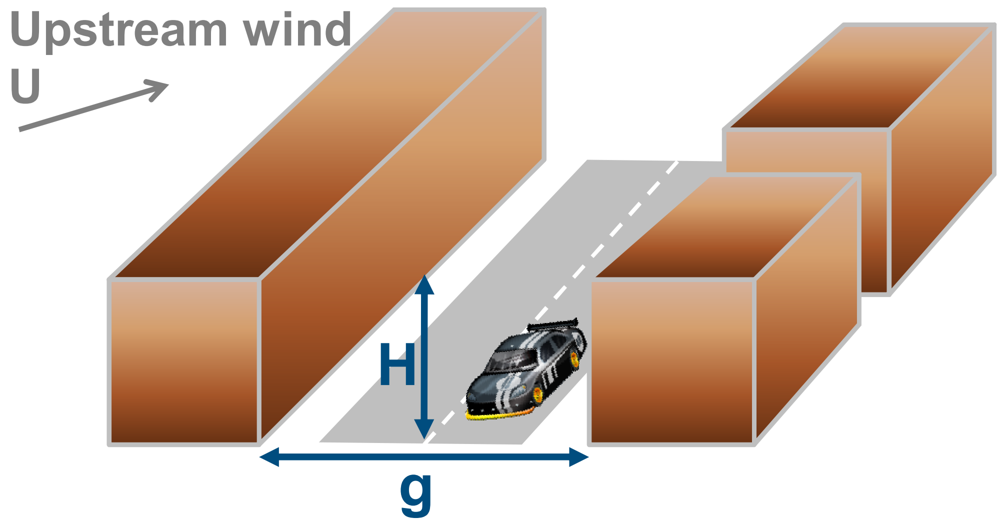
Each side of the canyon has properties

- Whether or not 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, i.e.

  1 - (building length / total length)

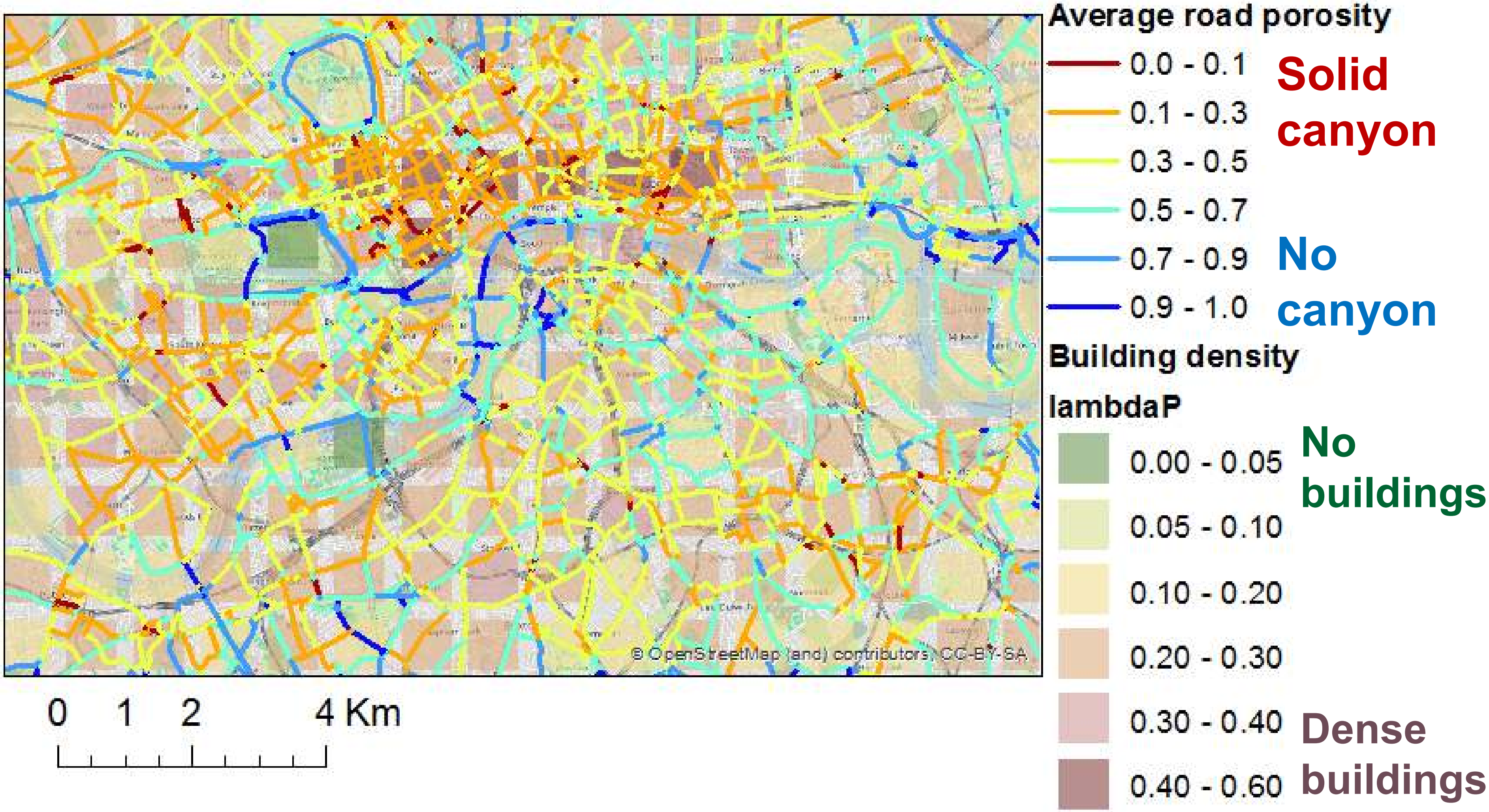
These are combined to find total canyon width (wall to wall) **g**, average height **H** and overall porosity **α**

Road width in interface needs to be redefined as **carriageway width**



Advanced street canyons: Porosity

Central London road porosity and 1 km building density values

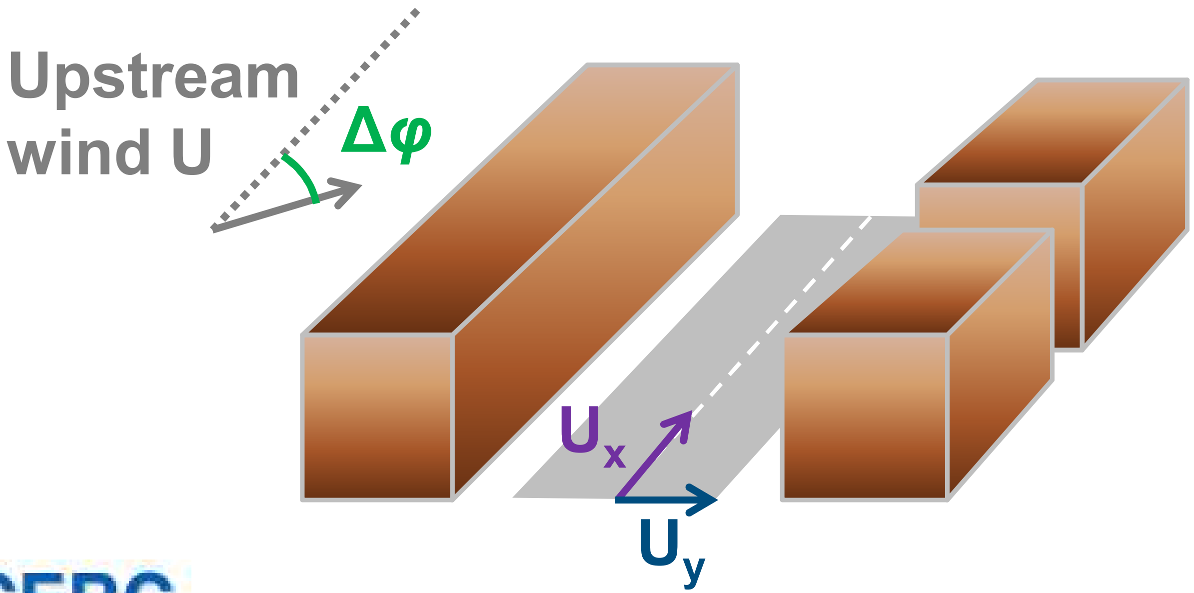


ADMS-Urban Implementation: Canyon flow

- 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 $\eta \leq 1$)

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

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

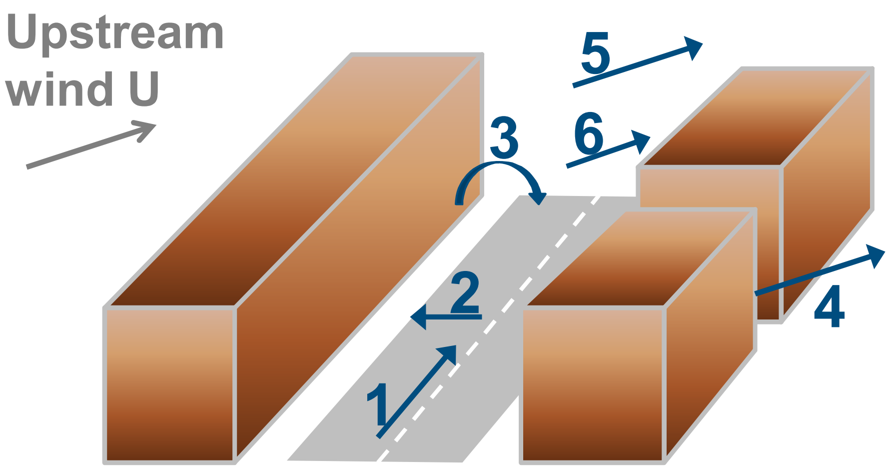


Canyon Flow and Dispersion
Component sources

Each effect is modelled using a component source, with differing

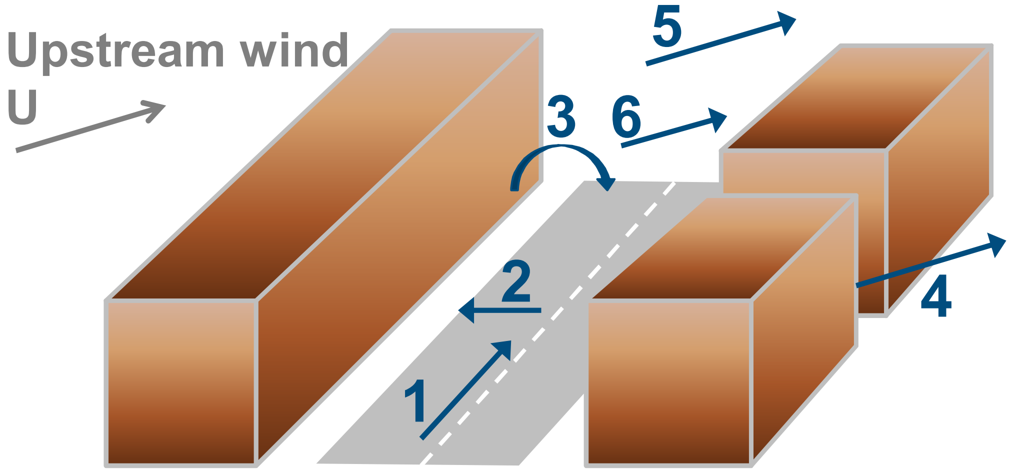
- Source **geometry**
- Source **dispersion** type
- **Wind direction**
- **Region of influence**
- Source strength

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



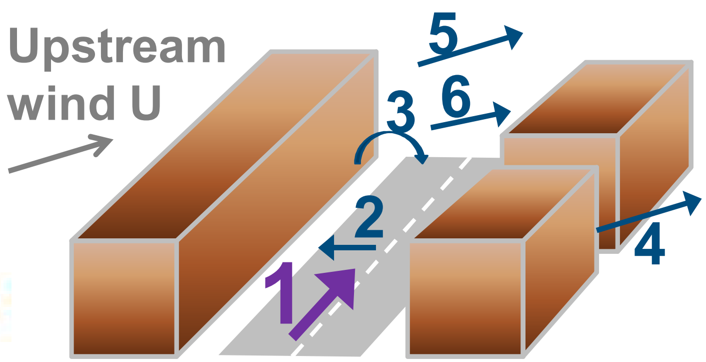
Canyon Flow and Dispersion
Component sources

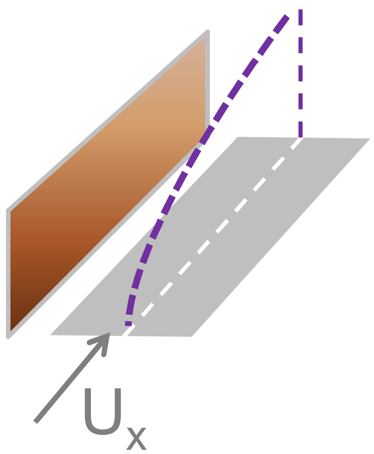
Source		Type	Wind direction	Region of influence
1	Along canyon	Road with reflections	Along canyon	Within canyon
2	Across canyon	Simplified road	Across canyon	Within canyon
3	Recirculation	Well-mixed cells	n/a	Within canyon
4	Non-canyon	Road	Upstream	Everywhere
5	Canyon-top	Volume	Upstream	Outside canyon
6	Canyon-end	Volume	Upstream	Downwind of canyon



Canyon Flow and Dispersion
ADMS-Urban Implementation: S1 Along canyon

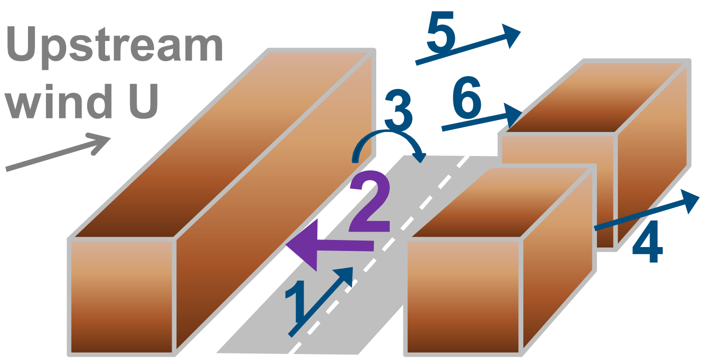
- Pollution is advected and dispersed by flow channelled along the canyon
  - **Geometry**: standard road
  - **Dispersion**:
    - standard ADMS-Urban road with width limit due to canyon walls and simplified calculation of mean plume height
    - well-mixed across canyon after a reflection reaches the opposite wall
    - allows for advection from upstream canyon
  - **Wind direction**: along canyon
  - **Region of influence**: within canyon

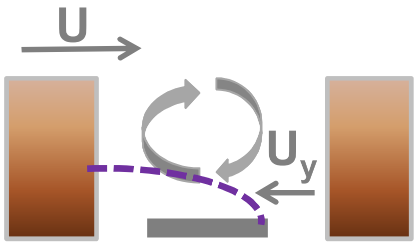




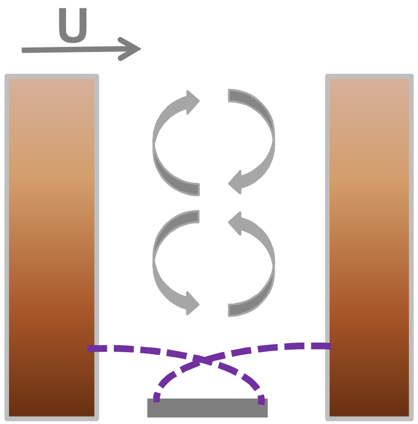
Canyon Flow and Dispersion
ADMS-Urban Implementation: S2 Across canyon

- 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

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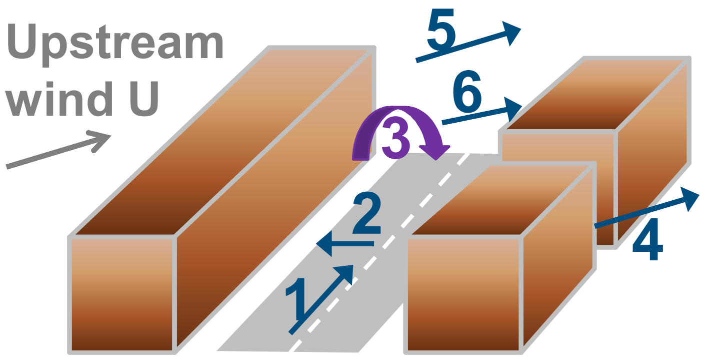
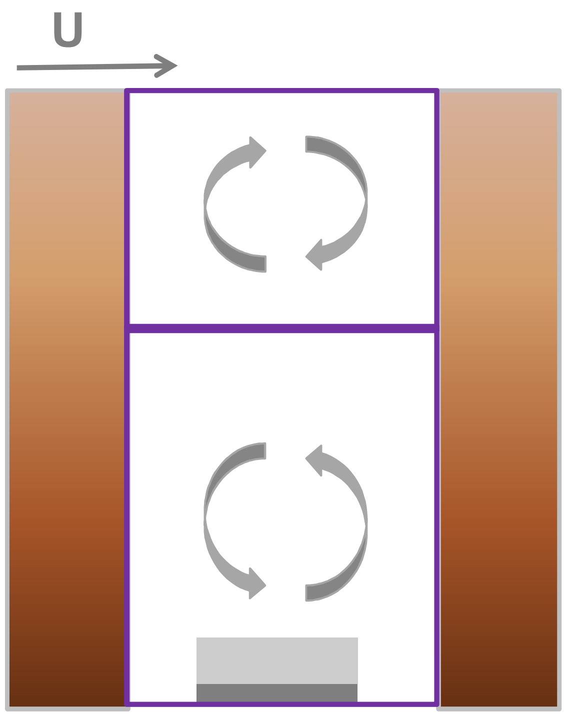
Canyon Flow and Dispersion
ADMS-Urban Implementation: S3 Recirculation

- Pollution can be trapped within the canyon by the recirculating flow
  - **Geometry**: full width and depth of canyon, divided into cells
  - **Dispersion**: analytical solution, concentration reducing for each cell moving up away from the road, with horizontal variation of concentration in the lowest cell
  - **Wind direction**: n/a
  - **Region of influence**: within canyon





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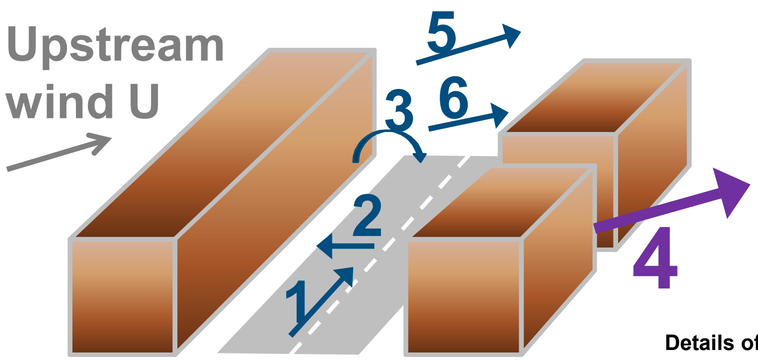
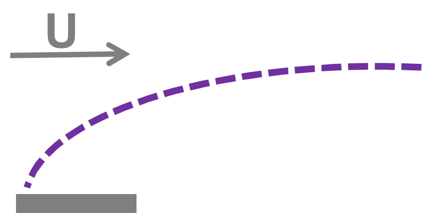
Canyon Flow and Dispersion
ADMS-Urban Implementation: S4 Non-canyon

- 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

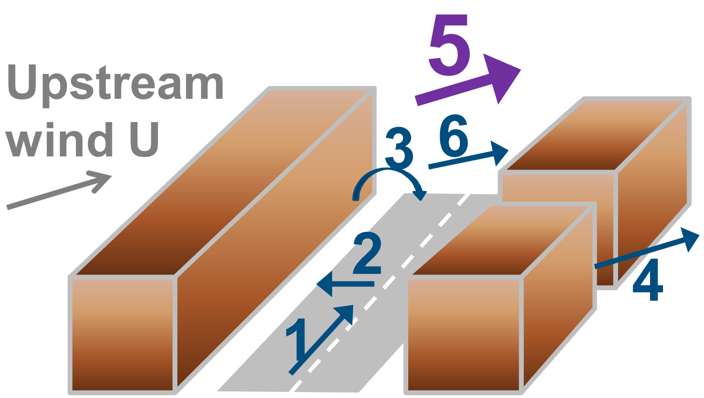


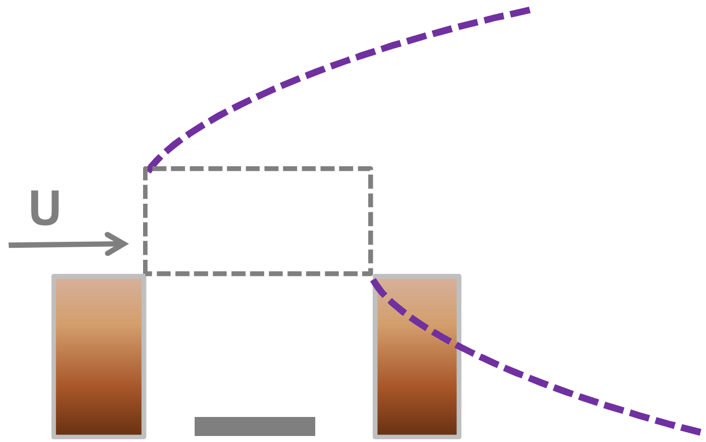


Details of standard ADMS source definitions and dispersion calculations can be found at http://www.cerc.co.uk/environmental-software/technical-specifications.html

Canyon Flow and Dispersion
ADMS-Urban Implementation: S5 Canyon top

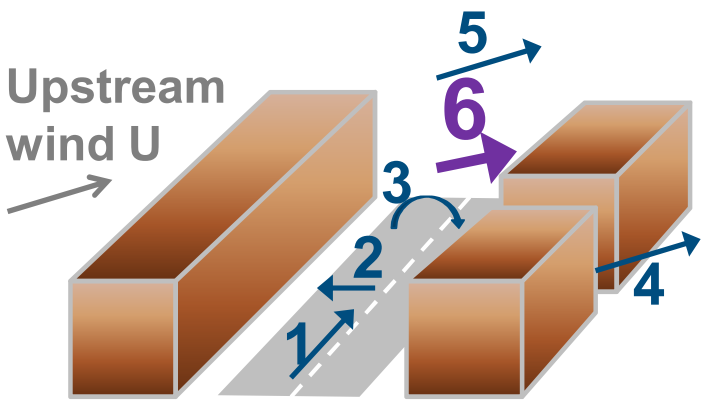
- Pollution leaves the canyon from the top
  - **Geometry**: volume source with canyon width, depth depends on canyon height;
  - **Dispersion**: standard ADMS-Urban volume source; source strength reduced if pollutants not mixed to canyon top
  - **Wind direction**: upstream
  - **Region of influence**: outside canyon

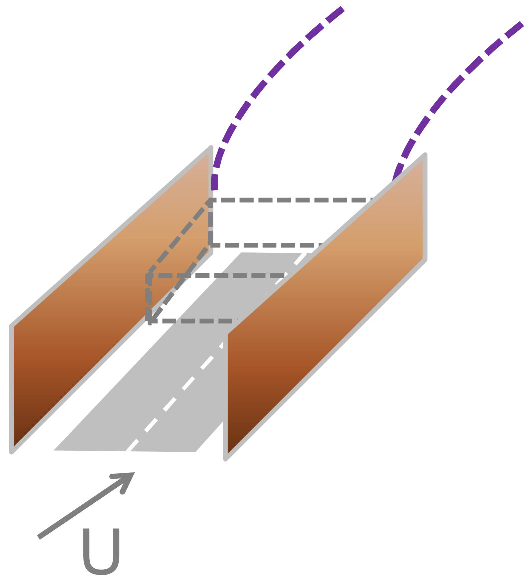




Canyon Flow and Dispersion
ADMS-Urban Implementation: S6 Canyon end

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

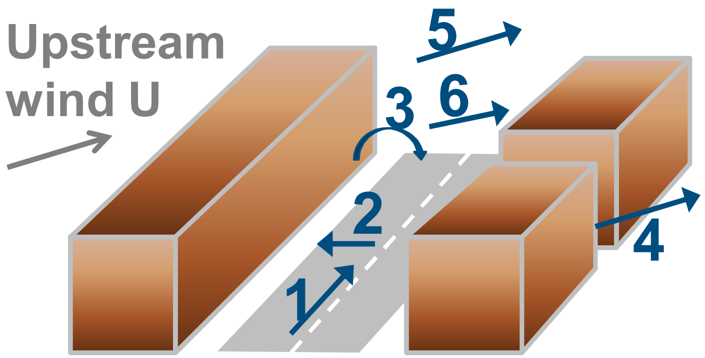




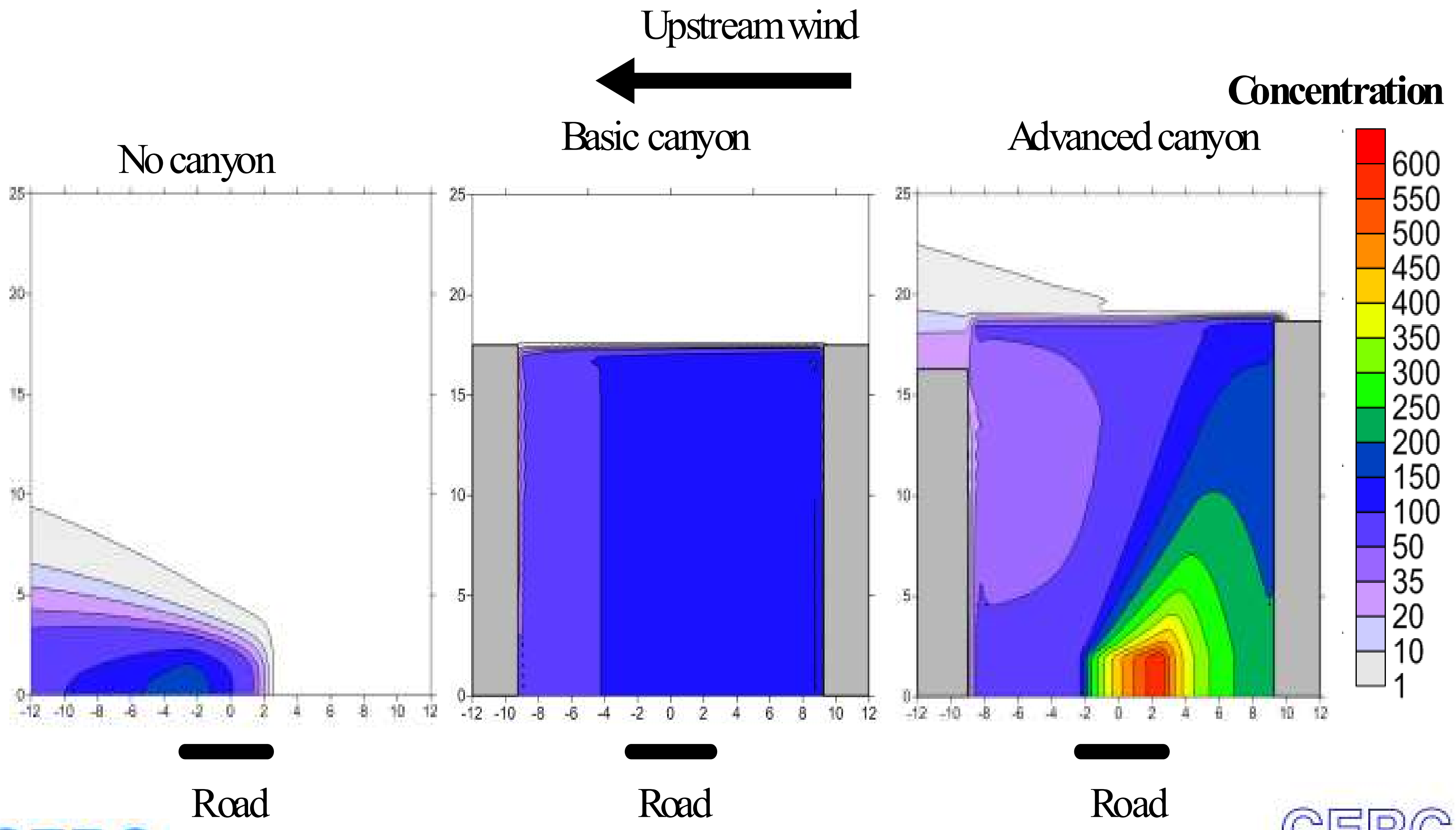
Canyon Flow and Dispersion

ADMS-Urban Implementation: Source weightings

- Balance between in-canyon (**S1,S2**) and non-canyon (**S4**) weighting based on porosity
- 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 affected by canyon asymmetry
- Canyon-top (**S5**) equal to in-canyon (**S1+S2**); reduced if not mixed to canyon top (**S5**)
- Recirculation (**S3**) equal to across-canyon (**S2**)
- End-canyon (**S6**) based on along-canyon (**S1**)



Advanced street canyons: model results



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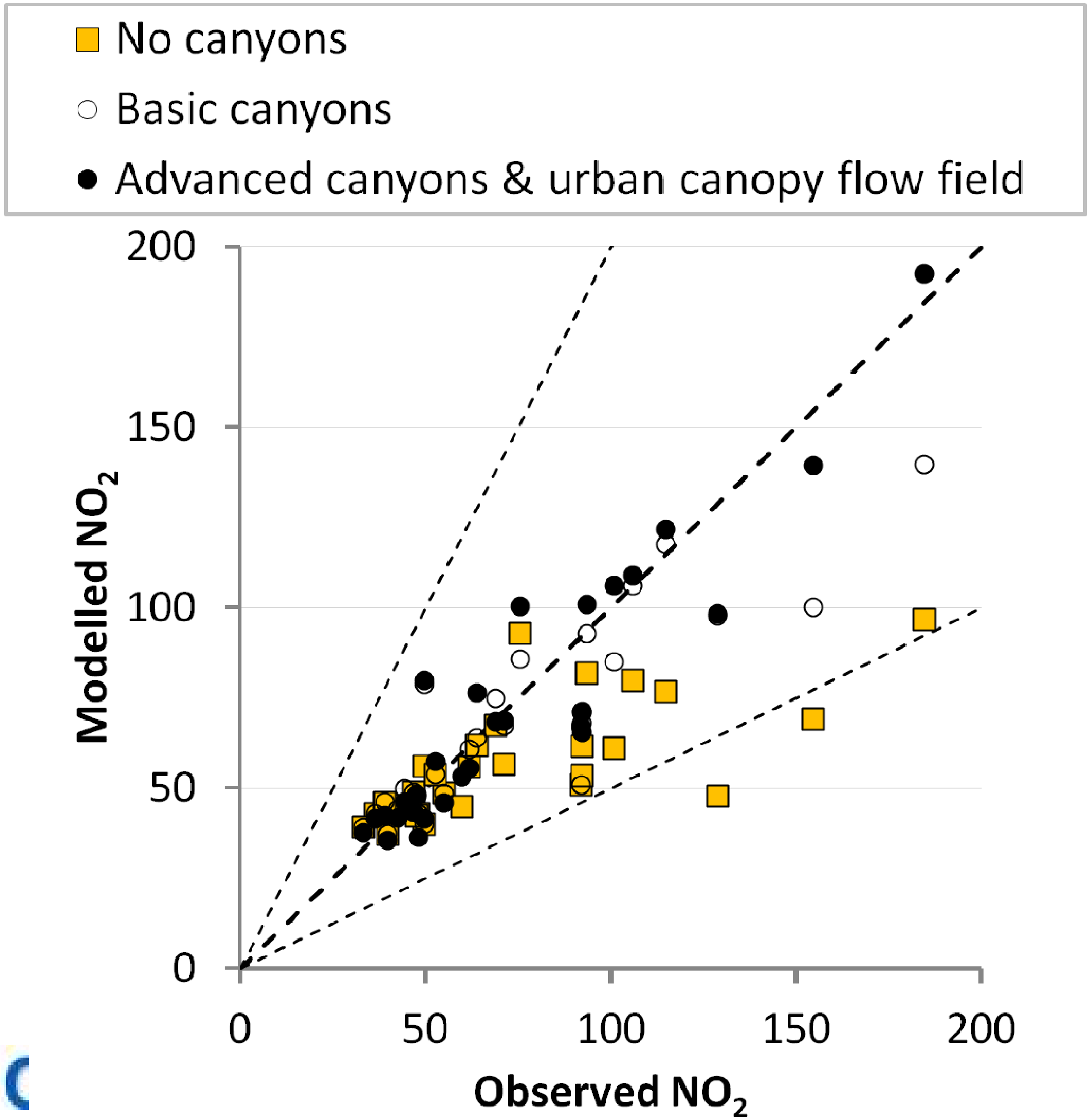
Advanced canyon: validation - results



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

Advanced canyon: validation - results

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

Average statistics

Data	Mean	NMSE	R	Fac2	Fb
Observed	70.8	0.00	1.00	1.00	0.00
No Canyon	54.8	0.73	0.38	0.74	-0.26
Basic Canyon	65.0	0.40	0.61	0.82	-0.09
Advanced Canyon & Urban Canopy	**67.9**	**0.32**	**0.70**	**0.83**	**-0.04**

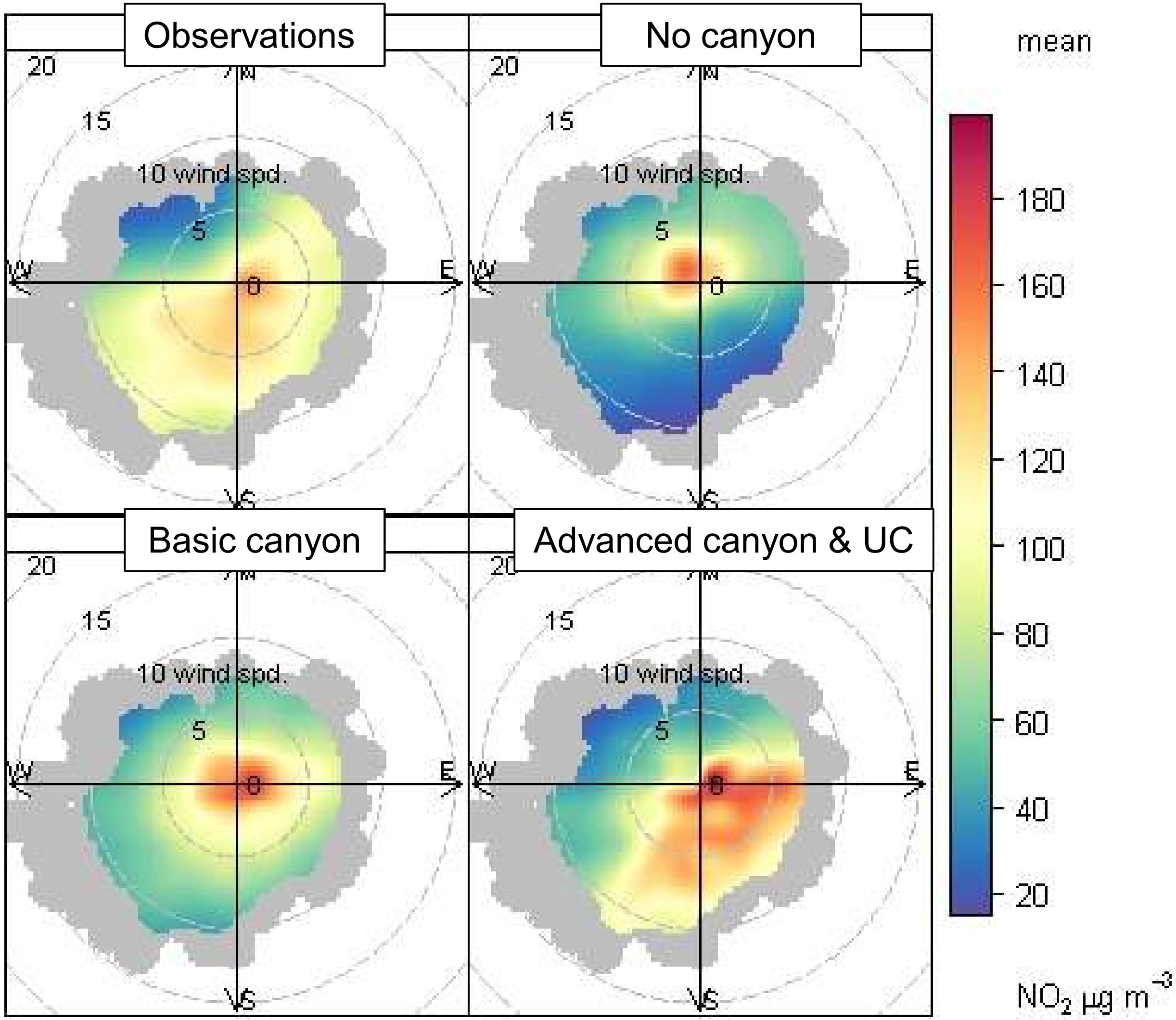
Maximum statistics

Data	Observed maximum	Modelled maximum
No Canyon	541	347
Basic Canyon	541	386
Advanced Canyon & Urban Canopy	541	**519**

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



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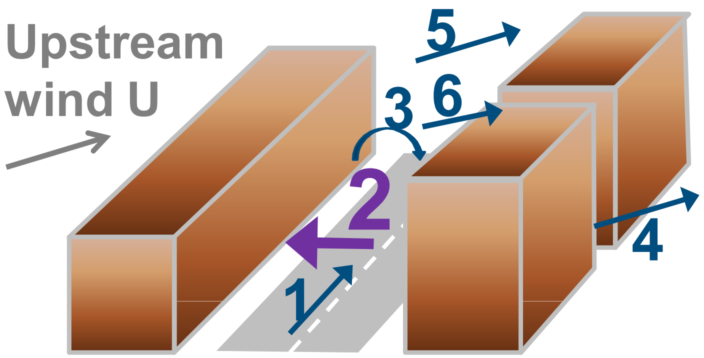
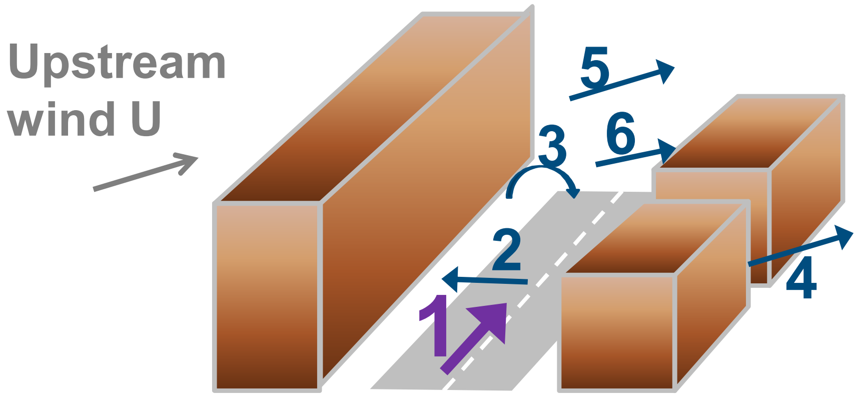
NO_2 concentrations

Canyon Flow and Dispersion
ADMS-Urban Implementation: Asymmetry

- If upstream building lower than downstream building, reduce across canyon (**S2**) and increase non-canyon (**S4**)



- If downstream building lower than upstream building, reduce along-canyon (**S1**) and increase non-canyon (**S4**)

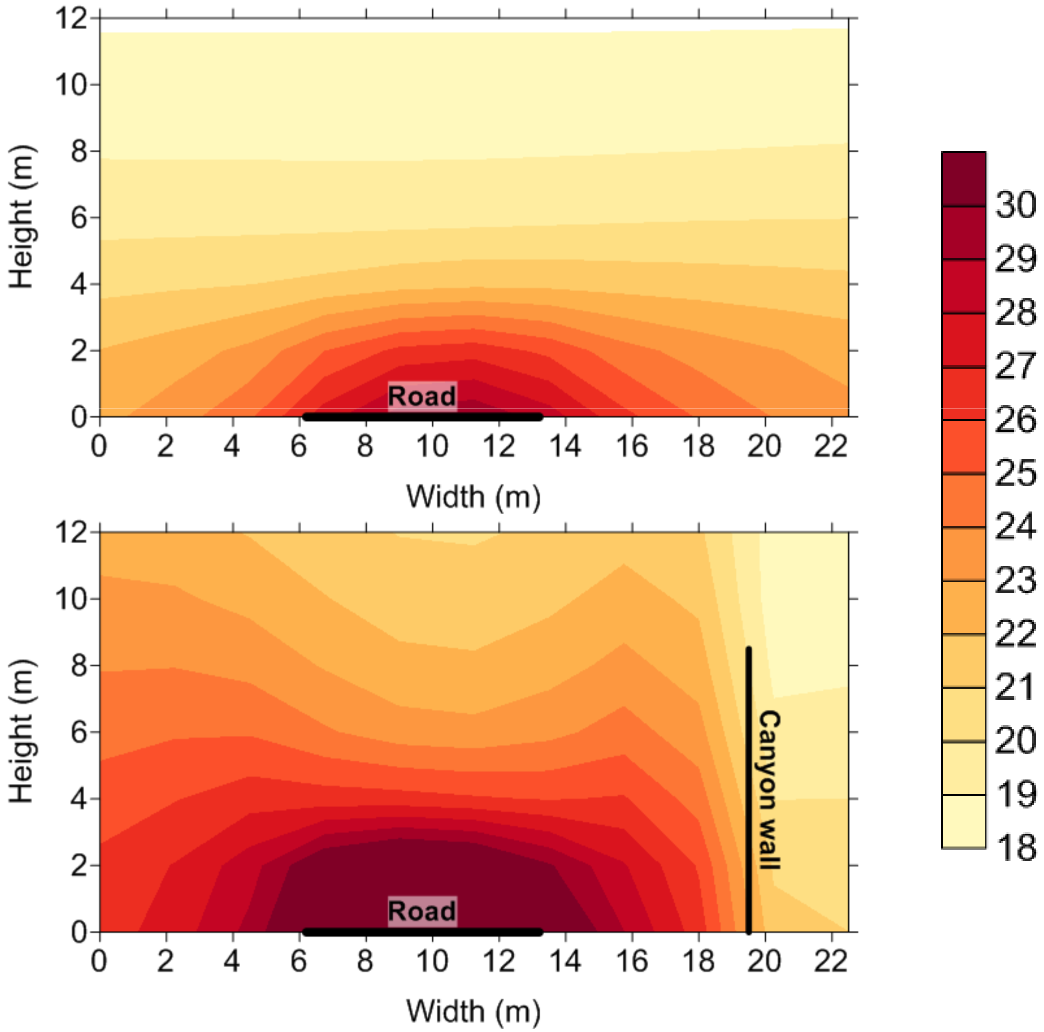


Case study – asymmetrical canyon

Annual average NO_2 concentrations (µg/m³) on Parkside

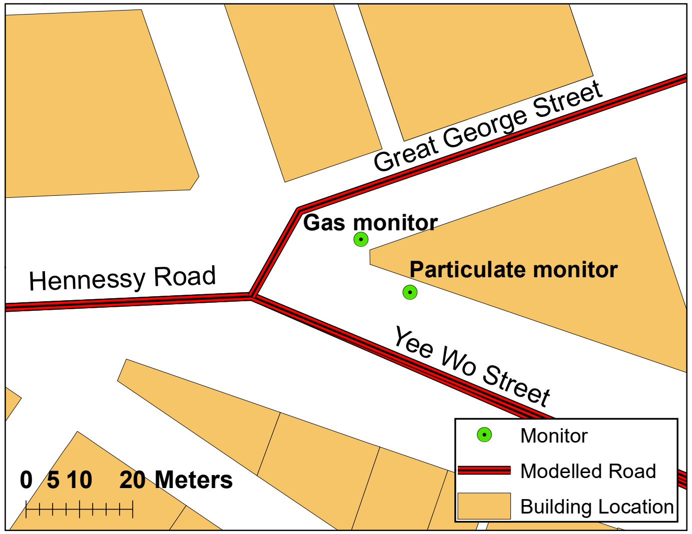
No canyon

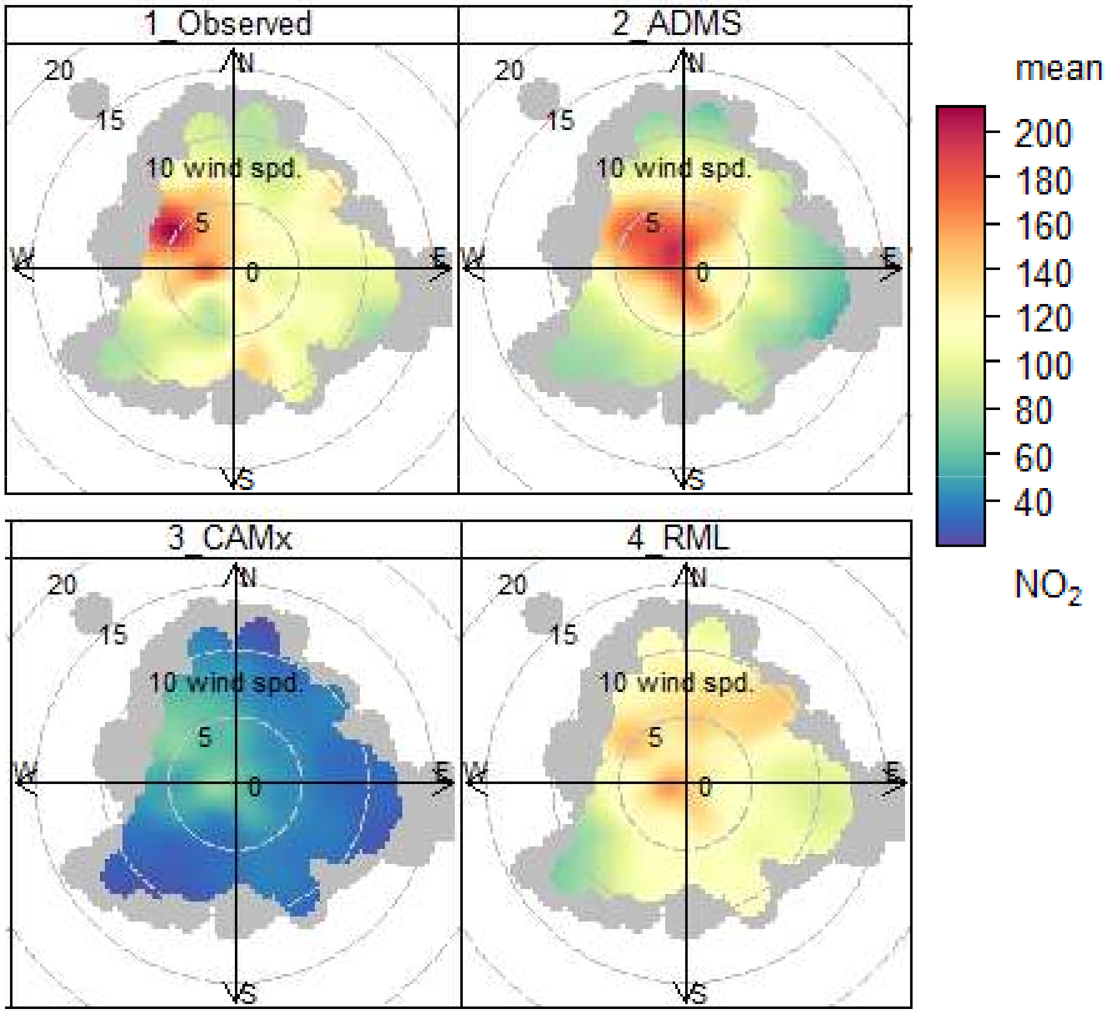
Advanced canyon



Street canyon results in HK

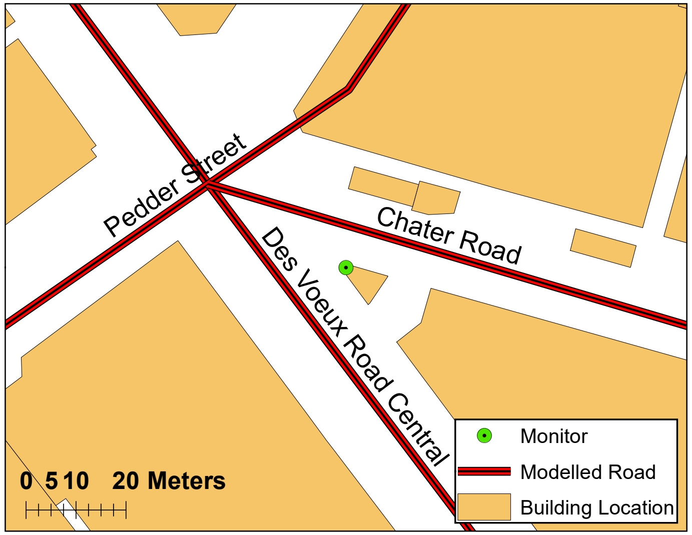
- Causeway Bay

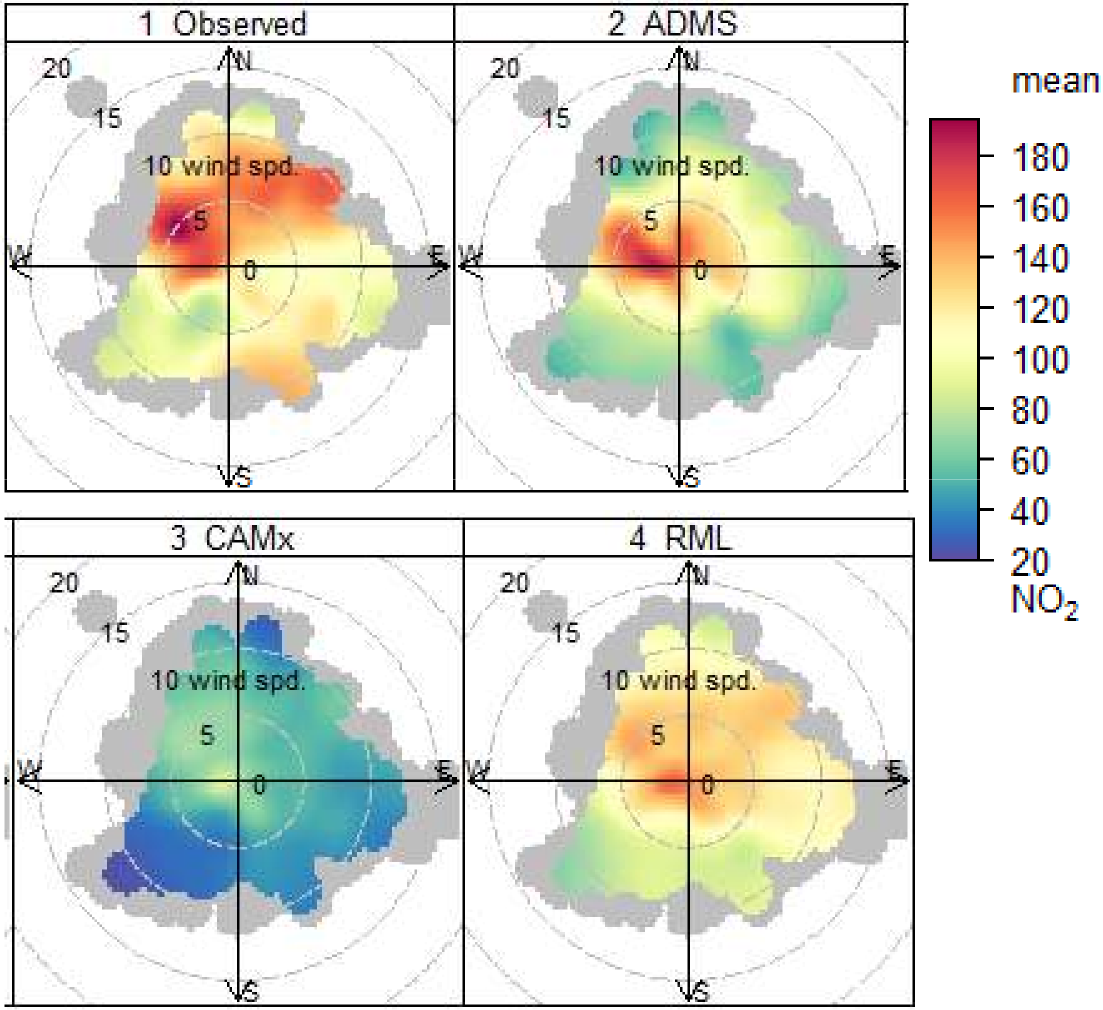




Street canyon results in HK

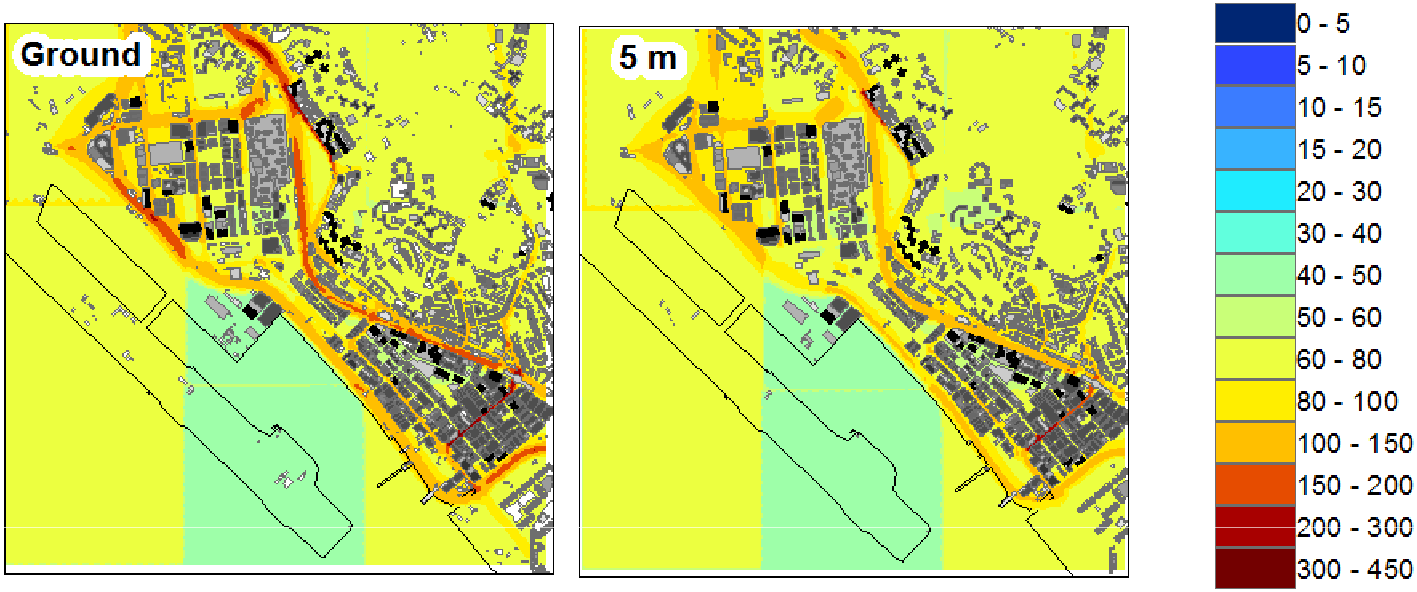
- Central





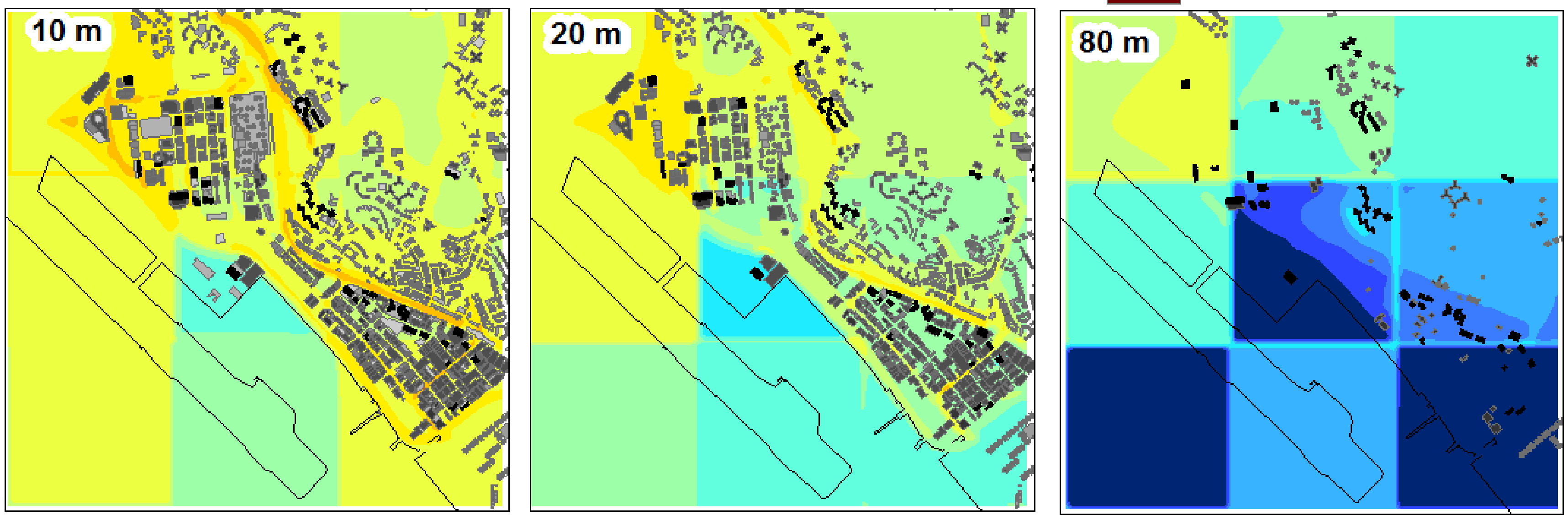
CERC

Concentration Contour output at different heights



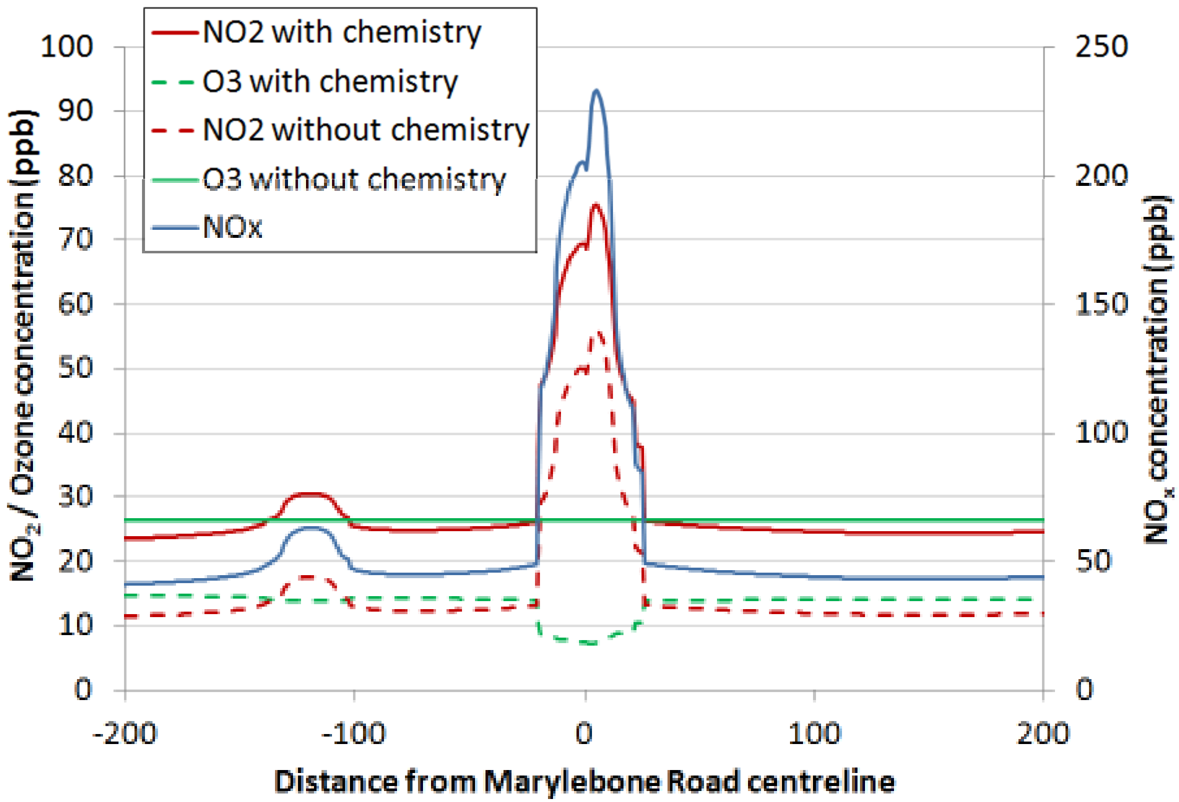
NO_2 concentration ($\mu g/m^3$)

Plots show a single hour of data



NOx chemistry in street canyons

- London case study considering primary and secondary contributions to roadside NO_2
- Assumes primary NO_2 emitted as 20% of NO_x
- Background NO_2 enhanced by chemistry with ozone



- **Within road canyon modest contribution from chemistry (small drop in ozone)**
- **Peak in NO_2 dominated by primary NO_2 contribution**

Current Developments/Opportunities

- Data from traditional air quality monitors, sensor networks CFD and wind tunnels can be used improve parameterisations in ADMS – both flow and dispersion.

- Using measured data and Bayesian based inversion techniques to improve model input (e.g. emissions) to improve model performance and improve understanding of emission factors etc. Opportunities with networks of sensors (e.g. Cambridge).

- Network of sensors also offer opportunity to examine in detail/ verify/improve performance of street canyon model both flow and concentrations. Sensors can also offer detailed insight into outdoor - indoor exchange.

- **Thank you!**