Croucher Advanced Study Institute 2011-2012
Urban Climatology for Tropical & Sub-tropical Regions

Modelling Urban Air Quality using the Street Scale Resolution Atmospheric Dispersion Model ADMS-Urban

- David Carruthers
- Technical Director
- Cambridge Environmental Research Consultants

Contents

- Introduction
- Examples of model performance
- Modelling methods
- ADMS-Urban features
- Application of ADMS- Urban in London and Beijing
- Nesting of ADMS-Urban in a regional air quality model

London smog 1952

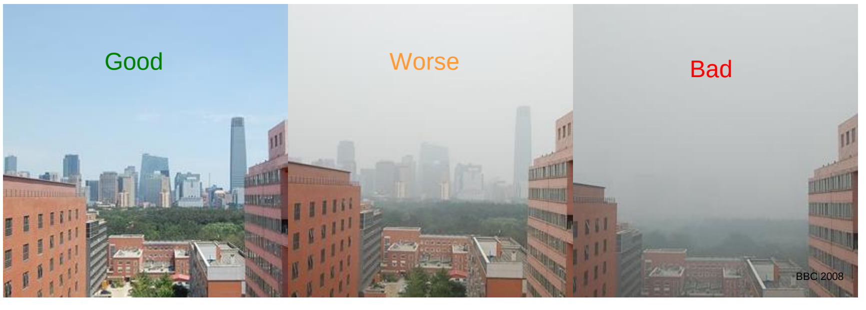
Chang An Avenue Beijing in 1979

Pollution sources in China

Industrial Sources 工业污染源 Inner Mongolia

Traffic in Modern Beijing 现代北京的交通

Same place, different days...



Impacts of Air Pollution

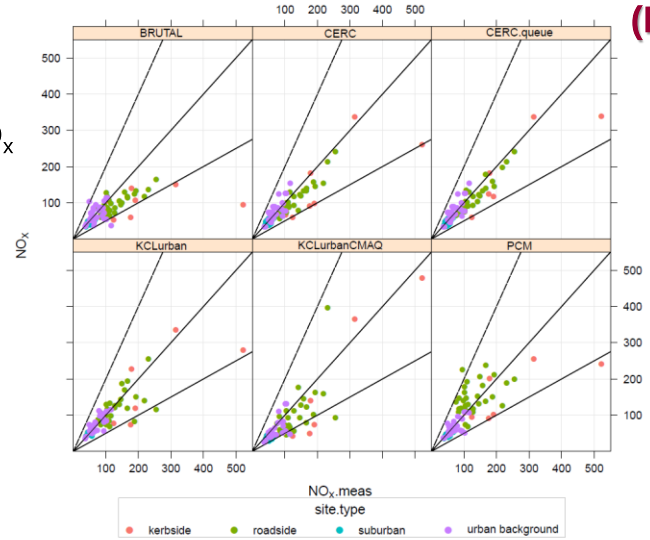
- Serious health effects - mainly respiratory:
  -estimated 35,000 premature deaths in Europe per year due to particulate pollution;
  -10% Beijing population have some respiratory problems;
  -estimated (GAINS ASIA model) average of 40 months loss of life expectancy per person in China due to particulate pollution;
  -cost to economies of lost work days and of health care;
- Impacts on natural environment - affects plant growth, crop yield, water quality etc.
- Visibility impairment

Examples of air quality model performance in urban areas

CERC

From DEFRA model inter-comparison exercise (D Carslaw)

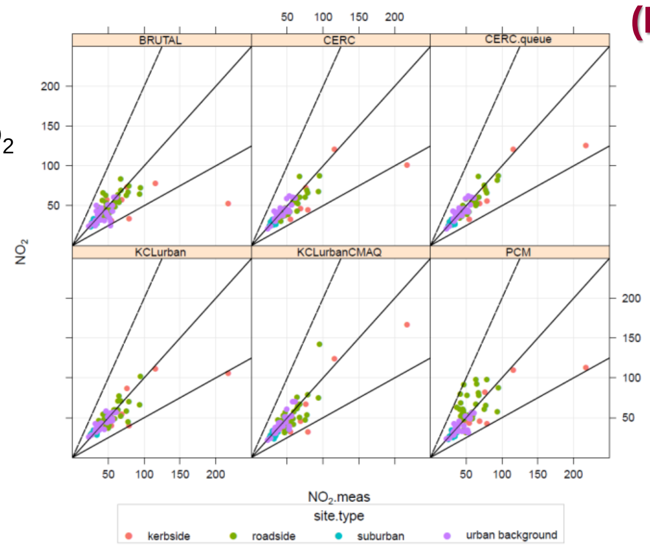
- NO_x



CERC

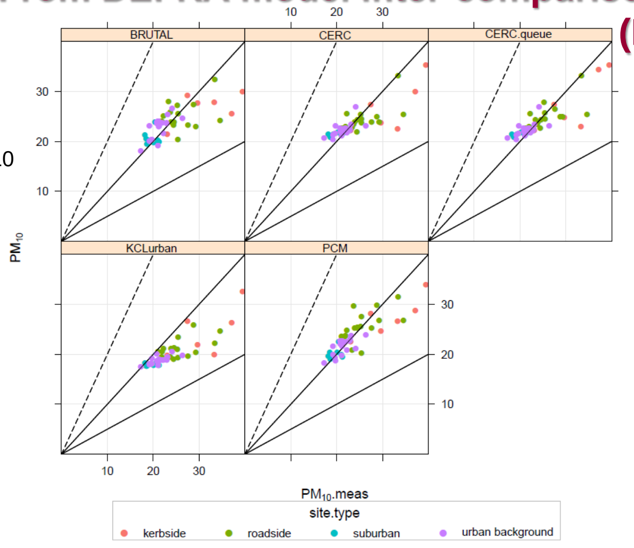
From DEFRA model inter-comparison exercise (D Carslaw)

- NO_2



From DEFRA model inter-comparison exercise (D Carslaw)

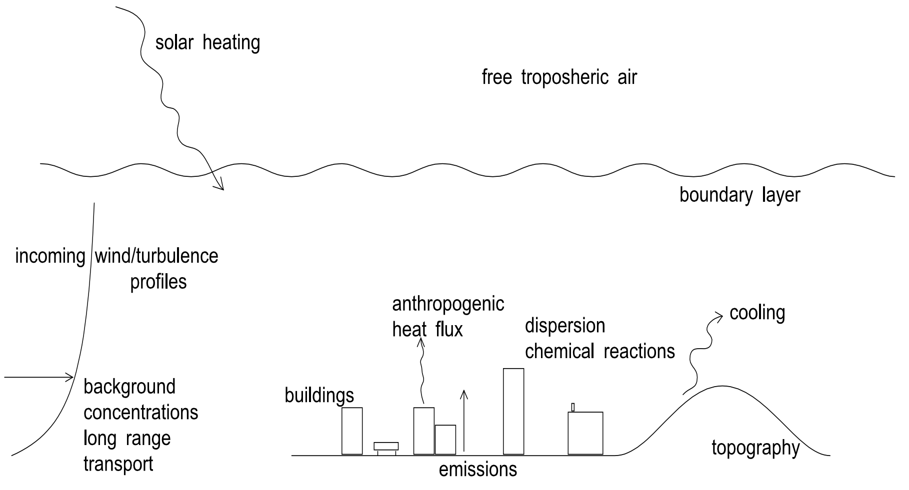
- PM_{10}



CERC

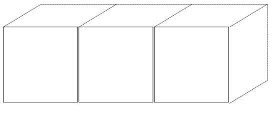
Modelling methods

Factors affecting air quality in urban areas

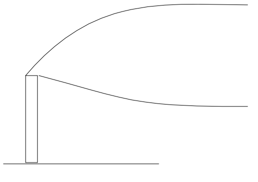


Modelling Methods

<u>Box models</u> - uniform concentration in each box



<u>Gaussian type models</u> - assumed concentration distributions



simple	ISC (point sources)
	CALINE (traffic)
advanced	ADMS (4, Urban)
	AERMOD
	AirQUIS
	OML

<u>Puff Models</u> eg CALPUFF, SCIPUFF, RIMPUFF

Modelling Methods cont'd

Particle models - Stochastic or random walk models calculate trajectories of large number of particles as series of steps eg NAME (UK Met Office), AUSTAL (Germany)

Complex numerical models

Steady state (CFD) computational fluid dynamics – eg eddy diffusivity models; Reynolds stress

Time dependent – Large Eddy Simulations, Chemical Transport Models eg MM5 or WRF and CMAQ

ADMS-Urban features

ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

ADMS-Urban Model Capabilities I

- ADMS-Urban is designed to model dispersion scenarios of varying complexity, from a single isolated industrial site or road to multiple industrial, domestic and road traffic emissions over a large urban area
- Fully integrated street canyon model based on Danish OSPM model
- Local and regional NOX chemistry calculation (NO, NO_2 and O_3)

ADMS-Urban Model Capabilities II

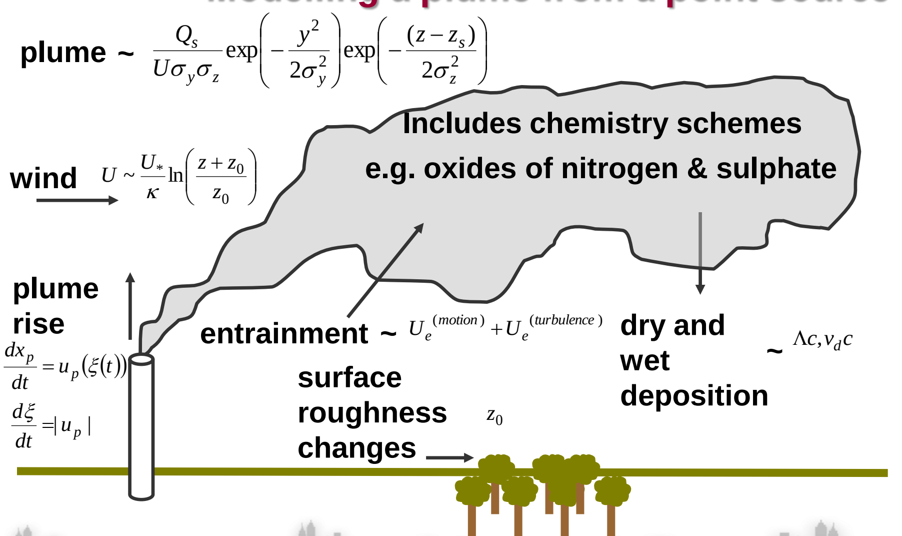
- Based on current understanding of atmospheric boundary layer. A dispersion model in which the boundary layer structure is characterised by the height of the boundary layer and the Monin-Obukhov length
- A non-Gaussian vertical profile of concentration in convective conditions
- A meteorological pre-processor – flexible input
- Models the effect of complex terrain (hills)
- Calculates emissions from traffic flows or accepts calculated emissions

ADMS-Urban Model Capabilities III

- Integration with Geographical Information Systems (GIS) and an Emissions Inventory Database (EMIT)
- Output via GIS includes high resolution pollutant concentration maps
- Can consider Air Quality Management and Mitigation Options e.g. Low Emission Zones, Technical Options, Traffic management.
- Used in many major cities, for example: London, Birmingham, Budapest, Rome, Beijing, Shanghai, Hong Kong

建築中大 THE CROUCHER FOUNDATION 裘槎基金會 CERC

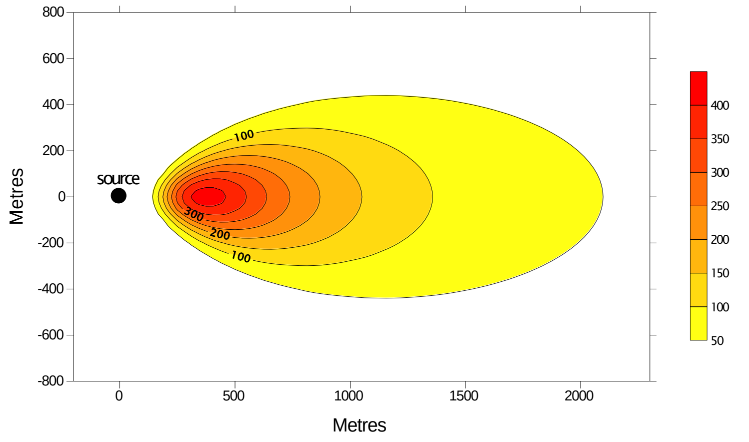
Modelling a plume from a point source I



CERC

Modelling a plume from a point source II

1 hourly concentration of NOx in µg/m³



ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

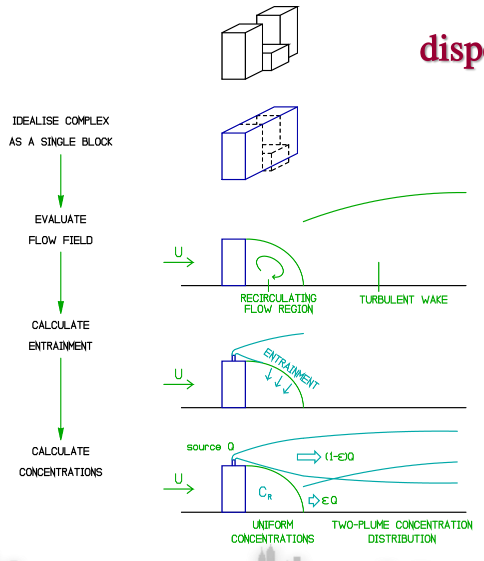
CERC

Road and other source types including roads

- Integrate point sources to model **line sources**
- Integrate line sources to model **volume sources**
- Add a crosswind exit velocity to model **jet sources**
- Include traffic-induced turbulence and the effect of street canyons to model **road sources**

ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

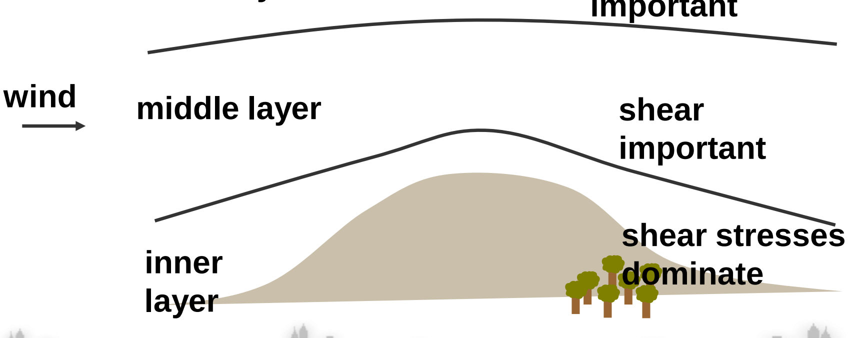
Stages in the analysis of dispersion close to a building



Modelling flow over hills I – semi analytic approach

2 Regimes:

- Moderately stable, neutral or convective meteorological conditions

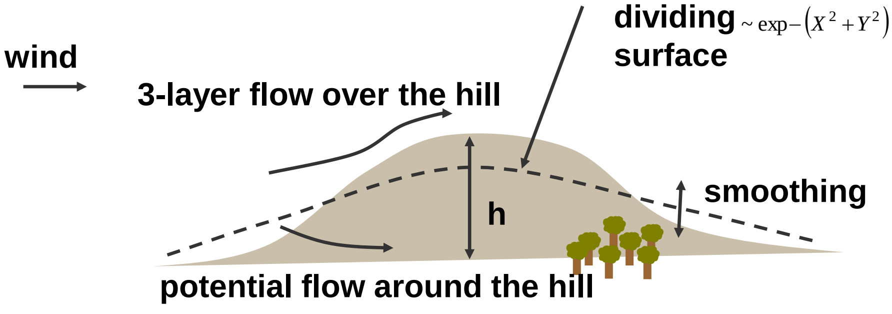


Modelling flow over hills II

2 Regimes:

- Very stable meteorological conditions ("Froude Number < 1")

$$Froude\_Number = \frac{U(h)}{N(h)(h - h_{mean})}$$



Modelling NO_x and NO_2

- GRS Chemistry Scheme

(1) $ROC + hv \rightarrow RP + ROC$

(2) $RP + NO \rightarrow NO_2$

(3) $\boldsymbol{NO_2 + hv \rightarrow NO + O_3}$

(4) $\boldsymbol{NO + O_3 \rightarrow NO_2}$

(5) $RP + RP \rightarrow RP$

(6) $RP + NO_2 \rightarrow SGN$

(7) $RP + NO_2 \rightarrow SNGN$

(8) $2NO + O_3 \rightarrow 2NO_2$

where

ROC = Reactive Organic Compounds

RP = Radical Pool

SGN = Stable Gaseous Nitrogen products

SNGN = Stable Non-Gaseous Nitrogen products

- **Venkatram A. et al "The Development and Application of a Simplified Ozone Modelling System", Atmospheric Environment, Vol 28, No. 22, pp 3665-3678, (1994)**

ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

Modelling road traffic sources – Local effects

- Street canyons/ building effects
- Vehicle induced turbulence
- Initial mixing depth – exhaust height and buoyancy

- *Tunnels, embankments, cuttings, flyovers, noise barriers*
- *Different vehicle mixes in different lanes*
- *Queues*
- *Different speeds in different directions*
- *Road gradients*
- *Bus stops, Bus stations*
- *Car parks*

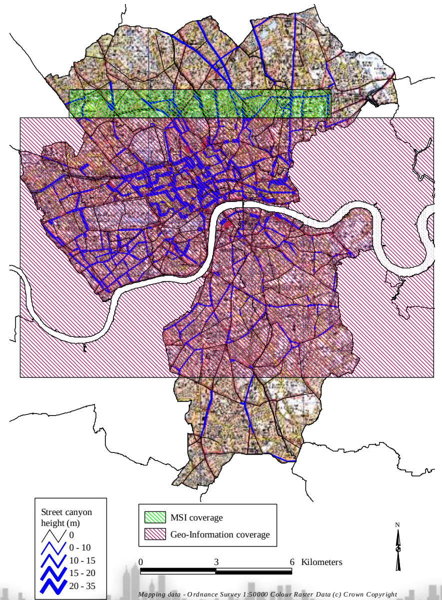
CERC

Street canyons

ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

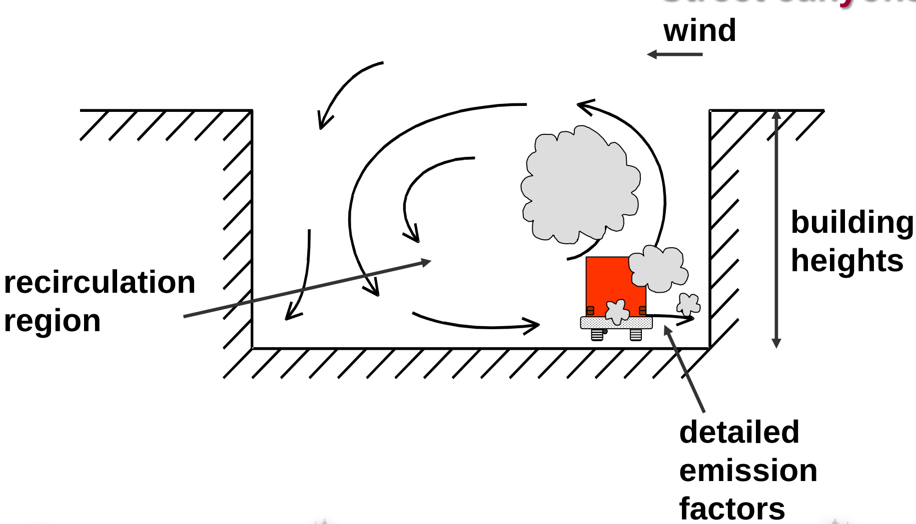
Street Canyons

Estimated street canyon heights for Central London



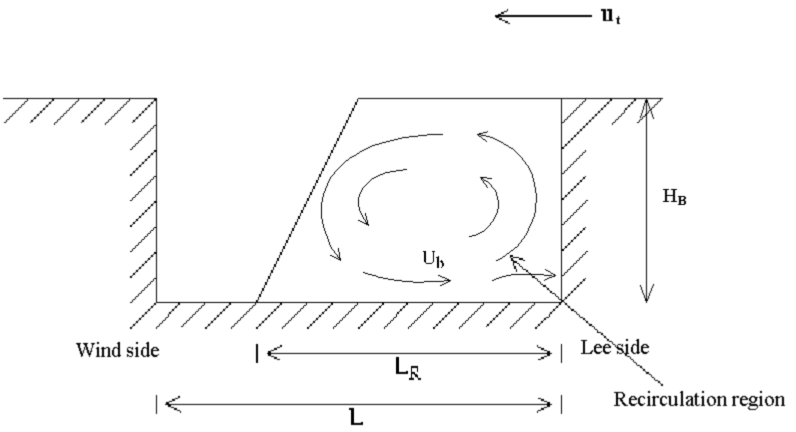
THE CROUCHER FOUNDATION
CERC

Street canyons



ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

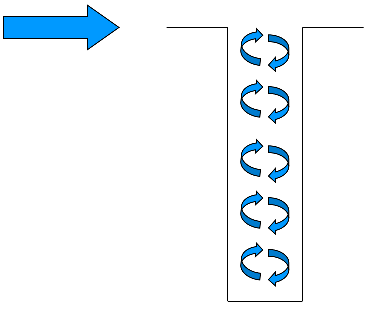
Street canyons



CERC

Street canyons

- Street canyon modules (eg OSPM used in ADMS)
- Currently:
  - 2-dimensional solution used within the canyon
- Possible improvements:
  - Model end effects (junctions)
  - Have some account taken of effect of street canyon externally (similar to noise barriers)
  - Model asymmetric canyons
  - Model multiple re-circulation regions for tall thin canyons

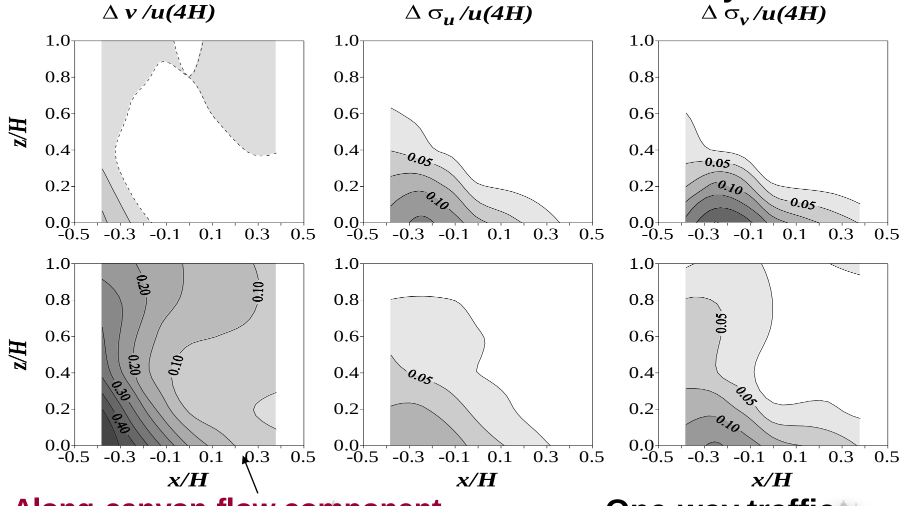


ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

Vehicle induced turbulence

Vehicle produced turbulence - FLOW and TKE

Two-way traffic

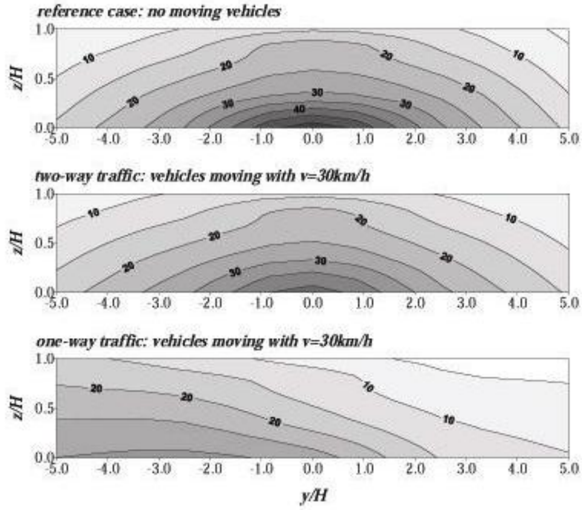


Along-canyon flow component

One-way traffic

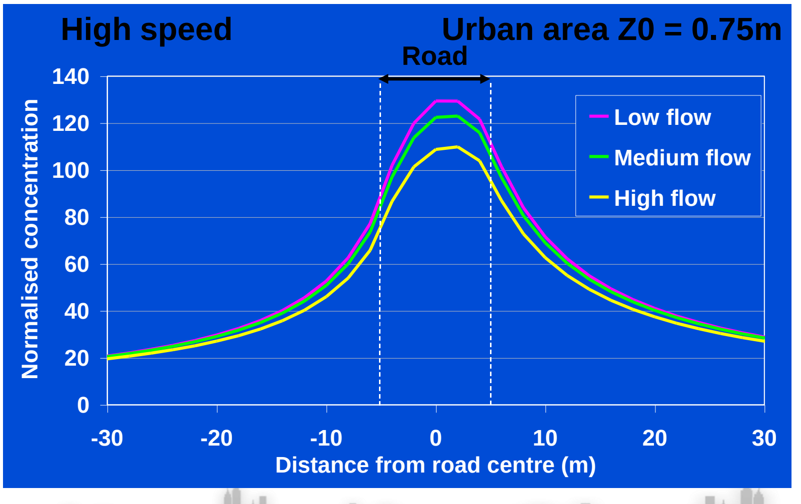
Vehicle produced turbulence – Dispersion

$$c_* = cUHL_s / E_s$$



THE CROUCHER FOUNDATION 裘槎基金會 CERC

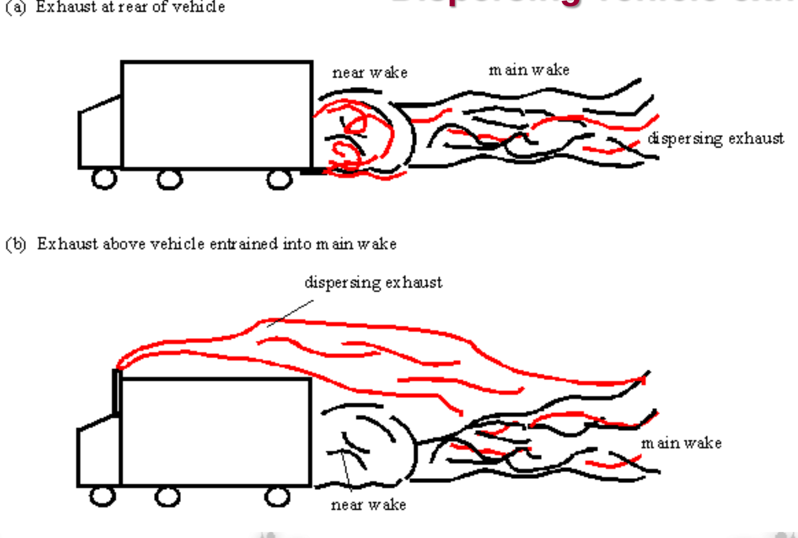
Vehicle-induced turbulence Results
ADMS-Urban: annual average concentrations



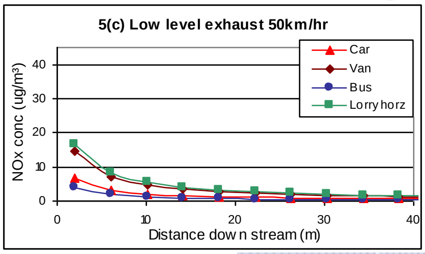
ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

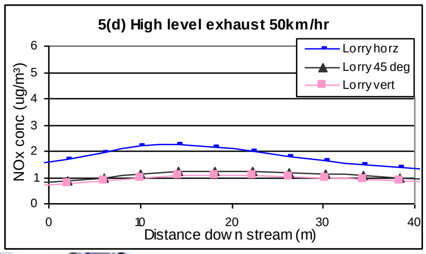
Initial Mixing depth
Effects of exhaust height and buoyancy

Dispersing vehicle exhaust



Initial Mixing – Exhaust Location Impacts





THE CROUCHER FOUNDATION 裘槎基金會
CERC

Initial mixing height in model

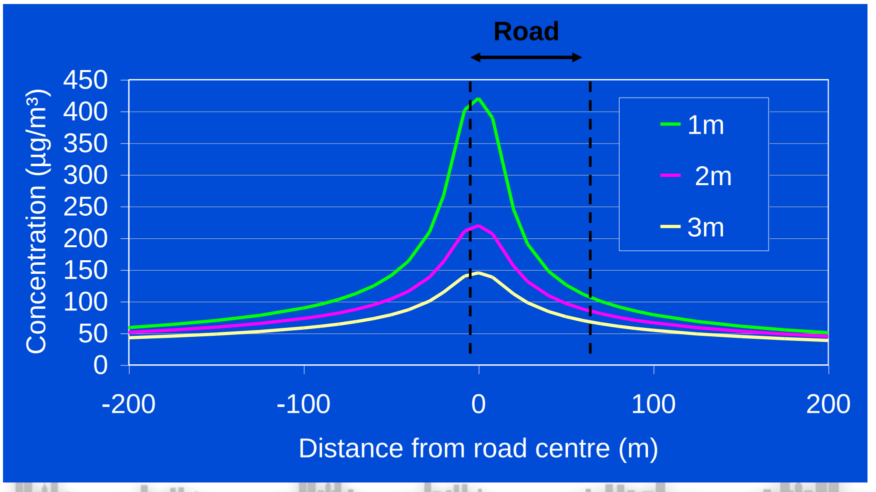
- **Consider**
  - Height of line source that represents the road
  - Initial vertical plume spread parameter

→ **Initial mixing height parameter**

ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

CERC

Initial mixing height
ADMS-Urban: annual average concentrations

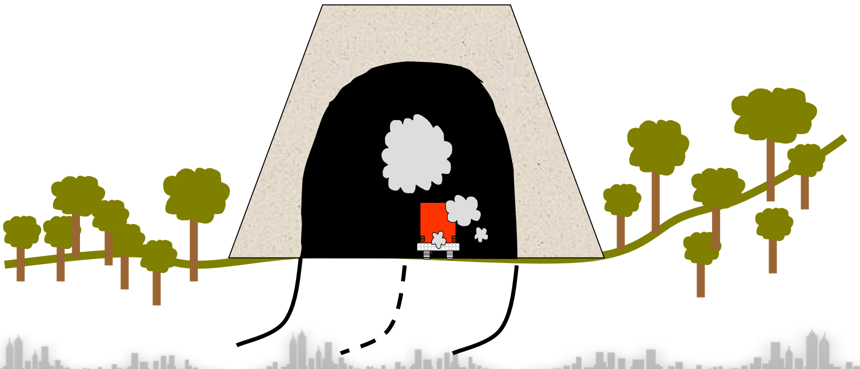


CERC

Other features near roads

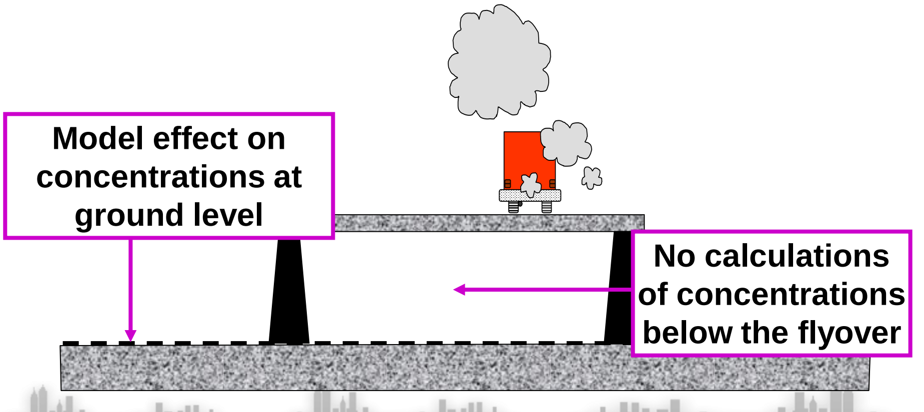
Tunnels

- Tunnels
  - User enters traffic flows and speeds within the tunnel
  - Emissions modelled as volume sources at tunnel exits
  - Account taken for venting of emissions from tunnel?



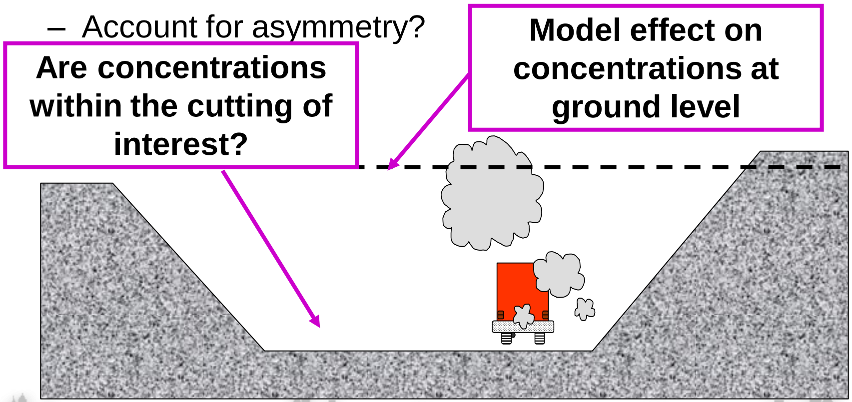
Flyovers .... etc

- Flyovers
  - Effectively an elevated line source, shielded underneath



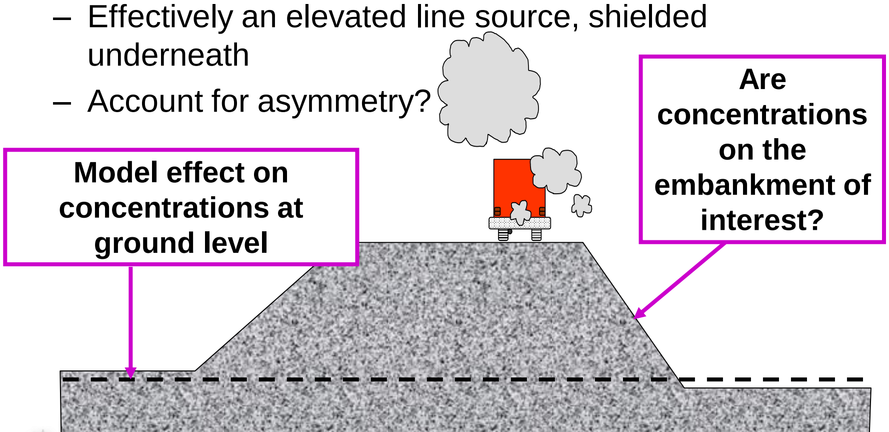
Modelling Issues
Road source attributes

- **Cuttings**
  - **NOT appropriate to model as complex terrain**
  - Similarities to street canyon module
  - Account for asymmetry?



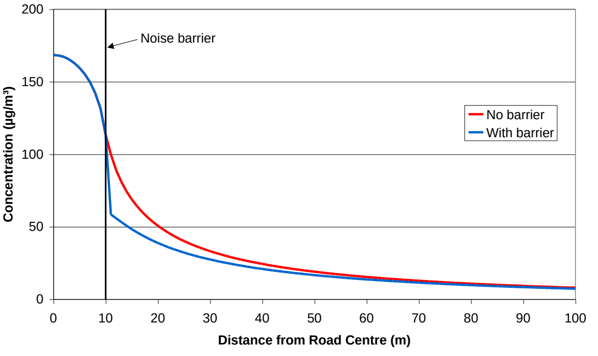
Modelling Issues
Road source attributes

- **Embankments**
  - **NOT appropriate to model as complex terrain**
  - Effectively an elevated line source, shielded underneath
  - Account for asymmetry?



Noise barriers

Noise Barriers–modelled using ADMS-Urban/Roads (barrier 5m)



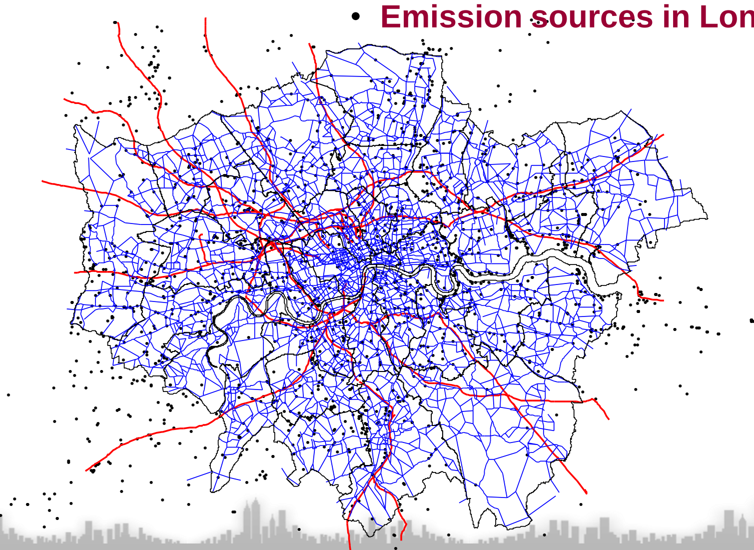
CERC

Application of ADMS-Urban in London and Beijing

ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

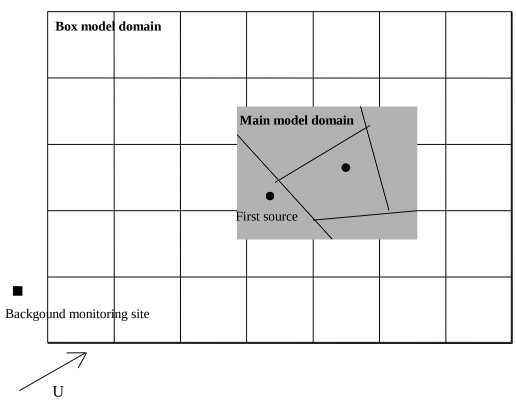
Modelling emissions in large urban areas

- Emission sources in London



THE CROUCHER FOUNDATION 裘槎基金會
CERC

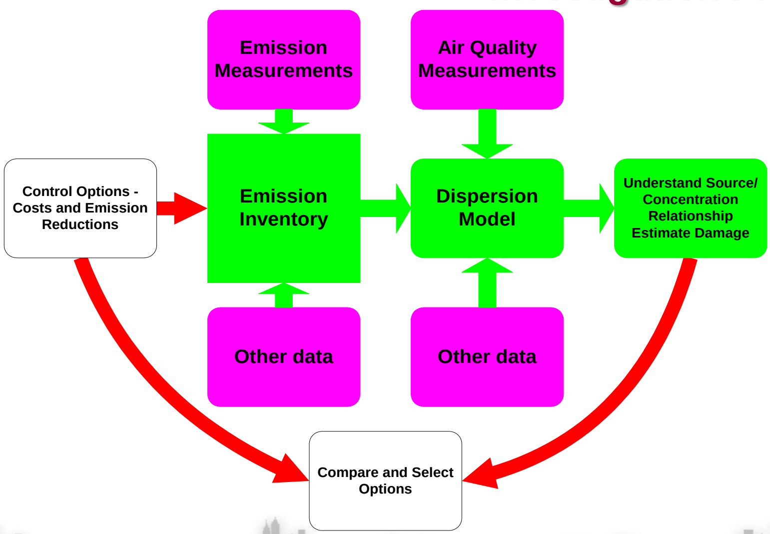
ADMS-Urban - Local and Regional Scales



- Main model nested with large, area-wide trajectory model

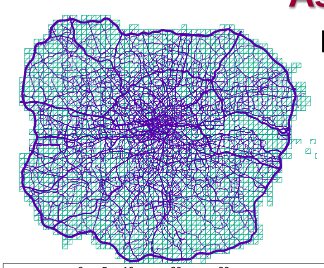
ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

Investigation Process

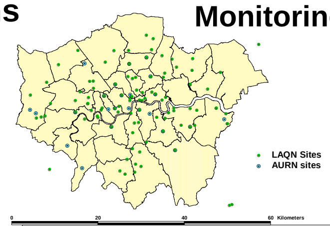


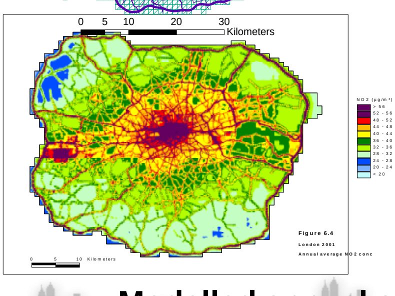
Assessment of Air Quality - London

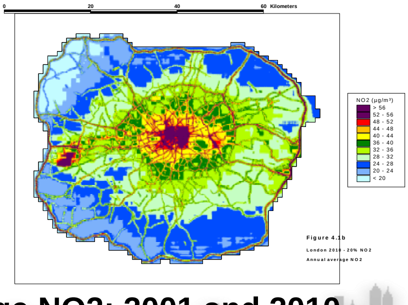
Emissions



Monitoring network

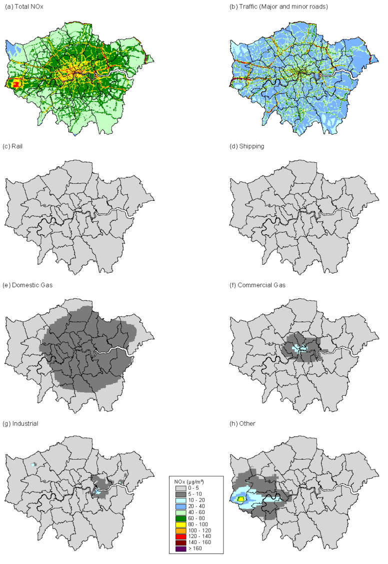






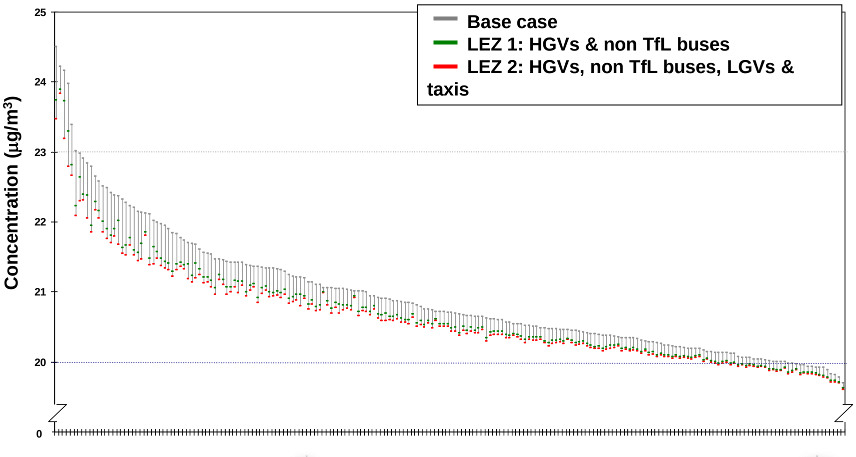
Modelled annual average NO2: 2001 and 2010

London 2005 Annual Mean NOx Concentrations by Source Category

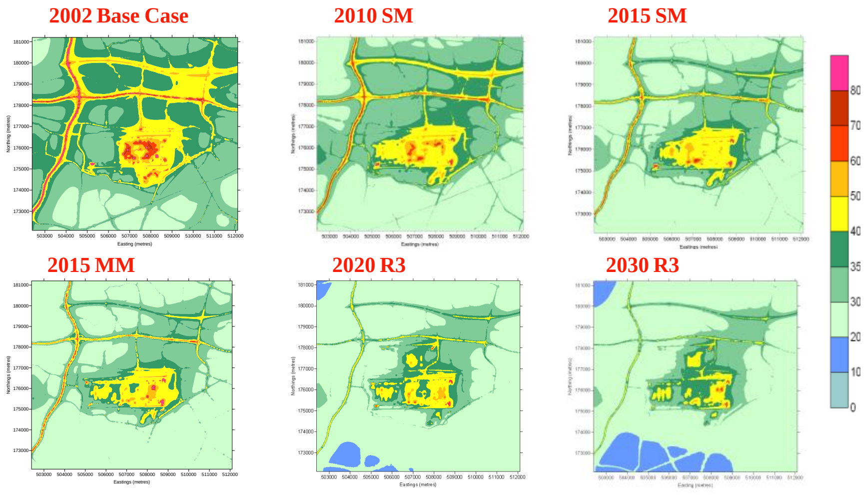


London: Source apportionment With ADMS-Urban

2010 Low emission Zone (LEZ) Reductions in PM_{10} at Receptor Points



Modelled NO_2 concentrations at London Heathrow Airport



THE CROUCHER FOUNDATION 裘槎基金會
CERC

Beijing's air quality: emission controls

Vehicles restricted to operating on alternate days according to whether the final number on their licence plate is odd or even

Green sticker for Euro I (III) or above for petrol (diesel) vehicles

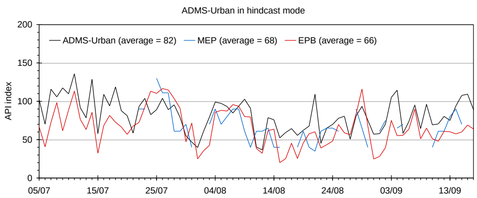
Signs alert drivers to areas of congestion and inform if the roads are free flowing

Higher polluting vehicles banned on urban roads from 1 July to 20 September - no yellow stickers

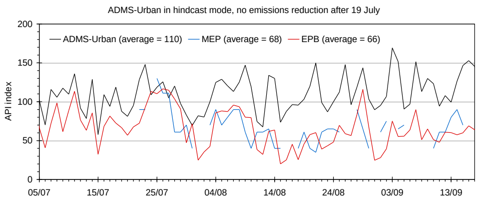
- Control of energy and industrial production, construction and transport;
- Final (Olympic) stage on 20 July 2008 - reduction in the use of private cars further reduction in the use of government cars;
- a temporary halt to construction during the Olympic period;
- more cleaning of the roads to reduce dust
- the suspension of heavily polluting industry;
- a reduction in production for coal-based enterprises.

ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

Beijing's air quality: emission controls



With emission reduction measures



Without emission reduction measures (black line)

Beijing air quality forecasts

Number of blue sky days increasing; concentrations high by European standards

THE CROUCHER FOUNDATION 裘槎基金會
CERC

Nesting ADMS-Urban within a regional model

ASI 2: URBAN CLIMATE AND AIR POLLUTION School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-8 Dec 2011

CERC

Nesting ADMS-Urban in a regional model - Motivation

- Why nest a local model within a regional model?
- What are the advantages of a **nested model**?

Model feature	**Model**	
	Regional (eg grid based)	**Local (eg Gaussian plume)**
Domain extent	**Country (few 1000 km)**	City (50km)
Meteorology	**Spatially and temporally varying from meso scale models**	Usually spatially homogeneous
Dispersion in low wind speed conditions	**Models stagnated flows correctly**	Limited modelling of stagnated flows
Deposition and chemical processes	**Reactions over large spatial and temporal scales**	Simplified reactions over short-time scales
Source resolution	Low	**High**
Validity	Background receptors	**Background, roadside and kerbside receptors**

CERC

CMAQ/ADMS-Urban nesting system

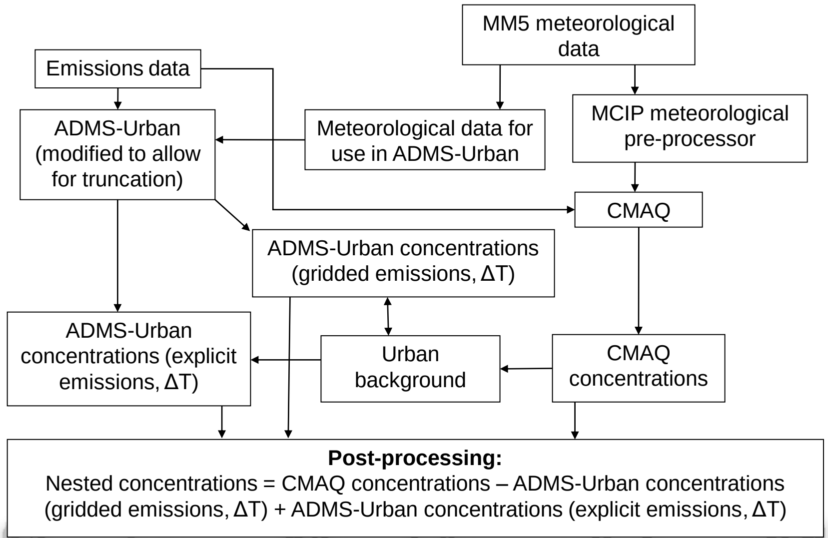
- **Aim:** to nest local model in regional model without double counting emissions i.e.:

Concentration within nested domain = Regional modelling of emissions - Gridded locally modelled emissions (ΔT) + Explicit locally modelled emissions (ΔT)

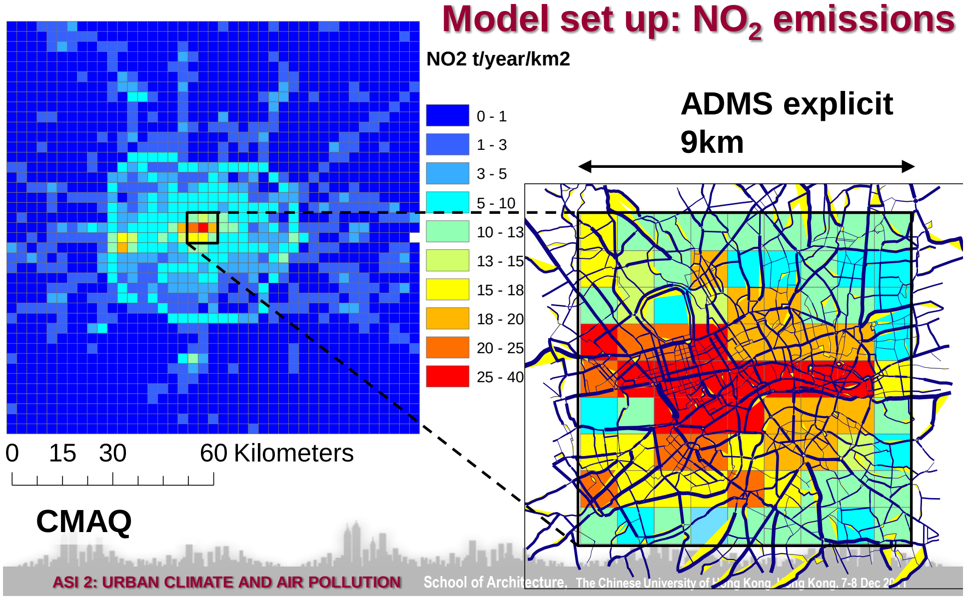
ΔT is the time taken to mix the explicitly defined emissions to produce a concentration field that varies spatially on the same scale as the regional model

ΔT varies with meteorology

CMAQ/ADMS-Urban nesting system

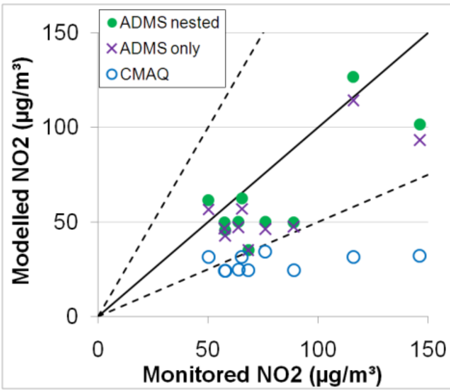


Preliminary modelling
Model set up: NO_2 emissions

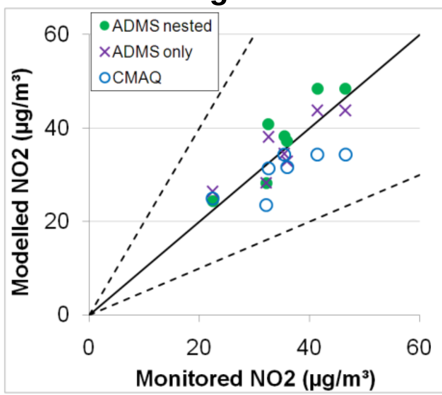


Preliminary modelling
Model results: receptors – NO_2

Roadside and Kerbside



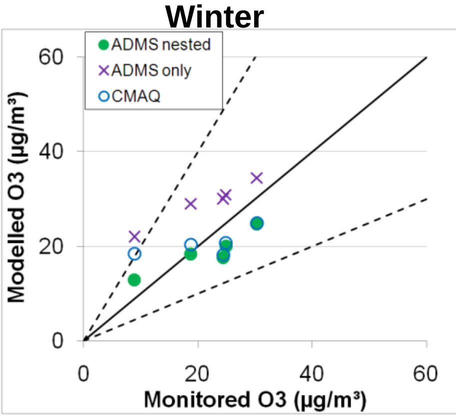
Background



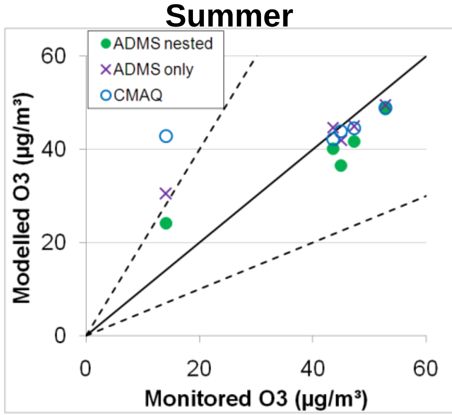
(Summer)

Preliminary modelling
Model results: receptors – O_3

Winter

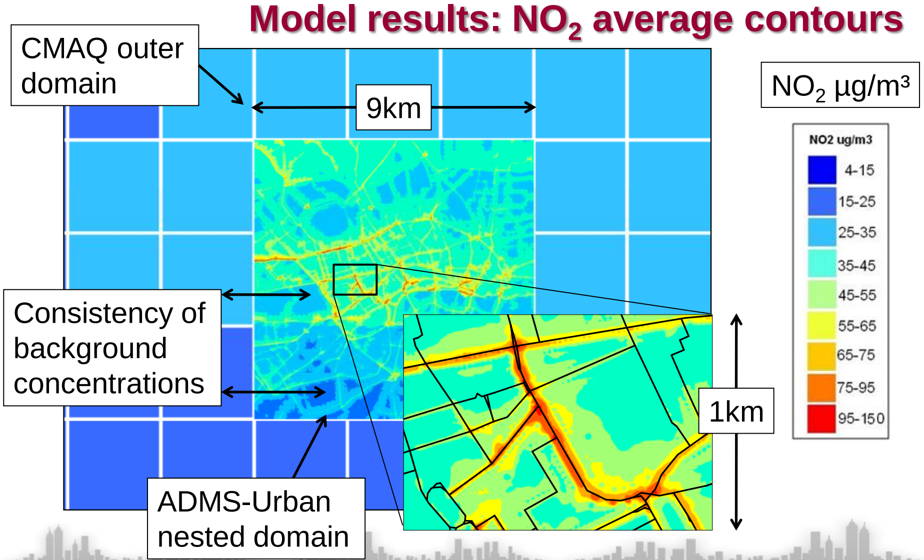


Summer



(All sites)

Preliminary modelling
Model results: NO_2 average contours



End, Thank You

David Carruthers
Cambridge Environmental Research Consultants
3 Kings Parade, Cambridge, CB2 1SJ, United Kingdom
Tel: +44 1223 357773
Email: david.carruthers@cerc.co.uk
Website: www.cerc.co.uk