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

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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  Traffic in Modern Beijing  现代北京的交通

Same place, different days...

Good  Worse  Bad
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
From DEFRA model inter-comparison exercise (D Carslaw)

- NO$_x$

- NO$_2$
From DEFRA model inter-comparison exercise (D Carslaw)

<table>
<thead>
<tr>
<th>PM$_{10}$</th>
<th>PM$_{2.5}$</th>
<th>PM$_{0.1}$</th>
<th>Site Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>15</td>
<td>20</td>
<td>Urban</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
<td>30</td>
<td>Suburban</td>
</tr>
<tr>
<td>30</td>
<td>35</td>
<td>40</td>
<td>Rural</td>
</tr>
</tbody>
</table>

**Modelling methods**
Factors affecting air quality in urban areas

- Solar heating
- Free tropospheric air
- Background concentrations
- Long range transport
- Emissions
- Buildings
- Anthropogenic heat flux
- Dispersion chemical reactions
- Cooling
- Topography
- Incoming wind/turbulence profiles

Modelling Methods

**Box models** - uniform concentration in each box

**Gaussian type models** - assumed concentration distributions

- Simple:
  - ISC (point sources)
  - CALINE (traffic)
- Advanced:
  - ADMS (4, Urban)
  - AERMOD
  - AirQUIS
  - OML

**Puff Models** 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

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ADMS-Urban features
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\textsubscript{2} and O\textsubscript{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

Modelling a plume from a point source

plume \( \sim \frac{Q_y}{U \sigma_y \sigma_z} \exp \left( \frac{-y^2}{2 \sigma_y^2} \right) \exp \left( \frac{-(z-z_f)}{2 \sigma_z^2} \right) \)

wind \( U = \frac{U_z}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right) \)

entainment \( \sim U_{x \text{motion}} + U_{x \text{turbulence}} \)

dry and wet deposition \( \sim \kappa_c \nu_c c \)

Includes chemistry schemes e.g. oxides of nitrogen & sulphate

surface roughness changes

\( \frac{dx_p}{dt} = u_p(t) \)
\( \frac{dz}{dt} = \left| u_p \right| \)
Modelling a plume from a point source II

1 hourly concentration of NOx in µg/m³

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**
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
  - inviscid flow stratification important
  - outer layer

- Shear stresses dominate
  - middle layer
  - inner layer
  - shear important
Modelling flow over hills II

2 Regimes:

• Very stable meteorological conditions (“Froude Number < 1”)

\[
\text{Froude Number} = \frac{U(h)}{N(h)(h - h_{	ext{cor}})}
\]

\[
\text{dividing surface} \quad \text{exp} \left(-\left(x^2 + y^2\right)\right)
\]

wind \quad \rightarrow \quad 3\text{-layer flow over the hill} \quad \text{smoothing}

potential flow around the hill

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Modelling NO\textsubscript{x} and NO\textsubscript{2}

• GRS Chemistry Scheme

(1) \(ROC + h\nu \rightarrow RP + ROC\)
(2) \(RP + NO \rightarrow NO_2\)
(3) \(NO_2 + h\nu \rightarrow NO + O_3\)
(4) \(NO + O_3 \rightarrow NO_2\)
(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”,
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
Estimated street canyon heights for Central London

Street canyons

wind

recirculation region

detailed emission factors

building heights

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

- Street canyon modules (e.g., 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
Vehicle induced turbulence

Two-way traffic

One-way traffic

Along-canyon flow component

Vehicle produced turbulence - FLOW and TKE

Δv/\upsilon(4H)  Δσ_u/\upsilon(4H)  Δσ_v/\upsilon(4H)

-0.5  -0.3  -0.1  0.1  0.3  0.5
x/H

-0.5  -0.3  -0.1  0.1  0.3  0.5
z/H
Vehicle produced turbulence – Dispersion

\[ c_* = \frac{c_{UHL}}{E_*} \]

Vehicle-induced turbulence Results

ADMS-Urban: annual average concentrations

High speed

Urban area \( Z_0 = 0.75m \)

Road

Normalised concentration

Distance from road centre (m)
Initial Mixing depth
Effects of exhaust height and buoyancy

Dispersing vehicle exhaust

(a) Exhaust at rear of vehicle

(b) Exhaust above vehicle entrained into main wake
Initial Mixing – Exhaust Location Impacts

5(c) Low level exhaust 50km/hr

5(d) High level exhaust 50km/hr

Initial mixing height in model

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

Initial mixing height parameter
Initial mixing height
ADMS-Urban: annual average concentrations

Other features near roads
**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**

- Effectively an elevated line source, shielded underneath

*No calculations of concentrations below the flyover*
Modelling Issues

Road source attributes

- **Cuttings**
  - NOT appropriate to model as complex terrain
  - Similarities to street canyon module
  - Account for asymmetry?
  - Are concentrations within the cutting of interest?
  - Model effect on concentrations at ground level

- **Embankments**
  - NOT appropriate to model as complex terrain
  - Effectively an elevated line source, shielded underneath
  - Account for asymmetry?
  - Are concentrations on the embankment of interest?
  - Model effect on concentrations at ground level
Noise Barriers—modelled using ADMS-Urban/Roads (barrier 5m)

<table>
<thead>
<tr>
<th>Distance from Road Centre (m)</th>
<th>Concentration (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>40</td>
<td>200</td>
</tr>
</tbody>
</table>

- No barrier
- With barrier

Application of ADMS-Urban in London and Beijing
Modelling emissions in large urban areas

- Emission sources in London

ADMS-Urban - Local and Regional Scales

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

Control Options - Costs and Emission Reductions

Emission Measurements

Air Quality Measurements

Emission Inventory

Dispersion Model

Understand Source Concentration Relationship Estimate Damage

Other data

Other data

Compare and Select Options

Assessment of Air Quality - London

Emissions

Monitoring network

Modelled annual average NO2: 2001 and 2010
London: Source apportionment With ADMS-Urban

2010 Low emission Zone (LEZ) Reductions in PM$_{10}$ at Receptor Points

- Base case
- LEZ 1: HGVs & non TFL buses
- LEZ 2: HGVs, non TFL buses, LGVs & taxis
Beijing’s air quality: emission controls

- 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.

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.
Beijing’s air quality: emission controls

Beijing air quality forecasts

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

Nesting ADMS-Urban within a regional model
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?

<table>
<thead>
<tr>
<th>Model feature</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain extent</td>
<td>Regional (eg grid based) Local (eg Gaussian plume)</td>
</tr>
<tr>
<td>Meteorology</td>
<td>Spatially and temporally varying from meso scale models Usually spatially homogeneous</td>
</tr>
<tr>
<td>Dispersion in low wind speed conditions</td>
<td>Models stagnated flows correctly Limited modelling of stagnated flows</td>
</tr>
<tr>
<td>Deposition and chemical processes</td>
<td>Reactions over large spatial and temporal scales Simplified reactions over short-time scales</td>
</tr>
<tr>
<td>Source resolution</td>
<td>Low High</td>
</tr>
<tr>
<td>Validity</td>
<td>Background receptors Background, roadside and kerbside receptors</td>
</tr>
</tbody>
</table>

CMAQ/ADMS-Urban nesting system

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

\[
\text{Concentration within nested domain} = \text{Regional modelling of emissions} - \text{Gridded locally modelled emissions} + \text{Explicit locally modelled emissions} (\Delta T)
\]

\(\Delta T\) 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.

\(\Delta T\) varies with meteorology.
CMAQ/ADMS-Urban nesting system

**Post-processing:**
Nested concentrations = CMAQ concentrations – ADMS-Urban concentrations (gridded emissions, ΔT) + ADMS-Urban concentrations (explicit emissions, ΔT)

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Preliminary modelling
Model set up: NO\(_2\) emissions

**ADMS explicit 9km**

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CMAQ
Preliminary modelling
Model results: receptors – NO$_2$

Roadside and Kerbside

- ADMS nested
- ADMS only
- CMAQ

Background

- ADMS nested
- ADMS only
- CMAQ

(Summer)

Preliminary modelling
Model results: receptors – O$_3$

Winter

- ADMS nested
- ADMS only
- CMAQ

Summer

- ADMS nested
- ADMS only
- CMAQ

(All sites)
Preliminary modelling
Model results: NO$_2$ average contours

End, Thank You

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