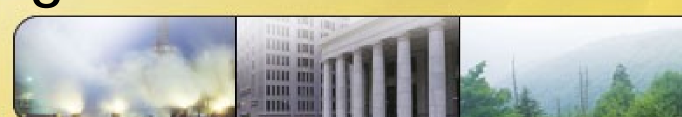
Linking urban (street canyon) models with regional air quality models through urban boundary conditions

Clemens Mensink, Karen Van de Vel,
Koen De Ridder, Peter Viaene and Stijn Janssen

VITO

Environmental Modelling unit

Boeretang 200, B-2400 Mol, Belgium



How can we integrate

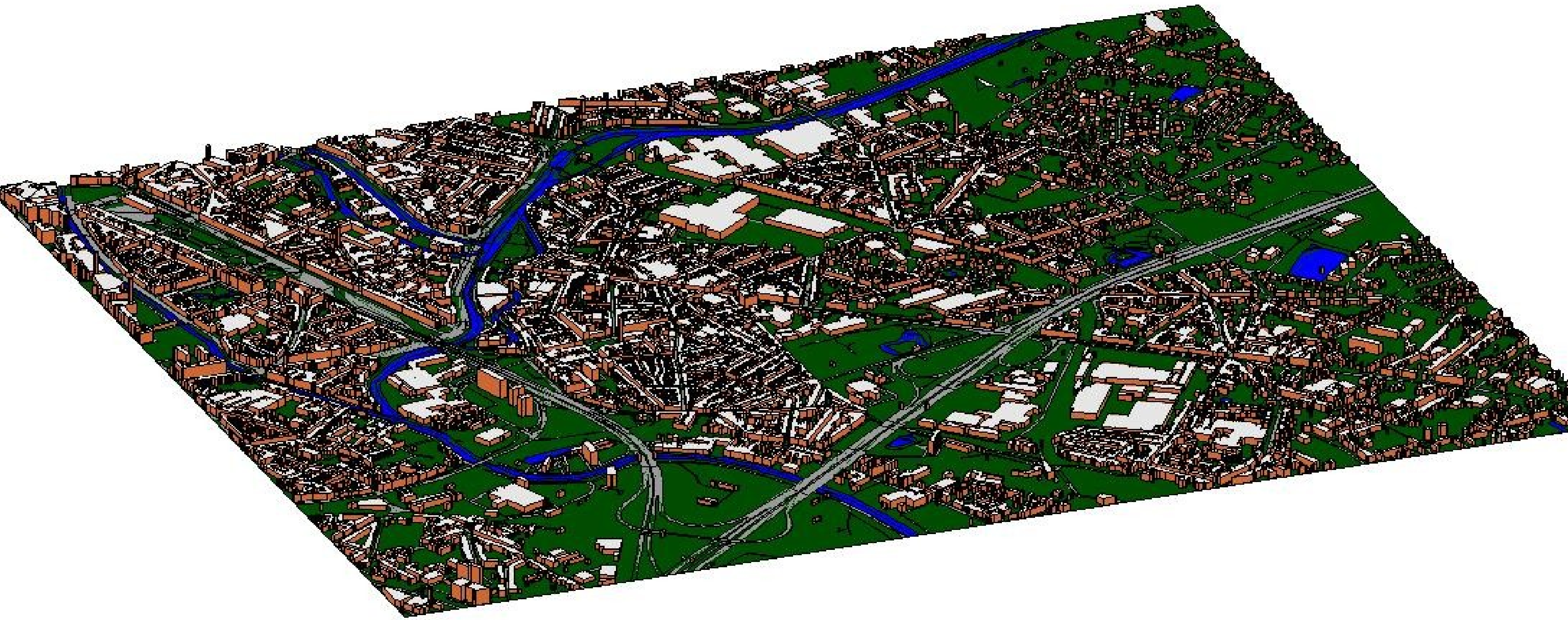
detailed information

from the urban canopy

into regional AQ models ?

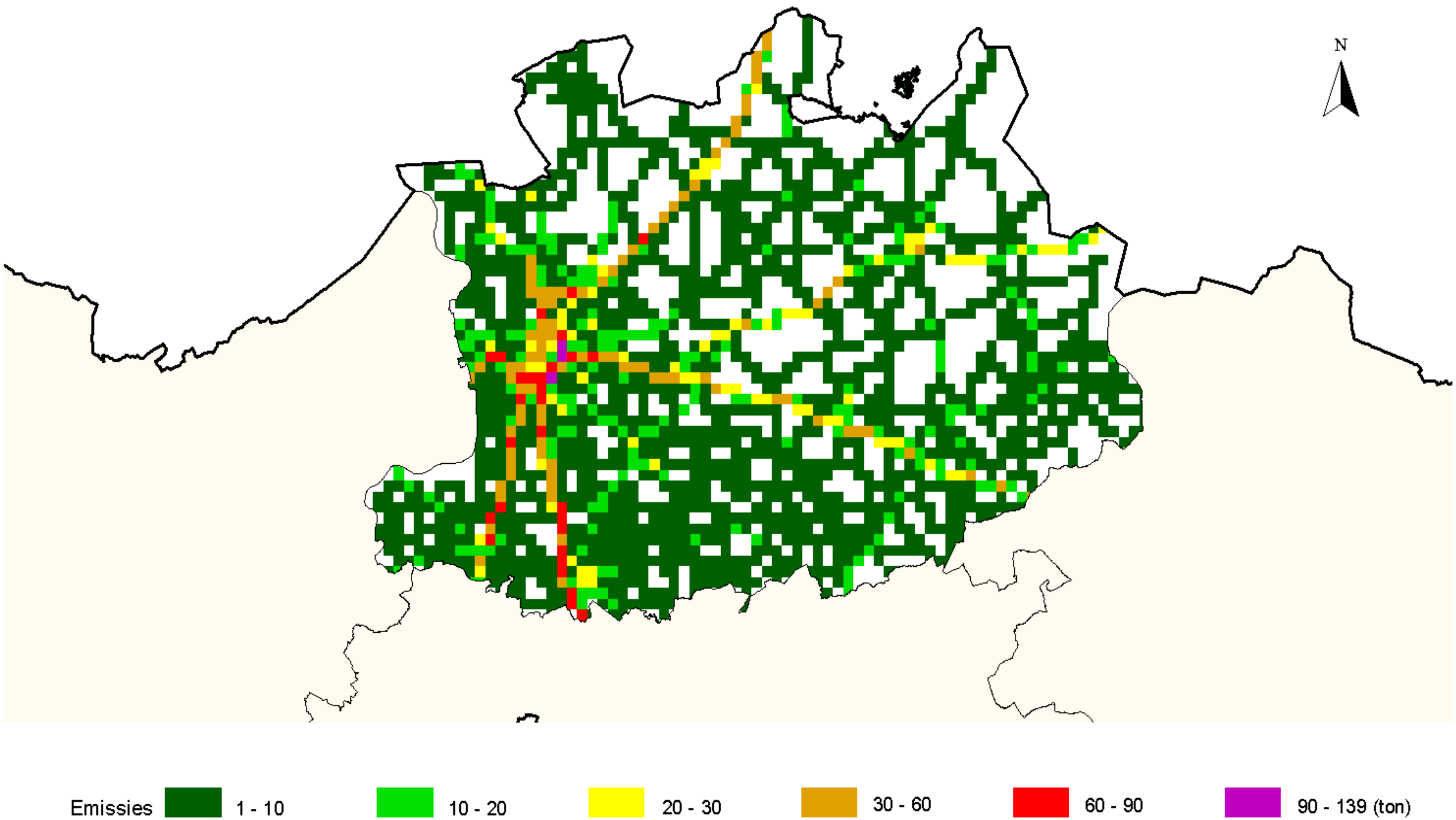
Many of the dynamics of the urban canopy are not represented in regional models despite the fact that we have a lot of detailed information about these dynamics…

…e.g. on canopy structure and roughness

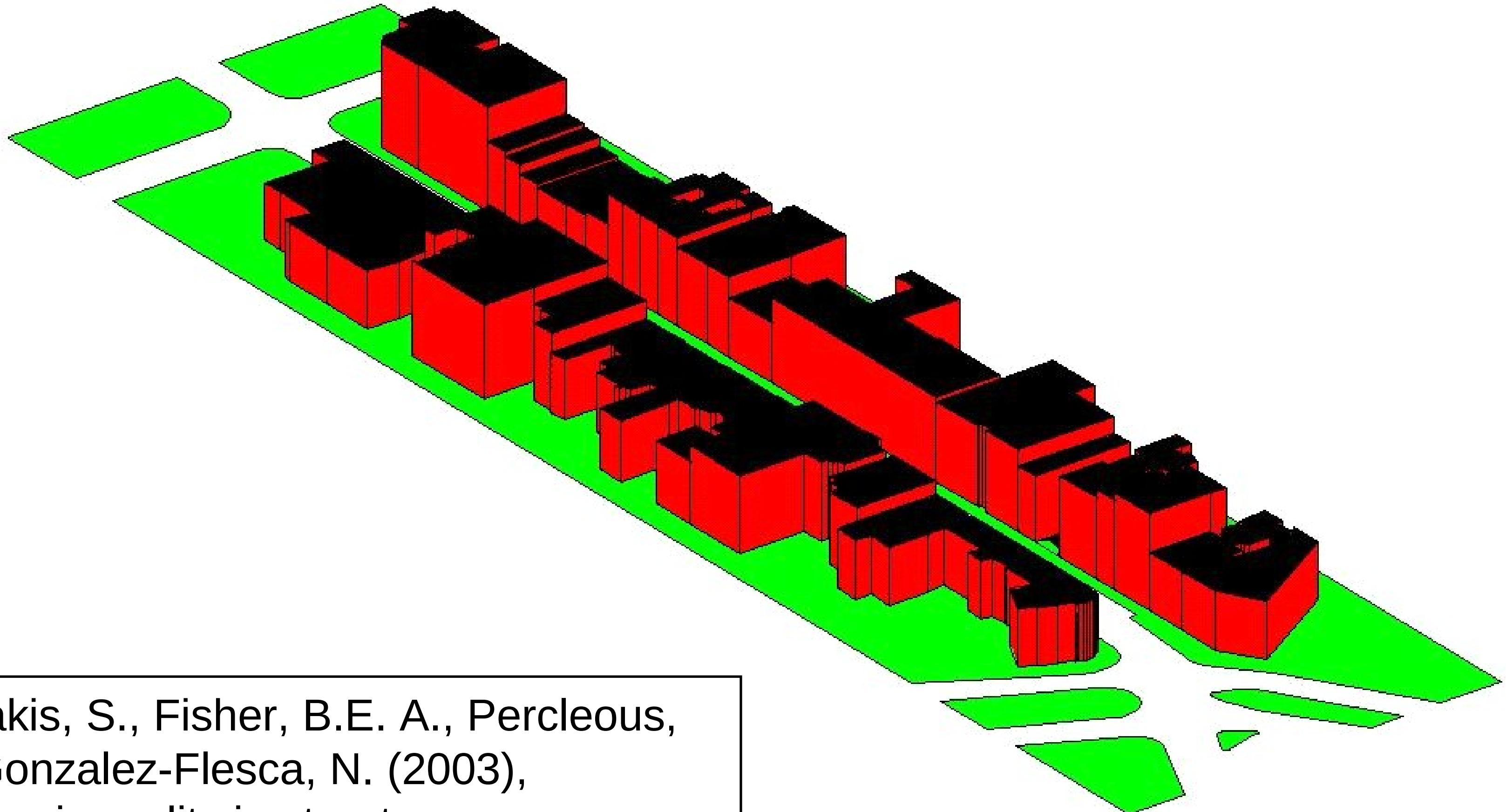


COST Action 715: Meteorology applied to Urban Air Pollution Problems

…e.g. on traffic emissions

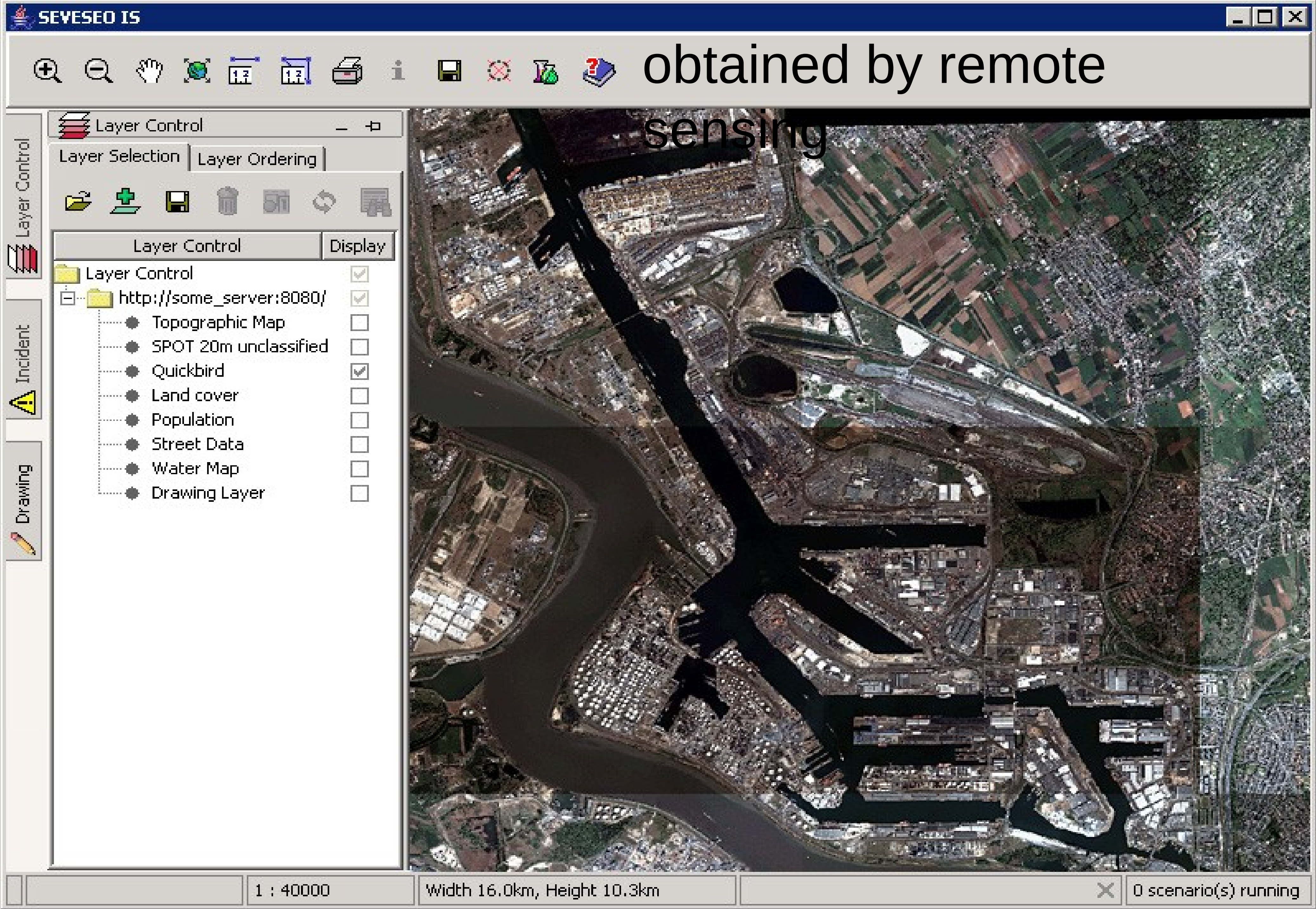


…e.g. on street canyon dynamics



Vardoulakis, S., Fisher, B.E. A., Percleous, K. and Gonzalez-Flesca, N. (2003), Modelling air quality in street canyons: a review, *Atmospheric Environment* **37**, pp. 155-182.

obtained by remote sensing

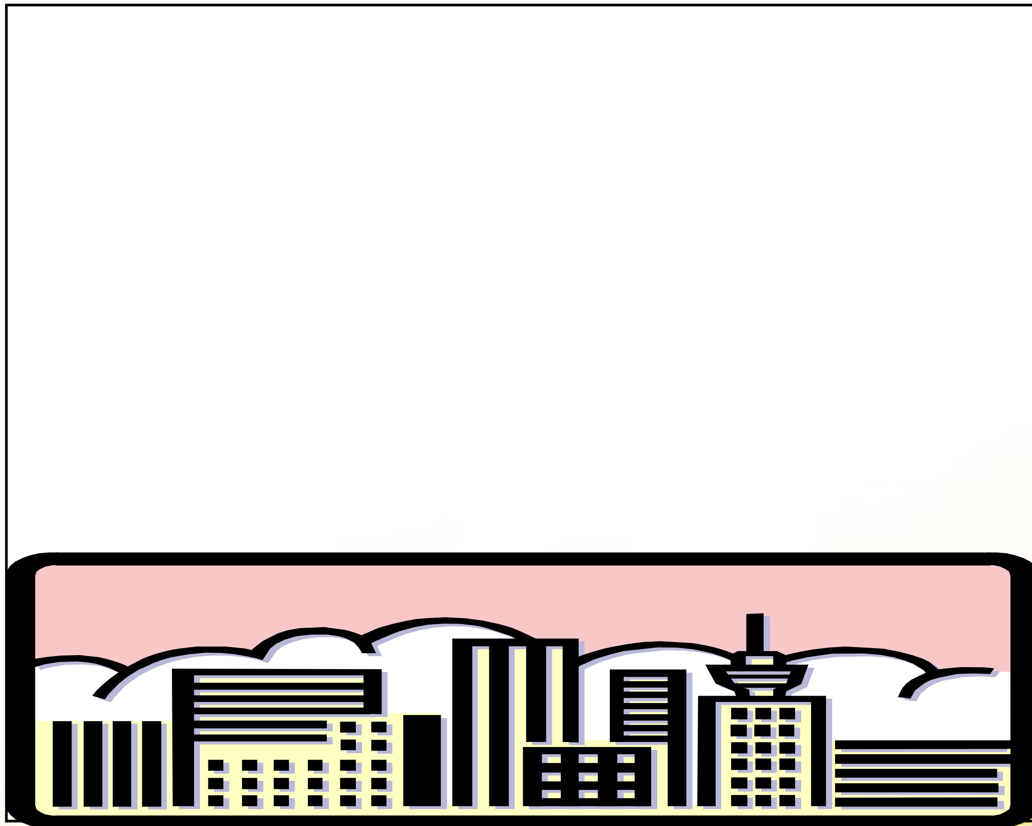


How can we include information

from the urban canopy

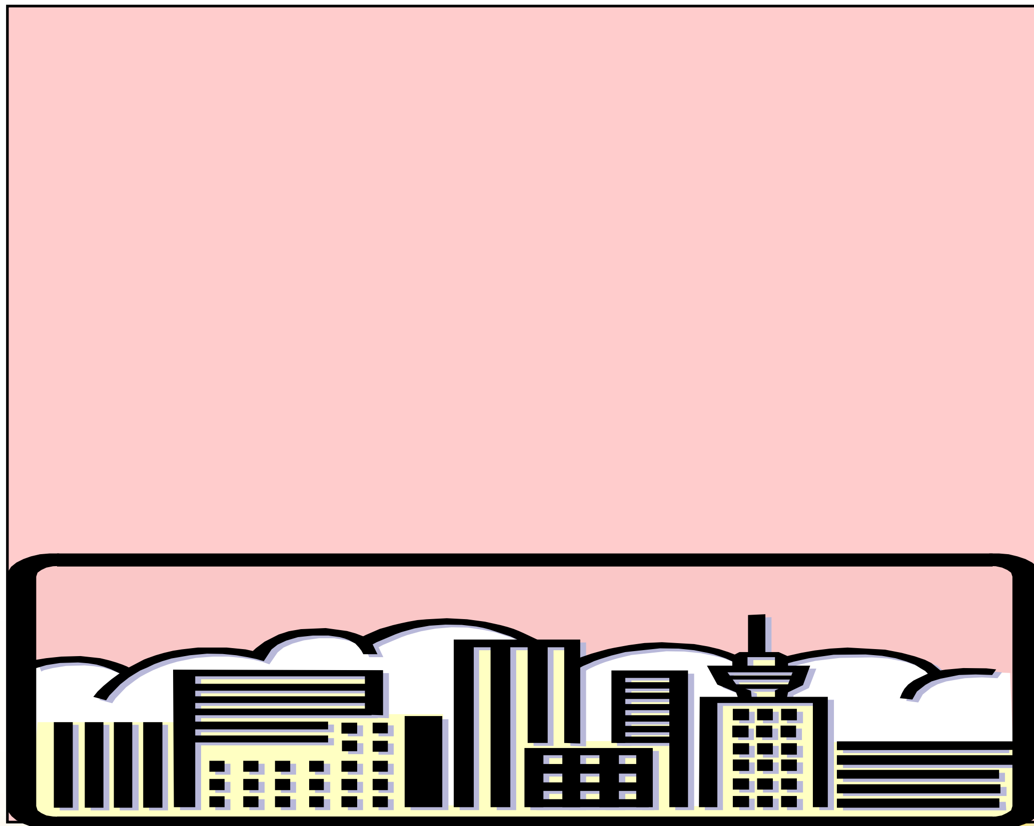
into regional models ?

$t = t_0$



$z = z_0$

$$t = t_0 + \Delta t$$



$z = z_0$

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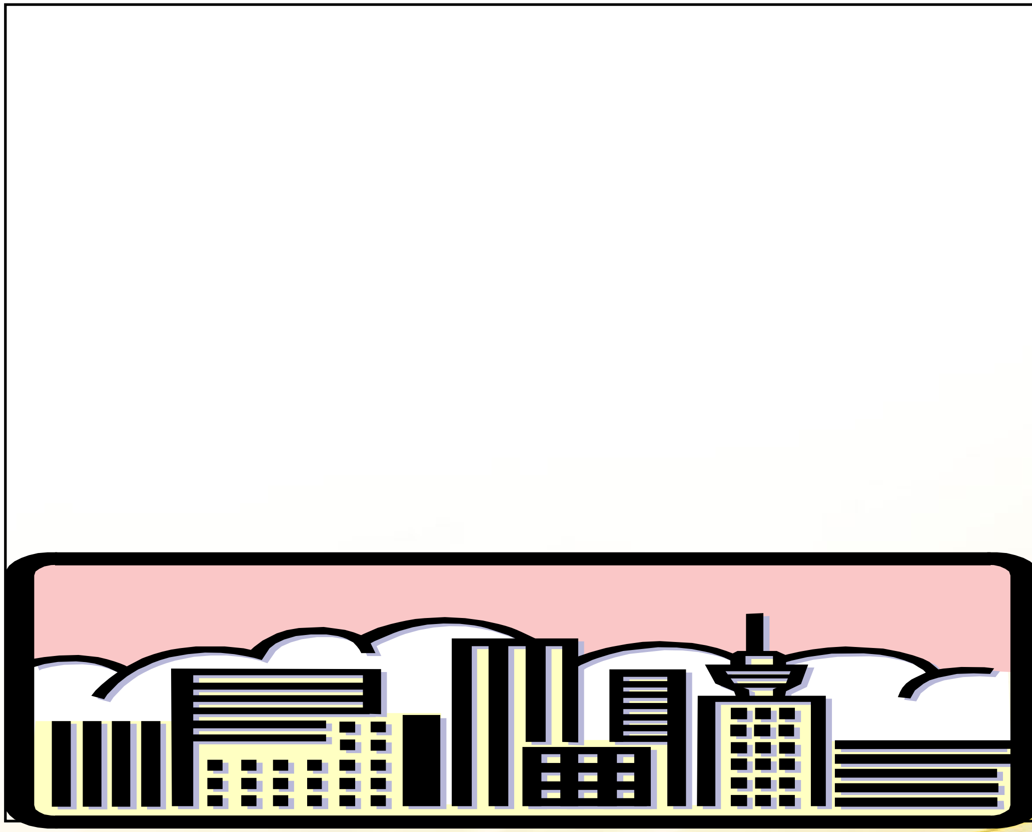
$$z = z_0$$

$t = t_0$



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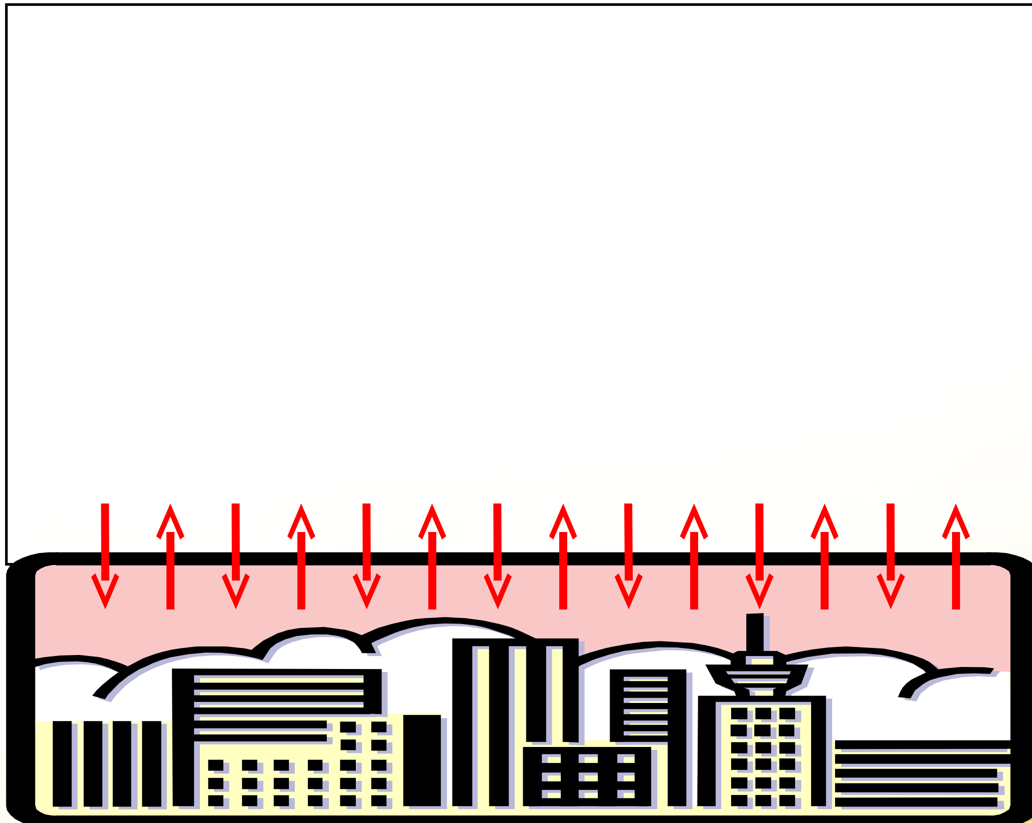
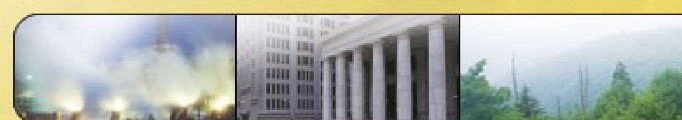




$$\frac{\partial c_s}{\partial t} = -\frac{1}{r\cos\vartheta}\left[\frac{\partial(uc_s)}{\partial\varphi} + \frac{\partial(vc_s\cos\vartheta)}{\partial\vartheta}\right] + \frac{K}{r^2\cos\vartheta}\left[\frac{1}{\cos\vartheta}\frac{\partial^2 c_s}{\partial\varphi^2} + \frac{\partial c_s}{\partial\vartheta}\frac{\partial c_s(\cos\vartheta)}{\partial\vartheta}\right] +$$

horizontal advection — horizontal diffusion

$$+\underbrace{Q}_{\text{emission}} + \underbrace{R(c_s)}_{\text{chemistry}} + \underbrace{D(c_s)}_{\text{deposition}} + \underbrace{V_1(c_s)}_{\text{vertical diffusion}} + \underbrace{V_2(c_s)}_{\text{vertical exchange due to fumigation}}, \qquad s = 1, 2, \ldots, q,$$

We propose to replace

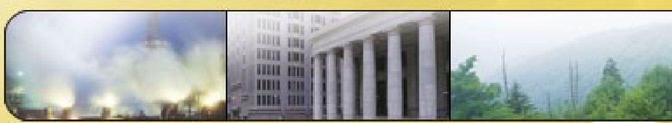
the source and sink terms by a

turbulent diffusive boundary flux

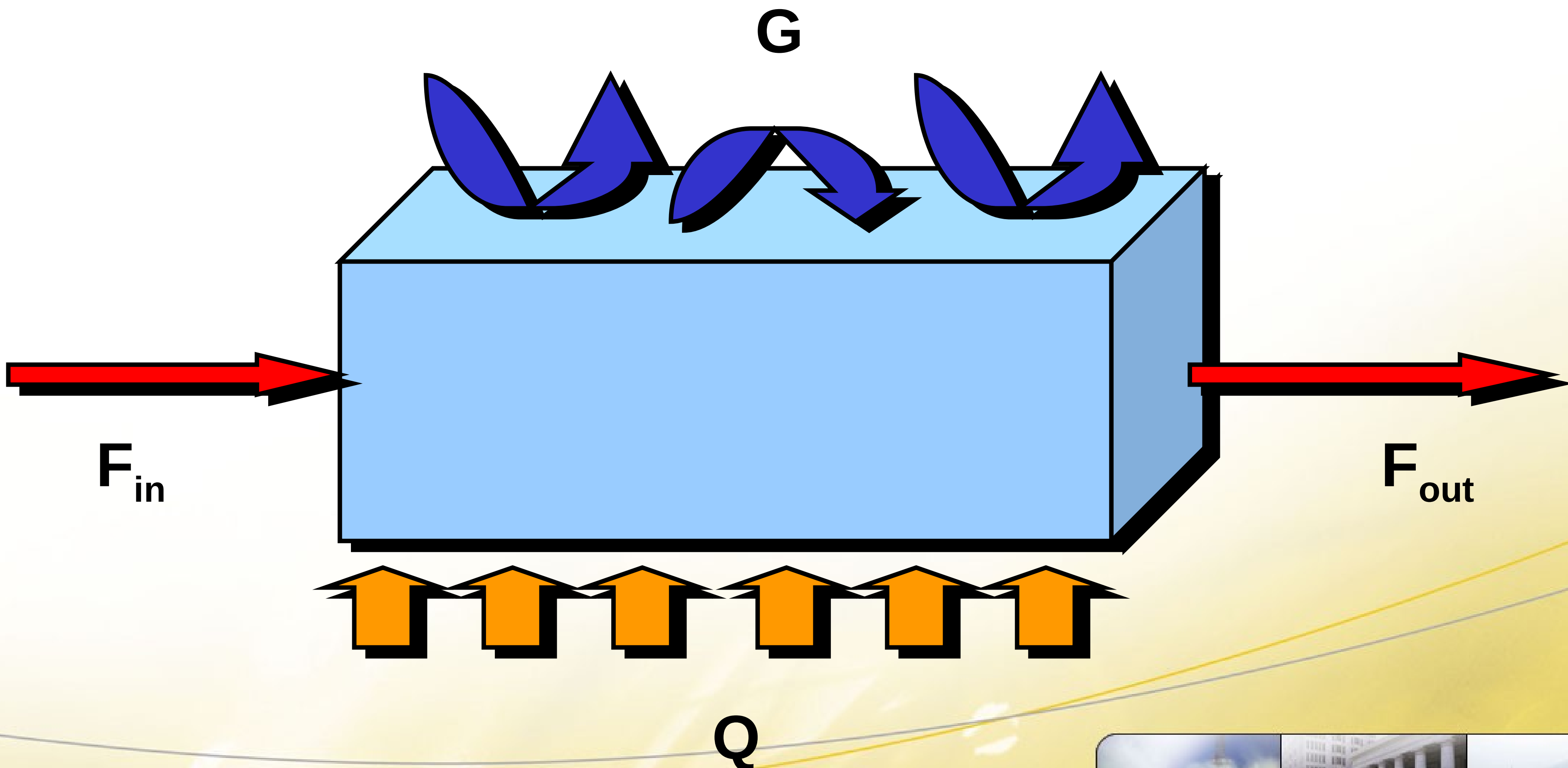
describing the interactions between

the urban canopy and

the regional model domain



Implementation for street canyons



In the box, only horizontal advection along the street (x-direction) and vertical diffusion processes (z-direction) are considered, together with a continuous source term *S*. Net contributions of horizontal turbulent fluxes are neglected as well as diffusion in horizontal directions:

$$\frac{\partial \bar{c}}{\partial t} = -\frac{\partial}{\partial x}\left(\overline{v_x}\,\bar{c}\right) - \frac{\partial}{\partial z}\left(\overline{v_z^{'}\,c^{'}}\right) + D\,\frac{\partial^2 \bar{c}}{\partial z^2} + S$$

The vertical turbulent mass flux term is approximated by applying the eddy diffusivity concept in analogy of Fick's law:

$$\overline{v_z^{'}\,c^{'}} = -K\,\frac{\partial \bar{c}}{\partial z}$$

For a turbulent free stream flow the eddy diffusivity K (m^2 s^{-1}) can be related to a characteristic length scale and the free stream flow velocity gradient by applying the Prandtl-Taylor hypothesis (Hinze, 1987):

$$\overline{v_z^{'}\, c^{'}} = -\ell^2 \left|\frac{\mathrm{dU}}{\mathrm{dz}}\right| \frac{\partial \bar{c}}{\partial z}$$

The characteristic length ℓ is associated with a typical mixing length created by turbulent eddies shedding off at roof level. The velocity gradient over this mixing length is assumed to be constant and equal to the free stream velocity $U_{\perp}$ divided by the characteristic length ℓ

$$C - C_b = \frac{Q}{U_{\equiv} \cdot \left(\frac{H}{L}\right) \cdot W + (D + \ell\, U_{\perp}) \cdot \left(\frac{W}{H}\right)}$$

Where:

C	: concentration (µg/m³)
C_b	: background concentration (µg/m³)
Q	: emission source strength (µg/m/s)
D	: diffusion at low wind speeds (D = 1.5 m²/s, Copalle, 2001)
L,W,H	: length, width and height of the street canyon (m)
$U_{\perp}$	: wind speed perpendicular to the street (m/s)
$U_{\equiv}$	: wind speed parallel to the street (m/s)
ℓ	: characteristic shedding length for mass and momentum momentum exchange (ℓ = 1.0 m)

$$G = -L \cdot W \cdot \left(D + \ell\, U_{\perp}\right) \frac{C_b - C}{H}$$

Where:

C : concentration (µg/m³)

C_b : background concentration (µg/m³)

Q : emission source strength (µg/m/s)

D : diffusion at low wind speeds (D = 1.5 m²/s, Copalle, 2001)

L,W,H : length, width and height of the street canyon (m)

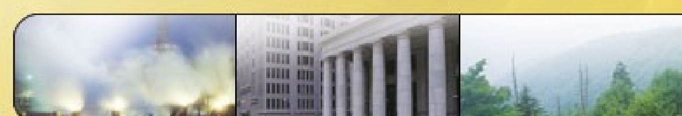
$U_{\perp}$: wind speed perpendicular to the street (m/s)

$U_{\equiv}$: wind speed parallel to the street (m/s)

ℓ : characteristic shedding length for mass and momentum momentum exchange (ℓ = 1.0 m)

Advantages of a turbulent diffusive boundary flux as an urban boundary condition (von Neumann type boundary condition)

2. It is bi-directional (two-way mass exchange between the urban sub-layer and the regional model).
3. It can be an alternative for the formulation of a dry deposition flux over urban areas, where the application of the classical resistance approach is rather difficult.
4. It is scalable. You can apply it for a whole city, a grid cell of any size or just a street canyon.
5. It is independent of the type of (street canyon) model applied in the urban sub-layer.



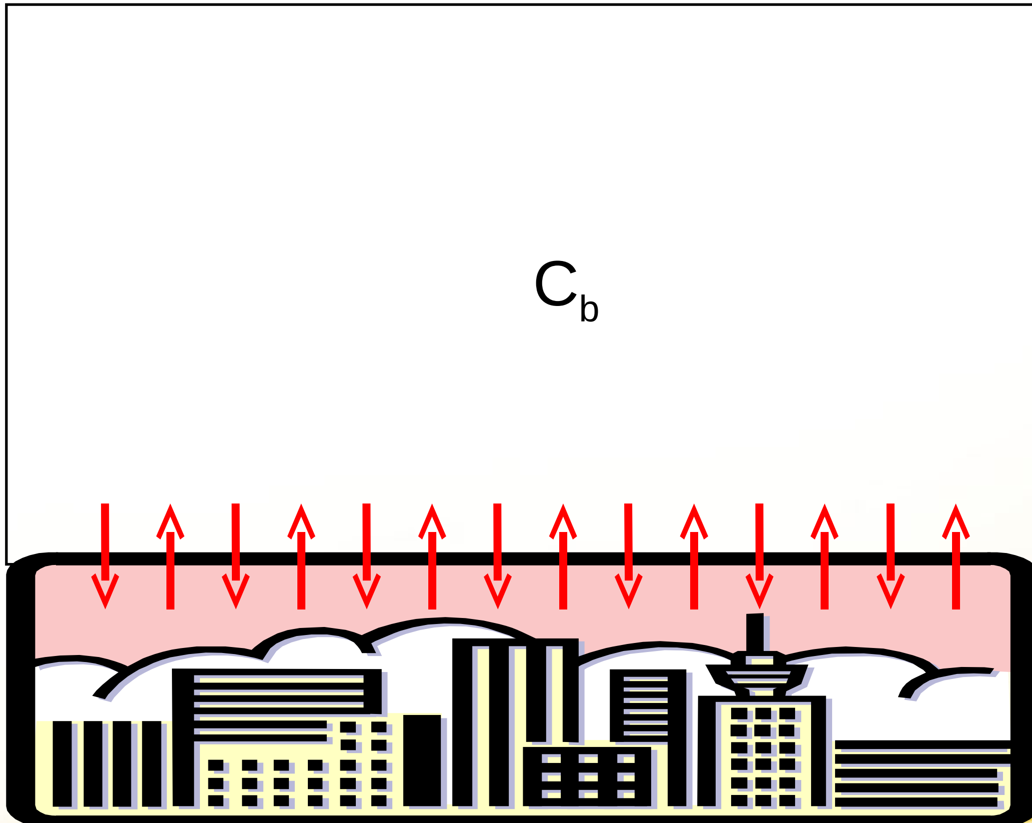
Application & testing

- Calculation of benzene concentrations & fluxes for the entire city of Antwerp and comparisons with the Macbeth measurement campaign

- Calculation of NO_x concentrations & fluxes for a single street canyon and comparisons with measurements from an urban monitoring station

$t = t_0 + \Delta t$

$z = z_0$

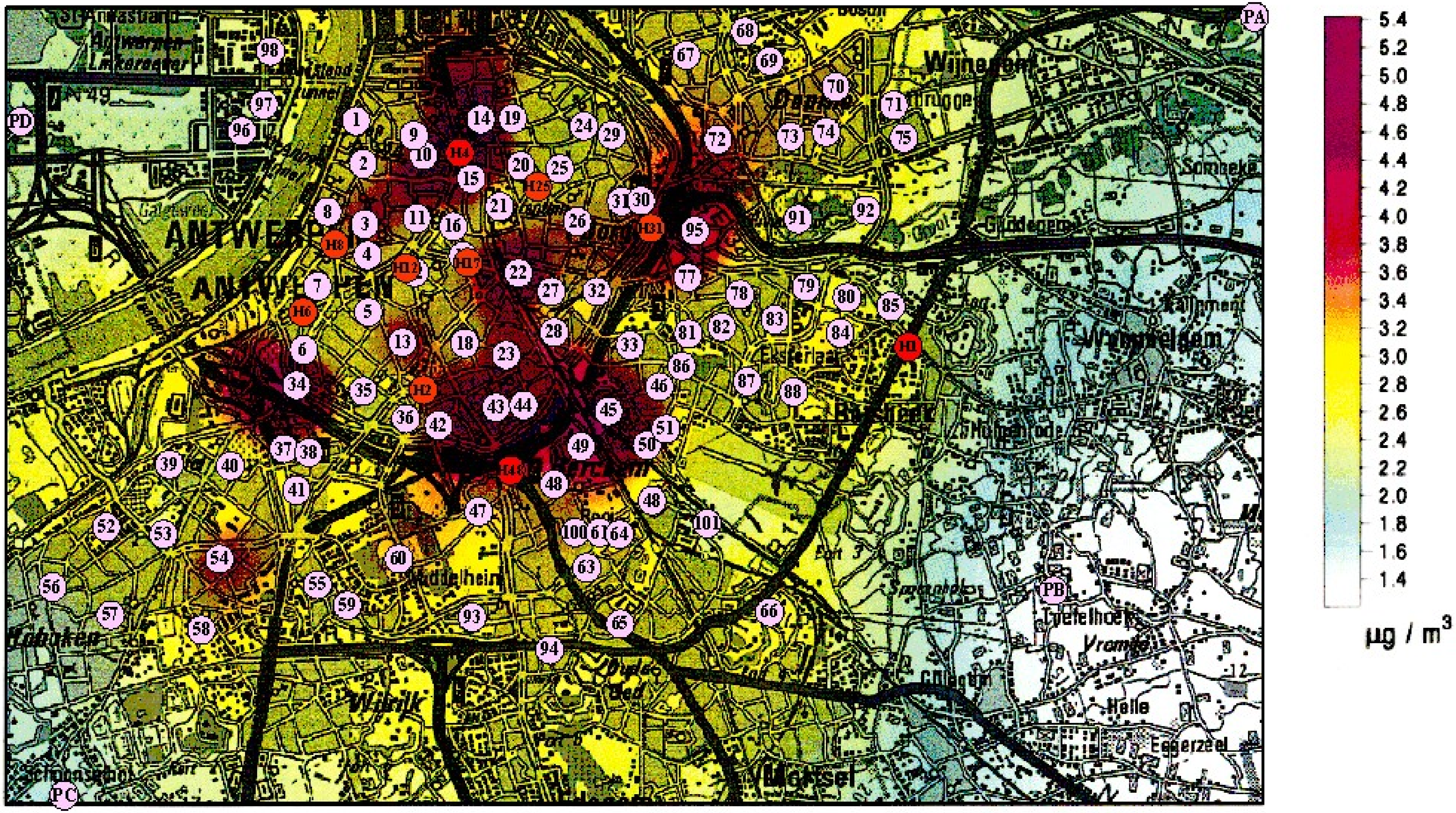


Antwerp

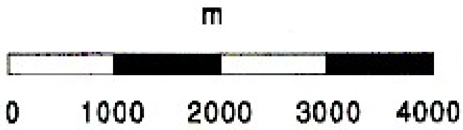
MACBETH (LIFE96ENV/IT/70)

- Benzene measurements in 6 European cities (Antwerp, Copenhagen, Rouen, Murcia, Padova and Athens)
- Four measurement periods of 5 days (Mo-Fr) in 1998:
  - 19 - 23 January 1998
  - 23 - 27 March 1998
  - 25 - 29 May 1998
  - 28 Sep - 2 Oct 1998
- Diffusive sampler measurements in 101 streets in Antwerp and 4 regional background locations
- Comparisons of period averages

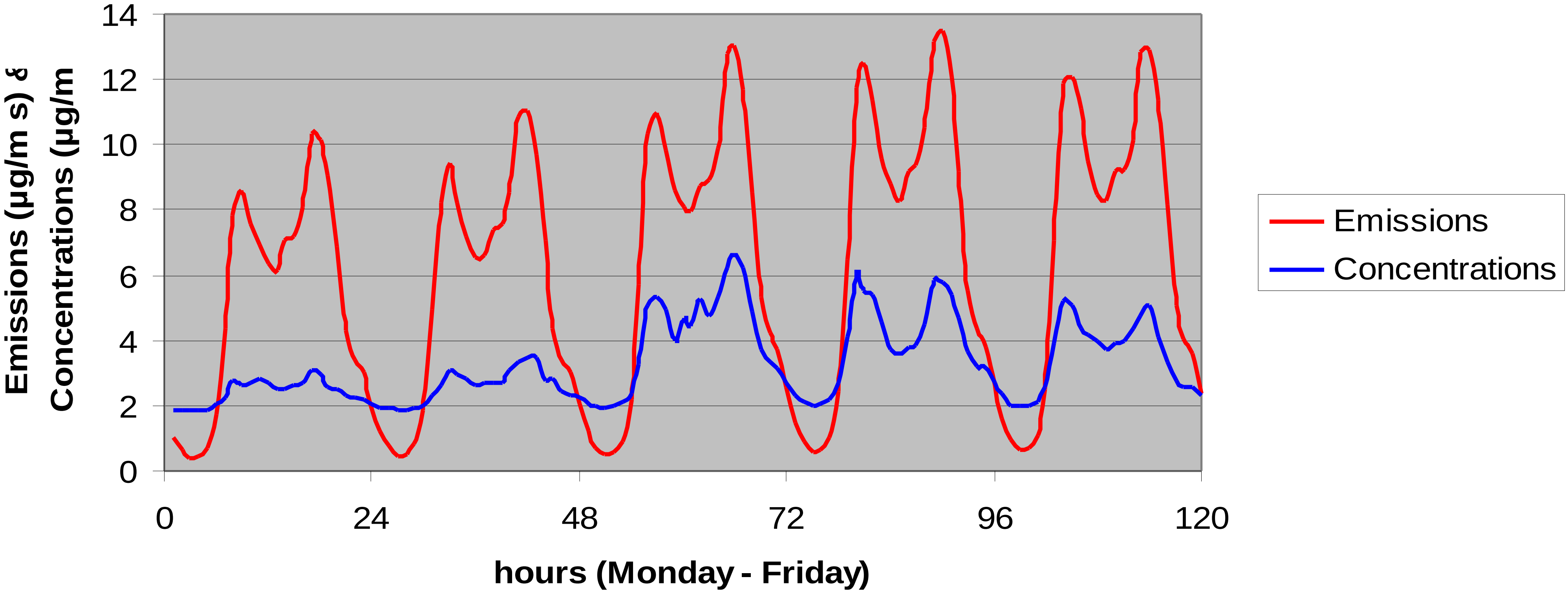
Diffusive Sampler and Protective Shelter



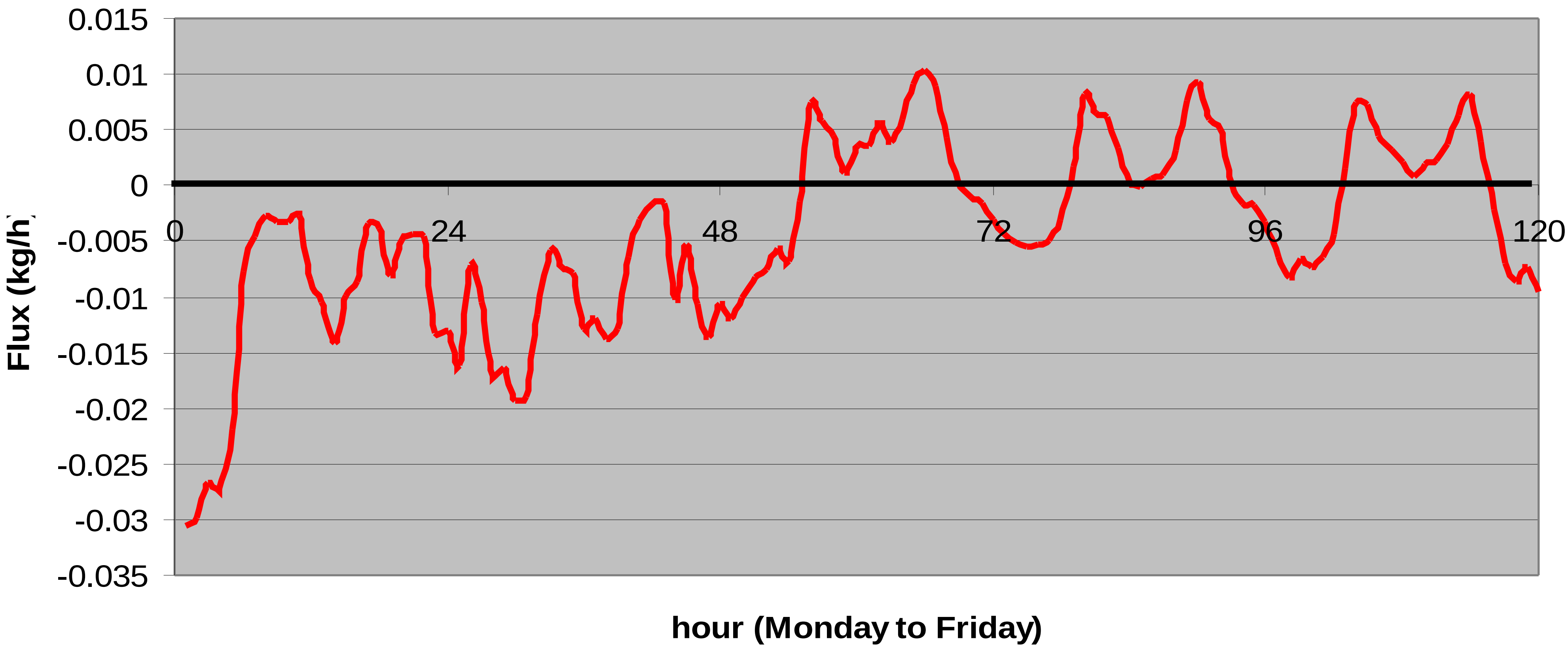
Observed weekly average concentrations



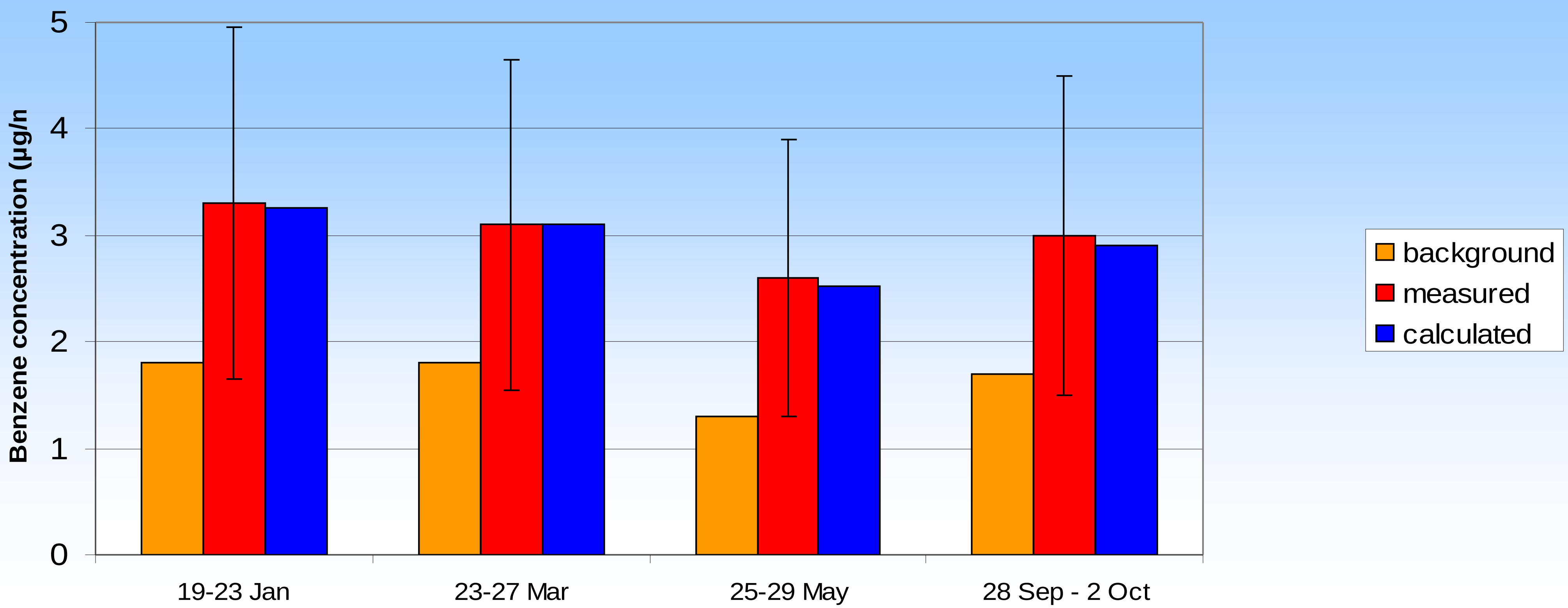
Benzene emissions & concentrations in Antwerp (19-23 January 1998)



Benzene flux in Antwerp (19-23 January 1998)



Comparison of ensemble averages of measured benzene concentration with ensemble averages of calculated concentrations in the streets of Antwerp

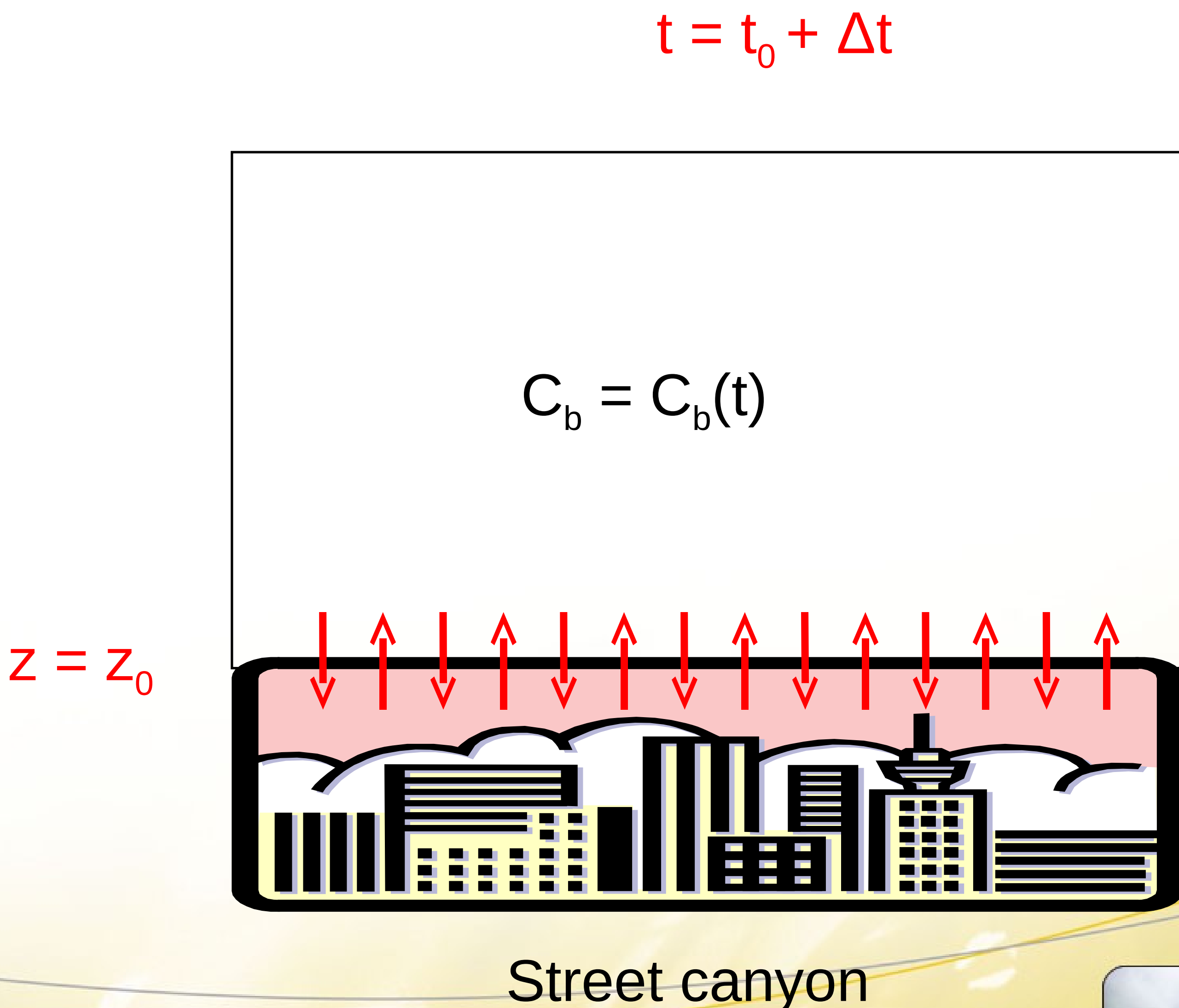


Benzene concentration (µg/n
0
1
2
3
4
5
19-23 Jan
23-27 Mar
25-29 May
28 Sep - 2 Oct
background
measured
calculated

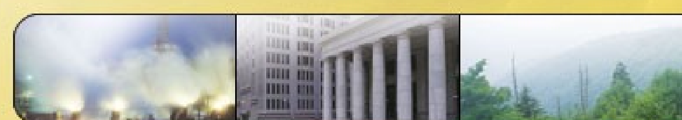
Application & validation

- Calculation of benzene concentrations & fluxes for the entire city of Antwerp and comparisons with the Macbeth measurement campaign

- Calculation of NO_x concentrations & fluxes for a single street canyon and comparisons with measurements from an urban monitoring station

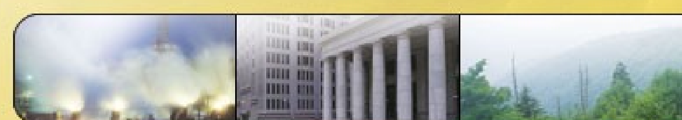


$t = t_0 + \Delta t$
$C_b = C_b(t)$
$z = z_0$
Street canyon



Model application

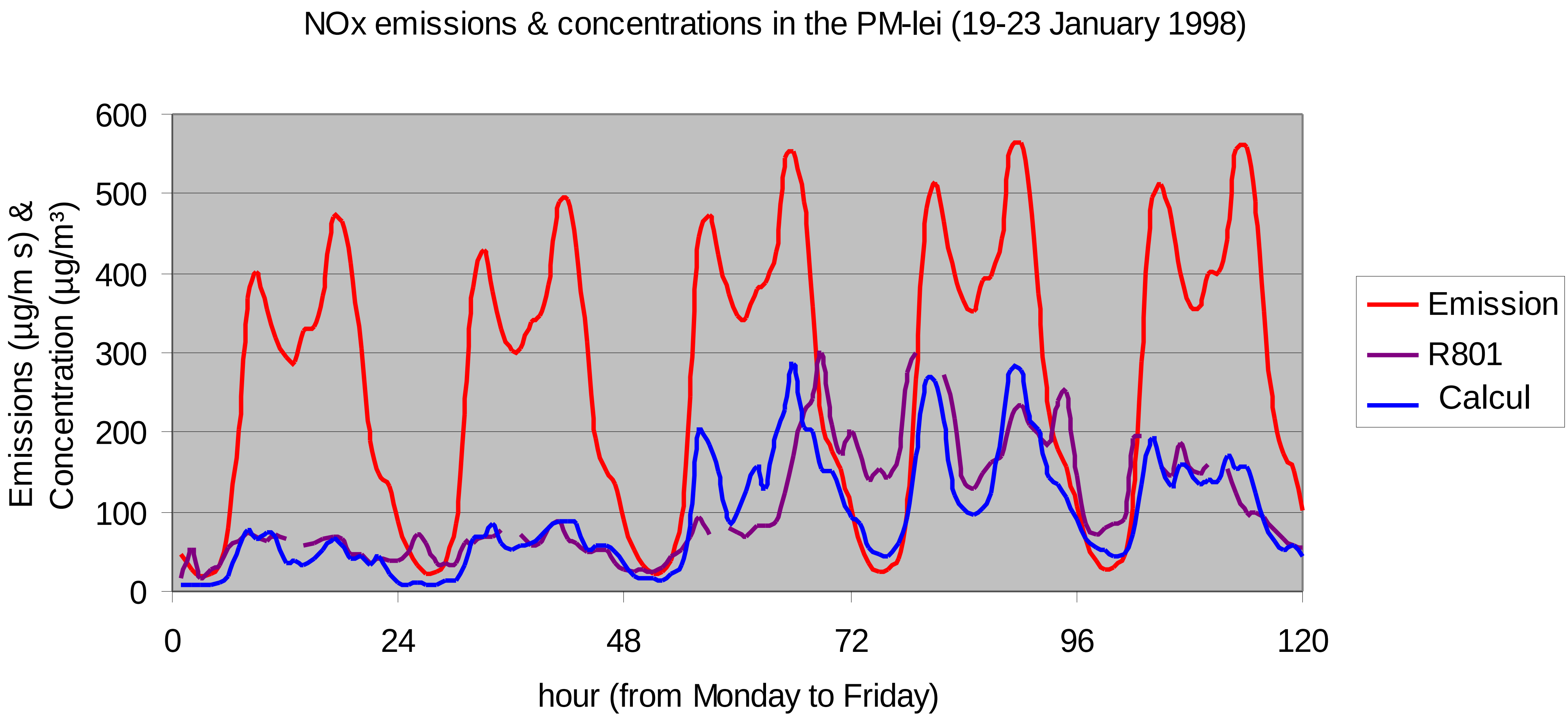
- Application of the emission and street canyon model to calculate the hourly concentrations of NO_x in a main passage road in Antwerp, i.e. the “Plantin en Moretuslei”
- Same 4 measurement periods of 5 days (Mo-Fr) in 1998:
  - 19 - 23 January 1998
  - 23 - 27 March 1998
  - 25 - 29 May 1998
  - 28 Sep - 2 Oct 1998
- Compare the results with hourly observations from a measurement station in the “Plantin en Moretuslei”

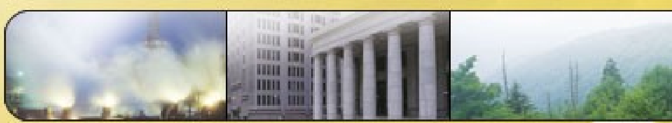


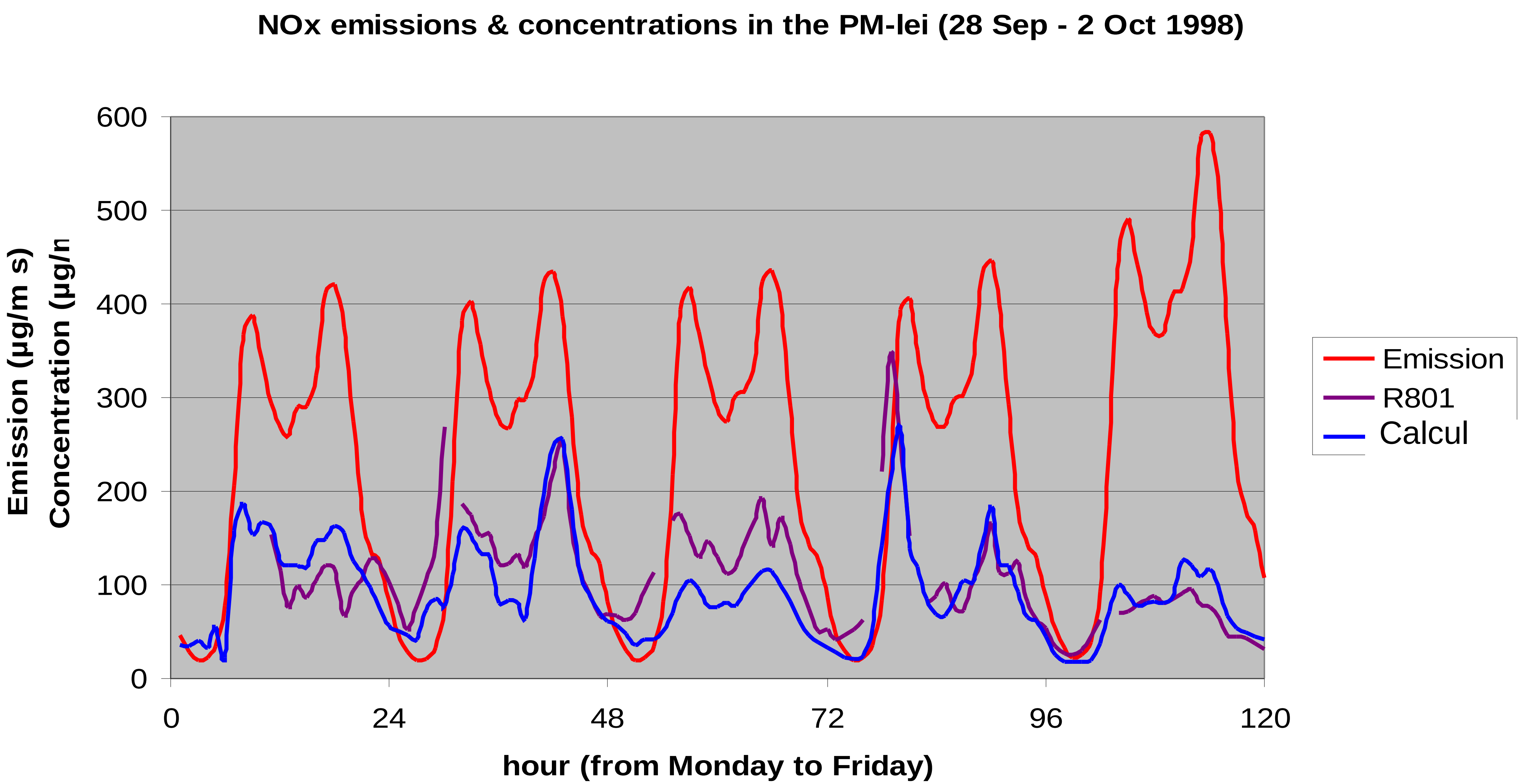

Street width: 29 m.
Street length: 436 m.
Av. building height: 20 m.
Traffic volume: 1200-1300 v/h
PRIST
SANITAIR & C.V.
AARTSELAAR
APARTHOTEL
16 13:53

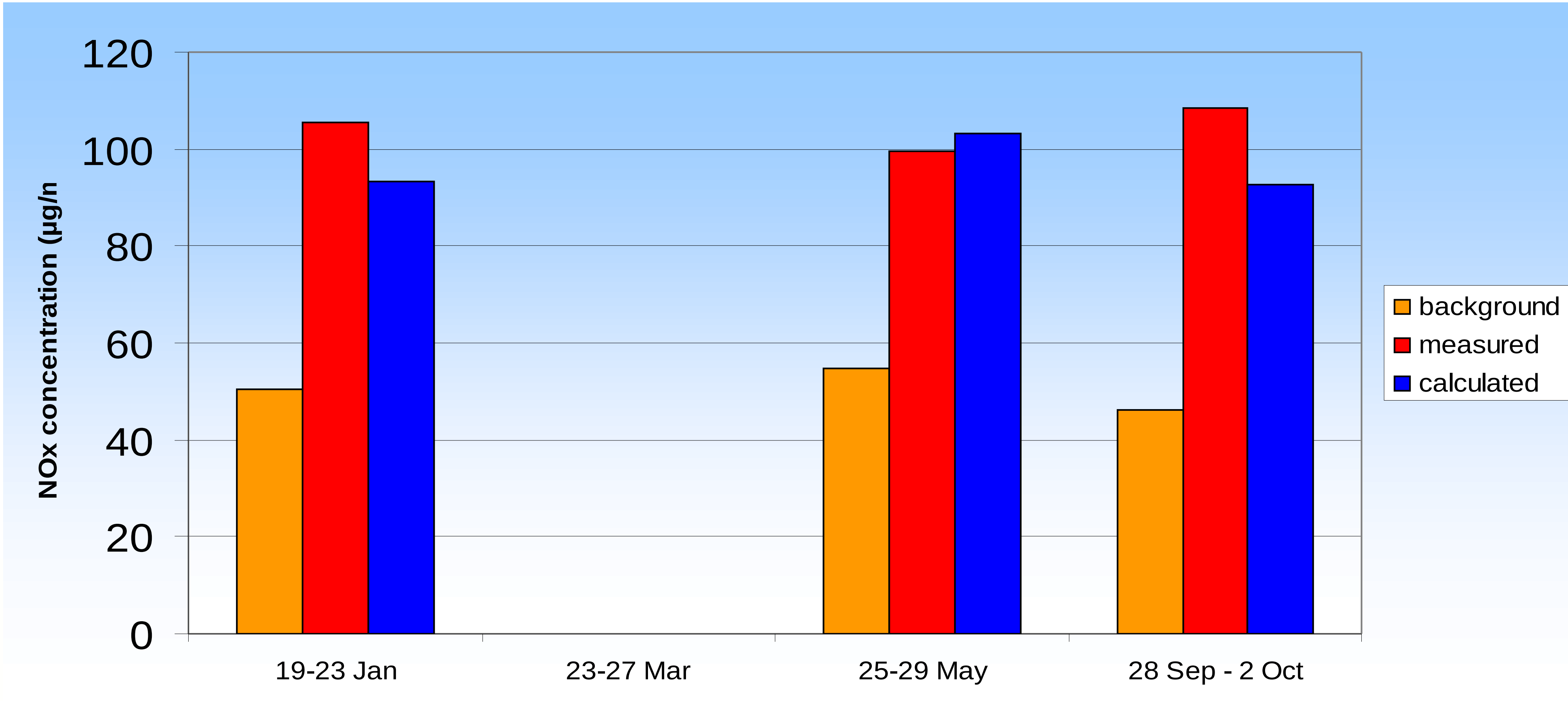

16 14:05

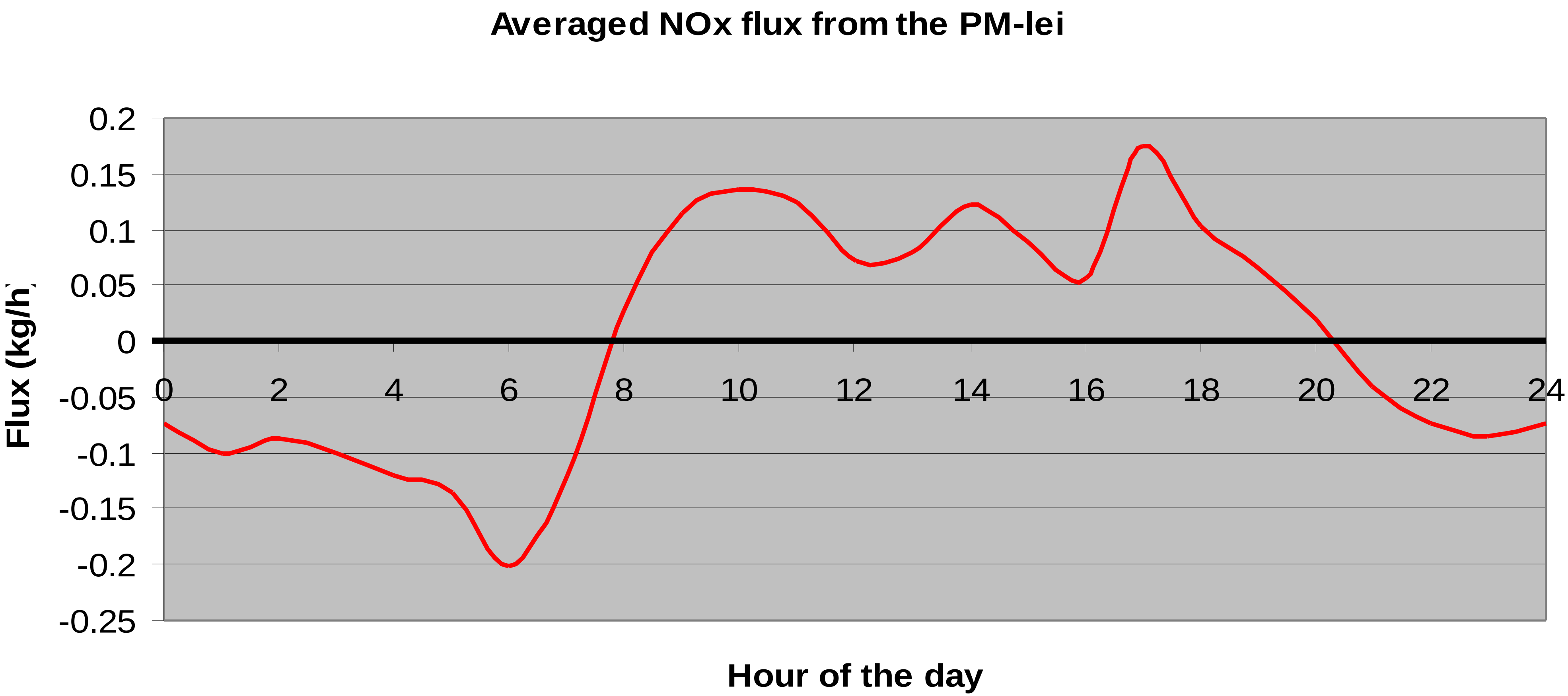

Hier meet
de Vlaamse Milieumaatschappij
de **luchtkwaliteit**.
Dit meetstation (42R801)
controleert de aanwezigheid van :
Stikstofdioxide (NO_2)
Stikstofmonoxide (NO)
Fijn stof (PM 10)
Zwaveldioxide (SO_2)
Koolmonoxide (CO)
Ozon (O_3)
Zwarte rook
Benzeen, Tolueen,
Ethylbenzeen en Xyleen (BTEX)
Geïnteresseerd in de resultaten ?
Surf naar **www.vmm.be**
of bel naar het infoloket :
(053) 72 64 45
VMM
Vlaamse Milieumaatschappij
16 14:04


NOx emissions & concentrations in the PM-lei (19-23 January 1998)
600
500
400
300
200
100
0
Emissions (µg/m s) &
Concentration (µg/m³)
0
24
48
72
96
120
hour (from Monday to Friday)
Emission
R801
Calcul




NOx emissions & concentrations in the PM-lei (28 Sep - 2 Oct 1998)
Emission (µg/m s)
Concentration (µg/m
600
500
400
300
200
100
0
0
24
48
72
96
120
hour (from Monday to Friday)
Emission
R801
Calcul


120
100
80
60
40
20
0
NOx concentration (µg/n
19-23 Jan
23-27 Mar
25-29 May
28 Sep - 2 Oct
background
measured
calculated


Averaged NOx flux from the PM-lei
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
0
2
4
6
8
10
12
14
16
18
20
22
24
Flux (kg/h)
Hour of the day

CONCLUSIONS

- It is possible to construct and calculate a turbulent diffusive boundary flux that can replace the (emission) source & sink terms
- This flux can take into account some of the dynamics in the urban canopy (traffic, vertical exchange, wind, temperature)
- It allows a two way interaction between the urban canopy and the regional model domain