Urban Boundary Layer: structure and modelling

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Lectures for
the Summer School on Planetary Boundary Layers over Complex and Vegetated Land Surfaces
Sodankylä, Finland, 4-14.6.2005

The urban BL: structure and modelling:
Lecture schedule

Wednesday 8 June

9:30 – 11:00: The PBL over complex surfaces: challenges and gaps (S. Zilitinkevich)

11:00 – 12:00: The urban BL: structure and modelling (Alexander Baklanov)

13:30 - 14:00: The urban BL: structure and modelling (Alexander Baklanov)

14:30 - 15:00: Turbulence observed during a total solar eclipse: a particular PBL behaviour (Guy Schayes)

15:00 – 16:30: Re-stating the PBL parameters in off-line dispersion models (Mikhail Sofiev)

16:30 -17:30: Student presentations:

Implementation of a multi-urban classification and the urban heat island effect using the mesoscale model MM5: an insight of the ATREUS project: Agnes Dudek (Met.no)

Street canyon simulation comparing with wind tunnel experiment: Jose Luis Santiago (CIEMAT)

Thursday 9 June

9:30 – 11:30: Mesoscale effects and PBL (Hannu Savijärvi)

11:30 – 12:00: The urban BL: structure and modelling (Alexander Baklanov)

14:00 – 16: 00: High-resolution simulation of interactions in the urban canopy and boundary layer (A. Martilli)

16:00 – 18:00: Working Group discussions on urban meteorology (incl. FUMAPEX): linkages between NWP-air quality models,

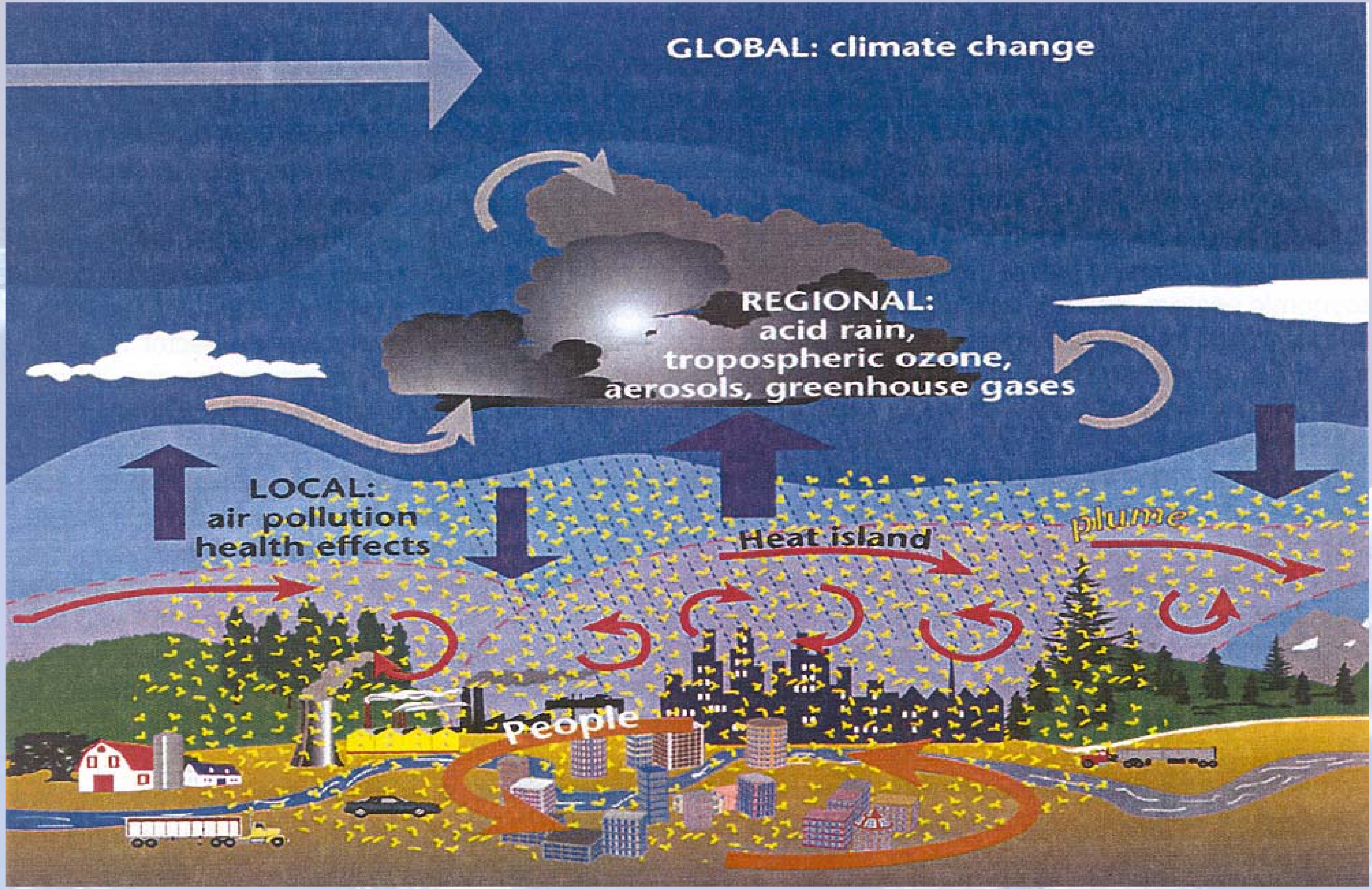
Structure of the Lectures

I. Introduction
II. Structure of the urban boundary layer
III. Modification of flow and turbulence structure over urban areas
IV. The surface energy balance in urban areas
V. The mixing height and inversions in urban areas
VI. Urban-scale meteorological modelling and input data for urban air pollution models
VII. Integrated modelling : Forecasting Urban Meteorology, Air Pollution and Population EXposure (FUMAPEX) and COST 728
VIII. Summary of achievements, gaps in knowledge, recommendations for further research

Why Urban Meteorology Now?

- ***Technological Advances***
  - Powerful computers for high-resolution modeling
  - Remote sensing and other platforms
- ***Weather, Health, Comfort and Safety***
  - High impact weather and feedbacks
  - Air quality in urban areas
  - Urban climate, incl. indoor-climate
  - Urban planning and architecture
- ***Emergency Issues and Security***
  - Risk of accidents and terror in urban areas
  - Atmospheric transport and diffusion in urban areas

Why do we have to consider the urban effects? What kind of effects?



A city can be considered as a protect area for meso scale atmospheric events:

- Urban heat island has a positive influence in the winter outdoor thermal comfort and the energy consumption
- Urban roughness mitigates wind speed actions on tall buildings above the mean roof level

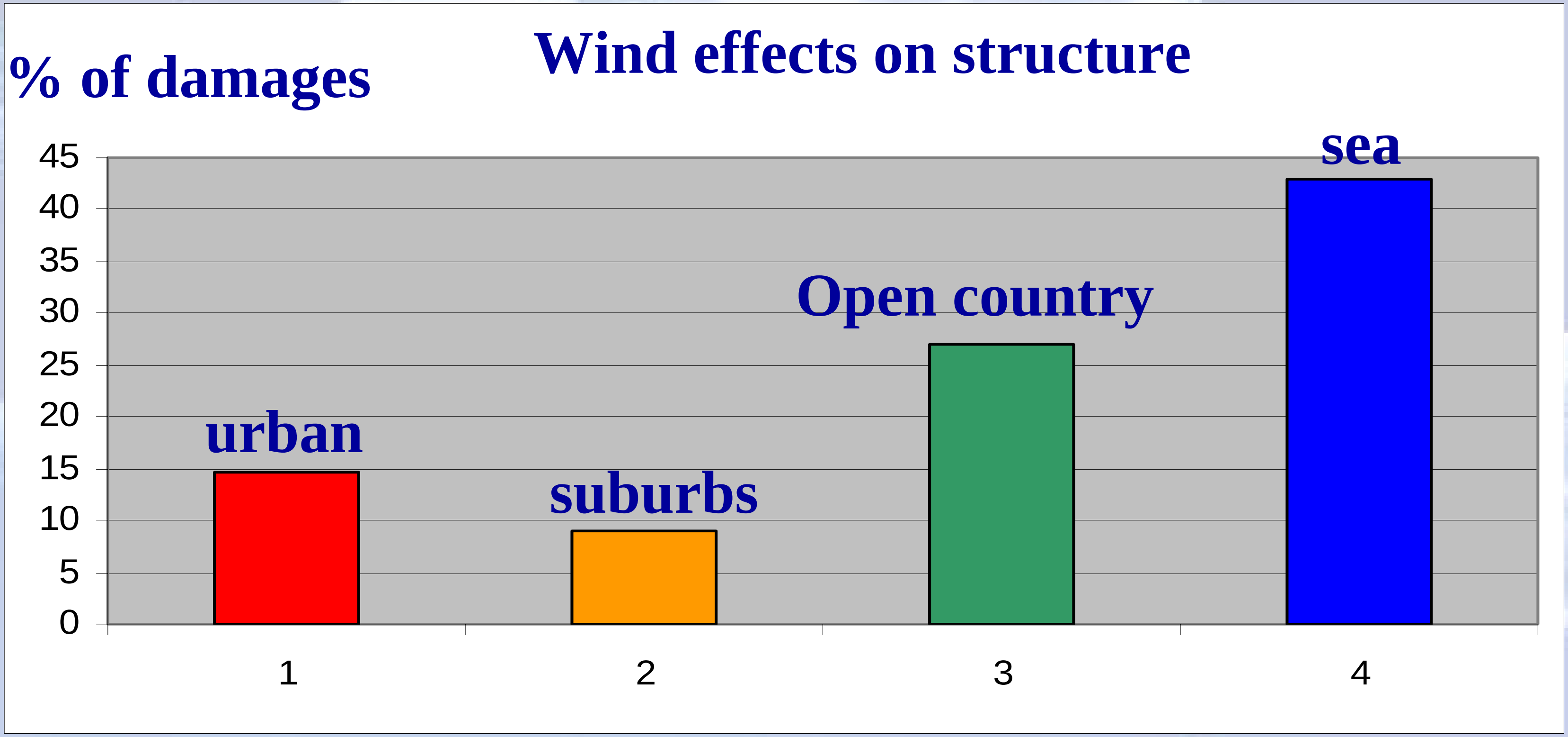
From other side:

At small scale in the urban canopy, the built environment can induce negative effects:

- over speed area around buildings
- low diffusion of pollutants in street canyon
- Lack of ventilation for indoor and outdoor comfort

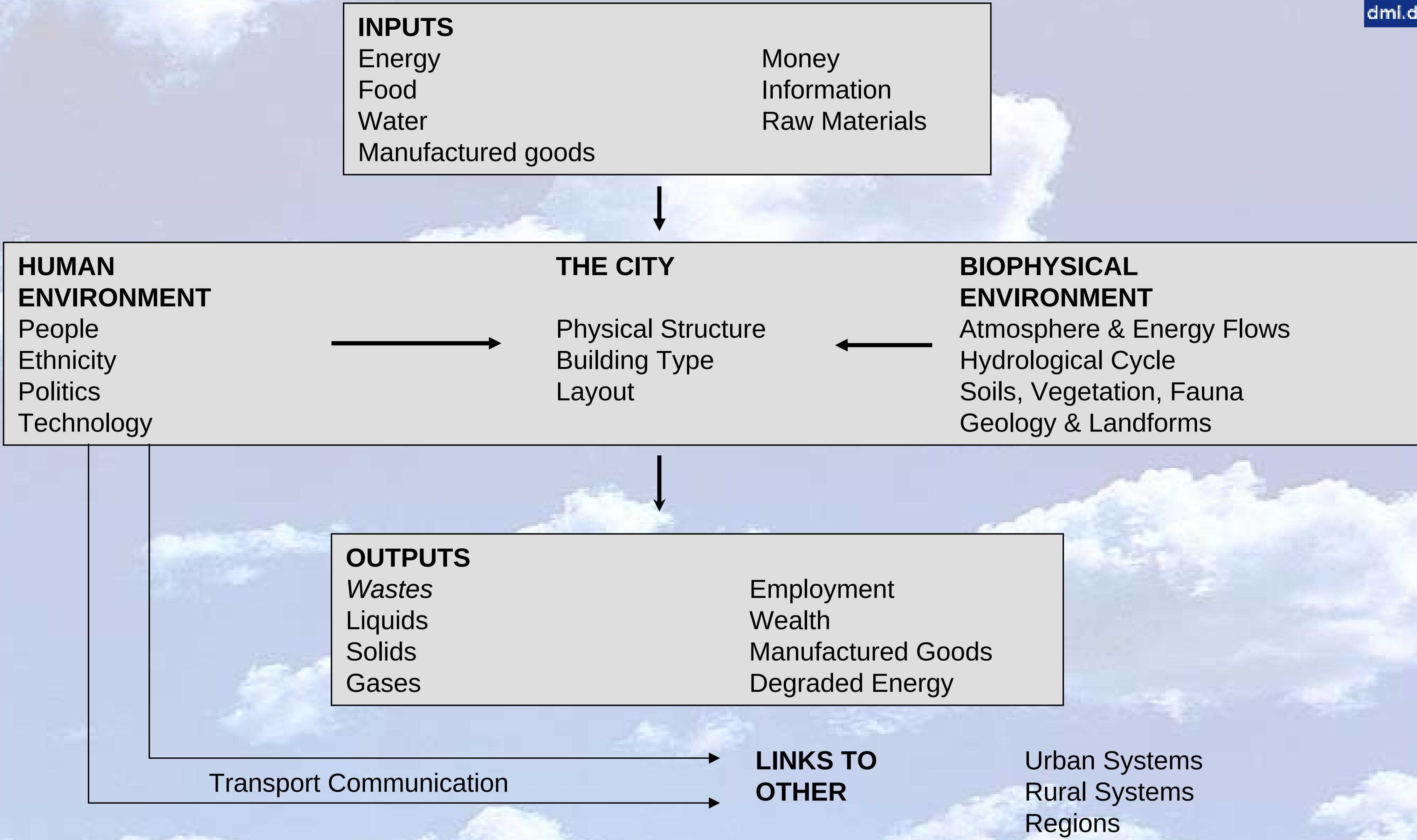
Example: effects of storm *Lothar (1999)*

Buildings located downwind of small roughness (sea and open country) had more damages on structure



The Urban System (EU 5FP City of Tomorrow)

Interactions between the city, human environment and biophysical environment



From Bridgman et al. (1996)

European research projects

- COST Actions 710, 715, 728, 732,
- SATURN/EUROTRAC/TRAPOS,
- CLEAR cluster,
- FUMAPEX project,
- ACCENT Network of Excellence,

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WMO GURME project

US EPA/NOAA projects

COST Action 715: Urban Meteorology

”Meteorology applied to Urban Air Pollution Problems”

1998 - 2004

WG 1: Urban wind fields

WG 2: Energy budget and mixing height in urban areas

WG 3: Meteorology during peak pollution episodes

WG 4: Input data for urban air pollution models

FUMAPEX: ***Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure***

Project objectives:

(i) **the improvement of meteorological forecasts for urban areas,**

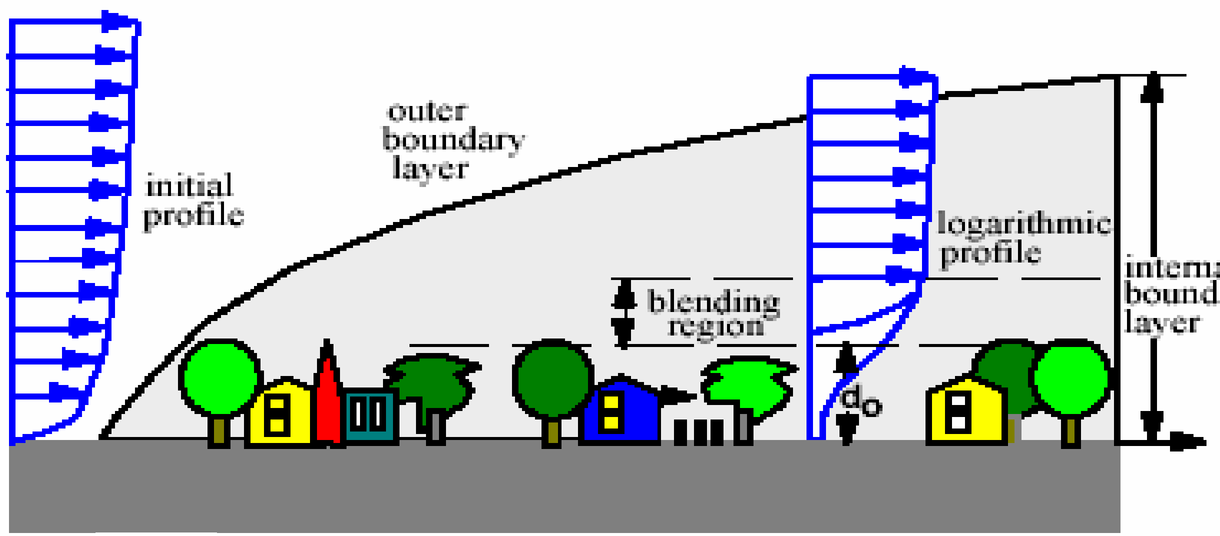
(ii) **the connection of NWP models to urban air quality (UAQ) and population exposure (PE) models,**

(iii) **the building of improved *Urban Air Quality Information and Forecasting Systems* (UAQIFS), and**

(iv) **their application in cities in various European climates.**

Part II: Structure of the urban boundary layer

- Vertical structure
- Horizontal non-homogeneity
- Temporal variability



Schematic development of an urban boundary layer.

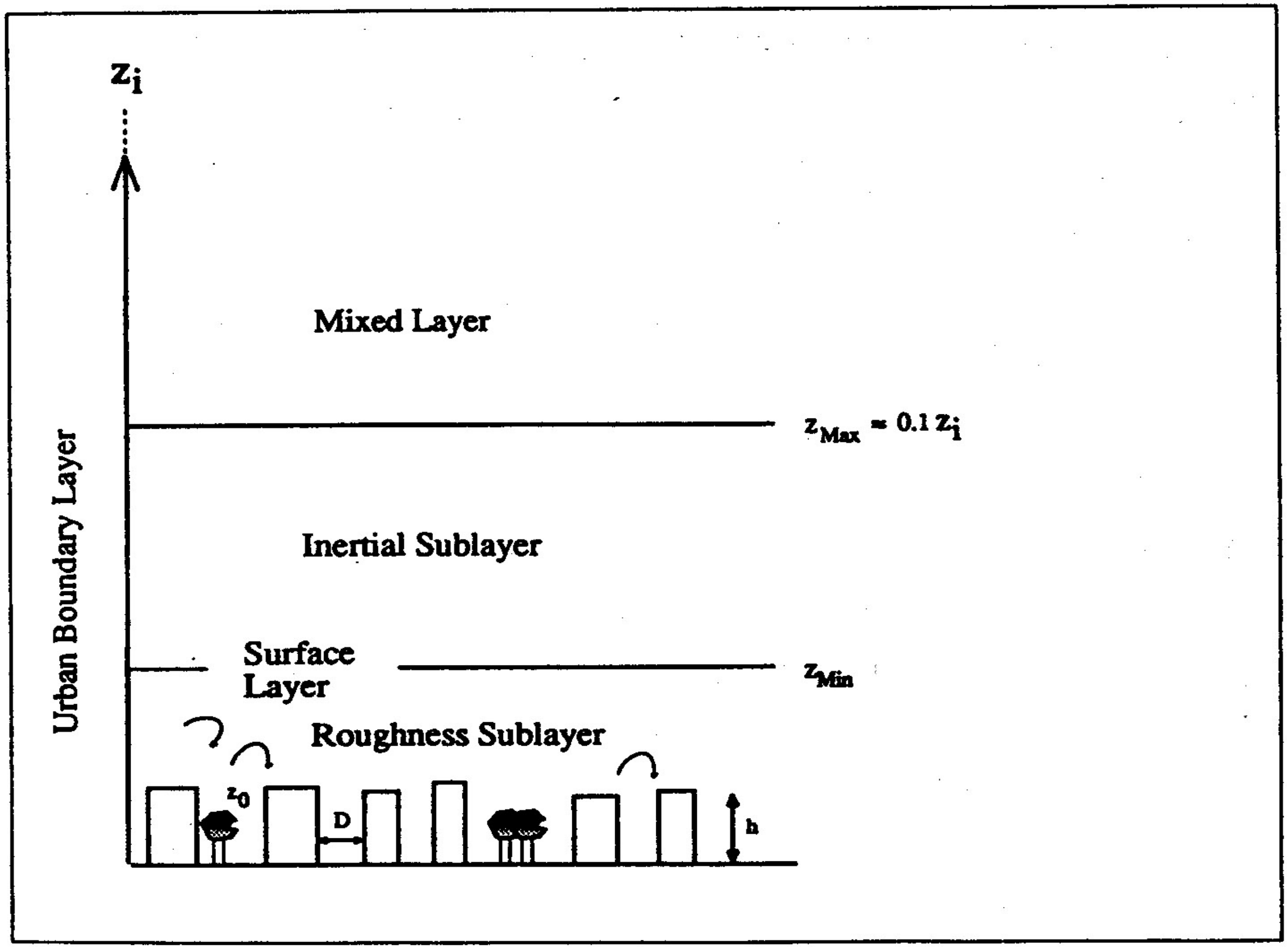
Problems in defining the boundary layer

- Complicated vertical structure
- Sub-layers grow and decay over the diurnal cycle
- Turbulence is often intermittent, complicating the classification of stability
- Boundary layer top is not necessarily at inversion

Urban BL features:

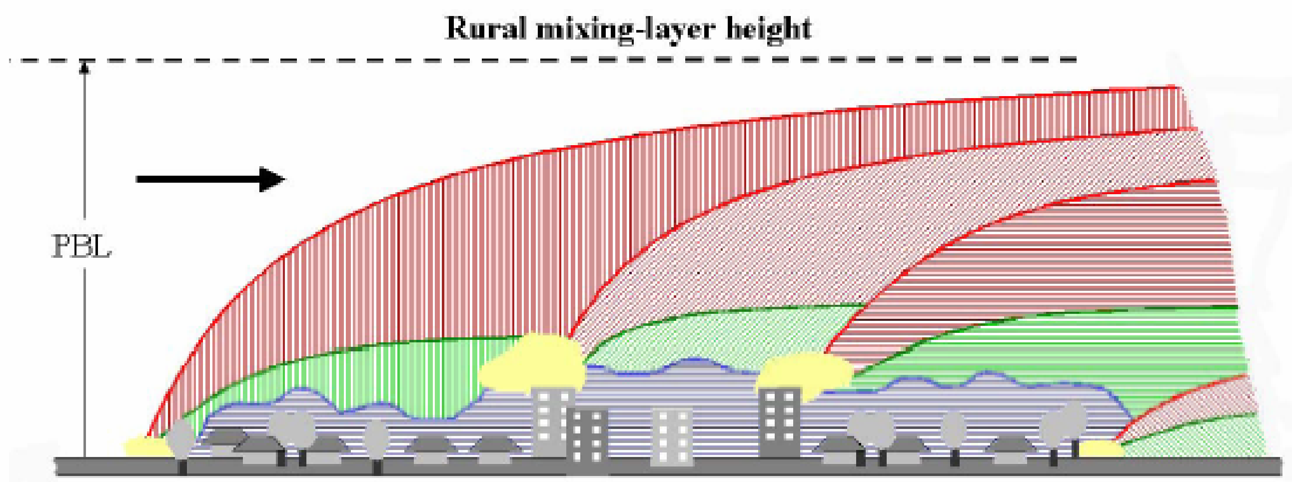
- Local-scale inhomogeneties, sharp changes of roughness and heat fluxes,
- Wind velocity reduce effect due to buildings,
- Redistribution of eddies due to buildings, large => small,
- Trapping of radiation in street canyons,
- Effect of urban soil structure, diffusivities heat and water vapour,
- Anthropogenic heat fluxes, urban heat island,
- Internal urban boundary layers (IBL), urban Mixing Height,
- Effects of pollutants (aerosols) on urban meteorology and climate,
- Urban effects on clouds, precipitation and thunderstorms.

Vertical structure of UBL



after T. Oke (1988)

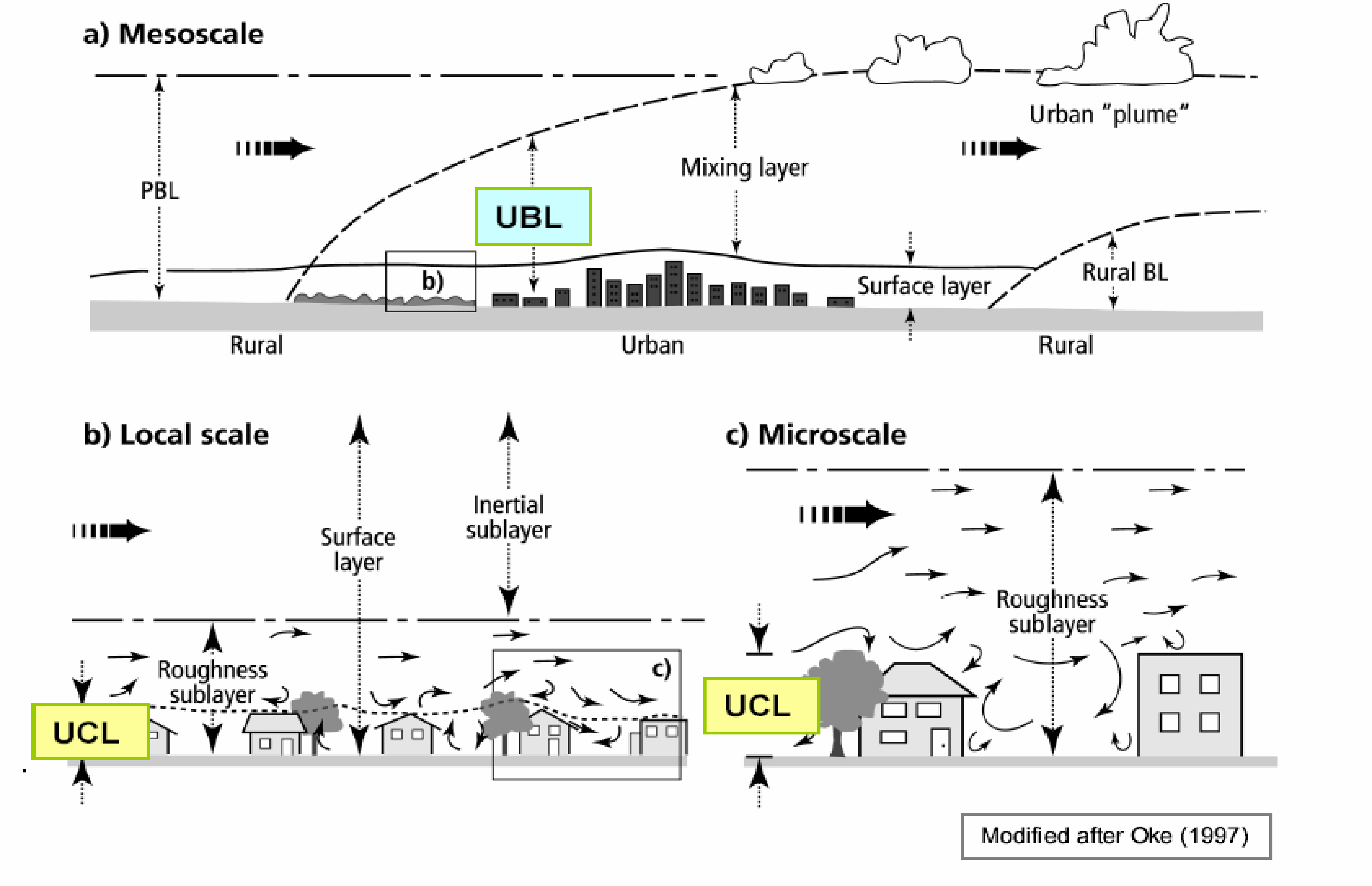
Horizontal structure of UBL



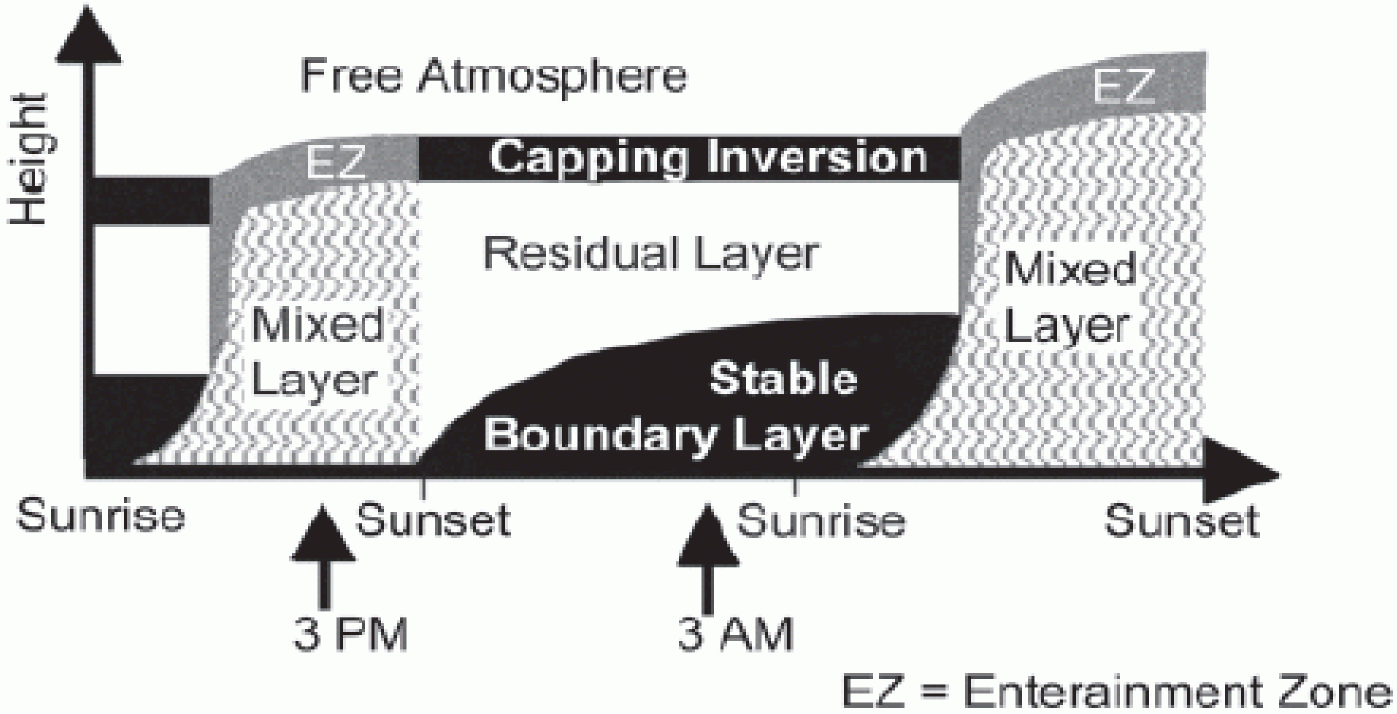
Schematics of boundary layer over an urban area. Red represents the urban internal boundary layers where advection processes are important. Green shows the inertial layers that are in equilibrium with the underlying surface and where Monin-Obukhov scaling applies. The blue region is the roughness layer that is highly inhomogeneous both in its vertical and horizontal structure. The yellow region represents adjustment between neighbourhoods with large accelerations and shear in the flow near the top of the canopy.

Courtesy of S.-E. Gryning

Scales in an Urban Environment



Diurnal evolution of the PBL

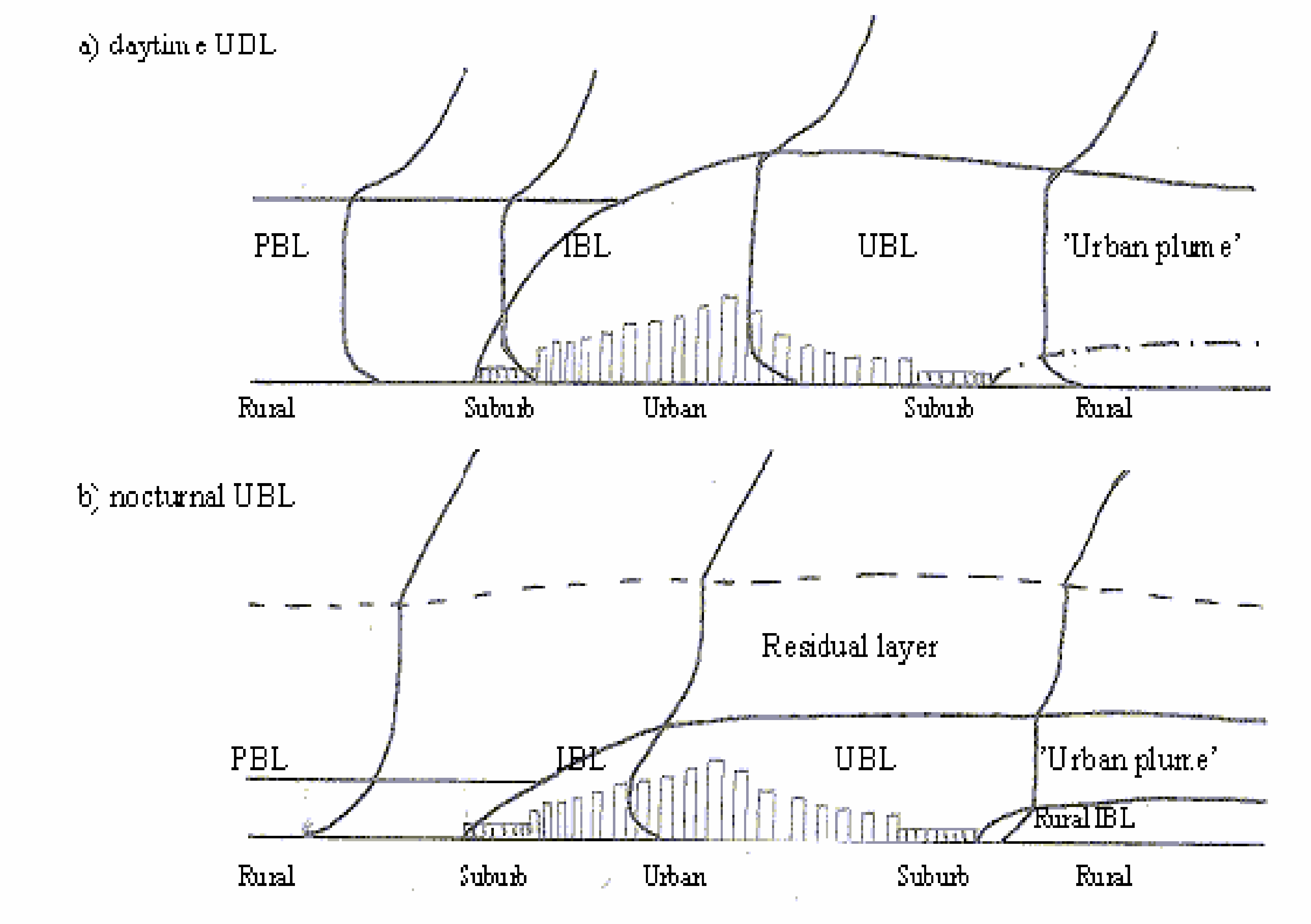


Schematic of mixed-layer evolution (Stull 2000).

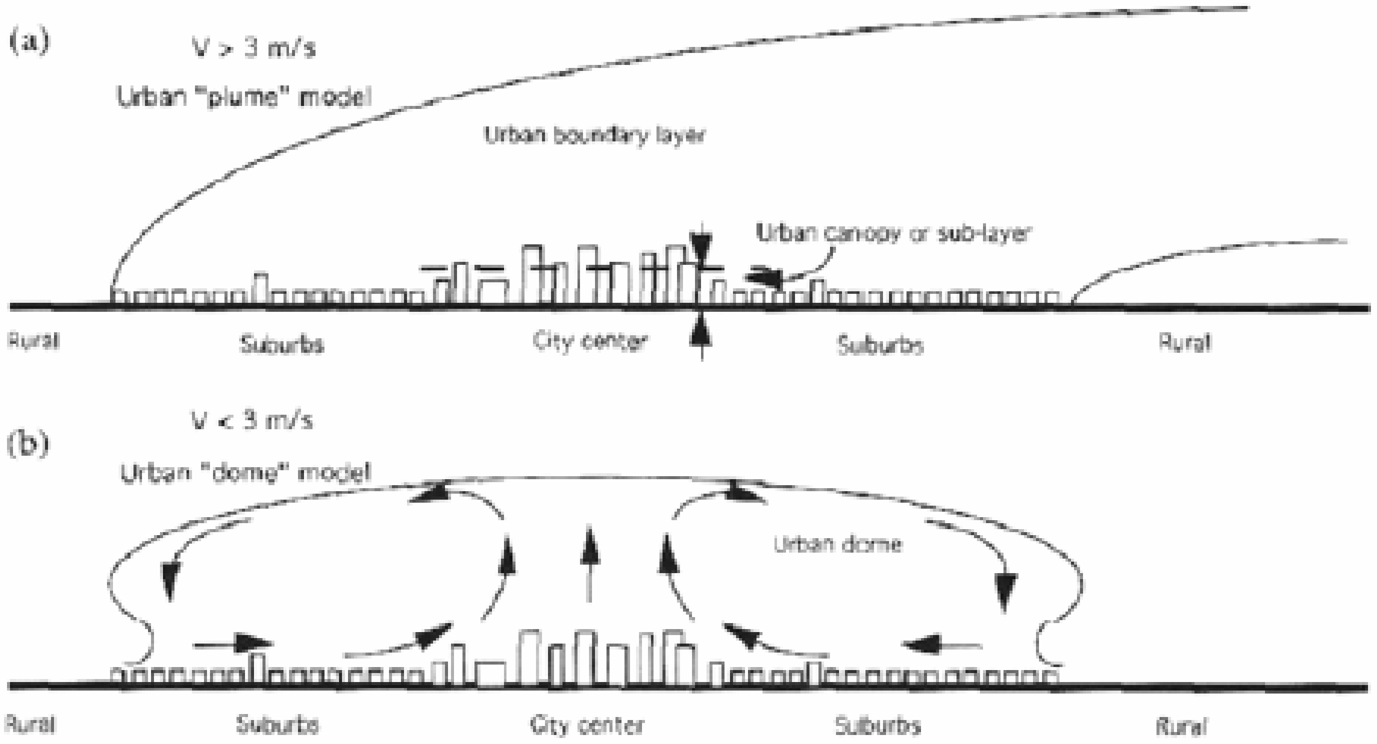
Diurnal evolution of urban BL

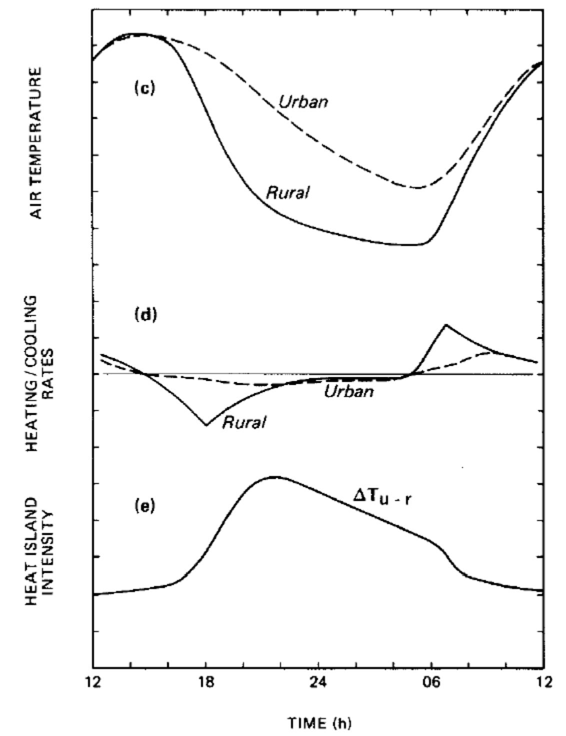
day

night



Urban heat island effect





Boundary layer characteristics

- Daytime:
  - Deep mixed layer from surface heating
  - Turbulent eddies on the scale of BL depth
  - Thermally driven flows can develop from spatial variations in surface heating
- Nighttime:
  - Surface inversion develops from radiational cooling
  - Mixed layer can persist above inversion
  - Turbulence can be intermittent and mix down faster and warmer air

Characteristics of urban surfaces

- Altered albedo – can be higher or lower
- Higher heat capacity
- Lower moisture flux to atmosphere
- Larger roughness elements
- Increased surface area
- Source of anthropogenic heat and emissions
- Impermeable to water
- Decreased net longwave raditaion loss

Part III: **Ways to resolve the UBL structure**

1. Obstacles-resolved numerical models
- CFD => turbulent closure, bc, geometry, etc.
- LES, …, DNS
- simple box models

2. Parameterization of sub-grid processes
- theoretical
- experimental
- numerical

3. Downscaling of models / Nesting techniques
- NWP-local-scale meteorological models
- Mesoscale models – CFD tools
- Mesoscale models – Parameterized models

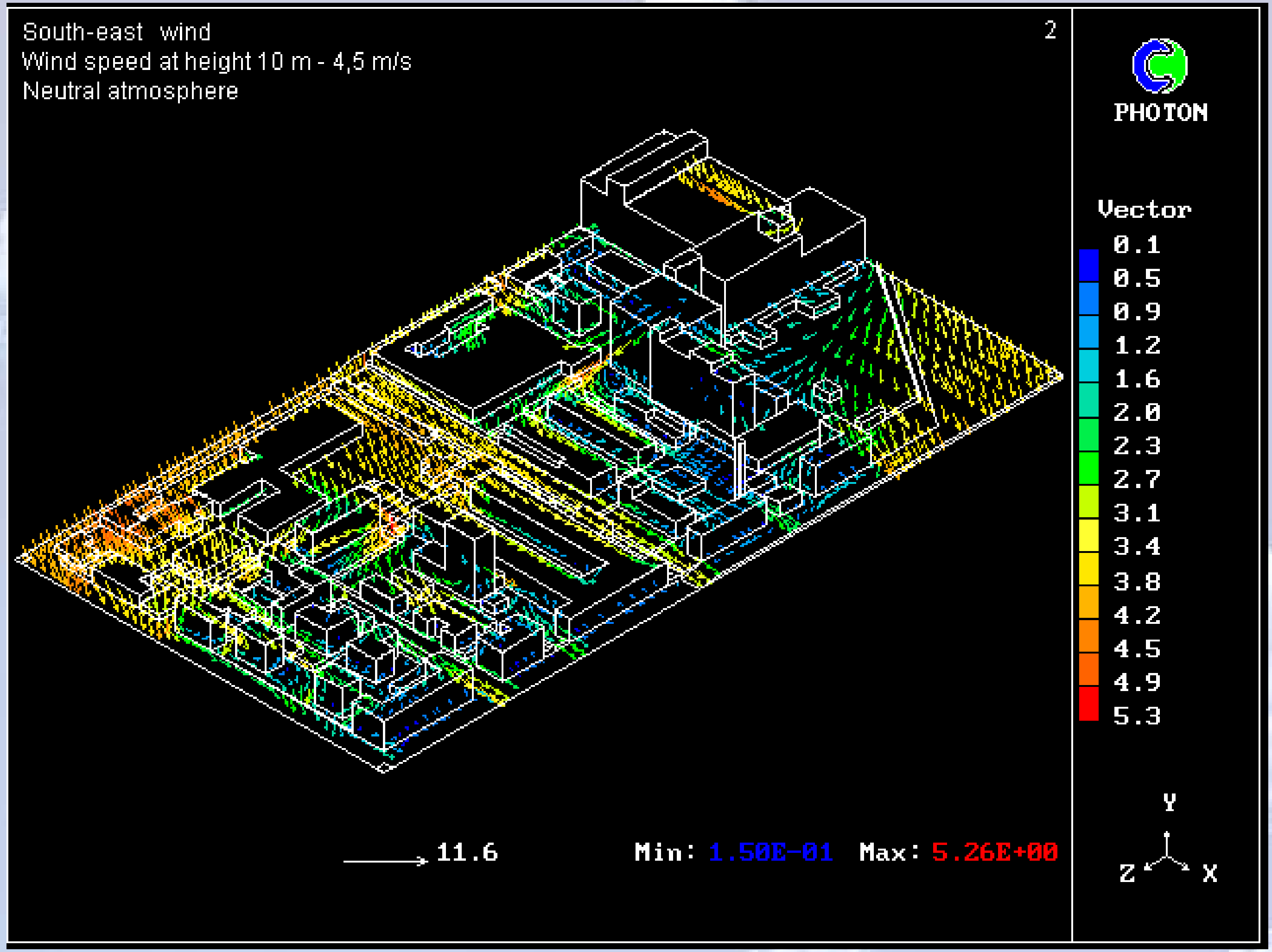
Key parameters for urban models of different scales (COST715)

Mesoscale models	Sub-meso scale models	Street canyon scale models
z_0, z_{0T}	$z_0(x)$, d(x)	
h_{UBL}	L_c, L_a, z_*	Detailed geometry
'Surface' fluxes (effective)	u_*^{IS}, H^{IS}, general: x_*^{IS}	$\bar{u}(h)$ second velocity scale for **horizontal** transport
Anthropogenic heat flux (non-surface) at some representative height	Dispersive fluxes	Heat exchange at vertical and horizontal building surfaces
Profiles of turbulent fluxes	Profiles of turbulent fluxes	Characteristic velocity variance in street canyon
Higher order moments?	Higher order moments (skewness, ...)	Higher order moments?
Synoptic forcing, average albedo	Mesoscale stability, albedo(x)	

One example of the first way (CFD)

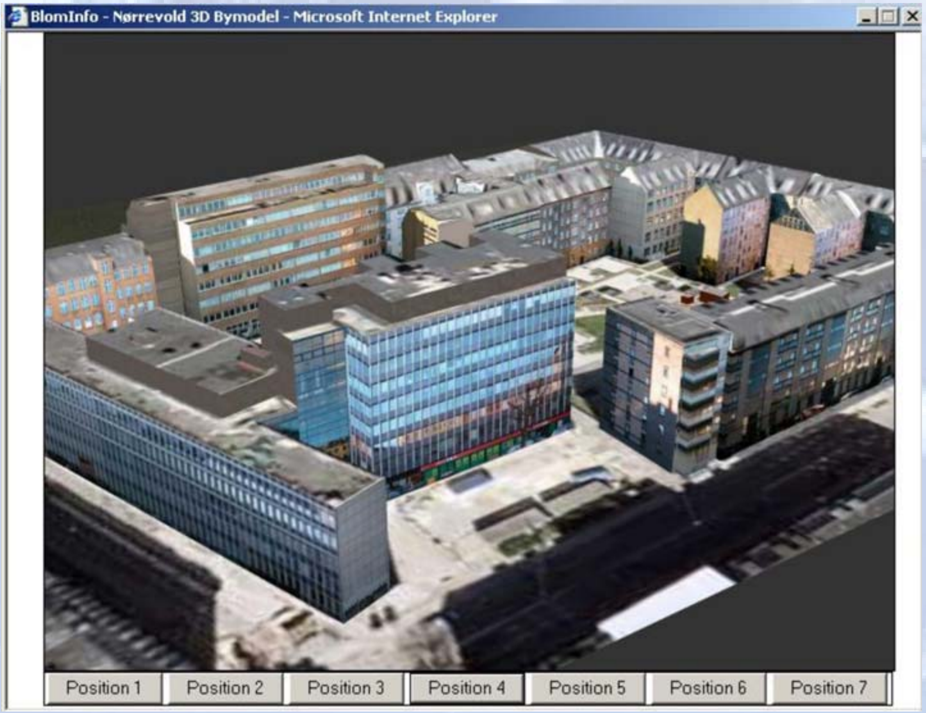
Scheme of the building complex and 6 m height horizontal wind field

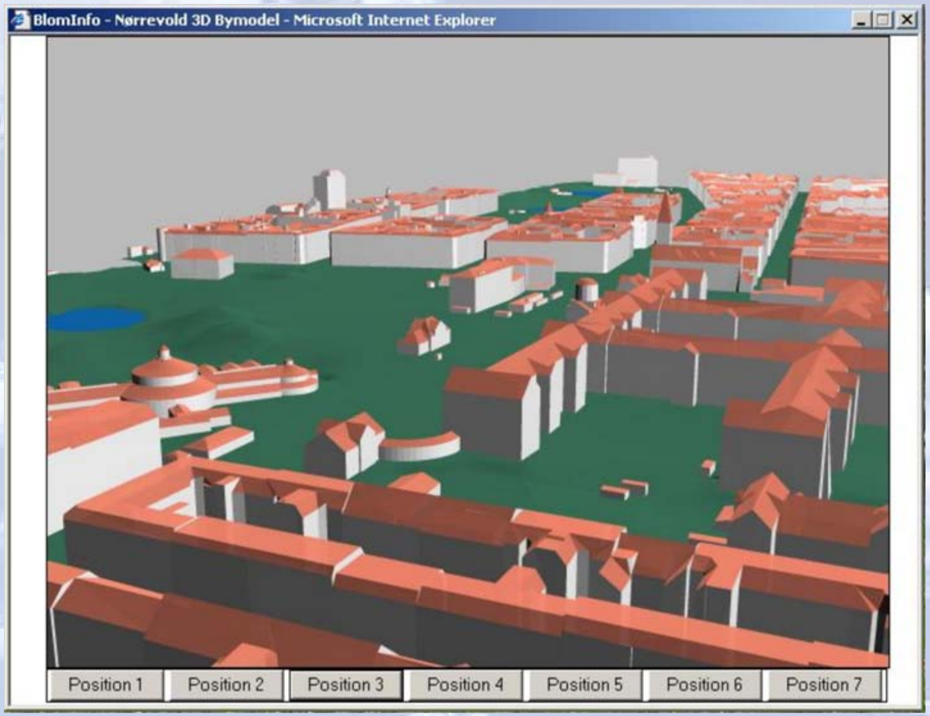
(after Mastryukov et al.)



High-resolution mapping of urban areas

- CORINE and PELCOM data up to 250 m resolution
- Land-use database with the resolution 25 x 25 meters (DMU)
- GIS databases of urban structure (BlomInfo A/S)





Urban effects in improved urban-scale meteorological and NWP models:

- Higher spatial grid resolution and model downscaling;
- Improved physiographic data and land-use classification;
- Calculation of effective urban roughness;
- Calculation of urban heat fluxes;
- Urban canopy and soil sub-models;
- Simulation of the internal boundary layers and mixing height in urban areas;
- Urban measurement assimilation in NWP models.

Modification of flow and turbulence structure in urban areas

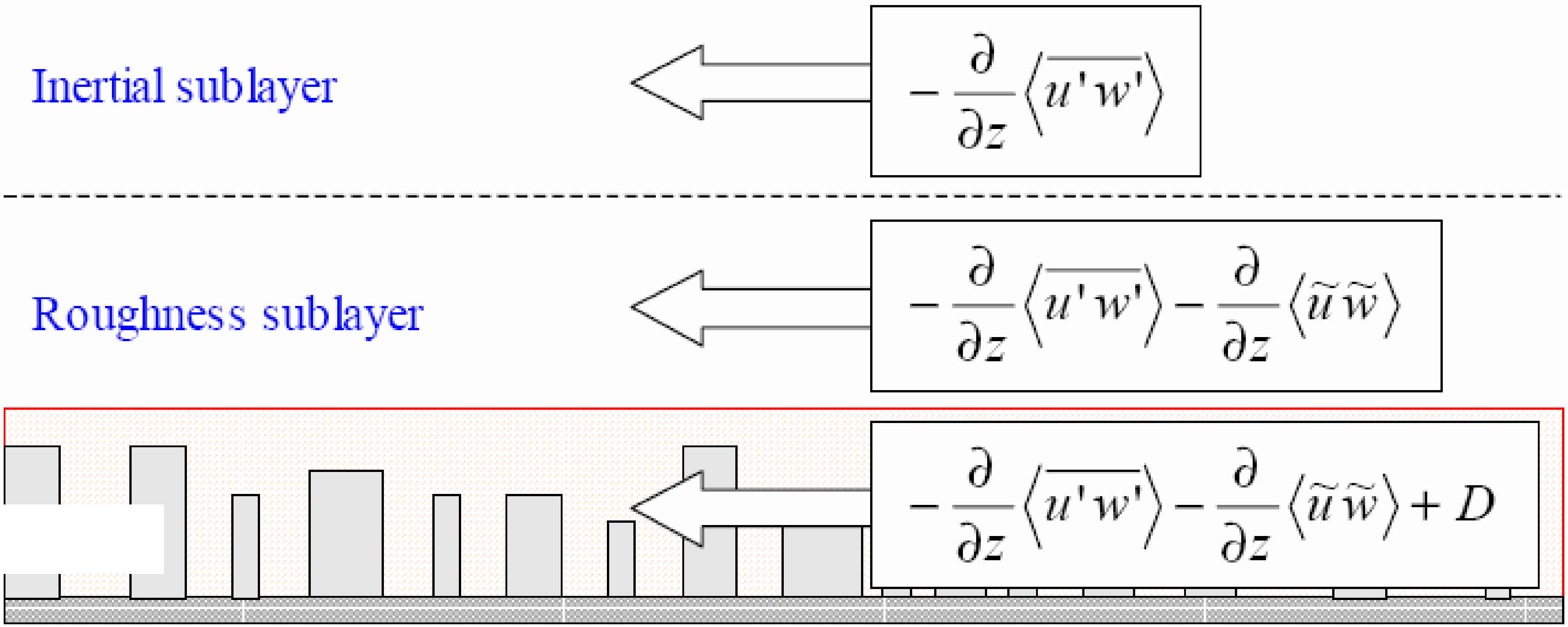


Figure 1 Schematic showing how the different components of the stress act in different layers.

(Belcher et al., 2000)

Momentum equations for urban canopy model

$$\rho\frac{DU}{Dt}=-\frac{\partial P}{\partial x}-\rho\frac{\partial}{\partial z}\left\langle\overline{u'w'}\right\rangle-\rho\left\langle\tilde{u}\tilde{w}\right\rangle-D\ .$$

Notice how three new terms appear on the right hand side as a result of the two averaging procedures. They are

$\rho\left\langle\overline{u'w'}\right\rangle \rightarrow$ Spatial average of the turbulent stress (Reynolds stress):

This term represents the transport of momentum by turbulent eddies and occurs in all turbulent flows

$\rho\left\langle\tilde{u}\tilde{w}\right\rangle \rightarrow$ Dispersive stress:

This term represents the transport of momentum by spatial fluctuations
Has been quantified for flow over hills and ocean waves (Belcher & Hunt 1998)

$D \rightarrow$ Distributed aerodynamic drag:

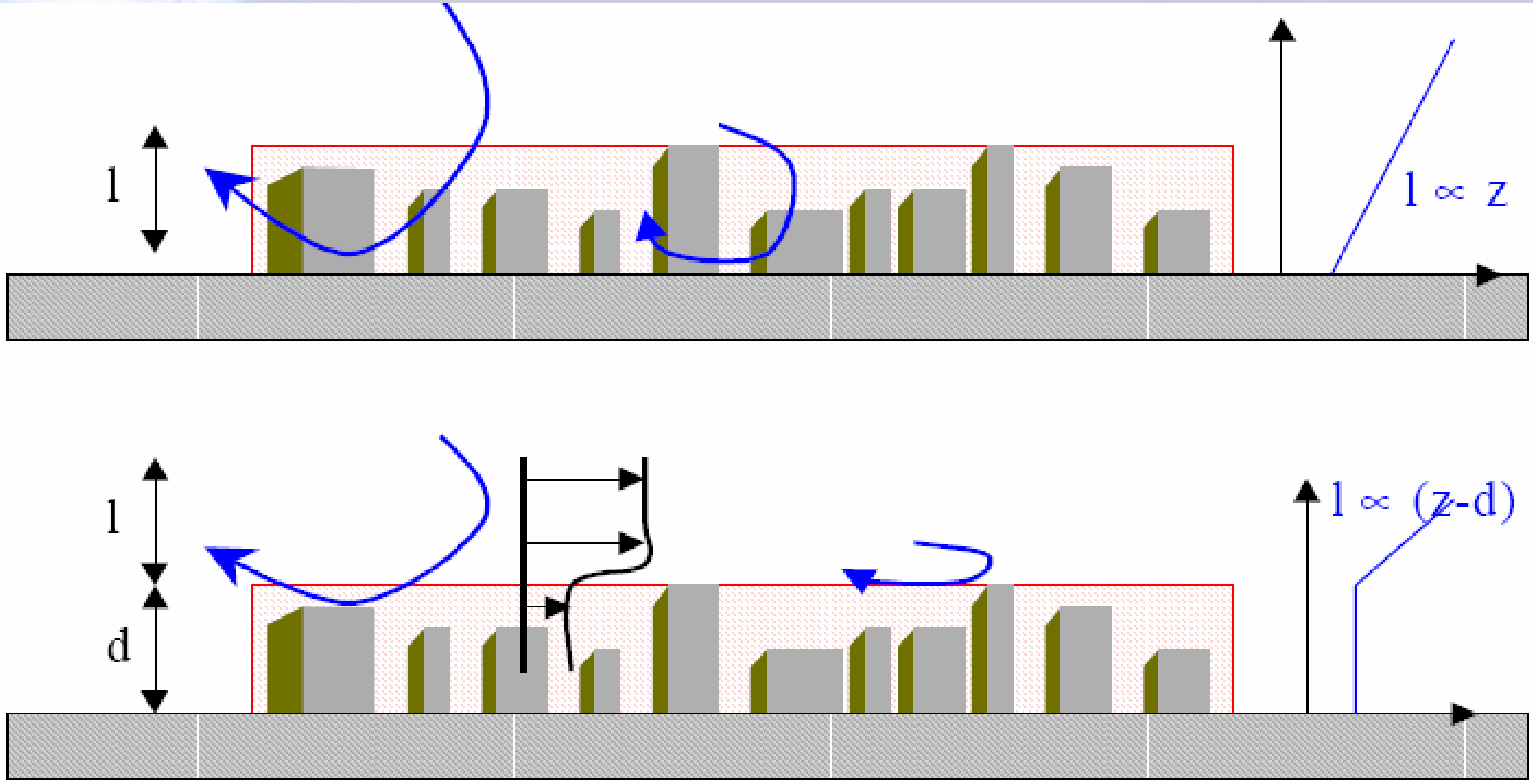
Represents the pressure and viscous forces exerted on roughness elements:
It has been studied in flow through vegetation canopies (Finnigan 2000)

Two approaches to parameterise the urban canopy effect:

1. Modifying the existing non-urban (e.g. MOST) approaches for urban areas by finding proper values for the effective roughness lengths, displacement height, and heat fluxes (adding the anthropogenic heat flux, heat storage capacity and albedo change). In this case, the lowest model level is close to the top of the urban canopy (displacement height), and a new analytical model is suggested for the Urban Roughness Sublayer which is a critical region where pollutants are emitted and where people live.

2. Alternatively, source and sink terms are added in the momentum, energy and turbulent kinetic energy equation to take into account the buildings. Different parameterizations (*Masson, 2000; Kusaka et al., 2001; Martilli et al., 2002*) had been developed to estimate the radiation balance (shading and trapping effect of the buildings), the heat, the momentum and the turbulent fluxes inside the urban canopy, taking into account a simple geometry of buildings and streets (3 surface types: roof, wall and road).

Displacement mixing lenght model for UBL



Schematics showing eddies represented by (a) the standard mixing length model and (b) the displaced mixing length model. (Belcher et al., 2000)

$$U_h(z_s) = \frac{u_{*s}}{\kappa} \cdot \ln\left(\frac{z_s - z_d}{z_o} - \psi_m(z_s / L)\right)$$

Roughness sublayer and Displacement heights

- **Roughness sublayer height:**

Zs = 2Zh to 5Zh for forest canopies

Zs = 2Zb for urban canopies

Max Reynolds stress: 1.5Zb < Z > 2.5Zb (COST715, 2000)

Depends on the building density.

- **Displacement height:**

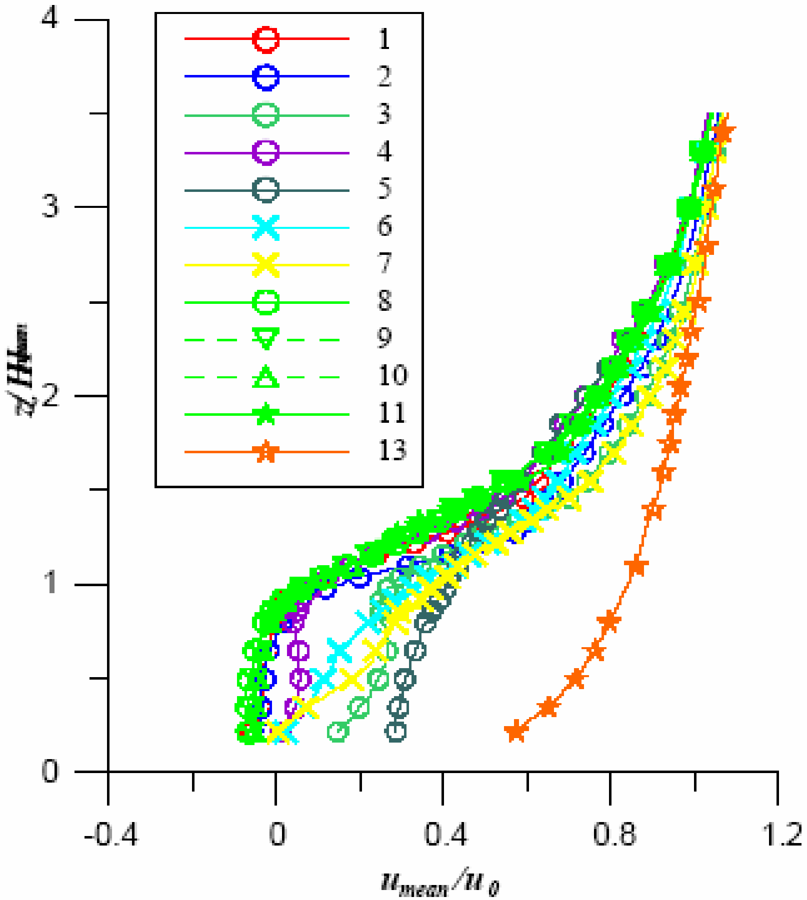
d = 0.7 Zb for 0.3 < λp < 0.5; 0.1 < λf < 0 (Grimmond & Oke, 1999)

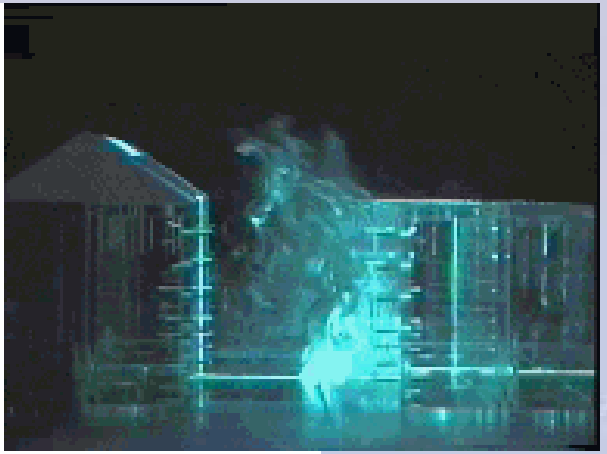
d = h*λp^0.29 for low building density λp < 0.29 (Kutzbach, 1961)

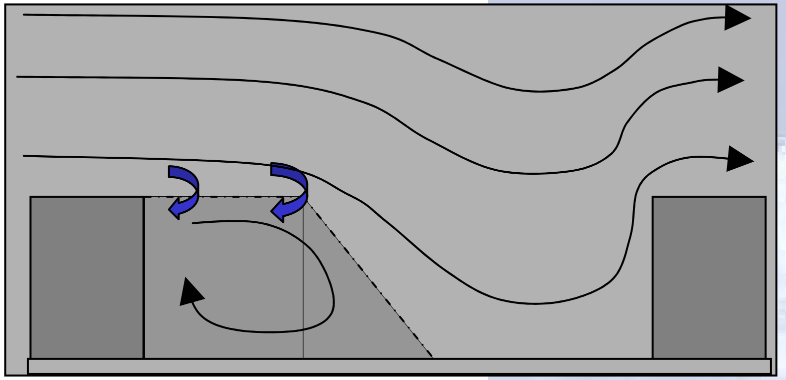
where: λp = Ap/At; λf = Ap/At.

Stratification effect on d (Zilitinkevich et al., 2004)

Wind tunnel data for urban canopy

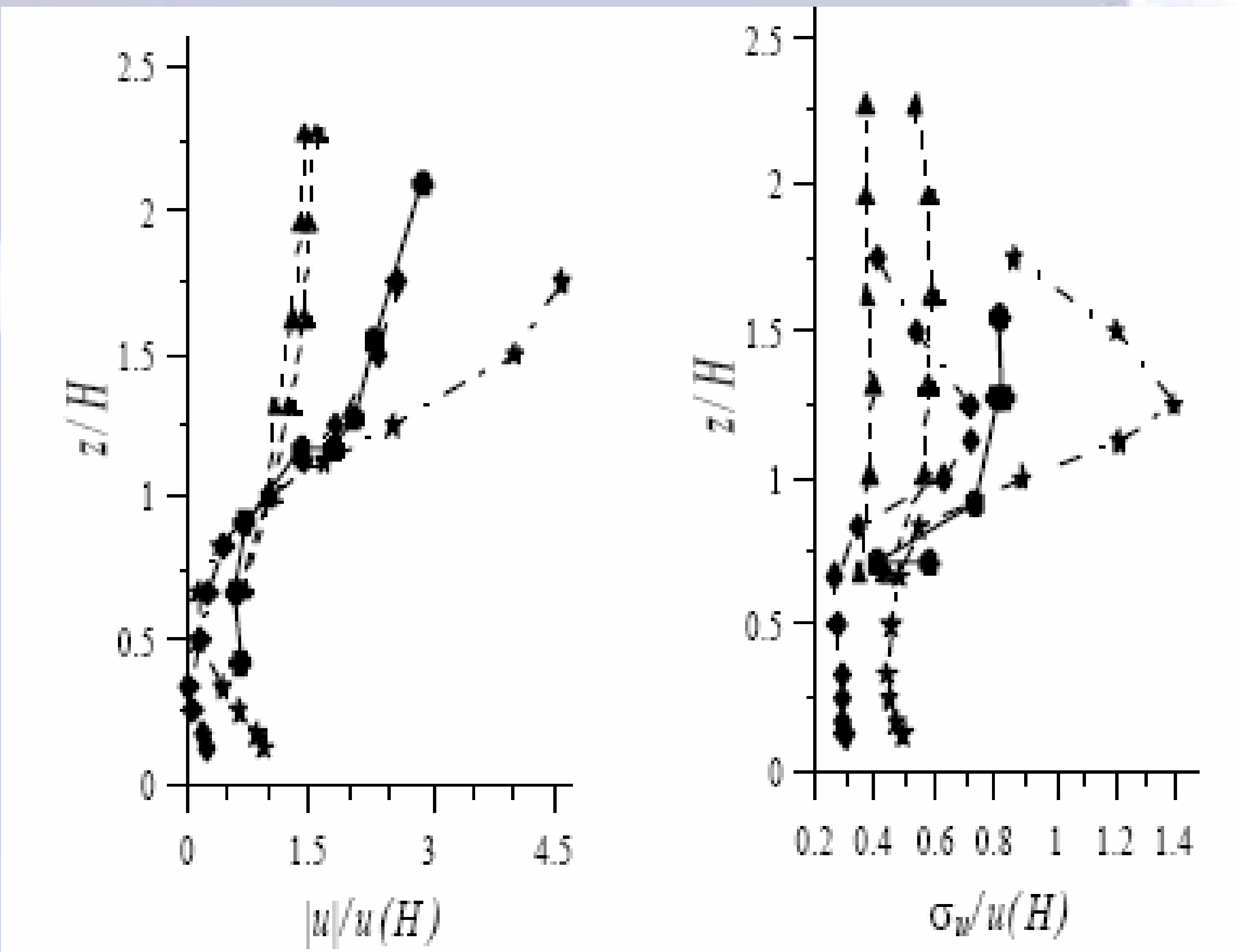






Profiles of scaled mean wind speed at various sites over an urban surface. Data from a wind tunnel study (Kastner-Klein et al., 2000) under neutral stability. The numbers in the inlet refer to different positions, profile 13 is the approaching flow.

Flow and Turbulence in and above Urban Street Canyons



Wind-tunnel data (* - 120cm-long and ◊ - 60cm-long canyon);

Full-scale urban data (●);

Full-scale isolated canyon (▲, Δ)

Rotach et al., 2003

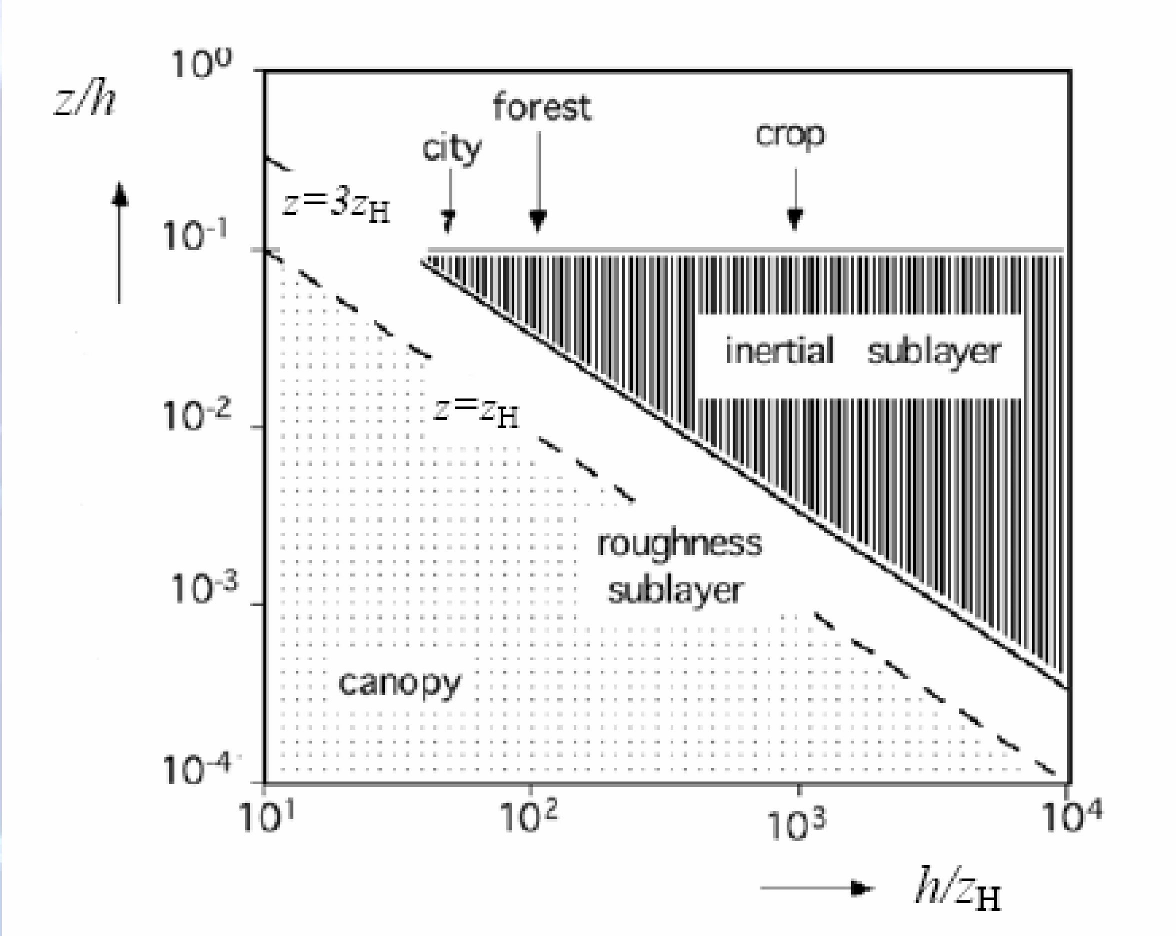


Fig. 2.2 Sketch of the vertical extension of the various layers over rough surfaces and their variation with the non-dimensional quantities z/h and h/z_H, where h denotes the boundary layer height and z_H stands for the canopy height. The height of the roughness sublayer z^* is assumed to equal $3z_H$. The arrows 'city', 'forest' and 'crop', are drawn using h = 1000m together with z_H = 20 m (city), z_H = 10m (forest) and z_H = 1m (crop), respectively. From Rotach (1999).

Review: theories relating to urban wind profiles (WG1 COS715)

Roughness sublayer (RS):

• *profile* of Reynolds stress & local scaling within RS => wind profile

• no theory, but good results; parameterisation exists for Reynolds stress profile (to be extended to more data sets)

• Required: friction velocity of inertial sublayer (IS), ; z_* and d

• Stability effects: (profile of sensible heat flux? => WG2)

Review: theories relating to urban wind profiles (WG1 COS715)

Urban canopy layer (as a part of RS)

• Little variation within canopy [height and position]
• Sharp transition from canopy to above roof region
• Similar to plant canopies:

$$\frac{\bar{u}(z)}{\bar{u}(h)} = \exp\{-\,a_e(1-z/h)\}$$

$$a_e = ?$$

• Theory (Raupach et al., 1996; Hunt et al., 2004; Zilitinkevich et al., 2005)
• Possible approach: match the canopy and the RS profiles for 0<z<z*
• Alternative: sinh formulation (instead of exp): Gayev (2004)

Review: theories relating to urban wind profiles (WG1 COS715)

UBL

• Urban mixed layer: ‘normal‘ BL scaling regimes and approaches? (e.g. Sorbjan, 1986). Any evidence for this?; effects of sea/topography?

• Urban stable boundary Layer: see above: UML; data?

rural - urban transition:

(e.g. information (data) from an airport sampling station, but required knowledge in the city centre)

• required parameters: scaling velocity / temperature ‘urban‘ and rural. Which level? (see above: RS)

• theory? (e.g. ; Bottema, 1995)

• Model for ‘surface‘ heat flux: based on Oke’s data, empirical

• Alternative: approach for heat flux (based on the notion that this quantity is very much like over rural surfaces even for urban surfaces, see Rotach, 1994)

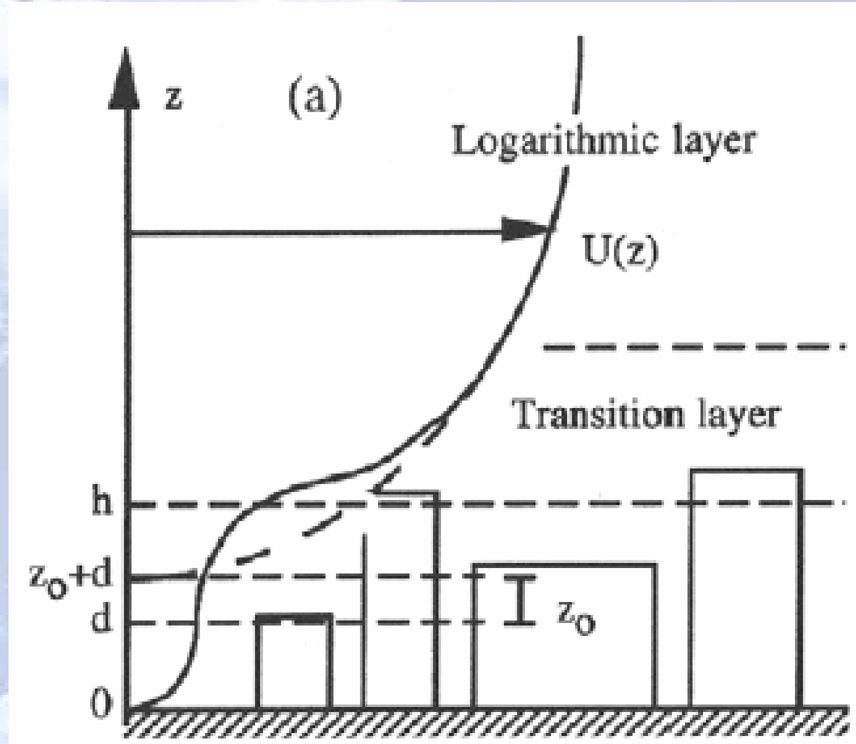
spatial inhomogeneity: city ‘regions‘

• internal BL growth [thermal – mechanical]: growth rate ‘as usual‘? => test on Barcelona data

• city regions (down town, city, residential....): back to IBL?

1: Analytical urban parameterisations

i. Land-use classification, including evaluation of the urban class contribution and several urban sub-classes (such as: city center, industrial commercial districts, residential districts, etc.),
ii. Displacement height for the urban and forest canopies,
iii. Effective roughness and flux aggregation to the model grid,
iv. Effects of stratification on the roughness,
v. Different roughness lengths for momentum, heat, and moisture,
vi. Anthropogenic and storage urban heat fluxes for NWP models;
vii. Prognostic MH parameterisations;
viii. Parameterisation of wind and eddy profiles within the canopy layer.



The effect of stratification of the surface resistance over very rough surfaces

S. Zilitinkevich et al. (2003)

The roughness length depends on the atmospheric temperature stratification.

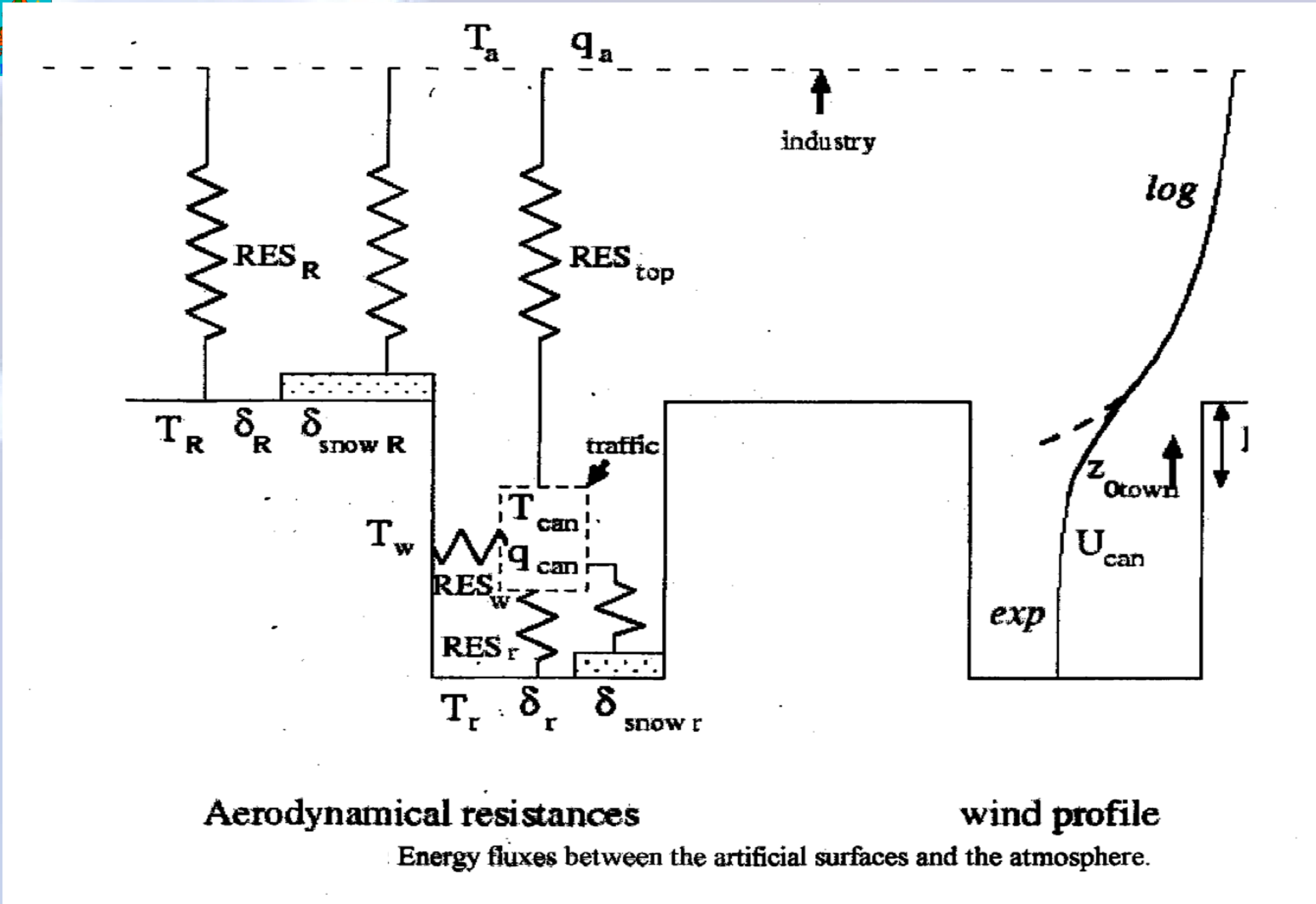
New parameterisations for the effect of stratification on the surface resistance over very rough surfaces are suggested:

- **Stable stratification:**

$$\frac{1}{z_{0u-effective}} = \frac{1}{z_{0u}} + \frac{C_{0S}}{L} + \frac{C_{0\nu} u_*}{\nu}, \text{ which yields } z_{0u-effective} = \frac{z_{0u}}{1 + C_{0S} z_{0u} / L + C_{0\nu} z_{0u} u_* / \nu},$$

- **Unstable stratification:**

$$\frac{z_{0u-effective}}{z_{0u}} = \left[1 + (C_1 - 1)\exp(-C_2 z_{0u} / |L|\right], \text{ or } \frac{z_{0u-effective}}{z_{0u}} = \left[\frac{1}{1 + z_{0u} / |L|} + C_1 \frac{z_{0u} / |L|}{C_2 + z_{0u} / |L|}\right]$$



From Masson (2000)

A simple model of turbulent mixing and wind profile within urban canopy

S. Zilitinkevich and A. Baklanov (2004)

the vertical profiles of the velocity:

$$u = \frac{2}{3C_M}\frac{u_*}{1-\delta}\left\{\left[\delta + (1-\delta)\frac{z}{h_0}\right]^{3/2} - \delta^{3/2}\right\} \quad \text{where} \quad \delta \equiv \frac{\tau_0}{u_*^2}$$

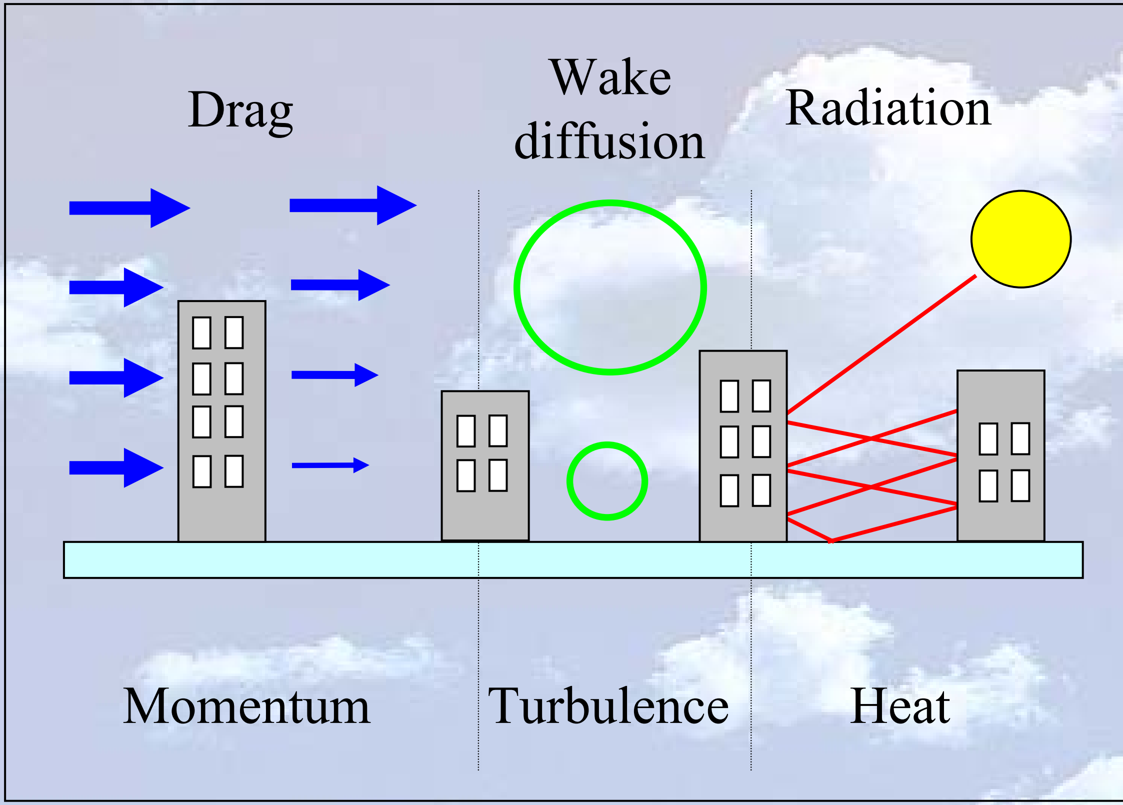
the vertical eddy diffusivity:

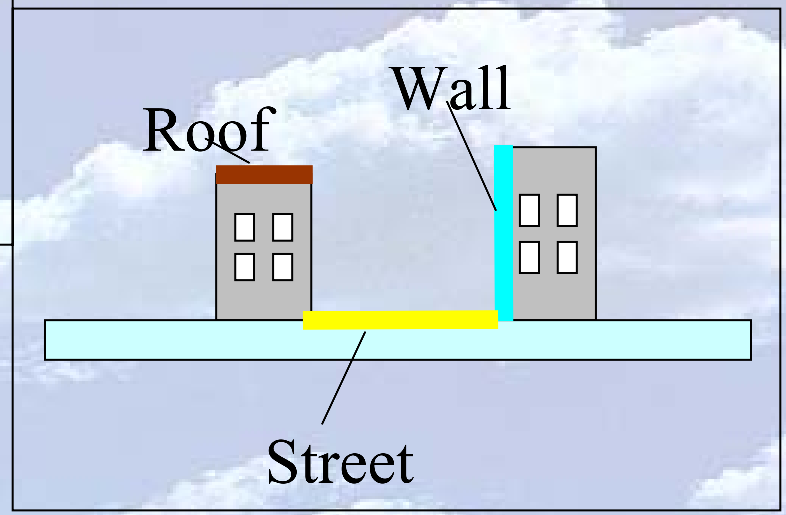
$$K_D = C_D h_0 u_* \left[\delta + (1-\delta)\frac{z}{h_0}\right]^{1/2}$$

the horizontal diffusivity:

$$K_{DX} = C_{DX} X_0 u_* \left[\delta + (1-\delta)\frac{z}{h_0}\right]^{1/2}$$

2 (BEP model): Urban effects in the Martilli et al. (2002) parameterization:





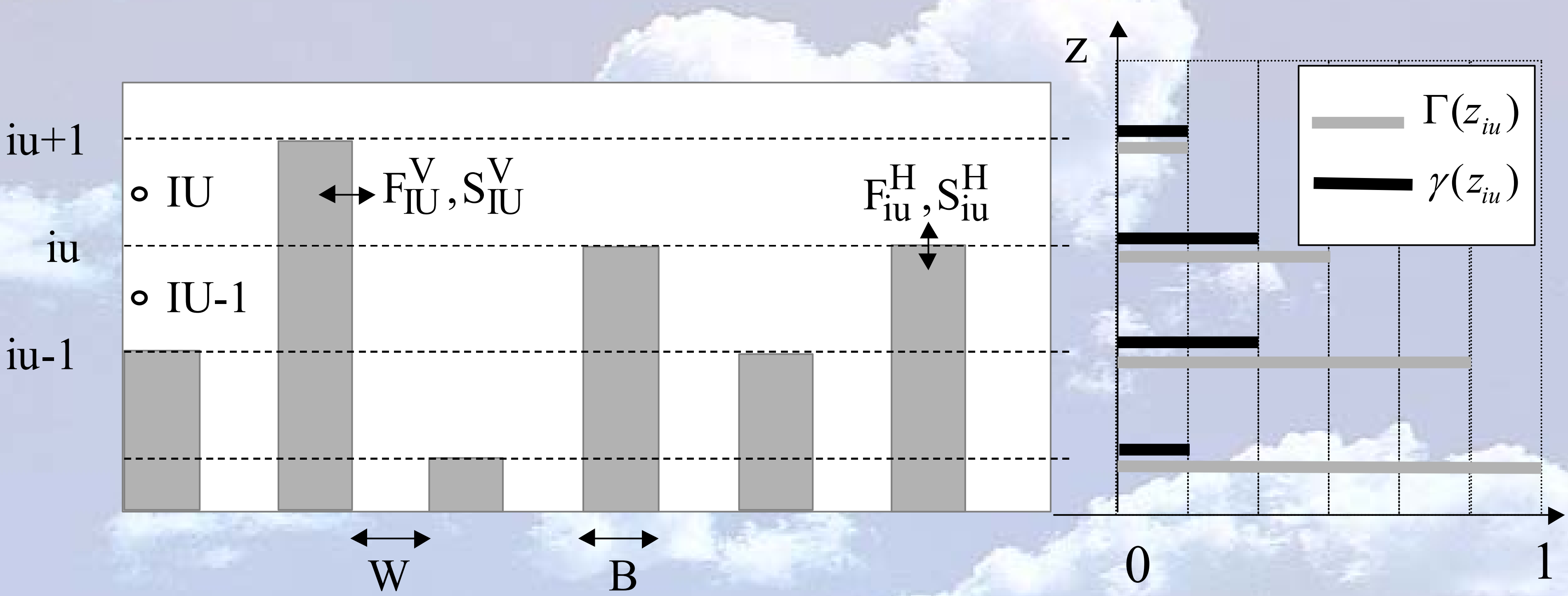
BEP Model: parameterization of Martilli et al. (2002)

$$\frac{\partial \rho N}{\partial t} + \frac{\partial U_i \rho N}{\partial x_i} = \frac{\partial F_i}{\partial x_i} + S + \boxed{\mathbf{F_{bc}}}$$

Horizontal surfaces Street and Roof	u_*^2	$u_* \theta_*$	MOST (Louis formulation)
Vertical surfaces Wall	$\rho C_{drag} U^2$	$\frac{\eta}{C_p}(\theta_{air} - \theta_{wall})$	
	Momentum	**Heat**	

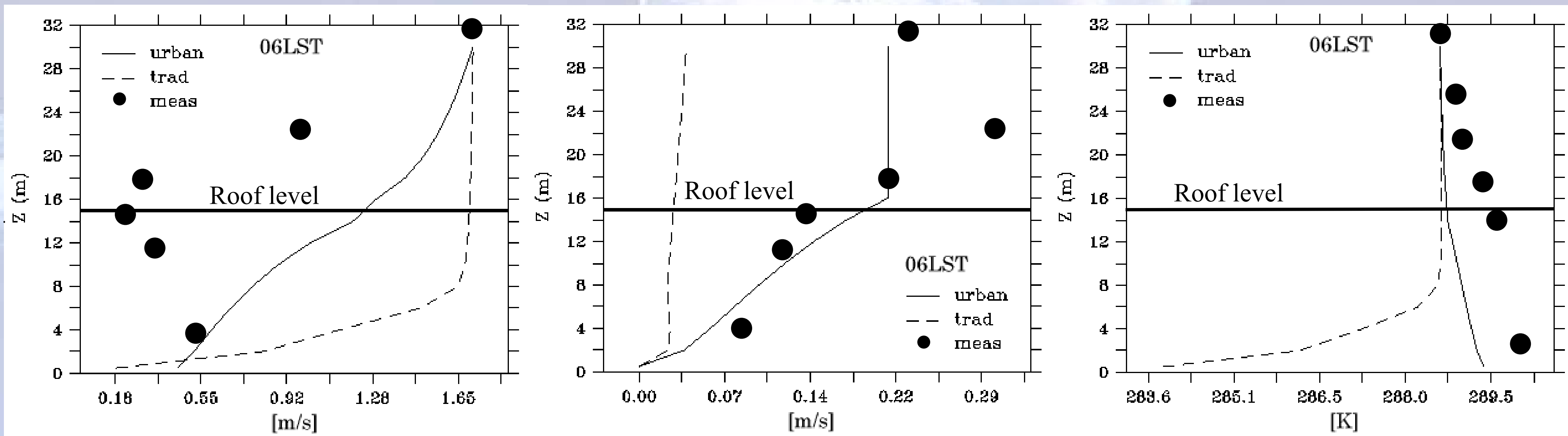
Improvement of the BEP model by Hamdi and Schayes (2004)

Schematic representation of the numerical grid in the urban module



Where *W* is street width, *B* is buildings width, *iu* are the face and *IU* centre of the urban model levels, $\gamma(z_{iu})$ density of building of height z_{iu} and $\Gamma(z_{iu})$ density of buildings higher than z_{iu}.

Verification of the BEP model versus the BUBBLE experiment



Vertical profiles of wind velocity (left), friction velocity (middle), and potential temperature (right) measured (points), simulated with MOST (dashed line) and with the urban parameterization of *Martilli et al. (2002)* (solid line).

Part IV: **Energy budget in urban areas**

- The **radiation budget** does not differ significantly for urban and rural surfaces, as the increased loss of net thermal longwave radiation is partly compensated by a gain in net shortwave radiation due to a lower albedo.
- The **turbulent fluxes of sensible and latent heat**, as well as their ratio ($\beta = H/L_vE$, the Bowen ratio) are variable, depending in particular on the amount of rainfall that fell during the preceding period. However, the impermeability of urban surfaces generally reduces the availability of soil moisture for evaporation after a few rainless days, generally leading to high values of the Bowen ratio.
- The **storage heat flux** usually is significantly higher in urban areas compared to densely vegetated surfaces. This cannot be explained entirely by a higher thermal inertia, as this quantity is only slightly higher for urban as compared to rural environments. Other factors of importance are the low moisture availability and the extremely low roughness length for heat fluxes. OHM model (Grimmond et al., 1991).
- The **anthropogenic heat flux** is a most typical urban energy component as it is absent over rural or natural surfaces.

Energy budget and additional sources of energy need to be considered for cities

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow = Q_H + LvE + Q_G + Q_F$$

the fluxes of heat due to combustion of fuels (Q_F) by:

- the traffic, at ground level,
- the domestic heating, through wall heat transfers and direct release from chimneys,
- the similar heat releases by small dispersed industries,
- elevated point sources of warm discharges (high stacks).

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow = Q_H + Q_E + \Delta Q_S$$

Variability in Morphology

Implications, across & between cities, for:

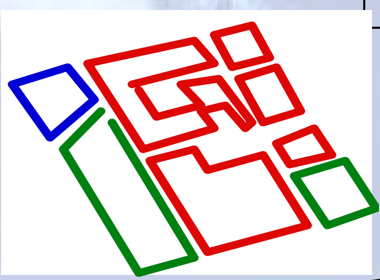
- **Wind flow**
- **Dispersion**
- **Flux partitioning**
- **BL height**
- **Air quality**
- **Surface runoff**
- **Solar access**
- **Radiative cooling**

Grimmond & Oke, 1999; *JAM*

Urban Fabric Classification – Method

Database: BD Topo (IGN):

- Building altitudes
- Building surfaces
- Road surfaces
- Vegetation surfaces
- Hydrographic surfaces



DFMap software

Morphology parameters:

- Average height
- Volume
- Perimeter
- Compactness
- Space between buildings

Cover Modes:

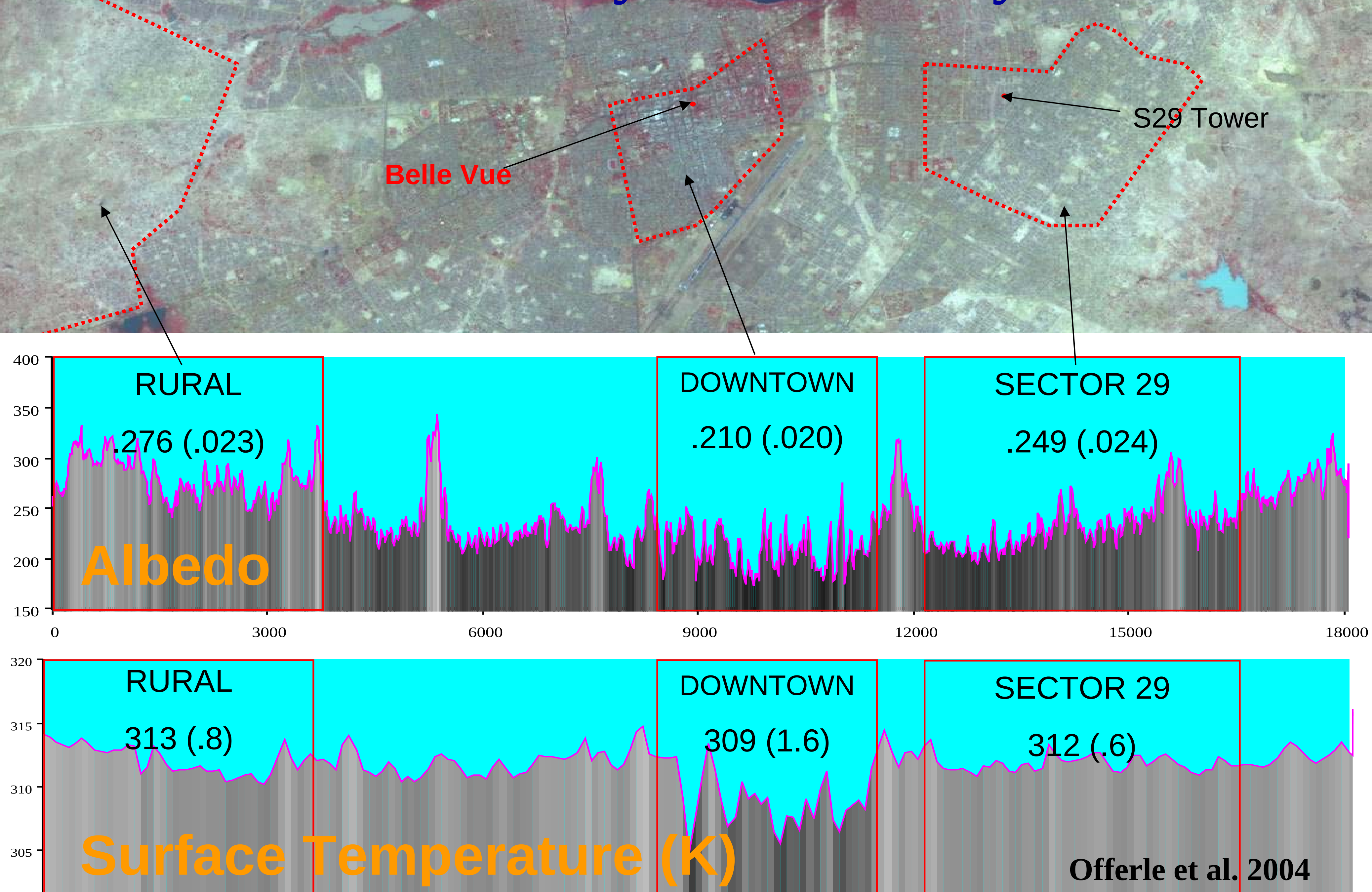
- Surface density (SD) of buildings
- SD of vegetation
- SD of hydrography
- SD of roads
- Number of buildings

Aerodynamic parameters:

- Roughness length
- Displacement height
- Frontal & lateral SD

GIS

Variability Across a City



Ranges of average daily maximum values of net radiation and fluxes in North American cities

(after Grimmond and Oke, in COST-715, 2001)

Parameter	Range (W m^{-2})
Net all-wave radiation Q*	**< 400 - 650**
Latent heat flux LE	**10 - 235**
Sensible heat flux H	**120 - 310**
Storage heat flux G	**150 - 280**
Average daytime Bowen ratios H/LE:	**(Dimensionless)**
Residential sites	**1.2 - 2**
During irrigation ban Vancouver	**~ 2.8**
Light industrial site	**~ 4.4**
Downtown	**~ 9.8**

Roughness for momentum, heat, and moisture

The roughnesses are different for urban areas, but they are considered as equal in NWP models.

Several possible parameterisations for the scalar roughness length for urban areas can be recommended to improve urban-scale NWP models:

1) *Brutsaert (1982)* and *Brutsaert and Sugita (1996)*:

$$z_{0t} = z_0 \left[7.4 \exp(-2.46 \,\mathrm{Re}_*^{0.25}) \right],$$

2) *Hasager et al. (2002)*: $z_{0t} = \dfrac{z_0}{\exp\left(23.1\sqrt{u_*}\right)}$.

They need to be verified and improved.

The objective hysteresis model (OHM)

Grimmond *et al*., 1991; Grimmond and Oke, 1999

$$\Delta Q_S = \sum_{i=1}^{n} (\lambda_i \alpha_{1i})\, Q^* + \sum_{i=1}^{n} (\lambda_i \alpha_{2i})\, \partial Q^*/\partial t + \sum_{i=1}^{n} (\lambda_i \alpha_{3i})$$

where *Q** is the net all-wave radiation, λi are the plan fractions of each surface type in the area of interest and the $\alpha 1$- α 3i are the corresponding empirical coefficients. These α coefficients have been deduced from a re-analysis of the Multi-city Urban Hydrometeorological Database (MUHD)

Urban anthropogenic heat flux

Average Annual Anthropogenic Heat Flux Densities (Q_P) Of Urban Areas [1]

Urban Area	Year	Population Density (persons $km^{-2} \times 10^3$)	Per Capita Energy Use ($GJ\ y^{-1}$)	Q_P ($W\ m^{-2}$)	Q_N ($W\ m^{-2}$)	Q_P/Q_N
Manhattan (40°N)	1965	29.8	169	159	93	1.71
Moscow (56°N)	1970	7.3	530	127	42	3.02
Montreal (45°N)	1961	14.1	221	99	52	1.90
Budapest (47°N)	1970	11.5	118	43	46	0.93
Hong Kong (22°N)	1971	37.2	28	33	~110	0.30
Osaka (35°N)	1970-74	14.6	55	26		
Los Angeles (34°N)	1965-70	2.0	331	21	108	0.19
West Berlin (52°N)	1967	9.8	67	21	57	0.37
Vancouver (49°N)	1970	5.4	112	19	57	0.33
Sheffield (53°N)	1952	10.4	58	19	56	0.34
Fairbanks (64°N)	1967-75	0.55	314	6	18	0.33

Sources: Bowling and Benson (1978); Kalma and Newcombe (1976); Ojima and Moriyama (1982); Oke (1978b); SMIC (1971).

[1] All data relate to areas within the urbanized limits of the cities, not their surrounding territories.

Urban anthropogenic heat flux calculation

based on an assumption of dependency/proportionality to other urban characteristics, e.g.:

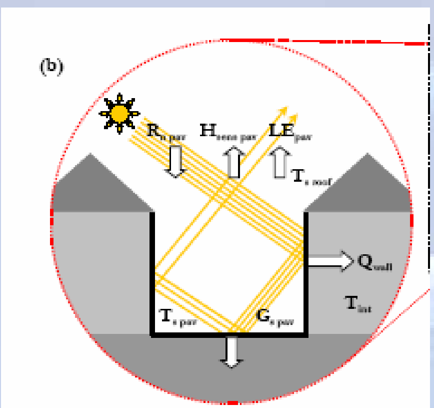
1. Population density maps with a high resolution in urban areas.
2. Satellite images of the night lightness over urban areas. Difficulties to use for industrial and developing countries (should be corrected).
3. Land-use classification as a percentage of urban classes (central part, urban, sub-urban, industrial, etc.)
4. Emission inventory for specific pollutants, which are typical for urban areas (e.g., due to traffic emission: NOx, …).
5. Monitoring or simulation fields of air pollution concentration for the specific pollutants, which are typical for urban areas (see above #4).

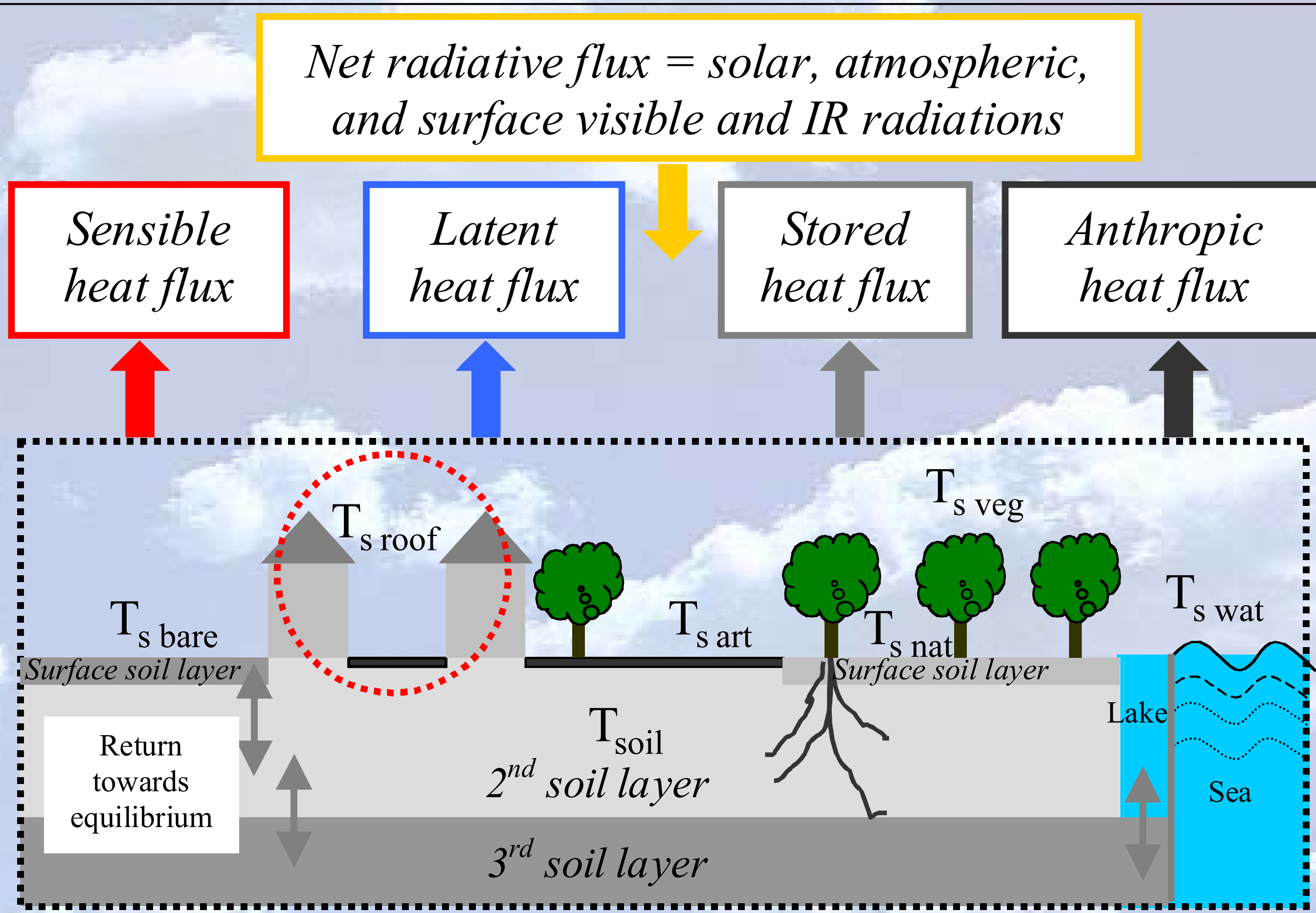
Reference values 20-80 W/m2

Module 3: SM2-U model (Mestayer et al., 2003; Dupont et al., 2005)

Within each cell SM2-U computes the energy budget of each of the 5 cover modes according to their coverage percentage, balancing the net radiation with the heat fluxes, accounting for the transfers to soil layers. The buildings/roofs cover mode receives a special modeling for canopy. The model output is the cell-averaged temperature (plus the heat fluxes).

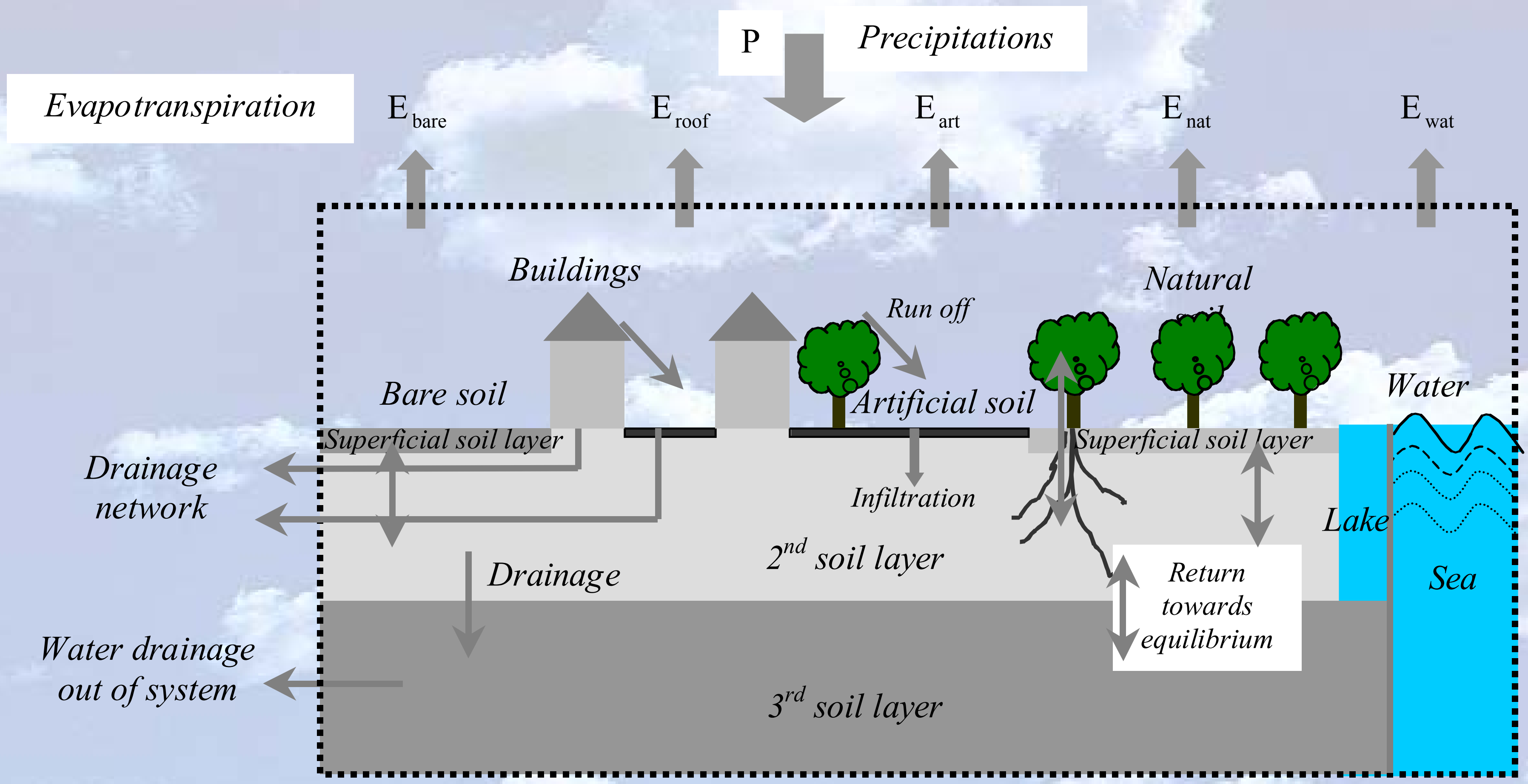
SMU2-U Energy Budget





SM2-U WATER BUDGET

Within each cell SM2-U computes the water budget of each of the 5 cover modes according to their coverage percentage, balancing precipitation with surface evaporation and vegetation transpiration, accounting for the water transfers between the surfaces and the soil.
The model output is the cell-averaged specific humidity (plus vapour and drainage fluxes)



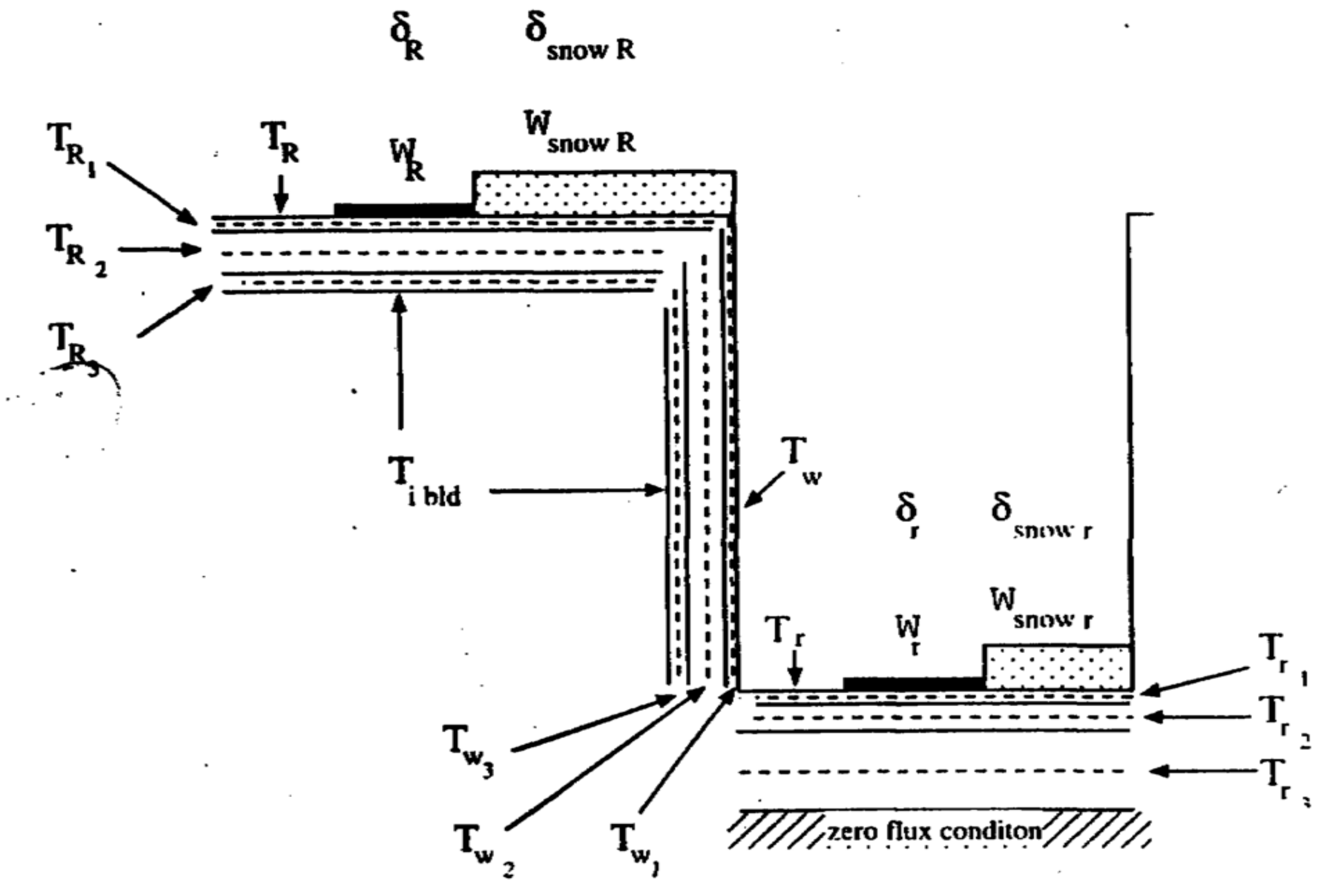
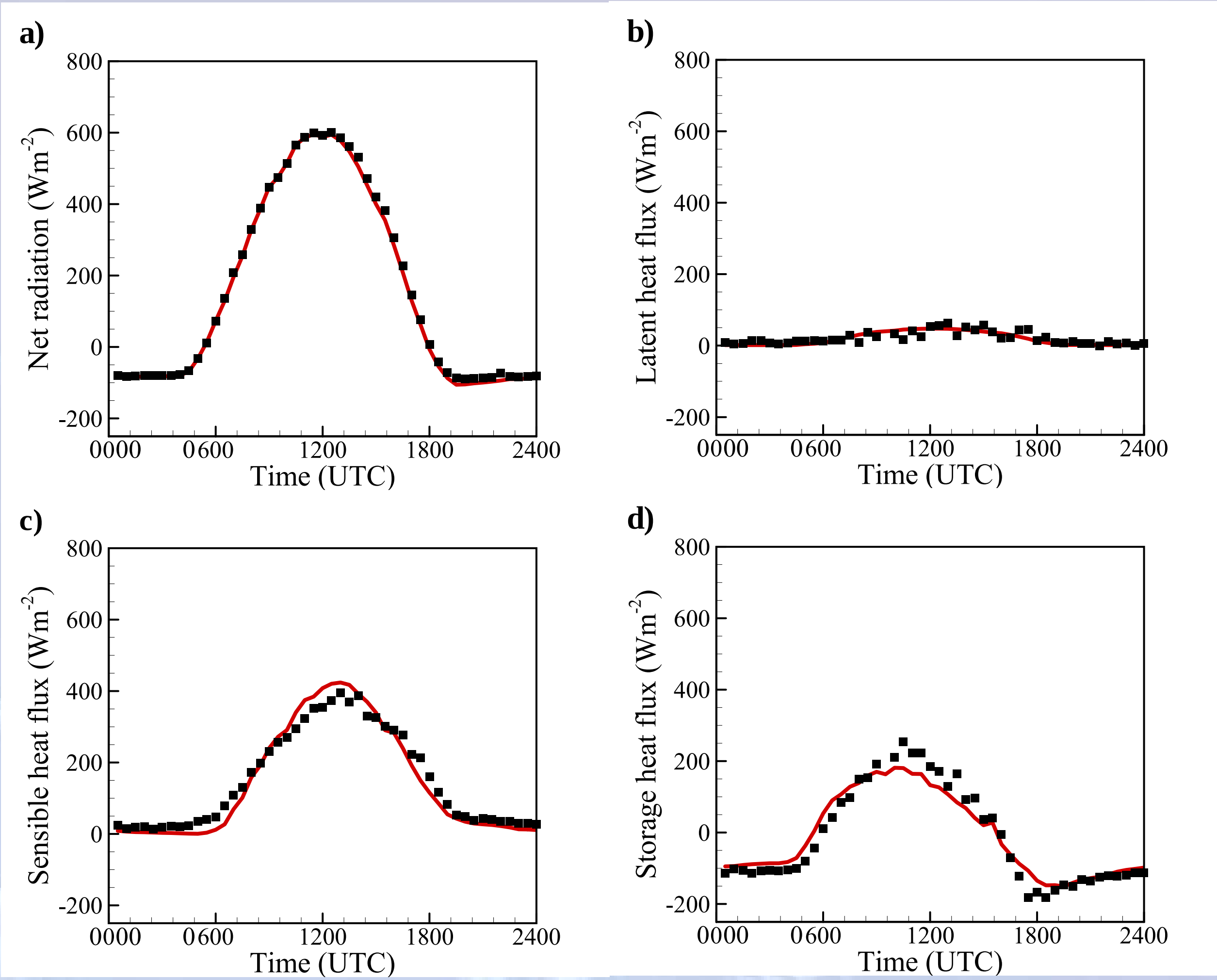


Figure 1. Discretization of the surfaces (roof, wall, road) and prognostic variables: layer temperatures $T_{\star_k}$ ($\star = R, w, r$; here three layers are displayed for each surface, so $k = 1, 2, 3$), surface water content $W_\star$ ($\star = R, r$), surface snow content $W_{snow_\star}$ ($\star = R, r$). The layer temperatures are representative of the middle of each layer (dotted lines). The surface temperatures are assumed to be equal to the surface-layer temperature: $T_\star = T_{\star_1}$. The internal building temperature $T_{i_{bld}}$ is prescribed. Fractions of water or snow ($\delta_\star$ and $\delta_{snow_\star}$ respectively) are computed from the water and snow contents (see text). Snow density, albedo and temperature are computed independently for roof and road by a snow mantel scheme (in this paper, a one-layer scheme was chosen).

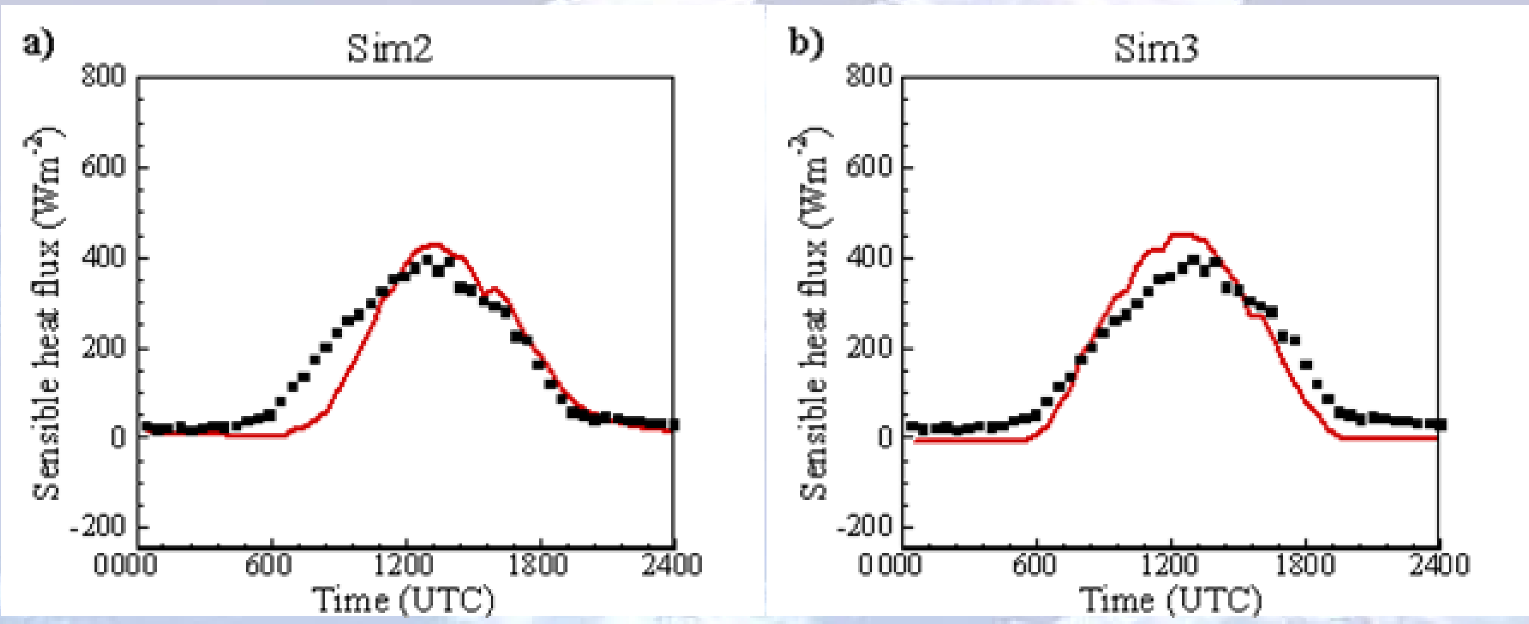
From Masson (2000)

Verification of SM2-U versus ESCOMPTE experiment



Comparison on an average diurnal cycle between observed (dots) and simulated (solid line) net radiation (a), latent heat flux (b), sensible heat flux (c), and storage heat flux (d) for the Marseilles city centre site during the UBL-ESCOMPTE experimental campaign in June-July 2005 (for the measurements, see Grimmond et al., 2005; for the simulations, see Dupont et al., 2005a).

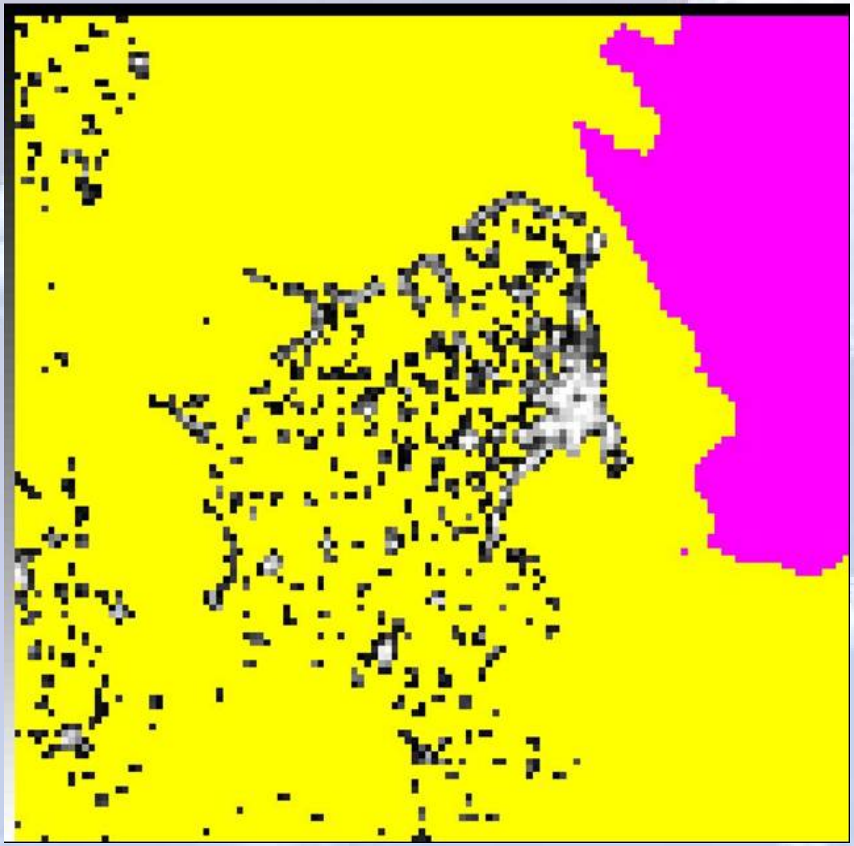
Verification of SM2-U versus ESCOMPTE experiment



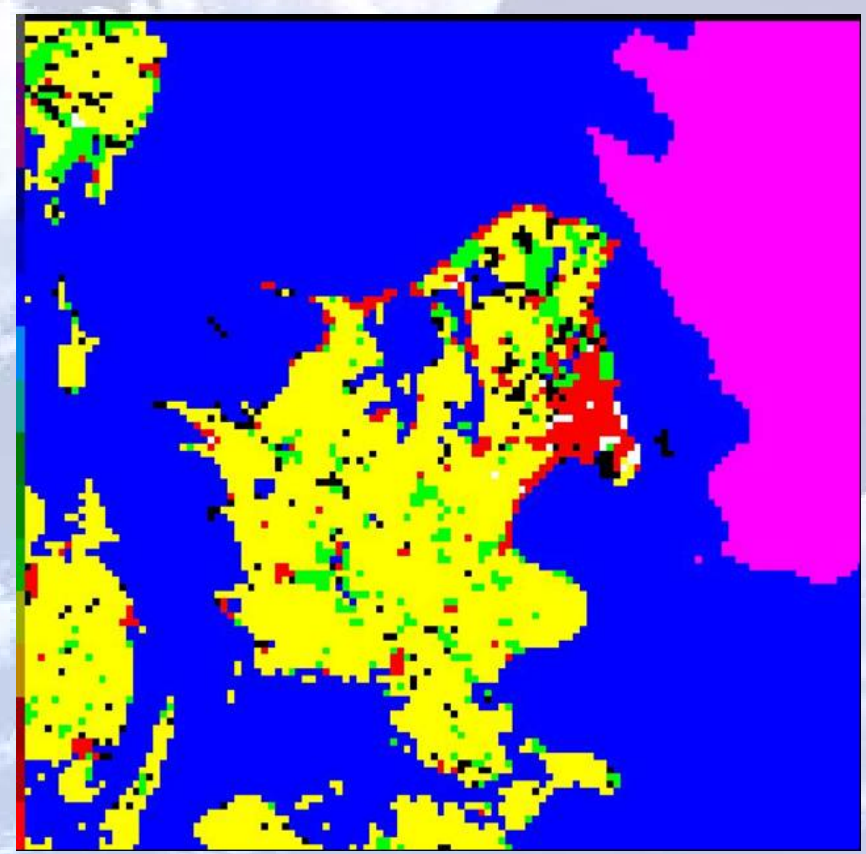
Comparison of the simulated average sensible heat flux diurnal cycle (solid line) with the observations (dots) for the alternative simulations : sim2, one-layer modelling of heat transfers in artificial materials ; sim3, building walls not simulated (*H/W* = 0).

Urban classes presentation in SM2-U for DMI-HIRLAM for the Copenhagen region

SM2-U classes: 1: veg on nat soil, 2: veg on art soil, 3: nat soil veg, 4: art soil veg, 5: bare soil, 6: buildings, 7: water



FUMAPEX - SM2 U :106: bat - buildings
-1 Magenta 14.60%
0 Yellow 75.86%



FUMAPEX - SM2 U : DOMINATING CLASS 1-7
-1 Magenta 14.60%; 1 Green 2.74%; 2 White 0.08%; 3 Black 1.83%; 4 White 0.12%; 5 Yellow 21.79%; 6 Red 2.25%; 7 Blue 56.58%

Improved urban surface parameters based on the morphologic methods

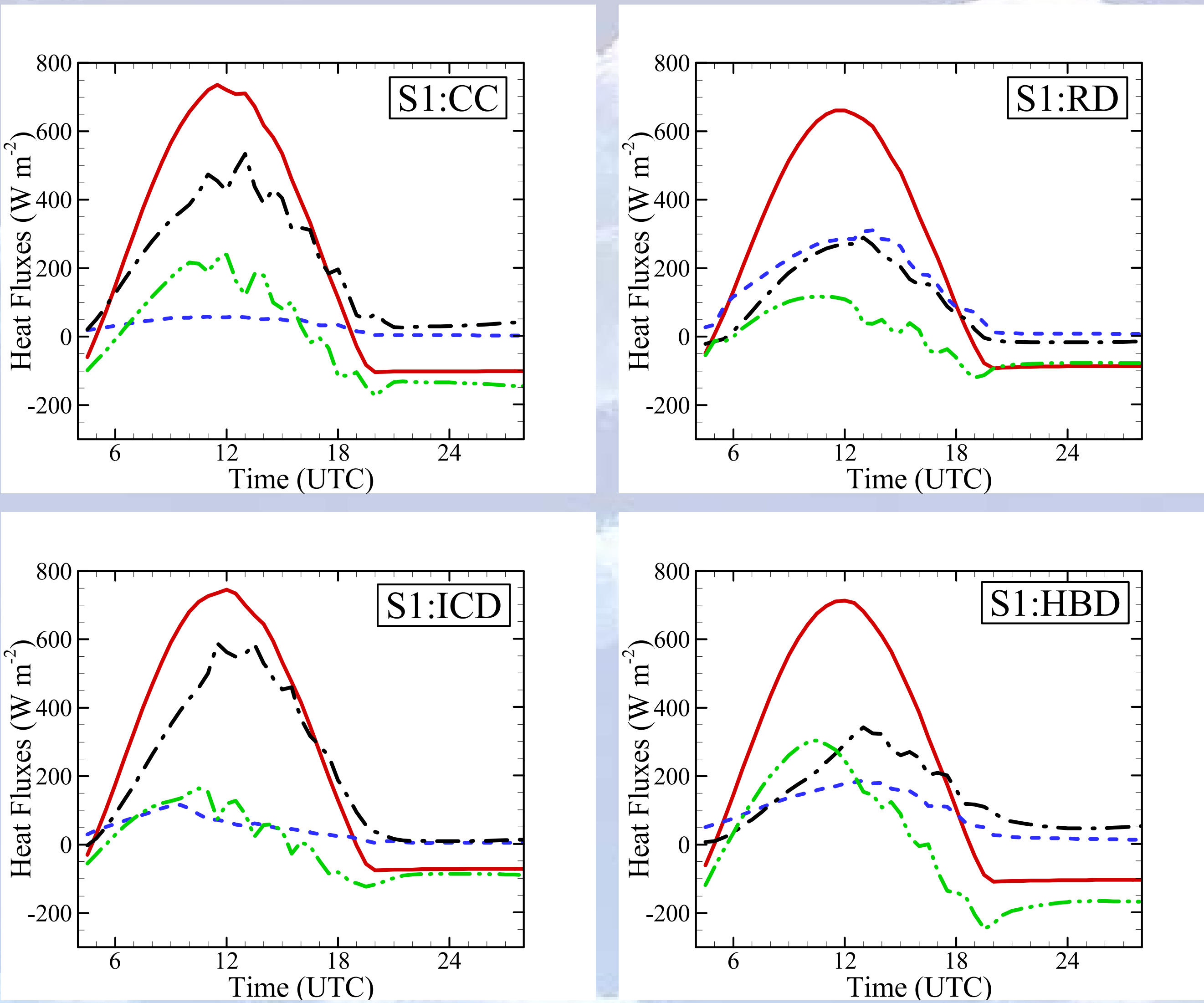
Residential District (RD)

Industrial Commercial District (ICD)

City Center (CC)
/ High Building District (HBD)

Energy budgets over four urban districts

(CC: city centre; RD: residential district; ICD: industrial-commercial district; HBD: high building district) simulated by SM2-U for an average diurnal cycle in July (*FUMAPEX D4.1, 2004*)



(——): net radiation flux;

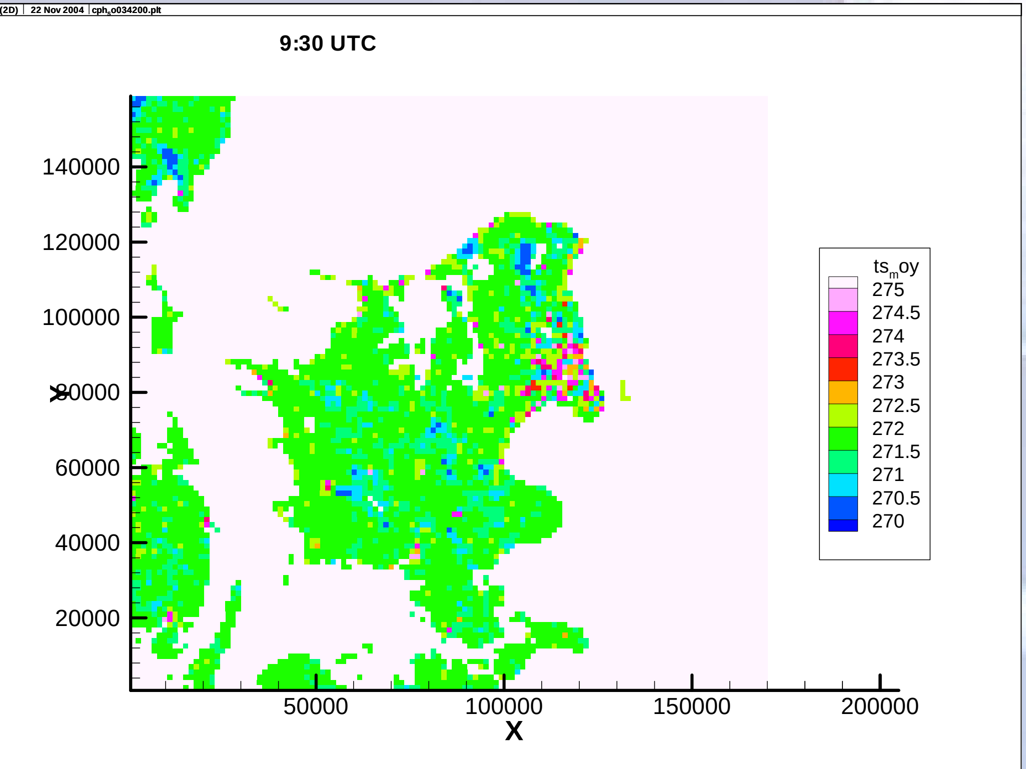
(----): latent heat flux;

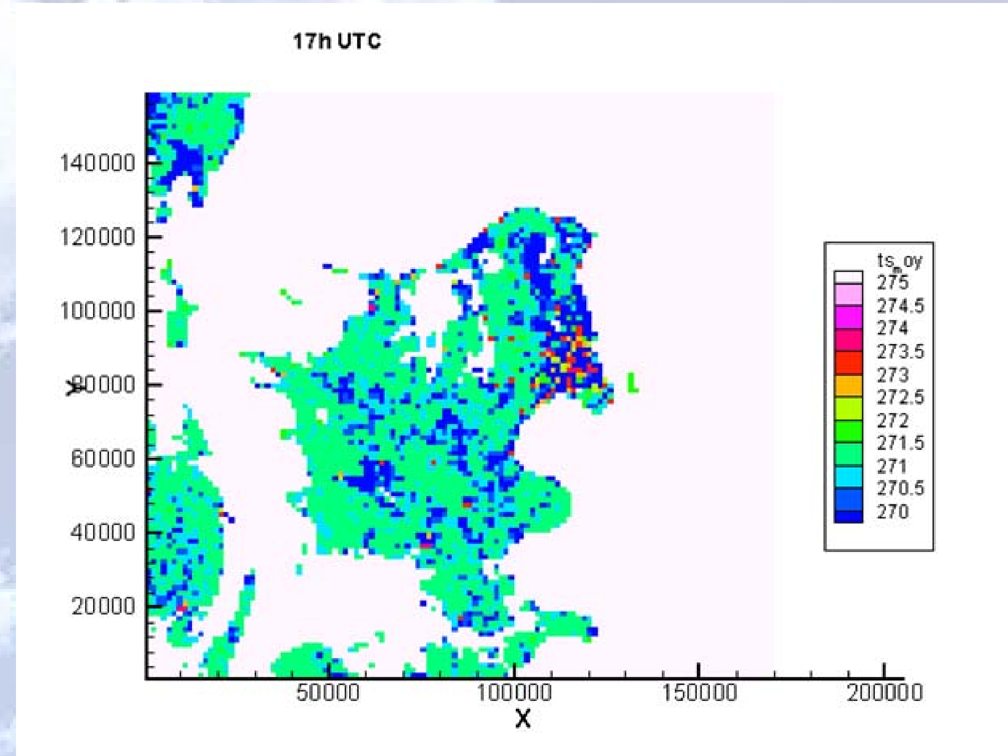
(–·–·–): sensible heat flux;

(–··–··–): storage heat flux

SUBMESO CLIMA RUNS FOR COPENHAGEN

TEMPERATURE OF THE SURFACE

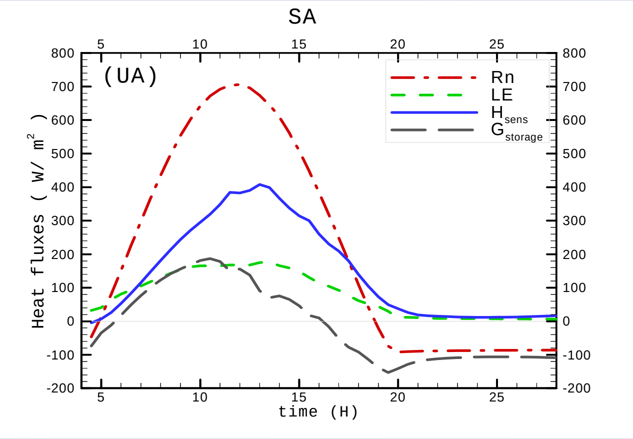


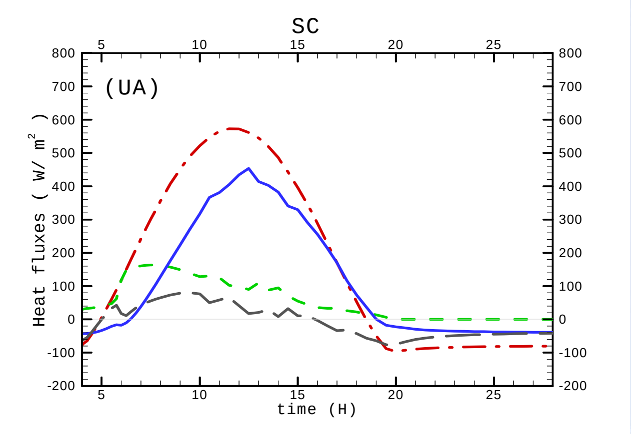


Sensitivity Study on City Representation

SA : Detailed city **SB** : Homogeneous mean city
SC : Mineral city (used in LSM, no buildings, dry bare soil)

Mean fluxes (whole urban area)





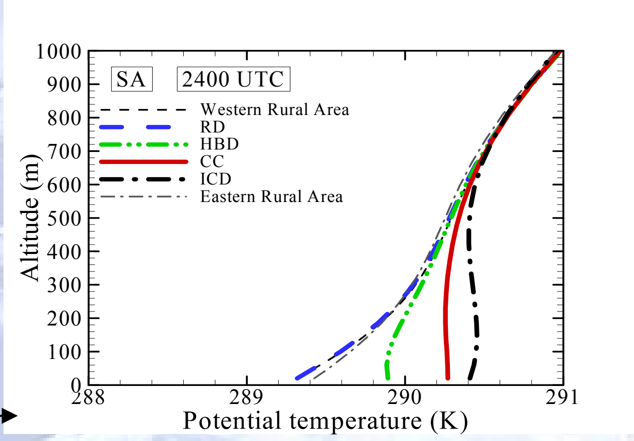
ALL : Different behavior

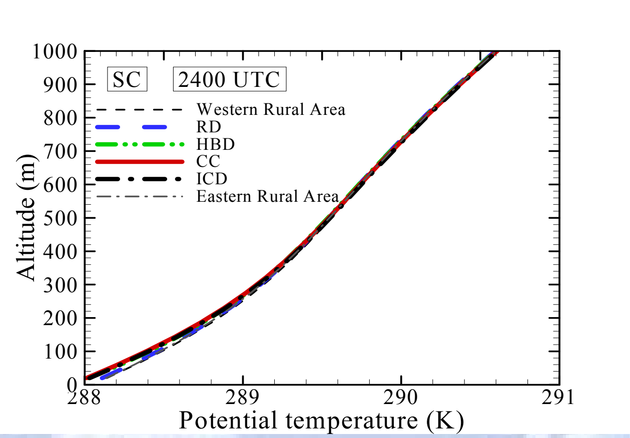
SC vs SA :
stores & releases less energy (no radiative trapping) ;
Rn is weaker (higher albedo)

SA : at 00h neutral stratification above CC & HBD, stable - others.
Urban Heat Island is seen (Surface air temperature above the city higher than on the rural area).
SC : Stable stratification & temperature homogeneity for all.

Importance of urban surface characteristics description

Temperature profiles (above districts)





Part V: Estimation of BL height

The PBL height in the models can practically be determined by two basic ways:

- It can be obtained from profile measurements, either *in-situ* or by remote sounding.
- The other possibility is to use parameterisations with only a few measured parameters as input or to substitute output from NWP models for observed parameters.

Urban BL features for MH estimation

(i) internal urban boundary layer (IBL),
(ii) elevated nocturnal inversion layer,
(iii) strong horizontal inhomogeneity and temporal non-stationarity,
(iv) so-called 'urban roughness island', zero-level of urban canopy, and $z0u \neq z0T \neq z0q$,
(v) anthropogenic heat fluxes from street to city scale,
(vi) downwind 'urban plume' and scale of urban effects in space and time,
(vii) calm weather situation simulation,
(viii) non-local character of urban MH formation,
(ix) urban soil, albedo, effect of the water vapour fluxes.

Questions to answer for analysing the urban MH based on experimental data:

- How much does the MH in urban areas differ from the rural MH ?
- How does the temporal dynamics of MH in urban areas differ from the rural MH ?
- What is the scale of urban effects in space and time and for how long distance does the downwind ‘urban plume’ effect the MH ?
- How important is the internal urban boundary layer in forming the MH?

Experimental studies of the mixing layer in urban areas

- ***ESCOMPTE*** experiment in the **Marseille** area *(Frédérique et al, 2001)*
- ‘**Basel** UrBan Boundary Layer Experiment’ (***BUBBLE***) *(Rotach et al., 2001)*
- The ***KONGEX*** experiment in the **Vienna** area, Austria *(Piringer et al., 1996, Piringer et al., 1998)*
- The **Vienna** Summer Aerosol Study (***VISAS***) during July and Aug. 1987 *(Piringer, 1988)*
- The ***ECLAP*** experiment: the atmospheric boundary layer in **Paris** and its rural suburbs *(Dupont, 1999)*
- An environmental experiment over **Athens** urban area under sea breeze conditions *(Kambezidis et al., 1995)*
- The valley of **Athens**: the ***MEDCAPHOT-TRACE*** experiment, September 1994 *(Frank 1997; Batcharova & Gryning 1986)*
- **ATHens** Internal Boundary Layer Experiment (***ATHIBLEX***) in summer 1989 and 1990 *(Melas & Kambezidis, 1992)*
- **Copenhagen**: The internal boundary layer study *(Batcharova & Gryning 1989; Rasmussen et al, 1997)*
- The **Milan** urban area: Study of nocturnal mixing height during spring and summer 1996 *(Lena & Desiano 1999)*
- Acoustic sounding of the urban boundary layer over **Berlin**-Adlershof in summer *(Evers, 1987)*
- The BL experiment, autumn 1991 over a flat, built-up urban area in Southeast **Sofia** *(Donev et al., 1995, Donev et al., 1993)*
- Studies of the atmospheric boundary layer over **Moscow** by remote sensing and in situ methods *(Lokoshchenko et al., 1993)*
- Lower Fraser Valley: **Vancouver,** in summer 1993: IBL over a coast region *(Pottier et al, 1994, Stein et al., 1997, Batcharova et al., 1999)*
- Study of the boundary layer over **Mexico** City *(Cooper et al., 1994)*
- **St. Louis**, MO. Observations obtained from near sunrise to noon on July 25, 1975 during the ***METROMEX*** (Metropolitan Meteorological Experiment) and ***RAPS*** (Regional Air Pollution Study) field programs *(Seaman, 1989; Westcott, 1989, Hildebrand & Ackerman, 1984)*
- **St. Louis**, MO, metropolitan area: Observations of high-resolution temperature profiles obtained by a helicopter during 35 intensive morning experiments *(Godovich et al, 1987; Godovich 1986)*
- **Beijing**, China: Study of wind and temperature profiles and sensible heat flux in July and December of 1986 *(Zhang & Sun, 1991)*
- **Shenyang** City, Liaoning Province, China: the field experiments carried out in December 1984 *(Sang & Lui, 1990)*
- The city of **Delhi,** 5 years of data: the mean diurnal variation of the mixing depth in different months *(Kumari, 1985)*

Some answers on the above questions:

- There are several geographically different types of cities (e.g., on a flat terrain or in mountain valleys, coastal area cities, northern or southern cities), peculiarities of each type can affect the forming the urban boundary layer as well.
- The sensible heat flux in cities was generally found larger than in rural suburbs (e.g., for Paris the difference range from 25-65 W m-2, corresponding to relative differences of 20-60%). The differences of unstable MH between both sites were less than 100 m most of the time. However, Sodar and temperature data showed that the urban influence was enhanced during night-time and transitions between stable and unstable regimes.
- The rural MH growth rate was about twice as large as urban values for as long as 3 hr after sunrise. The slower growth rate of the urban MH was attributed primarily to advection of relatively cold air and lower MHs from the upwind nonurban environment.
- The scale of urban effects in space could be very significant on the mesoscale, the downwind ‘urban plume’ can effect the ABL up to hundreds kms.

Methods for urban MH estimation

Can be distinguished in three main categories:

- with a local correction of the heat fluxes and roughness length due to urban effects,
- with estimations of the internal boundary layer (IBL) height growth,
- with a direct simulation of the TKE or eddy profiles in 3D meteorological models.

Specific methods for MH determination in urban areas:

- **Henderson-Sellers (1980) developed a simple model for urban MH as a function of distance downwind into the city.**
- **Arya and Byun (1987) suggested to solve the rate equations for the urban MH in the framework of a 2- 3-D mesoscale numerical model.**
- **Melas and Kambezidis (1992) suggested models of the height of the internal boundary layer over urban areas under sea-breeze conditions.**
- **Batchvarova et al. (1999) – IBL over urban areas under sea-breeze conditions.**
- **Baklanov (2000), Zilitinkevich and Baklanov (2002) – IBL over urban areas under stably stratification conditions.**

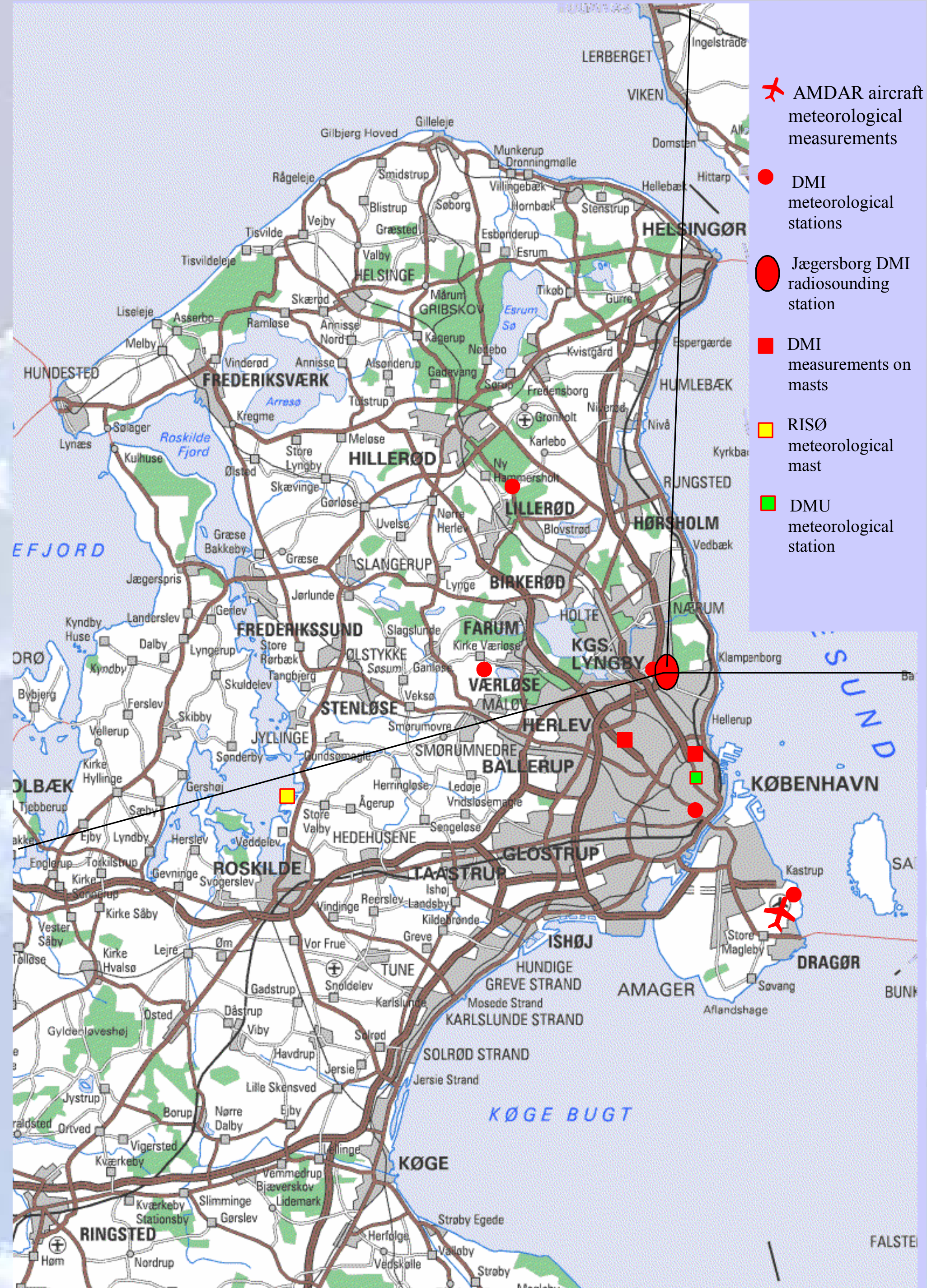
DMI routines for MH estimation:

Bulk Richardson number method	**(Sørensen et al., 1997)**
Corrected bulk Ri- method	**(Vogelezang & Holtslag 1996)**
Daytime MH growth model	**(Bartchvarova & Gryning 1991)**
Parcel method	**(Seibert et al. 1998)**
Turbulent kinetic energy decay method	
Multi-limit SBL depth formulation	**(Zilitinkevich & Mironov 1996)**
New diagnostic SBL depth formulation	**(Zilitinkevich et al. 2002)**
Modified bulk Ri-method	**(Baklanov 2000; Zilitinkevich & Baklanov 2002)**
Prognostic formulations for SBL depth	**(Zilitinkevich et al. 1998)**
Library of common ten methods	**(e.g. Lena & Desiato 2000)**

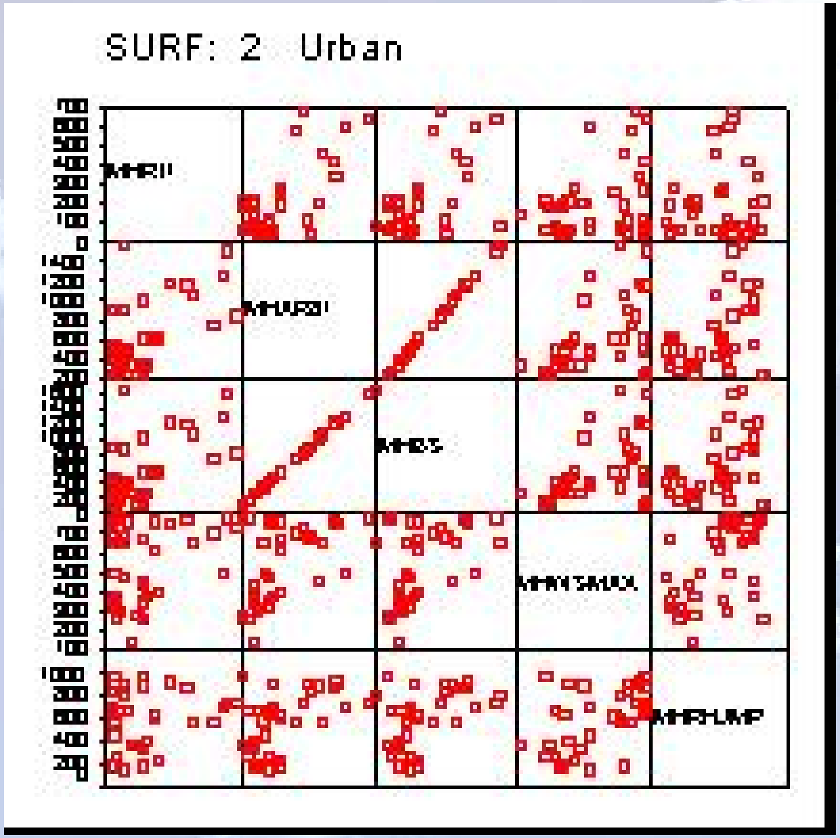
Some current formulations for estimating the mixing height:

Reference	SBL height equations
1. Zilitinkevich (1972)	$h = c_2 \left(\frac{u_* L}{f} \right)^{1/2}$, $c_2 \approx 0.4$ (varies between 0.13 and 0.72 according to different authors)
2. Venkatram (1980)	$h = u_* \sqrt{\frac{2}{fN}}$
3. Arya (1981) (after Zilitinkevich, 1972)	$h = a \left(\frac{u_* L}{f} \right)^{1/2} + b; \qquad a = 0.43, b = 29.3$
4. Nieuwstadt (1981)	$h = L \frac{0.3 u_*}{\lvert f \rvert L} \frac{1.0}{1.0 + 1.9\, h/L}$
5. Zilitinkevich and Mironov (1996)	$\left(\frac{fh}{0.5 u_*} \right)^2 + \frac{h}{10L} + \frac{Nh}{20 u_*} + \frac{h \lvert f \rvert^{1/2}}{(u_* L)^{1/2}} + \frac{h \lvert Nf \rvert^{1/2}}{1.7 u_*} = 1$
6. Zilitinkevich *et al.* (2002)	$h = \frac{C_R u_*}{\lvert f \rvert} \left[\left(1 + C_h \frac{w_h}{u_*} \right) \Big/ \left(1 + \frac{C_R^2 u_* (1 + C_{uN} NL / u_*)}{C_S^2 L \lvert f \rvert} \right) \right]^{1/2}$ with: $C_R = 0.4$, $C_S = 0.74$, $C_{uN} = 0.25$ and $C_h = 0.3$.
7. Zilitinkevich and Baklanov (2002)	$\frac{\partial h}{\partial t} + \mathbf{V} \cdot \nabla h = -C_E \lvert f \rvert (h - h_{CQE}) + K_h \nabla^2 h \qquad$ with $C_E \approx 1$
8. Joffre and Kangas (2002)	$h = \frac{b'}{2a'} \mu_N \left\{ -1 + \left[1 + \frac{4 a' m'}{b'^2} \mu_N^{-2} \right]^{1/2} \right\} L_N$ with $a' = 0.12$, $b' = 2.85$ and $m' = 24$ (very rough surface)

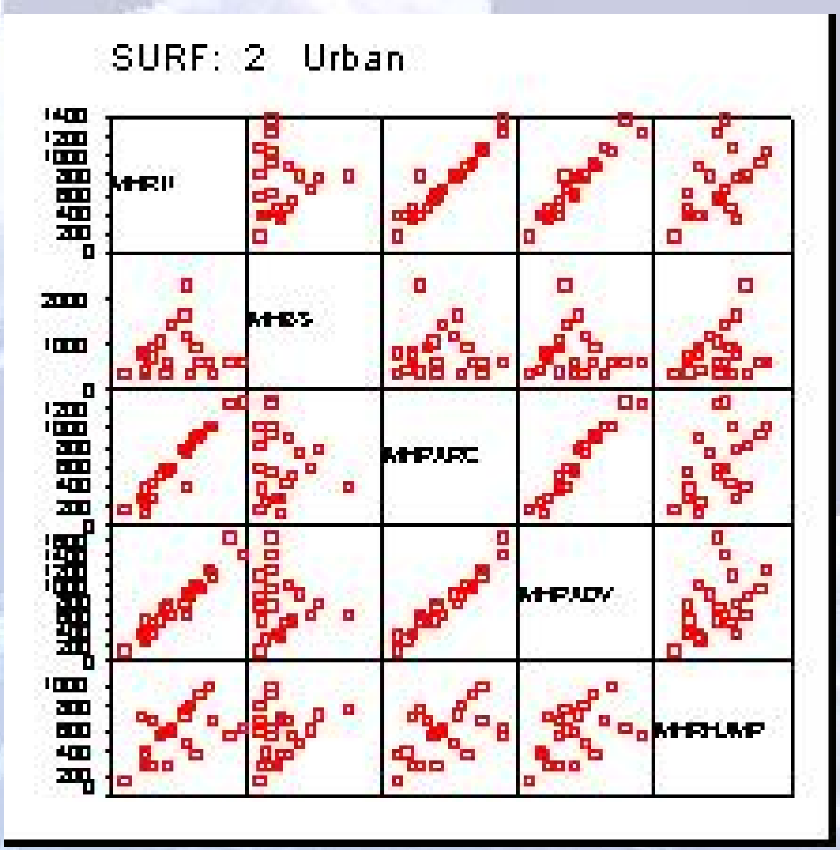
Meteorological measurements in the Copenhagen metropolitan area



Intercomparison of MH estimation methods for Copenhagen



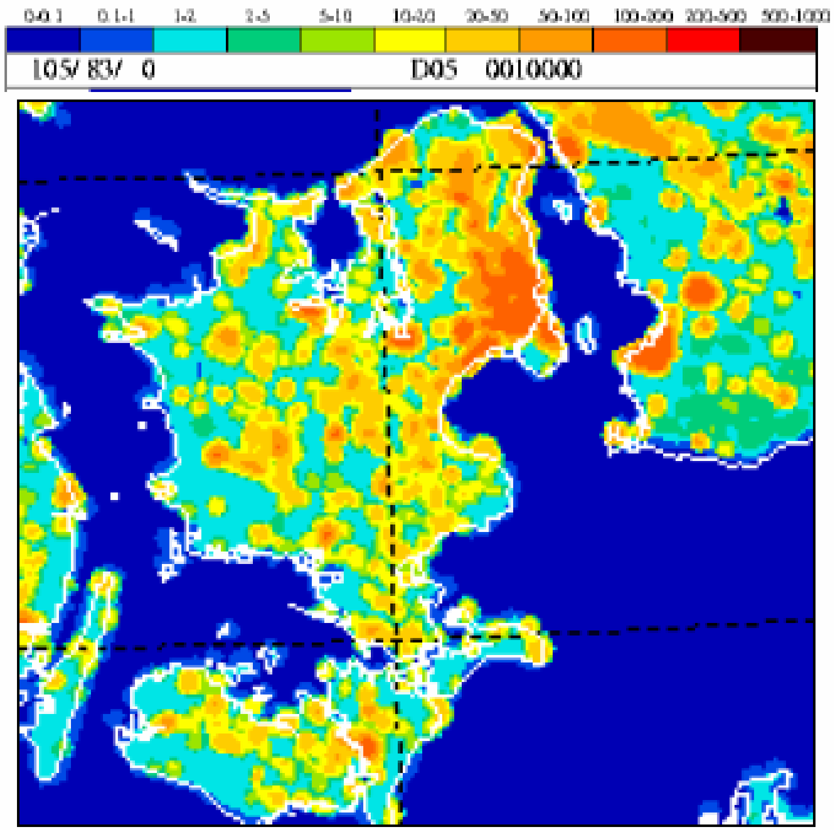
SBL



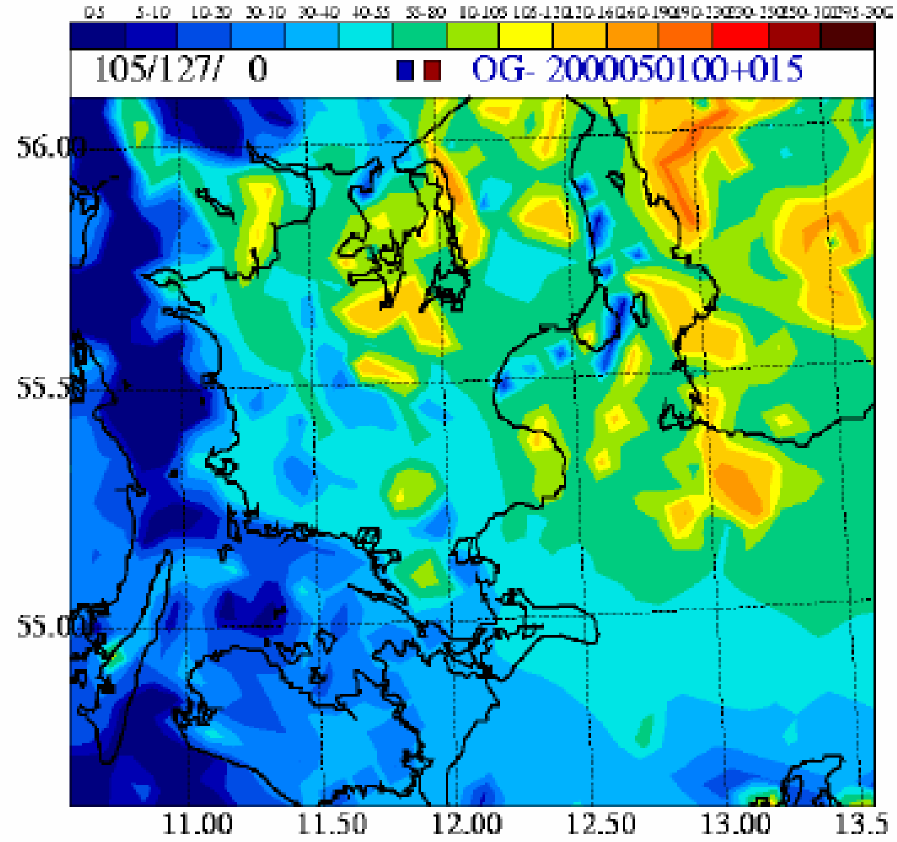
CBL

The nocturnal PBL height forecasted by the DMI-HIRLAM model

with the CBR scheme and the turbulent energy depletion approach for the PBL height for Copenhagen

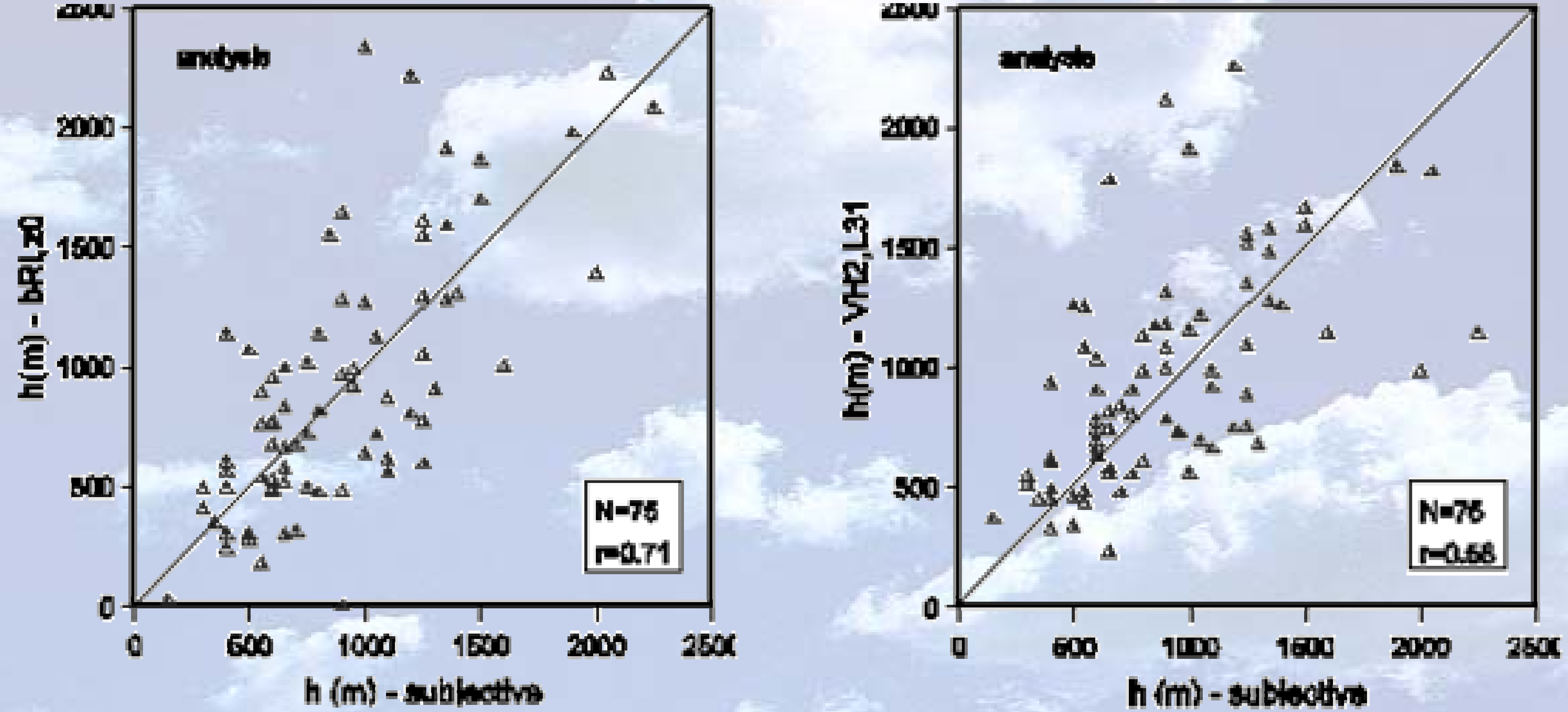


Roughness length

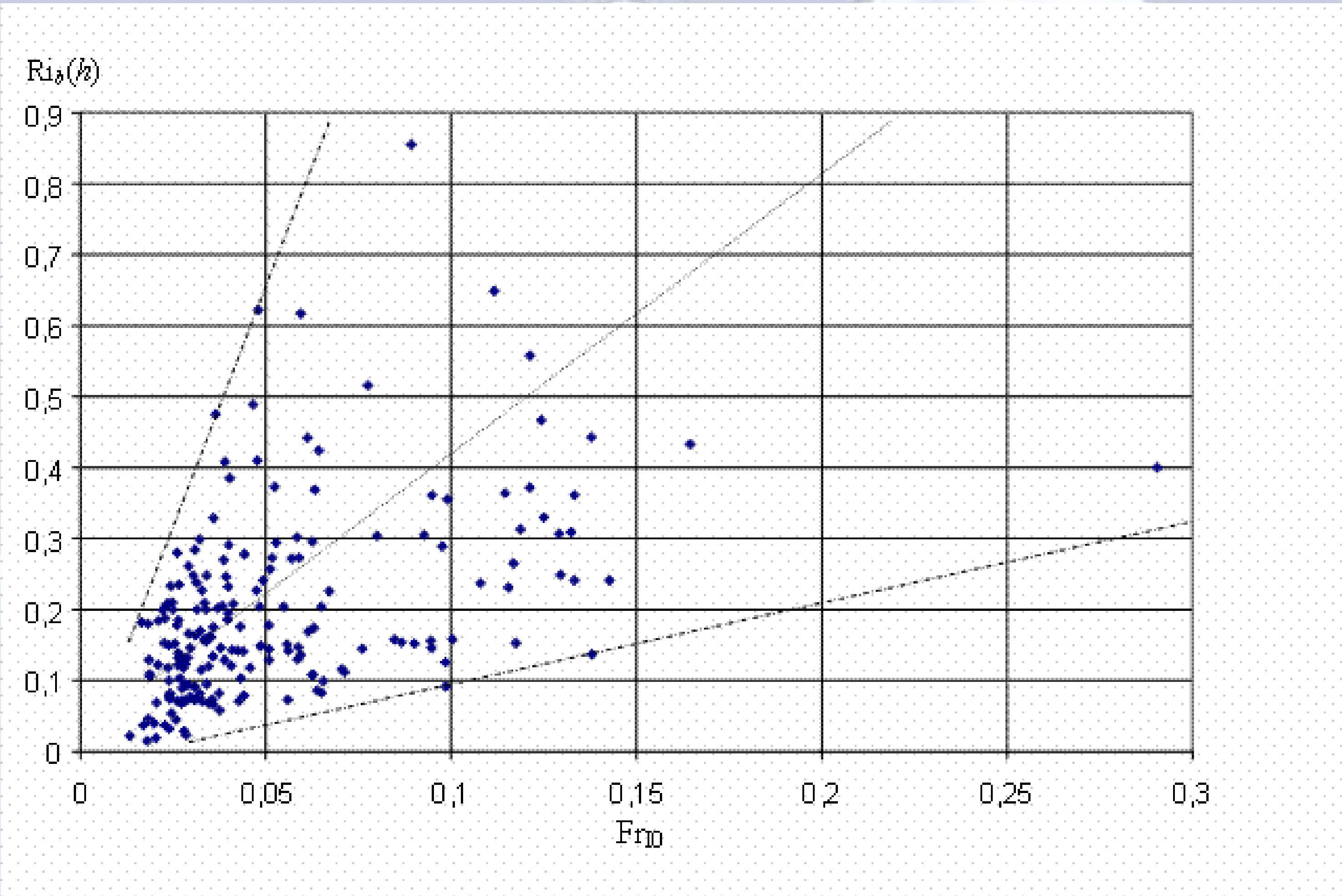


Mixing height

Scatter plots of subjective MH from Jægersborg, and the MH calculated from DMI-HIRLAM data by standard bulk Richardson method (left) and by Vogelezang-Holtslag method (right).



The standard critical bulk Richardson number, Ri*bc*, estimated at the measured SBL height versus the external inverse Froude number, FrI0, for the measurement data



Prognostic formulations for MH estimation

- The slab model extended for IBL over terrain with abrupt changes of surface for near neutral and unstable atmospheric conditions (Gryning and Batchvarova, 1996):

$$\left\{ \frac{h^2}{(1+2A)h - 2B\kappa L} + \frac{C u_*^2 T}{\gamma g[(1+A)h - B\kappa L]} \right\} \left(\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} - w_s \right) = \frac{\left(\overline{w'\theta'}\right)_s}{\gamma},$$

- Extension of the SBL height model, accounting for the horizontal transport through the advection term and the sub-grid scale horizontal motions through the horizontal diffusivity (Zilitinkevich & Baklanov, 2002):

$$\frac{\partial h}{\partial t} + \mathbf{V} \cdot \nabla h = -C_E \,|\, f \,|\, (h - h_{CQE}) + K_h \nabla^2 h$$

SBL MH formulations based on equation of TKE budget

Zilitinkevich *et al*. (2002), Zilitinkevich & Baklanov (2002), Zilitinkevich and Ezau, 2003) suggested new diagnostic and prognostic parameterisations for SBL height, including effects of the IBL, free-flow stability and baroclinity:

$$\frac{\partial h}{\partial t} + \mathbf{V} \cdot \nabla h = -C_E \,|\, f \,|\, (h - h_{CQE}) + K_h \nabla^2 h$$

$$h_E = C_R \frac{u_*}{|\, f \,|} \left[1 - \left(\frac{\mathrm{Ri}_c}{\mathrm{Ri}} \right)^{1/2} \right]^{-1/2}$$

$$\left(1 + \frac{C_R^2 C_{uN}}{C_S^2} \mu_N + \frac{C_R^2}{C_S^2} \mu \left[1 - \left(\frac{\mathrm{Ri}_c}{\mathrm{Ri}} \right)^{1/2} \right] \right)^{-1/2}$$

Stability parameters: $\mu = \frac{u_*}{|\, f \,|\, L}$ internal, $\mu_N = \frac{N}{|\, f \,|}$ external.

Zilitinkevich et al. SBL height formulation (Cont.)

The MO length scale L and the internal-stability parameter

$\mu = u_* |f| L$ are modified $$L_{baroclinic} = \frac{u_T^3}{-F_{bs}} = L\left[1 - \left(\frac{\mathrm{Ri}_c}{\mathrm{Ri}}\right)^{1/2}\right]^{-3/2}$$

$$u_T^2 = \frac{u_*^2}{1 - (\mathrm{Ri}_c/\mathrm{Ri})^{1/2}}$$

Free-atmosphere parameters:

baroclinic shear $$\Gamma = \frac{g}{|f|T}\left[\left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial x}\right)^2\right]^{1/2}$$

Brunt-Väisälä frequency $$N \equiv \left(\frac{g}{T}\frac{\partial \theta_v}{\partial z}\right)^{1/2}$$

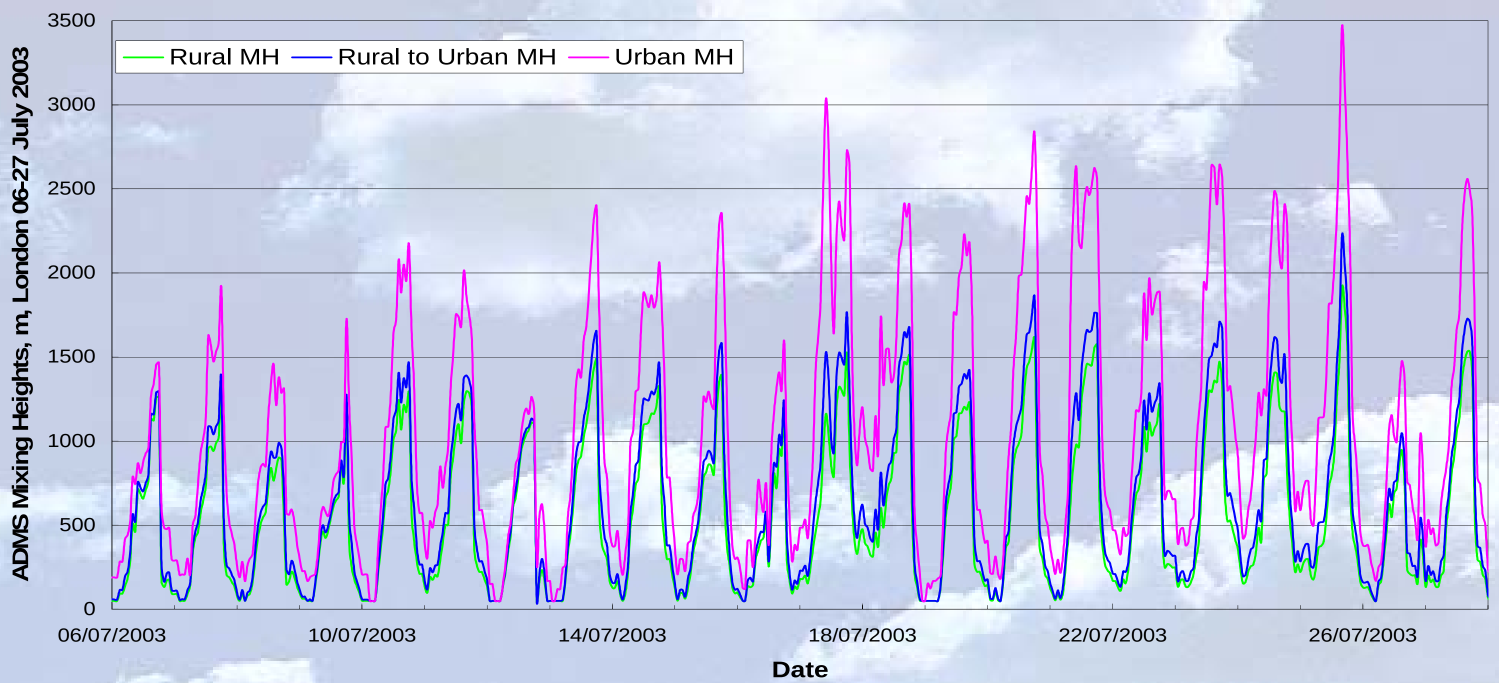
Richardson number $$1 < \mathrm{Ri} = \left(\frac{N}{\Gamma}\right)^2 < 10$$

Applicability of ‘rural’ methods of the MH estimation for urban areas:

- For estimation of the daytime MH, applicability of common methods is more acceptable than for the nocturnal MH.
- For the convective UBL the simple *slab models* (e.g. Gryning and Batchvarova, 2001) were found to perform quite well.
- The formation of the nocturnal UBL occurs in a counteraction with the negative ‘non-urban’ surface heat fluxes and positive anthropogenic/urban heat fluxes, so the applicability of the common methods for the SBL estimation is less promising.
- The determination of the SBL height needs further developments and verifications versus urban data. As a variant of the methods for SBL MH estimation the new Zilitinkevich *et al*. (2002) parameterisation can be suggested in combination with a prognostic equation for the horizontal advection and diffusion terms (Zilitinkevich and Baklanov, 2002).
- Meso-meteorological and NWP models with modern high-order non-local turbulence closures give promising results (especially for the CBL), however the urban effects need to be included.

ADMS mixing heights using London Heathrow observations, 6-27 July 2003

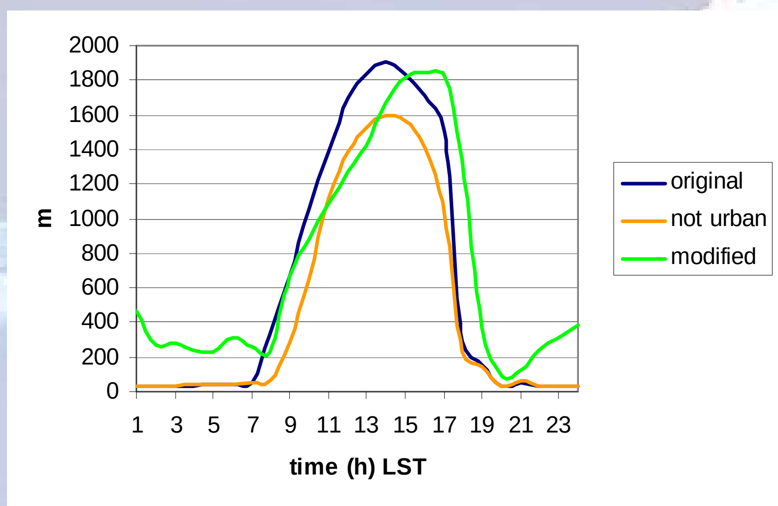
(Piringer and Joffe, WG2 COST715, 2005)

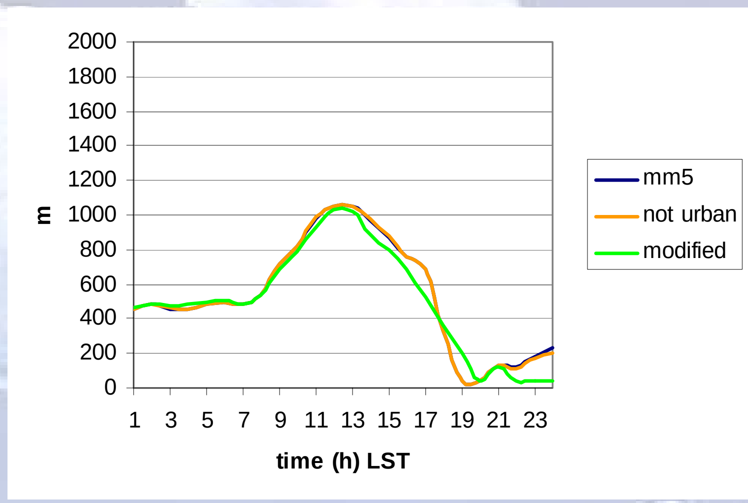


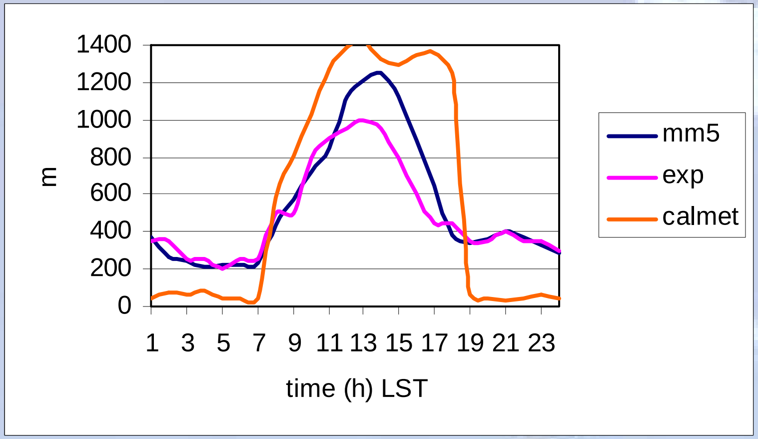
Cases (1): rural roughness z_o=0.1 m (green); (2): urban roughness z_o=1.0 m (pink); (3): rural roughness z_o=0.1 m at airport with urban roughness at city z_o=1.0 m (blue).

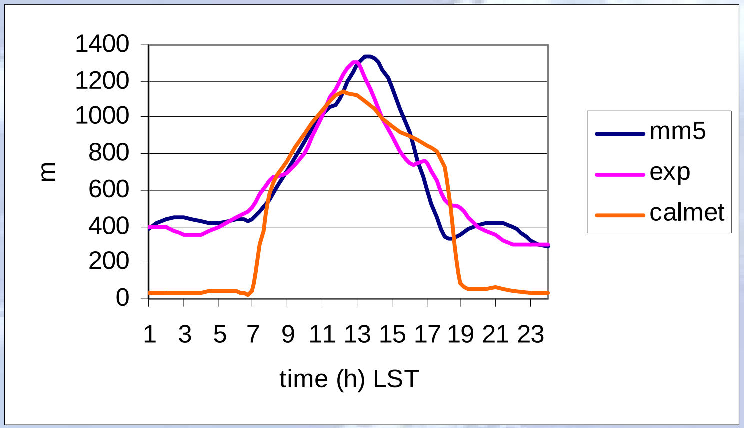
Diurnal variation of UMH over Athens

(WG2 COST715)









FUMAPEX: *Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure*

Project objectives:

(i) the improvement of meteorological forecasts for urban areas,

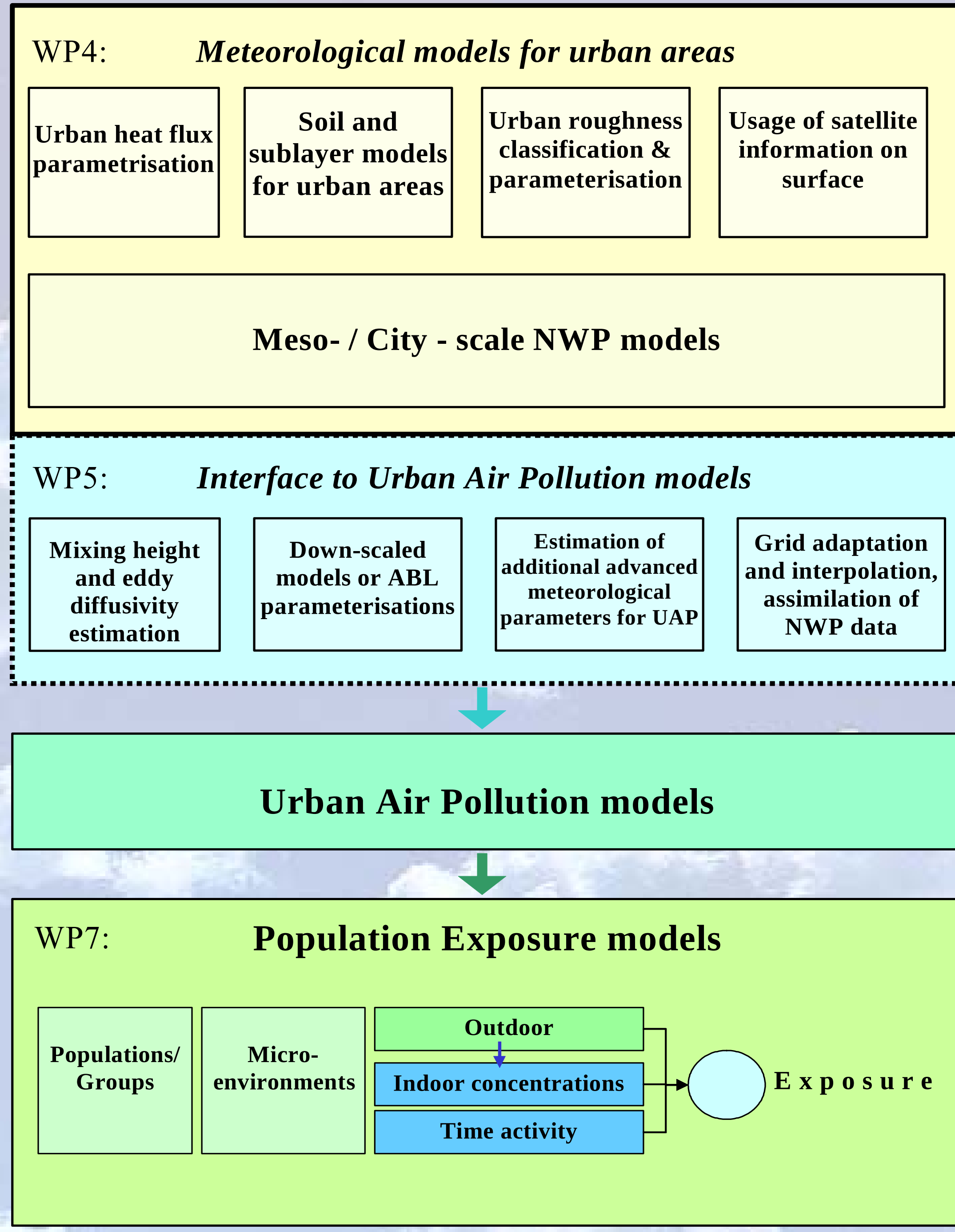
(ii) the connection of NWP models to urban air quality (UAQ) and population exposure (PE) models,

(iii) the building of improved *Urban Air Quality Information and Forecasting Systems* (UAQIFS), and

(iv) their application in cities in various European climates.

UAQIFS:

Scheme of the suggested improvements of meteorological forecasts (NWP) in urban areas, interfaces to and integration with UAP and PE models

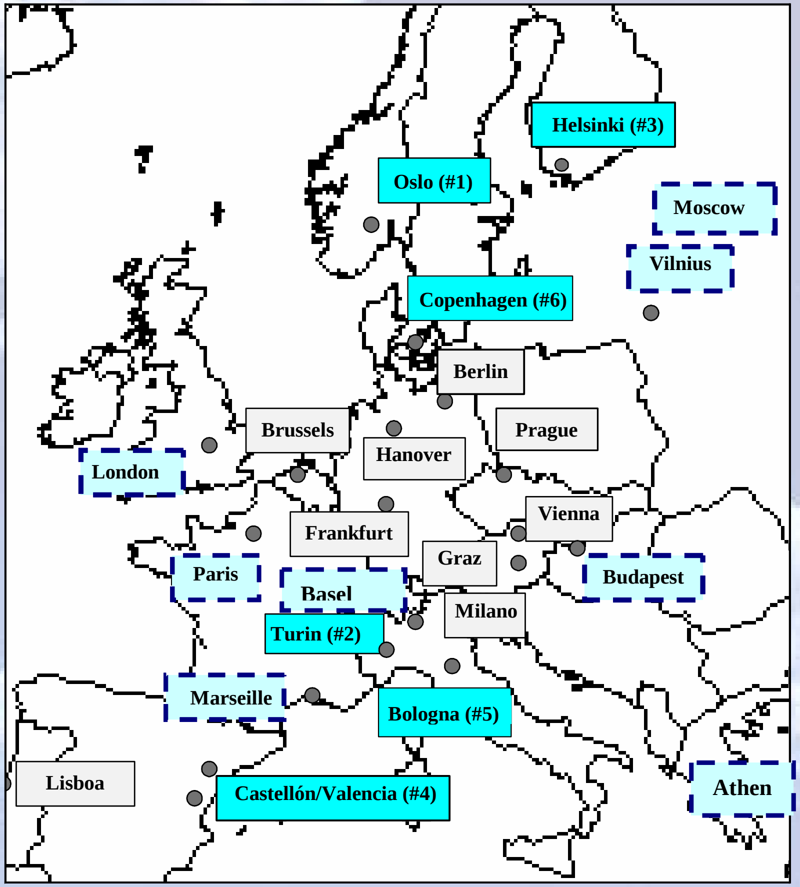


FUMAPEX target cities for improved UAQIFS implementation

#1 – Oslo, Norway
#2 – Turin, Italy
#3 – Helsinki, Finland
#4 – Valencia/Castellon, Spain
#5 – Bologna, Italy
#6 – Copenhagen, Denmark

Different ways of the UAQIFS implementation:

(i) urban air quality forecasting mode,
(ii) urban management and planning mode,
(iii) public health assessment and exposure prediction mode,
(iv) urban emergency preparedness system.



Map of the selected European cities for air pollution episode analysis. The target city candidates for UAQIFS implementation in FUMAPEX are marked by a # and blue background. Potential target cities for applying the FUMAPEX technique in future are marked with a dark-blue shaded border.

Met.no

FUMAPEX: Forecast procedure in Oslo

NILU

NWP model output (regional)

HIRLAM10 (~05:00)

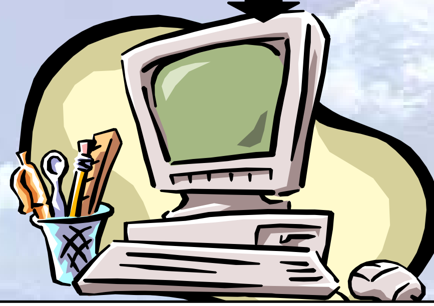
MM5 1-3km (~05:30)

Met-preprocessor

AirQUIS (~06:30)

Global weather information

Meteorological Interpretation



MODEL OUTPUT PLOTS ON WEB FOR END-USERS (~06:30)

WG2: Integrated systems of MetM and CTM/ADM: strategy, interfaces and module unification

The overall aim of WG2 will be to identify the requirements for the unification of MetM and CTM/ADM modules and to propose recommendations for a European strategy for integrated mesoscale modelling capability.

WG2 activities will include:

- **Forecasting models**
- **Assessment models**

Meteorology and Air Pollution:

as a joint problem

- Meteorology is a main source of uncertainty in APMs => needs for NWP model improvements
- Complex & combined effects of meteo- and pollution components (e.g., Paris, Summer 2003)
- Effects of pollutants/aerosols on meteo&climate (precipitation, thunderstorms, etc)

<u>Three main stones for Atmospheric Environment modelling:</u>

1. Meteorology / ABL,
2. Chemistry, => *Integrated Approach*
3. Aerosol/pollutant dynamics (*“chemical weather forecasting”*)
4. Effects and Feedbacks

Why we need to build the European integration strategy?

• NWP models are not primarily developed for CTM/ADMs and there is no tradition for strong co-operation between the groups for meso/local-scale

• the conventional concepts of meso- and urban-scale AQ forecasting need revision along the lines of integration of MetM and CTM

• US example (The models 3, WRF-Chem)

• A number of European models …

• A universal modelling system (like ECMWF in EU or WRF-Chem in US) ???

• an open integrated system with fixed architecture (module interface structure)

European mesoscale MetM/NWP communities:

• ECMWF
• HIRLAM
• COSMO
• ALADIN/AROME
• UM

• WRF
• MM5
• RAMS

European CTM/ADMs:

• a big number
• problem oriented
• not harmonised (??)
• …..