Urban Boundary Layers:
Experience from EU-FUMAPEX

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and COST715 & 728 colleagues

FUMAPEX web-site: *http://fumapex.dmi.dk*

International course of lectures
"Geophysical turbulence and boundary layers: nature, theory and role in Earth's systems"
University of Helsinki and Finnish Meteorological Institute
Helsinki, Finland, 27 May – 1 June 2007

Structure of the Lecture

I. Introduction into the problem

II. Structure of urban boundary layers (UBL)

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. FUMAPEX: Urbanisation of NWP and ACT models

VII. Integrated modelling : FUMAPEX, COST-728 and hopefully MEGAPOLI

Part I: Introduction into the problem
Why and where urban boundary layers are important?

- ***Scientific and Technological Advances***
  - New achievements in UBL research
  - Computer possibilities and high-resolution models
  - Remote sensing and other measurement platforms
- ***Weather, Environment, Health and Safety***
  - High impact weather
  - Air quality forecast
  - Urban climate and regional effects
- ***Emergency Preparedness and Security***
  - Urban air dispersion models for emergency issues

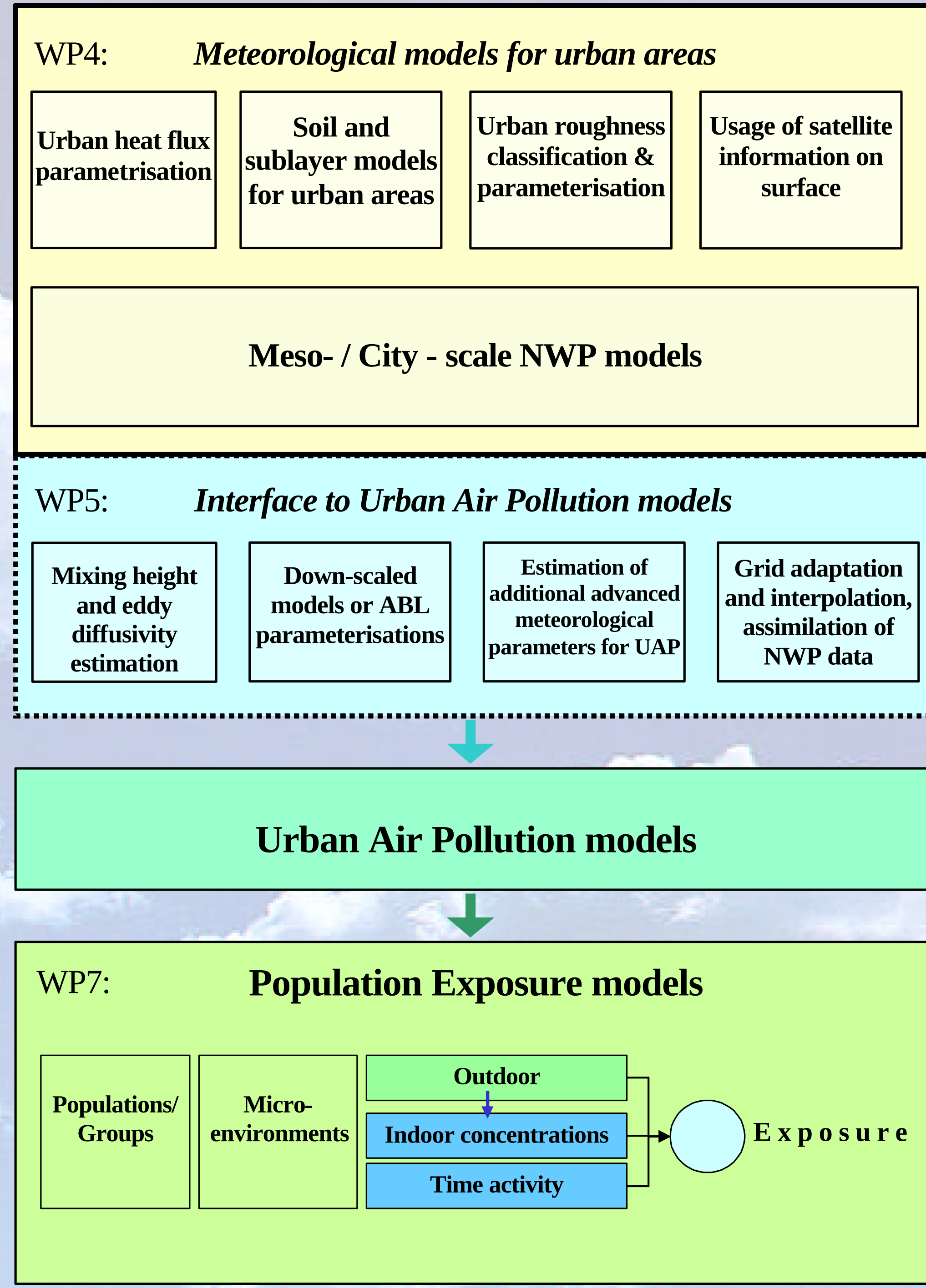
FUMAPEX
Project objectives:

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

(ii) the connection of NWP models to urban air pollution (UAP) 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.



Motivation

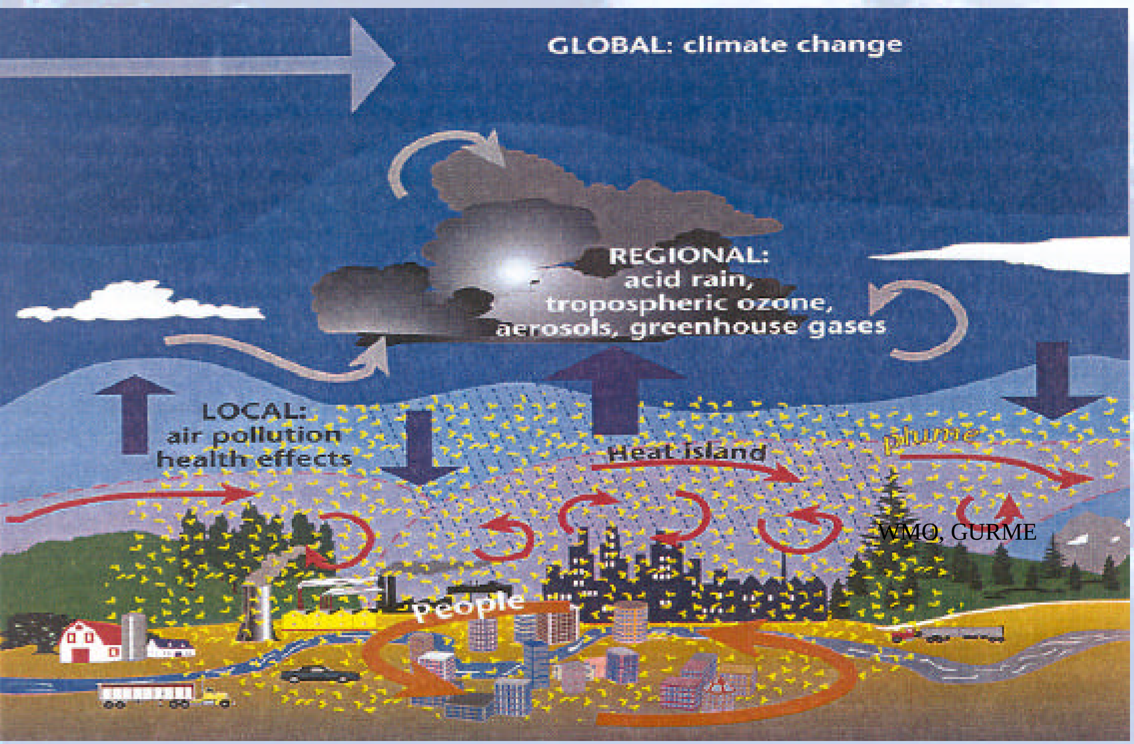
Meteorological fields constitute a main source of uncertainty in urban air quality (UAQ) models

UAQ and NWP models developed separately – insufficient co-operation between modelling groups

This was plausible with low resolution NWP models but not applied to city-scale air pollution

Strategy for model urbanization

Different requirements for NWP and environmental models
(e.g. in UBL structure)

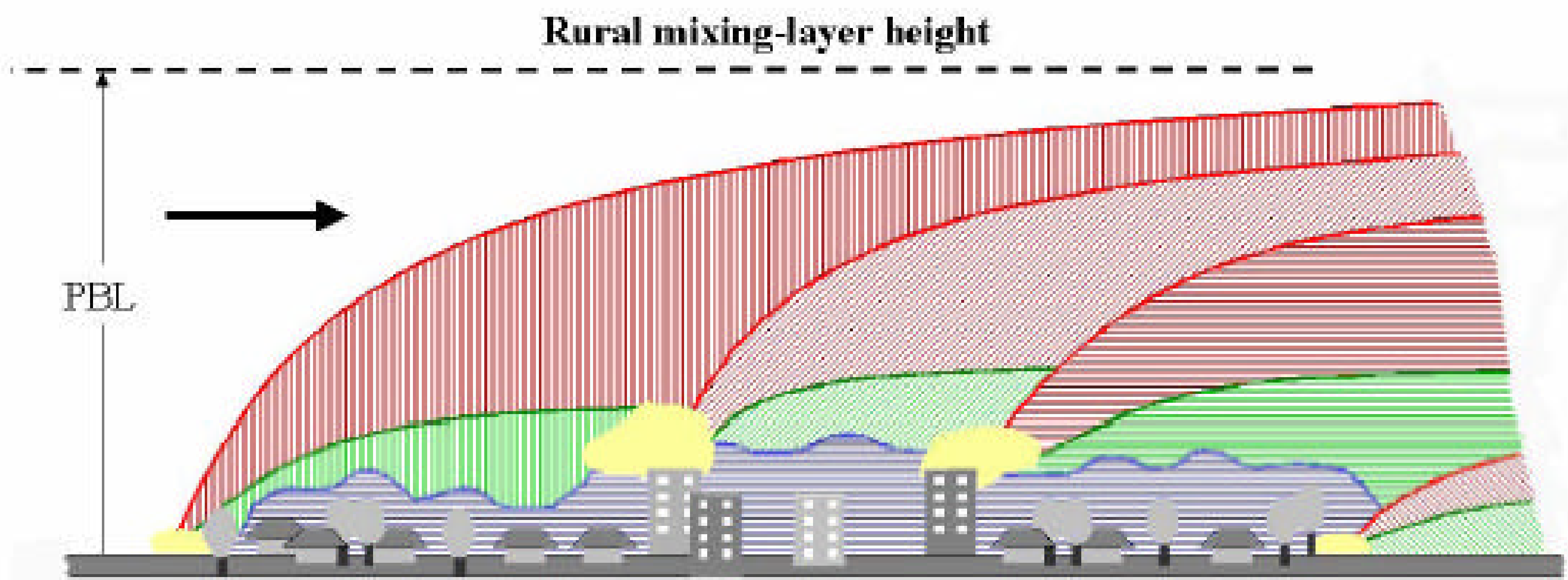


- Model scales (regional, city, local, micro, …)
- Climate models (regional, urban, ..)
- Research meso-meteorological models
- Numerical weather prediction models
- Atmospheric pollution models (city-scale)
- Emergency preparedness models
- Meteo-preprocessors (or post-processors)

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.

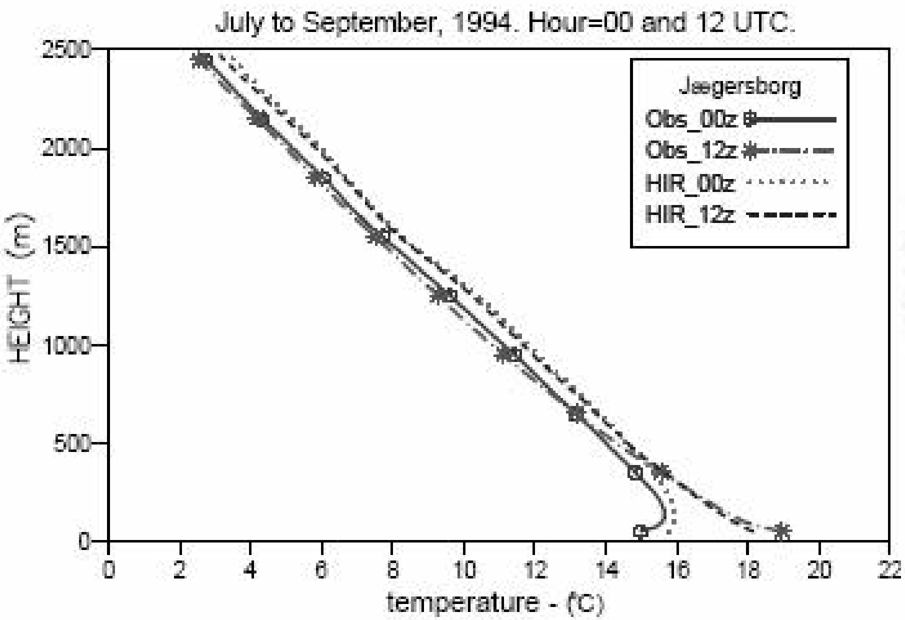
Urban BL: Horizontal non-homogeneity



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

Urban nocturnal boundary layer over Northern cities



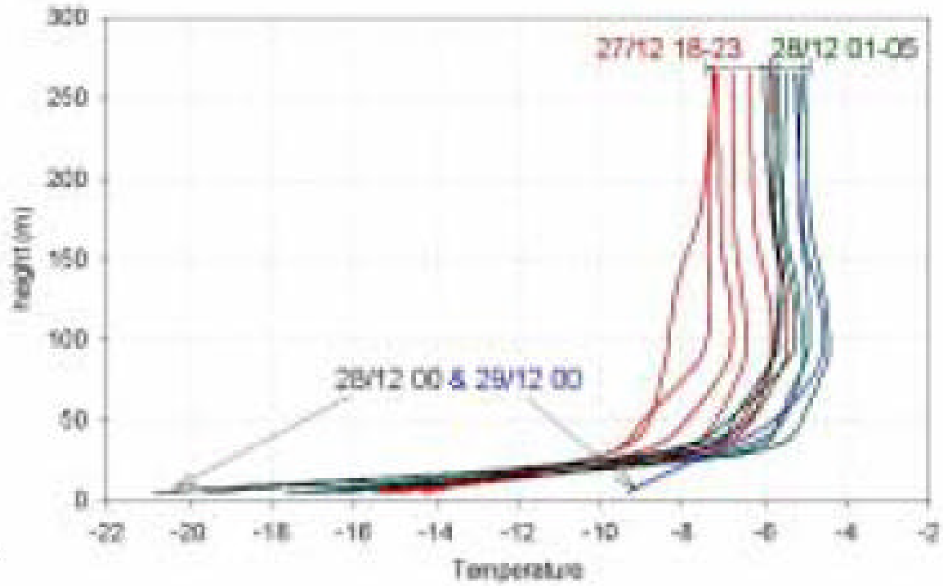


Figure 7.1: Temperature vertical profiles for North-European cities. *Left*: The 3-month mean measured (Obs) and modelled (HIR) profiles of temperature at 00 and 12 UTC for the radiosonde station Jægersborg in the metropolitan Copenhagen area (Rasmussen *et al.*, 1999). *Right*: Evolution of a temperature inversion during an air quality episode in December 1995 for the Helsinki metropolitan area. The curves are numerical fits of the data measured at the Kivenlahti mast.

A city can be considered as a protect area for mesoscale 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

But

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

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)	

Urbanisation of NWP models:

1. Model down-scaling, including increasing vertical and horizontal resolution and nesting techniques (one- and two-way nesting);
2. Modified high-resolution urban land-use classifications, parameterizations and algorithms for roughness parameters in urban areas based on the morphologic method;
3. Specific parameterization of the urban fluxes in meso-scale models;
4. Modelling/parameterization of meteorological fields in the urban sublayer;
5. Calculation of the urban mixing height based on prognostic approaches;
6. Assimilation surface characteristics based on satellite data into Urban Scale NWP models;
7. Feedback mechanisms: Effects of pollutants (aerosols) on urban meteorology and climate, urban effects on clouds, precipitation and thunderstorms, etc.

Urban Meteorology for Air Quality Models

- Urban meteo-preprocessors based in-citu measurements and NWP data
- Interfacing improved urbanised NWP data
- Down-scaling/nesting high-resolution meteo-models
- Urban sub-models as modern interface from operational NWP to UAQ models
- Turbulent diffusion and deposition parameterisations in urban areas
- Obstacle-resolved CFD/RANS/LES types of models
- Feedbacks between meteorological and atmospheric chemistry/urban aerosols processes (on-line coupling)

FUMAPEX Meteo-models for urbanization

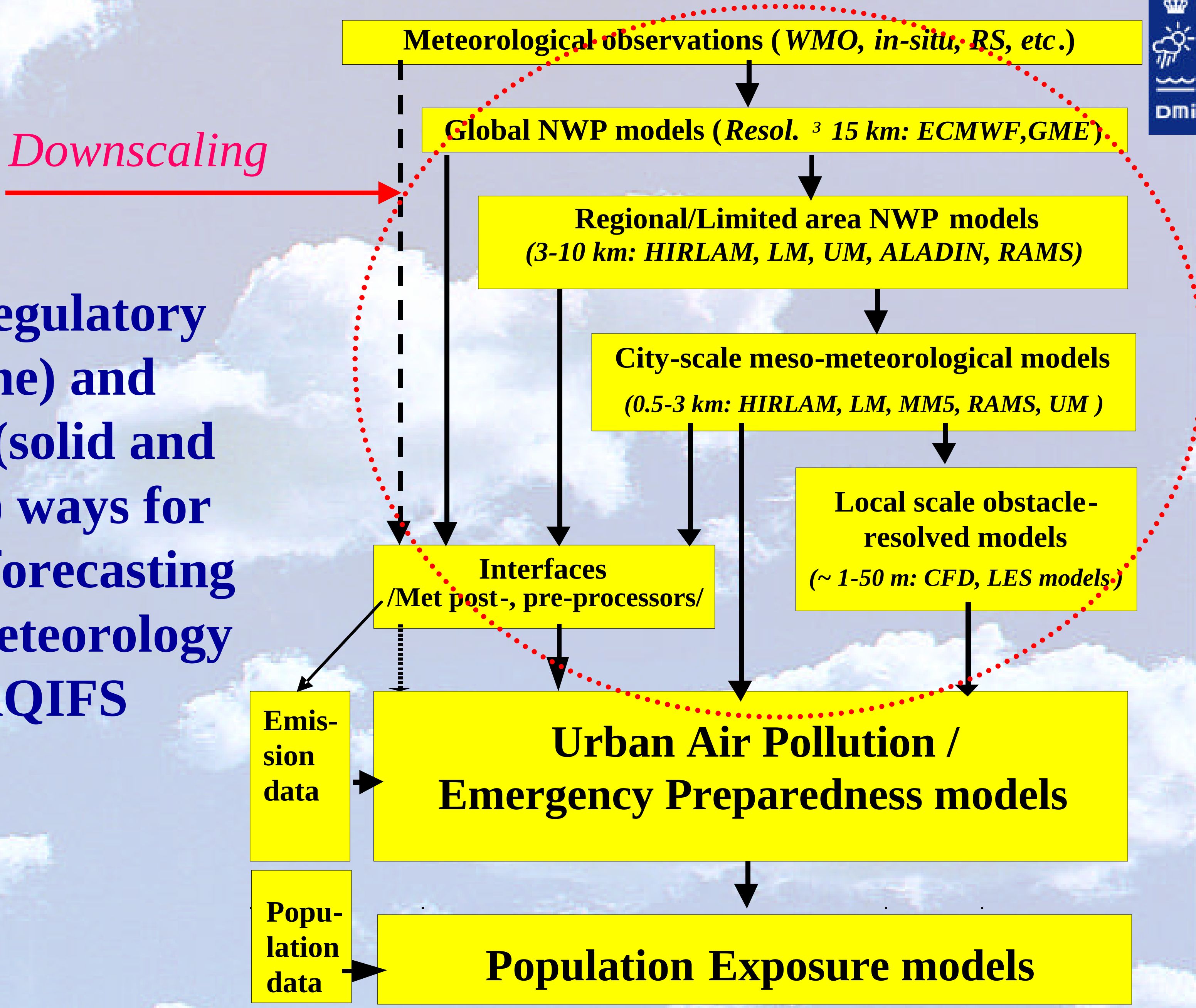
Research meso-scale models:

- SUBMESO Model (ECN);
- Finite Volume Model, FVM (EPFL);
- Topographic Vorticity-Mode Mesoscale (TVM) Model (UCL);
- MM5-SM2U (ECN, CORIA, cooperation with US EPA);

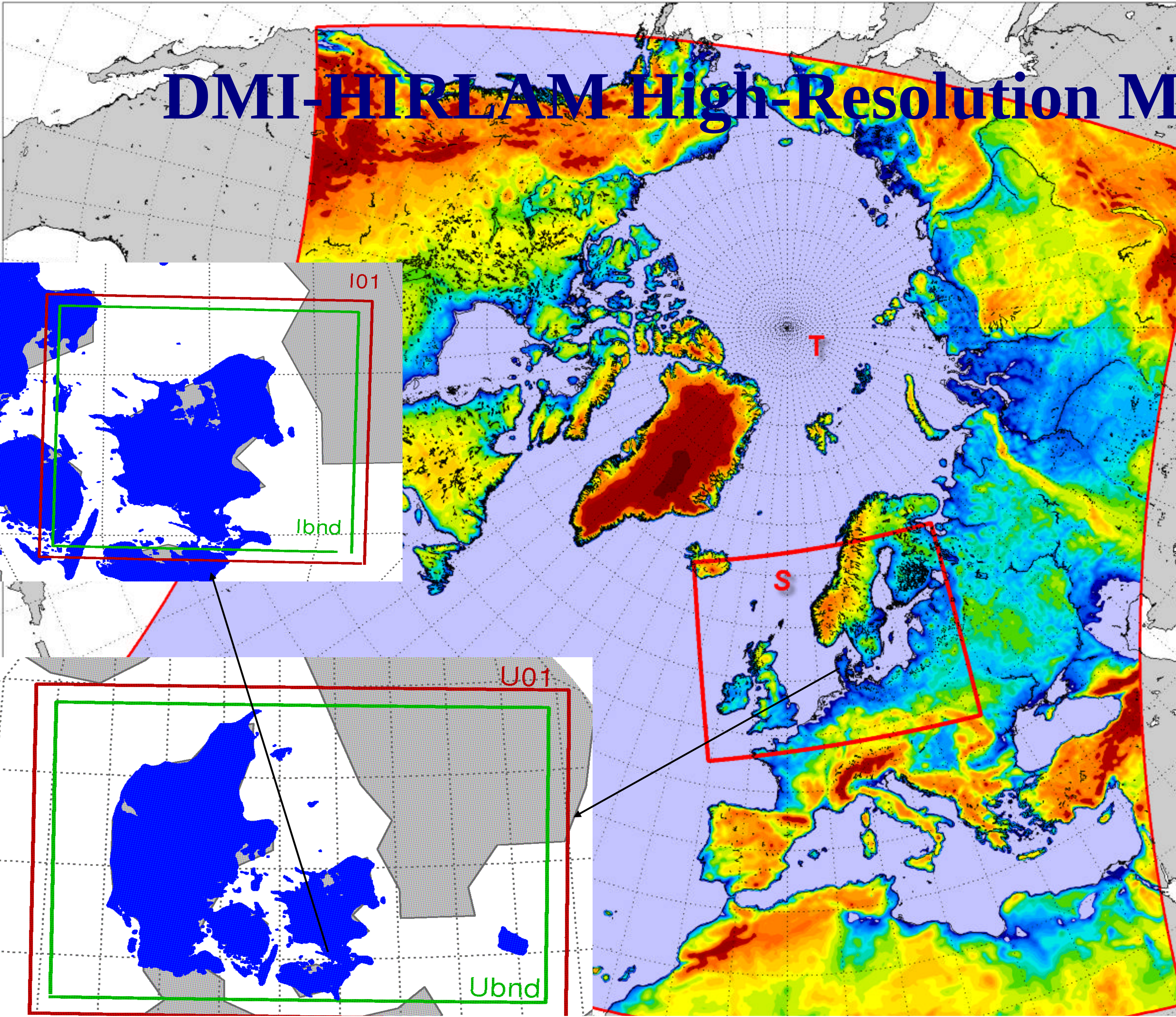
NWP models:

- DMI-HIRLAM (DMI);
- Lokalmodell, LM (DWD, ARPA), aLMo (MeteoSwiss);
- MM5 (UH, CORIA, DNMI, FMI);
- RAMS (CEAM, Arianet).

Current regulatory (dash line) and suggested (solid and dash lines) ways for systems of forecasting of urban meteorology for UAQIFS



DMI-HIRLAM High-Resolution Modelling



Hor. Resol.:

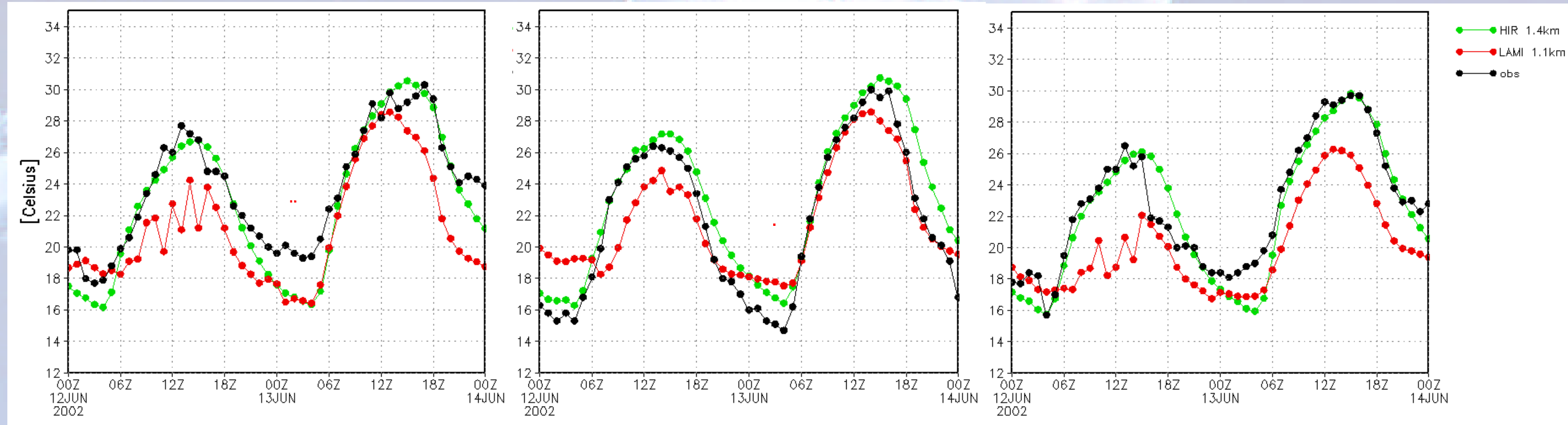
T: 15 km

S: 5 km

U01: 1.4 km

I01: 1.4 km

DMI-HIRLAM and ARPA-LAMI verification vs. Bologna episode data



Urban **Rural** **Semi-urban**

Time series of 2m temperature for DMI-HIRLAM 1.4km, ARPA-LAMI 1.1km and observations, 12 Jun 2002. Left: Bologna Piazza VIII Agosto. Middle: San Pietro Capofiume. Right: Sasso Marconi.

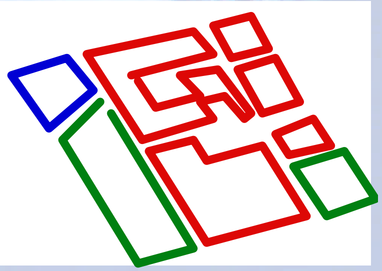
(FUMAPEX D3.4 Report)

Urban Land-Use Classification – Method (ECN)

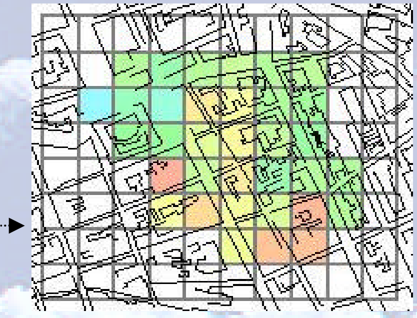
Long & Kergomard, 2004

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:

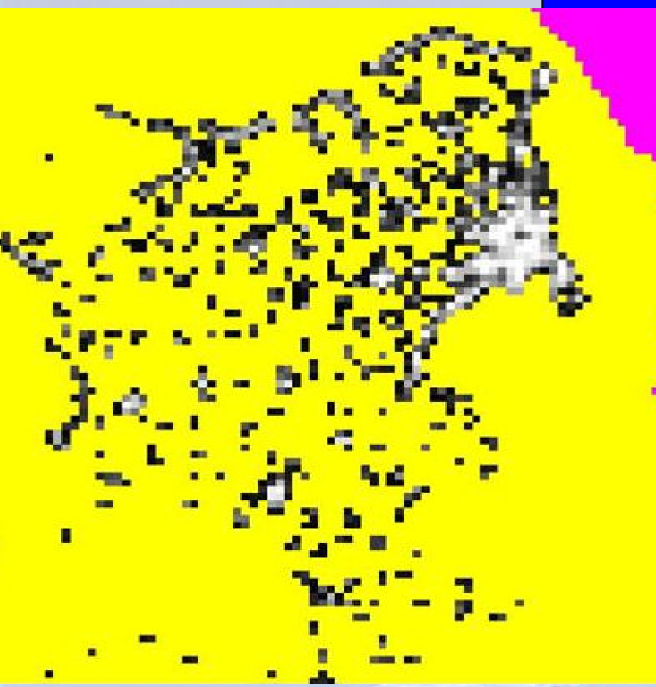
- Roughness length
- Displacement height
- Frontal & lateral SD

GIS

Land-Use Classification / Modification

Copenhagen Metropolitan Area

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



Dominating Class

Vegn - Green 2.74%
Vega & Art – White **0.08% + 0.12%**
Nat - Black 1.83%
Bare -Yellow 21.79%
Bat - Red **2.25%**
Eau - Blue 56.58%

Residential District

$BARE = 0.5\ BARE_{old}$
$ART = ART_{old} + 0.5\ BARE_{old}$

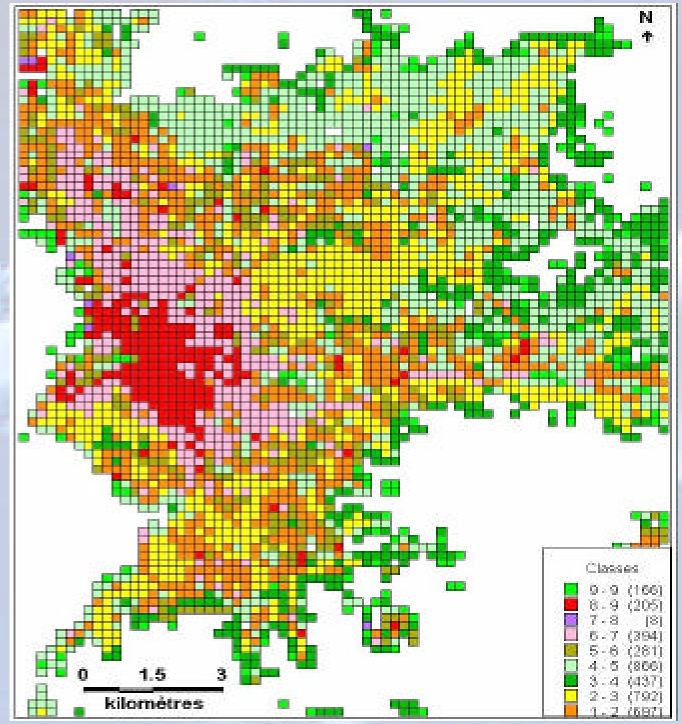
Industrial Commercial District (ICD)

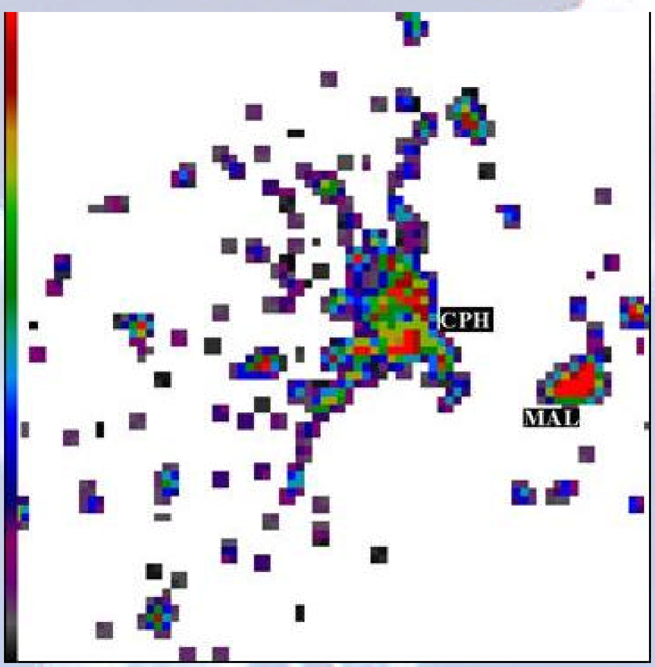
$BAT = 0.4\ BAT_{old}$
$ART = ART_{old} + 0.6\ BAT_{old}$

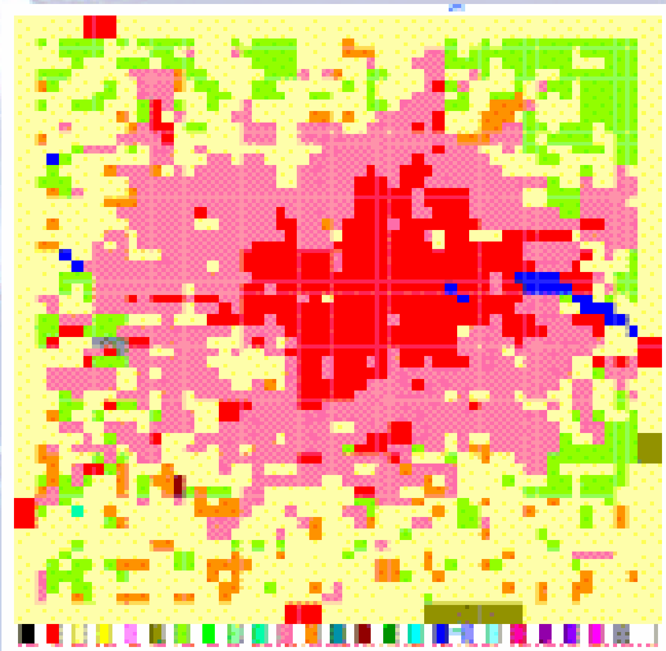
City Center (CC)/ High Building (HBD)

$BAT = 0.8\ BAT_{old}$
$ART = ART_{old} + 0.2\ BAT_{old}$
$BARE = 0.5\ BARE_{old}$
$VEGN = VEGN_{old} + 0.5\ BARE_{old}$

Examples of the urban land-use classification







Marseilles

Copenhagen

London

Ways to resolve the UBL structure

1. Obstacles-resolved numerical models

- CFD-RANS => 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

Different components of the stress in different layers

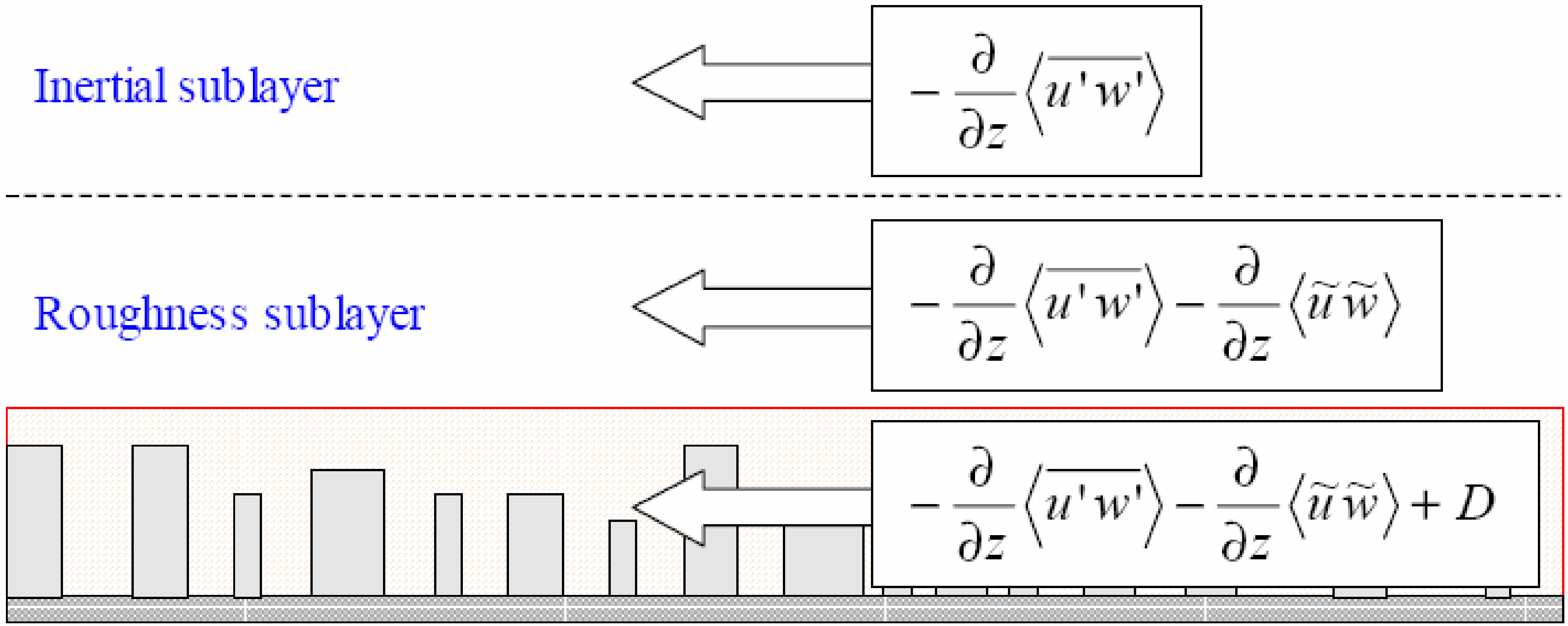


Figure 1 Schematic showing how the different components of the stress act in different layers.

COST-715 (2003)

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)

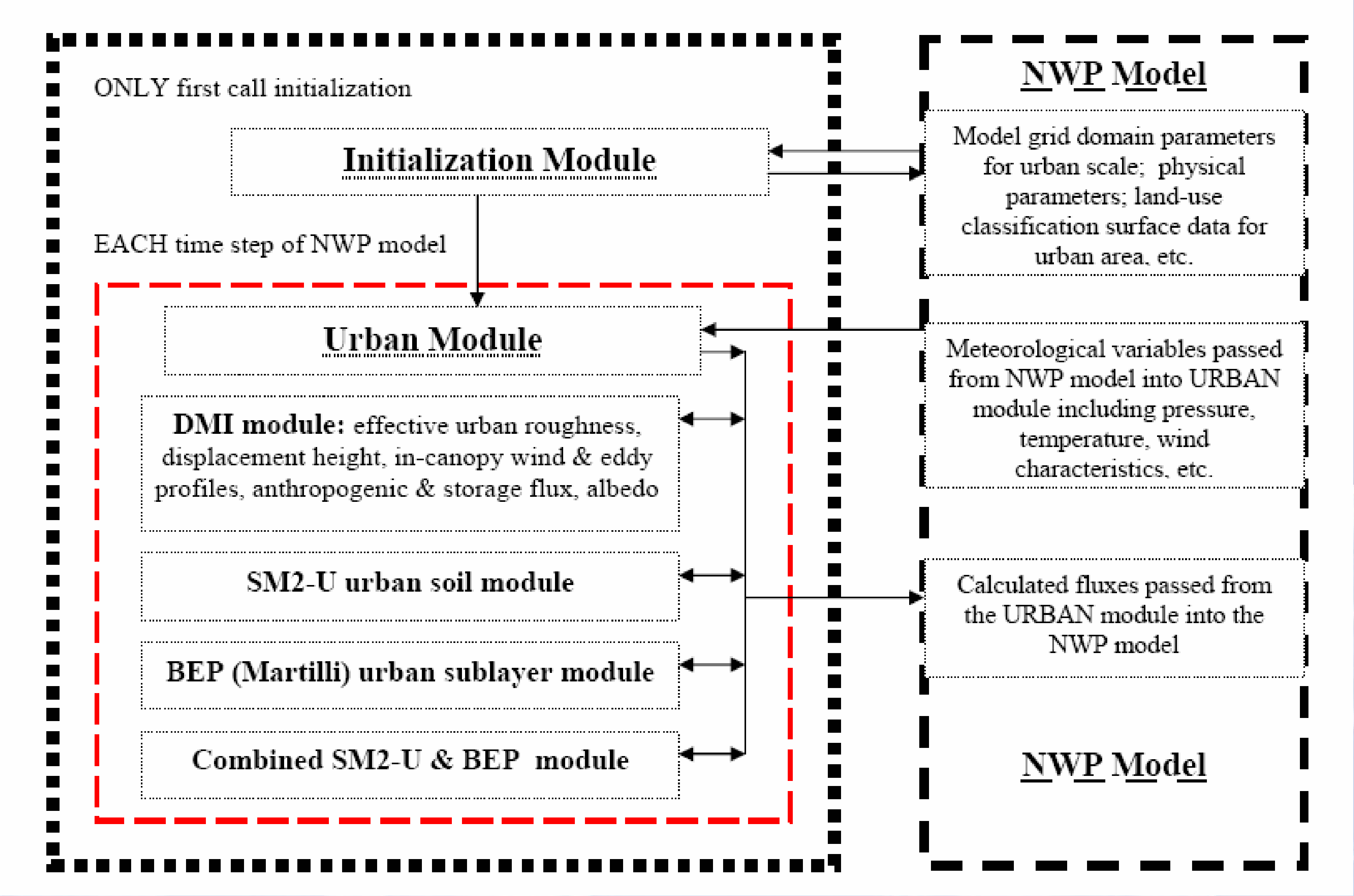
Two approaches to simulate the urban canopy effect:

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 *(Zilitinkevich and Baklanov, 2005)* 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).

Integrated Fumapex urban module for NWP models

including 4 levels of complexity of the NWP 'urbanization'



Module 1 (*DMI etc*): Analytical urban parameterisations

(i) Displacement height,

(ii) Effective roughness and flux aggregation,

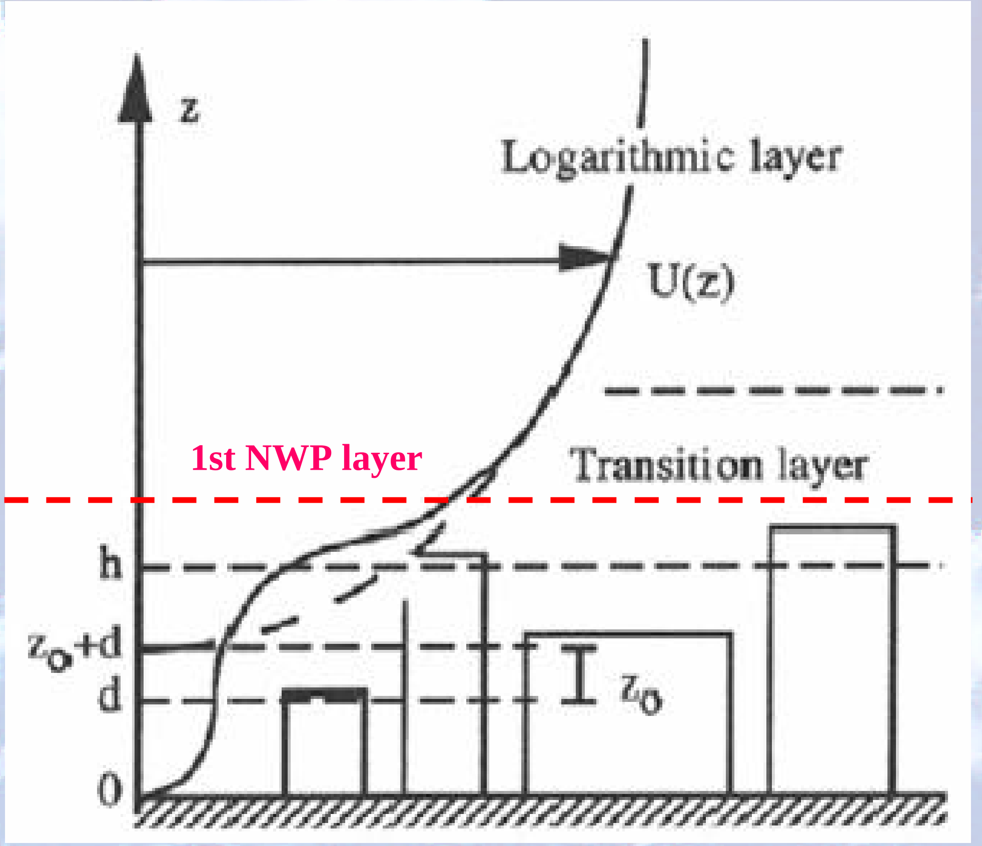
(iii) Effects of stratification on the roughness (Zilitinkevich et al, 2004),

(iv) Different roughness for momentum, heat, and moisture;

(v) Calculation of anthropogenic and *storage* urban heat fluxes;

(vi) Prognostic MH parameterisations for SBL;

(vii) Parameterisations of wind profile in canopy layer (Coceal and Belcher, 2004; Zilitinkevich and Baklanov, 2004).



$$U_h(z_s) = \frac{u_{*S}}{\kappa} \cdot \ln\left(\frac{z_s - z_d}{z_0} - \Psi_m(z_s/L)\right)$$

$$u_c = u_* \, (\lambda_f/2)^{-1/2}$$

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, 2005)

Depends on the building density.

- **Displacement height:**

d = 0.7 Zb for 0.3 < ?p < 0.5; 0.1 < ?f < 0 (Grimmond & Oke, 1999)

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

where: ?p = Ap/At; ?f = Ap/At.

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

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

Zilitinkevich et al. (2005)

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:**

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

• **Unstable stratification:**

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

Energy budget in urban areas

- **radiation budget**

  correction of albedo, ….
- **turbulent fluxes of sensible and latent heat**

  urban surfaces reduces the availability of soil moisture, …
- **storage heat flux**

  OHM model (Grimmond et al., 1991)
- **anthropogenic heat flux**

  simple parameterisation model is suggested.

$$\mathbf{Q^* = K^{-} - K- + L^{-} - L- = Q_H + LvE + Q_G + Q_F}$$

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).

The objective hysteresis model (OHM)

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

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

where *Q** is the net all-wave radiation, ?i are the plan fractions of each surface type in the area of interest and the a1- a 3i are the corresponding empirical coefficients. These a coefficients have been deduced from a re-analysis of the Multi-city Urban Hydrometeorological Database (MUHD)

Urban anthropogenic heat flux calculation

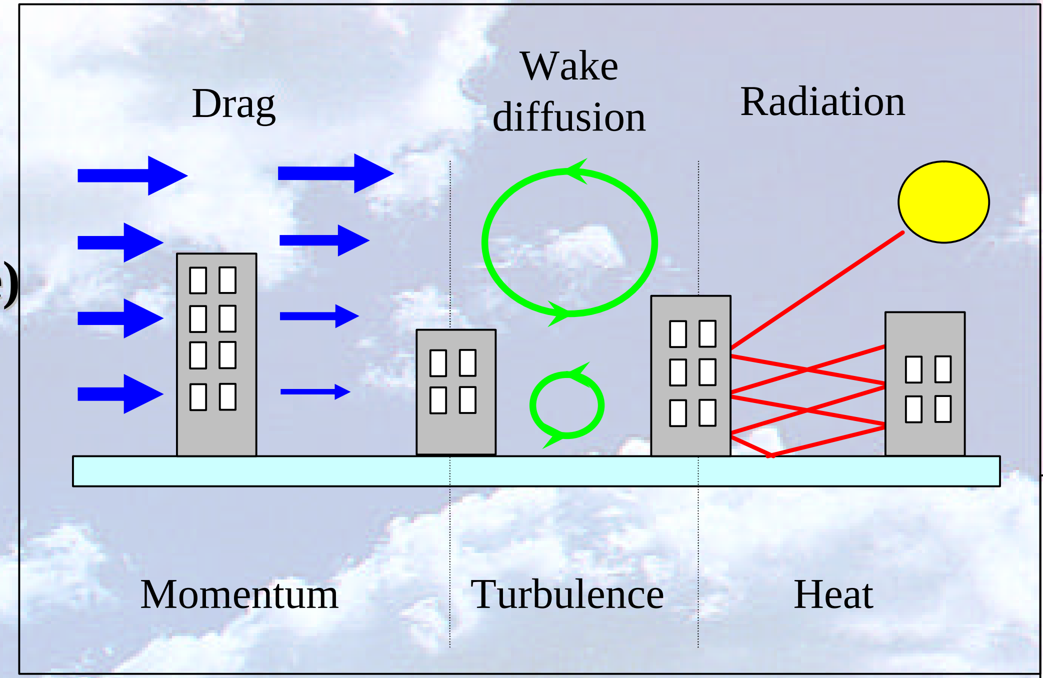
based on an assumption of dependency/proportionality to other urban characteristics, e.g.:

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).

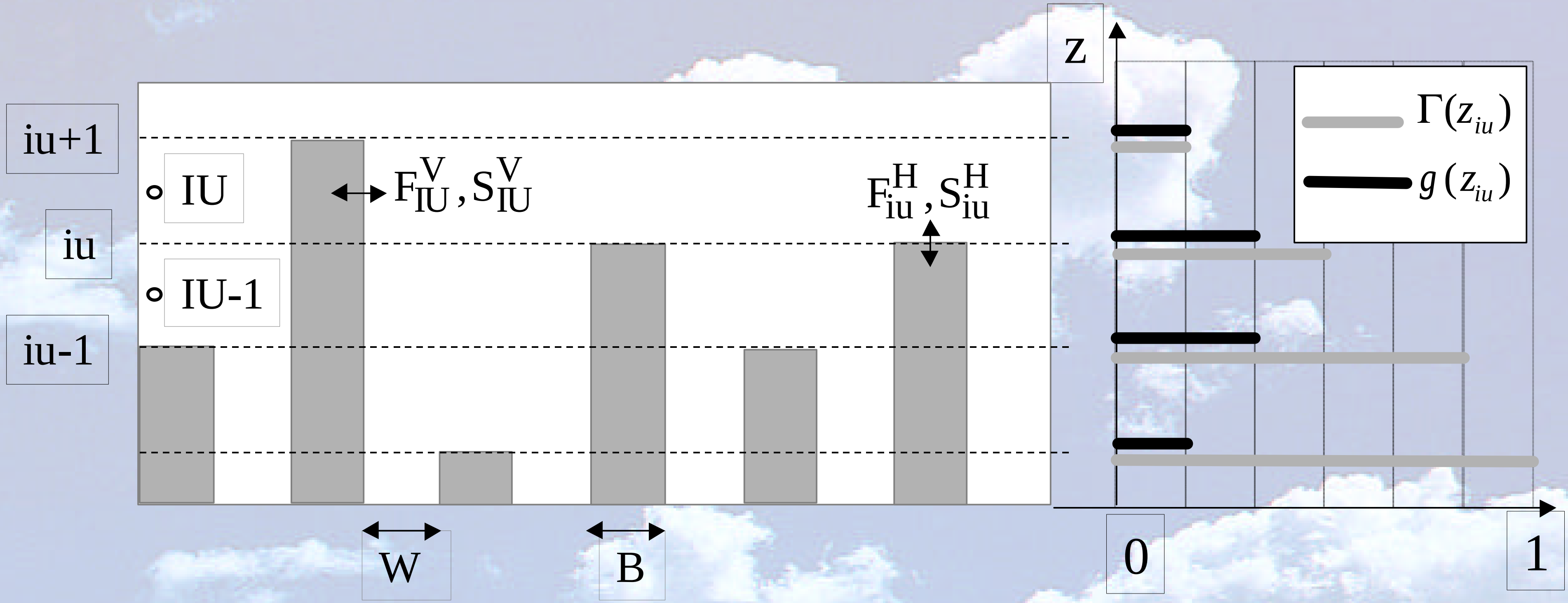
Reference values 20-**80**-160 W/m2

Module 2 (*EPFL etc*): BEP implemented in DMI-HIRLAM & LM:

• Modification of the original version (Martilli et al., 2002) for NWP
• Implementation of additional anthropogenic heat flux
• Improvements by UCL (Hamdi and Schayes, 2004) due to:
- new drag formulation (cumulated surface)
- Introduction of the fraction of vegetation
- Introduction of a new lateral friction
• Realization of BEP as a post-processor
• Implementation and tests in TVM, FVM, HIRLAM, aLMo
• Verification vs. urban experiments BUBBLE, ESCOMPTE
• Combination with the analytical profile into the urban canopy
• Improved formulation for different turbulence closure models



Schematic representation of the numerical grid in the BEP urban module



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

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

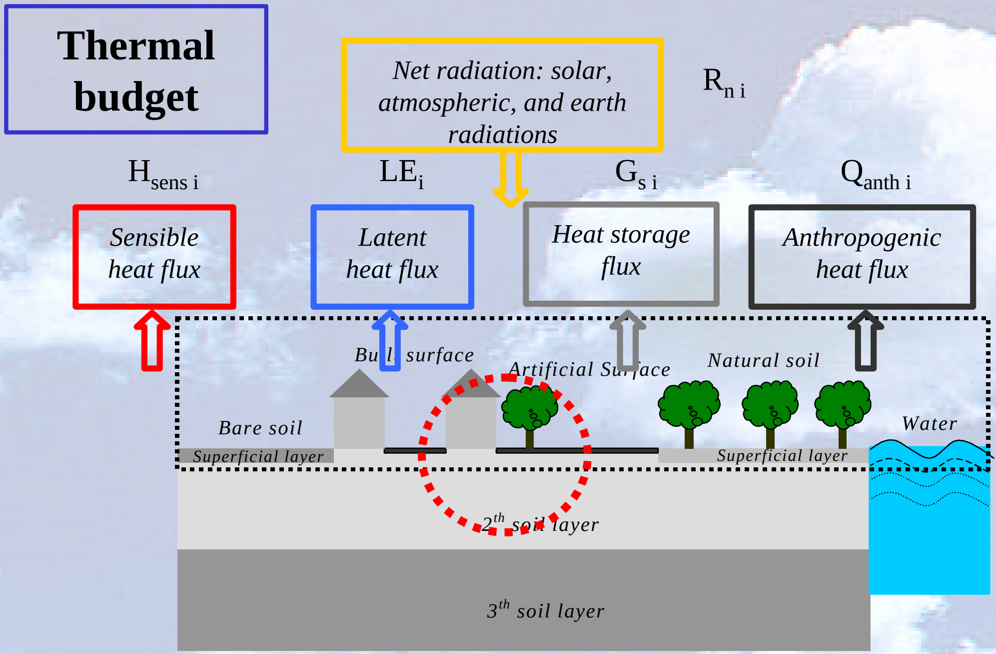
BEP Model: parameterization of Martilli et al. (2002)

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

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

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

Module 3 (ECN) SM2-U : Soil-Canopy-Atmosphere Energy Budget Model Adapted to Urban Districts



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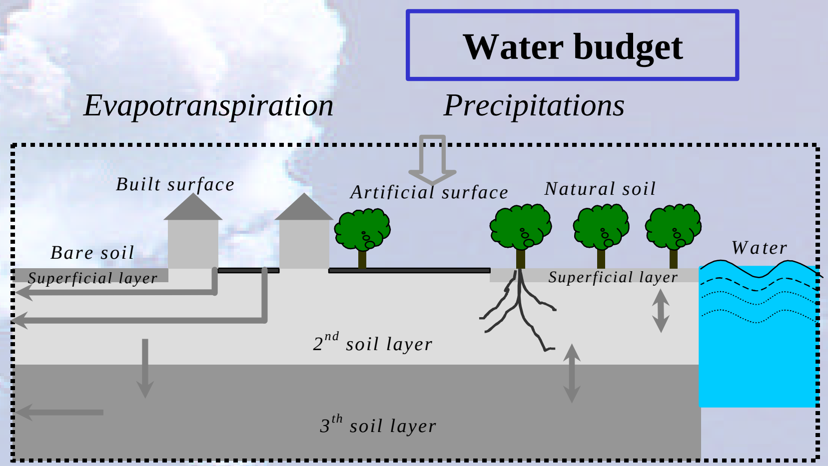

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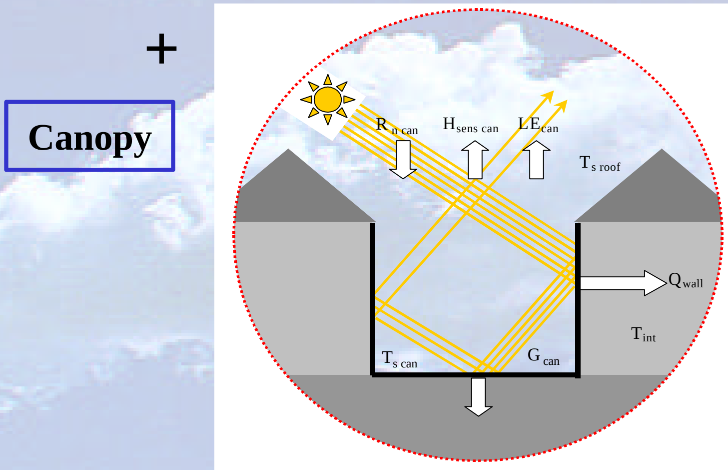


$$Q_H + Q_E + Q_G = Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

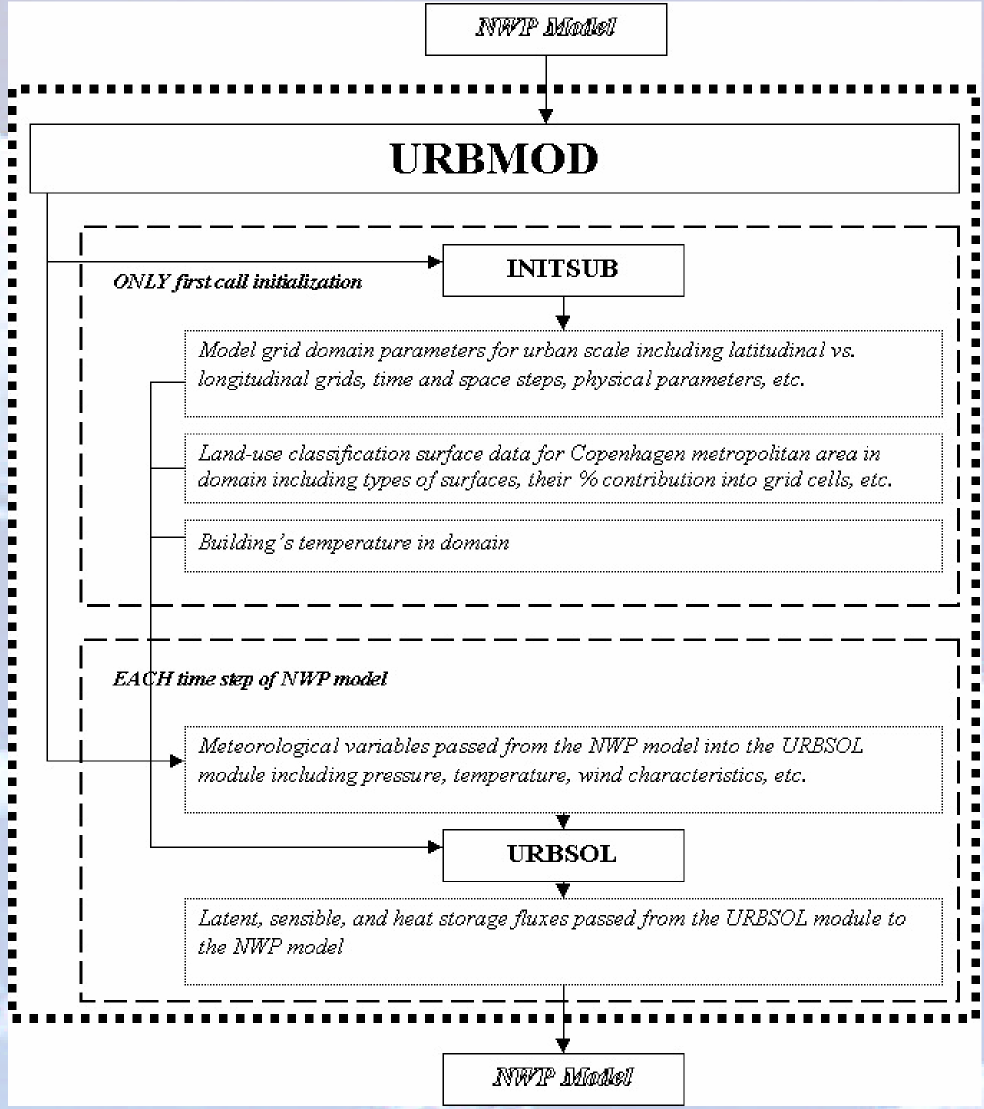
$$dT_s/dt = C_T Q_G - (2\pi/\tau)(T_s - T_{soil})$$

$$Q_G = \text{Ground flux} \ ; \ \tau = 24 \text{ h}$$

(Mestayer et al., 2004; Dupont et al., 2005ab)

Modifications of SM2-U

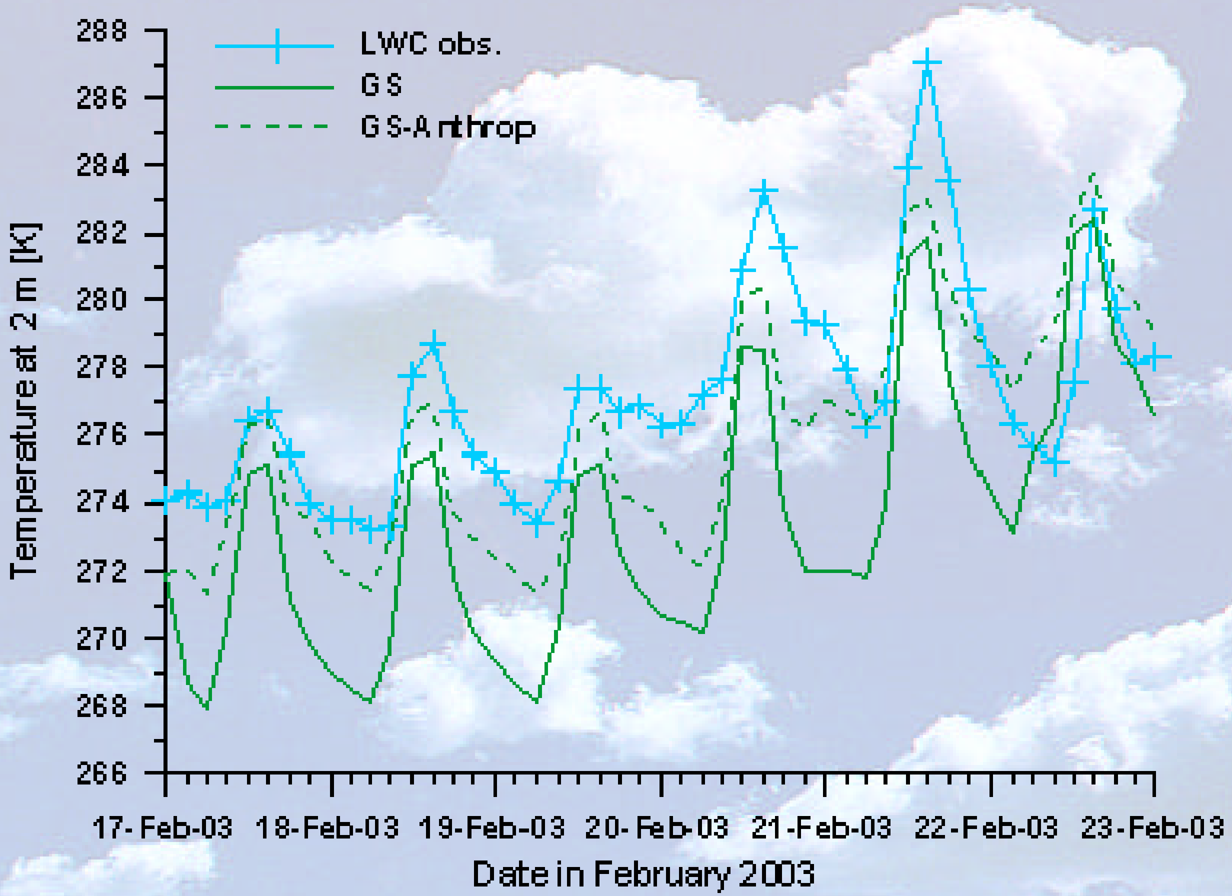
- Modification and simplification for NWP
- SM2-U realization only for urban grid-cells
- Implementation of anthropogenic heat fluxes
- Realization of SM2-U as an LES mode
- Implementation and tests in HIRLAM
- Combination with Martilli drag formulation
- Verification vs. urban experiment ESCOMPTE
- Tests for Marseilles, Copenhagen, Paris



Urbanization of the FUMAPEX NWP models

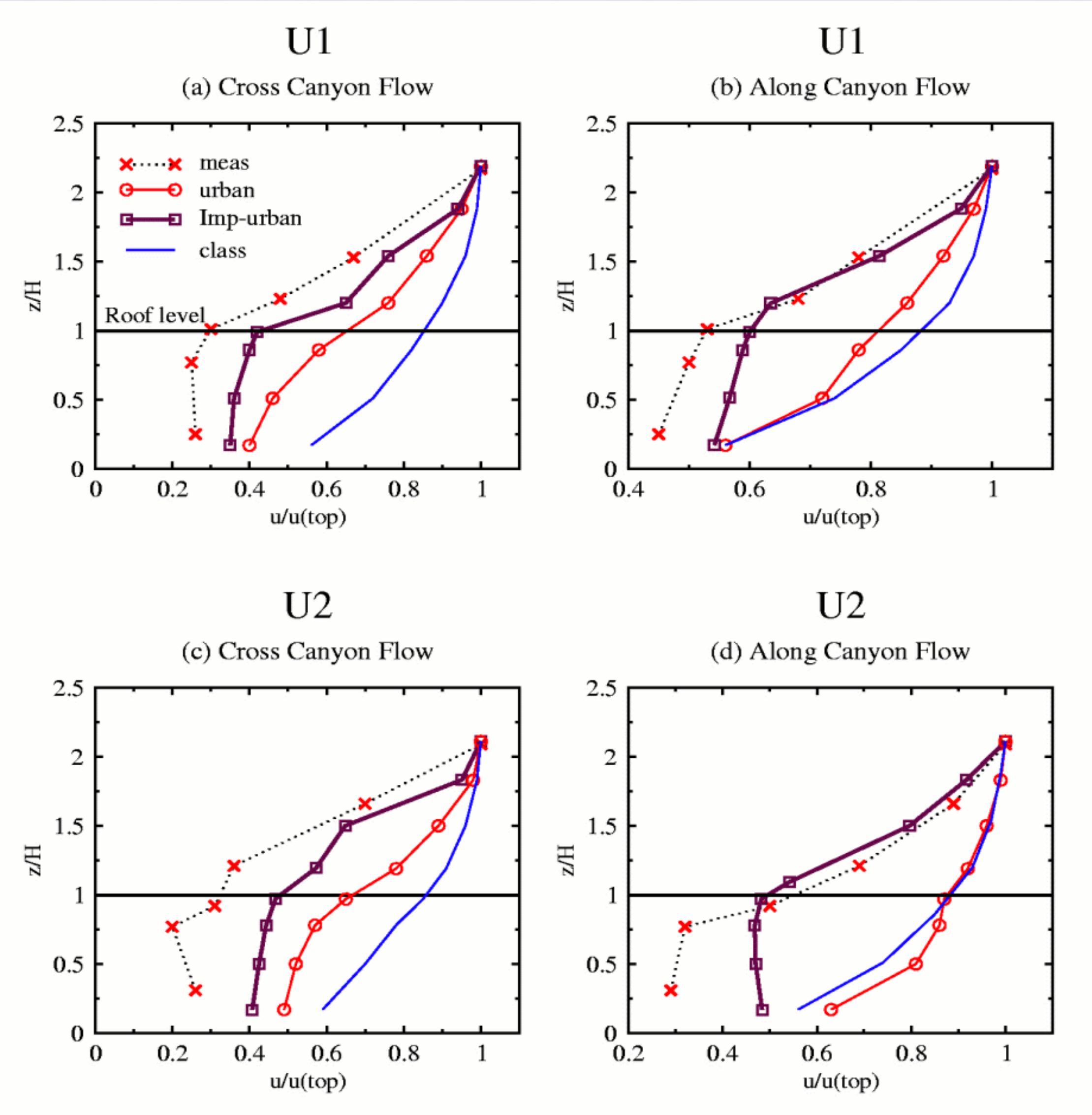
Models	Partner	Resolution	Urb. LUC	Roug. appr.	Urb. fluxes	BEP	SM2-U	UMH	Cities
Research:									
Sub-Meso	ECN	1 km	4(9)				+		Copenhagen, Marseilles
FVM	EPFL	1 km	1(up to 10)			+			Basel
TVM	ECL	1 km	1 + char.			+			Basel, Marseilles
MM5-SM2U	ECN, CORIA	3 km	1 uc + 4 sc	+		+	+		Paris
NWP:									
HIRLAM	DMI	1.4 km	1 + 4	+ (+USL)	+	+	+	+	Copenhagen, Malmø
Lokalmodell	DWD	1.1 km	1	+	+			+	Helsinki, Bologna, etc.
aLMo	EPFL/MetSwiss	7 km	1 + char.	+		+			Basel
MM5	UH	1 km	1	+	+				London
RAMS	CEAM	1.5 km	1(imp.LUC)						Valencia/Castellon
MM5+HIRLAM	Met.no	1 km	1?	+				+	Oslo, Bergen, etc.
RAMS	ARIANET	1 km	1	+	+			+	Torino
LAMI	ARPA	1.1 km	1	+				+	Bologna

Verification of improved MM5 runs for London



2m-temperature at London Weather Centre predicted by GS and GS with added anthropogenic heating

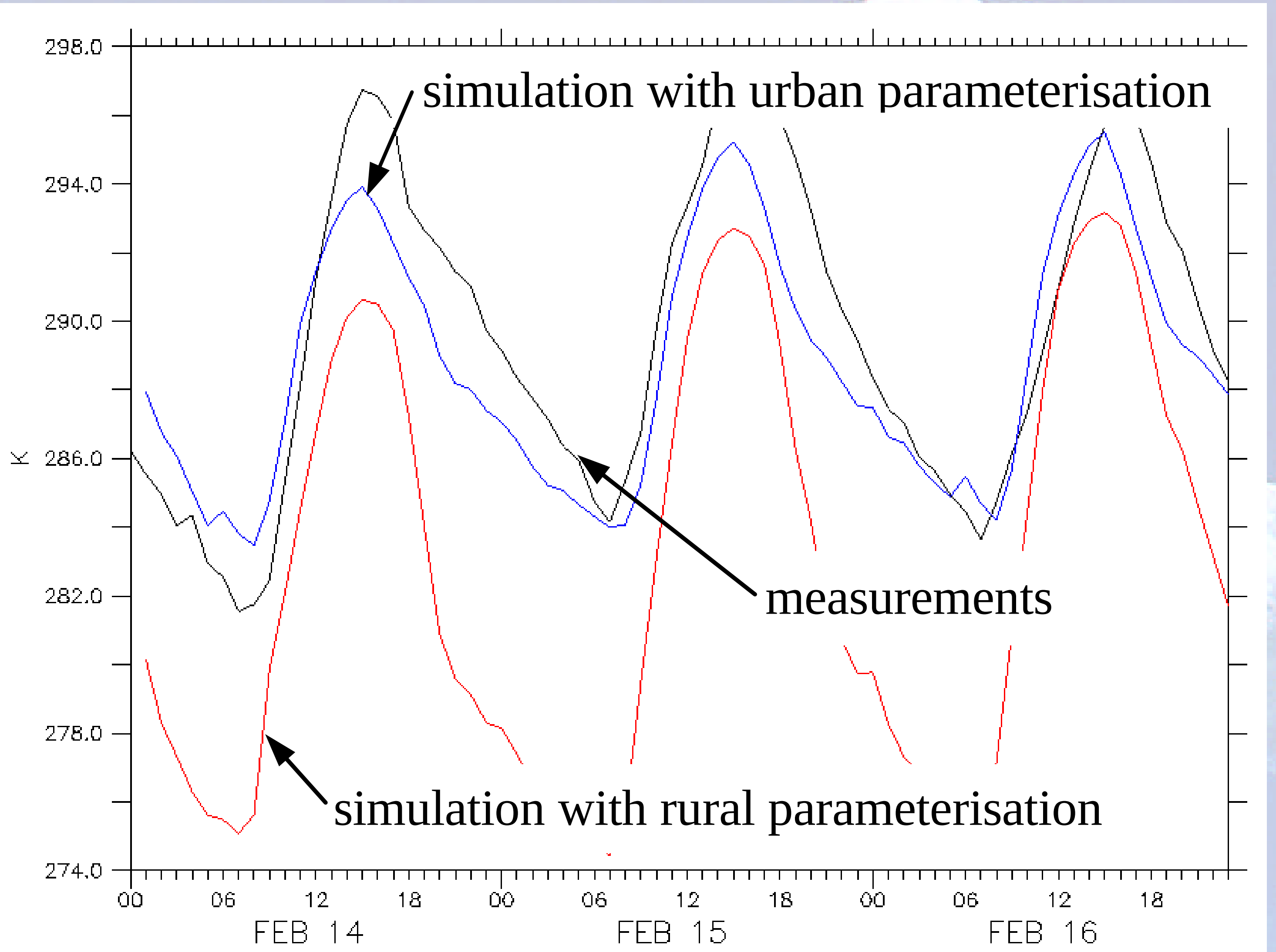
Verification of the improved Martilli model



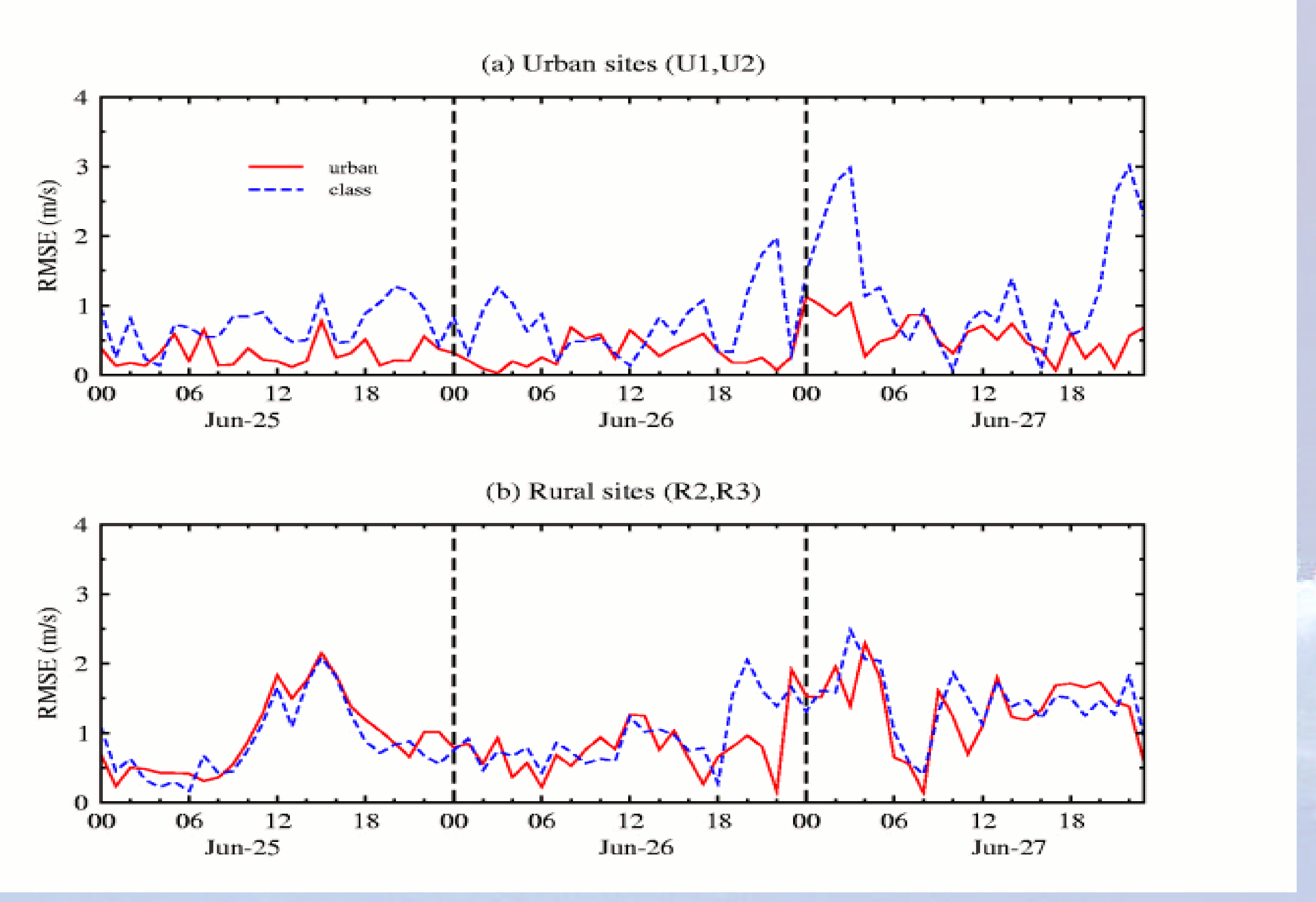
The wind speed profile normalized by u (top) at the tower for cross canyon (left) and along canyon flow (right) for the two sites U1 and U2 in Basel.

UCL contribution

Temperature measured & simulated with and without urban parameterization (version 2) for Mexico City



Verification of the improved BEP model (cont.)



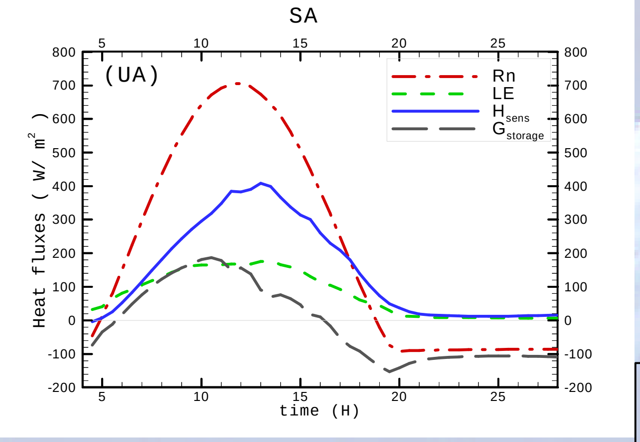
The RMSE of the difference in wind speeds between observations with classical simulation (blue) and urban ones (red).

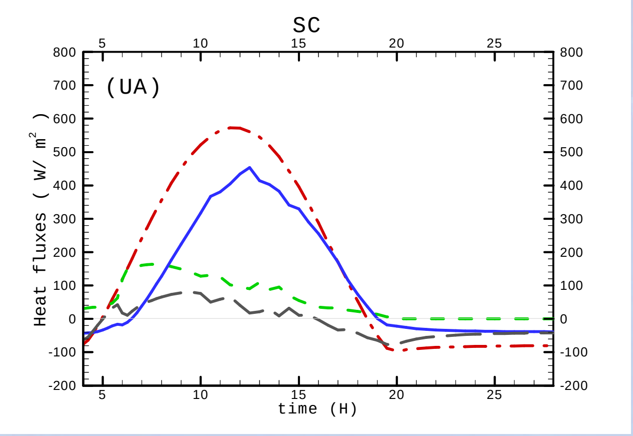
SM2-U Sensitivity Study on City Representation

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 :

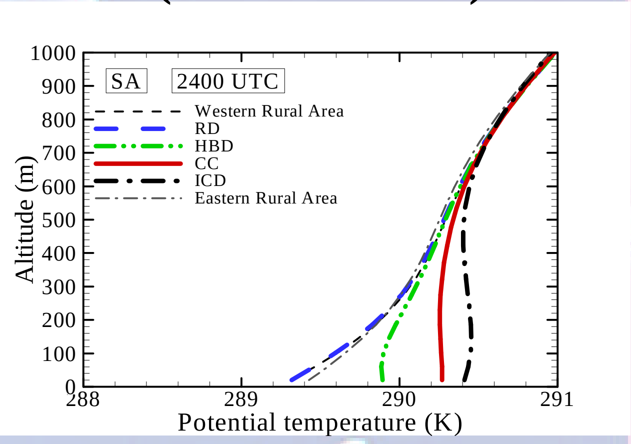
stores & releases less energy (no radiative trapping) ;

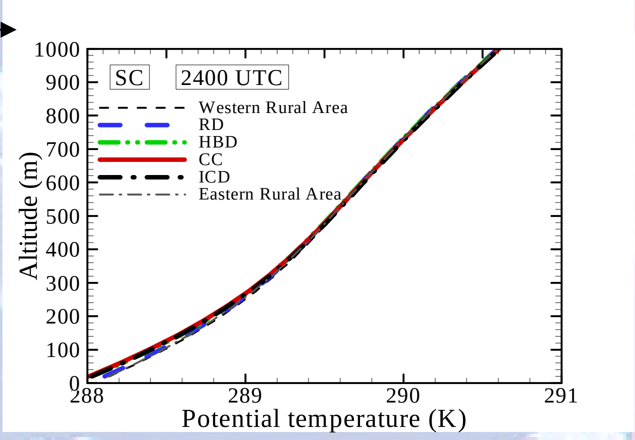
Rn is weaker (higher albedo)

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)



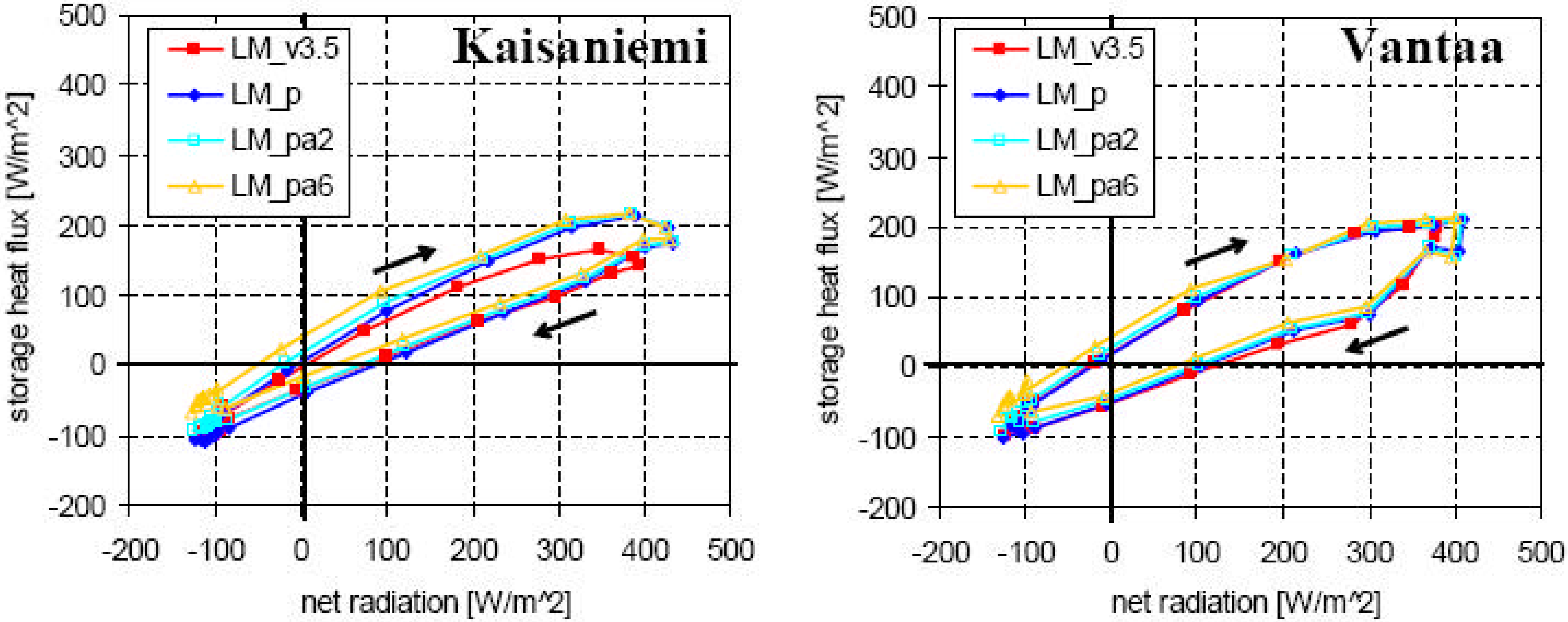


With ECN contributions of I. Calmet, S. Leroyer, N. Long

Assessment of urbanisation effect

Hysteresis loop: storage heat flux vs. net radiation (Grimmond et al., 1999)

Helsinki, 10 Apr 2002, forecast hours 1 - 24



Downward fluxes positive

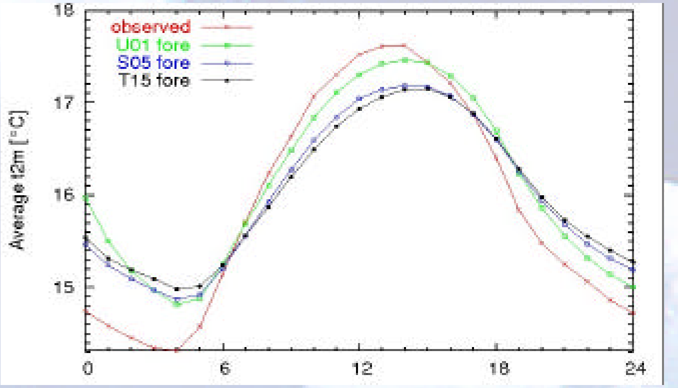
urbanised external parameters: axis of loop turns towards diagonal

=> storage heat flux becomes more important ✓

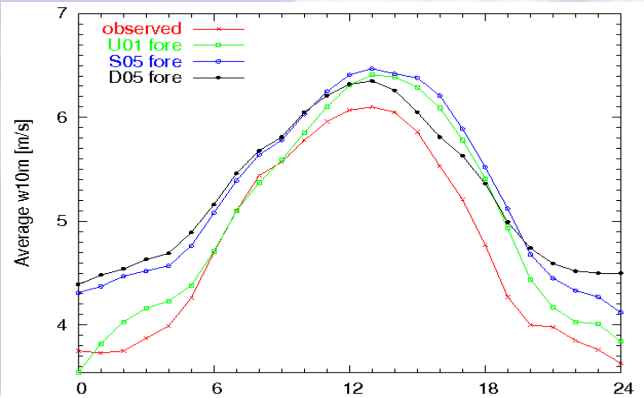
anthropogenic heat source: axis turns back

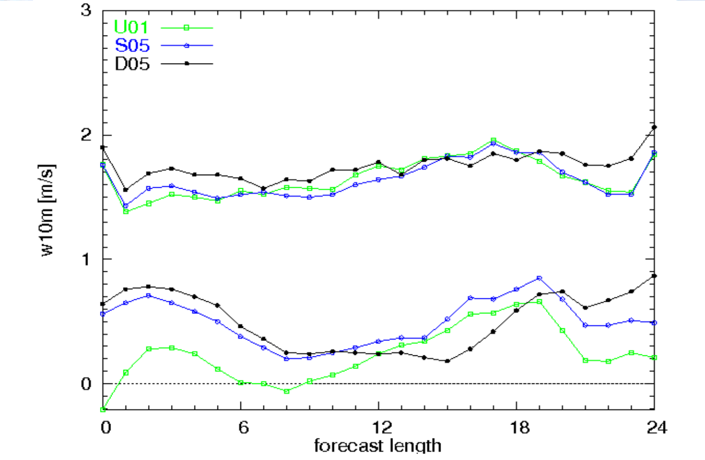
=> caused by increase of storage heat flux during night

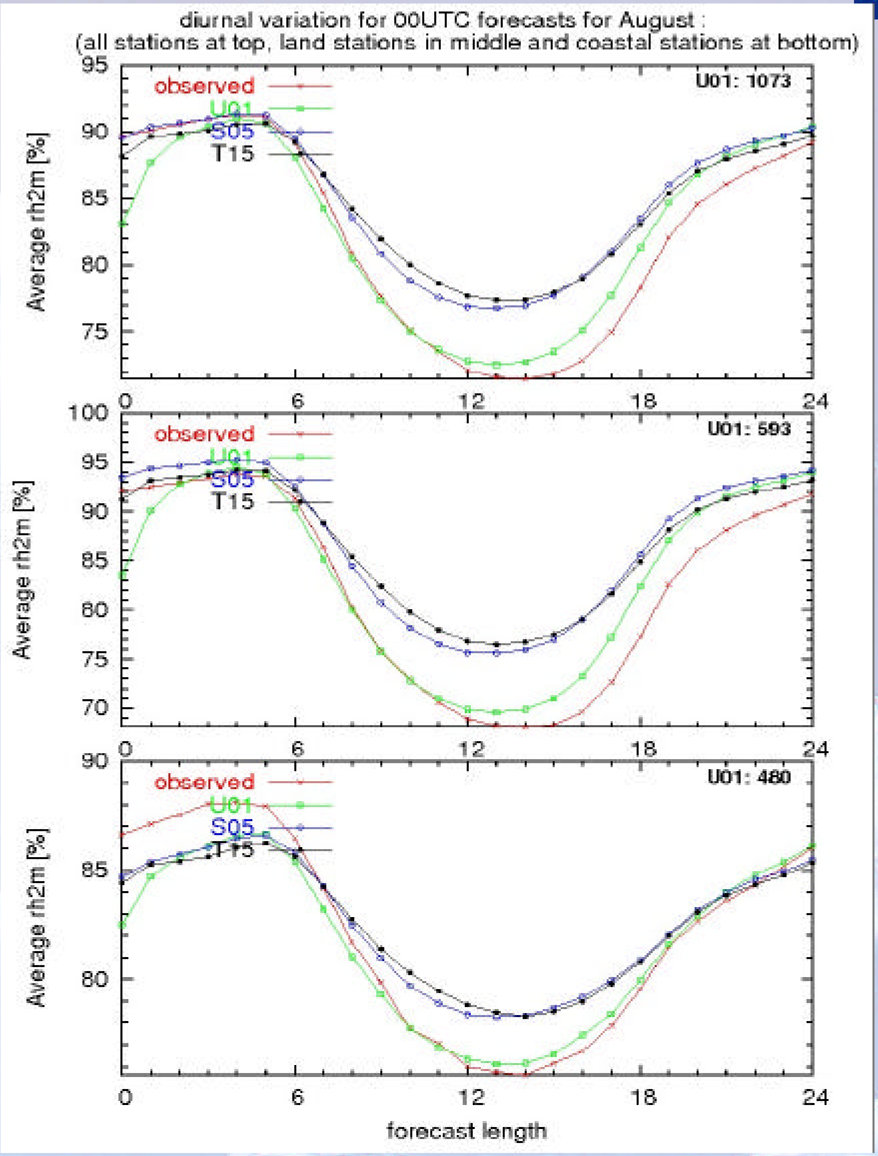
HIRLAM NWP Model Performance: Overall



all stations

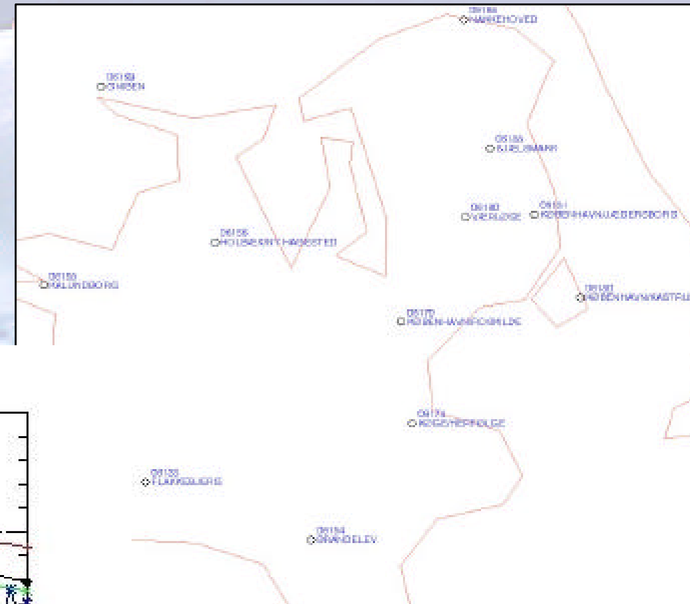


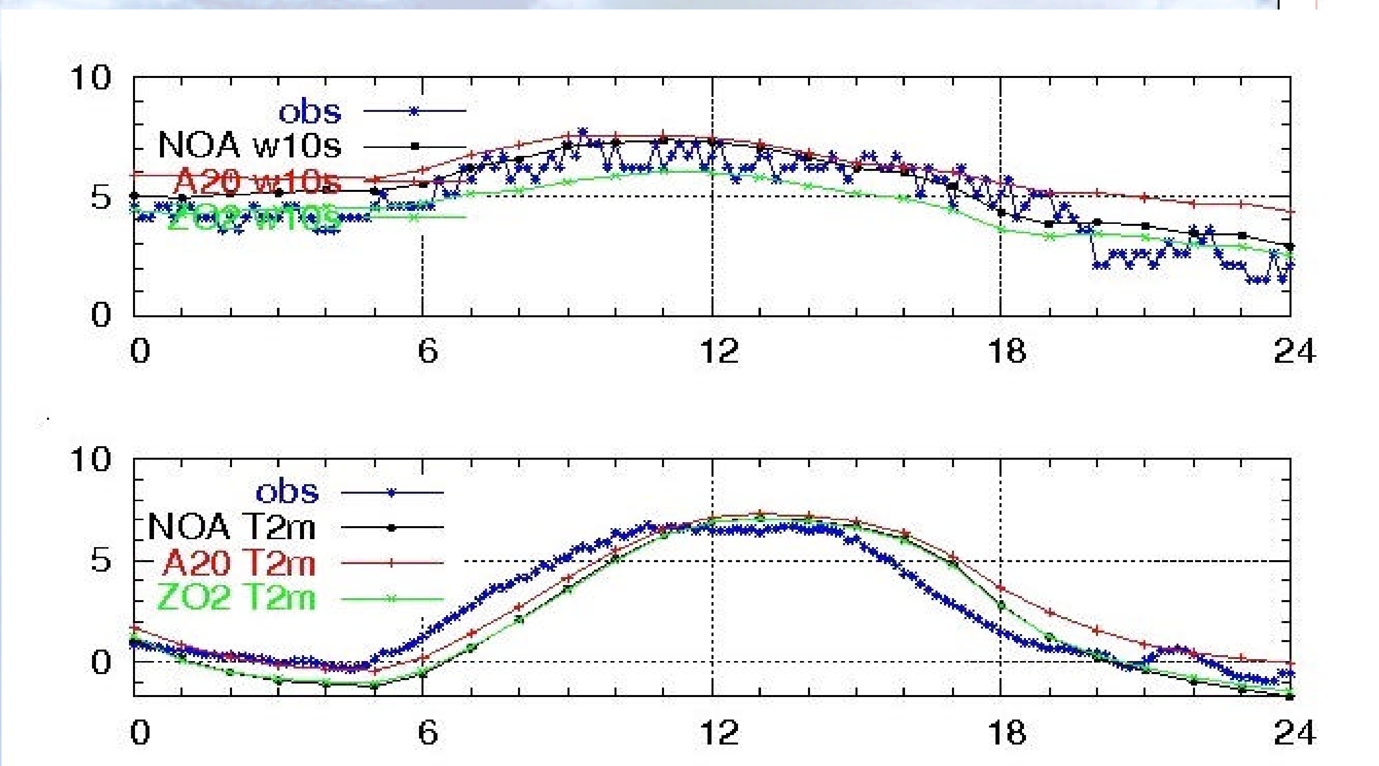




HIRLAM NWP Model Performance: Over Urban Areas

Wind velocity at 10 m (w10s, in m/s; top panel) &
Air temperature at 2 m (T2m, in deg. C; lower panel)
based on the DMI-HIRLAM-U01 control (NOA) vs
urbanized runs (A20, ZO2) vs. observational data (obs)





Værløse urban station
(55.8ºN, 12.3ºE)
located in metropolitan
Copenhagen

HIRLAM NWP Model Performance: Conclusions

- Long-term runs with the DMI-HIRLAM-U01/I01 high resolution urbanized model showed a slight improvement for the overall NWP model performance, &

  this improvement is more considerable over the urbanized areas

Differences between NWP control vs. urbanized runs:

- **For typical wind conditions**:
  - wind at 10 m (m/s) <0.5 (max up to 1.5, at midday)
  - temperature at 2 m (ºC) <0.25 (max up to 0.5, at nighttime)
  - relative humidity (%) > 3 (max up to 5, at midday)
- **For low wind conditions**:
  - wind at 10 m (m/s) >1 (max up to 3 at nighttime)
  - temperature at 2 m (ºC) >0.5 (max up to 1.5, at nighttime)
  - relative humidity > 4 (max up to 7, at midday)

Approaches applicability

- All 3 approaches give reasonable improvements of meteorological fields over urban areas.
- The first module is the cheapest way of “urbanising” the model and can be easily implemented into operational NWP models as well as in Regional Climate Models.
- The second module is a relatively more expensive (˜ 5-10 % computational time increase), but it gives a possibility to consider the energy budget components and fluxes inside the urban canopy. However, this approach is sensitive to the vertical resolution of NWP models and is not very effective if the first model level is higher than 30 meters. Therefore, the increasing of the vertical resolution of current NWP models is required.
- The third module is considerably more expensive computationally than the first two modules (up to 10 times!). However, it provides the possibility to accurately study the urban soil and canopy energy exchange including the water budget. Therefore, the second and third modules are recommended for use in advanced urban-scale NWP and meso-meteorological research models.

Further improvements

- The current versions of the considered urban modules have several shortcomings and have to be improved and further developed.
- For the first approach (module 1), the complemented analytical model for wind velocity and diffusivity profiles inside the urban canopy (e.g. *Zilitinkevich and Baklanov*, 2006) has to be tested with different NWP models and meteorological preprocessors, and carefully verified vs. experimental data for different regimes. Besides, it is advisable to extend this model for temperature and humidity profiles.
- The current version of the second module (BEP) does not consider the moisture and latent heat fluxes and does not completely incorporate the anthropogenic heat flux. Therefore, these should be included into a new version of the BEP module. Besides, recalculation of accessible meteorological fields in the lowest sub-layers is necessary.
- The third module (SM2-U) needs further development considering the building drag effect (it is realised in module 4), whereas snow and ice have to be included for NWP during winter periods, especially for northern areas. The existing version of this module, when run for every grid-cell, is too expensive for operational NWP models, therefore the module has to be optimised by making calculations only for the urban cells.
- The combined module (#4), including all non-overlapping mechanisms from the SM2-U and BEP models, have to be further tested.

Development of meteo-processor and interface between urban scale NWP and UAP models

WP5:	*Interface to Urban Air Pollution models*		
Mixing height and eddy diffusivity estimation	**Down-scaled models or ABL parameterisations**	**Estimation of additional advanced meteorological parameters for UAP**	**Grid adaptation and interpolation, assimilation of NWP data**

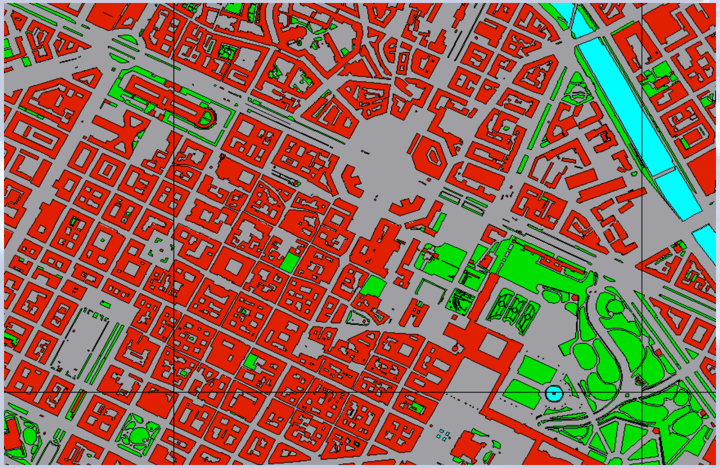
- **Guidelines for and improvements of interfaces (Finardi et al., 2004)**
- **Interface vs. pre-processors for modern UAQ models**
- **BEP urbanization module as a post-processor (Clapier et al., 2004)**
- **DMI new urban meteo-preprocessor (Baklanov and Zilitinkevich, 2004)**
- **MH methods for urban areas (WG2 COST715)**

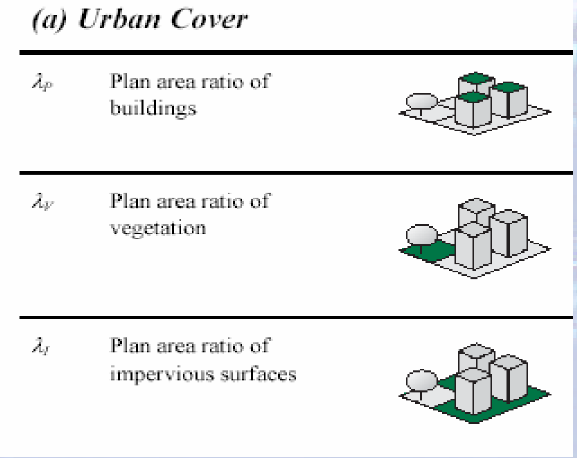
Urban Meteo-Preprocessor

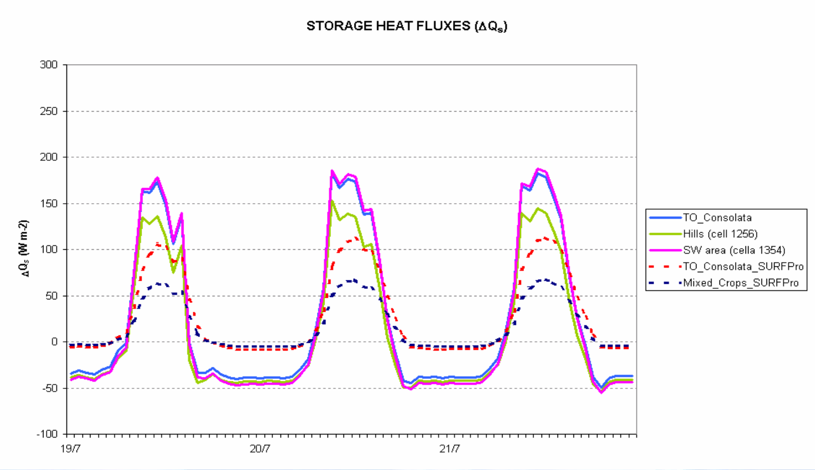
- High-resolution urban-scale NWP data
- Calculation of effective roughnesses (for momentum and scalars) and displacement height
- Parameterization of wind and eddy profiles in urban canopy layer
- Calculation of anthropogenic and storage urban heat fluxes
- Prognostic parameterizations for Mixing Height
- Improved sigma parameterization for SBL
- Urban module as post-processor for NWP data

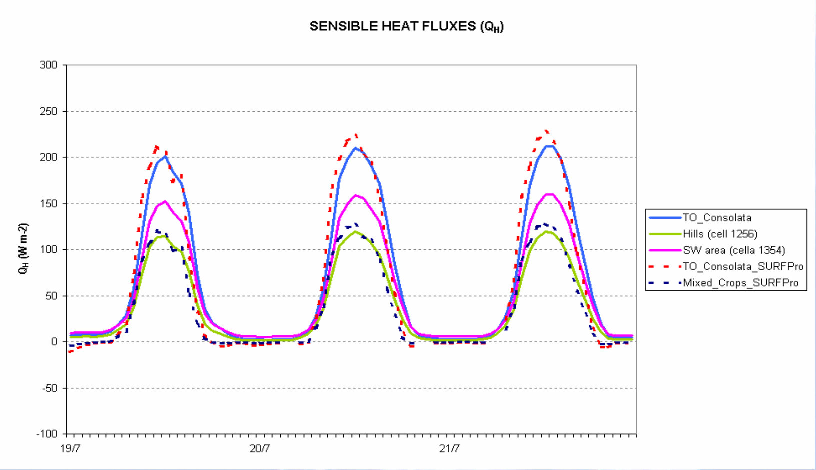
WP5: improved interface modules

Computation of Grimmond & Oke OHM model classes over Torino city and evaluation of Surface Energy Balance variations (P14-ARPAP)

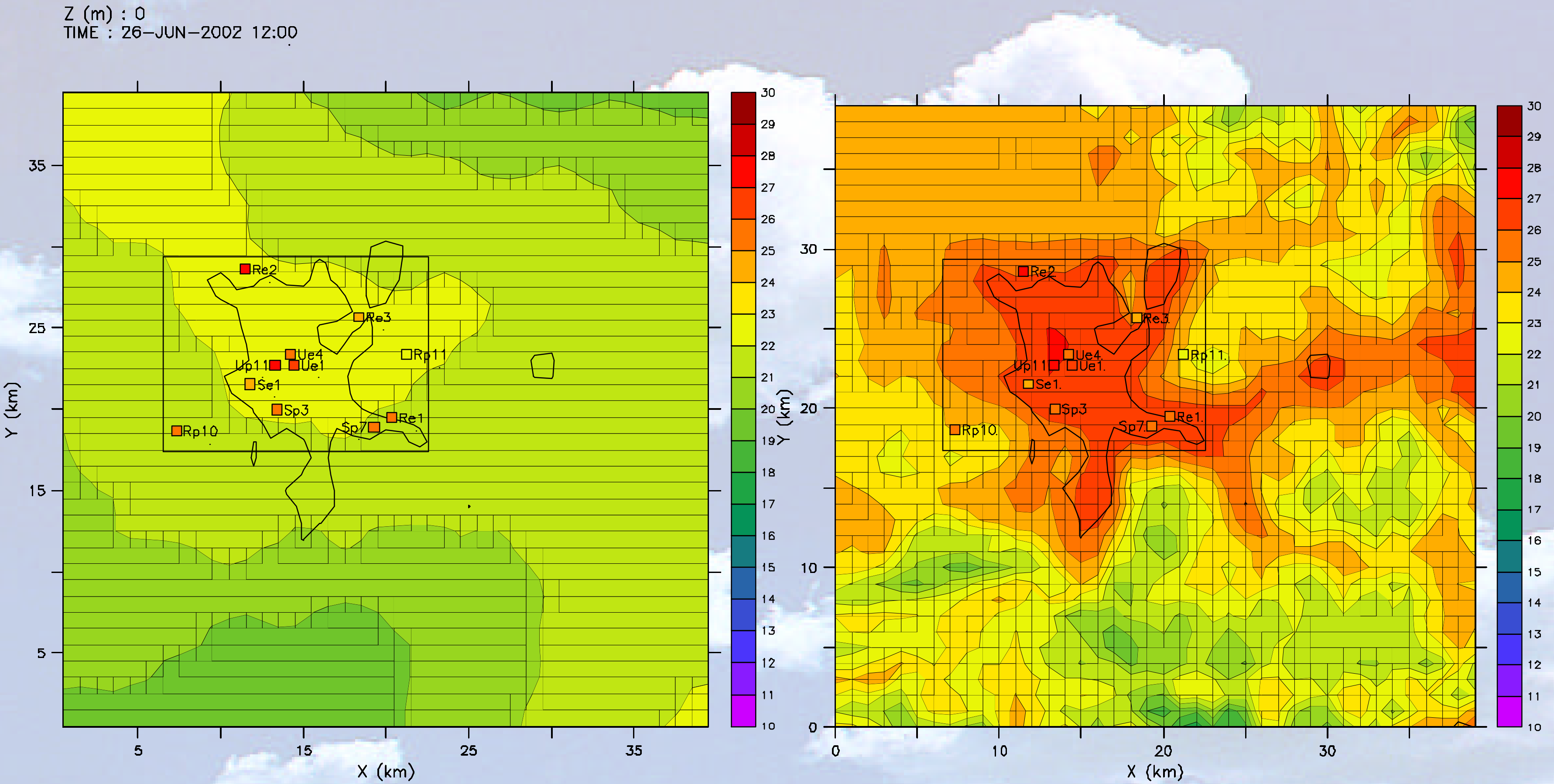








Simulation of Basel heat island by aLMo and BEP



Temperature fields at the ground level at noon June 26 over the Basel area: The temperatures are interpolated from LM (left) or recalculated with the urban parameterisation (right). The black line indicates the city boundaries .The squares show the measured temperature at several places.

(EPFL contribution: Clappier et al.)

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.

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):

$$\left\{ \frac{h^2}{(1+2A)h-2Bk\,L} + \frac{Cu_*^2 T}{g\,g[(1+A)h-Bk\,L]} \right\} \left(\frac{\P h}{\P t} + u\frac{\P h}{\P x} + v\frac{\P h}{\P y} - w_s \right) = \frac{\left(\overline{w'q'}\right)_s}{g},$$

- 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:

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

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

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

Stability parameters: $m = \dfrac{u_*}{|\, f \,|\, L}$ internal, $m_N = \dfrac{N}{|\, f \,|}$ external.

Zilitinkevich et al. SBL height formulation (Cont.)

The MO length scale L and the internal-stability parameter

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

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

Free-atmosphere parameters:

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

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

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

Empirical evaluation of different SBL height parameterisations

Reference	SBL height equation	Bias	RMS error	Correlation coefficient
Benkley & Schulman, 1979	$h = 125\, u_{10}$	208	264	0.48
Arya, 1981	$h = 0.42\, u_*^2 \mid fB_s \mid^{-1/2} + 29.3$	64.0	218	0.27
Arya, 1981	$h = 0.089\, u_* / \mid f \mid + 85.1$	103	86.3	0.48
Mahrt, 1982	$h = 0.06\, u_* / \mid f \mid$	-24.4	18	0.48
Niewstadt, 1984	$h = 28\, u_{10}^{3/2}$	6.27	13.9	0.48
Niewstadt, 1984	$h = 0.4\, u_*^2 \mid fB_s \mid^{-1/2}$	24.4	173	0.27
Zilitinkevich & Mironov, 1996	$\left(\frac{fh}{0.5u_*}\right)^2 + \frac{h}{10L} + \frac{Nh}{20u_*} + \frac{h\lvert f\rvert^{1/2}}{(u_* L)^{1/2}} + \frac{h\lvert Nf\rvert^{1/2}}{1.7u_*} = 1$	-33.8	33.8	0.38
Zilitinkevich et al., 2001a	$h = \frac{0.4u_*}{\lvert f\rvert}\left[\left(1+0.3\frac{w_h}{u_*}\right)\Big/\left(1+\frac{0.16u_*(1+0.25NL/u_*)}{0.55L\lvert f\rvert}\right)\right]^{1/2}$	6.21	19.2	0.60

Ri-number methods for SBL height estimation

Following Zilitinkevich & Baklanov (2002), we can distinguish four different Ri methods.

1. Gradient Richardson number. Infinitesimal disturbances in a steady-state homogeneous stably stratified sheared flow decay if the gradient Richardson number Ri exceeds a critical value Ri*c*,

$$\mathrm{Ri} \equiv \frac{b\left(\partial q_v / \partial z\right)}{\left(\partial u / \partial z\right)^2 + \left(\partial v / \partial z\right)^2} > \mathrm{Ri}_c = 0.25$$

2. Bulk Richardson number. An alternative, widely used method of estimating *h* employs, instead of the gradient Richardson number Ri, the boundary-layer bulk Richardson number, Ri*b*, specified as

$$\mathrm{Ri}_B \equiv \frac{b\Delta q_v h}{U^2}$$

   through the wind velocity at the upper boundary of the layer and the virtual potential temperature increment across the layer.

3. Finite-difference Richardson number. The idea is to exclude the lower portion of the SBL and to determine a "finite-difference Richardson number", Ri*F*

$$h_E \approx \frac{(h_E - z_2)^2}{h_E - z_1} = \frac{\mathrm{Ri}_{Fc}(dU)^2}{bdq_v}$$

4. Modified Richardson number method. The SBL critical bulk Richardson number, Ri*Bc*, is not a constant and evidently increases with increasing free flow stability and very probably depends on the surface roughness length, the Coriolis parameter and the geostrophic wind shear in baroclinic flows. For practical use Zilitinkevich and Baklanov (2002) recommended:

$$\mathrm{Ri}_{Bc} \approx 0.1371 + 0.0024\frac{N}{|\,f\,|}$$

   where N is the Brunt-Väisälä frequency in the adjacent layer of the free atmosphere.

FUMAPEX

Critical values of the bulk Richardson number given by different authors

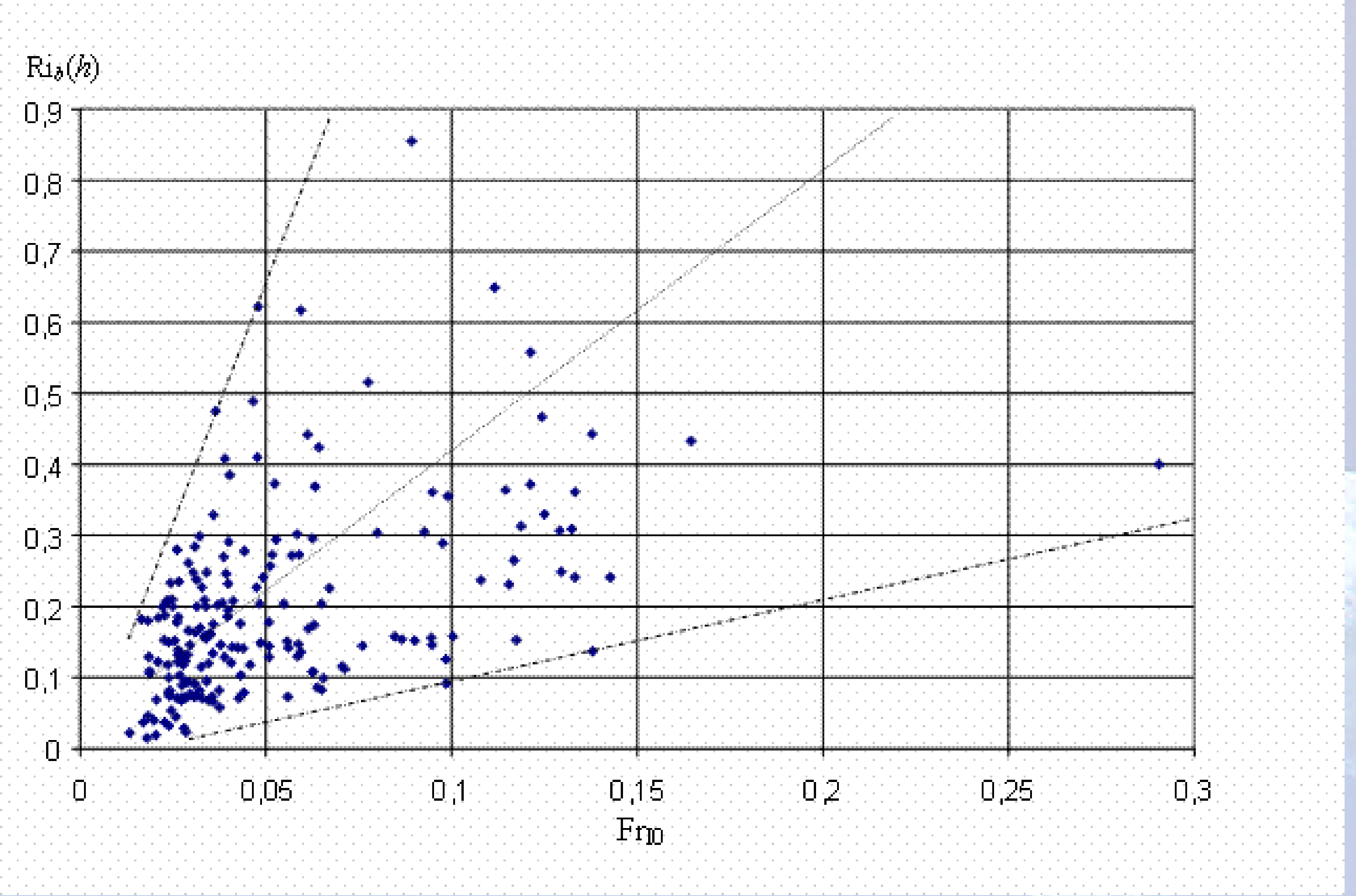
Variations from 0.1 up to 7

Alternative critical values of the bulk Richardson number Ri_{Bc} ($z_1 = z_2 = 0$) and the finite-difference Richardson number Ri_{Fc}.

Reference	z_1, *m*	z_2, *m*	$\mathrm{Ri}_{\{B,F\}c}$	*Comments*
Laikhtman, 1961	0	0	1.65	Ri_B in terms of geostrophic wind, data from Main Geo. Obs. expeditions in Russia
Hanna, 1969	0	0	0.33-0.56	Ri_B in terms of temperature gradients in lower 100 m, data from O'Neill, Nebraska
Melgarejo and Deardorff, 1974	0	0	Average 0.55 typical 0.3	Data from Wangara exp.; h determined through the wind maximum height, h_u
Brost and Wyngaard, 1978	1	1	0.11-0.22	Data from measurements and 2nd order closure model
Anisimova et al., 1978	0	0	up to 7	Lab experiments with down slope drainage flows (analysed by Mahrt 1981)
Zeman, 1979	$\frac{1}{2}h$	$\frac{1}{2}h$	0.5	Data on nocturnal jets over the Great Plains, O'Neill, h compared with the Brost – Wyngaard closure model
Mahrt et al., 1979	2	0	average 0.3-0.5 maximum 15	Data from Wangara, Risø, O'Neill and Haswell; h compared with h_u
Mahrt, 1981	0 2	0	0.5 – 1.0	Typical values of Ri_{Bc} or Ri_{Fc} from different sources
Wentzel, 1983	2	0	0.33	Wangara data (mainly for radiation dominated SBLs) with different estimates of h
Troen and Mahrt, 1986	0	0	0.5	Dara from LES (Deardorff model) and Wangara exp.
Byzova et al., 1989	0	0	0.6-1.0	Data on turbulence and mean profiles from 300-m tower, Obninsk, Russia, 1972-1974
Heineman and Rose, 1990	2	0	0.3-0.55 typical 0.33	Tethered balloon sounding, Filchner/Ronne Ice Shelf, Antarctica; h compared with h_u, the Zilitinkevich (1972) SBL height scale, and the height, h_q, of lowest q gradient discontin.
Holtslag et al., 1990	2	0	0.25-0.5	Best fit for radiosounding data from de Bilt
Holtslag and Boville, 1993	10	0	0.5	Modelling and radiosonde data from several sites
Sørensen et al., 1996	30	0	0.14-0.24	Ri_B from either HIRLAM or radiosoundings, h from radiosoundings at weakly stable SBLs, Jægersborg
Vogelezang and Holtslag, 1996	20 40 80	20 40 80	(i) 0.21–0.22 (ii) 0.30–0.32	(i) For nocturnal SBLs, (ii) for well-mixed SBLs – both from Cabauw-mast data and SODAR data (for h)
Fay et al., 1997	0	0	0.38	Ri_B from German NWP model and actual h from either radiosoundings or 2nd order closure model
Makshtas et al., 1998	2	0	0.4	Ri_F from aerological and balloon observations over Weddell sea; h compared with wind-maximum and inversion heights (h_u and h_i)
Andreas et al., 2000	0	0	0.4	Ri_B from radiosoundings at the Ice Station Weddell; h compared with h_u and h_i

DMI

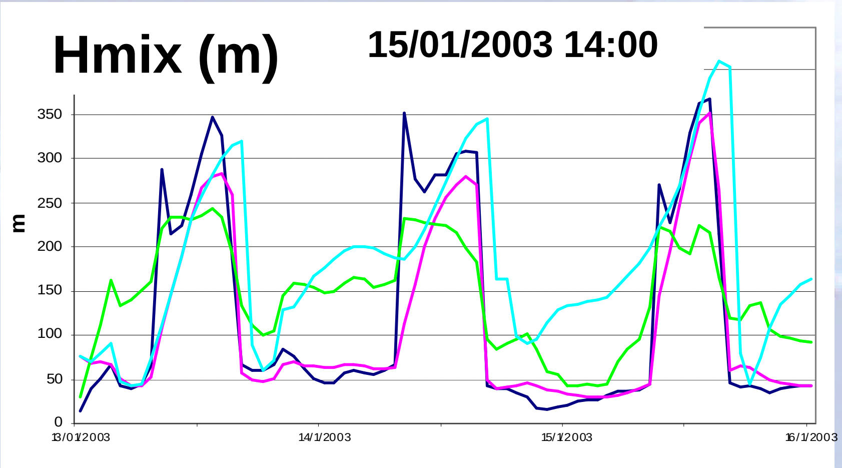
The standard critical bulk Richardson number, Ri*bc*, estimated at the measured SBL height versus the external inverse Froude number, FrI0, for the measurement data

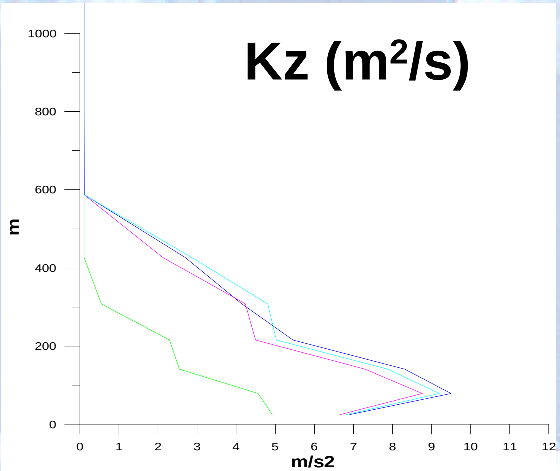


Baklanov (2001)

Improved interface module for UBL height

Upgraded and "urbanised" SURFPRO interface module: effects of OHM surface energy balance and MH schemes on dispersion parameters (P7-ARIANET)





MOST+Carson+ Zili72

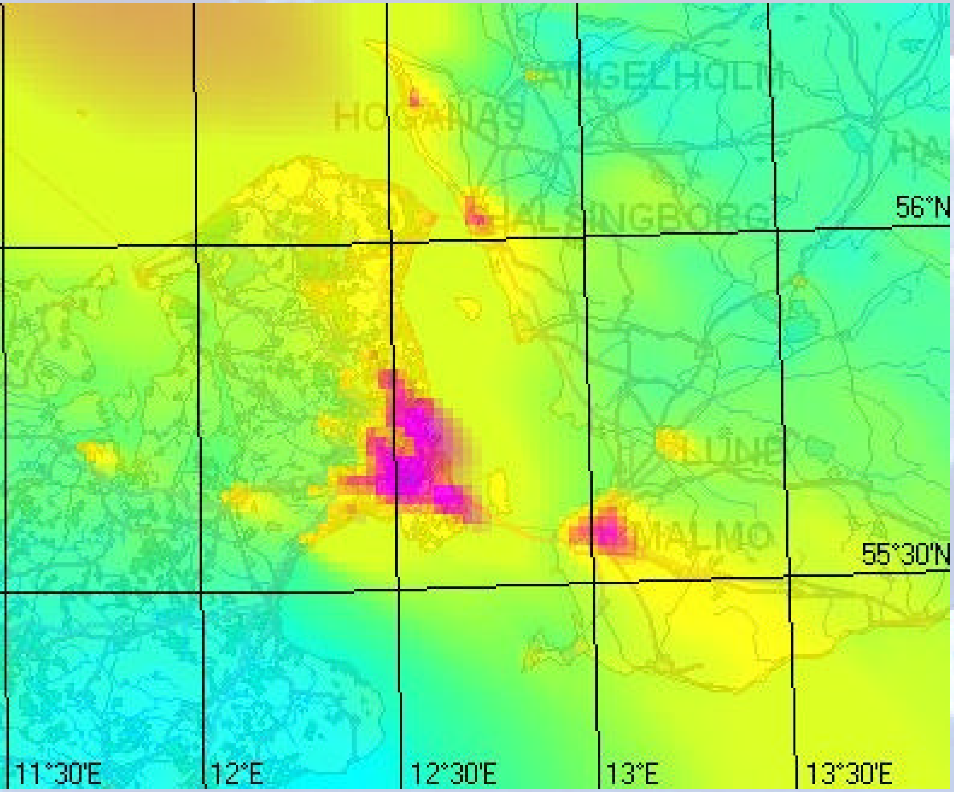
MOST+RiB

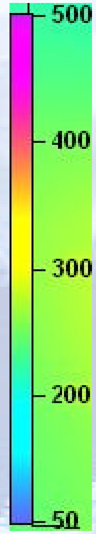
MOST+GB96+ZB02-adv/diff

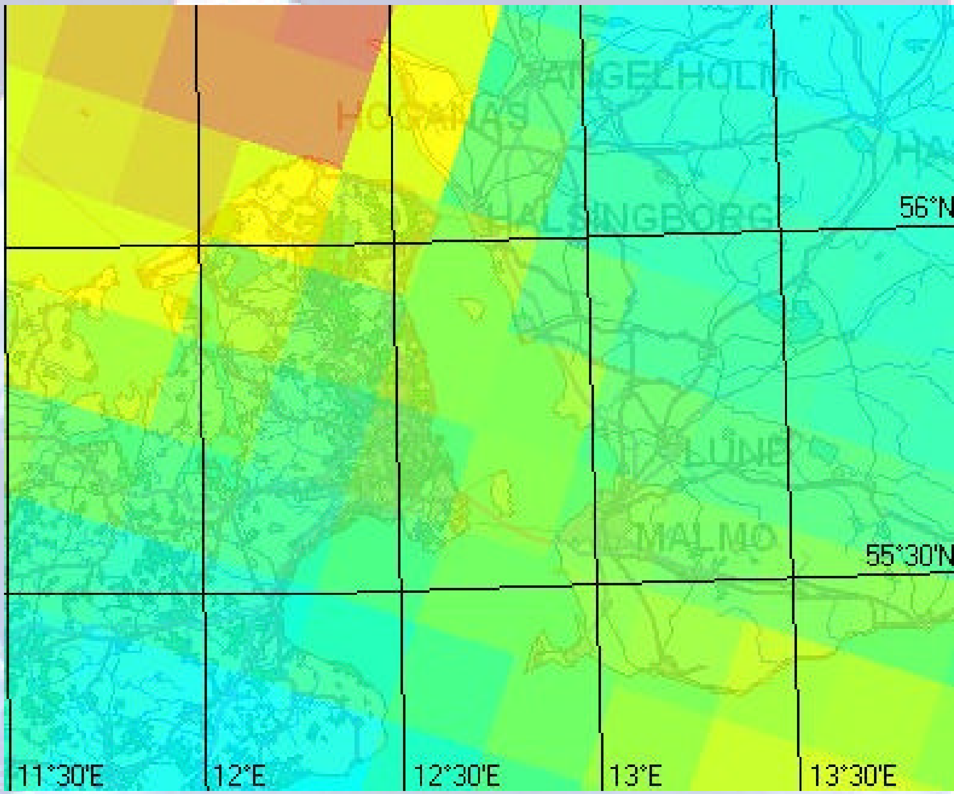
= + OHM Surf. Energy Balance

15/01/2003 14:00

The mixing height in ARGOS as calculated from different versions of DMI-HIRLAM

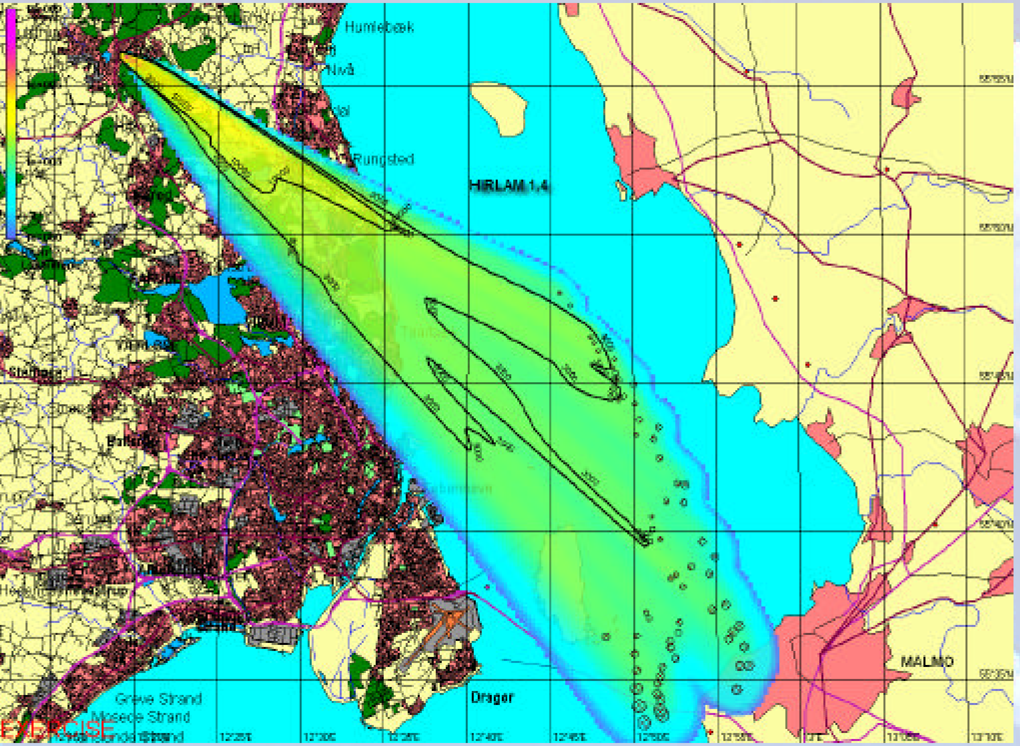




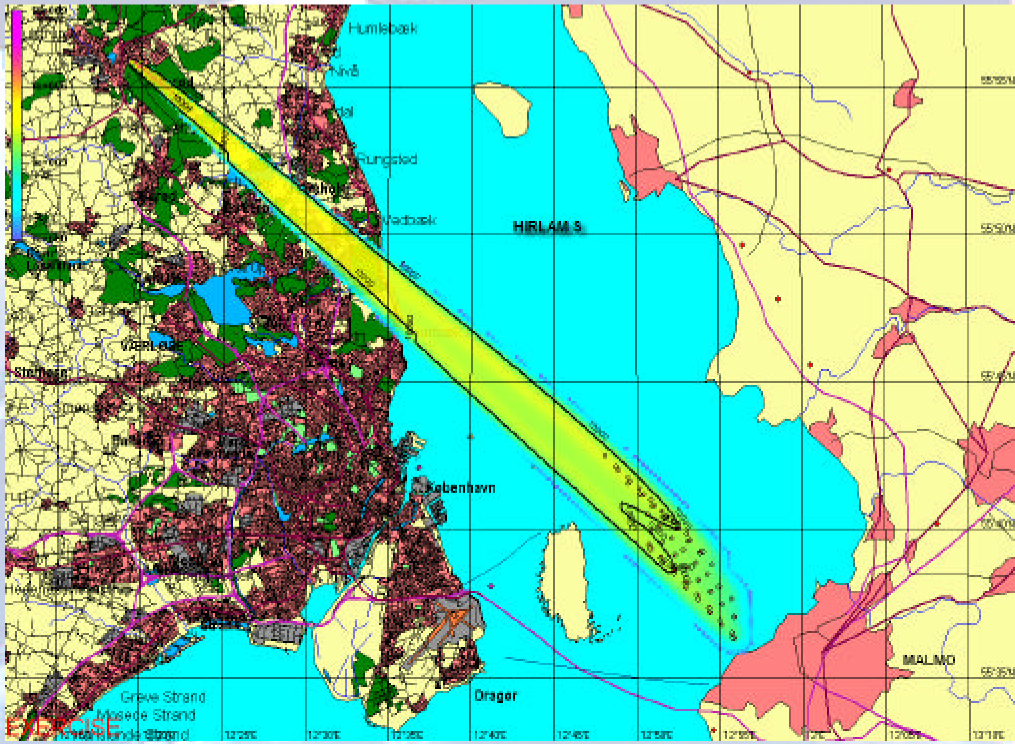


urbanised U01 **operational T15**

Sensitivity of ARGOS dispersion simulations to urbanized DMI-HIRLAM NWP data



urbanised U01, 1.4 km resolution

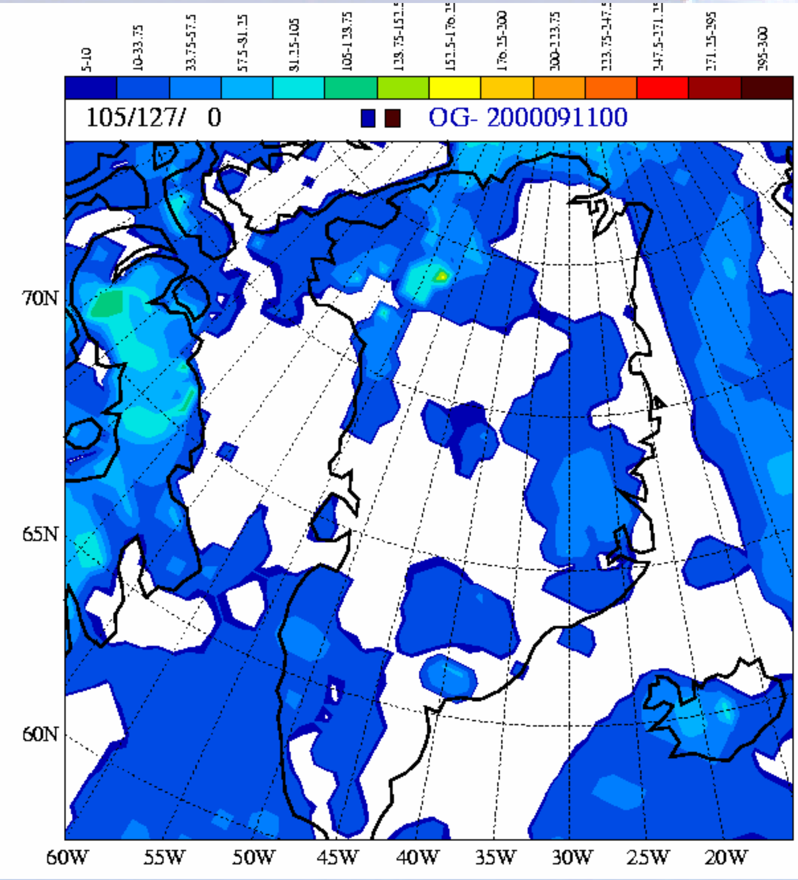


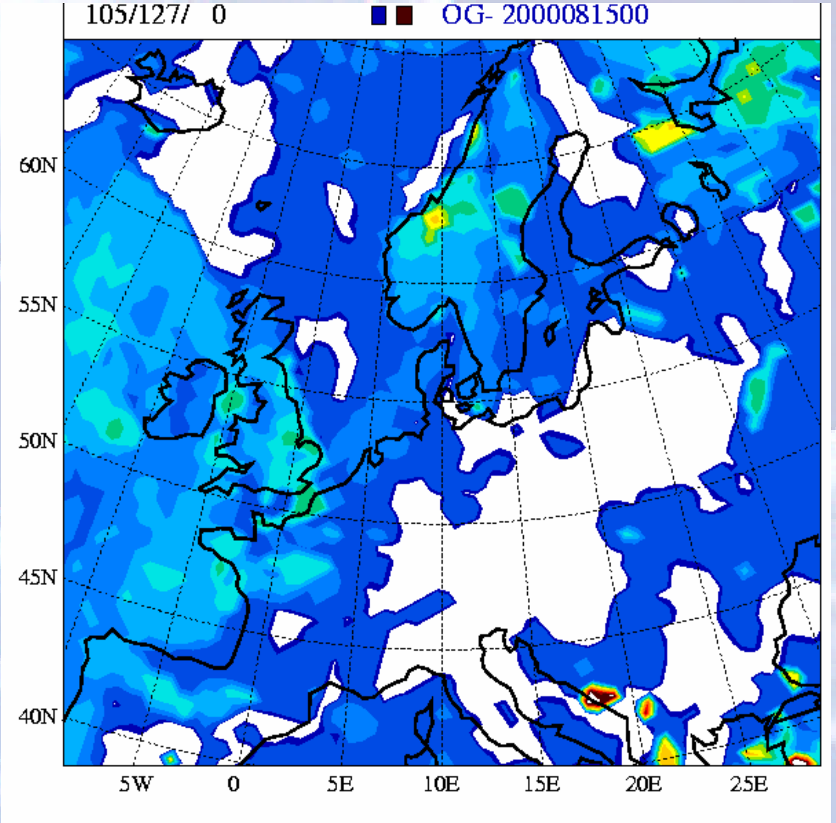
operational S05, 5 km resolution

Cs-137 air concentration for different DMI-HIRLAM data
A local-scale plume from the ^{137}Cs hypothetical atmospheric release in Hillerød at 00 UTC, 19 June 2005
as calculated with RIMPUFF using DMI-HIRLAM and visualised in ARGOS for the Copenhagen Metropolitan Area.

The nocturnal PBL height forecasted by the DMI-HIRLAM model

with the CBR scheme and the TKE decay approach for the PBL height for Greenland (left) and Europe (right)





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, 2007) 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 currently the urban effects in such models are not included or included with great simplifications.

(WG2 COST715: Baklanov, 2002)

FUMAPEX WP4 reports and issue:

(available from: *http://fumapex.dmi.dk*)

1. Baklanov, A. and Joffre, S. (eds.) (2003) Improved Models for Computing the Roughness Parameters of Urban Areas. / Baklanov, A., P. Mestayer, M. Schatzmann, S. Zilitinkevich, A. Clappier, etc. D4.4 FUMAPEX Report, November 2003. DMI Sci. Report 03-19, ISBNnr.: 87-7478-495-1, 51 p.
2. Mestayer, P., S. Dupont, I. Calmet, S. Leroyer, A. Mahura, T. Penelon, 2004: SM2-U : *S*oil *M*odel for *S*ub-*M*eso scales *U*rbanized version. Model Description. Deliverable D4.2 for FUMAPEX WP4, Project report, Spring 2004, Nantes, ECN, France.
3. Baklanov, A. and P. Mestayer (eds.), 2004: Improved parameterisations of urban atmospheric sublayer and urban physiographic data classification. / A. Baklanov, E. Batchvarova, I. Calmet, A. Clappier, J.V. Chordá, J.J. Diéguez, S. Dupont, B. Fay, E. Fragkou, R. Hamdi, N. Kitwiroon, S. Leroyer, N. Long, A. Mahura, P. Mestayer, N.W. Nielsen, J.L. Palau, G. Pérez-Landa, T. Penelon, M. Rantamäki, G. Schayes and R.S. Sokhi. D4.1, 4.2 and 4.5 FUMAPEX Report, April 2004, Copenhagen, DMI, Denmark. DMI Scientific Report: #04-05, ISBN nr. 87-7478-506-0.
4. Eastwood, S., V. Ødegaard and K.H. Midtbø (2004) Algorithms for assimilation of snow cover. D4.3 FUMAPEX Report, September 2004, Norwegian Meteorological Institute, Oslo. 21 p.
5. Baklanov, A. and S. Zilitinkevich (eds.) (2004) Parameterisation of nocturnal UBL for NWP and UAQ models. D4.6 FUMAPEX Report. Danish Meteorological Institute, Copenhagen. 70 p.
6. Hamdi, R. and Schayes, G. (2004) Improving the Martilli's urban boundary layer scheme: off-line validation over different urban surfaces, *FUMAPEX WP4 report.* UCL contribution. UCL, Louvain-La-Neuve, Belgium.
7. Baklanov (ed.) et al., 2005: Integrated and validated NWP systems incorporating urban improvements. M4.4 Report
8. Baklanov, A., S. Joffre, and S. Galmarini (Eds.), 2006: "Urban Meteorology and Atmospheric Pollution. EMS-FUMAPEX", Special Issue of *Atmospheric Chemistry and Physics* Journal, 2006, No 6.

PhD dissertations by FUMAPEX partners:

Long, N. (2003) Analyses morphologiques et aérodynamiques du tissu urbain : application à la micro climatologie de Marseille pendant la campagne Escompte, Thèse de Doctorat en Dynamique des Milieux Naturels et Anthropisés Passés et Actuels de l'USTLille, 5 décembre 2003.

Roulet, Y.-A. (2004) Validation and application of an urban turbulence parameterisation scheme for mesoscale atmospheric models, Thèse de l'EPFL n° 3032

Hamdi, R. (2005) On the study of the atmospheric boundary layer over urban areas with the urbanized version of TVM. Université catolique de Louvain, Belgium. PhD dissertation.

Fragkou, E. (2005) Application of a Mesoscale Model to Analyse the Meteorology of Urban Air Pollution Episodes. University of Hertfordshire. PhD Thesis.

Alessio D'Allura (2005) A three-dimensional numerical model for the prevision of air pollutant dispersion, transformation and deposition. Urban Air Quality Information and Forecasting Systems. Tesi di Dottorato. Matricola R00327. Universita' Degli Studi di Milano-Bicocca, Italy. Anno Accademico 2004-2005

Sylvie Leroyer (2006) Urban atmosphere numerical simulations with the model SUBMESO. Application on the Marseilles' agllomeration during the UBL-ESCOMPTE experiment. Superv. Patrice G. Mestayer and Isabelle Calmet, Ecole Centrale de Nantes. Ecole Doctorale "Mécanique, Thermique et Génie Civil", PhD Thesis.

Urban Meteorology and Air Pollution:
as a joint problem

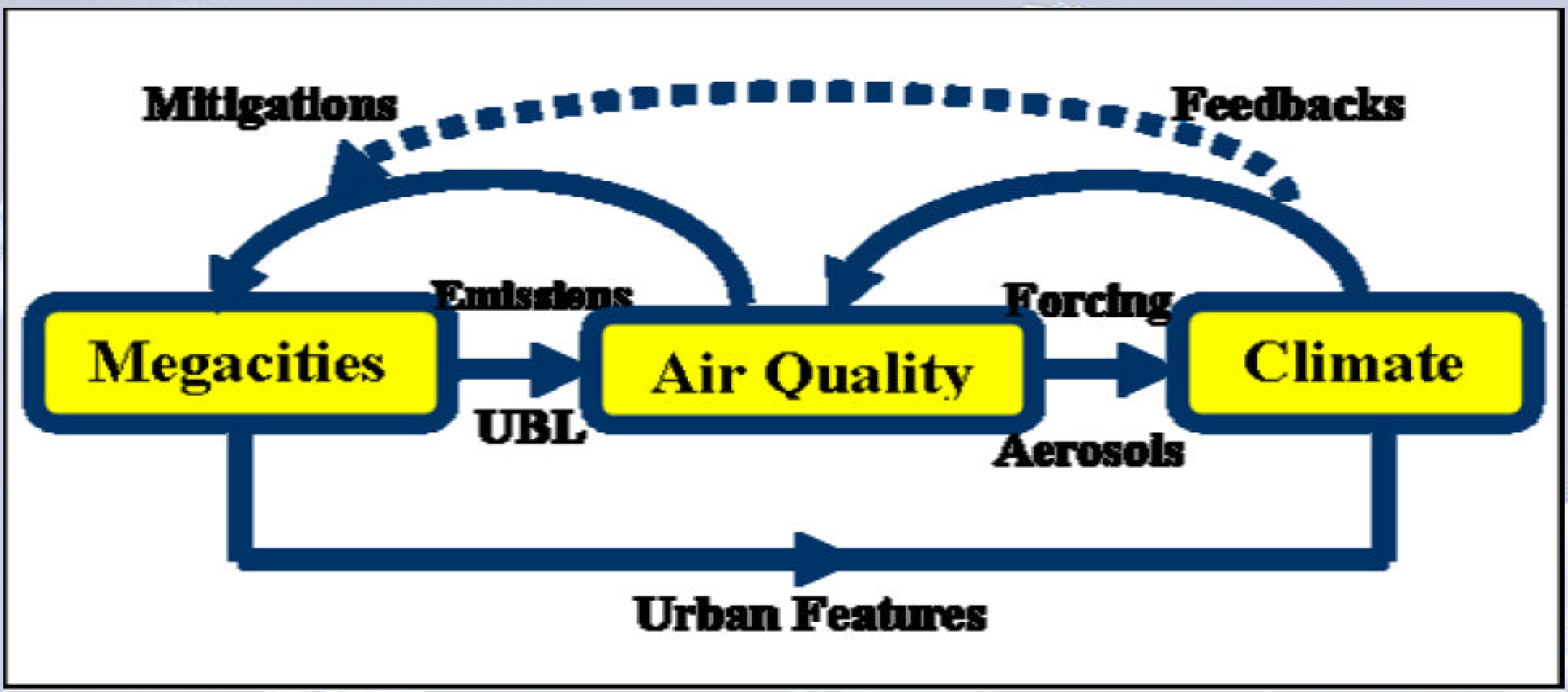
- **Meteorology is a main source of uncertainty in ACTMs => needs for meso-scale MetM / NWP model improvements**
- **Complex & combined effects of meteo- and pollution components (e.g., Paris, Summer 2003)**
- **Effects of pollutants/aerosols on meteo-processes (precipitation, thunderstorms, etc) and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

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

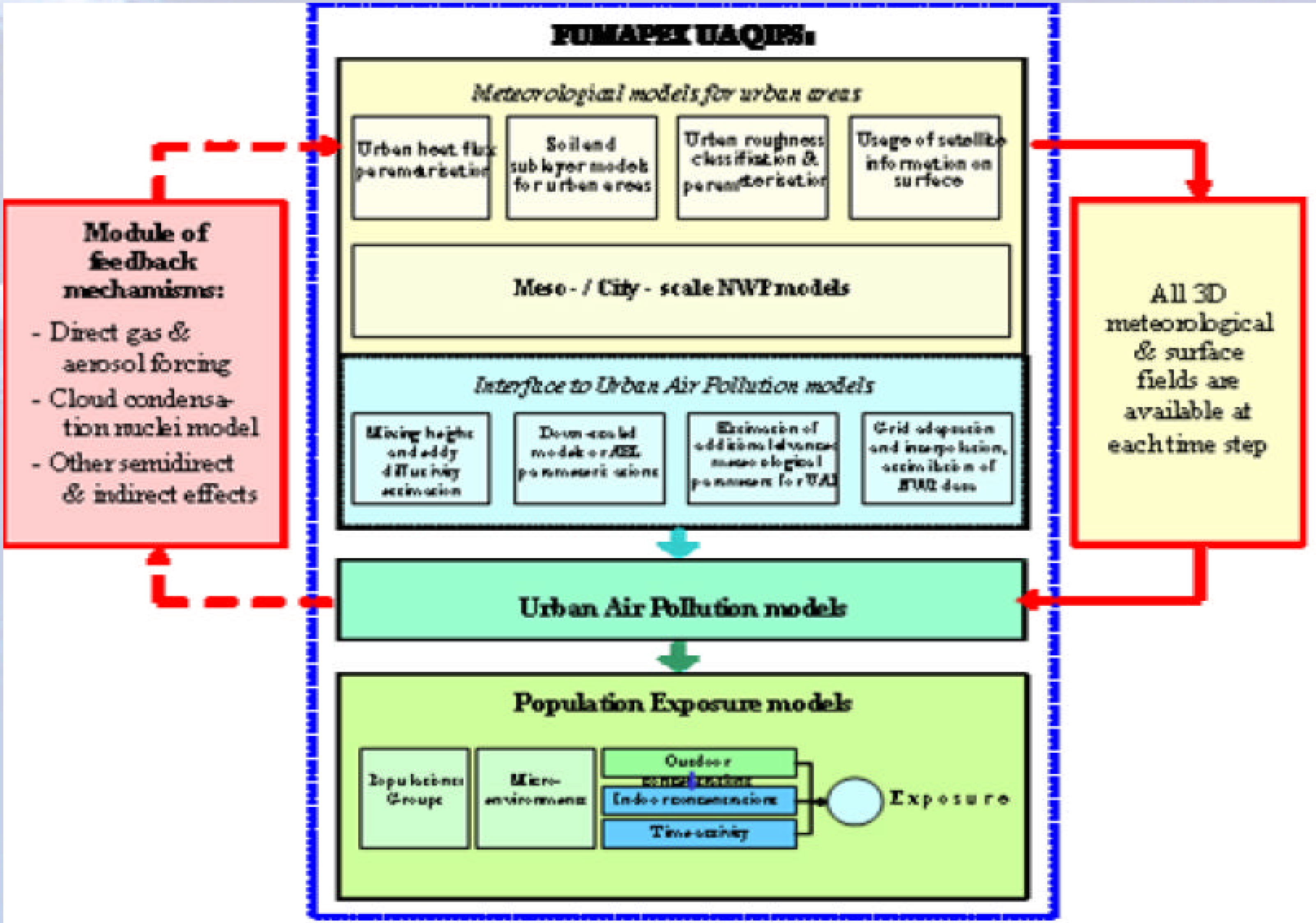
1. **Meteorology / ABL structure,**
2. **Chemistry,**
3. **Aerosol/pollutant dynamics**
4. **Effects and Feedbacks**

=> ***Integrated MetM & ACTM Approach***
("Chemical Weather Forecasting")

From FUMAPEX to Megacity & Climate



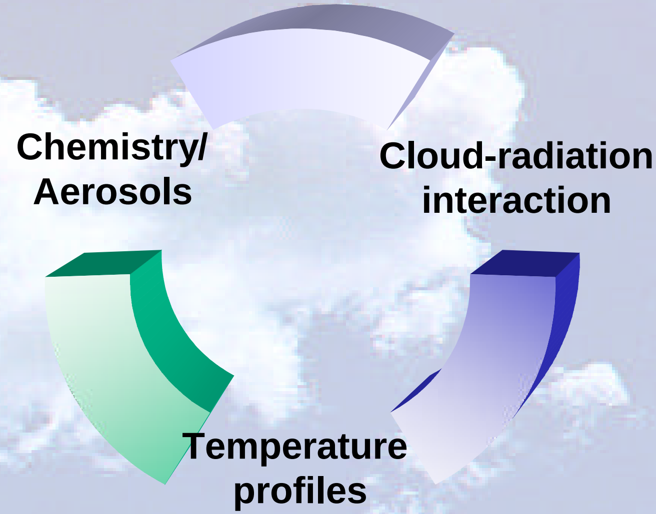
On-line integrated system structure

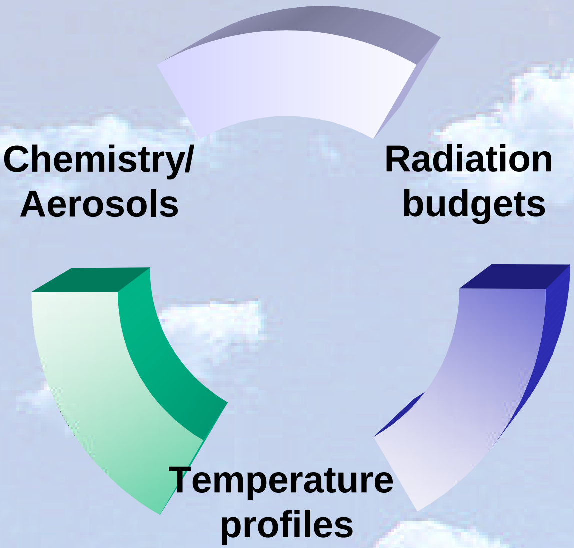


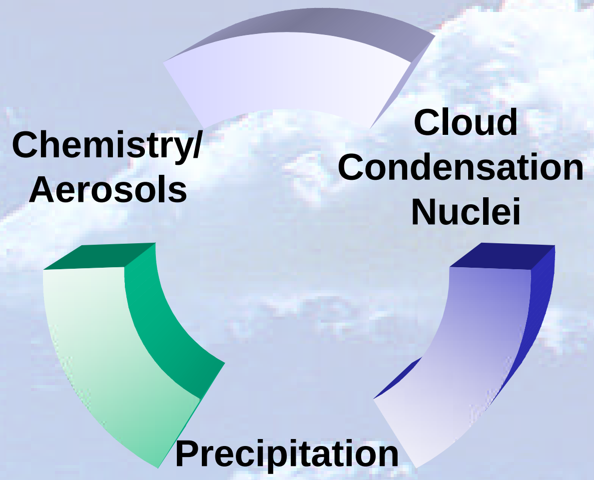
Extended FUMAPEX scheme of the improvements of meteorological forecasts (NWP) in urban areas, interfaces and on-line integration with UAP and population exposure models for urban air quality information forecasting and information systems (UAQIFS).

Examples of feedbacks

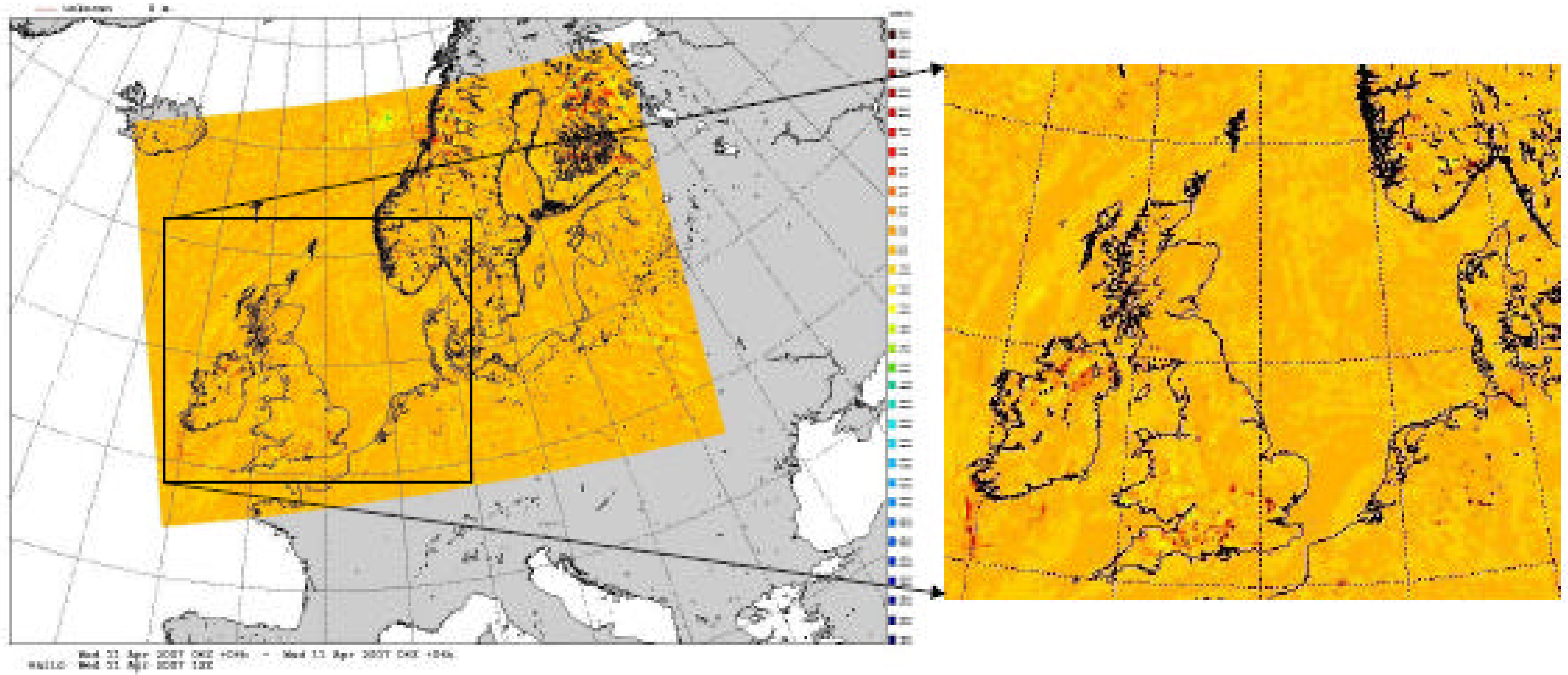
- Photochemistry effect
- Daytime stability effect
- Indirect effect
- Semi-direct effect
- Smudge-pot effect
- Self-feedback effect







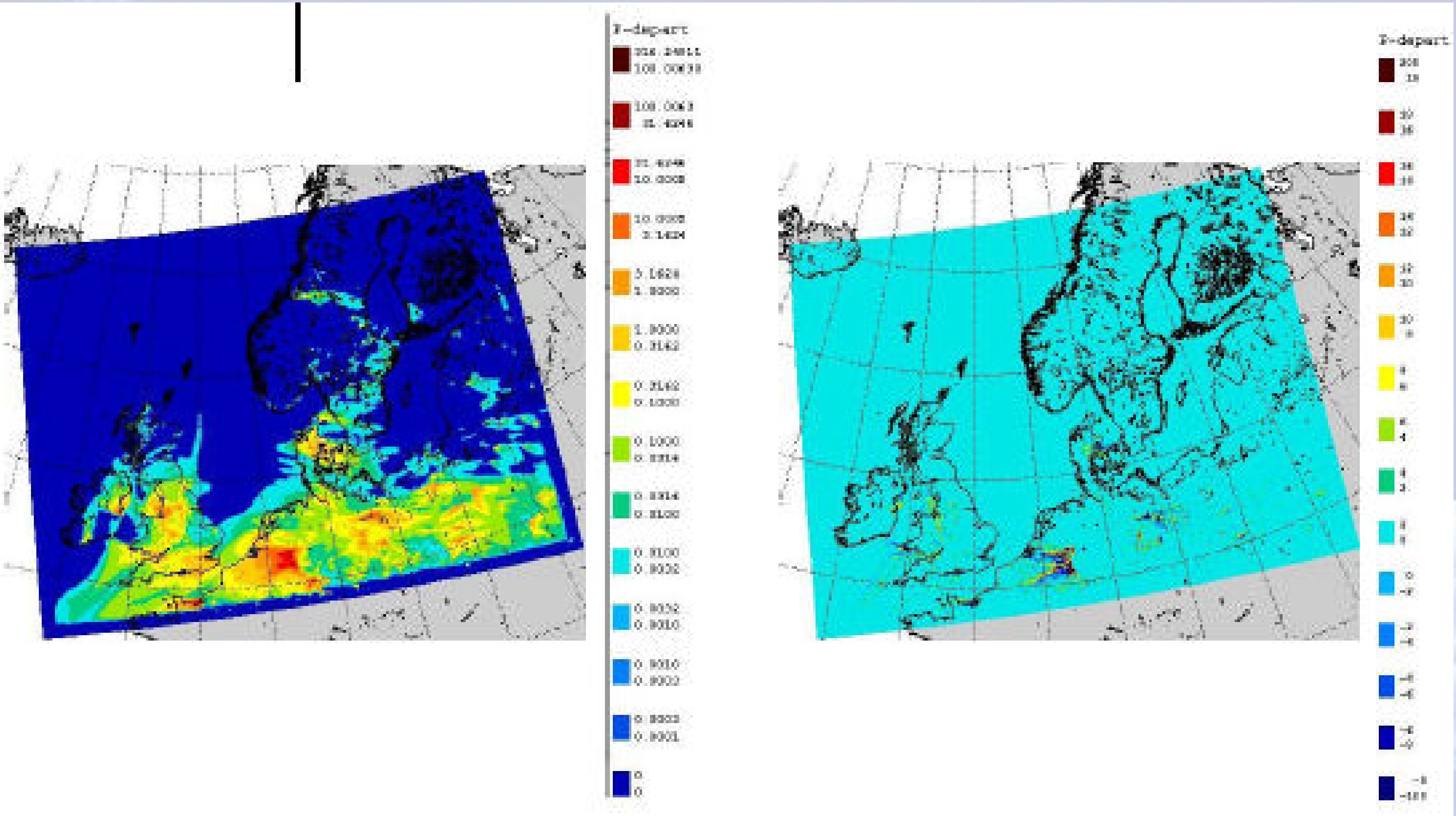
Urban Aerosol Feedbacks on PBL Height



PBLH (m) average from 06 UTC 11-04-2007 to 06 UTC 13-04-2007

At a given time the increase in boundary layer height may of the same order (100 m) as the effect of urban representations on boundary layer height.

Urban Aerosol Feedbacks on Deposition



Accumulated dry deposition (left) and difference in dry deposition (right) in µg/m² at 06 UTC 13-04-2007. Max difference app. +/- 100 µg/m²

European COST Actions (2005-2009):

Action 728: "Enhancing Meso-scale Meteorological Modelling Capabilities for Air Pollution and Dispersion Applications"

Coord. – *Ranjeet S Sokhi* , University of Hertfordshire

- **WG1: Meteorological parameterization/ applications (*Maria Athanassiadou*, Met Office)**
- **WG2: Integrated systems of MetM and CTM: strategy, interfaces and module unification (*Alexander Baklanov*, DMI)**
- **WG3: Mesoscale models for air pollution and dispersion applications (*Mihkail Sofiev*, FMI)**
- **WG4: Development of evaluation tools and methodologies (*Heinke Schluenzen*, University of Hamburg)**

Action 732: 'Quality Assurance and Improvement of Micro-Scale Meteorological Models'

Coord. –*Michael Schatzmann*, University of Hamburg

For more information:

FUMAPEX web-site: ***http://fumapex.dmi.dk***

COST 728 web-site: ***http://www.cost728.org***

Thank you !